Geoinformation System for Analytical Control and Forecast of the Earth's Magnetosphere Parameters

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Abstract: Geomagnetic field and its variation can influence on systems and objects of various origins. The estimation of the influence requires an effective approach to analyze the principles of distribution of geomagnetic field parameters on the Earth's surface, its subsoil and in circumterrestrial space. The main thing here is how to register and monitor parameters of geomagnetic field both globally and for the given geodetic coordinates. All data measured and collected about geomagnetic field is distributed in various sources and storages. It is obvious that necessity in integrated information space is very acute. Development of such integrated information space will provide a possibility to get any data about geomagnetic field at any point of the Earth's surface at any moment of time. The obvious way to solve the problem is to implement innovative information technologies there. In particular the most expectations are about using geoinformation systems to solve the problem. In this paper the authors suggest an approach to study, monitoring, analyze and visualize space weather and geomagnetic field parameters, which is based on modern Web and geoinformation technologies. This solution is the project GEOMAGNET with four web services and mobile applications included.

1 INTRODUCTION

"Data is next Intel Inside" is one of the key principles of modern information technologies. One of the best examples of this is a special class of information systems, which is widely known as GIS. GIS stands for geographical information system and is aimed to store, query, manipulate and display geospatial data which is referred to information explaining where something is and what is at a given location. In other words GIS can process any data which contains location (geodetic latitude and longitude, address, etc.). With GIS this data can be overlaid on top of one another on a single map. GIS may be used for any number of different purposes and may combine countless sources of data that can be manipulated and updated at any time.

In the modern World, specialists in many spheres pay great attention to correlations between external geomagnetic variations (GMV) and 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).

The problem of monitoring of geomagnetic field (GMF) and its variations parameters is partially solved by a number of magnetic observatories – scientific organizations for parametric and astronomical observations of the Earth's magnetosphere (Vorobev and Shakirova, 2015). The registered information is regularly sent to the International centers in Russia, USA, Denmark and Japan, where the information is registered, analyzed and partially available to the broader audience with some delay. All data measured and collected about geomagnetic field is distributed in various sources and storages. It is obvious that necessity in integrated information space is very acute. Development of such integrated information space will provide a possibility to get any data about geomagnetic field at any point of the Earth's surface at any moment of time. And the initial step here is concerned with specialized applications which

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provide calculation of parameters of normal (undisturbed) geomagnetic field in real-time mode for any point on the Earth's surface.

The obvious way to solve the problem is to implement innovative information technologies there. In particular the most expectations are about using geoinformation systems to solve the problem. In this paper the authors suggest an approach to study, monitoring, analyze and visualize geomagnetic field, its variations and anomalies, which is based on modern Web and geoinformation technologies.

2 GEOMAGNETIC FIELD AND ITS VARIATIONS

The first question to be discussed is what geomagnetic field is and why is it important to study this subject? According to the modern science, the Earth's outer core is liquid and mainly iron. Its chemical elements (such as iron and nickel) respectively make ~85.5 % and ~5.2 % of Earth's core mass fraction, i.e. totally more than 90 %. Permanent rotations of the Earth and its core cause the constant flows inside of the core and corresponding electric currents. According to the laws of magnetic hydrodynamics, these flows and currents provide the existence of geomagnetic field (Campbell, 2003).

Geomagnetic field 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 terrestrial objects / processes on the Earth's surface, subsoil and in near-Earth space (Mandea, 2011)(Merrill, 1996).

Because of the permanent interaction with the magnetic fields, which are generated by the Sun, the planets of the Solar system and other celestial bodies and systems, the Earth's magnetic field can be significantly deformed. Herewith geomagnetic field becomes some kind of protective shield, which prevents a penetration of the Solar wind to the geospace (the Solar wind is a flow of ionized particles, which radially spreads from the solar corona to the outer space). The Solar wind interacts with this barrier, flows around the Earth and creates a special region with the geomagnetic field inside, which is known as the Earth's magnetosphere with its typical teardrop shape.

Geomagnetic variations are declinations of observed amplitude parameters of the Earth's magnetosphere from the calculated values, which are defined as a normal (or undisturbed) state of geomagnetosphere. The events and processes, which cause geomagnetic variations, have various and independent origin. Besides, all local and global deformations of geomagnetosphere significantly differ by both their amplitude-frequency and probabilistic estimations and characteristics. As a result the actual picture of geomagnetic field is a complicated superposition of probabilistic set of geomagnetic variations, which are caused by the number of uncoordinated events. That's why their estimation by traditional physical quantities (magnetic field intensity, frequency, magnetic induction, etc.) is useful.

Today the specialists in many scientific and applied spheres (such as biology, medicine, geophysics, geology, technics, sociology, psychology and many others) consider parameters of geomagnetic field and its variations as one of the key factors, which can influence on systems and objects of various origins. They pay great attention to correlations between external geomagnetic variations and existence and evolution of various objects and systems.

This interest is based on idea that some components of geomagnetic variations or their combinations can influence on biological, technical, geological and other objects and systems in common and on human in particular. As a result, distorted normal conditions of existence force these objects and systems to either adapt to changes of magnetic state (via deformation, mutation, etc.) or keep existing there in stressed (or unstable) mode (Vorobev and Shakirova, 2015).

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 geomagnetic field of magnetosphere currents, which is calculated in solar-magnetosphere coordinate system; $\boldsymbol{B}_3$ is a geomagnetic field intensity vector component with technogenic origin.

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

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

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

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

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

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

where r is a distance from the Earth's center to the observation point (geocentric distance), [km]; λ is a longitude from Greenwich meridian, [degrees]; θ is a polar angle (collatitude, θ = (π/2)-φ', [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 geomagnetic field.

The amount of performed spherical harmonic analysis is significant. However a problem of spherical harmonic optimal length is 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 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 temporal variations of the main field the coefficients of harmonic series (spherical harmonic coefficients) are periodically (once in 5 years) recalculated with the new experimental data. The changes of the main field 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).

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

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

3 GIS TO ANALYZE AND VISUALIZE GEOMAGNETIC FIELD

The most common problem to be solved is to calculate parameters of normal geomagnetic field in the point with given geographical coordinates. Its solution is based on applications of special type which are known as geomagnetic calculators. Here is a list of the most popular services:

- NGDC NOAA (http://www.ngdc.noaa.gov/geomag-web/)
- INTERMAGNET (http://www.intermagnet.org/data-donnee/data-eng.php)
- British Geological Survey (http://www.intermagnet.org/data-donnee/data-eng.php)
- U.S. Geological Survey (http://geomag.usgs.gov/)
- etc.

All of them provide the simplest functionality. When a user enters a location to be calculated, the application estimates parameters of geomagnetic field in the point. The common problem here is concerned with defining a location to be studied. All applications provide simple input fields for geodetic coordinates of the point. A user has to know exact parameters of the place that is impossible sometimes. So, it is a limitation of the application, and some users are aware of using it due to this reason.

Another problem is reliability of calculation results. It is well-known that parameters of geomagnetic field depend on three values: latitude, longitude and altitude of the point. All applications suppose altitude as 0 km by default, so results of calculation are correct just for this elevation. A user can enter the altitude value into input field, but these data is also specific. Nobody knows the elevation of his position (except the professionals). So, this value is always referred to as 0.

To improve geomagnetic calculators the authors suggest the following points to be added:

- maps, e.g. geographical information technologies. Geomagnetic field is estimated by geodetical coordinates of a given point on Earth. This class of data is referred to as geospatial and is traditionally processed by geoinformation systems and technologies. With a map in application a user can simply pick up the point by mouse clicking.
- altitude calculation. To increase the accuracy of calculation it is necessary to provide an actual value of an altitude of the given point. The best solution is to get the value automatically on the basis of geodetic latitude and longitude of a point. However this feature does not exclude a possibility of correcting data just to see how magnetic field changes with elevation.
- visualization. The most popular approach to visualize parameters of geomagnetic field is a set of contours. Each contour is a curve along which the parameter of geomagnetic field has a constant value. A user chooses a parameter to be visualized and the system renders on the map a set of contours, which represent a distribution of magnetic field on the Earth's surface.
- three-dimensional representation. It is obvious, that in this case geoinformation system provides much more information than any other system or technology. And it is even more important due to the dynamic properties and multilevel scale ability.

To provide the defined requirements the authors suggested and developed specialized Web-based information system for calculation of parameters of geomagnetic field "S-Service" (Geomagnetic Calculator (WMM2015)) – one of the four services provided by GEOMAGNET.

4 WEB-PORTAL "GEOMAGNET"

In 2014 GIMS Research Laboratory (Russian Federation) with support of Russian Foundation of Basic Research introduced an innovative geographical web-portal "Geomagnet" (http://www.geomagnet.ru/index-en.html) with four services providing observation, analysis, three-dimensional visualization and calculation of parameters of geomagnetic field.

One of them is the application (service) for calculation of parameters of normal geomagnetic field – S-Service (http://www.geomagnet.ru/S/index-en.html) (Vorobev and Shakirova, 2015).

S-Service (Geomagnetic Calculator (WMM2015)) is a Web-based application providing calculation parameters of geomagnetic field and secular variations according to the set of coordinates and dates (Fig. 1). 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.

S-Service is a responsive application which does not depend on device type and parameters and looks and works similarly at any devices – from phones to tablets to desktops. This platform- and device-independency is realized on the basis of special framework "Bootstrap" (http://getbootstrap.com/) that is a set of programming libraries for HTML, CSS and JavaScript (JQuery). Flexibility and performance of the application are also increased by supporting HTML5 and CSS3 standards.

Interface of the application consists of two functional parts. First (and the biggest) panel was developed for map rendering. All manipulations with geospatial data are visualized in this area (markers, zoom, geolocation, contours, etc.). Another panel is used to display information about both initial (spatiotemporal coordinates) and calculated (characteristics of geomagnetic field) parameters. Information panel also provides a possibility to see coordinates of the mouse pointer during its moving on map.

Functions providing map rendering and functionality are based on two APIs: ESRI ArcGIS for JavaScript and Google Maps API. Depending on the demand and available functionality scripts in the application operate with either one or both of them. For example, to initialize the map the following ArcGIS API functions are used:

```
require(["esri/map",
"dojo/domReady!"], function(Map) {
  map = new Map("map", {
    basemap: "streets",
  center: [54.7249, 55.9425],
  zoom: 5,
  minZoom: 3,
    sliderPosition: "top-right"
   });
});
```

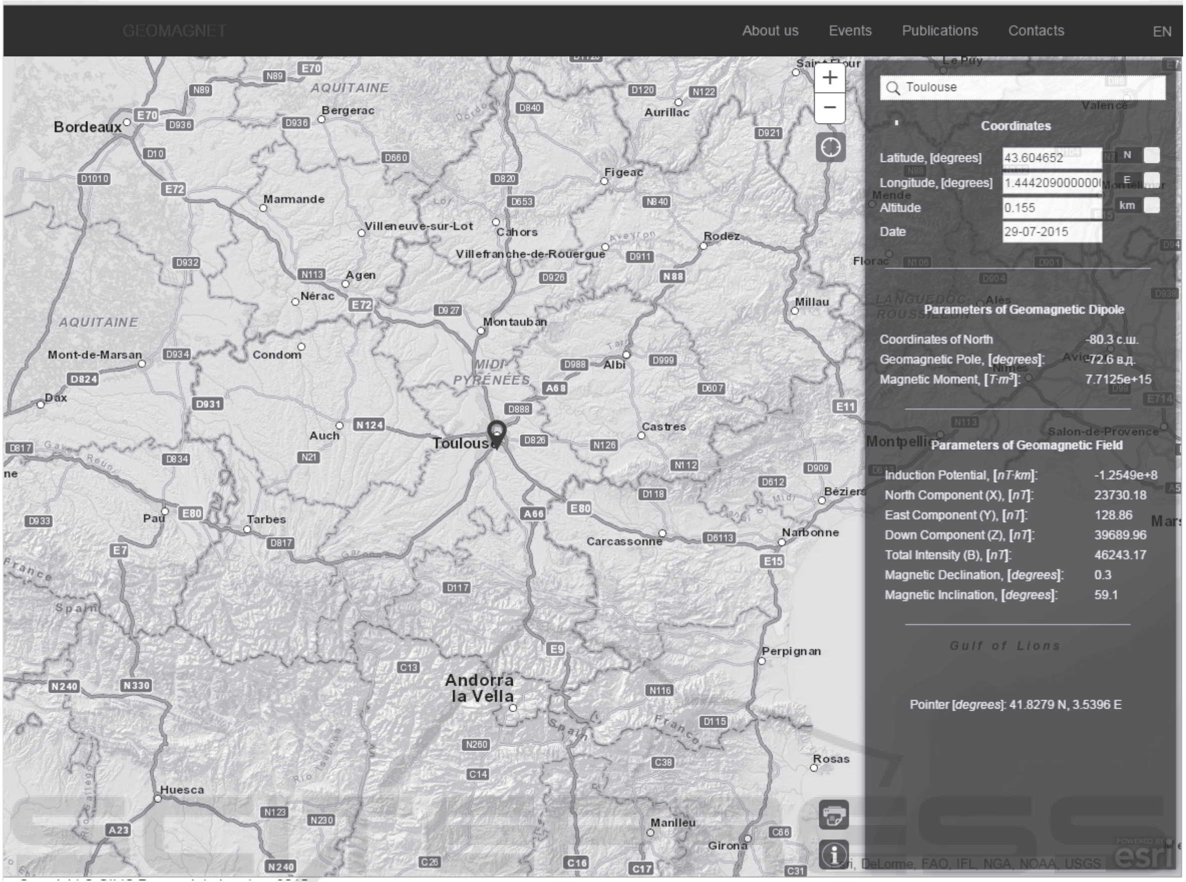

Figure 1: S-Service / Geomagnetic Calculator (WMM2015) (http://geomagnet.ru/WMM/index.html).

The code fragment creates a map instance which is centered at default coordinates (54.7249, 55.9425) and located in "div" HTML-element with id equal to "map". Due to demands of interface conception the "sliderPosition" option is also set. This option sets a position of zoom slider on the map and it is necessary to declare it in map initialization code, because CSS settings of map elements can be just partially changed from ESRI CSS (http://js.arcgis.com/3.12/dijit/themes/claro/claro.css).

To calculate parameters of geomagnetic field a user has to define spatiotemporal coordinates of the point on the Earth's surface. In S-Service geodetic latitude and longitude can be defined by various ways.

The simplest way to define the current geographical position of the user is a geolocation function (Haklay, 2007). This function takes IP address of device, which a user operates to access the Internet. This possibility allows the user to get the point without its searching on the map or filling the appropriate input fields.

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

Both mentioned ways of point definition do not require exact coordinates of location. All necessary geospatial data can be obtained automatically. More complicated way is concerned with entering coordinates into input fields. It is a good way to calculate parameters of geomagnetic field and see the point on map with high accuracy (up to a few meters). After that the application displays the point on the map and the parameters of normal geomagnetic field there.

Also S-Service provides a geocoding functionality to define a point to be calculated. Geocoding is a transformation from address full form "postal code, country, city, street, building number" or short form (just one item or their combination) into the coordinates set "north latitude, east longitude". To find the point a user enters address of the place he is interested in.

Parameters of geomagnetic field in the geographical point depend on its elevation. With defined geographic coordinates S-Service gets elevation value automatically. However ArcGIS API does not provide any obvious methods to get this value. That is why there is another cartographical technology in S-Service code – Google Maps API. In the API the application uses a special service "ElevationService" which provides elevation data for all locations on the Earth surface. It is an object with an asynchronous interaction: after sending a request to the server a user (or a web page) does not wait for its response and keeps performing all existing operations (or start new ones) in background mode.

Parameters of geomagnetic field are calculated according to mathematical model that is represented in previous chapters. Its program realization in PHP is a set of functions to calculate such parameters as:

- 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.

PHP script of calculation of parameters of geomagnetic field generates result set in XML format. In S-Service XML is preferred format due to large amount of parameters and the necessity of their processing and decomposition on client side. There are also some other known approaches to get a set of different values, but this way seem to be the most effective for the authors.

It is important to mention that this realization is based on the authors-suggested algorithm of calculation of parameters of geomagnetic field. The algorithm supposes special scheme to minimize the possible error because of the rounding. The error of the calculation is less than 2 %.

Geomagnetic variations are mainly caused by events of the solar activity (space weather). Its parameters are measured in 24-7-mode by satellites and ground observatories. However the problem is still the same: a lot of heterogeneous data, which is hard to find and use. Real-time mode monitoring of the space weather is provided by another service in web-portal "Geomagnet". This application is M-Service ("Space Monitoring of GMF Parameters").

M-Service is a powerful tool for monitoring, analysis and three-dimensional representation of the geomagnetic field parameters (Fig. 2). Data is obtained from satellite observations in real time mode. A user can choose single or group of parameters and visualize them on globe with both histograms and isolines, generated according to data in KML format.

The service is based on technology of a software interface for accessing graphics hardware from within a web browser without installing additional plug-ins. In particular realization of M-Service is based on Cesium API – a set of modern technologies of globe rendering in Web via HTML5, the most important of which is WebGL.

An instance of the globe is created with "Viewer" a base Cesium widget for building applications:

```
var viewer =
new Cesium.Viewer('cesiumContainer',
{ homeButton:false,
   navigationHelpButton:false,
   baseLayerPicker:false});
```

An interface to datasources, which turn arbitrary KML-data into an "EntityCollection" for generic consumption is performed with special method-constructor "KmlDataSource":

```
var dataSource =
new Cesium.KmlDataSource();
```

The innovation solution of web-portal "Geomagnet" is a web application "**G-Service**", which provides registration and visualization of partial observations of the geomagnetic field with a high density distribution over the surface of the Earth (Fig. 3). The data comes on the portal from mobile devices with the developed in the laboratory GIMS application G-module (https://play.google.com/store/apps/details?id=com.hiktronic. Gims4rc). The application detects and transmits to the server measurement data from the magnetic sensors, which are inbuilt in the vast majority of today's mobile devices.

Along with control, visualization and processing of the parameters of geomagnetic field and its variations web-portal "Geomagnet" is a powerful tool for monitoring and analyzing the space weather.

Space weather parameters are measured by both astronomical and geophysical observatories and satellite observations. Measured data is stored in heterogeneous sources – relational databases, textual files, image data, etc. However the most of the data is available via web services, for example, from NOAA Space Weather Prediction Center (http://www.swpc.noaa.gov/SWN).

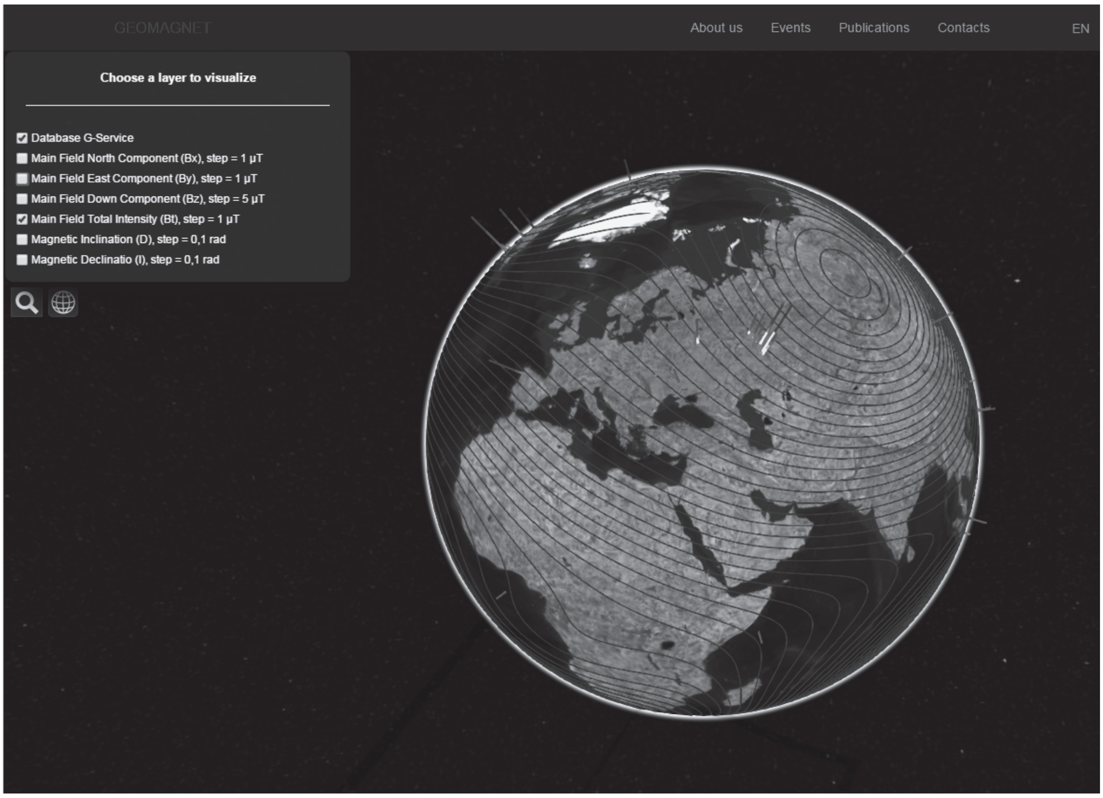

Figure 2: M-Service (http://geomagnet.ru/M/index.html).

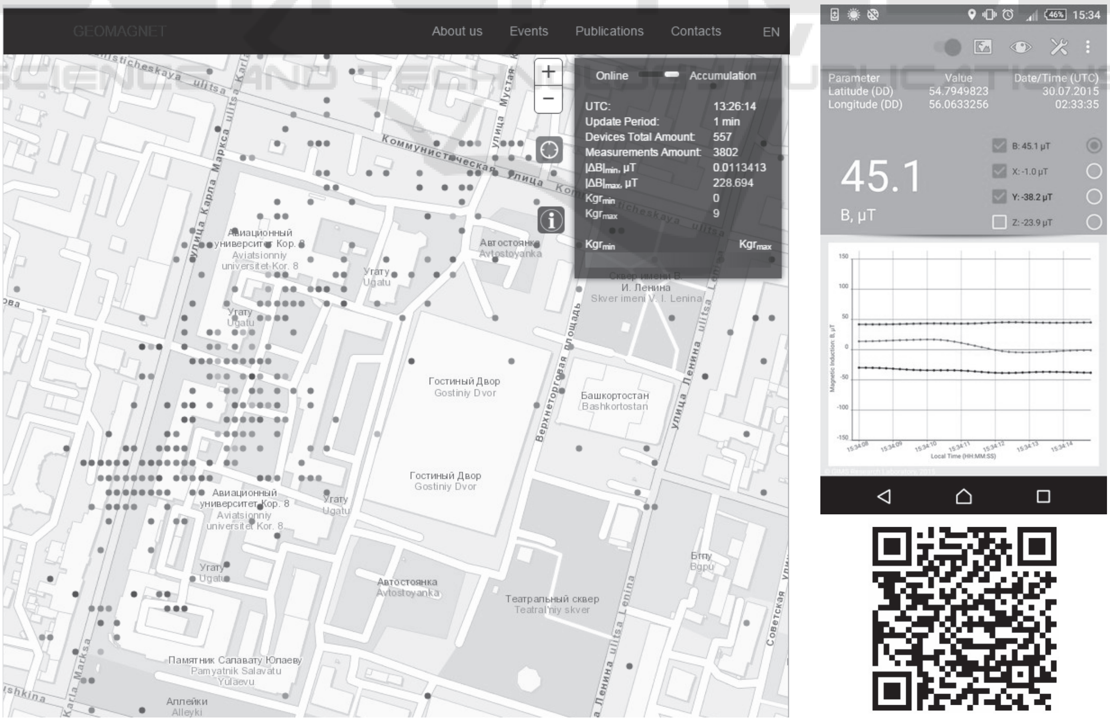

Figure 3: G-Service (http://geomagnet.ru/GroundMonitoring/) and G-module.

Web application "**I-service**" ("Solar Activity: Monitoring and Analysis") allows users to monitor solar weather in real time (on the basis of satellite observations) and carry out a comprehensive analysis of its parameters, to assess how their values change for different periods of time (from one hour to several days). Data analysis is also available in amplitude and frequency mode by single or groups of parameters of space weather.

It is also necessary to mention that GEOMAGNET includes a set of mobile applications: "Ground Monitoring App", "Solar Activity App", "Intellection Test Module App", "Magnetic Error Calculator App" and others. The applications provide collection and transmition of data about magnetic state parameters. Today the applications are widely used by specialists in geophysics, medicine, metrology and many other areas (about several thousand downloads all around the world). Data obtained is stored on server and available via web-portal "Geomagnet", so any user can access it anywhere anytime.

5 CONCLUSION

Geomagnetic field 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. Geomagnetic field and its variation can influence on systems and objects of various origins. The estimation of the influence requires an effective approach to analyze the principles of distribution of geomagnetic field parameters on the Earth's surface, its subsoil and in circumterrestrial space. The approach causes a complicated problem to be solved, which is concerned with modeling and visualization of geomagnetic field and its variations parameters. The most effective and obvious solution to this problem is supposed to be a geoinformation system.

Web-portal "Geomagnet" (Russian Federation) provides the complex calculation, analysis and 2D/3D-visualization of geomagnetic field and its variations parameters. Geomagnetic field and its variations models, which are represented and described by "Geomagnet", meet the requirements of specialists in various areas. They effectively provide formatting and structuring the data about the Earth magnetosphere parameters and their further analysis.

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