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Glyph-Based Approach to Web Rendering of Geophysical Fields in Geoinformation Systems

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Abstract

One of the significant problems in visualizing geophysical fields is the inability to simultaneously represent them as an integrated spatial layer, taking into account the complex nature of the parameters being analyzed. Currently, the designated visualization task is solved by decomposing the set of parameters into separate components, followed by rendering spatial layers that are not connected to each other either visually or logically. As a result, information that is important for research or decision-making is lost due to excessive overload of the geopatial image.

The paper proposes an approach to visualizing multicomponent geophysical fields based on graphical primitives called tensor glyphs, which are combined into a single spatial layer to represent several components of the geophysical field. Each individual image is a superellipse, composed of ellipses distributed along the axes and scaled according to the analyzed values, whose intersection points with each other and with the axes provide reference points connected using Lamé curves.

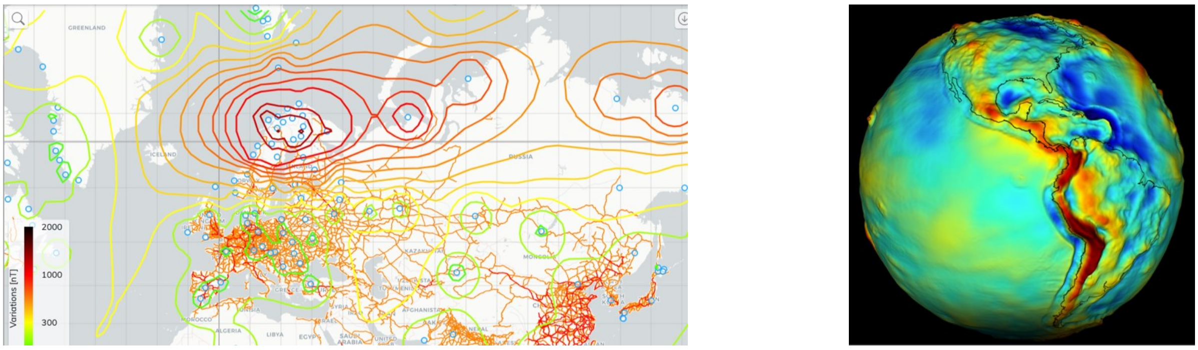
The operability and clarity of the proposed solution are examined using the parameters of the geomagnetic field as an example. Additionally, an analysis of performance metrics for its web implementation is conducted, which allows evaluating the quality of the corresponding solutions.

Keywords: field visualization, geospatial image, tensor field, glyph, superellipse.

1. Introduction

In Earth sciences, one of the key development areas is creating solutions that ensure visualization of geomagnetic, gravitational, and other fields of natural and anthropogenic origin. The complexity of field visualization lies in their anisotropic nature of spatial distribution, as well as the large amount of data that needs to be processed and displayed, for example, on a cartographic background.

The significance of geophysical field visualization is difficult to overestimate. For example, visualization of geomagnetic and gravitational fields is an important tool for seismologists to detect anomalies, as well as for interpreting geophysical data for the geological interpretation of magnetic and gravitational anomalies. Visualization of geophysical fields is an important tool for modeling complex physical and geological processes occurring in near-Earth space, on the surface, and within the Earth (Figure 1).

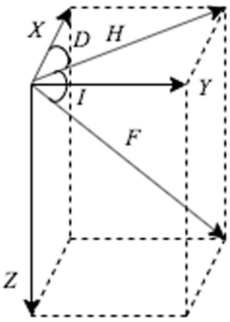


a *b*

Fig. 1 – Examples of geophysical field visualization: a – geomagnetic field in the form of a system of spatial contour lines [1], b – gravitational field in the GRACE project.

The complex nature of geophysical field parameters is largely determined by the fact that at each spatial point, the corresponding field is set by one or more vectors (two-dimensional vectors or multidimensional tensors), each of which, in turn, is characterized by a set of parameters. For example, the geomagnetic field at each point in the earth's space is defined as a vector, which in turn is determined by a set of parameters, characterized by its own gradient, and in general can be characterized as a second-order tensor. In general, the parametric composition of the geomagnetic field vector is presented as shown in Fig. 2, and is characterized by the following main parameters [1]:

– nothern X, eastern Y and vertical Z components,
– full vector F, declination D and inclination I,
– horizontal H and vertical components Z, declination D.



$$F = \sqrt{X^2 + Y^2 + Z^2} = \sqrt{H^2 + Z^2},$$
$$H = F \times \cos I,\ Z = F \times \sin I,$$
$$X = H \times \cos D,\ Y = H \times \sin D.$$

Fig. 2 – Geomagnetic Field Vector Parameters Interrelation Scheme

The analysis of known solutions for visualizing geophysical fields has shown that in the vast majority of cases, there is a simplification of the available data by dividing their representation into separate spatial layers. Each spatial layer corresponds to one parameter of the corresponding vector or tensor, while the final spatial image is formed using known interpolation methods (walking squares, sweep, etc.), depending on the capabilities of the geoinformation technologies applied for this purpose.

Such an approach is associated with a loss of complex interactivity of the solution, which is due primarily to the fact that it becomes impossible or excessively difficult for the user to visualize many or all parameters of the geophysical field vector or tensor simultaneously, which in turn leads to a loss of information content of the geospatial image and complexity of its retrospective analysis.

In addition, it is important to note here that multilayer geospatial imagery is not without visual artifacts caused by representation overload (in particular, in many solutions, overlapping or superimposition of spatial layers can be observed, which does not allow identifying a specific parameter visually and assessing it in the context of anisotropy of the remaining analyzed parameters of the geophysical field vector/tensor).

Taking the above into account, there is an actual scientific and technical task of visualizing vectors and tensors of geophysical fields in such a way as to ensure the possibility of their simultaneous integrated representation, regardless of the number of analyzed parameters, in the form of an integrated spatial layer.

It seems appropriate to develop and formalize such a method of visualizing a geospatial image that will allow describing the vector and/or tensor nature of the field, taking into account variations in the values of attributive parameters in relation to different axes (directions) of geophysical values in the context of their gradient.

The solution is proposed to be implemented in the form of a web-oriented service or application to ensure the possibility of its widespread distribution and use both by end users using standard web browsers and by third-party applications using API services operating according to standard web interaction protocols.

2. State of Art

Modern software solutions in general and geoinformation solutions in particular, focused on visualizing multicomponent vector and tensor geophysical fields, are based mainly on the use of specialized color solutions in geospatial images, on the one hand, and the use of various conditional images to represent the analyzed parameters, on the other. An example of this are various heat maps that use color scheme variation to characterize the variability of a single parameter/component of a geophysical field vector. As another example, we can cite a solution that uses arrow pictograms to display the direction of the geomagnetic field gradient in the section of a single component of its vector (Figure 3).

When analyzing and visually interpreting a single parameter of a geophysical field, each of the presented options is quite informative. However, when transitioning to the analysis of a complex of parameters of the corresponding field, the application of this approach can be associated with significant difficulties in interpreting the resulting spatial image. Thus, at each spatial point during a comprehensive analysis, multiple vectors (vector pictograms) are set that overlap each other and cause significant overload of the generated geospatial image. In the case of a high density of visualized spatial data, the situation is further aggravated.

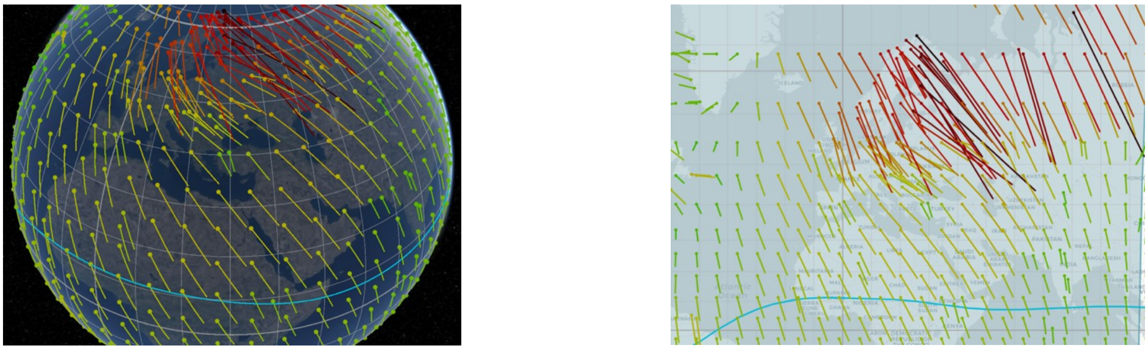


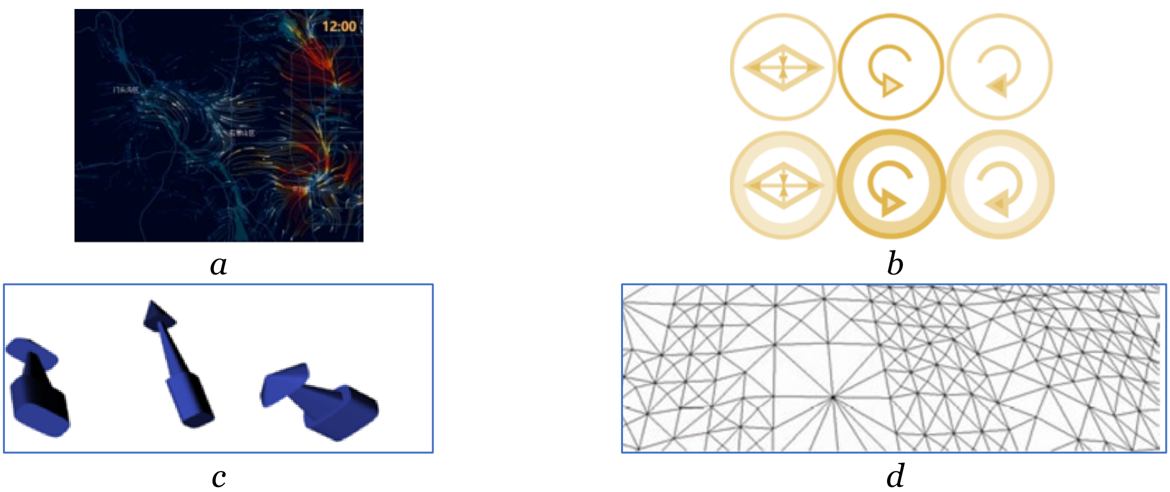
Fig. 3 – Visualization of geomagnetic field vector components using arrow pictograms on flat maps (two-dimensional representation) and virtual globe (three-dimensional representation) [1]

In fact, the considered well-known approaches assume a simplified representation of geophysical fields by reducing the corresponding vectors/tensors to their scalar components with the formation of corresponding spatial layers (surfaces). In any case, this leads to a loss of significant information necessary for understanding the studied process/phenomenon, since in the vast majority of cases, information about the complete vector in the совокупности of its components is required.

In some cases, solutions used for data visualization in related scientific and applied fields are applied to visualize geophysical fields (Figure 4). For instance, there is an approach to visualizing a vector field that effectively visualizes particle movement patterns and provides a more intuitive representation of the field as a whole (Figure 4a) [2]. The approach in question uses so-called travel vectors, which allow, on the one hand, to identify points with the highest movement intensity and, on the other hand, to improve the understanding of the movement state of the analyzed objects. However, it should be noted that the application of this method is limited due to the high computational load during the processing and rendering of a large number of points, which can lead to display delays and reduced performance. Additionally, when using travel vectors, there is a risk of data distortion or loss of important information due to the simplification of more complex trajectories, which can affect the accuracy of movement dynamics analysis and interpretation. This visualization technique, despite its advantages in intuitively presenting movement patterns, has certain limitations that need to be considered when applying it to geophysical field visualization tasks.

It is also appropriate to consider a well-known approach [3] that provides field visualization as a result of combining vector and tensor fields to represent global and local features of the corresponding parameters (Figure 4b). In general, the visualization result according to the considered approach is represented by a combination of two components: background visualization to display large trends and local visualization to highlight significant characteristics. In the context of formalization, the designated method includes decomposition of the corresponding tensor into isotropic scaling, shear, and rotation, for which special icons are used for local visualization. The advantages of this approach lie in its universality (it is possible to visualize various fields in this way, not only geophysical ones) and the ability to perform complex visualization (several components such as scaling, shear, and rotation are used, which positively affects the quality of subsequent result interpretation). However, the solution also has some disadvantages. These include the high computational load associated with implementing the tensor decomposition procedure and subsequent clustering, as well as possible data loss due to simplified visualization based essentially on the use of uniform icons, which can lead to loss of important details, especially in complex datasets.

Reference [4] presents a method for visualizing uncertainty in three-dimensional vector fields using three-dimensional glyphs. The solution proposes the use of a specialized "squid-like" glyph (squid glyph), which generally effectively visualizes field uncertainties in both magnitude and direction, improving the interpretability of the final image (Figure 4c). Additionally, an extra parameter is introduced – a vector depth metric, which allows analyzing the distribution of vectors within the corresponding dataset without prior analysis, thus enhancing the understanding of the overall structure of the visualized data. However, the considered visualization method is associated with a high computational load during software implementation due to the large number of parameters used and the complexity of the resulting glyph.



a *b* *c* *d*

Fig. 4 – Common Approaches to Field Visualization

Reference [5] presents a method that provides detailed visualization of the Earth's gravitational field using a quadratic grid with multiple nodes. The method is characterized by the ability to implement adjustable detailing of the resulting image, which allows for a sufficiently detailed display of flows in the gravitational field (Figure 4d). The resulting three-dimensional grid is simple to interpret and clearly shows any changes and/or anomalies in the field, which are expressed by its fluctuations. However, the method has some disadvantages. Firstly, it has a high computational complexity. If too high a value is initially set for the image detailing parameters, the number of nodes for subsequent rendering increases significantly, increasing the load on the hardware capacity. Secondly, the method cannot account for a large number of attributive parameters, as the used graphic primitive has a limited and not very large number of properties.

Based on the analysis of known solutions for visualizing various fields (not only geophysical), it is possible to conclude that all the considered models and methods have the following disadvantages:

– High computational complexity;

– Inability to comprehensively visualize attributive parameters.

In most cases, the geospatial binding of data is not taken into account, which:

– Prevents the visualization of the final image on a cartographic background

– Significantly complicates the visual interpretation of the result by the end user.

These limitations make it difficult to effectively use the existing visualization methods in practical applications, especially when it is necessary to provide a comprehensive analysis of field data with geospatial context.

3. Initial data characteristics

For a clearer presentation of the proposed geophysical field visualization solution, it is advisable to first describe the characteristics of the relevant data. As an example, let us consider geomagnetic data, which result from continuous recording of the Earth's magnetic field parameters and its variations by ground-based (magnetic observatories and variometer stations) and near-Earth (satellites) information-measurement systems.

The recorded geomagnetic data undergo multistage processing and are then stored on specialized open-access web resources for further use by end users. One such example is the SuperMAG project (https://supermag.jhuapl.edu/), which is used as the primary source in this study. SuperMAG provides access to annual archives of geomagnetic observations from over 300 ground-based magnetic observatories and variometer stations [6-7].

Geomagnetic data represent characteristics of the Earth's magnetic field generated by internal terrestrial sources [8]. At each spatial point, the geomagnetic field can be defined by a complete intensity vector, i.e., both its direction of action and corresponding magnitude [8].

The geomagnetic field serves as an example of a tensor field, generally defined as a surface described by a given function where each point is associated with a tensor. This tensor is referenced to a corresponding coordinate system and originates at a specific spatial point.

In general terms, the geomagnetic tensor field can be represented as an initial point with a set of characteristic vectors emanating from it. When the geomagnetic field vector is decomposed into its constituent components, at the tensor level it can be represented as a collection of scalar values. Each of these scalar values, in turn, can be visualized as a separate spatial layer.

If we consider the geomagnetic gradient G, which characterizes the rate of change of the geomagnetic vector parameters along three directions (x, y, and z, respectively) in the Cartesian coordinate system, then its tensor can be represented as follows [9]:

$$G = \begin{bmatrix} \frac{\partial F_x}{\partial x} & \frac{\partial F_x}{\partial y} & \frac{\partial F_x}{\partial z} \\ \frac{\partial F_y}{\partial x} & \frac{\partial F_y}{\partial y} & \frac{\partial F_y}{\partial z} \\ \frac{\partial F_z}{\partial x} & \frac{\partial F_z}{\partial y} & \frac{\partial F_z}{\partial z} \end{bmatrix} \quad (1)$$

where F_x, F_y and F_z are the three components of the geomagnetic field vector in their projections onto the respective axes x, y and z.

For greater clarity, as a convolution:

$$G = \begin{bmatrix} g_{xx} & g_{xy} & g_{xz} \\ g_{yx} & g_{yy} & g_{yz} \\ g_{zx} & g_{zy} & g_{zz} \end{bmatrix} \quad (2)$$

From the given relations (1) and (2), it follows that the geomagnetic field gradient constitutes a second-rank tensor composed of 3×3=9 corresponding spatial derivatives [8]. Given that both the divergence and curl of the geomagnetic field vanish, then

$$\begin{gathered} g_{xx} + g_{yy} + g_{zz} = 0; \\ g_{xy} = g_{yx}, g_{xz} = g_{zx}, g_{yz} = g_{zy}. \end{gathered} \quad (3)$$

Then, considering (3), the tensor from expression (2) can be represented as a symmetric 3×3 matrix with five independent components denoted as g_{xx}, g_{yy}, g_{xy}, g_{yz} and g_{zx} [8]. Thus, in accordance with Laplace's equations, the sum of the diagonal matrix elements equals zero [8].

The resulting geomagnetic field tensor is rectangular, with the length of each of the tensor axes (tensor shape) equal to 3, the number of axes (tensor rank) also being 3, and the total number of elements in the tensor (tensor size) accordingly being 27.

In each spatial point, the geomagnetic field is given by a corresponding dyad (second-rank tensor). If we consider, for example, a pair of adjacent spatial points A and B, it is possible to obtain a new tensor of the same second rank, obtained by algebraic summation of each component of one tensor addend with the corresponding component of the other tensor addend [8]:

$$\begin{gathered} G_A = \begin{bmatrix} g_{xx_A} & g_{xy_A} & g_{xz_A} \\ g_{yx_A} & g_{yy_A} & g_{yz_A} \\ g_{zx_A} & g_{zy_A} & g_{zz_A} \end{bmatrix}, \qquad G_B = \begin{bmatrix} g_{xx_B} & g_{xy_B} & g_{xz_B} \\ g_{yx_B} & g_{yy_B} & g_{yz_B} \\ g_{zx_B} & g_{zy_B} & g_{zz_B} \end{bmatrix}, \\ G_{AB} = \begin{bmatrix} g_{xx_A} + g_{xx_B} & g_{xy_A} + g_{xy_B} & g_{xz_A} + g_{xz_B} \\ g_{yx_A} + g_{yx_B} & g_{yy_A} + g_{yy_B} & g_{yz_A} + g_{yz_B} \\ g_{zx_A} + g_{zx_B} & g_{zy_A} + g_{zy_B} & g_{zz_A} + g_{zz_B} \end{bmatrix}. \end{gathered} \quad (4)$$

4. The proposed approach description

The main goal of the research described in this paper is to increase the informativeness of the visual representation of tensor fields in geoinformation systems in such a way as to integrate multiple scalar components of the tensor into a single graphic object, taking into account the position of the corresponding parameter in the general characteristic of the field. The formed geospatial image should provide the end user with the ability to simultaneously display all parameters of the tensor field, observing the direction of its constituent vectors and preserving all related information.

The essence of the proposed approach lies in representing the tensor as a geospatial primitive, the form of which characterizes the rank and form of the visualized tensor. The conducted analysis of possible graphic representation options allowed us to identify a glyph as the main graphic primitive, which is currently used to solve applied and research tasks for displaying complex data, taking into account their specific features (shape, size, orientation) that determine the appearance and location of the base graphic primitive on the cartographic background.

In the context of a possible glyph representation, it is appropriate to note such forms as ellipsoid, cuboid, cylindrical glyph, and superquadric. When choosing the base glyph form, it is necessary to consider the number of axes comprising the visualized tensor (tensor rank). It is proposed to use ellipsoidal glyphs as a geospatial primitive for displaying geophysical tensor fields. Given the complexity of the geomagnetic field vector/tensor, it is advisable to expand the chosen glyph form and represent field components as a superellipse defined by a set of Lamé curves.

To implement the proposed solution, it is proposed to place axes emanating from the centroid of the superellipse, each of which corresponds to a separate component of the visualized tensor (in the case of a geomagnetic field, the components of the Earth's magnetic field vector are considered as such). By varying the length and color of each component of the superellipse, it is possible to control the representation of the corresponding component of the tensor field (for example, geomagnetic or gravitational).

In particular, in the context of controlling the color scheme of superellipses, it is possible to use a monochrome representation of values along each virtual axis of the glyph. The corresponding color mask is formed preliminarily so that, depending on the magnitude of the visualized parameter, the resulting color is presented in the form of a corresponding gradient with a width determined by the size of the glyph and the number of axes provided in it.

As a result, the intensity of the gradient along each of the axes of the tensor glyph as part of a single figure will allow you to visually assess their distribution, taking into account similar geospatial images at neighboring spatial points.

Controlling the color scheme of the superellipse allows avoiding the use of additional images (for example, bulky arrow pictograms) to describe the vector components of the corresponding field. As a result, the final geospatial image will be characterized by the intensity of the corresponding color solutions, providing an informative representation of various (including multi-directional) components of the geophysical field (for example, various components of the complete geomagnetic field vector).

With each spatial point, a unique superellipse is associated, whose centroid coincides in coordinates with the corresponding geospatial point and is defined by a pair of geographic coordinates. As a result, the formed geospatial image represents a collection of many superellipses tied to points in space and having their own color and geometric characteristics.

In general, the expression for a superellipse constructed based on n spatial axes can be represented as follows [13-14]:

$$\left(\frac{x}{a}\right)^n + \left(\frac{y}{b}\right)^n = 1, \tag{5}$$

where coefficients a and b determine the compression of the superellipse along the coordinate axes, respectively.

It is important to note that the greater the number of axes represented in the superellipse, the more its shape tends to become rectangular. For example, if a single axis is used, then the superellipse is a flat rhombus with vertices on the coordinate axes. If two axes are considered, then the visualization result is an ellipse (if $a = b$, the ellipse transforms into a circle) [15].

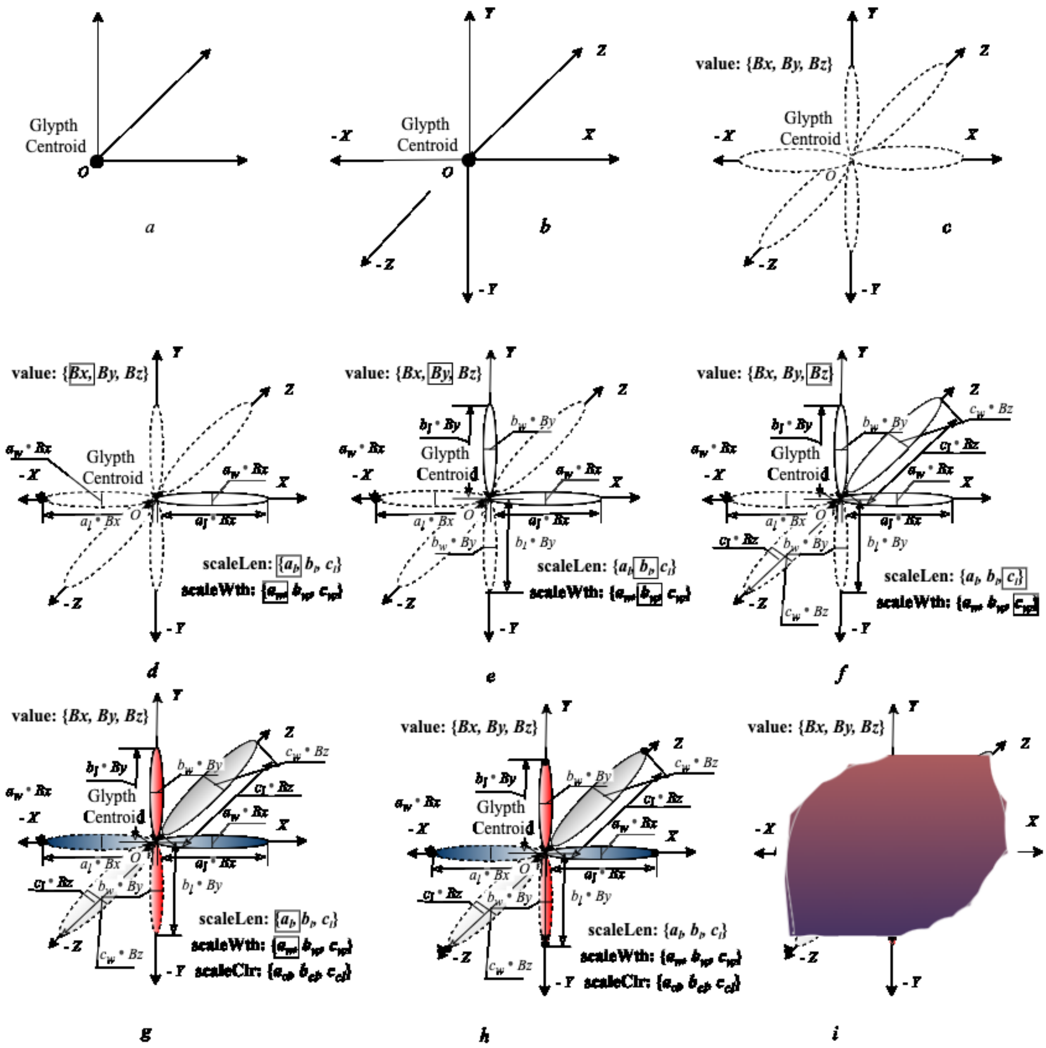


Fig. 5 – The sequence of stages for forming a tensor glyph based on a superellipse, using the example of the geomagnetic field and its complete vector with given component

However, even if in the first approximation the visualization of the superellipse tends to the shape of a rectangle, its constituent segments still represent curves (the segments connect all the points formed at the intersection with the corresponding axes of the superellipse), i.e. in fact, all segments of the superellipse are always slightly curved [15]. Moreover, the curvature of the superellipse lines changes everywhere in a generally continuous manner.

The general process of constructing a superellipse is shown in Fig. 5, where the visualization of tensor components is shown using the example of the geomagnetic field. In the first step of the corresponding method for constructing a superellipse in the first approximation, it is necessary to determine the number of axes emanating from its centroid. The number of axes must be proportional to the number of components making up the visualized tensor. For example, for a geomagnetic field with rank 2, the number of axes in the superellipse is a multiple of three.

It is important to note that if the values of the displayed tensor components can be negative (as is the case, in particular, in the case of components of the geomagnetic field vector), then the corresponding axis must be duplicated relative to the centroid of the superellipse and rotated in space by 180 degrees. Accordingly, the number of superellipse axes doubles, and, for example, for the Earth's magnetic field, it will be three pairs or six corresponding axes emanating from one point - the centroid of the superellipse. The features of all known types of geophysical fields are such that when constructing corresponding superellipses, it is necessary to consider opposite axes (positive and negative axes) associated with individual components of the total vector of the parameter in question (for example, the total vector of the geomagnetic field).

At the next step, scaling coefficients for the values of geophysical field vector components are determined in relation to the superellipse visualization component. It is assumed that a proper ellipse should be constructed along each individual axis, the width and length of which are determined by the corresponding values of the attributive parameter, on the one hand, and the scaling coefficient, on the other. Oval glyphs, depending on the domain of the corresponding attributive parameter of the geophysical field tensor, are placed in the positive and/or negative direction relative to the selected superellipse axis. In fact, in the pre-final glyph image, a complex figure is formed, composed of multiple proper ellipses stretched/compressed relative to the corresponding axes in all possible directions.

At the next step, each designated oval within the corresponding axis/semiaxis of the final tensor glyph is assigned its own color scheme. It seems appropriate to define a monochrome representation for each such figure with a direction of color gradient and magnitude as the corresponding visualized value changes. For the same axis, a gradient of the same type is set with opposite gradations for different semiaxes (or with one in the case of a single semiaxis).

In the last stage, the intersection points of oval primitives with each other and with the axes/semi-axes of the superellipse are determined (preliminary). The designated points are proposed to be called reference points of the superellipse here and hereafter. Lamé curves sequentially connect the highlighted reference points, color schemes undergo additional transformation to smooth out clear boundaries between existing ovals. The resulting figure will represent a superellipse – a tensor glyph of the geophysical field.

5. Validation of the Solution and Evaluation of Its Effectiveness

To confirm the operability and evaluate the effectiveness of the proposed solution, a research prototype of a web-oriented application was developed, providing visualization of the main geomagnetic field parameters. As initial data, the results of calculating the parameters of the undisturbed Earth's magnetic field were used according to the World Magnetic Model (WMM); in this case, three components of the total magnetic field vector (northern, eastern and vertical components) were highlighted as the main ones [16-17].

The software implementation of the research prototype of the web-oriented application was developed using Python 3.9+ with specialized scientific computing libraries (NumPy, SciPy) and visualization tools (Matplotlib, VTK). This setup ensured precise analytical definition of superellipses through Lamé curve parameterization with adaptive scaling of coefficients according to the magnitude of tensor field components. The proposed visualization solution supports both 2D mode (Matplotlib) and 3D implementation (VTK) with glyph texturing. Color coding of components is performed using LinearSegmentedColormap (Matplotlib) with data normalization. The developed software solution can be converted into an API format, enabling its integration into modern GIS platforms for analyzing multicomponent geophysical fields.

Calculation and visualization of geomagnetic field parameters were performed on the Earth's surface using a uniform spatial grid with a discretization step of 1 degree. For each point, taking into account the calculated values of the magnetic field vector components, the corresponding gradient was calculated, characterizing the direction of growth of the analyzed quantities. The obtained values were then organized into a second-order tensor for further processing [18-19].

Visualization of the calculated values was performed by generating a spatial layer consisting of tensor glyphs tied to the corresponding geographic coordinates. Each component of the vector (gradient of the corresponding component) field was assigned its own tensor glyph at a spatial point node of the monitoring network. To enhance informativeness, color schemes were introduced (monochrome representations were used for each individual component of the geomagnetic field vector) [20].

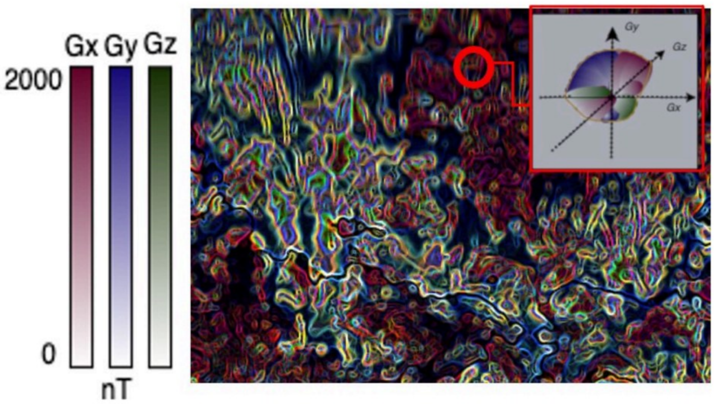


Fig. 6 – Example of a screen form fragment with tensor glyphs for representing the geomagnetic field

As a result of the computational operations performed, a spatial layer was formed, visualized on a flat cartographic base. The layer, in general, allows one to judge the nature of the spatial distribution of geomagnetic field parameters and their variations, taking into account the gradients of the corresponding parameters. This can subsequently be used by specialists to assess the geomagnetic environment in the decision-making process based on this information in applied and research fields.

To assess the effectiveness of the presented solution, a series of computational experiments was conducted to compare the results of the proposed solution and known approaches according to certain qualitative and quantitative criteria. During the computational experiments, a client-server stand with the following characteristics was used: on the client side using a computer (CPU Intel Core i5 10300H GHz, 4 GB RAM, internet connection speed ~52.4 Mbit/s); on the server side - based on a web server with a 72 * Intel® Xeon® Gold 6140 CPU @ 2.30GHz processor.

In the context of qualitative evaluation criteria, the conducted experiments established that the proposed solution allows for the representation of the entire analyzed group of geophysical field parameters as a single layer, to which integral instrumental and software tools for data processing and visualization using geoinformation libraries and technologies are applicable.

Specifically, a single spatial layer can utilize a frame-by-frame layer switching element with successive time stamps to assess the spatio-temporal dynamics of parameter distribution for the corresponding process or phenomenon (in this case, referring to the geomagnetic field). Other visualization approaches suppose the creation of a separate spatial layer for each analyzed parameter, excluding the possibility of operating them as a single entity.

Furthermore, such a multi-layer approach can result in significant overlaps of spatial images, substantially complicating their visual analysis. The proposed solution, by combining the axes of the tensor glyph at a given spatial point, generally avoids or significantly reduces (for a large number of spatial points) such cluttering of spatial graphical primitives.

Quantitative criteria for evaluating the effectiveness of the proposed solution were generally reduced to analyzing the performance of its web implementation on both the client and server sides. A developed web-oriented geographic information system prototype was used as a sample, in which the proposed visualization approach based on tensor glyphs was directly implemented. The following criteria were selected to evaluate performance:

– Response time, ms. This criterion characterizes the amount of time a user waits for a response from the server (from the moment the request is sent until the results are received in one format or another);

– TTFB (Time to first byte), ms;

– FCP (First Contentful Paint), s. This criterion characterizes the time that elapses from the moment a request is sent to the server until the browser displays the first bit of content from the DOM tree of the corresponding page;

– LCP (Largest Contentful Paint), s. This metric characterizes the time required to complete rendering of the largest visual element in the browser. In the example under consideration, it is appropriate to consider the drawing of the spatial layer with tensor glyphs on the corresponding cartographic background as such;

– FID (First Input Delay), ms. This metric allows us to assess the time required for the user to be able to interact with the web application using the appropriate interactive elements. In this case, it seems appropriate to measure this indicator in terms of the possibility of scaling the drawn spatial image with tensor glyphs using appropriate interface elements.

A series of computational experiments was conducted for geomagnetic data and their gradients, calculated for different time periods. In total, more than 300 different spatial layers were formed, during the creation and visualization of which the aforementioned web application characteristics were measured accordingly. The objective of these experiments was to demonstrate that introducing the proposed solution into a web-oriented geographic information system would not reduce its performance as a highly responsive web application. As a result, the following values for the specified quantitative quality metrics were obtained: response time = 298 ms; TTFB = 289 ms; FCP = 1.65 s; LCP = 2.34 s; FID = 98 ms. These values indicate that the final web application maintains its performance metrics and is highly responsive.

6. Perspectives of applying the proposed approach

The visualization method proposed in this research, which employs specialized superellipsoid glyphs for tensor geophysical fields, provides a comprehensive solution to one of the key challenges in analyzing complex geophysical data. This challenge frequently arises during data processing and stems from interpretation overload when simultaneously working with multiple scalar and vector parameters.

It should be re-emphasized that the use of traditional visualization methods in the context of the identified problem is based on the separate display of scalar and vector components. This combination leads to the loss of correlation relationships between parameters, overloading of graphic space when spatial layers are superimposed, and various subjective errors when comparing heterogeneous data. The proposed approach avoids these errors through tensor-adaptive geometry and polychromatic coding of superellipses, providing an integrated perception of the corresponding spatial patterns.

Superelliptical glyphs allow preserving tensor invariants (trace, determinant, anisotropy, etc.) during data visualization, which is critical for analyzing relevant information in various fields. For example, the use of superellipses enables identifying spatial zones with high divergence of the geomagnetic field and geomagnetic anomalies, which is generally represented on the map of geomagnetic field parameter distribution (Fig. 6, 7). Based on the visualization result presented on the screen form, it can be concluded that there is a pronounced high-latitude distribution of geomagnetic variations and anomalies across all components of the corresponding vector.

Similarly, the gravitational gradient proposed in this work can be used to reflect local density variations through the shape of the glyph. For example, in magnetic exploration, with this approach, the ellipticity of the glyph correlates with the magnetic susceptibility anisotropy coefficient, and the orientation of the axes corresponds to the magnetization direction.

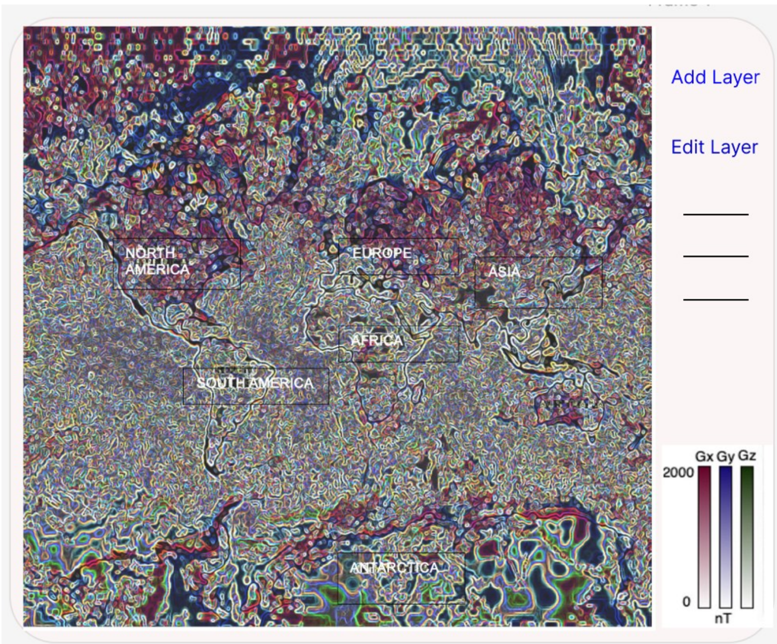


Fig. 7 – Screen form with the result of visualization of geomagnetic anomalies

In general terms, the following areas of practical application of the proposed solution can be formulated

– unified presentation of multi-component data: the user does not need to compare disparate graphs or arrow diagrams, since all components of the corresponding tensor (for example, the geomagnetic field) are integrated into one intuitive object. As a result, the user has access not to three separate vectors, but to a single superellipse in which the length, color and curvature of the axes reflect the relationship of the components and their direction;

– preservation of the context of spatial relationships: varying the color gradient and the shape of the glyph demonstrates a change not only in the absolute values of the corresponding parameters, but also in their distribution relative to neighboring points / regions. For example, on a map of geomagnetic anomalies, the use of a gradient allows the user to visually determine the zone with maximum deviations, while the curvature of the corresponding contours indicates the presence of nonlinear effects of spatial distribution;

– reduction of time spent on analysis: automatic scaling of axes and smoothing of corresponding color gradient transitions allows the user to focus directly on data interpretation and not apply manual visualization settings for each parameter.

In summary, it seems appropriate to note that the proposed approach allows transforming abstract tensor data into expressive objects in terms of geometry and color, which, in turn, reduces the cognitive load on the user when working with multidimensional geophysical fields, allows identifying patterns and anomalies more clearly than known methods, and can also be integrated into standard GIS interfaces without the need to master more complex tools. At the same time, for practitioners (geophysicists, geologists, ecologists, etc.), this means the ability to make faster and more accurate decisions, for example, in the search for minerals, monitoring natural risks or analyzing climate data.

7. Conclusion

One of the main tools for operational analysis of geophysical fields at present is their visualization on a cartographic base using the corresponding geoinformation software and tools and systems. At the same time, the complex multicomponent composition of the analyzed fields at each spatial point significantly complicates such analysis in an integrated format. In addition, a number of geoinformation tools and software are oriented towards working with a single spatial layer, which is technically impossible in the context of known solutions.

In this regard, in this article the authors propose and formalize an approach to visualization of vector and tensor geophysical fields based on tensor glyphs as part of an integrated spatial layer. As the main geospatial primitive, it is proposed to use a superellipse, the axes of which correspond to the rank of the visualized tensor, and the attribute values are expressed by the values of the corresponding ellipses, stretched or compressed relative to the corresponding axes with specified scaling factors.

Using the example of the main geomagnetic field parameter values calculated in accordance with the WMM model, a research prototype of a web application was developed that implements the proposed approach to visualizing geophysical fields. Comparison with other solutions for visualizing similar parameters showed the qualitative advantage of using the proposed approach, which consists in the fact that it becomes possible to represent a set of parameters as part of a single software-controlled spatial layer.

The analysis of quantitative characteristics of the given solution was carried out in accordance with the metrics of web application performance evaluation and was focused mainly on the evaluation of the response time from the server and the completion of the procedure of rendering the geospatial image based on it. Computational experiments carried out on the research stand showed that the performance parameters of the web application implementing the proposed solution do not cause a negative response from the standpoint of its performance.

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