Physics – Uspekhi **37** (9) 921 – 925 (1994)

PACS numbers: 01.10.Fv

Scientific session of the Division of General Physics and Astronomy of the Russian Academy of Sciences (25th May 1994)

A scientific session of the Division of General Physics and Astronomy of the Russian Academy of Sciences was held on 25 May 1994 at the P L Kapitza Institute of Physics Problems. The following papers were presented at this session:

K M Salikhov "Spatial organisation of the spin polarisation in solid paramagnets";

V A Blednov "Geomagnetic component measurements on board of a moving ferromagnetic carrier".

A summary of the second paper is given below.

PACS numbers: 91.25.Ga; 91.25.Le; 93.85.+q

Geomagnetic component measurements on board a moving ferromagnetic carrier

V A Blednov

A fundamentally new method of vector geomagnetic measurements on board a moving ferromagnetic carrier [1] is described below: it is known as the method of determination of the angular components (MDAC). In contrast to the existing methods, the majority of which rely to a greater or lesser extent on the principles of compensation, the MDAC is based on the effects that appear as a result of magnetisation of the magnetically soft ferromagnetic body of a carrier by the geomagnetic field (GMF). The intrinsic field of the ferromagnetic carrier is not regarded as a perturbation but as a source of information, which makes it possible to determine the parameters of the magnetising primary (in this case, geomagnetic) field. Since the solution should be not only theoretical, but also practical, the task has been to develop a method which makes it possible to determine the GMF parameters correctly [2]. Other solutions requiring special conditions for magnetisation of a ferromagnetic carrier, including prolonged stability of the Poisson parameters, have been ignored. This formulation of the problem has made it necessary to classify the GMF components in accordance with the feasibility of their correct determination on the basis of the information on board a ferromagnetic carrier. It has been found that only the angular components, i.e. the components which govern the direction of the GMF induction vector (in particular, the magnetic inclination and the magnetic course), can be measured reliably. The force components, such as the modulus of the field vector and any of its components (measured in nanoteslas), belong to the group of GMF characteristics which can be determined on board a carrier only with limited precision and only subject to a number of assumptions [3, 4]. This has governed the main direction chosen in the work on the problem in hand, because highly precise of calculation of the GMF components should be attained under the following conditions:

— measurements are carried out only on board a carrier;

— the magnetic field of the carrier is formed in the presence of a constant and arbitrary action on the body of this carrier of a large number of external forces (elastic stresses of various types, time-dependent magnetic fields, variations of temperature, etc.);

— the intrinsic magnetic field of the carrier can have any structure (any gradient) and can vary from the minimum to the maximum value;

— there is no information whatsoever on the GMF and on the parameters of the intrinsic magnetic field of the carrier.

In each fairly short time interval the magnetisation of the ferromagnetic body of a carrier consists of a constant part, which governs its average value, and a variable part. The constant part is determined by the conditions during a magnetisation process that has taken place relatively long ago. The variable (induced) part reflects the influence of the magnetising field acting at a given moment and its nature depends on the relationships between its components. Therefore, if the parameters of the external field vary sufficiently slowly so that the magnetic viscosity can be ignored, the induced magnetisation of the ferromagnetic carrier and, consequently, the changes in the components of its intrinsic magnetic field depend on the parameters of the magnetising field. If we assume that during the data collection time the process of magnetisation of the ferromagnetic carrier, which has different but relatively large demagnetisation coefficients, occurs under the influence of extremely small (compared with the coercive force) changes in the external field and of relatively small changes in the external forces, it is possible to use a linear model of the formation of the intrinsic magnetic field. This is one of the main hypotheses underlying the MDAC, which needs to be proved and which requires special technology of data collection.

The physical characteristics of the MDAC can be explained by considering the simplest model for the solution of the problem in hand. Let us assume (Fig. 1) that an instrument consisting of a transducer, magnetically sensitive to the field components and attached rigidly to a ferromag-netic rod, is placed in the GMF. This instrument

Received
Uspekhi Fizicheskikh Nauk **164** (9) 1001 – 1005 (1994)
Translated by A Tybulewicz

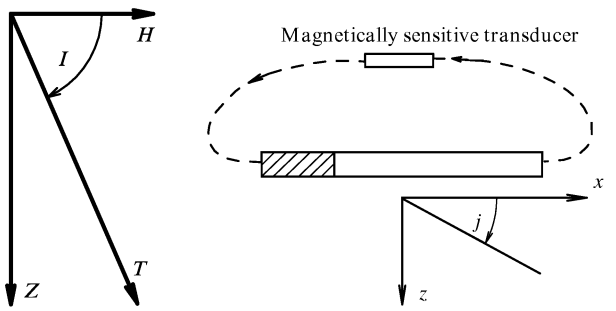

Figure 1.

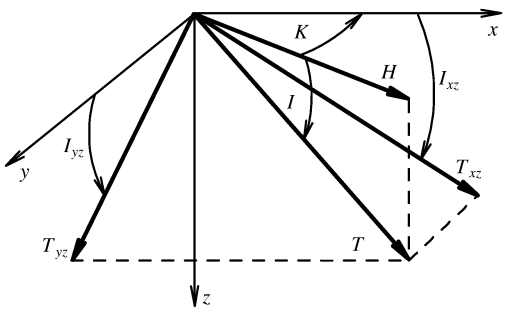

Figure 2.

can be reoriented in the geomagnetic meridian plane to an angle j. The rod has permanent and induced components of its magnetisation. If all the Poisson parameters (except a) vanish, a component of the combined magnetic field can be found from the equation

$$X' = (1+a)H\cos j + (1+a)Z\sin j + P\,,$$

where h and Z are the horizontal and vertical GMF components. The unknowns are the permanent field P and the induced magnetisation components $(1+a)H$ and $(1+a)Z$. They can be calculated if three measurements are made of the combined magnetic field at different values of the angle j and a system of algebraic equations is constructed. The solution of this system yields the values of these unknowns. Determination of the ratio

$$I = \operatorname{arccot}\frac{(1+a)H}{(1+a)Z}$$

makes it possible to find the direction of the GMF induction vector. The solution is correct and, which is of greater importance, it is independent of the parameter a, i.e. it is inde-pendent of the intrinsic field of the ferromagnetic rod and of the gradient of this field.

This approach makes it possible to consider the feasibility of determination of the direction of the GMF induction vector on board a ferromagnetic carrier subject to arbitrary vibrations. The Poisson equation for the component X' of the combined magnetic field is

$$\begin{aligned} X' = {} & (1+a)H\cos j\cos k - (1+a)Z\sin j \\ & + bH\cos i\sin k + bH\sin j\sin i\cos k \\ & + bZ\cos j\sin i + cZ\cos j\cos i - cH\sin i\sin k \\ & + cH\sin j\cos i\cos k + P\,, \end{aligned}$$

where a, b, and c are the Poisson parameters. Several simultaneous measurements of the component X' and of the angles i, j, and k representing the position of the carrier in transverse, longitudinal, and horizontal planes, respectively, yields a system of algebraic equations. This system is used to calculate all the unknowns which are the components of the intrinsic magnetic field of the carrier. Let us assume that the following ratios are determined (Fig. 2):

$$I_{xz} = \operatorname{arccot}\frac{(1+a)H\cos k}{(1+a)Z}\,,\quad I_{yz} = \operatorname{arccot}\frac{bH\sin k}{bZ}\,.$$

If the magnetic course coordinates are introduced (in this system the xOy plane is horizontal and the x axis coincides with the vertical plane containing the longitudinal axis of the carrier), it is found that the angles representing the directions of I_{xz} and I_{yz} govern the direction of the GMF induction vector. The magnetic inclination I and the magnetic course K are then calculated. If the readings of gyroscopic instruments give the true course, then the magnetic declination can also be found.

Let us consider whether the solution of the problem can be obtained and whether it is unique. In vector measurements of the combined magnetic field in a carrier we can use the vector Poisson equation:

$$\boldsymbol{T}' = |\boldsymbol{R}||\boldsymbol{S}|\,\boldsymbol{T} + \boldsymbol{T}_{\mathrm{p}}\,, \tag{1}$$

where $\boldsymbol{T}'$ is the induction vector of the combined magnetic field; $|R|$ is the sum of a unit matrix and the matrix of the Poisson parameters; $|S|$ is a matrix that describes the orientation of the carrier in a given coordinate system; $\boldsymbol{T}$ is the GMF induction vector; $\boldsymbol{T}_{\mathrm{p}}$ is the induction vector of the permanent field of the carrier. The solution of the system of vector equations (1), constructed on the basis of the results of a series of measurements, is obtained subject to the normalisation condition: $T_{\mathrm{m}} = 1$. In the actual investigations it is preferable to use the following difference equations based on Eqn (1):

$$\boldsymbol{V}_n = |R||G_n|\,\boldsymbol{T}\,,$$

where $\boldsymbol{V}_n = \boldsymbol{T}'_n - \boldsymbol{T}'_1$; $|G_n| = |S_n| - |S_1|$; $n = 2, 3, \ldots, N-1$; N is the number of measurements. Since in three-dimensional space only three vectors $\boldsymbol{V}_{\mathrm{n}}$ are linearly indepen-dent, it follows that five independent measurements can be used to calculate the fourth vector $\boldsymbol{V}_4$ from a linear combination of the three other vectors:

$$\boldsymbol{V}_4 = \sum_{i=1}^{3} a_i \boldsymbol{V}_i\,, \tag{2}$$

where a_i are constant coefficients. The dependence (2) reduces to the vector equation

$$|B_n|\,\boldsymbol{T} = 0\,,$$

where

$$|B_n| = \sum_{i=1}^{3} a_i|G_i| - |G_4|$$

is a 3×3 square matrix. In this matrix each row determines three components of the vector $\boldsymbol{b}(l)$, where l is the number of the row $(n = 1, 2, 3)$. The expression (2) corresponds to three scalar products:

$$\boldsymbol{b}(1)\cdot\boldsymbol{T} = 0,\qquad \boldsymbol{b}(2)\cdot\boldsymbol{T} = 0,\qquad \boldsymbol{b}(3)\cdot\boldsymbol{T} = 0\,.$$

It follows from these products that the vector $\boldsymbol{T}$ is orthogonal to the vectors $\boldsymbol{b}(l)$ and passes through the origin of the coordinate system. This vector lies in three

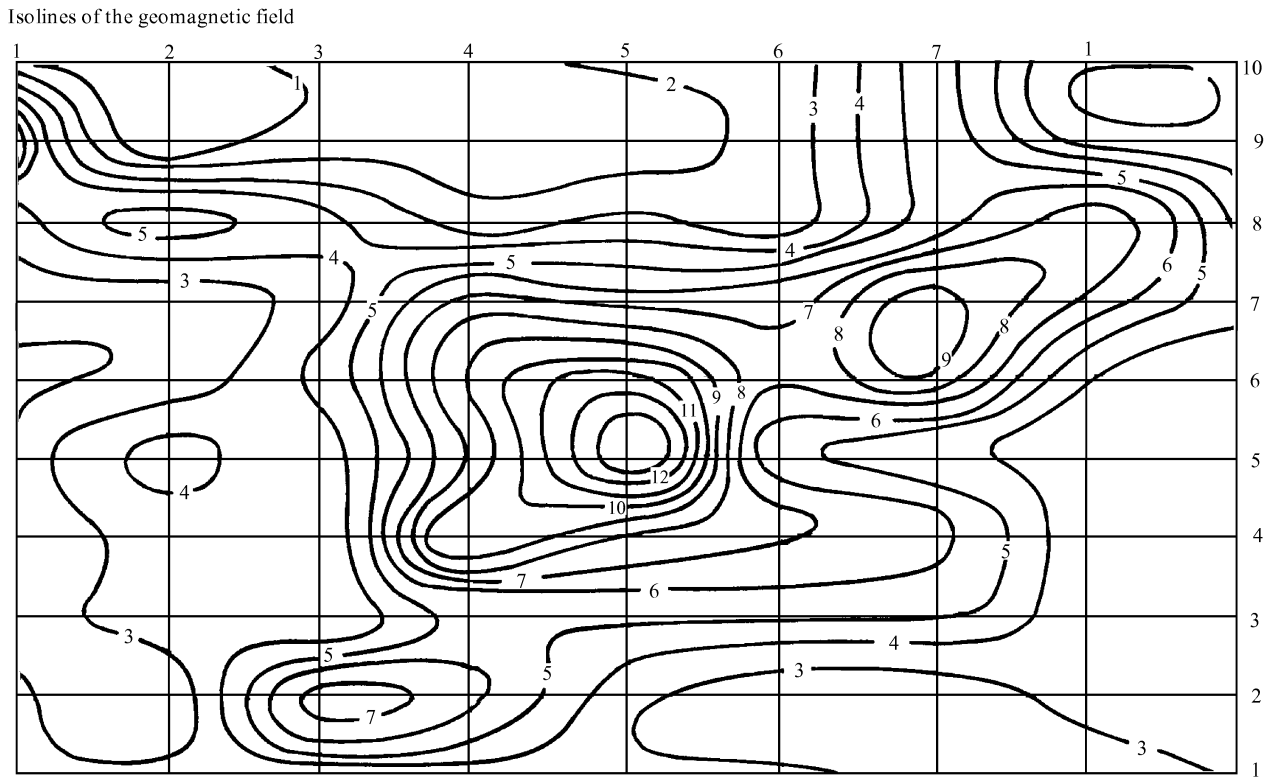

Figure 3. Chart showing the distribution of the modulus T. The numbers in the chart represent the following fields (nT): (*1*) 51 350; (*2*) 51 450; (*3*) 51 560; (*4*) 51 660; (*5*) 51 770; (*6*) 51 870; (*7*) 51 980; (*8*) 52 080; (*9*) 52 190; (*10*) 52 290; (*11*) 52 400; (*12*) 52 500; (*13*) 52 610.

planes and each of these planes is perpendicular to one of the vectors $\boldsymbol{b}(l)$. If at least two vectors $\boldsymbol{b}(1)$ and $\boldsymbol{b}(2)$ are noncollinear, which happens if the carrier is reoriented between at least two mutually orthogonal planes, the vector $\boldsymbol{T}$ coincides with the line of intersection between these planes. In this case the solution of the problem is unique.

The main physical principles of the MDAC were checked and the feasibility of its implementation in a carrier was determined by an experimental investigation under laboratory conditions and also on board a ferromagnetic ship.

The laboratory investigation, carried out on a specially constructed prototype, demonstrated that:

— the MDAC makes it possible to determine the angular components of the GMF induction vector from the results of measurements carried out in the combined magnetic field;

— the intrinsic fields of the ferromagnetic carrier do not, in principle, affect the precision of determination of these angular components (ferromagnetic carriers with very different magnetic characteristics are placed at a distance of 1–2 cm from a magnetically sensitive transducer);

— the MDAC can be used to determine the components of the intrinsic magnetic field of the carrier, formed by its permanent and induced magnetisations;

— the MDAC can be used when the measuring systems are reoriented along two or three mutually perpendicular planes;

the orientation of the measuring systems should be varied by angles which amount to at least 0.5°;

— the MDAC can be implemented on the basis of the magnetometric data obtained at any distance from the ferro-magnetic bodies which can have in practice any (in respect of the intensity and direction) intrinsic magnetic field;

— the components of the combined magnetic field can be measured in practically any magnetic field no matter how inhomogeneous;

— the rms error in the determination of the angular components is basically the same for measurements in the geomagnetic and combined magnetic fields, and it amounts to 0.6′–1.2′;

— the algorithms developed for solving ill-conditioned systems of equations can be used to obtain a stable solution.

The MDAC was then applied repeatedly on board a ferromagnetic ship. The suitability of the MDAC for geomagnetic measurements was checked on the basis of the data obtained when the ship was anchored, as well as in the course of its travel in one direction and over a large area. Moreover, the vector components were determined over an area in the following way; the direction of the GMF induction vector was determined on board of this ship and measurements of the modulus were made with an instrument towed behind the ship. A measuring– computing system was used and its operation was checked under laboratory conditions: it was accurate to within 4′–6′. The same result was obtained also on board our ferromagnetic ship, indicating that it should be possible to improve the precision of the measurements if the measuring–computing system were to include measuring instruments of higher precision. The distributions of the GMF components obtained over an area of a testing ground (the magnetic declination chart was not plotted because of the low precision of the ship gyrocompass), based on the results of measurements carried out on board

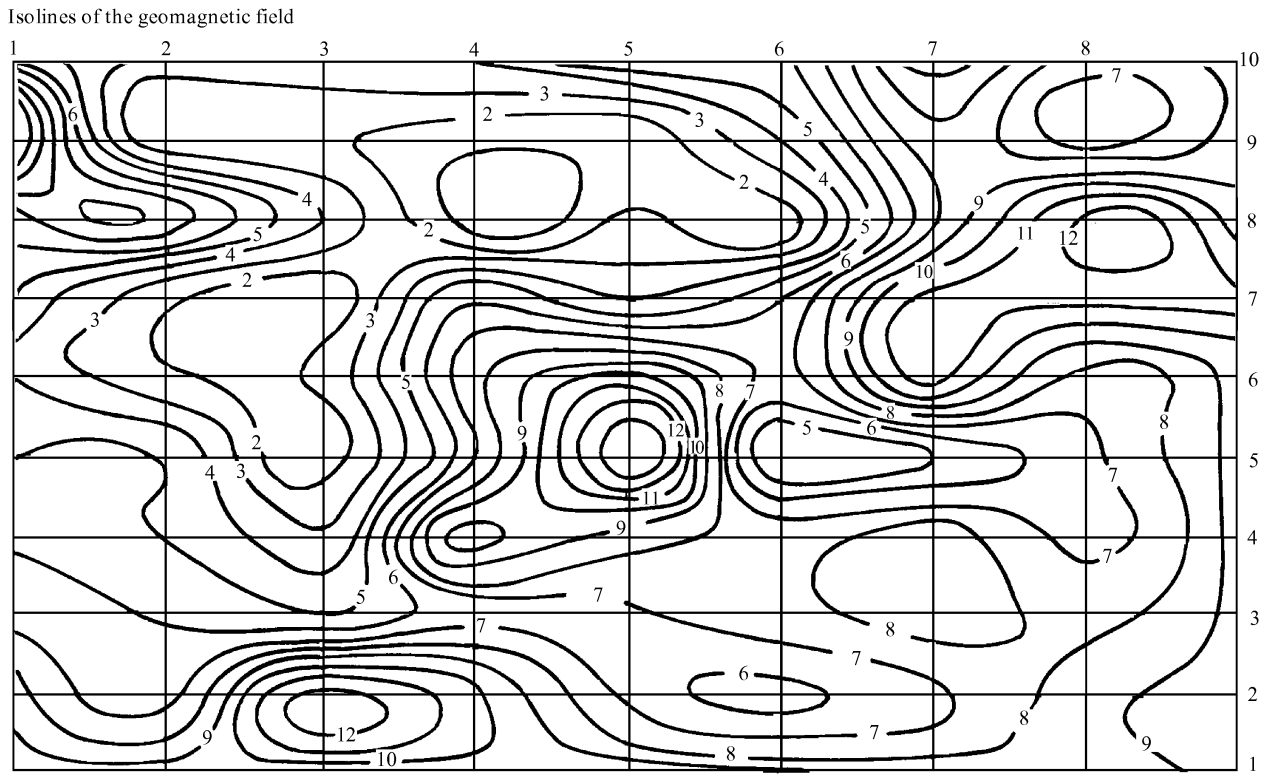

Figure 4. Chart of the distribution of the magnetic inclination *I*. The numbers in the chart represent the following values of the magnetic field (angular minutes): (*1*) 71.66; (*2*) 71.78; (*3*) 71.89; (*4*) 72.00; (*5*) 72.11; (*6*) 72.22; (*7*) 72.33; (*8*) 72.44; (*9*) 72.55; (*10*) 72.66; (*11*) 72.78; (*12*) 72.89; (*13*) 73.00.

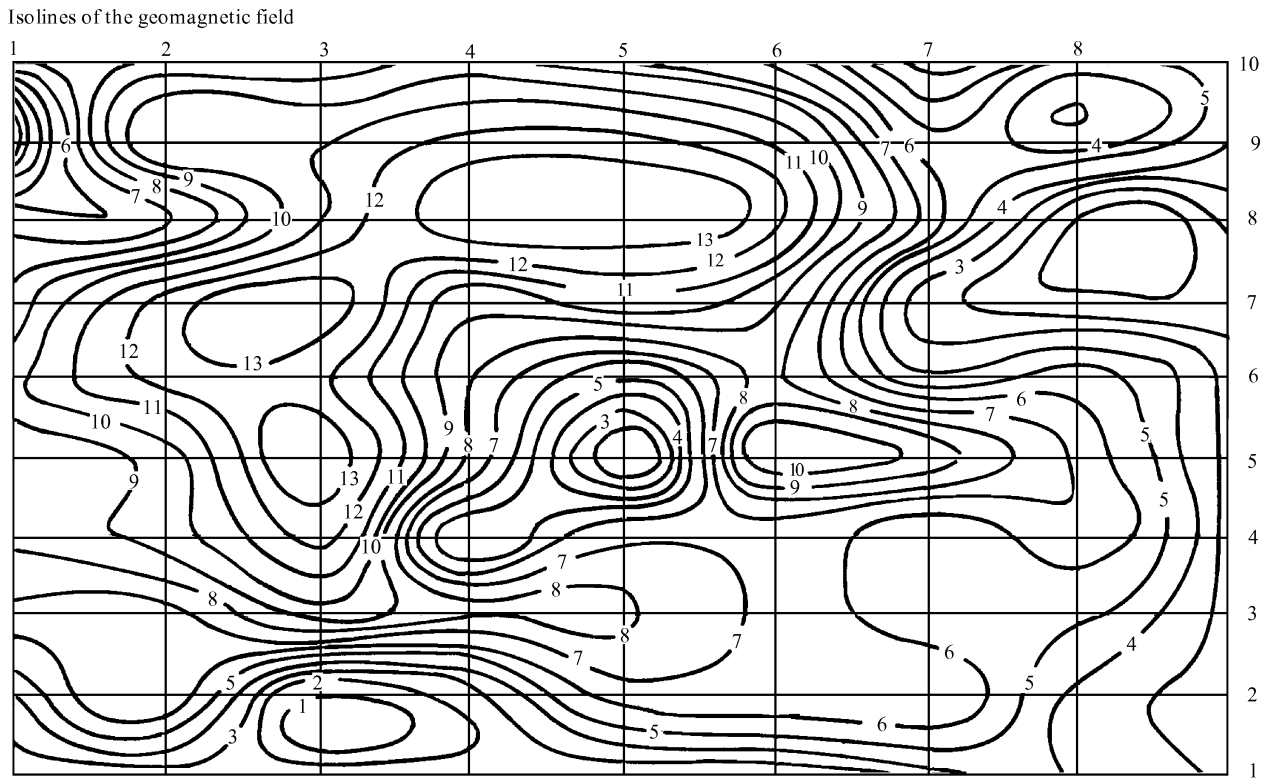

Figure 5. Chart of the distribution of component *H*. The numbers in the chart represent the following values of the component (nT): (*1*) 15 290; (*2*) 15 360; (*3*) 15 430; (*4*) 15 510; (*5*) 15 580; (*6*) 15 650; (*7*) 15 720; (*8*) 5 790; (*9*) 15 860; (*10*) 15 930; (*11*) 16 010; (*12*) 16 080; (*13*) 16 150.

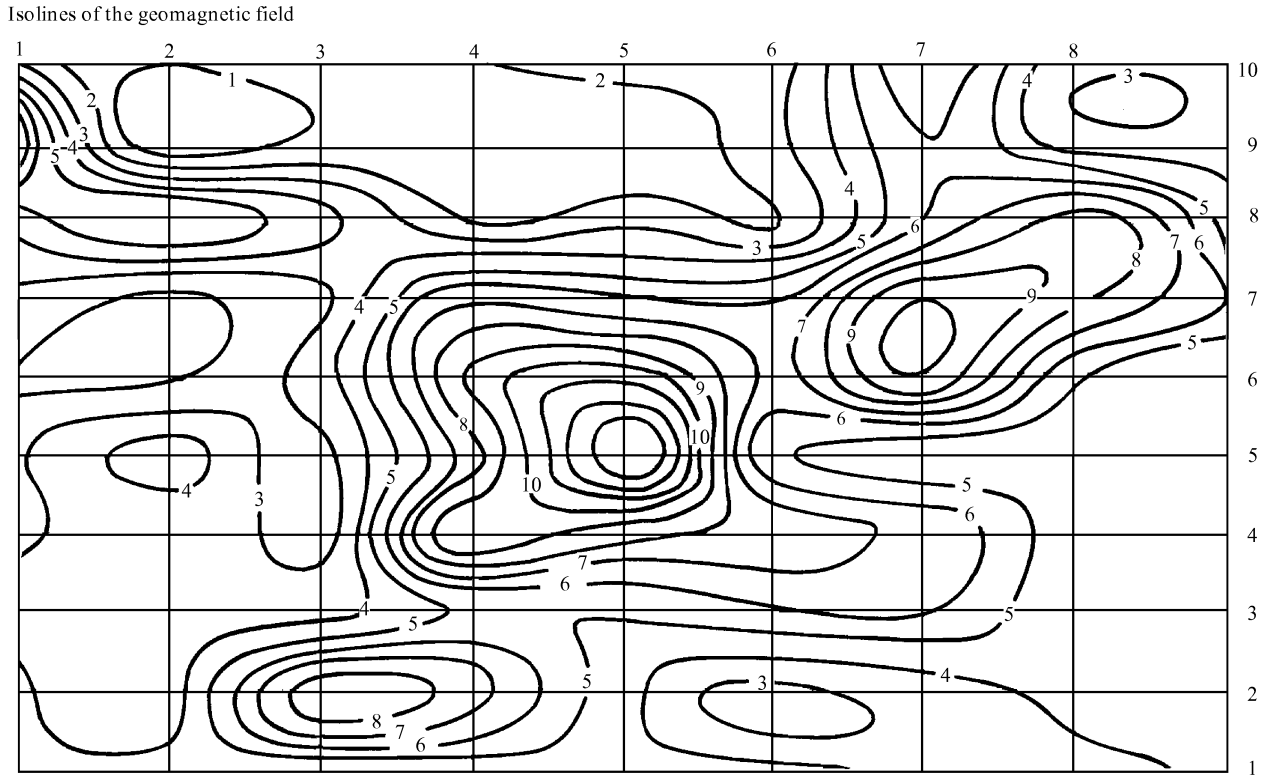

Figure 6. Chart of the distribution of component Z. The numbers in the chart represent the following values of the component (nT): (*1*) 48 780; (*2*) 48 910; (*3*) 49 030; (*4*) 49 160; (*5*) 49 280; (*6*) 49 410; (*7*) 49 530; (*8*) 49 660; (*9*) 49 780; (*10*) 49 910; (*11*) 50 030; (*12*) 50 160; (*13*) 50 280.

, based on the results of measurements carried out on board of our ferromagnetic ship, are reproduced in Figs. 3–6.

The results of our investigations confirmed that the MDAC can be used on board ferromagnetic carriers. They showed that the intrinsic fields of a ferromagnetic ship have practically no effect on the precision of determination of the direction of the GMF induction vector. The level of technological development of the MDAC reached so far makes it possible to undertake the construction of apparatus which could be used to tackle a variety of geophysical and geological tasks, including navigation measuring instruments and systems. The results of this investigation also demonstrate that the MDAC may be implemented not only on carriers moving on the surface of water, but also in the atmosphere or in space. As such carriers are constructed from nonmagnetic and weakly magnetic alloys, the technique which has to be used in measurements of the angular components is simplified and it should be possible to determine the modulus of the GMF on board a carrier.

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