Atlas of Earth's magnetic field

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Received 23 June 2011; accepted 10 July 2011; published 25 July 2011.

The paper describes the methods of producing magnetic charts used in the recent Atlas of the Earth's magnetic field. Evolution and spatial-temporal variations of the geomagnetic field are recovered from 1500 to 2010. This Atlas represents a unified set of physical, general geographic, thematic, including historical charts, as well as background (text and spreadsheet) materials. *KEYWORDS: Geomagnetism; geoinformatics; modeling; digital cartography.*

Citation: Berezko, A. E., A. V. Khokhlov, A. A. Soloviev, A. D. Gvishiani, E. A. Zhalkovsky, and M. Mandea (2011), Atlas of Earth's magnetic field, *Russ. J. Earth. Sci., 12,* ES2001, doi:10.2205/2011ES000505.

Introduction

Historical, paleomagnetic and archeomagnetic records are used in both regional and global studies of the Earth's magnetic field. Numerous attempts in global magnetic field modeling are spread over scientific publications since the progress in such modeling depends mainly on the newly compiled data sets. Any particular model is attributed to its own timescale and there is neither unique precision requirement nor presentation standard for published models. Geophysical Center of the Russian Academy Sciences has collected several significant results in global modeling in order to reconstruct the Earth's magnetic field over last five centuries of the Earth's magnetic field study.

Generally speaking the Atlas presents several types of the magnetic field description:

1. Ancient charts that were produced from the old direct observations, (XVII–XIX centuries);

2. Charts attributed to 1500–2010, however constructed in recent time using both direct and indirect data;

3. Lithospheric magnetic field of the Earth;

4. Magnetic storms and magnetic indices.

The intrinsic idea of this Atlas is to present the magnetic charts of the second type attributed to given time intervals (usually from few decades to few years) in the same format and explicit precision parameters. We also provide supplementary materials related to the Earth's main and crustal magnetic fields including texts, tables and graphs reflecting the present state of geomagnetic research. The Atlas is created for the first time and will represent a fundamental cartographic product with the most complete and scientifically founded characteristics of the mapped phenomenon – geomagnetism. It will contain results of both historical and present-day levels of the Earth's main magnetic field studiness [*Gvishiani et al.*, 2010].

All charts in the Atlas are released both in hard copy and electronic GIS format. This article describes the basics of the modeling technology and its formal constraints.

General Principles of Magnetic Data Presentation

Magnetic field of the Earth is time-dependent vector field (Figure 1), so the visual image should distinguish vector characteristics. Traditional approach to 3D data representation consists in local coordinate separation that leads to several plots of the same vector field, one plot per each component of vector field. Therefore we may expect at least 3 plots for each time argument, however there are at least two standard approaches to the parameterization:

- the modern approach that uses Cartesian local frame of North-East-Down directions;

- traditional approach that uses angular parameters Inclination and Declination together with Intensity parameter.

Therefore we get the total number of plots equal to six at any time moment. This is not the case for ancient charts since the systematic worldwide direct measurements of the geomagnetic field have been carried out for approximately two centuries only, but incomplete (and also imprecise), data is known for at least three times longer period (Figure 2).

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http://elpub.wdcb.ru/journals/rjes/doi/2011ES000505.html

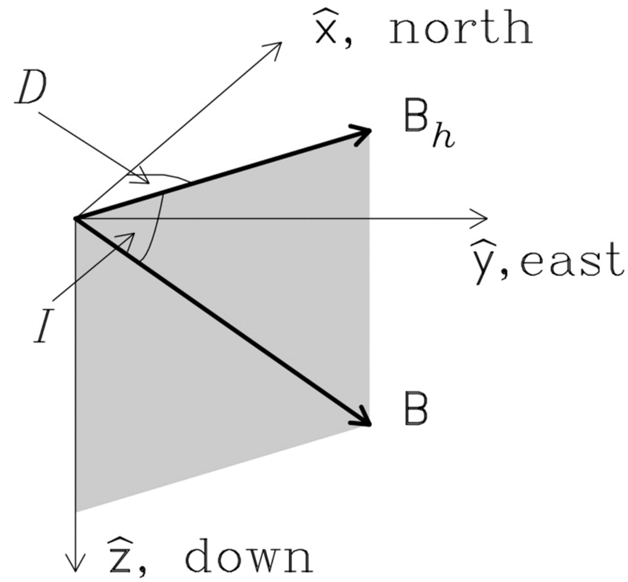

Figure 1. Different representation of geomagnetic vector components: North (x), East (y), Down (z) directions; Intensity (B), Declination (D), Inclination (I).

The charts of the first type given in the introduction (i.e. those that were produced long time ago and that were based on direct observations) keep only partial information, for instance, the intensity observations appeared much later than the observations of declination (Figure 3) are also other limitations of the old charts.

The main geomagnetic field originating in the Earth's core shows significant change at long timescales from centuries to millions of years, directional change vary from few angular degrees to complete reversals. Magnetic intensity also varies, however the corresponding total scale of its variation until now is not completely clear, most researchers believe that the intensity rate is subjected to small variations only at least during stable polarity periods. The Atlas presents these secular variations by means of simultaneous plots of the single-type characteristics (e.g., declination) attributed to different epochs. So the total collection of charts in the Atlas is increased by the additional charts of the "magnetic field time-derivatives". An important feature of the Atlas is its global choice of the plot format; real-valued functions (i.e. the components of magnetic field) of 2D argument (geographical position) are presented in terms of their isovalues, that are continuous closed curves. No doubt the total precision of the resulting plot depends on the discrete step that defines isolines. Such approach to magnetic charts is known since 1701 when Edmund Halley published the first worldwide system of lines of equal declination values (isogons, then known as "Halleyan lines", Figure 3). Since then this technique remains classic.

General Principles of Magnetic Field Modeling

It is well known that the Earth's magnetic field varies in both space and time, and its evolution has been studied both regionally and globally. The regional modeling approach has been the most effective in Europe where data density is relatively high (Figure 4) and considering a region of interest enables evaluation of internal consistency of the data and study of the temporal evolution of the geomagnetic field.

When several regions are examined, it is then also possible to investigate the spatial scale of field variations. A set of geographic regions are defined, charts for each region are calculated and then averaged within overlapping temporal windows to provide regional temporal variation. Global spatial variations are determined from the average of all regions within each time window. However, this approach was only partly used namely in calibrating models that belong to the first half of XX century. In contrast, the Spherical Harmonic approach is generally used to represent the geomagnetic field in space and time during various time-scales. Such models have a long tradition of providing a mathematical description for the spatial structure of the field, and over the past few decades it has become common to include a temporal parameterization in terms of cubic splines for the Gauss coefficients in the models. To build these models the time-varying coefficients of the geomagnetic field are derived directly from the available observations. There are many solutions that would satisfy a particular data set, especially when the data are sparse and limited in accuracy, and so a regularization technique is applied that favors models with minimal complexity and reasonable fit to the data.

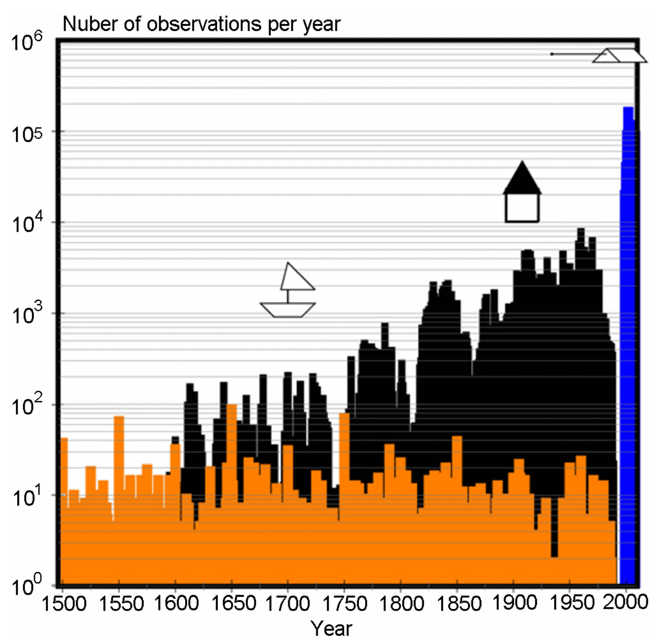

Figure 2. Data availability since 1500: marine (orange), on-ground (black) and satellite (blue).

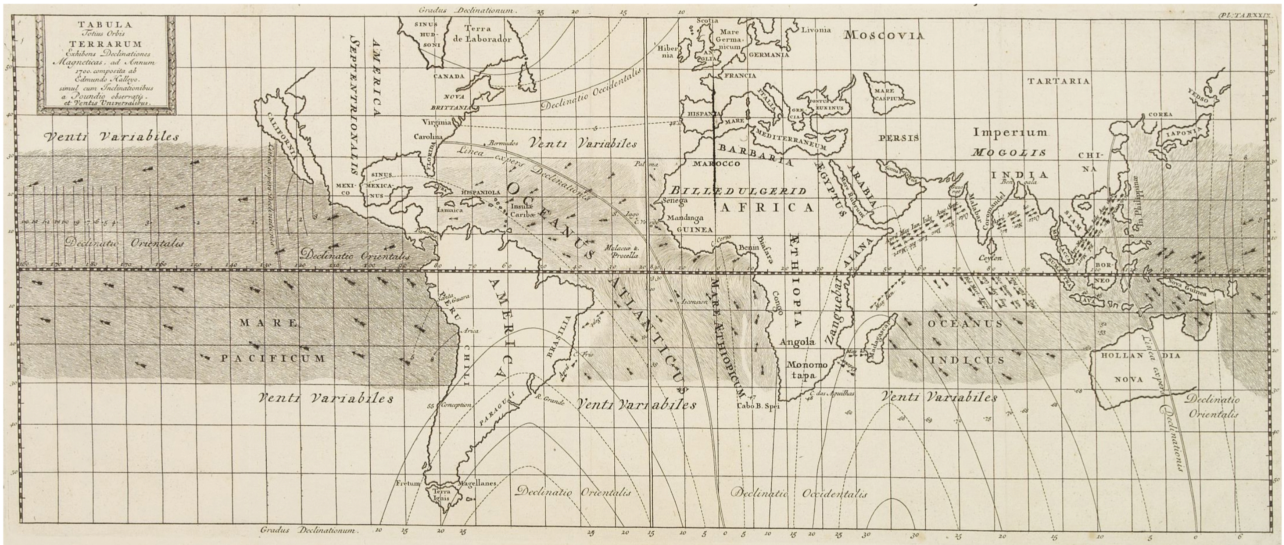

Figure 3. Halley's World Chart of the equal declination (1701) [*Halley*, 1701].

However this approach has significant drawbacks when the data distribution is far from uniformity over the surface of the Earth (Figure 5). The corresponding mathematical argument known as Sampling Theorem can be found in [*Driscoll, Healy*, 1994]: when data is sparse then its spatial spectral context is uncertain both in low and high spatial frequencies. The resolution of the resulting model depends on how the complexity is measured, the distribution of measurements in time and space, and their perceived accuracy. The accuracy determines how observations are weighted in the modeling and what is a reasonable fit to the data, which ultimately controls the choice of the regularization parameter.

Since the beginning of instrumental observation period, collecting highly accurate data is carried out also at geomagnetic observatories whose coordinates are distributed very unevenly. At the moment, the largest global network of ground-based observatories INTERMAGNET ([http://www.intermagnet.org/]) has more than 100 observatories (Figure 4). Representativeness of data are qualitatively changed with the beginning of the space era: several magnetic satellites ([http://www-app2.gfz-potsdam.de/pb1/op/champ/]) provide suitable number of measurements to select from them the subset that has almost uniform spatial distribution (Figure 6).

So the global models are published in the Atlas in their

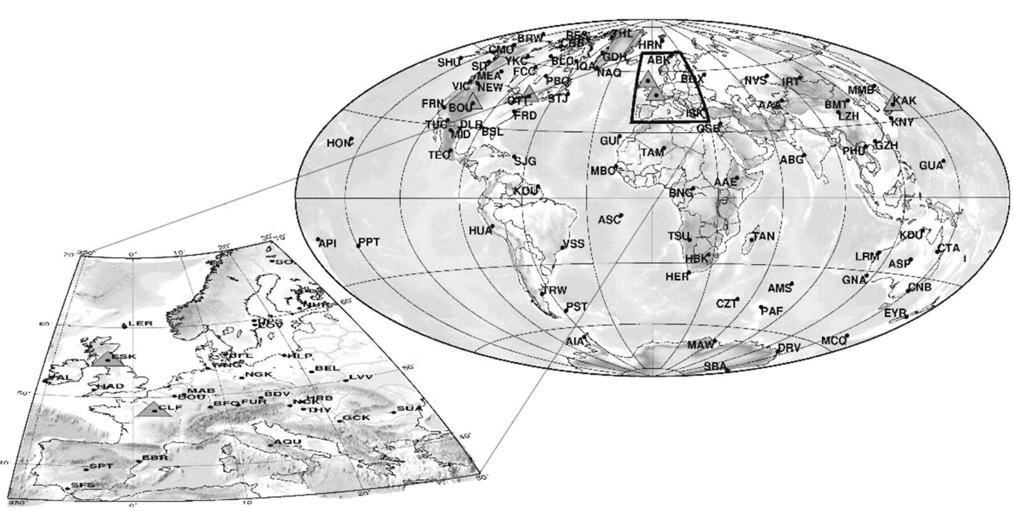

Figure 4. Distribution of currently operating geomagnetic observatories.

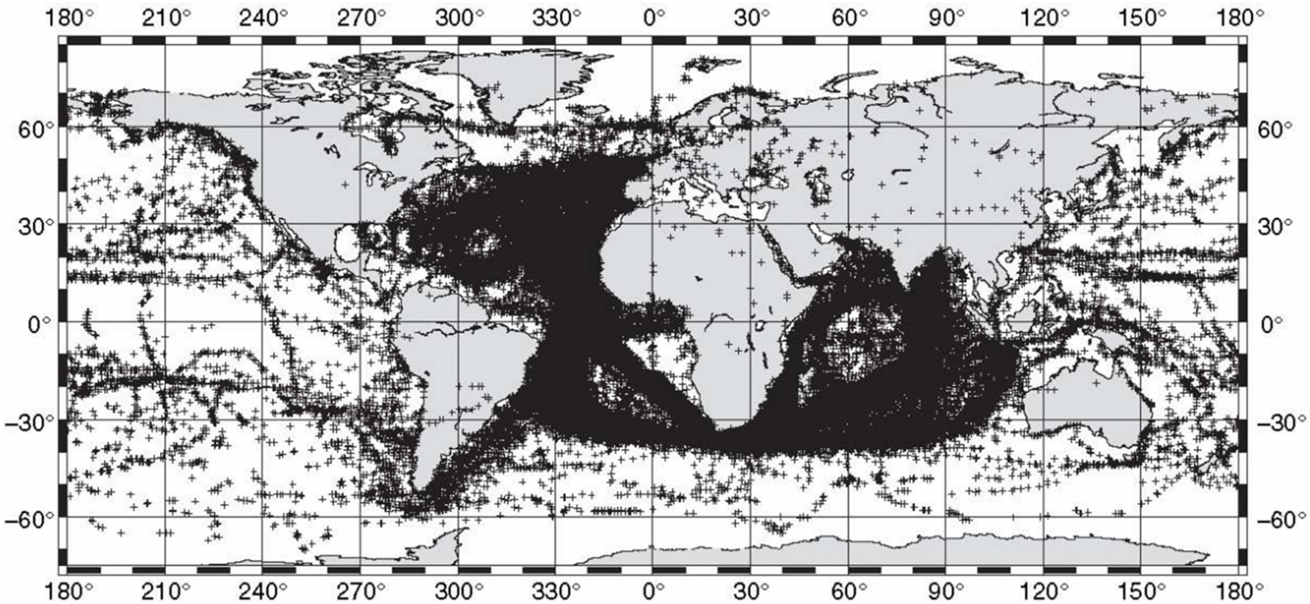

Figure 5. Locations of declination observations in XVII century [*Jonkers et al.*, 2003].

spectral representation, therefore the corresponding charts are nothing else than the (inverted) spectral (i.e. generalized Fourier) transform of the published Gauss coefficients set. The main parameter related to spatial resolution is the maximal degree of the spherical harmonics in use.

In the chart preparation we used spectral expansion coefficients from degree 13 (in the framework of the IGRF model), to a degree 6 in earlier models. Field components were calculated at the nodes of a geographical grid with a step of 0.2 degrees in latitude and longitude. For the period of 1900–2010 the time step is 5 years (Figure 7),[1] for the period of 1500–1900 – 25 years. For each grid point seven components of the magnetic field were calculated: declination, inclination, intensity, the three axial projections and the length of horizontal component. The estimated elevation above sea level assumed to be zero [*Berezko et al.*, 2010].

[1] *Editor's note*: This figure is presented as six flash objects. Use Adobe Reader, version 8 or newer to see maps in detail. Click on mouse right button and select *Zoom In*, then you can move the map inside the figure area while pressing mouse left button.

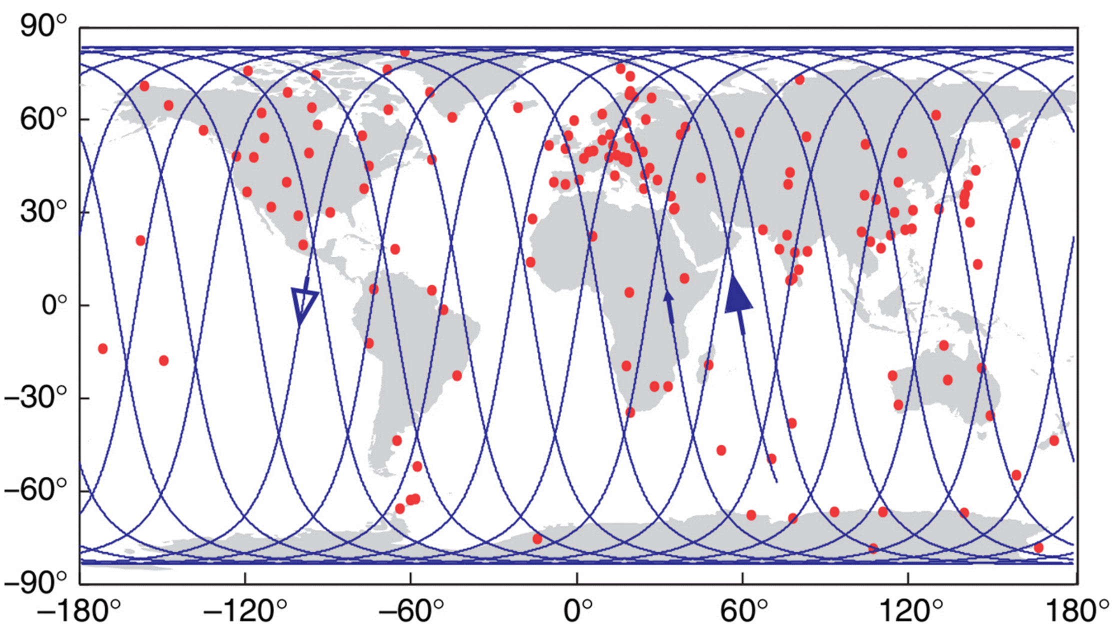

Figure 6. Observatories (red dots) and 24-hour ground track of the satellite (blue curve).

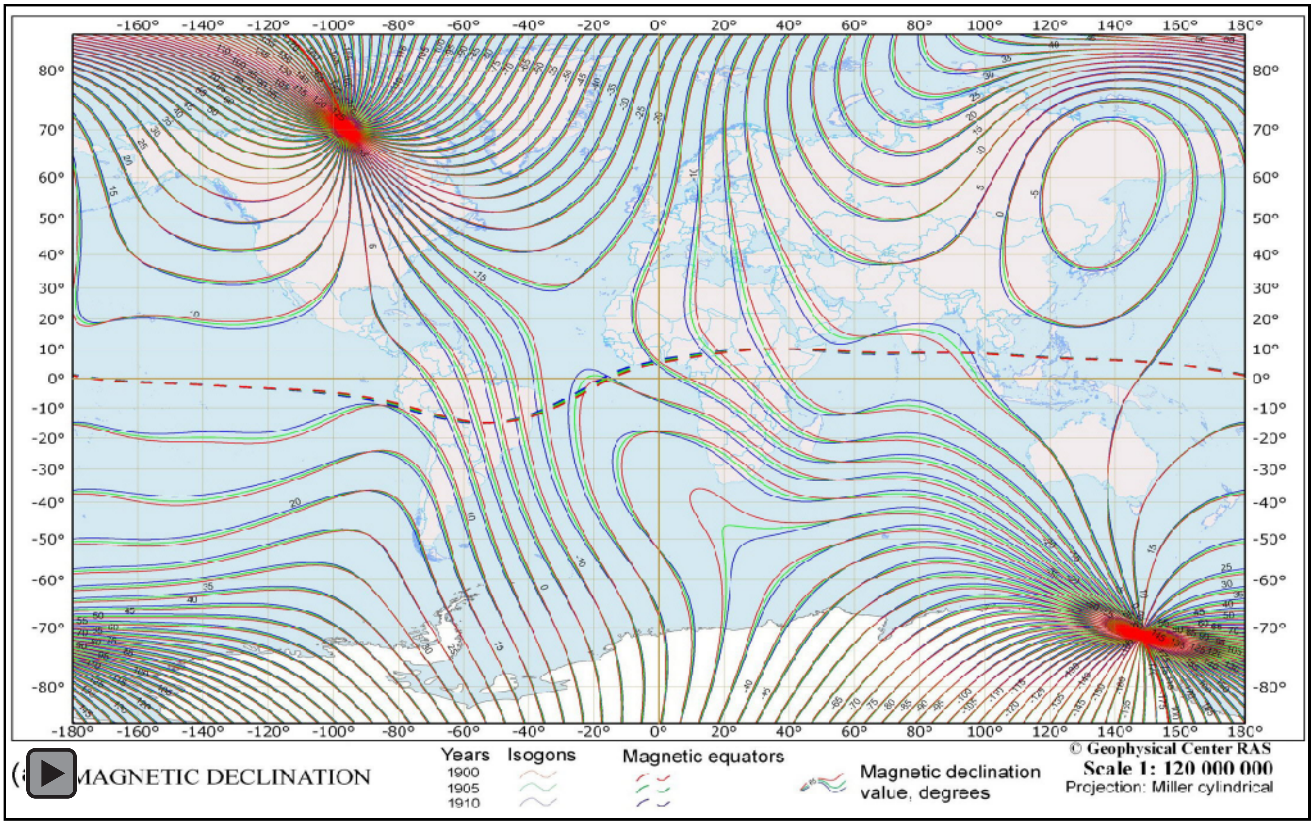

Figure 7. The Altas charts for the Earth's main magnetic field for the three neighboring epochs 1900, 1905 and 1910: (a) Magnetic declination.

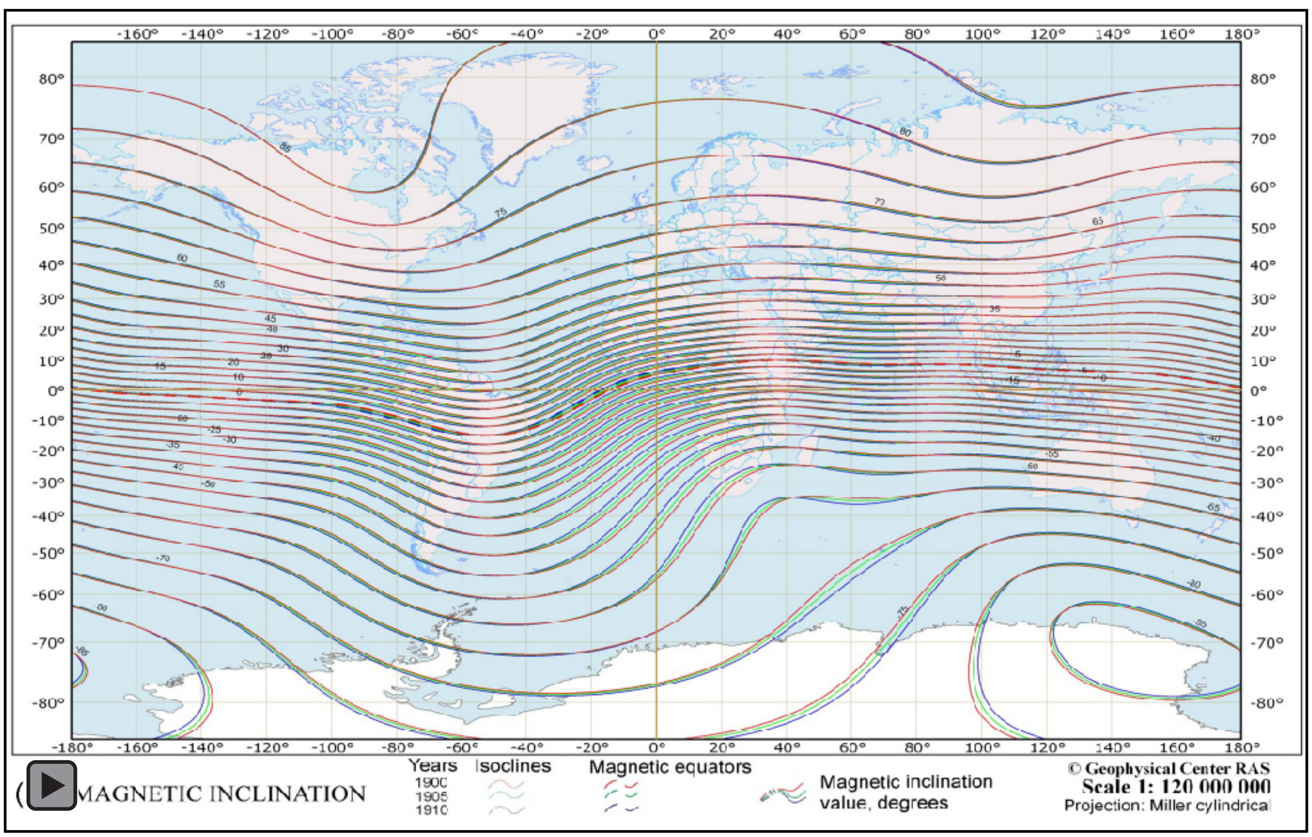

Figure 7. (continued) (b) Magnetic inclination.

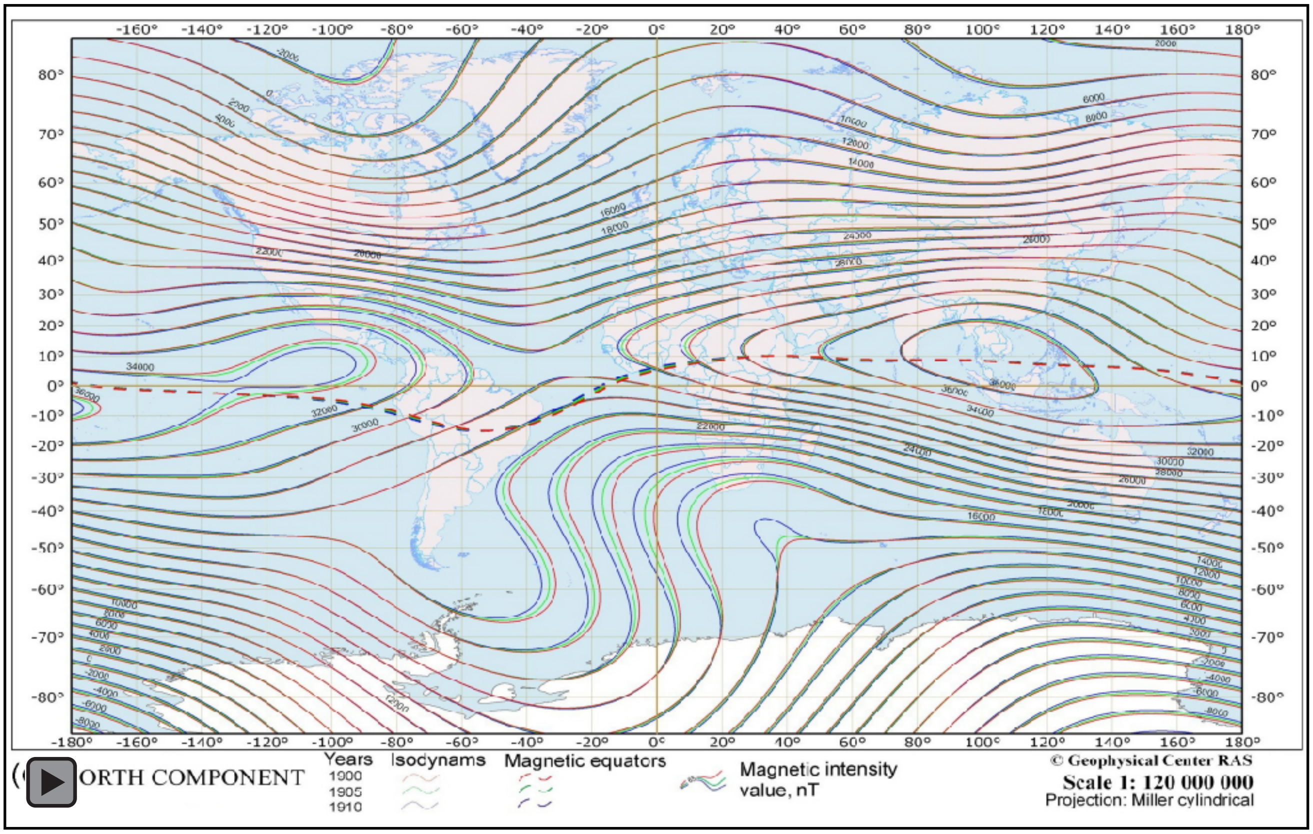

Figure 7. (continued) (c) North component.

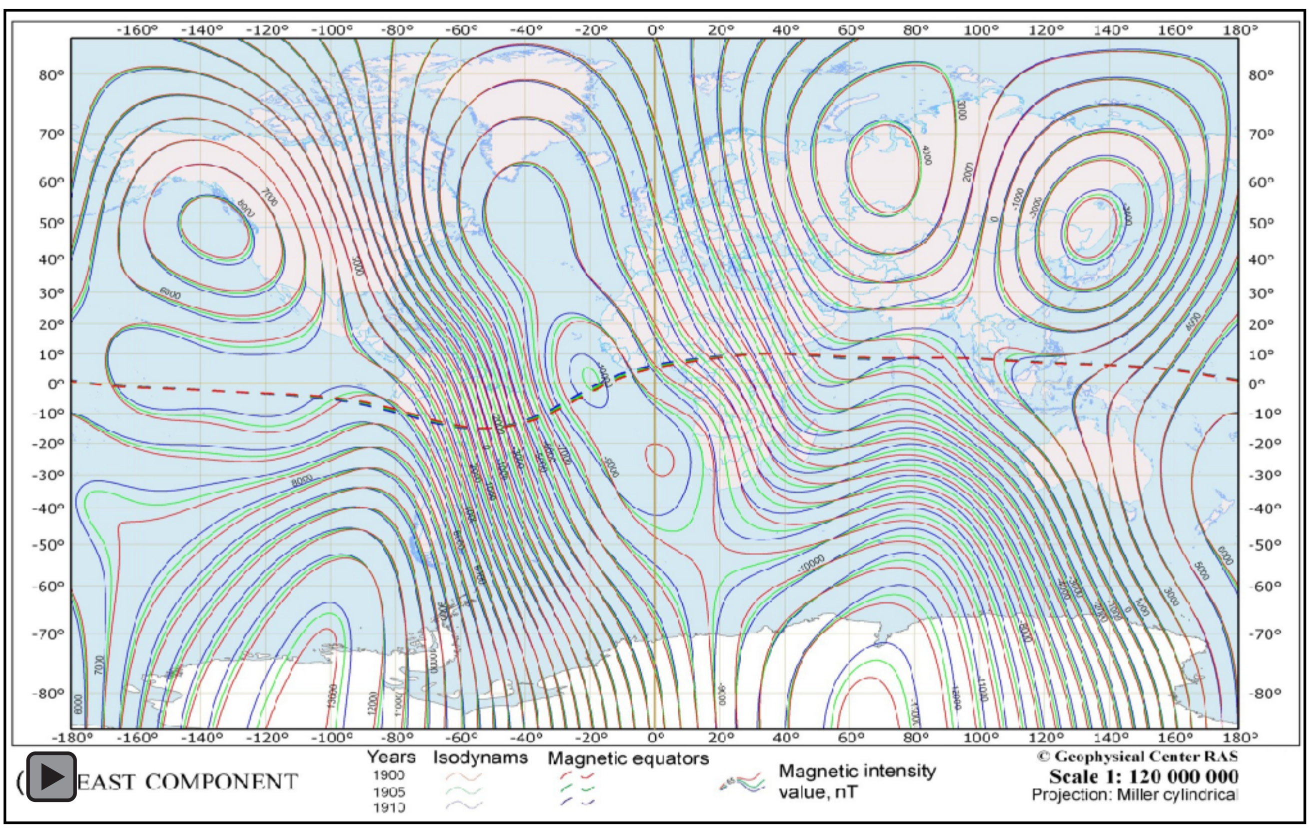

Figure 7. (continued) (d) East component.

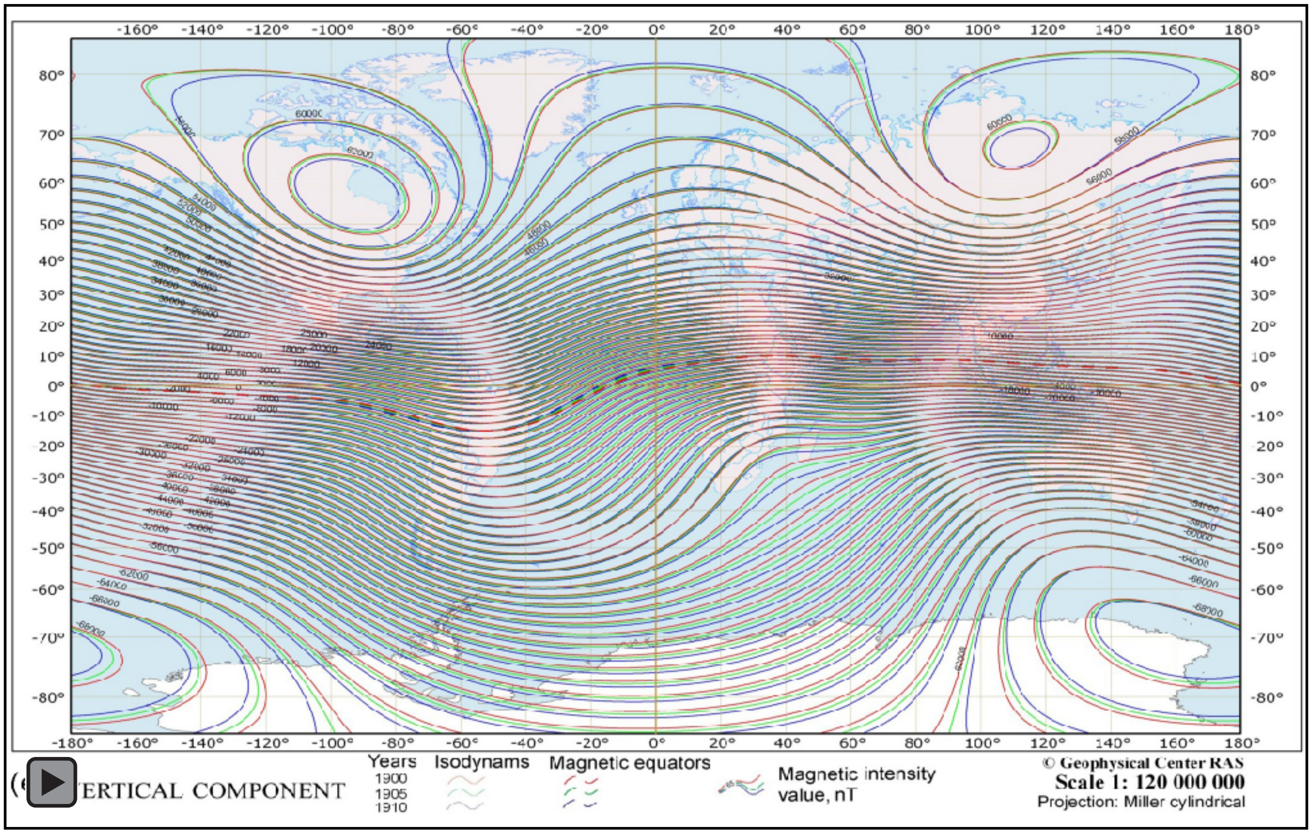

Figure 7. (continued) (e) Vertical component.

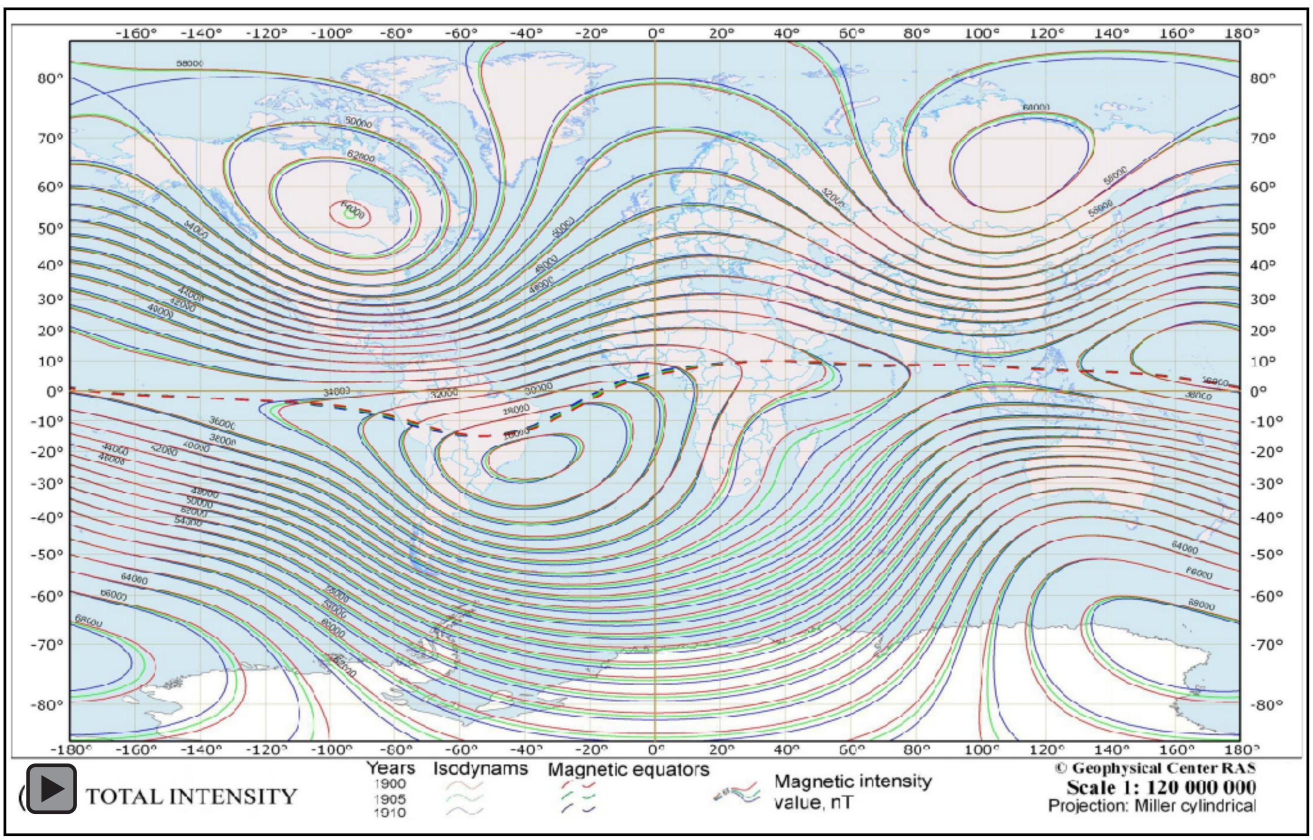

Figure 7. (continued) (f) Total intensity.

Data Types and Sources

As mentioned above the Atlas is nothing more than the collection of already published models presented as the worldwide charts. We first list the data types in use [*Zhalkovsky et al.*, 2009]:

- Coefficient values of the Earth's magnetic field spherical harmonic expansion for the period of 1900–2010 ([http://www.ngdc.noaa.gov/IAGA/vmod/igrf.html]);
- Coefficient values of the Earth's magnetic field spherical harmonic expansion for the period of 1500–1900, obtained by modern computations [*Jackson et al.*, 2000; *Korte et al.*, 2009];
- Coefficient values of the Earth's magnetic field spherical harmonic expansion for the period of 1500–1900, obtained in XIX century;
- Empirical models of the Earth's magnetic field for the period of 1500–1800, created before XIX century;
- Data of geomagnetic observations obtained in 1510–1930 [*Jonkers*, 2003];
- Historical world charts of geomagnetic field components developed in 1500–1900;
- Model data on the Earth's crustal (lithospheric) magnetic field;
- Gridded observation data on the Earth's crustal (lithospheric) magnetic field.

All the data are resulted from the long-term research surveys, data collections available nowadays from the following sources:

- Data of IGRF released by IAGA;
- British Geological Survey, United Kingdom;
- IZMIRAN, Russia;
- GFZ German Research Centre for Geosciences, Germany;
- University of Leeds, United Kingdom;
- Sainte-Geneviéve Library, France;
- University of Utrecht, the Netherlands;
- Paris Institute of Physics of the Earth, France;
- World Data Center for Geomagnetism, United Kingdom;
- Paulus Swaen old Maps and Prints Gallery, USA;
- Martayan Lan Fine Antique Maps Collection, USA;
- David Rumsey Map Collection, USA;
- Philographikon Gallery, Germany;
- National Library of Sweden;
- NOAA's National Geophysical Data Center, USA;
- DB "National Atlas of Russia";
- DB on thematic maps of Russia and the world (geological, climate, etc.);
- DB of geomagnetic observatories of Russia (1984–2000) "Variations of the Earth's Magnetic Field";
- DB "Maps for Universities, scales $1 : 4,000,000$; $1 : 8,000,000$ for the territories of USSR and Russia".

Model Categories

The first category of the models used reflects the modern history and includes IAGA IGRF data ([http://www.ngdc.noaa.gov/IAGA/vmod/igrf.html]). It contains the set of expansion coefficients up to degree 13 for the period from 1900 to 2010 with time step of 5 years.

The second category contains the spectral coefficients obtained and adopted by the international community on geomagnetism using several modern approaches to modeling historical period. Two main models that were used to create charts for 1500–1900 are CALS3K.3 [*Korte et al.*, 2009] and gufm1 [*Jackson et al.*, 2000]. The CALS3K.3 model includes spectral coefficients to degree 10 and covers the time period from 1000 BC to 1990 AD. The gufm1 model is represented by spectral degree 14 and covers time interval from 1590 to 1990 with time step of one year.

The third category includes spectral coefficients calculated by the founder of spherical harmonic modeling method K.-F. Gauss, as well as some of his contemporaries, in particular, by H. P. H. Fritsche [*Fritsche*, 1899]. The latter model contains spectral coefficients up to degree 7 and refers to 1600, 1650, 1700, 1780, 1842 and 1885 [*Zhalkovsky et al.*, 2009].

Technology

At the first stage seven components of the magnetic field were calculated: declination, inclination, intensity, the three axial projections and the length of horizontal component. The calculations were carried over a dense grid using direct calculation of the (inverse) spectral transform in MATLAB environment; the resulting file format is compatible with most of GIS systems. At the next stage the corresponding isolines were constructed using linear interpolation of raster maps obtained at the first stage. The calculation was performed by means of software ArcGIS 9.3.1. All the isolines are constructed as continuous lines except those of declination that appeared piecewise continuous. The final stage was generation of all the charts in automatic mode. The corresponding software module was developed in ArcGIS 9.3.1 environment using the embedded Visual Basic programming language. The input data for the software module are the calculated geomagnetic component isolines and a chart template, which completely defines the layout of all the generated charts. Thus, in total 77 charts for the period of 1900–2010 (5-year time step) and 56 charts for the period of 1500–1900 (25-year time step) were produced [*Berezko et al.*, 2010].

References

Berezko, A. E., A. D. Gvishiani, E. A. Zhalkovsky, A. A. Soloviev, A. V. Khokhlov, M. Mandea (2010), Atlas of the Earth's magnetic field and technology of charting the Earth's main magnetic field, *Open Education* (in Russian), *5*, 82, 24–30.

Driscoll, J. R., D. Healy (1994), Computing Fourier transforms and convolutions on the 2-sphere, *Adv. in Appl. Math., 15*, 202–250.

Fritsche, H. P., H. Die (1899), *Elemente des Erdmagnetismus fur die Epochen 1600, 1650, 1700, 1780, 1842 und 1885, und ihre saecularen Anderungen: berechnet mit Hulfe der aus allen brauchbaren beobachtungen abgeleiteten Coeffizienten der Gaussischen "Allgemeinen Theorie des Erdmagnetismus"*, 112.

Gvishiani, A. D., E. A. Zhalkovsky, A. E. Berezko, A. A. Soloviev, A. V. Khokhlov, V. V. Snakin, G. V. Mitenko (2010), Atlas of the Earth's magnetic field, *Geodesy and Cartography* (in Russian), 4, 33–38.

Halley, E. (1701), *Tabula Totius Orbis Terrarum Exhibens Declinationes Magneticas, ad Annum 1700 composita ab Edmundo Halleyo Simul cum Inclinationibus a Poundio Observatis et Ventis Universalibus*, Paris.

Jackson, A., A. R. T. Jonkers, M. Walker (2000), Four centuries of geomagnetic secular variation from historical records, *Philos. Trans. R. Soc. London, Philos. Trans. Math. Phys. Eng. Sci.*, 358, 957–990.

Jonkers, A. R. T., A. Jackson, A. Murray (2003), Four centuries of geomagnetic data from historical records, *Reviews of Geophysics, 41*, 2, 1006.

Korte, M., F. Donadini, C. Constable (2009), Geomagnetic field for 0-3ka, part II: A new series of time-varying global models, *Geochem., Geophys. Geosys.*, 10, Q06008, doi:10.1029/2008GC002297.

Zhalkovsky, E. A., T. N. Bondar, V. P. Golovkov, A. V. Khokhlov, V. I. Nikiforov, A. E. Berezko, A. A. Soloviev, E. S. Bolotsky (2009), Initial data for Atlas of Earth's main magnetic field, *Russ. J. Earth. Sci.*, 11, ES2008, doi:10.2205/2009ES000412.

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