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Методы и проблемы калибровки космических магнитометров на анизотропном магниторезистивном эффекте

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В космической отрасли широко применяются приборы, измеряющие магнитное поле Земли. Всё чаще в состав систем ориентации и стабилизации низкоорбитальных космических аппаратов (КА) входят магнитометры, изготовленные с применением магниторезистивной технологии. Это обоснованно малым весом, размером и энергопотреблением таких приборов, что делает их идеальными для применения на малогабаритных космических аппаратах. Однако основной проблемой магниторезистивных магнитометров является необходимость оценки возможных ошибок измерений. Влияние ошибок значительно снижает точностные характеристики прибора. С целью решения представленной проблемы исследователи предлагают различные методы оценки и исключения влияния ошибок на измерения [1–7]. Среди способов устранения ошибок в показаниях прибора применяются конструктивные решения, такие как вынесение прибора на расстояние от КА при помощи выдвижной штанги, с целью уменьшения влияние помех на прибор от аппарата [2]. Такое решение целесообразно для крупногабаритных КА, где наличие устройства выдвижения магнитометра не усложнит конструкцию и не увеличит энергопотребление. Для малых КА подобное решение не целесообразно. По этой причине при обсуждении магнитометров малогабаритных КА большое внимание уделяется методам калибровки, математической оценке и устранению ошибок как в наземных, так и в лётных условиях. Целью работы является формирование общего представления о причинах искажений в показаниях анизотропных магниторезистивных магнитометров, способах их математической оценки. Проведён обзор методов и оборудования для проведения наземной калибровки. В работе рассмотрены методики наземной калибровки анизотропных магниторезистивных магнитометров, применяемых на низкоорбитальных космических аппаратах в составе системы ориентации и стабилизации. Дана характеристика калибруемым параметрам магнитометров и предложена математическая модель измерений прибора с учётом ошибок. Описаны основные операции и оборудование, применяемые в процессе калибровки. Результаты работы могут быть полезны при проектировании рабочих мест калибровки магнитометров, а также при проведении эмпирических исследований в области магнитометрических датчиков.

Ключевые слова: калибровка магниторезистивного магнитометра, математическая модель измерений магнитометра, методы калибровки магниторезистивного магнитометра.

Review of problems and methods of calibration of space magnetometers based on anisotropic magnetoresistive effect

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Instruments measuring the Earth's magnetic field are widely used in the space industry. Increasingly, low-orbit spacecraft orientation and stabilization systems include magnetometers manufactured using magnetoresistive technology. This is justified by the low weight, size and consumption of such devices, which makes them ideal for use on small-sized spacecraft. However, the main problem of magnetoresistive magnetometers is the need to estimate possible measurement errors. The influence of errors significantly reduces the accuracy characteristics of the device. In order to solve the problem, researchers propose various methods for evaluating and eliminating the influence of errors on measurements [1–7]. Among the ways to eliminate errors in the readings of the device, constructive solutions are used, such as putting the device at a distance from the spacecraft using a retractable boom, in order to reduce the influence of interference on the device from the apparatus [2]. Such a solution is advisable for large spacecraft, where the presence of a retractable boom will not complicate the design and will not increase energy consumption. For small spacecraft, such a solution is not advisable, for this reason, when discussing small-sized spacecraft magnetometers, much attention is paid to calibration methods, mathematical evaluation and error correction, both in ground and in flight conditions. The objectives of the article include the formation of a general understanding of the causes of distortions in the readings of anisotropic magnetoresistive magnetometers, methods of their mathematical evaluation. A review of methods and equipment for ground calibration is carried out. The characteristics of the calibrated parameters of magnetometers are given and a mathematical model of measurement of the device is proposed, taking into account errors. The basic operations and equipment used in the calibration process are described. The results of the work can be useful in designing workplaces for calibrating magnetometers, as well as in conducting empirical research in the field of magnetometric sensors.

Keywords: calibration of a magnetoresistive magnetometer, a mathematical model of magnetometer measurements, methods of calibration of a magnetoresistive magnetometer.

Introduction

Magnetometers are widely used in spacecraft (SC) in systems of orientation and stabilisation (SOS), and are a key component of scientific research in the study of the Earth and other planets in the solar system.

Currently, the SOS of most low-orbit satellites include magnetometers manufactured using the anisotropic magnetoresistive technology (AMR) [1–3], which is justified by low weight, size, and power consumption of such a device. Magnetometers are used in SOS to determine the magnitude and direction of the Earth's magnetic field vector. The obtained information is used to calculate spacecraft control torques; for example, to stabilise spacecraft rotation, control torques are formed by electromagnetic actuators (coils) based on magnetometer readings.

Nevertheless, the main problem of AMR magnetometers is the need to estimate potential measuring errors, i.e., the need to calibrate a device. In order to solve this problem, researchers propose various methods for estimating and reducing errors affecting measurements [2–7].

It should also be mentioned that errors are not divided into periodic and constant ones; they are combined in a common calibration methodology, which is universal for different types of magnetometers and their applications. The main parameters subject to calibration are the offset value of the output characteristics, slope coefficients of the output characteristics (sensitivity coefficients), coefficients of nonorthogonality (deviation of the device sensitivity axes from the device axes).

The paper considers the main trends in space magnetometer calibration methodology and summarises the following constituents of the methodology:

– mathematical model with error correction;
– equipment;
– operations carried out on a set of equipment.

Errors caused by nonretentive materials

Nonretentive materials in the device structure form their own magnetic field under the influence of an external field. The direction and magnitude of the magnetic field vector generated by nonretentive materials can vary in a wide range, which largely depends on the material, shape of the element and applied vector of the external magnetic field. As a result of such influence, an error with dependence on the external magnetic field is formed; it is often represented as a matrix of 'nonretentive errors' [4]:

$$D_{si} = \begin{bmatrix} a_{xx} & a_{xy} & a_{xz} \\ a_{yx} & a_{yy} & a_{yz} \\ a_{zx} & a_{zy} & a_{zz} \end{bmatrix}.$$

In some cases it can be simplified by excluding non-diagonal elements of the matrix.

It should also be mentioned that the coefficients of the D_{si} matrix are linear only under conditions of a small external magnetic field, since the relative magnetic permeability of the μ media, and hence the coefficients, are not linear at medium and large values of the magnetic field [4; 8].

Conversion factors

Any AMR sensor on each of the sensitivity axes has its own conversion factor; classically it is conversion of the magnetic strength into the output voltage value; thus, the dimension of the conversion factor is k [mV/(V·mT)], where 'mV' is the value of the output signal at the $U_{\text{power SE}}$ supply voltage (V) and magnetic induction (mT). The output value of the sensitive element (SE) can be amplified and digitized. These coefficients can be reflected in the mathematical model as follows [7]:

$$S = \begin{bmatrix} k_x^{-1} & 0 & 0 \\ 0 & k_y^{-1} & 0 \\ 0 & 0 & k_z^{-1} \end{bmatrix} U_{\text{power SE}}.$$

It should also be noted that in practice, in the presence of an SE in the device, it is not possible to separate the diagonal matrix D_{si} and S; thus, calibration coefficients are determined for their product.

Displacement

Displacement can be divided into three types, where the first one is a technological displacement of a sensor, the second one is a displacement of a device output signal under the action of nonretentive materials (permanent magnets provided that there are no external fields capable of remagnetising them) and current circuits, and the third one is a periodic effect of fields being generated by SC. All the listed types overlap and, as a rule, they are not separated during calibration:

$$b = \begin{bmatrix} b_x, & b_y, & b_x \end{bmatrix}.$$

Nonorthogonality

The SEs made on thin-film elements are not characterised by precision accuracy of the sensitivity axes location, from where some errors arise due to non-orthogonality of the sensitivity axes to each other, as indicated in Fig. 1:

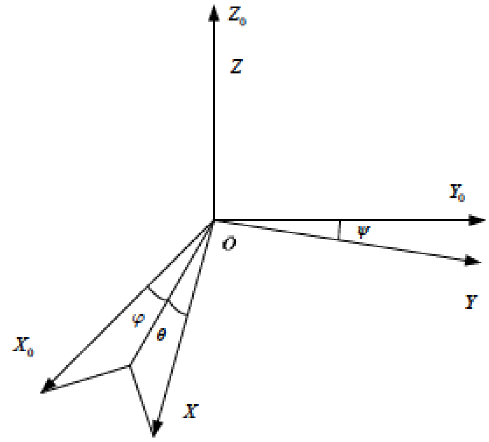

Рис. 1. Схематическая модель неортогональности, где X_0, Y_0, Z_0 – ортогональный базис

Fig. 1. Schematic model of non-orthogonality, where X_0, Y_0, Z_0 is the orthogonal basis

Non-orthogonality is normally described by a rotation matrix, e.g. [9]:

$$C_{NO} = \begin{bmatrix} \cos(\varphi)\cos(\theta) & \sin(\varphi)\cos(\theta) & \sin(\theta) \\ 0 & \cos(\psi) & \sin(\psi) \\ 0 & 0 & 1 \end{bmatrix}.$$

Misalignment

Apart from the non-orthogonality of the device sensitivity axes, the axes are usually not in axial alignment with the instrument axes, which also requires some mathematical correction, e.g. by means of a rotation matrix (Euler angles) [10]:

$$C_{NS} = \begin{bmatrix} \cos(\beta)\cos(\gamma) & -\cos(\beta)\sin(\gamma) & \sin(\beta) \\ \sin(\alpha)\sin(\beta)\cos(\gamma)+\sin(\gamma)\cos() & -\sin(\alpha)\sin(\beta)\sin(\gamma)+\cos(\alpha)\cos(\gamma) & -\sin(\alpha)\cos(\beta) \\ \sin(\alpha)\sin(\gamma)-\sin(\beta)\cos(\alpha)\cos(\gamma) & \sin(\alpha)\cos(\gamma)+\cos(\alpha)\sin(\beta)\sin(\gamma) & \cos(\alpha)\cos(\beta) \end{bmatrix}.$$

The C rotation matrix is a product of the C_{NO} matrix and C_{NS} matrix.

Temperature dependence

The temperature dependence of the AMR sensors and magnetometers is a rather serious and persistent issue about which surprisingly little has been written. Despite the fact that the physical properties of the sensing element imply the elimination of temperature drift, manufacturing defects of permalloy films and the temperature dependence of the supply voltage of the SE and analogue-to-digital converter (ADC) play a significant role in the formation of the output values of the device.

In a generalized sense, the temperature dependence can be expressed as follows [1]:

$$K_T = \begin{bmatrix} k_{xx} & k_{xy} & k_{xz} \\ k_{yx} & k_{yy} & k_{yz} \\ k_{zx} & k_{zy} & k_{zz} \end{bmatrix}.$$

Mathematical model of device measurements with consideration of errors

Above we have listed some errors common to most magnetometric sensors and magnetometers. When compiling a mathematical model, researchers often reflect in it all known effects affecting the readings of the device (Fig. 2).

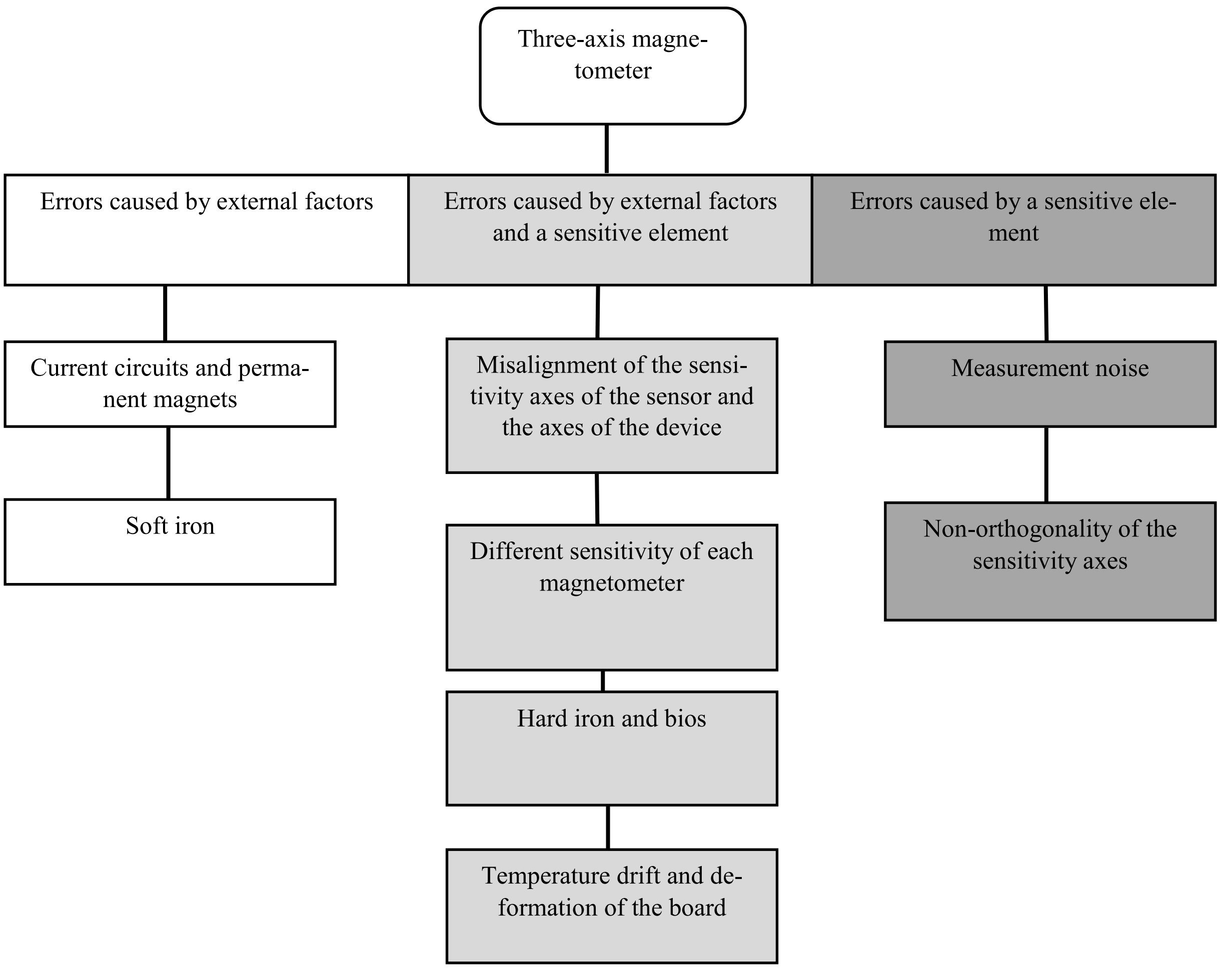

Рис. 2. Ошибки, влияющие на показания АМР магнитометра

Fig. 2. Errors affecting AMR magnetometer readings

The process of calibrating some of these errors is very resource-consuming and does not bring much gain in accuracy. For this reason, the mathematical model is simplified to a state in which it is possible to determine all its elements in the least costly way with the required accuracy.

In our opinion, the mathematical model will look as follows (which differs from the model proposed in [1]):

$$B_{real} = (SCD_{si} + K_T T)U_{mag} - SCD_{si}(b + K_{Tb}T),$$

where B_{real} is a vector of the reference magnetic field (mT) obtained from the readings of the reference magnetometer or in a different way; T is a temperature scalar (°C) of the magnetometer (in case of the arrangement of the SE and electronics unit in one case, it is the temperature of the sensitive element); K_{Tb} is a vector of temperature coefficients of zero shift (mV/°C); U_{mag} is a vector of magnetometer output signal (mV); b is an output signal of the device in the absence of external field and under normal conditions (mV).

The main task of a magnetometer calibration process is to find all the components of the mathematical model. The device is considered to be calibrated if at substitution of B_{mag} measurements under different external conditions into the mathematical model the result of its calculation does not deviate from the readings of the reference device by more than the value determined by the accuracy requirements of the device.

Calibration procedures

Calibration procedures of a magnetometer can be divided into two categories:

– position-dependent - require highly accurate data on the orientation of the device axes (and SC in the case of flight calibration);

– position-independent - used in conditions of lack of precise information about the position of magnetometer sensitivity axes relative to the reference magnetic field.

It should be noted that the mathematical methods used in both categories are very similar, but in the absence of position data, the parameters of the $[S \cdot C \cdot D_{si}]$ matrices are unobservable and cannot be determined [11; 12]. A fully filled matrix with 9 independent coefficients in space conditions can be computed only if the position of the spacecraft and the location of the device sensitivity axes in the associated spacecraft coordinate system are known [13].

Comparing ground and flight calibration of magnetometers, it should be noted that many researchers consider a ground calibration process to be very complicated [13, 14]. Such a point of view is justified by the necessity to use precision equipment and systems, as well as a test site protected from magnetic interference. In addition, mechanical impact during spacecraft orbital insertion can cause additional errors, not taken into account during ground calibration. In order to solve these problems, rough calibration is carried out on Earth, followed by on-orbit parameter adjustments.

Nevertheless, SC SOS magnetometers are also used in the attenuation regime of SC after separation from the launch vehicle, which in turn requires a quick response of the device and does not allow increasing its accuracy characteristics up to the transition to the mode of three-axis stabilisation of the SC. Proceeding from the above described, it is especially important to carry out accurate ground calibration for SC SOS, in which a magnetometer is the main device of the attenuation regime.

Equipment being used during ground calibration

Most particularly, the use of any magnetic materials and live conductors in the immediate vicinity of the test stand is avoided in order to attain this objective. It is also desirable to isolate a magnetic test stand and magnetometer mounting brackets from grounding circuits. To avoid man-caused interference, the facility may be located away from cities, power lines, or underground [5].

The application of magnetic shielding is worth mentioning individually. If it is necessary to achieve the best stability and avoid magnetic variations of the geomagnetic field (it depends on latitude and solar activity) [15], the test stand is placed in a shielding chamber made of three (or more) layers of material with high magnetic permeability (permalloy or steel) separated by non-magnetic layers. It should be noted that the volume of the chamber must be sufficient to ensure that the equipment located inside does not cause additional interference through the interaction of the alternating field of the equipment and the material of the chamber; and this is also justified by the effective operating zone of the magnetic shield [16].

The next important part of the stand is a device that allows setting the value and direction of the magnetic induction vector in the operation area of the stand. For this purpose, various solenoids and permanent magnets are used, but the most widely used is the Helmholtz ring system and its various modifications, such as the Maxwell, Barker, Brownback (Fig. 3) and Garrett ring systems [17]. The peculiarity of all the above systems is a high degree of magnetic field homogeneity in the operation area. The operating range and accuracy of the ring system can be adjusted according to the stand requirements by selecting the number, diameter, and shape of coil turns, as well as a programmable power supply. It should be noted that using three-axis ring systems allows setting a magnetic field vector of the operation area in any desired direction.

An important device influencing a calibration result is a source of data on the strength of the true (reference) magnetic field in the operation area of the stand. Most often, data on the reference magnetic field in the operation area are obtained from a reference ferroprobe magnetometer [1; 6]. In the absence of anthropogenic interferences, a reference magnetometer can be installed at a considerable distance from the stand in order to determine the strength and direction of the geomagnetic field. In such an arrangement, the reference magnetometer will not affect the magnetic field of the working area of the stand, and the data on the magnetic field of the working area will be determined mathematically based on the characteristics of the system of the stand rings and currents in their windings. Calibration can be performed only by using a ring system, but in this case there is no accurate data on the geomagnetic field of the Earth (the initial field in the absence of current in the ring system), which leads to additional errors during calibration. It is to be recalled that some methods do not provide accurate data on the strength and direction of the magnetic field [5; 6; 11]; thus, it is sufficient to know the modulus of the magnetic induction vector at the test location, for example, using the International Association of Geomagnetism and Aeronomy (IAGA) model data.

Another device used in a number of techniques is a turntable. It is usually used in the absence of a three-axis wheel system [18] or as additional equipment for it [6].

If it is necessary to carry out temperature calibration for checks in the area of negative and positive temperatures, it is possible to use a climatic chamber. The chamber is made of non-magnetic non-conductive material (Fig. 3) [6] (if the volume is much larger than the volume of the ring system, it can be made of a conductor). In the case when the nature of the temperature dependence of the device is known exactly, it is sufficient to use a heating element [1].

Operations being performed

The aim of calibrating is to determine all the coefficients of the mathematical model being considered. The model is determined based on the requirements to the device, available equipment and resources. The list of the operations being performed on the magnetometer is determined by finding the components of the model.

Zero or process shift of the ‘b’ device under normal conditions

1. When using a three-axis ring system, the Earth's geomagnetic field and permanent disturbances from current loops and magnets are compensated by feeding the calculated current value into the ring system. When performing this operation, the data of the reference magnetometer or calculated data are used. The use of calculated data entails some error, as they do not envision daily variations of the Earth's magnetic field and the influence of anthropogenic factor.

Рис. 3. Пример внешнего вида стенда магнитных испытаний [6], где применяется система колец Браунбека, испытуемый и эталонный магнитометры расположены на поворотном столе в термокамере (жёлтый ящик), термокамера устанавливается в центр колечной системы при помощи каретки

Fig. 3. An example of the appearance of a magnetic test stand [6], where the Brownback ring system is used, the test and reference magnetometers are located on a turntable in a thermal chamber (yellow box), the thermal chamber is installed in the center of the ring system using a carriage

2. When one-axle wheel system is used in conjunction with a reference magnetometer, compensation is performed along one axis only.

3. In the absence of a wheel system, reference magnetometer and turntable, the table axis is set perpendicular to the magnetic meridian (the reference magnetometer will show the absence of magnetic induction along a certain direction).

4. In the absence of equipment, the magnetometer is set with one axis along the magnetic meridian (the device will show a maximum or minimum value).

By performing the above operations, it is possible to determine the process shift of the device (readings in the absence of an external field). It should be noted that some magnetometers (as a rule, space magnetometers) are not able to operate in the conditions of the Earth's magnetic field (60 μT), as their measurement range is much smaller and varies with the field of application of the device. For example, in the TRIO-CINEMA mission an AMR magnetometer with an operating range of ± 50 μT was used; and in the Europa Clipper mission a ferroprobe magnetometer with an operating range of ± 4 μT was used. For this reason it is not possible to carry out ground calibration of some space magnetometers without field compensation in three axes.

Determining the deviation angles of the sensitivity axes from the axes of the '$C{\cdot}D_{si}$' device under normal conditions

At this stage, the magnetic induction vector is rotated in the plane of each of the three axes. If it is impossible to rotate the vector, the device is rotated. In the absence of the accurate data on the position of the reference field vector, it is not possible to determine the deviation angles of the sensitivity axes accurately.

Determining the slope coefficients of the '$S{\cdot}C{\cdot}D_{si}$' characteristic and linearity

At this stage, the magnetic field is applied alternately along the sensitivity axes of the device; the output characteristic (calibration characteristic) for each of the axes is plotted according to the data of the device at different field values. Knowing the output characteristics for each of the sensitivity axes at a known magnetic field, the nonlinearity of the output characteristic (Hysteresis) is determined.

It should be noted that it is possible to combine the operations to determine the deviation angles, slope coefficients and linearity by applying the field along the device axis; the subsequent processing of measurements allows determining the $[S{\cdot}C{\cdot}D_{si}]$ matrix and the magnitude of nonlinearity; nevertheless, due to the anisotropy of the nonretentive materials of the device body, the $[S{\cdot}C{\cdot}D_{si}]$ matrix is determined with some error.

Determining the $[S{\cdot}C{\cdot}D_{si}]$ matrix

The methods that do not provide accurate position information (in the absence of a reference magnetometer) rely only on calibration by ‘spherical’ rotation of the device in a homogeneous magnetic field [4; 9; 13] assuming that the magnitude of the magnetic induction vector is constant (Fig. 4).

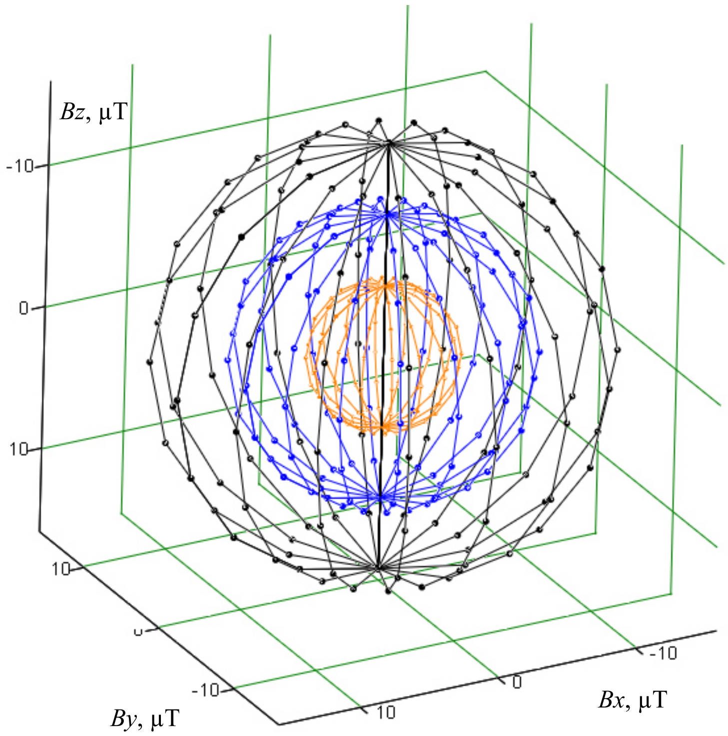

Рис. 4. Модели вращения вектора магнитного поля при шаге углов поворота θ_j = 22,5°, φ_i = 22,5° (углы азимута и высоты) и различной величине модуля вектора магнитного поля: B = 15 мкТл (чёрный), B_2 = 10 мкТл (синий), B_3 = 5 мкТл (оранжевый)

Fig. 4. Models of rotation of the magnetic field vector at a step of rotation angles θ_j = 22.5°, φ_i = 22.5° (azimuth and elevation angles) and different magnitudes of the magnetic field vector modulus: B = 15 µT (black), B_2 = 10 µT (blue), B_3 = 5 µT (orange)

If the data on the reference field are not available, at this stage the angular rotation velocity sensors [19; 20] of the device in a constant magnetic field are also used. The application of a three-axis wheel system also makes it possible to determine the hysteresis value of the output characteristics and the calibration characteristic for each of the sensitivity axes.

Determining the temperature coefficients K_{Tb} and K_T

At this stage, the device is heated and cooled in order to reveal the temperature dependence on the $S{\cdot}C{\cdot}D_{si}$ coefficients. For the purposes of laboratory research, the work is carried out in both positive and negative temperature ranges; the operations described earlier are carried out. It should be noted that, depending on the adopted test methodology, the repetition of the operations described above may not be carried out or not fully carried out. In order to save time, if the nature of the temperature dependence is known, it is sufficient to measure a technological shift and determine the slope coefficients of the output characteristic at positive temperatures.

The calibration procedure including all the previously discussed stages is shown in Fig. 5.

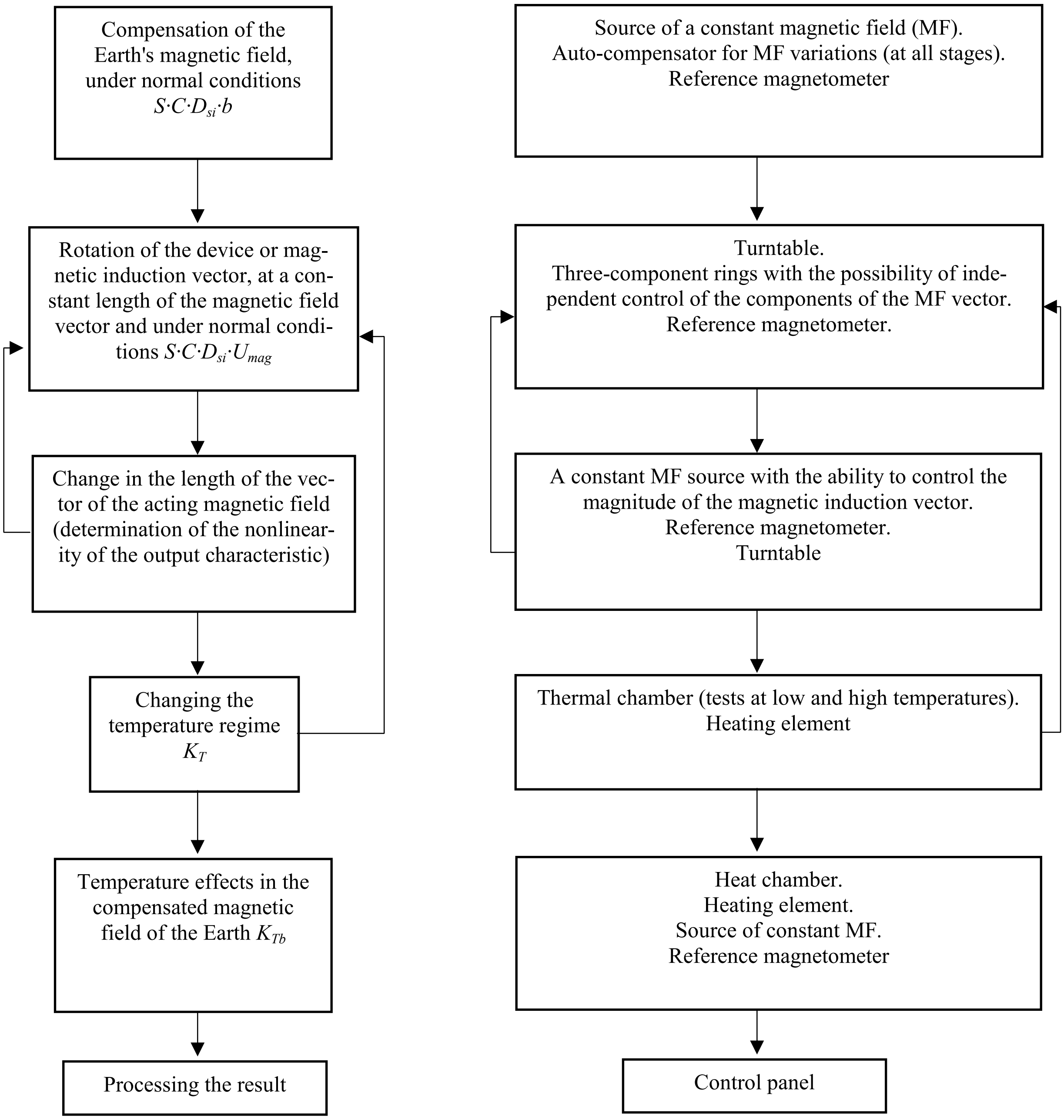

Рис. 5. Образец структурной схемы порядка калибровки (слева) и применяемого на соответствующих этапах оборудования (справа)

Fig. 5. A sample of the block diagram of the calibration procedure (left) and the equipment used at the corresponding stages (right)

Conclusion

In the presented paper the methods of calibration of magnetometers on anisotropic magnetoresistive effect have been considered. The requirements to the equipment and place of testing have been defined. The errors affecting the readings of an AMR magnetometer and an example of their mathematical modelling have been listed.

Herewith, the methodology is determined by a mathematical model based on the requirements of the device; the time required for calibration and capabilities of the equipment being used are also important in selecting a methodology.

The main task of any methodology is to ensure the search for coefficients determined by a mathematical model. For this purpose equipment is selected and refined, a test site is selected and prepared; otherwise the mathematical model is corrected.

The reason for the need to use complex and expensive test stands for calibrations of space magnetometers on the AMR effect is the non-repeatability of magnetometer properties (e.g., the direction of sensitivity axes), the impossibility of their physical adjustment, and, in the case of the joint location of the sensing element and the electronics unit (on the same board), the significant influence of nonretentive materials [2].

For the reasons stated, new methods and mathematical models are being developed to provide the performance required of the device in the least time-consuming manner and with the least expensive equipment.

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