Chart-making of the Earth's main magnetic field

Ye. A. Zhalkovsky[1]

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[1] Methods of magnetic prospecting have long history. Investigations of geomagnetism started when magnetic iron ore (rock rich of magnetite) was found. It is believed that a few hundreds years B. C. the Chinese were the first ones to use properties of magnetic iron ore to point out the directions. However, a thought that the Earth itself acts as a magnet appeared considerably later. First information on the use of magnetic compass in Europe relates to the end of XII century. Ideas on geomagnetic field, its direction and effects were put onto scientific grounds after the book "About magnet, magnetic bodies and about big magnet – the Earth" had been published. Systematic quantitative investigations on the direction of the magnetic field of the Earth commenced in London over the lifetime of Gilbert. In Sweden as early as 1640, observations of local anomalies of the geomagnetic field direction were used for the prospecting of the iron ore. Sphere of application of magnetic methods covers different areas of geomagnetism, magnetism of rocks, paleomagnetism, magnetic prospecting, navigation on the basis of magnetometry, effects of magnetic field variation on human health, including crews of air-crafts, etc. Variety of applications of magnetic methods is so broad that it is practically impossible to consider all aspects in one paper. Apart from that, by now the most effective results of research of geomagnetism are connected with getting data on such imagination taking hypotheses as continental drift, sea floor spreading and plates tectonics, movement of geographical and magnetic poles, etc. Intensity of geomagnetic field is measured from satellites, air-crafts/planes, ships, as well as in observatories, and then classified, formed and recorded every 5 years since 1945. Non-systematic measurements have been carried out considerably earlier. However, until now there is no sufficient visual interpretation of data on geomagnetic field with the purpose of its reliable analysis and study for the further fundamental and applied research. This work offers cartographic method of interpretation of geomagnetic field measurements, creation of geographic maps of the magnetic field of the Earth, and creation of geoinformation system. *INDEX TERMS:* 0925 Exploration Geophysics: Magnetic and electrical methods; 1500 Geomagnetism and Paleomagnetism; 1517 Geomagnetism and Paleomagnetism: Magnetic anomalies: modeling and interpretation; *KEYWORDS:* geomagnetic field, magnetic anomaly, Earth's main magnetic field, geographical map.

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Introduction

[2] Geomagnetic exploration has a long history. It started with a discovery of the "loadstone" (a rock, rich in magnetite). Aristotle supposed that the first research of the characteristics of magnetite, that can be called scientific, was the work by Thales of Miletus (who lived on the territory of modern Turkey between VII and VI centuries B.C., though some scientists think that it was already known and applied in Egypt (but none of the Egyptian descriptions of it remained). The first literary record of magnetite in China refers to IV century B.C., and the first mention of a magnetized arrow being attracted by a loadstone was made in China between 20 and 100 A.D. But the idea that the Earth acts like a magnet appeared much later. In 1088 a polymathic Chinese scientist Shen Kuo in his book "Dream Pool Essays" described the methods of improving navigation with the help of a compass and a notion of the "real" (geographical) direction to the North. In Europe the first ideas about using a compass for naval navigation were published in 1187 by a British theologian and historian Alexander of Neckam.

[3] In 1600, after a book by William Hilbert "About a

[1] Geophysical Center, Russian Academy of Sciences, Moscow, Russia

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magnet", a follower of Giordano Bruno, telling about magnetic bodies and a big magnet – the Earth, with a positive commentary by Galileo Galilei, was published, ideas about the geomagnetic field, its direction and activity were provided with a scientific foundation. Systematic numerical observations of the direction of the Earth's magnetic field started in London at the lifetime of W. Hilbert [*Sharma,* 1989]. In Sweden already in 1640 the observations of local anomalies of the direction of the Earth's magnetic field were used for discovering iron ore deposits.

[4] The sphere of application of magnetic methods, comprising the spheres of geomagnetism, rock magnetism, paleomagnetism, magnetic exploration, navigation on the basis of magnetometry, influence of the magnetic field on people's health, including crews of aircrafts, etc, are currently so wide, that it is impossible to cover all these aspects within the scope of one work. Moreover, by the present time the most impressive results of geomagnetic research are related to obtaining data on such thrilling phenomena, as the continental drift, spreading of the ocean floor, plate tectonics, movement of geographic and magnetic poles, etc. Paleomagnetic research produced the first grounds for the concept of mantle convection, underlying the notion of plate tectonics and rapidly developing during the last 15 years [*Bird,* 2003].

[5] The strength of magnetic field is measured by satellites, airplanes, ships, observatories and is systematized, formed and recorded every 5 years since 1945. Less accurate (but systematized) data after each 5 years are available since 1900. Non-systematic observations were carried out considerably earlier. However, until the present time the visualized interpretation of data of the Earth's magnetic field as a whole is still insufficient, having in view the purpose of its reliable analysis and study for carrying out the further fundamental and applied research.

[6] The work presents the cartographic method of interpretation of measurements of the geomagnetic field and of designing geographical charts of the Earth's main magnetic field and geoinformation system.

General Information

[7] The actual magnetic field of the Earth consists of a sum of several contributions: from the nucleus (the main geomagnetic field), from the crust (the field of local anomalies) and from magnetosphere (the field of sources, external in relation to the Earth's volume). The biggest contribution into the magnetic field of the Earth is made by the main magnetic field; even if you imagine that the Earth's crust (the layer ~30 km, the lower rock doesn't get magnetized due to exceeding the Curie point) is totally composed of strongly magnetized rock (basalt and gabbro), then the contribution of the Earth crust would equal only to a few per cent of the field observed [*Sharma,* 1989]. The fluid nucleus of the Earth cannot have a permanent magnetization, because the latter is of a quantum nature and intrinsic only to crystals [*Kitel,* 1978]; the origin of the main field is attributed to the presence of circular currents in a nucleus, acting like a dynamo mechanism. The central (located in the centre of Earth) magnetic dipole, best of all approximating to the Earth's magnetic field, has a magnetic moment 8.0 10^{22} A m^2, and its axis is tilted about the axis of Earth's rotation at approximately 11.5°. The first calculation of this magnetic moment was done by Gauss in 1835, the magnetic moment at that time was equal to 8.5 10^{22} A m^2; since then the Earth's field is getting weaker approximately by 5% in a century. P. Sharma [*Sharma,* 1989] thinks that "the magnetic fields of the Earth's main dipole could disappear in two thousand years and leave researchers of geomagnetism jobless in the near future". If the latter is correct, then the navigation systems in Russia, based on the use of magnetic field, could also stop working in the same period of time. The existence of inversions of the main magnetic field is supposed, i.e. magnetic poles change after each 2–5 thousand years. About a half of the Earth's crust is magnetized to the direction, opposite to the direction of the main magnetic field [*Sharma,* 1989]. The non-dipole part of the main field (average strength ~10,000 nT, at average full strength ~45,000 nT), i.e. obtained by subtracting the dipole field from the main geomagnetic field, isn't perhaps prone to inversions [*Sharma,* 1989]. The present main field changes unevenly in space, but has a tendency, on average, to drift to the west (western drift). In the present work the dynamics of the Earth's main magnetic field was examined only by three time series: in 1995, 2000 and 2005.

[8] The average value of the horizontal component of intensity of the main field is ~20,000 nT. The average intensity of the external field from electric currents in the ionosphere is much less, about 20 nT. Local anomalies of the field from the Earth's crust could be relatively large, reaching 190,000 nT for the Kursk magnetic anomaly [*Sharma,* 1989], but they aren't mapped on scale 1:25,000,000. Magnetic storms can cause changes up to 2000 nT, but they are short-lived (one or two days), and geomagnetic measurements aren't usually taken during storms. The points, where the horizontal component of the main magnetic filed is equal to zero, are called magnetic poles. The central magnetic dipole produces geomagnetic poles, not coinciding with magnetic poles (no geomagnetic poles were determined in this work). The magnetic poles aren't antipodes, they coincide with the tilted eccentric dipole, located at approximately 300 km from the Earth's center and inclined to the axis of Earth's rotation at an angle of about 11.5°. It was agreed to call the magnetic pole, situated near the northern geographical pole, the North magnetic pole, in spite of the fact that it corresponds to the southern pole of the main dipole (analogically the South magnetic pole). The line, on which the vertical component of the magnetic pole is equal to zero, is called magnetic equator. The main field to the north of this equator has a vertical component going deep into the Earth's interior, to the south – from the center of the Earth. A line, called magnetic meridian, a tangent in each point of which is parallel to the vector of horizontal component of strength of the main magnetic field.

[9] Strength of the main magnetic field is measured by satellites, airplanes, ships, observatories and is systematically recorded every 5 years (this period in application to magnetic field is called epoch), beginning from 1945. The main geomagnetic field, determined by these system-

atic measurements, is known as the International Geomagnetic Reference Field (IGRF). Velocity of change of the main field in each point is also recorded in IGRF. Results of these measurements are calculated into the potential of the main field and velocity of its change. The value of the field in a point between two dates of measurements in the given point within an epoch is determined by the field and velocity of its change by the linear interpolation method. The values of vector of the main field's strength are calculated as minus a gradient of potential for a selected date and a height above sea level. In the present work this height was selected equal to zero, and the data from 1995, 2000 and 2005 was used. (The last at the current moment of the epoch of IGRF measurements).

Structure of Data

[10] The International Association of Geomagnetism and Aeronomy (IAGA) deals with preparing the IGRF data. These data are presented by decomposition by spherical harmonics by converting vectors of full strength to coefficients of potential of the main geomagnetic field by formula

$$V(r,\theta,\lambda,t) = R\sum_{n=1}^{N}\left(\frac{R}{r}\right)^{n+1}$$

$$\times \sum_{m=0}^{n}\Big[g_n^m(t)\cos m\lambda + h_n^m(t)\sin m\lambda\Big]P_n^m(\cos\theta)\ ,$$

where R – average radius of Earth (6371.2 km), r,θ,l – geocentric spherical coordinates (r – distance from the center of Earth, θ – 90°-latitude, λ – Greenwich longtitude), $g_n^m(t), h_n^m(t)$ – Gauss coefficients for time t, $P_n^m(\cos\theta)$ – the seminormed by Schmidt associated Legendre functions with grade n and order m. Potential V beyond the Earth's scale satisfies the Laplas equation $\Delta V = 0$ and in the written form corresponds to the absence of electric currents outside the scale of Earth [*Sharma,* 1989]. The spherical harmonics are functions $Y_n^m(\theta,\lambda)$ in the form of $P_n^m(\cos\theta)\cos(m\lambda)$ and $P_n^m(\cos\theta)\sin(m\lambda)$; it was proved related to them that they are single-valued and continuous on the surface of a single sphere [*Stigan,* 1979]. The coefficients are functions of time and for the IGRF they are taken as changing at constant speed during an epoch. The table of coefficients from 1900 to 2005 in the form of an Excel file is available in the Internet (http://www.ngdc.noaa.gov/IAGA/vmod/). The biggest contribution to V is given by the member with coefficient g_1^0, proportionate to $\cos\theta/r^2$ and describes the field of the central magnetic dipole, directed along the axis of Earth's rotation. The adding of two other members (proportionate to P_1^1, or $\sin\theta$) entails tilting of the dipole axis, and the next senior members shift it at a distance of ~300 km from the Earth's center.

[11] In July 2003 the IAGA has completed its work of the new 9th IGRF generation. If the previous (for the epochs before 2000) generations were based on $N = 10$ (120 Gauss coefficients), then for 2000 and 2005 $N = 13$ (195 coefficients) and the Gauss coefficients are given already not with an accuracy to 1 nT, but 0.1 nT. For calculating velocity of change of the main field the same formula is used at N=8 (80 coefficients). According to the data for 1995, 2000 and 2005 we performed calculations for 0 latitude, converting from the geocentric to geodetic system of coordinates, based on reference-ellipsoid WGS-84 with semi-axis lengths a = 6378,137 km, b = 6356,752 km.

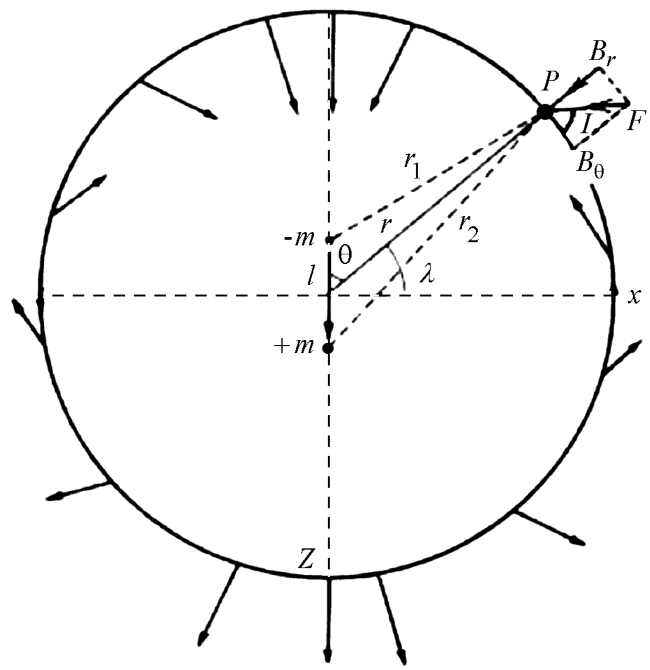

Figure 1. Scheme, illustrating the general distribution of directions of the Earth's main magnetic field.

[12] The general scheme of the distribution of the main magnetic field is shown in Figure 1. The main field located near the North geographic pole is directed towards the Earth's center, near the South geographic pole – from the center. The symbols of the field components are shown in Figure 2. The difference between the magnetic and geomagnetic poles are shown schematically in Figure 3 and on the world map (Figure 4).

[13] The three components of the main field vector F are designated by X, Y, Z. Component X is directed to the geographical North, Y – to the East, Z – to the center of Earth. H is the horizontal component of the main field vector. Angle D is called the field declination, angle I – inclination.

[14] The geomagnetic poles reflect only the main dipole of the main geomagnetic field; contrary to magnetic poles, they don't correspond to the reduction of horizontal component to zero. In practice (in navigation etc) magnetic, and not geomagnetic poles are used. The magnetic equator is also shown, that doesn't concur with the geographic one and isn't a circle.

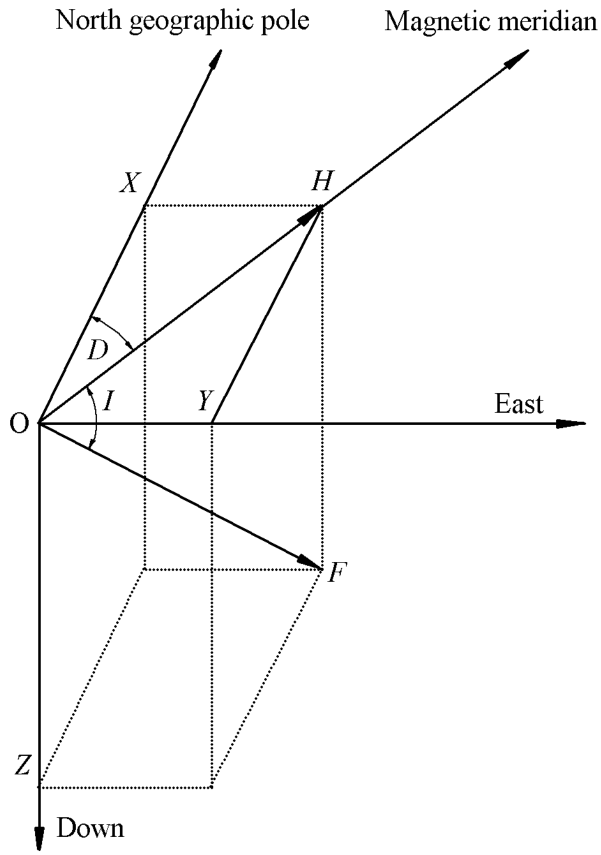

Figure 2. System of coordinates, used for the description of the Earth's main magnetic field.

Analysis of Data of the Earth's Magnetic Field

[15] The calculations were made in reference points through the Internet with the help of the web program of the British Geological Service (BGS – http://www.bgs.ac.uk/) for 1995, 2000 and 2005, the reference points were the same for all these years, their number was 1768. Each point contained a latitude, a longitude and three components – X, Y, Z of the vector of strength of the main field (axis X is directed along the geographical meridian to the north, axis Y – along the parallel to the east, axis Z – downwards), module of the horizontal component of the main field $|H|$, angle of declination D (between vector H of the horizontal component and geographic meridian) and angle of inclination I (between vector F of the full strength and vector H). The system of reference points on the chart was irregular, with extension at magnetic poles with the purpose of more accurate determination of location of these poles. Values $|H|$ in reference points were interpolated in matrix $|H|$ with the resolution of 1° of latitude and 1° of longitude (63525 elements in the matrix), at that the algorithm of interpolation of the program "Analytical GIS Eco" [*Shary et al.,* 2005] didn't alter the values in reference points. Isolines $|H|$ were generated according to this matrix, corresponding to values $|H|$, equal to 500, 1000, 2000, 4000,..., 40,000 nT (value $|H|$ changed from 0 to 41,380 nT). Relating to the necessity of the correct account of the matrix borders isolines $|H|$ were calculated to 87°N. The magnetic poles were determined by equation $|H| = 0$. Full strength of the main field $|F|$ altered from 22,870 to 67,140 nT. Isolines $|F|$ are shown in Figure 5.

[16] Figure 5 shows that both in 1995 and 2005 there were three maxima and one minimum $|F|$. The proximity of maxima $|F|$ to the magnetic poles is explained by the prevailing role of the main magnetic dipole, and these extrema's deviation from magnetic poles is related to the non-dipole component of the main field. The latter is also related to the presence of the maximum $|F|$ on the territory of Russia and of the minimum in South America.

[17] Analogically the magnetic equator was obtained ($|Z|$=0) according to the matrix of values of the vertical component of the main field Z. Value Z in the points of the matrix grid changed in 1995 from –67,157 to +60,703 nT, in 2005 – from –67,080 to 60,800 nT. The izolines of horizontal component $|H|$ of the main field and magnetic equator for 1995, 2000 and 2005 are shown correspondingly in Figures 6a and 6b. It is clear from them that $|H|$ has 4 extrema. The two of them (the minima) are magnetic poles, approximately corresponding to the main magnetic dipole of the Earth. In these minima $|H| = 0$. Another local minimum is located in the south of Africa, with $|H| = 10{,}410$ nT, and a local minimum is located near Singapore, with $|H| = 41{,}380$ nT. These last extrema are related to the non-dipole field. The North magnetic pole for 1995 and 2000 at the ocean level has coordinates 81°N, 110°W, and the South magnetic pole for 1995 and 2000 at the ocean level – 65°S, 138°E.

[18] Magnetic meridians were constructed the following way. From each point of the matrix grid along the horizontal components of the main magnetic field X and Y small segments were laid off towards the direction of horizontal component H of the main geomagnetic field. It was done by the special program[1] according to two matrices, of the eastern and western components of the main geomagnetic field.

[19] Since in the geographical projection[2] these hatches have considerably changed direction in comparison to equiangular projection (retaining angles and distances the same as on a sphere, different to a geographical projection), then the values of the horizontal component of the main geomagnetic field were transformed by stretching along axis x in $1/\cos\varphi$ times (here φ is a latitude ranging from –90° to +90°), that gave new values X', Y' of the horizontal components of the main field, $X' = X/\cos\varphi$, $Y' = Y$ according to which the angles of hatches were calculated. This method of transformation of hatches is approximate (the exact solution is considerably more complicated), but it is sufficiently precise for the scale 1:25,000,000. The sampling comparisons in the equiangular Gauss-Kruger projection (where angles aren't

[1] The program was developed by P. Shary

[2] In a geographical projection the chart is represented by a rectangle with longitude and latitude laid off on its axis

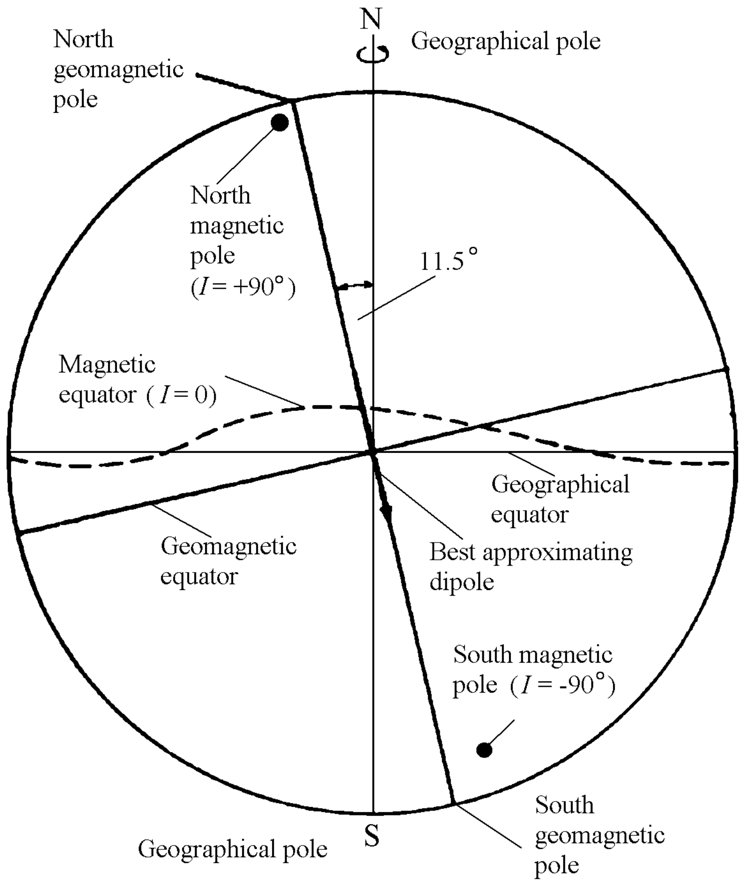

Figure 3. Scheme, illustrating the difference between the magnetic and geomagnetic poles.

distorted) have shown that the difference between the exact values and the values obtained by this method didn't exceed 0.5%.

[20] The hatches of the transformed directions of the horizontal component of the main field in the area of local minimum $|H|$ near the southern end of Africa are shown in Figure 7.

[21] It is noteworthy that the hatches of the transformed directions demonstrate on the chart the correct visually apprehended values of angles with geographic meridians only in equiangular projection, because only in these projections the angles on the chart and on the reference-ellipsoid do correspond to each other.

[22] At the geographical equator 18 points were marked in equal intervals (in 20° longitude), and a magnetic meridian was drawn through each of them. The last one is a smooth curve, due to the fact that potential V in the above-mentioned IGRF formula is infinitely differentiated. A tangent to this curve is the most close to the calculated transformed directions of hatches in the closest to magnetic meridian grid points of the matrix.

[23] Each magnetic meridian from a given point r of the geographical equator was drawn like a smooth curve, consisting of several sections; a tangent to this curve in each point is directed along the hatches (i.e. along the declination of the main geomagnetic field). Magnetic meridians are coming out of the South magnetic pole ending in the North. In areas free from external sources of the field (where the impact of magnetic anomalies of the Earth's crust is irrelevant) a compass is directed towards a magnetic meridian (Figure 8).

[24] Figure 8 also shows the magnetic equator. The chosen 18 magnetic meridians intersect with the geographical equator in each 20° of longitude. A magnetic meridian, corresponding to longitude –180° correlates with the one for longitude +180°, because it's the same. Some magnetic meridians, for example directed from the South pole along a geographical meridian to the south, are continued in the other hemisphere. In such cases in order to avoid artifacts in a browser (for example, in geographic information systems) a magnetic meridian is represented by numerical data as several sections of an integral curve – for the northern and southern hemispheres, or when a magnetic meridian intersects with the geographic meridian of 180°.

[25] It is worth mentioning that magnetic meridians demonstrate on the chart the correct visually apprehended values of angles with geographic meridians given in equiangular projections.

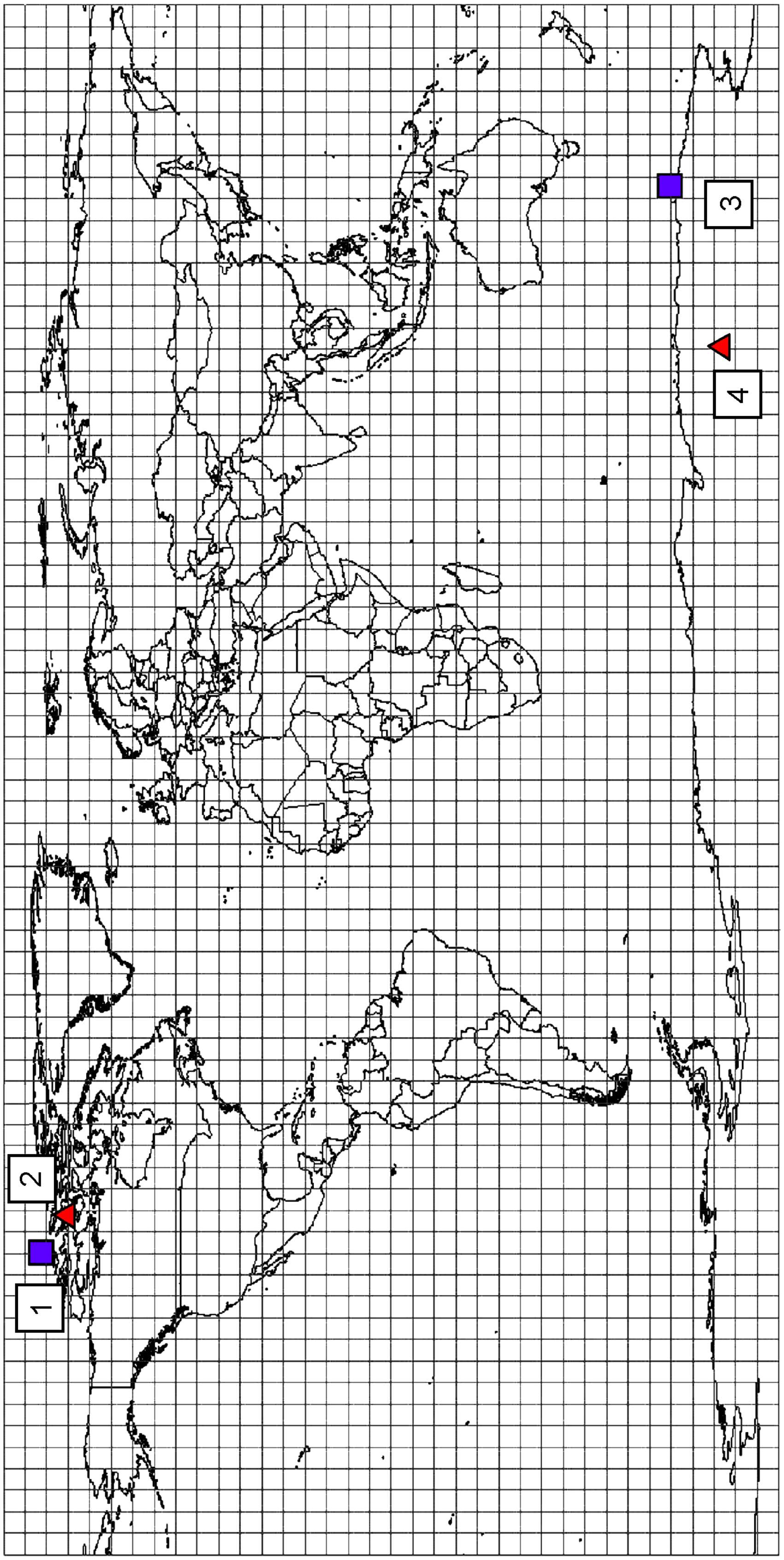

Figure 4. Approximate location of magnetic (1, 3) and geomagnetic (2, 4) poles on the world map: grid of geographic parallels and meridians in each 5°.

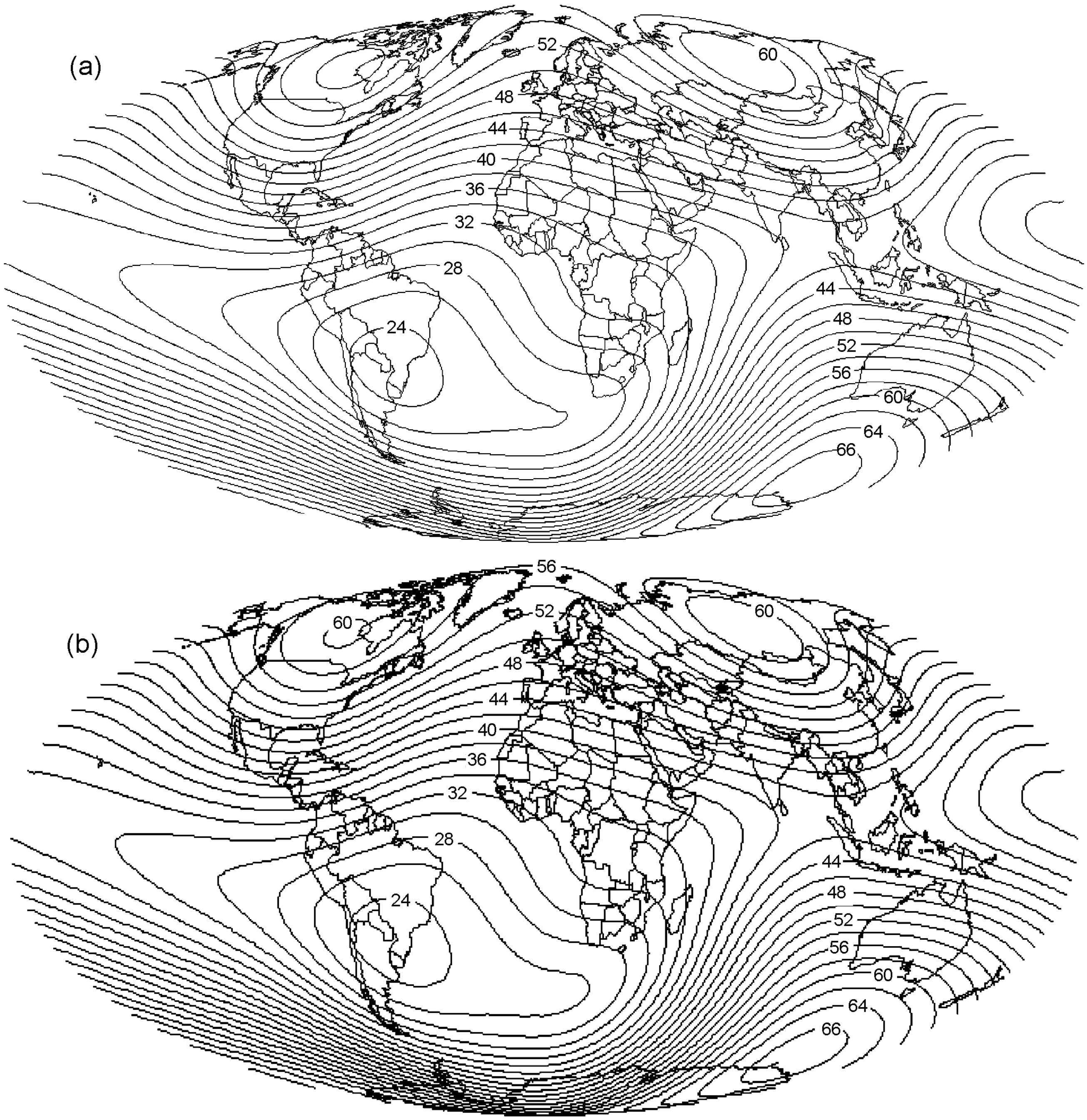

Figure 5. (a) Chart of isolines of full strength $|F|$ of the Earth's main magnetic field in equal-area Molveide projection for 1995. Isolines are drawn in 2 μT from 24 to 66 μT. (b) Chart of isolines of full strength $|F|$ of the Earth's main magnetic field in Molveide projection for 2005.

Geographical Maps and Analysis of Changes of the Earth's Magnetic Field in 1995–2005

[26] Full strength of the main field $|F|$ altered in 1995 from 23,058 to 67,219 nT at the average in reference points of 48,833 nT, in 2000 – from 22,890 to 67,120 nT at the average in reference points of 48,725 nT, and in 2005 – from 22,740 to 67,020 nT at the average in the same points of 48,668 nT. Module of the vertical component $|Z|$ changed in 2000 – from 0 to 66,990 nT at the average in reference points 42,113 nT, in 2005 – from 0 to 66,890 nT at the average in the same points of 42,069 nT. Value of the horizontal component $|H|$ changed in 1995 – from 0 to 41,370 nT at the average in

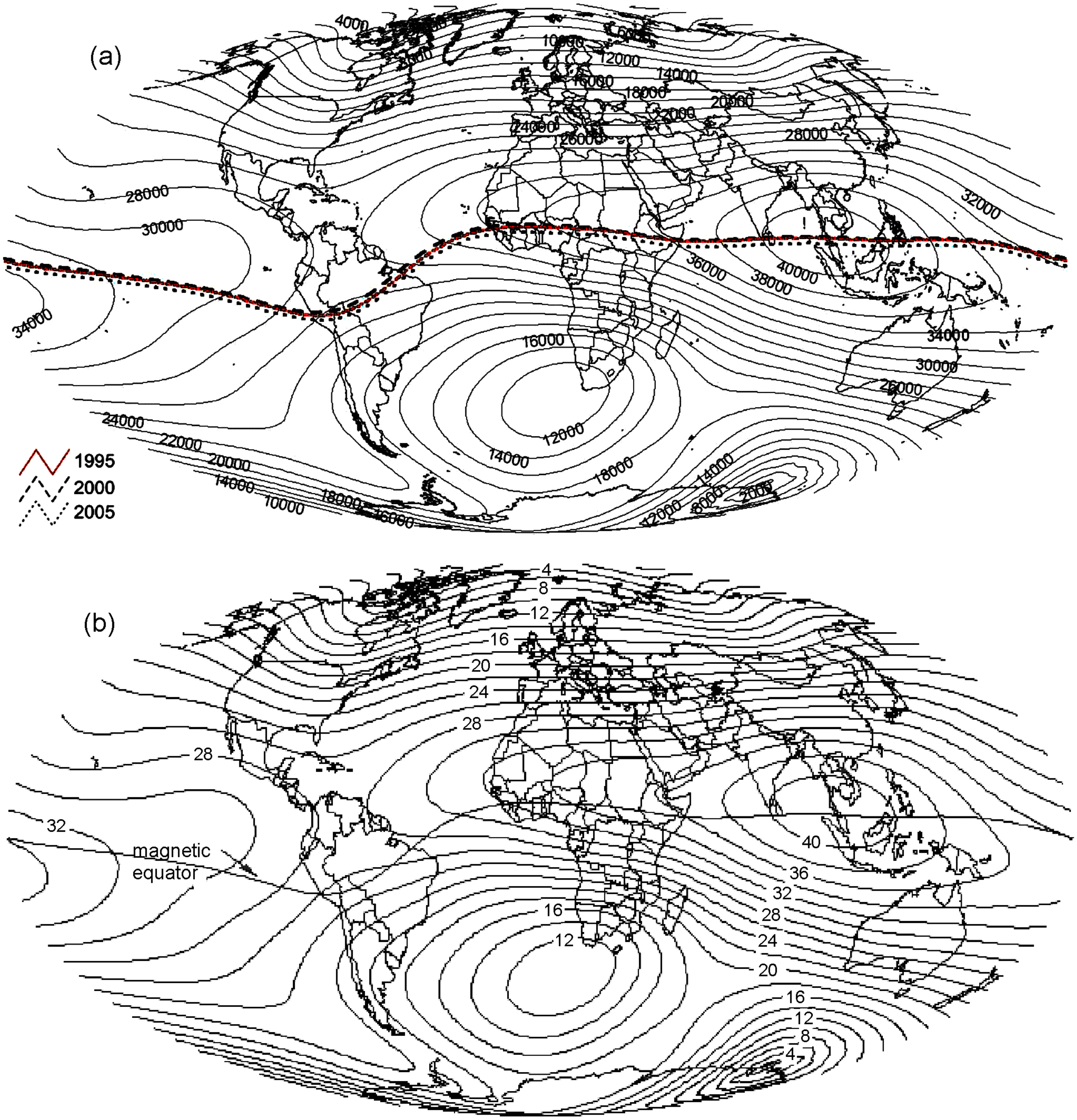

Figure 6. (a) Chart of isolines of the horizontal component $|H|$ of the strength of the main magnetic field of Earth and magnetic equators in equal-area Molveide projection. Isolines $|H|$ are drawn in 2000 nT from 2000 to 40,000 nT. Magnetic equators, calculated for different years, are shown by different hatching. (b) Chart of isolines of the horizontal component $|H|$ of the strength of the main magnetic field of Earth and magnetic equator (in μT).

reference points of 16,801 nT, in 2000 – from 0 to 41,370 nT at the average in reference points of 16,801 nT, in 2005 – from 0 to 41,480 nT at the average in the same points of 16,779 nT.

[27] Shift $|H|$ for 10 years is shown in Figure 9. Isolines $|H|$ are drawn in 2000 nT from 2000 to 40,000 nT, the isolines of 1000 nT and 500 nT are added to them at the magnetic poles. The apparent shift of isolines $|H|$, up to 12°

Table 1. Average value of decrease of the Earth's magnetic field in the period of 1995–2005

Field component	Decrease value in 10 years
Full strength $|F|$	0.34%
Horizontal component $|H|$	0.38%
Vertical component $|Z|$	0.33%

(1200 km), related to the western drift, entailing an average shift of the field in longitude 0.9° in 10 years. The adduced data provide the capability of estimating the decrease of average values for reference points in a period of 10 years (Table 1).

[28] These values are approximately half the known [*Sharma,* 1989] value of decrease (0.5%) for the main magnetic dipole of the Earth over the same period (about 5% over 100 years). This is explained by the evident relative role of multipoles of higher order of the main field, not displaying any trend towards subsiding [*Sharma,* 1989]. Due to this reason the results obtained (Table 1) according to the data of 1995–2005 are insufficiently characterizing the specifics of alterations of the Earth's main magnetic field. On the background of the subsiding main dipole the relative role of multipoles of higher order is strengthening. It entails a considerable growth of the relative role of local deviations of the magnetic field. However, the role of multipoles in navigation is irrelevant. Let us mention that the process of decline of the main dipole against the background of multipoles, changing insignificantly, can lead to a considerably more rapid deterioration of orientation based on magnetic navigational systems (due to the growth of the relative role of local deviations of the field's strength), than in the case of the field represented only by the main dipole. For solving tasks of this kind the main magnetic dipole plays a specific

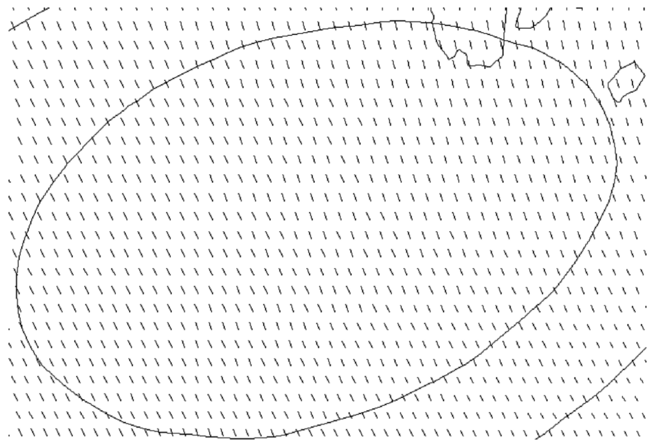

Figure 7. Hatching of the transformed directions of the horizontal component of the main geomagnetic field. The chart's section is shown in the area of a local minimum of the horizontal component $|H|$ of the main field, the closed curve is isoline $|H| = 12$ μT; to the north of this section the southern coastline of Africa is shown. Magnetic meridian on the sphere is perpendicular neither to isolines $|H|$, nor to isolines $|F|$.

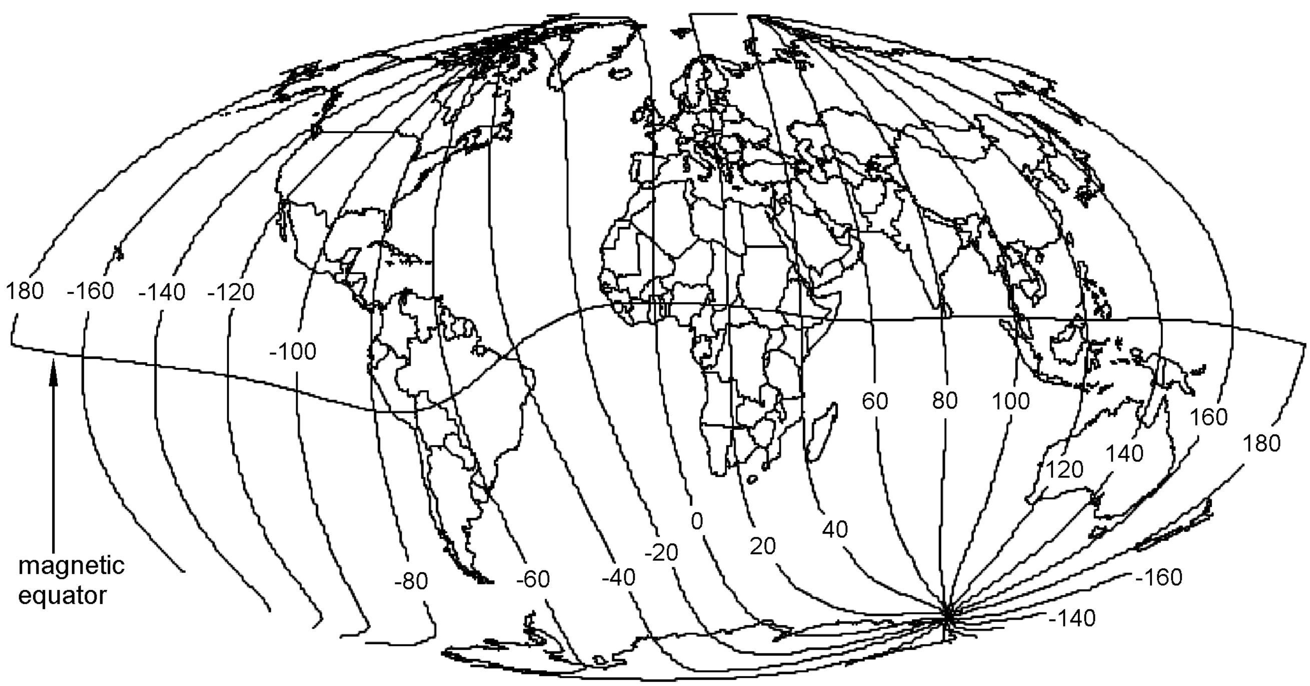

Figure 8. Chart of magnetic meridians of the Earth's main magnetic field in the equal-area Molveide projection.

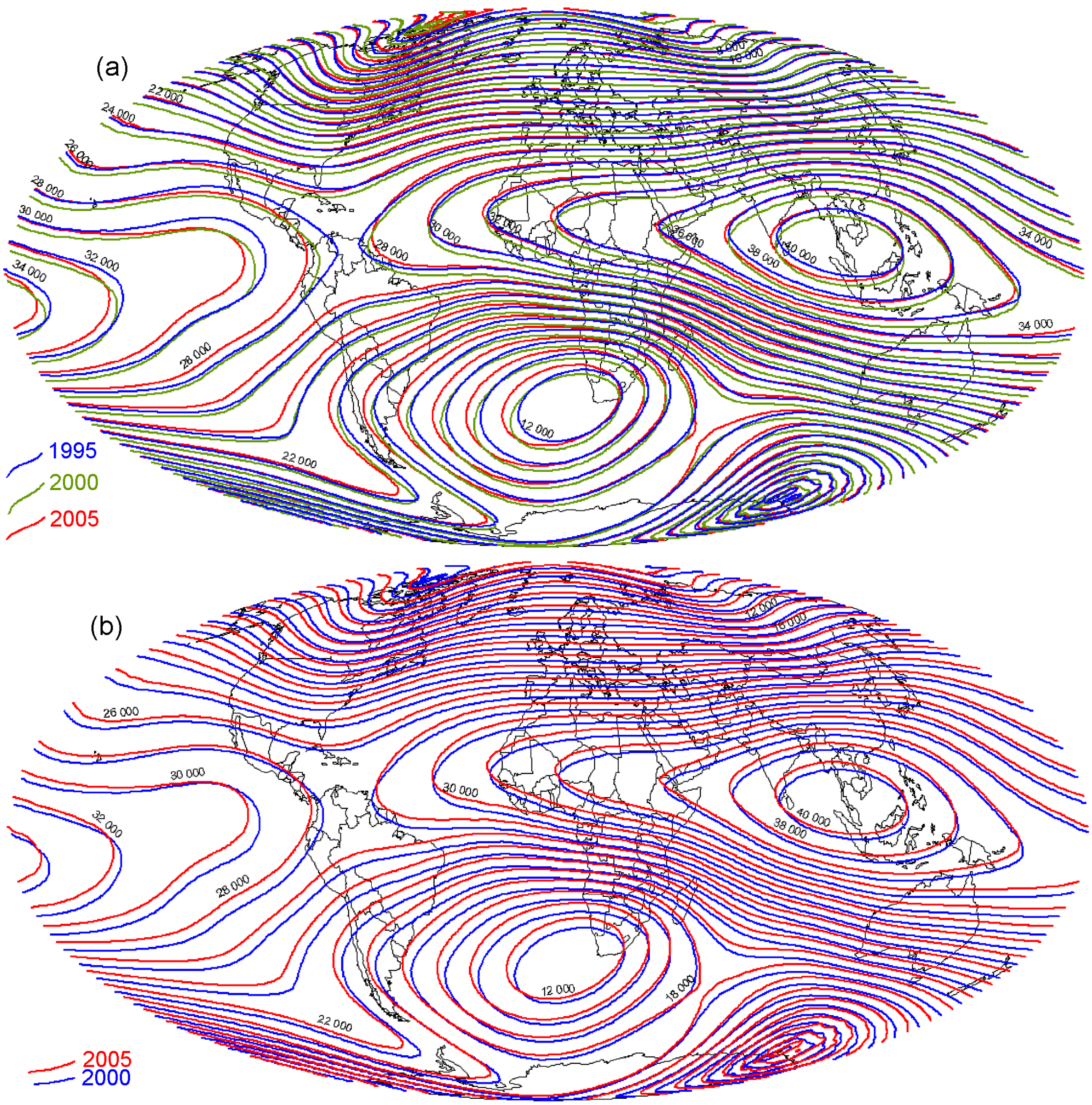

Figure 9. (a) Chart of the horizontal component of the Earth's main geomagnetic field $|H|$ in 1995, 2000 and 2005. (b) Chart of the horizontal component of the Earth's main geomagnetic field $|H|$ in 2000 and 2005.

part of a "signal", and the multipoles – a part of "noise", when a change of the ratio signal/noise is more important than a change of a signal's absolute level.

[29] For revealing these circumstances the corresponding approximate evaluation of the main field alterations for the period of 10 years is indicative. It can be obtained by subtracting from the field's components of strength in reference points in 1995 the analogical values in the same points in 2005. It would be more correct to make the vector subtraction of the full strength of the main magnetic field, and then examine the components of the difference obtained; hence we confined ourselves to the approximate evaluation, given the preliminary character of the obtained results, applied for a rough evaluation of the value and character of change of the main field. The point is that the single use of two time series doesn't allow us to conclude, whether these alterations would grow in the course of time or reach a certain limit. It's very likely to happen that even three time series would

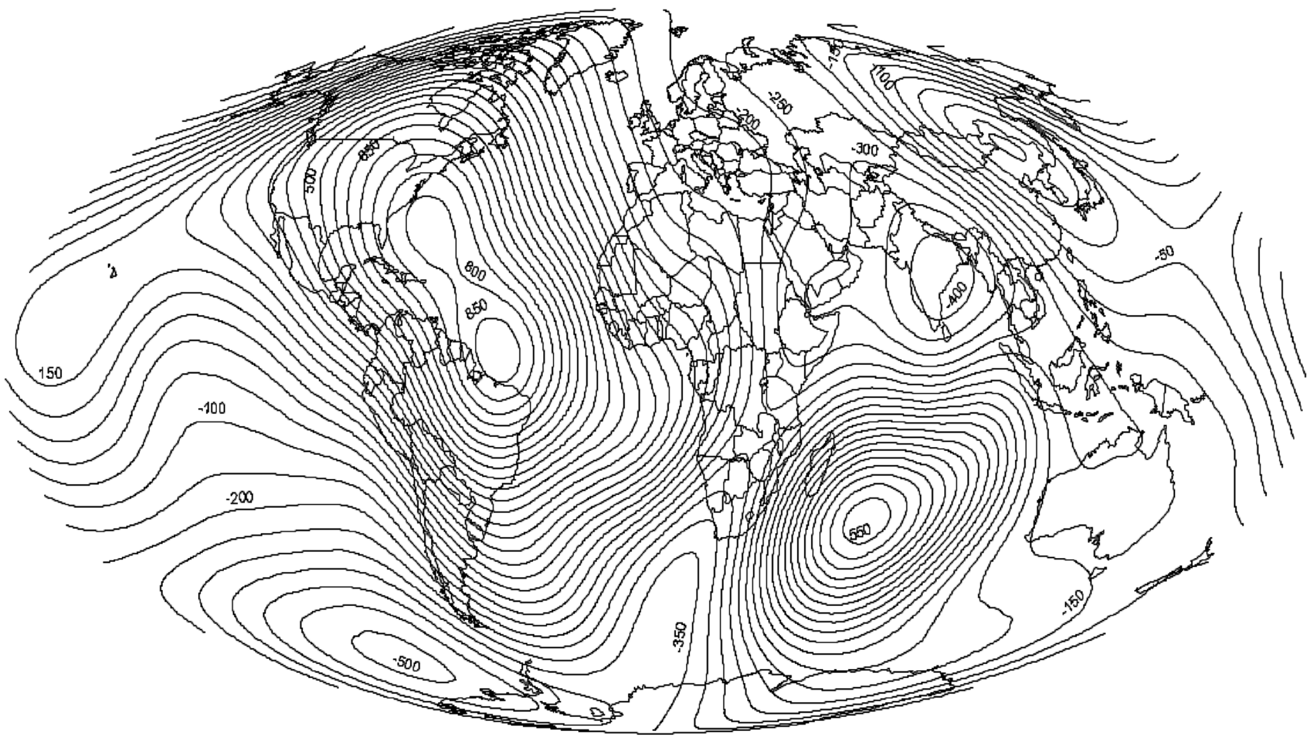

Figure 10. Difference of the vertical component of the main field strength $|Z|$ over 5 years.

be insufficient, as multipoles create complicated configurations, changing nonlinearly in space. At the present time the data (the Gauss coefficients) are available for evaluating 22 time series, from 1900 to 2005, i.e. in each 5 years. The results of subtracting the analogical values for 2000 in the reference points from the components of the field's strength in the same points for 1995 (the differences) are shown in Figures 10–13.

[30] Figure 10 shows subsiding $|Z|$ over five years in the territory of Russia by 300 nT and more, Figure 11 – oscillations $|H|$ in the territory of Russia, Figure 12 – subsiding $|F|$ in the territory of Russia and the increase in the territory of the USA, Figure 13 – decline of the average value $|F|$ in the eastern hemisphere and its increase in the western hemisphere.

[31] As it is clear from these results, the local changes of the main magnetic field over 5 years considerably exceed the average values for the whole globe, represented in Table 1. Furthermore, the average subsiding of the main field in Russia (especially of the full and vertical components) exceeds several times those for the Earth. In order to obtain the relevant evaluation for the territory of Russia we have determined the reference points, located in the territory of this country. The relevant parameters of subsiding of the main field for this region over the last 5 years for $|F|$ were – 0.38% (that is in 3.2 times more, then on average for the entire Earth), for $|H|$ – 0.04%, for $|Z|$ – 0.45% (in 4.3 times more, then on average for the entire Earth).

[32] The corresponding approximate evaluation of the main filed alterations over 10 years is indicative. It can be obtained by subtracting from the components of the field's strength in reference points in 1995 of analogical values in the same points in 2005. The results of such calculations are shown in Figure 14–17.

[33] The three time series (1995, 2000 and 2005) are obviously insufficient for making a reliable prediction of the prospects of change of the main magnetic field in the near future. Nevertheless these data show the relevant decrease of the field subsiding velocity over the period of 2000–2005 compared to the period 1995–2000. However, it could be not a real phenomenon, but the effect of the ten times increase of accuracy of measuring of coefficients. For a more substantial analysis of dynamics of the geomagnetic field it would be useful to apply the data available since 1900 up to the present time. If the pace of the demonstrated alterations of the main geomagnetic field increase, it might entail serious problems for the country's navigation, based on magnetometry.

[34] The comparison of results for Russia and for the whole globe shows that the present situation is inauspicious for Russia – here the main magnetic field subsides several times faster than averagely on Earth. In the United States, for example, over the same period of time the full strength of the magnetic field has increased (Figures 15–17).

Geographical Map "Geomagnetic Field of the Earth"

[35] This map (Figure 18) was developed for the Defense Ministry of Russia and Rosgidromet. It has the following parameters: scale 1:25,000,000; isolines of the absolute value

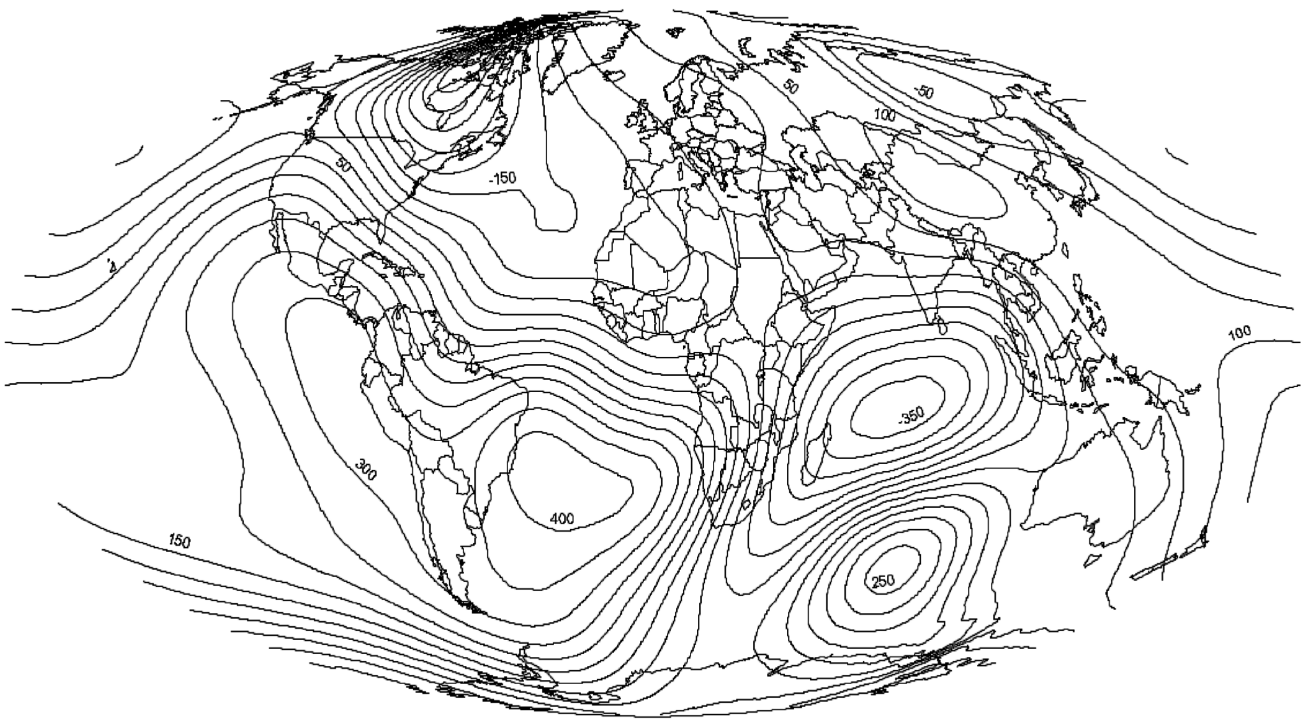

Figure 11. Difference of the horizontal component of the main field strength $|Z|$ over 5 years.

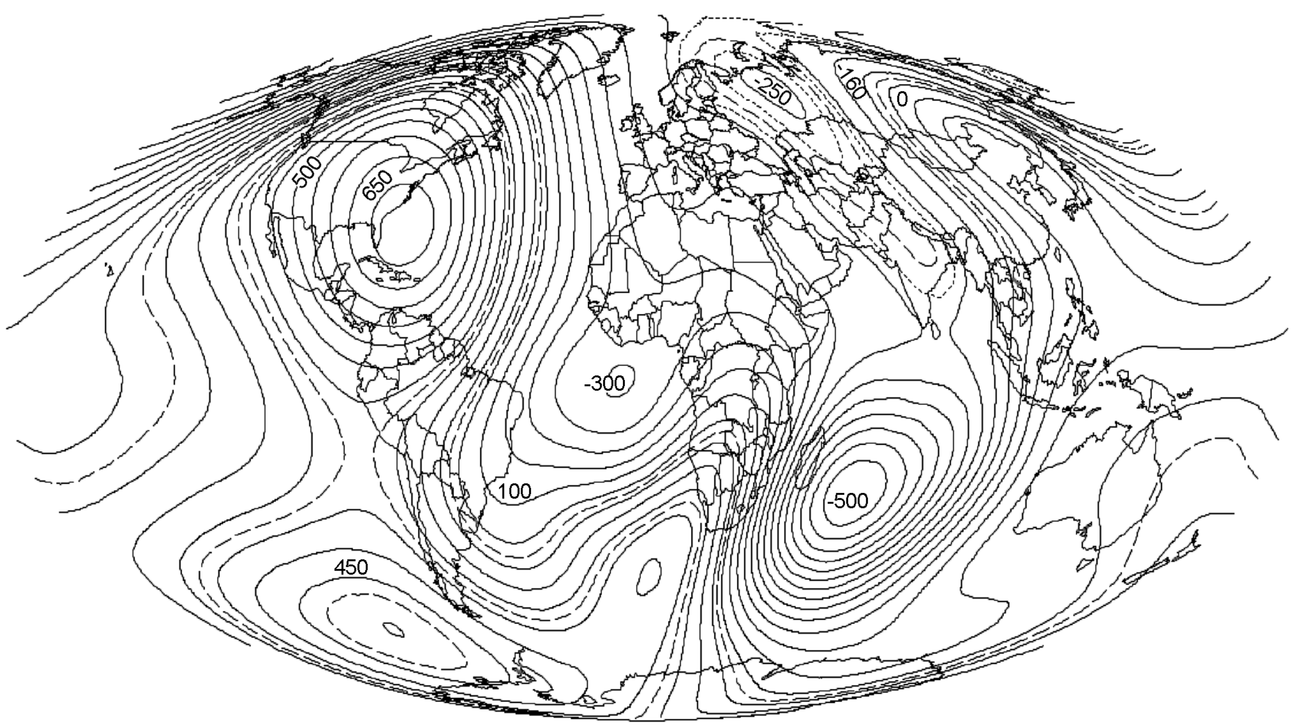

Figure 12. Difference of full strength of the main field $|F|$ over 5 years.

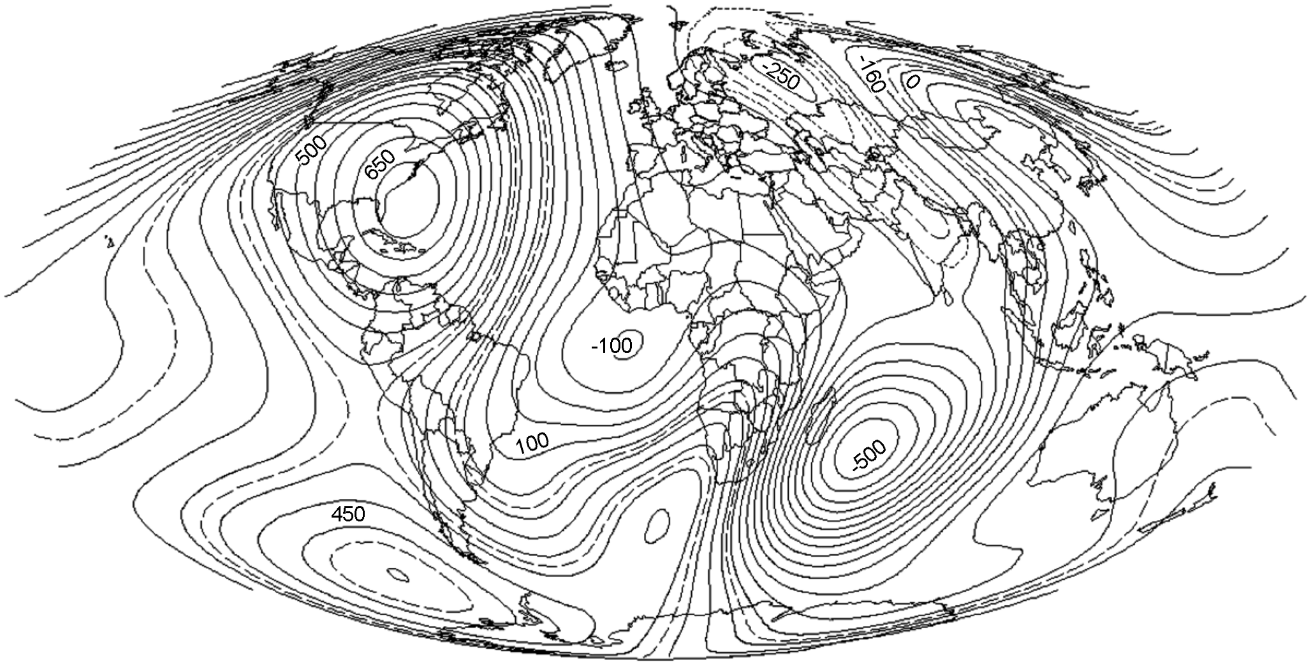

Figure 13. Decrease of average value of strength of the main field $|F|$ in the eastern hemisphere and its growth in the western hemisphere over 5 years.

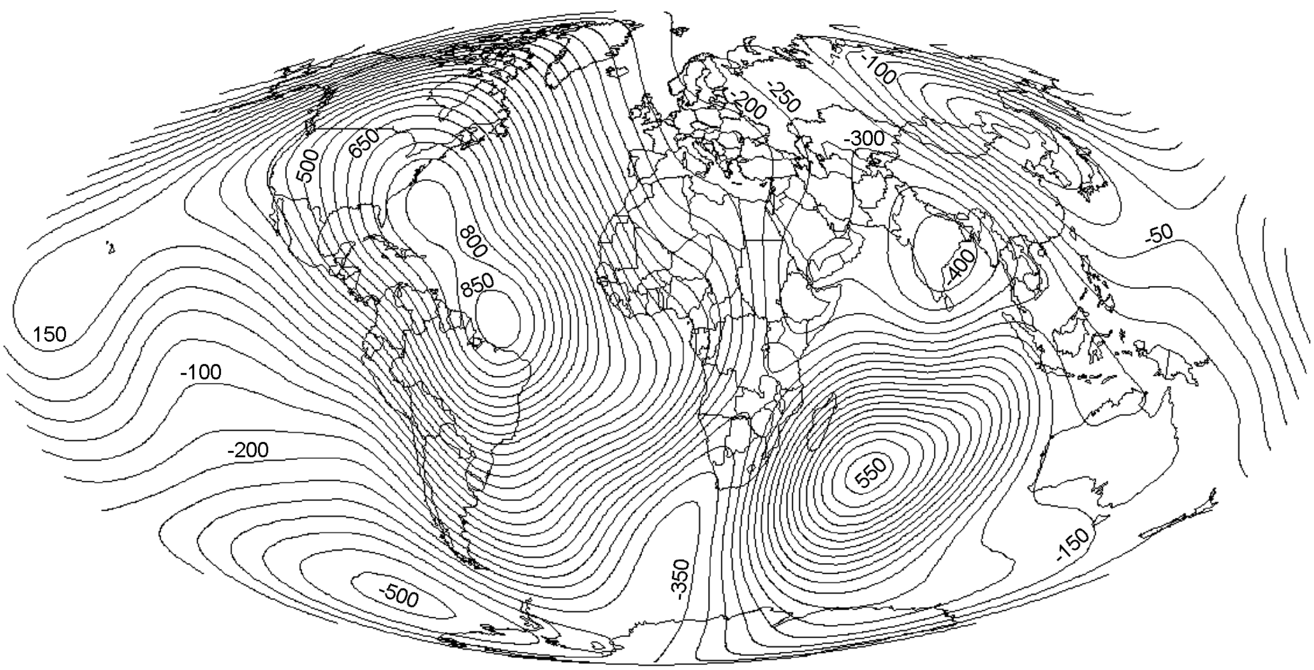

Figure 14. Difference of the absolute value of the vertical component of the main field strength $|Z|$ over 10 years, from the values for 1995 the values for 2005 are subtracted. Subsiding $|Z|$ in the territory of Russia by 300 nT and more is apparent.

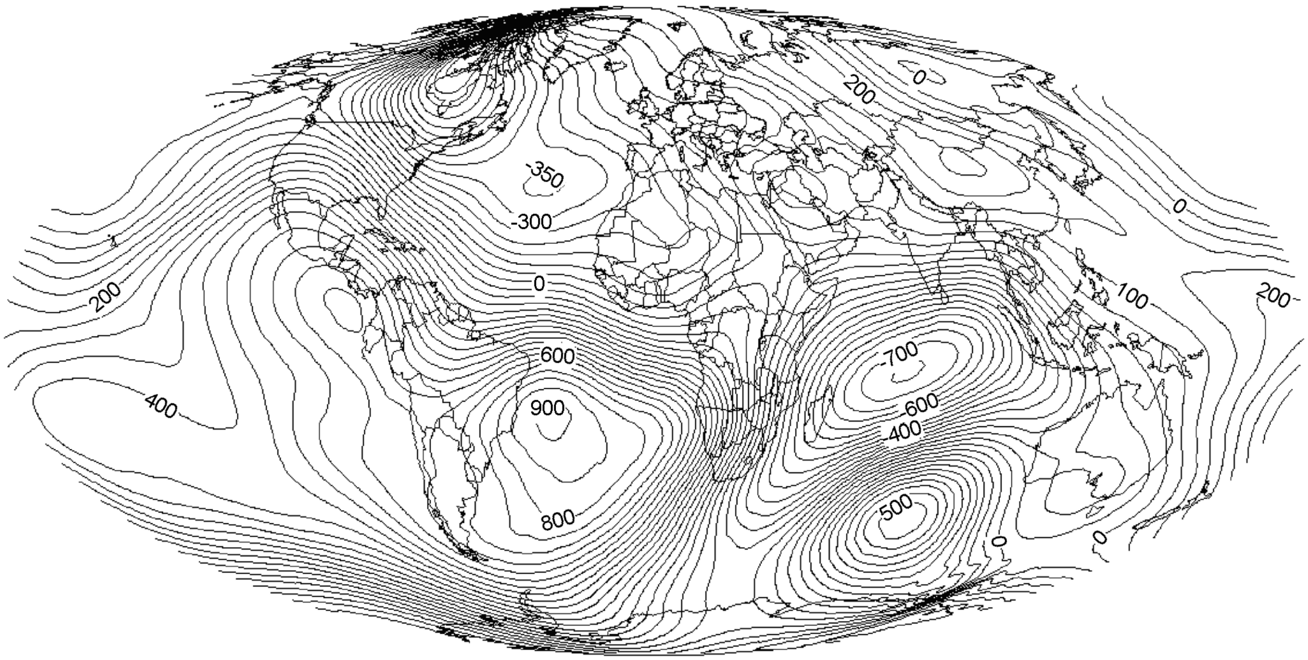

Figure 15. Difference of the horizontal component of the main field strength $|H|$ over 10 years, from the values for 1995 the values for 2005 are subtracted.

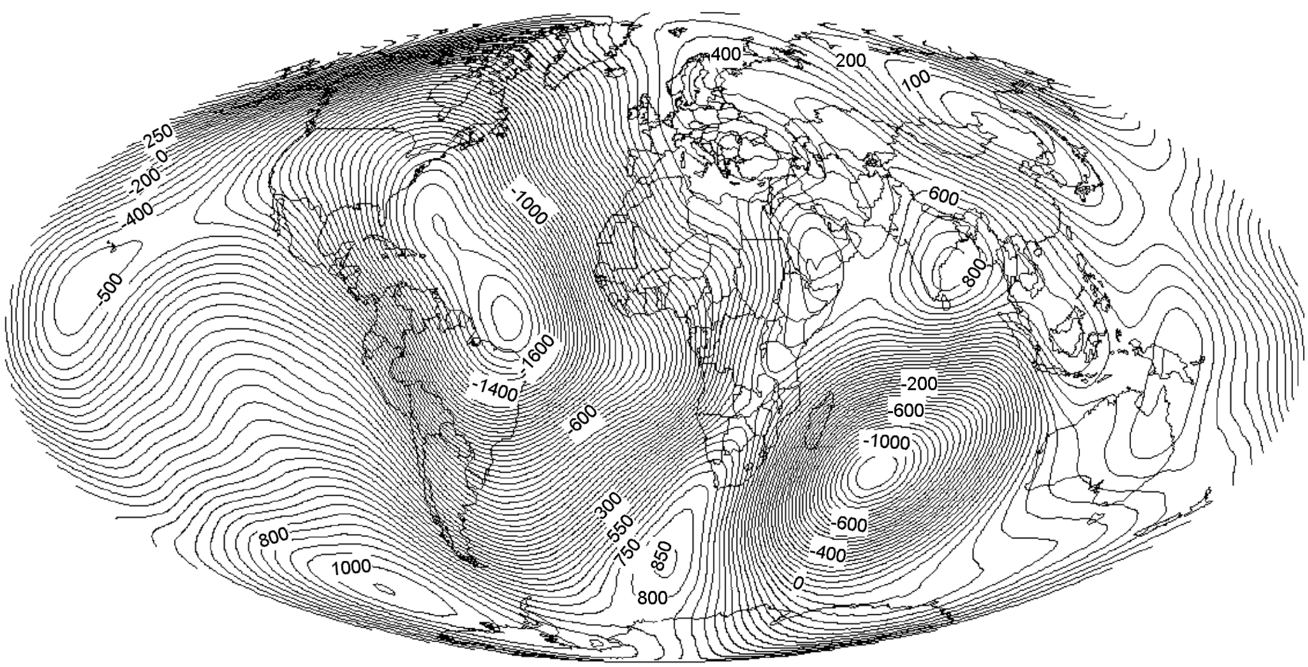

Figure 16. Difference of the full strength of the main field $|F|$ over 10 years; from the values for 1995 the values for 2005 are subtracted. As a whole average value $|F|$ over 10 years has slightly subsided in the eastern hemisphere and has increased in the western hemisphere.

of horizontal component of the Earth's main magnetic field vector of strength ($|H|$). The values of isolines lie within the range from 500 to 40,000 nT with interval of 2000 nT, isolines of 500 and 1000 nT are added to ensure the better mapping of the horizontal component of the main geomagnetic field near magnetic poles, for which $|H| = 0$; magnetic meridians of the Earth's main geomagnetic field, including the longitudes, where magnetic meridians intersect with the geographical equator and lie in the range from –160 to +180 with interval of 20°; magnetic equator with vertical component values $Z = 0$ of the main geomagnetic field; for the periods of 1995–2005: the North magnetic pole has coordinates: 81°N and 110°W, and the South magnetic pole – coordinates 65°S, 138°E; availability of the geographical grid and geographical equator.

[36] The map was developed using the data for the corresponding years for an altitude equal to 0, converting from a geocentric to geodetic system of coordinates. The calculations in reference points were carried out using the BGS program as described above. The special technology of data processing was developed for drawing isolines of horizontal component $|H|$, magnetic meridians and magnetic equator.

[37] All data of the electronic map have geographic coordinates – a Greenwich longitude (in the range from –180° to +180°) and latitude (from –90° to +90°).

[38] The data massifs of magnetic equator (the layer Magnetic equator) contain the curve of magnetic equator, the attributive database contains the value of vertical component Z of the main geomagnetic field ($Z = 0$ for magnetic equator). To the north of this curve Z is directed towards the Earth's interior, to the south – from the Earth's center.

[39] The data massifs of the isolines of absolute value of horizontal component $|H|$ of the main geomagnetic field (layer Isolines of IGRF horizontal component) contain the isolines of $|H|$, the attributive database for each isoline contains the corresponding value of $|H|$. These values range from 500 to 40,000 nT; isolines are provided for values of 2000, 40,000 nT with interval 2000 nT; isolines of 500 and 1000 nT are added for a better mapping of the main geomagnetic field near magnetic poles, corresponding to $|H| = 0$.

[40] The data massifs of the magnetic meridians of the main geomagnetic field (layer Magnetic meridians) comprise the curves of magnetic meridians, the attributive database for each curve comprises the longitude values, where a magnetic meridian intersects the geographic equator. These values range from –160° to +180°with interval 20°.

[41] The data massifs of angle of declination D of the main geomagnetic field (layer Vectors of IGRF declination) contain 64,257 hatches of a transformed direction; a hatch is a vector with the length of ~0.5°. The initial points of hatches are located periodically in one degree of latitude and in one degree of longitude. The attributive database for each hatch contains the initial (non-transformed) numerical values of declination angle D expressed in degrees. An angle of declination is counted from the direction of a geographic meridian; for the eastern declination of vector of the horizontal component of the main geomagnetic field of the geographic meridian angle D is positive, for the western – negative.

[42] The map was developed in a traditional paper variant, in digital variant and downloaded in a GIS at a scale of

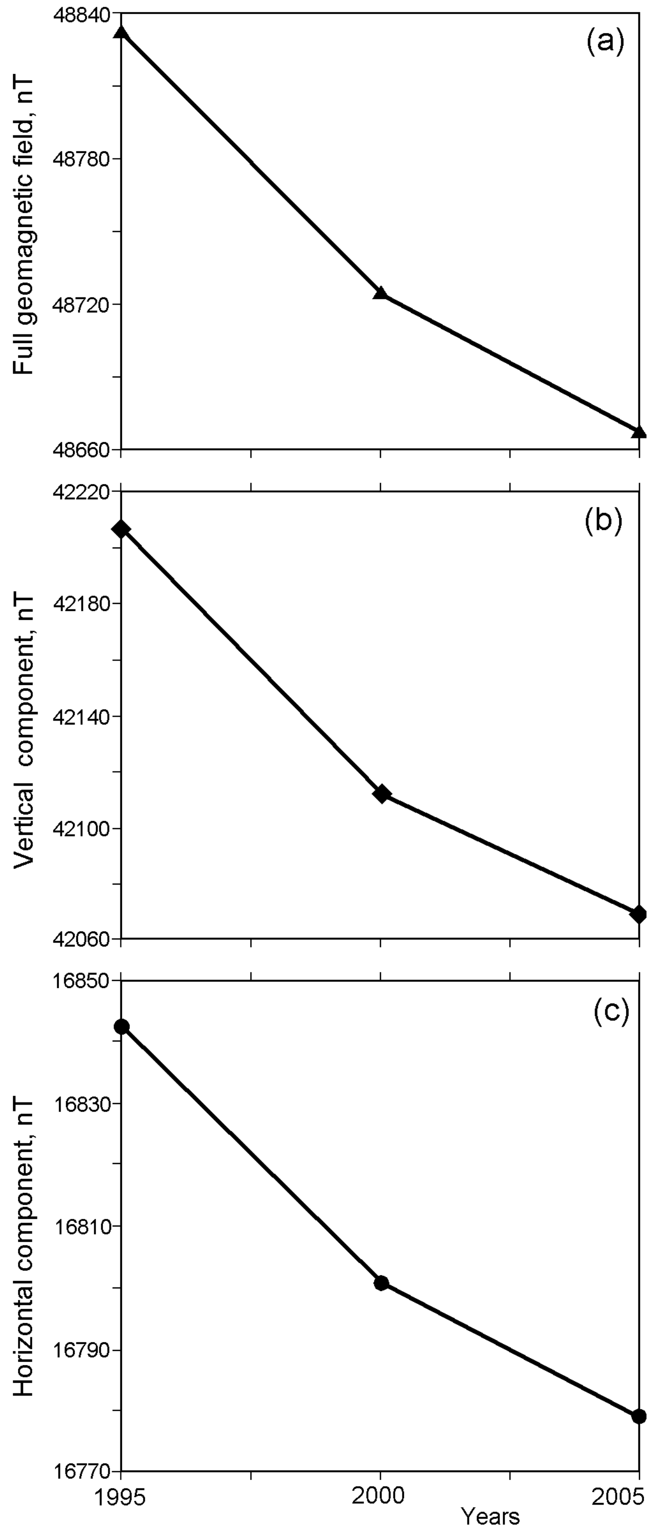

Figure 17. Change of the values of the full geomagnetic field, average in reference points of Earth (a), module of its vertical (b) and horizontal (c) components over 10 years. All presented parameters of the main geomagnetic field show the dynamics of subsiding of this field in time.

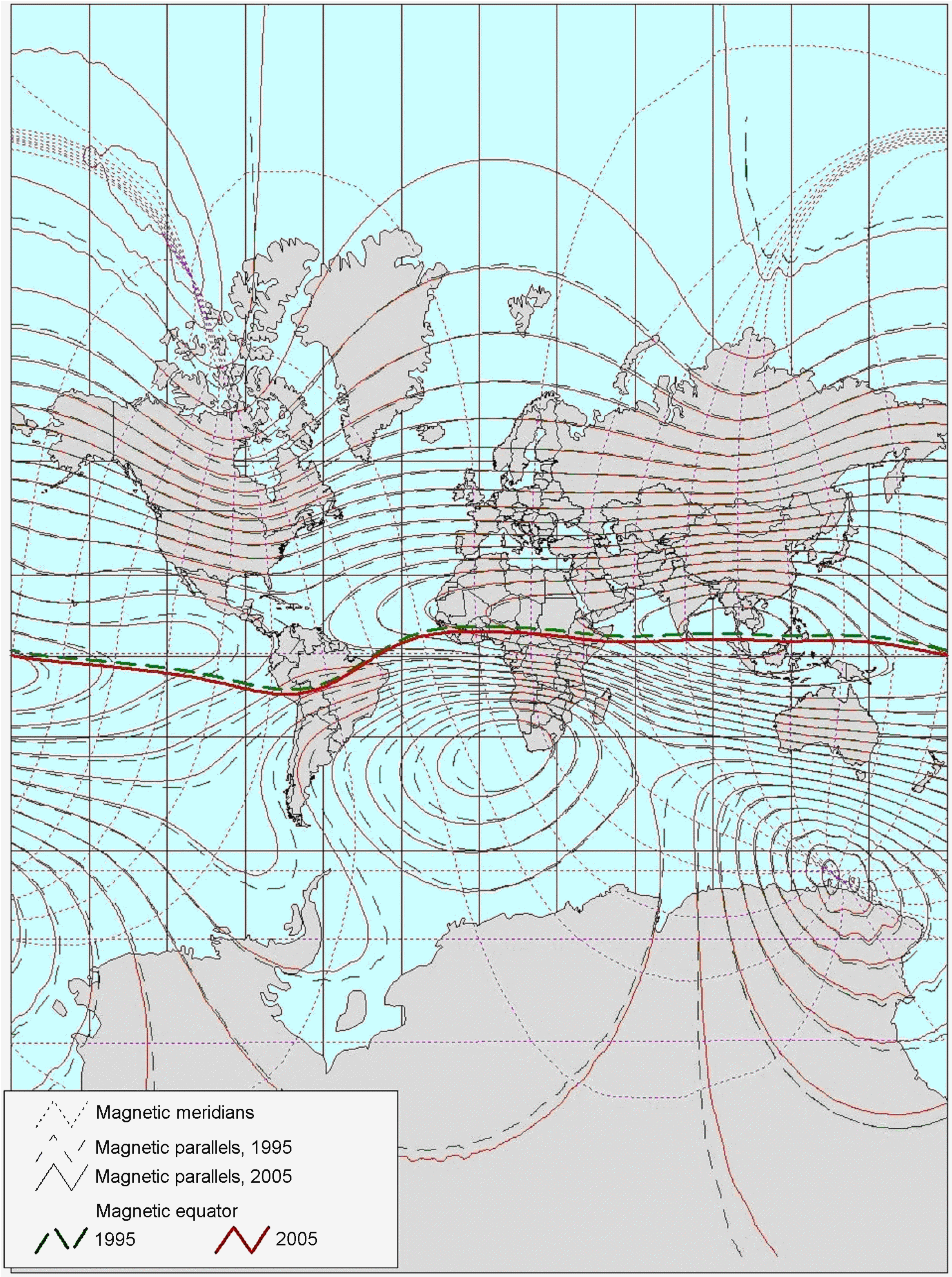

Figure 18. Geographical map "Geomagnetic field of the Earth". Comparison of data of 1995 and 2005.

1:25,000,000 in Mercator projection. The digital data contain the isolines of horizontal component $|H|$ of the main geomagnetic field with recorded values of $|H|$, magnetic meridians with recorded values, at which magnetic meridians intersect with the geographic equator, transformed hatches of directions of declinations of the main field, magnetic equator, geographical objects (countries, oceans etc.), the legend.

[43] The map's digital data are presented as the GIS database Geomagnetic field of the Earth, converted into compatible formats for the GIS ArcView and GIS "Neva" [*Zhalkovsky,* 2001, 2002, 2004].

Conclusions

[44] 1. The results of our work have indicated that the situation with the Earth's magnetic field is now extremely unfavorable for Russia – the main magnetic field here subsides several times more rapidly than on the entire planet. In the USA, for example, the full strength of the magnetic field has increased over the same period of time. Noteworthy that the local alterations of the main magnetic field over 5 years exceed considerably the average values for the whole Earth. Moreover, the average weakening of the main field in Russia (especially of its full and vertical components) several times exceeds the one for the Earth. It could be assumed that against the background of subsiding of the main dipole the relative role of multipoles of higher order is getting stronger, entailing the considerable impact of the relative role of local deviations of the magnetic field. Let us note that the process of subsiding of the main dipole against the background of insignificantly changing multipoles can lead to a considerably more rapid deterioration of orientation of the local magnetic navigation systems (due to the growing role of local deviations of the field's strength), than if the field was presented by the main dipole only. For solving these tasks the main magnetic dipole acts like a specific "signal", and multipoles as "noises", when changing of the "signal/noise" ratio is more important than the change of a signal's absolute level.

[45] 2. It was established that the horizontal component of the vector of strength of the Earth's main field has 4 extrema: three minima (two of them are the Earth's magnetic poles, the third, the local minimum, is located near the southern end of Africa – $|H|$ = 10,410 nT) and the local maximum ($|H|$ = 41,380 nT), located near Singapore, intersected by the magnetic equator – the area, where strong earthquakes have been the most frequent over the last time. The last two extrema are related to the non-dipole field.

[46] 3. The technology of elaboration of the geographical map, the adopted system of coordinates, altitudes and legend have provided the opportunity to display the entire structure of the Earth's main magnetic field according to the scale 1:25,000,000 and analyze the tendencies of its change.

[47] 4. The geographical map was elaborated, that can be used in scientific research and practical work. It will help to solve various tasks of prediction, related to the weather, navigation, based on magnetometry, quality of the people life and study of other physical fields of the Earth. Time series of 1995–2005 are insufficient for a well-founded prediction of changes of the magnetic field for the next decades. It is still difficult to establish, whether these negative tendencies grow or reach its maximum. For the corresponding analysis and making conclusions it is necessary to use the data from 1900 up to the present time. If the pace of the described changes of the main magnetic field continue to grow in Russia and in the CIS countries, then in the next decades significant problems, can arouse related to the national navigation, based on magnetometry.

[48] 5. The work fulfilled and results obtained were applied in the Defense Ministry of Russia and in Rosgidromet and also were reported at the Scientific Council on geoinformatics of the presidium RAS. The examined directions of research are completely in line with the program of RAS "Electronic Earth", and the results are included into the list of completed projects of this program.

[49] 6. The results of data analysis on the direction and change of strength of the magnetic field are of tremendous practical importance, especially for Russia, because navigation in this country (in contrast to the USA) is mainly related to the use of vector and value of strength of the magnetic field. Given the diverse character of changes of the field's strength in many areas of the Earth, calculations in reference points, analogical to the carried out analysis, are necessary. The number of these points is 1768. Thus the future research will require considerably more efforts and time, including preparing special programs of calculation and presentation of results of the data analysis of the Earth' magnetic field.

[50] 7. The results, obtained during the carried out research are intended to be used at elaborating the federal Atlas of the main magnetic field of the Earth.

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Ye. A. Zhalkovsky, Geophysical Center, Russian Academy of Sciences, Moscow; e-mail: e.jalkovsky@gcras.ru