Computational technology for uncertain spacecraft magnetic cleanliness control

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Abstract

Research presents the development of computational technology for prediction and control by orbital spacecraft magnetic cleanliness based on geometric inverse magneto static problem solution with consideration of magnetic characteristics uncertainty to improve the spacecraft magnetic cleanliness and its controllability in orbit. Geometric inverse problem solution reduced to vector game solution with COMSOL Muliphysics software calculated payoff vector. Game solution calculated based on heuristic optimization algorithms from Pareto-optimal solutions taking into account binary preference relations local games solutions. Based on developed computational technology results of prediction and control by «Sich-2» microsatellite family for ensuring microsatellite magnetic cleanliness presented.

Keywords

orbital spacecraft, magnetic cleanliness, uncertainty, geometric inverse magneto static problem, heuristic optimization algorithms

1. Introduction

The urgency of the work is due to the need to ensure high accuracy of the magnetic control system for the angular orientation of the spacecraft in near-Earth space [1, 2, 3]. Among the factors that determine the accuracy of the angular orientation of the spacecraft: the reliability of current measurements of the magnetic induction of the Earth magnetic field by the on-board magnetometer of the magnetic control system; an error in the calculation of the spacecraft magnetic moment with turned on electromagnets, which are components of the magnetic control system. The initial data of this calculation, along with magnetic moment value of the electromagnets, also include the spacecraft magnetic moment values; magnetic induction at the place of installation of the on-board magnetometer of the magnetic control system.

Modern requirements [1] for magnetic control system spacecraft weighing up to 100 kg require, on the one hand, a reduction of their magnetic moment (to $0.1A * m^2$), and, on the other hand, high accuracy of its determination with a distribution capacity of no more than $0.02A * m^2$. The same "hard" requirements established for magnetic induction, which formed by the component parts of the spacecraft at the place of installation of the magnetic control system magnetometer.

Technologies for ensuring the spacecraft "magnetic cleanliness" managed by NASA and ESA include interrelated works of an organizational, technical and metrological nature. The foundation of this technology is the calculation models of the spacecraft, which allow analytical or numerical prediction of

CMSE'25: International Workshop on Computational Methods in Systems Engineering, June 12, 2025, Kyiv, Ukraine

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the spacecraft magnetic characteristics based on the knowledge of the magnetic field of its constituent parts [1] . At the same time, the magnetic characteristics of the component parts presented in the format of numerical multiple magnetic dipole models, according to which the corresponding component part of the spacecraft represented as a set of point magnetic moments with the corresponding location coordinates.

One of the fundamental components of this technology is the organization of metrological support for determining in the multiple magnetic dipole models format the magnetic characteristics of the component parts of the spacecraft on specialized magnetic measuring stands [3, 4, 5] . The main provisions of the organization of work on reducing the magnetic characteristics of spacecraft are implemented by such leading developers as the National Aeronautics and Space Administration (NASA), the European Space Agency (ESA), and the Chinese Academy of Space Technologies (CAST). The presence of these specialized magnetic measuring stands allows them to create spacecraft with high accuracy of reference to the coordinate system of the Earth surface and to carry out remote sensing of the Earth surface with high resolution.

Anatolii Pidhornyi Institute of Power Machines and Systems of the National Academy of Sciences of Ukraine (IPMash of the National Academy of Sciences of Ukraine) has a powerful specialized experimental base, the basis of which is the unique and unique Magnetodynamic complex in Ukraine, which is included in the list of scientific objects that constitute the national property of Ukraine. At the IPMash magnetodynamic complex the experimental part of the fundamental studies of the magnetism of various technical objects and their physical models (spacecraft, ships, electric power equipment, building structures, pipelines) is carried out, the analysis of the spatio-temporal structure of their magnetic field (including ultra-small level - with induction less than 10-8 T). At the IPMash stand experimental studies of developed methods and means of targeted change of magnetic characteristics of various technical objects are carried out. Since 2003 year, the magnetometer stand has been providing tests of all orbital spacecraft launched into near-Earth orbit, namely "Microsat" (2003), "EgiptSat-1" (2007), "Sich-2" (2011), "Sich-2-30" (2022).

During space engineering testing in accordance to latest standards of the European Space Agency ECSS-E-HB-20-07A [1] it is necessary to take into account test conditions, input tolerances and measurement uncertainties. The main uncertainties of the spacecraft magnetic cleanliness are the changing values of the magnetic moments of the spacecraft elements when the spacecraft operating modes changing [1]. In particular, the magnetic moments change most strongly when the polarization relays operate in the “on” and “off” positions, when the battery operates in the “charge” or “discharge” mode, during operation of high-frequency valves etc. Therefore, an urgent problem is develop of method to improve spacecraft magnetic cleanliness which is robust to the spacecraft elements magnetic moments uncertainties.

This work is devoted to the development of computational technology for control by orbital spacecraft magnetic cleanliness based on geometric inverse magneto static problem solution with consideration of magnetic characteristics uncertainty to improve the spacecraft magnetic cleanliness and its controllability in orbit.

2. Mathematical model of the spacecraft magnetic field

When designing a mathematical model of the spacecraft magnetic field the Gauss equation [2] for the scalar magnetic potential of the source in the surrounding space written the following form in spherical coordinates R, θ, ϕ :

$$U = \frac{1}{4\pi} \sum_{n=1}^{\infty} \frac{1}{R^{n+1}} \sum_{m=0}^{n} (g_n m cos m \ \phi + h_n m sin m \phi) P_n^m(cos\theta), \tag{1}$$

where R is the radius of the sphere on which the potential is determined; g_{nm}, h_{nm} - constant coefficients. The magnetic field strength, calculated from (1) determined by the equations:

$$H_r = \frac{1}{4\pi}\sum_{n=1}^{\infty}(n+1)\frac{1}{R^{n+2}}\sum_{m=0}^{n}(g_{nm}\cos(m\phi)+h_{nm}\sin(m\phi))P_n^m(\cos\theta); \tag{2}$$

$$H_\phi = \frac{1}{4\pi}\sum_{n=1}^{\infty}\frac{1}{R^{n+2}}\sum_{m=0}^{n}(g_{nm}\sin(m\phi)-h_{nm}\cos(m\phi)\frac{P_n^m(\cos\theta)}{\sin\theta};$$

$$H_\theta = \frac{1}{4\pi}\sum_{n=1}^{\infty}\frac{1}{R^{n+2}}\sum_{m=0}^{n}(g_{nm}\cos(m\phi)+h_{nm}\sin(m\phi))\frac{1}{\sin\theta}\cdot\ldots$$

$$\cdot(n-m+1)\overline{P_{n+1}^m}(\cos\theta)-(n+1)\cos\theta P_n^m(\cos\theta).$$

The solution of equation (2) with respect to the coefficients g_{nm}, h_{nm} represents spacecraft multipole mathematical model.

The mathematical model of spacecraft magnetic field in the form of a multipole model (2), proposed by K. Gauss in the study of Earth magnetism [2], makes it possible to describe the distribution of the spacecraft's magnetic field at any point in space. However, to date, there are insufficiently developed methods that would allow in practice to use the spatial harmonics of the magnetic field of a spacecraft. The need to develop such methods confirmed by one of the latest standards of the European Space Agency ECSS-E-HB-20-07A [1], which recommends using spherical harmonics as integral characteristics of the spatial distribution of the magnetic field to ensure the magnetic purity of the spacecraft [2, 4, 5].

As follows from the analysis of expressions (2) the spacecraft magnetic field at distances is greater than three of its maximum overall dimensions are determined mainly by members of the first degree series, i.e. the first three multipole coefficients [2]. Therefore, if the measurement of the spacecraft magnetic field performed at a distance greater than three of its maximum overall dimensions, then it can be limited to the construction of the spacecraft mathematical model in the form of a multiple magnetic dipole model [5].

All spacecraft elements undergo strict control for magnetic cleanliness and, as a rule, their preliminary demagnetization is performed. The components M_{nx}, M_{ny}, M_{nz} – of the spacecraft magnetic moment elements are measured before installation and meet the stringent requirements of magnetic cleanliness.

Then, the components B_{KX}, B_{KY}, B_{KZ} of technical object magnetic field at any point P_k of space with coordinates x_k, y_k, z_k in the form of the multiple magnetic dipole models (MDM) of the spacecraft with the magnetic moment M_{nx}, M_{ny}, M_{nz} of N dipole located at the points of the space of the spacecraft with coordinates (x_n, y_n, z_n) calculated [2]

$$\begin{bmatrix} B_{KX} \\ B_{KY} \\ B_{KZ} \end{bmatrix} = \mu_0\sum_{n=1}^{N}\frac{1}{4\pi r'^5}\begin{bmatrix} 2x'^2-y'^2-z'^2 & \ldots & 3x'y' & 3x'z' \\ 3x'y' & \cdots & 2y'^2-x'^2-z'^2 & 3y'z' \\ 3x'z' & \ldots & 3y'z' & 2z'^2-y'^2-x'^2 \end{bmatrix}\cdot\begin{bmatrix} M_{nx} \\ M_{ny} \\ M_{nz} \end{bmatrix} \tag{3}$$

Here the designations are introduced

$$x^i = x_k - x_n, y^i = y_k - y_n, z^i = z_k - z_n,$$

$$r' = ((x_k-x_n)^2+(y_k-y_n)^2+(z_k-z_n)^2)^{\frac{1}{2}}.$$

3. Statement of the problem

All Ukrainian spacecraft after installing all the elements are examined for magnetic cleanliness at the magnetic measuring stand Anatolii Pidhornyi Institute of Mechanical Engineering Problems of the National Academy of Sciences of Ukraine. According to real measurements, the spacecraft magnetic moment and the magnetic field at the installation point of the onboard magnetometer are calculated. For this purpose, according to the data of measurements of the magnetic field in the near zone of the spacecraft, the real values of the moment vectors of the dipoles of the received M_n are restored. In this case, it is assumed that the coordinates of the location of the dipoles in the space of the spacecraft remain unchanged.

If the spacecraft multiple magnetic dipole model (3) obtained based on the vector Y_M of measured magnetic field is too rough, then on the basis of the vector Y_M of the measured magnetic field, not only the magnetic moments M_{nx}, M_{ny}, M_{nz} of the dipoles, but also their position in the space of the technical object with coordinates x_n, y_n, z_n can be calculated.

Let us consider the design of the technical object multiple magnetic dipole models only based on the vector Y_M of the measured magnetic field. Let us introduce the vector of desired parameters X, the components of which are the desired values magnetic moments M_{nx}, M_{ny}, M_{nz} of the dipoles and coordinates x_n, y_n, z_n of their position in the space of the spacecraft.

We also introduce the vector G of uncertainty parameters of the magnetic moments of the spacecraft the components of which are the deviations during the operation of the spacecraft of the magnetic moments of the spacecraft elements from their central values, taken in the design of the control system for the magnetic field of the spacecraft [2, 4, 5]. Then, based on (3), the initial nonlinear equation for the spacecraft multiple magnetic dipole model can be obtained.

$$Y_M = F(X, G). \tag{4}$$

Here, the vector nonlinear function$F(X, G)$ obtained on the basis of expression (3) with respect to the vector X of unknown variables, whose components are the desired values magnetic moments M_{nx}, M_{ny}, M_{nz} of the dipoles and coordinates x_n, y_n, z_n of their position in the space of the spacecraft and the vector G of the parameters of the uncertainties of the magnetic moments of the elements of the technical object.

In nonlinear equation (4) the number of unknown components of the vector X equal to six times the number N of dipoles, and the number of equations is equal to three times the number K of measurement points.

Let us introduce the E vector of the discrepancy between the vector Y_M of the measured magnetic field and the vector Y_C of the predicted by model (4) magnetic field

$$E(X, G) = Y_M - Y_C(X, G) = Y_M - F(X, G). \tag{5}$$

We write the objective nonlinear function as the weighted sum of squared residuals between the measured and predicted by the model (4) values of the magnetic field

$$f(X, G) = (E(X, G))^T W E(X, G). \tag{6}$$

The nonlinear objective function (6) obtained on the basis of expression (2) with respect to the vector X of unknown variables, whose components are the desired values magnetic moments M_{nx}, M_{ny}, M_{nz} of the dipoles and coordinates x_n, y_n, z_n of their position in the space of the spacecraft and the vector G of the parameters of the magnetic moments uncertainties of the spacecraft elements.

As a rule, when optimizing the nonlinear objective function (6)

$$Y^{\cdot} = argminf(X, G), G^{\cdot} = argmaxf(X, G), \tag{7}$$

it is necessary to take into account restrictions on the values of magnetic moments M_{nx}, M_{ny}, M_{nz} of the dipoles and coordinates x_n, y_n, z_n of their position in the space of the spacecraft.

Let's consider another approach to the design of spacecraft multiple magnetic dipole models. Usually the designer of the spacecraft knows the N of the elements of the spacecraft, which are the main sources of the initial magnetic field of the technical object. These are polarization relays, batteries and high-frequency valves. The technical object designer knows the number N of these elements, the coordinates x_n, y_n, z_n of their location in the spacecraft space, as well as the nominal values M_{nx}, M_{ny}, M_{nz} of their magnetic moments. Then the vector Y_C of the magnetic field components B_{KX}, B_{KY}, B_{KZ} at the given points P_k of the space with coordinates x_k, y_k, z_k can be calculated based on spacecraft multiple magnetic dipole model (3).

Note that the values M_{nx}, M_{ny}, M_{nz} of the magnetic moments of these N main elements of the spacecraft can be refined on the basis of the vector Y_M of the measured magnetic field.

As a rule, the spacecraft multiple magnetic dipole models obtained in this way is a rather rough approximation to the actual magnetic range of the spacecraft. To refine this model, consider the following approach. Let's introduce more M dipoles wits magnetic moment M_{mx}, M_{my}, M_{mz} located at the points P_m of the spacecraft with coordinates x_m, y_m, z_m. Let us introduce the vector of desired parameters X, the components of which are the desired values magnetic moments M_{mx}, M_{my}, M_{mz} of the M dipoles and coordinates x_m, y_m, z_m of their position in the space of the spacecraft. We also introduce the vector G of uncertainty parameters of the magnetic moments of the spacecraft. Then, based on the spacecraft multiple magnetic dipole models (4) calculated the vector $Y_A(G, X)$ of additional magnetic field, generated by only M additional dipoles at the measurement points.

$$Y_A(G, X) = F_A(G, X). \tag{8}$$

We introduce the vector Y_I of the initial magnetic field of the spacecraft, the components of which are the components of the magnetic field of the spacecraft calculated in this way at the measurement points generated by the main N elements of the technical object with known values of the magnetic moments and the coordinates of their location in the space of the spacecraft.

Then one can calculate the vector Y_R of resulting magnetic field generated by N dipoles with known magnetic moments nominal values M_{nx}, M_{ny}, M_{nz} and coordinates x_n, y_n, z_n of their location in the technical object space and generated by M additional dipoles with unknown magnetic moments M_{mx}, M_{my}, M_{mz} and unknown coordinates x_m, y_m, z_m of their location in the spacecraft space

$$Y_R(G, X) = Y_I + Y_A(G, X). \tag{9}$$

Then the problem (7) of calculated the vectors of unknown parameters of additionally introduced M dipoles solved similarly to the problem (9) of calculated the vector of unknown parameters of N dipoles for design of the spacecraft multiple magnetic dipole model.

Usually, the spacecraft magnetic cleanliness requirements presented in the form of restrictions on the total magnetic moment of the spacecraft and the magnitude of the magnetic field at the installation point of the onboard magnetometer [1]. If the magnetic properties of the spacecraft do not satisfy the overall magnetic cleanliness requirements magnetic compensation tests conducted. According to the spacecraft multiple magnetic dipole models obtained in the form (8), it is possible to calculate the spacecraft far magnetic field components B_{KX}, B_{KY}, B_{KZ}, and in particular, at the point of installation of the onboard magnetometer and technical object magnetic moments M_{nx}, M_{ny}, M_{nz}. Let us now consider the application of the developed technical object multiple magnetic dipole models to ensure the spacecraft magnetic cleanliness by introducing additional magnetic dipoles to compensate for the far magnetic field of the spacecraft, in particular, at the point of the onboard magnetometer installation [3, 4, 5].

To compensate for the initial magnetic field of the spacecraft we introduce C magnetic dipoles with unknown magnetic moments M_{cx}, M_{cy}, M_{cz} located at C points P_c with unknown coordinates x_c, y_c, z_c.

Let us introduce the vector X of the desired parameters for solving the problem of compensating the initial magnetic field of the technical object, whose components are the oblique values of the magnetic moments M_{cx}, M_{cy}, M_{cz} and coordinates x_c, y_c, z_c of the location of the compensating magnetic dipoles in the spacecraft space. Then, for a given value of the vector X of the desired parameters of the compensating dipoles, the vector $B_C(X)$ of the compensating magnetic field generated by all compensating dipoles at the installation point of the onboard magnetometer and the vector $M_C(X)$ of the compensating magnetic moment generated by all compensating dipoles calculated [6, 7, 8].

Then we calculated the vector $M_R(X, G)$ of resulting magnetic moment and vector $B_R(X, G)$ of resulting magnetic field generated at the installation point of the onboard magnetometer by the spacecraft elements and all compensating dipoles

$$M_R(X,G) = M(G) + M_C(X), B_R(X,G) = B(G) + B_C(X). \tag{10}$$

Then the problem of calculated the coordinates x_c, y_c, z_c of spatial arrangement and magnetic moments M_{cx}, M_{cy}, M_{cz} of the compensating dipoles can be reduced to solving the problem of vector minimax optimization of resulting magnetic moment of the spacecraft and the resulting magnetic field at the installation point of the onboard magnetometer

$$X^{\cdot} = argminM_R(X,G), X^{\cdot} = argminB_R(X,G), \tag{11}$$

$$G^{\cdot} = argmaxM_R(X,G), G^{\cdot} = argmaxB_R(X,G), \tag{12}$$

Note that this approach is standard when designing of robust control, when the coordinates of the spatial arrangement and the magnitudes of the magnetic moments of the compensating dipoles are found from the conditions for minimizing the modulus of spacecraft magnetic field at the magnetometer installation point for the "worst" values of the magnetic moments of the elements of the spacecraft [9, 10, 11, 12].

4. The problem solving method

The solution of the vector minimax optimization problem wits vector objective function (11) and (12) is the set of unimprovable solutions – the Pareto set of optimal solutions if only one vector objective function given [13, 14, 15]. Such a statement of the optimization problem is an ill-posed problem, since the solution in the form of a Pareto optimal set of unimprovable solutions is devoid of engineering sense from the point of view of practical application [16]. In addition to the vector optimization criterion (10), it is also necessary to have information about the binary relations of preference of local solutions to each other in order to correctly solve the problem of multi-criteria optimization. This approach makes it possible to significantly narrow the range of possible optimal solutions to the original multi-criteria optimization problem [17, 18, 19].

The problem of finding a local minimum at one point of the considered space is, as a rule, multi-extreme, containing local minima and maxima, therefore, for its solution, it is advisable to use algorithms of stochastic. Currently, the most widely used are multi-agent stochastic optimization methods that use only the speed of particles. To find the solution of minimax vector optimization problem (11) from Pareto-optimal decisions [20, 21, 22] taking into account the preference relations, we used special nonlinear algorithms of stochastic multi-agent optimization. First-order methods have good convergence in the region far from the local optimum, when the first derivative has significant values [23].

The main disadvantage of first-order search methods, which use only the first derivative – the speed of particles, is their low efficiency of the search and the possibility of getting stuck in the search near the local minimum, where the value of the rate of change of the objective function tends to zero. The advantage of second-order algorithms is the ability to determine not only the direction of movement, but also the size of the movement step to the optimum, so that with a quadratic approximation of the objective function, the optimum found in one iteration [24, 25, 26].

To search the components $X_{ij}(t)$ optimal values of the vector X of the desired parameters minimizing vector optimization criterion (11) and (12) for calculating velocities $V_{ij}(t)$ and accelerations $A_{ij}(t)$ of i particle of j swarm using the following steps [27, 28, 29, 30]

$$V_{ij}(t+1) = W_{1j}V_{ij}(t) + C_{1j}R_{1j}(t)H(P_{1ij}(t) - E_{1ij}(t))\left[Y_{ij}(t) - X_{ij}(t)\right] + \tag{13}$$

$$C_{2j}R_{2j}(t)H(P_{1ij}(t) - E_{2ij}(t))\left[Y_j^*(t) - X_{ij}(t)\right].$$

$$A_{ij}(t+1) = W_{2j}A_{ij}(t) + C_{3j}R_{3j}(t)H(P_{3ij}(t) - E_{3ij}(t))\left[Z_{ij}(t) - V_{ij}(t)\right] + \tag{14}$$

$$C_{4j}R_{4j}(t)H(P_{4ij}(t) - E_{4ij}(t))\left[Z_j^*(t) - V_{ij}(t)\right].$$

Here, $Y_{ij}(t)$ and $Y_j^*(t)$ – the best–local and global positions $X_{ij}(t)$, $Z_{ij}(t)$ and $Z_j^*(t)$ – the best-local and global velocity $V_{ij}(t)$ of the i–th particle, found respectively by only one i–th particle and all the particles of j swarm.

Random numbers $R_{ij}(t)$, $E_{ij}(t)$ and constants C_{ij}, P_{ij}, $W_j$are tuning parameters, H – Heaviside function.

To search the components $X_{ij}(t)$ optimal values of the vector δ of the parameters of the uncertainty of the control object of the system of active silencing maximizing the same vector optimization criterion (10) for calculating velocities $V_{ij}(t)$ and accelerations $A_{ij}(t)$ of i particle of j swarm using the steps similarly (13), (14). However, unlike (13), (14), the best local and global position and velocity components are those that lead not to a decrease in the corresponding components of the vector objective function (10), but vice versa to their increase. This is where the "malicious" behavior of the vector δ of uncertainties of the designed system manifested.

The use of the Archimedes algorithm for calculating minimax vector optimization problem (10) solutions with binary preference relations it possible to reduce the calculating time.

5. Experimental research

Anatolii Pidhornyi Institute of Power Machines and Systems of the National Academy of Sciences of Ukraine (IPMash of the National Academy of Sciences of Ukraine) has the magnetodynamic complex includes premises with a total area of about $2000m^2$ and consists of a magnet measuring stand with an area of $450m^2$ equipped with unique world-class magnetometric equipment, a technological plot of land with an area of $5.3ha$, which ensures a "magnetic silence" mode, power supply systems with a capacity of $800kVA$ and others engineering systems and structures.

The measurements procedure of components of the spacecraft magnetic moment involves compensation of the Earth magnetic field in three orthogonal directions X, Y and Z. The procedure for determining the components of the magnetic moment of the test object involves the alternating influence on it of the magnetic field of the windings in three orthogonal directions X, Y and Z with induction $40mT$. Measurements of the spacecraft magnetic moment according to the existing technology, involves the stationary installation of twelve magnetometer "Magnetomat 1.782" at the corresponding points of the sphere with a radius of 2 m. For measuring the magnetic moment of the component parts (blocks) of the spacecraft magnetometer "Magnetoscop 1.069" used.

Figure 1 shows the spacecraft "SICH-2-1" on the measuring stand.

Ensuring the high accuracy of the MSU operation, with modern trends in the reduction of spacecraft mass, requires the minimization of its magnetic moment and high accuracy of its determination.

6. Simulation results

Let us consider the application of the developed method for solving the problem of ensuring the magnetic cleanliness of the «Sich-2-1» spacecraft. Experimental measurements of the magnetic characteristics of the «Sich-2-1» spacecraft carried out at the Anatolii Pidhornyi Institute of Power Machines and Systems of the National Academy of Sciences of Ukraine stand. Based on these measurements, we calculate the model of the «Sich-2-1» spacecraft. The experimentally measured value of the total magnetic moment of spacecraft is equal M = [0.24, 0.5, 0.4]. The dispersion of the magnetic field prediction error in this case is D = 7560.6. The value of the experimentally measured magnetic moment of the spacecraft implies the presence of several dipoles located in the space of the spacecraft. In the calculation it is assumed that the model of the magnetic field of the spacecraft represents one dipole located at the origin of the spacecraft.

Based on the experimental measured magnetic field at first the spacecraft magnetic field model presented as a single dipole located in the center of the spacecraft. Based on the vector of the measured magnetic field of the spacecraft YM, the moments of this single dipole M = [0.24, 0.5, 0.4] were calculated. The dispersion of the magnetic field prediction error in this case is D = 7272.7.

Figure 1: The spacecraft "SICH-2-1" on the measuring stand.

Let us now consider the mathematical model of the magnetic field of the spacecraft in the form of a single dipole, the location coordinates of which in the space of the spacecraft also need to be calculated. For the calculated value of the moment M = [0.2664, 0.1641, 0.1434] and coordinates P = [0.2158, -0.4136, 0.0859] of the location of such a single dipole, the prediction error variance is D = 3239.8. Note that the location of the only dipole not at the origin of the coordinates, but at the point with the optimal coordinates made it possible to reduce the dispersion of the magnetic field prediction by a factor of 2.3337.

If, when solving the problem of optimizing the values of the magnetic moments and the coordinates of the location of one dipole, we introduce restrictions on the magnitude of the dipole moments in the form of restrictions [-0.8, -0.8, -0.8] $\leq M \leq$ [0.8, 0.8, 0.8], optimal values of the moments M = [0.2388, 0.1921, 0.1258] and coordinates P = [0.2056, -0.4146, 0] of the location of such a single dipole, the prediction error variance is D = 3325.1. Thus, under restrictions on the magnitude of the dipole moments, the optimum values of the magnetic moments are at the limits and, in this case, the dispersion increases by a factor of 2.2738.

Let us now consider the model of the spacecraft magnetic field in the form of two dipoles. If, when solving the problem of optimizing the values of the magnetic moments and the coordinates of the location of two dipoles, we introduce restrictions on the magnitude of the dipole moments in the form of restrictions [-0.8, -0.8, -0.8] $\leq M \leq$ [0.8, 0.8, 0.8], optimal values of the moments $M1$ = [0.3538, -0.0326, -0.0345] and $M2$ = [-0.6137, 0.6695, -0.2802] and the coordinates $P1$ = [0.3090, -0.3080, 0.0867] and $P2$ = [-0.0657, -0.0789, -0.3908] of the location of two dipoles, the dispersion the prediction error is D = 1203.4. Thus, under restrictions on the magnitude of the two dipoles moments, the optimum values of the magnetic moments are at the limits and, in this case, the dispersion increases by a factor of 6.2827.

The simplest satellite multiple magnetic dipole models is a model consisting of two dipoles with magnetic dipoles

$$M1 = \begin{bmatrix} 1.8404 & -0.4147 & 0.1316 \end{bmatrix}, M2 = \begin{bmatrix} -1.9641 & 1.3347 & -0.3664 \end{bmatrix},$$

and coordinates

$$P1 = \begin{bmatrix} 0.2173 & -0.1625 & -0.0366 \end{bmatrix}, P2 = \begin{bmatrix} 0.1609 & -0.0306 & -0.1397 \end{bmatrix}.$$

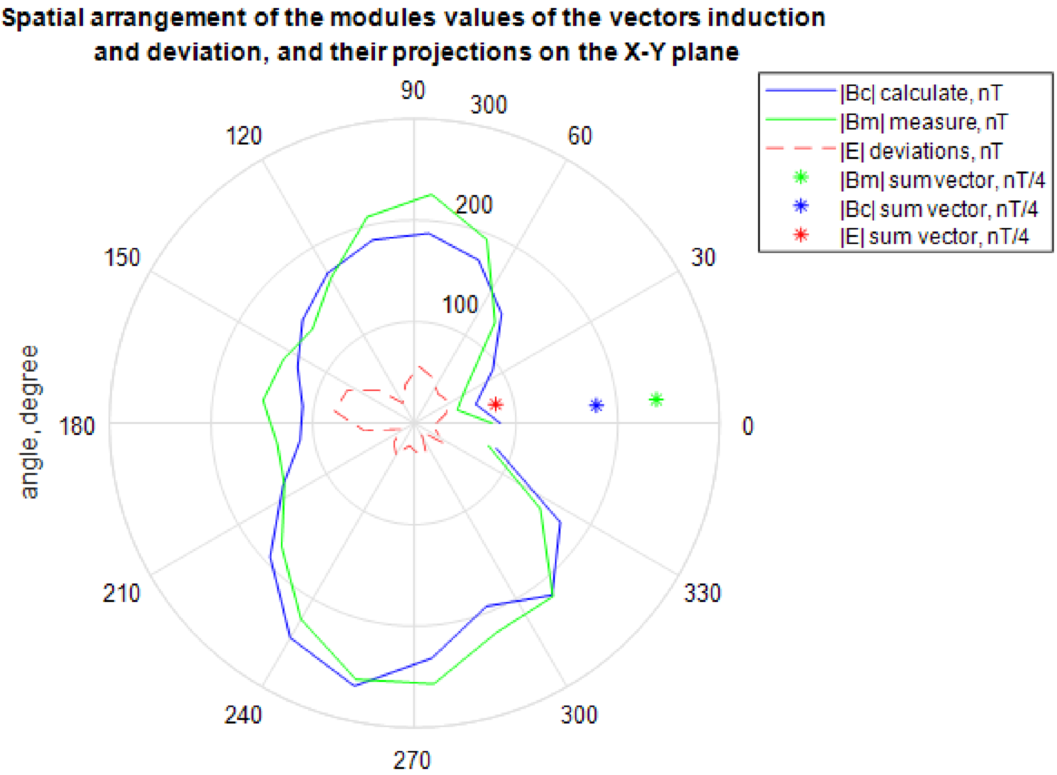

Figure 2: Circular diagrams of the distribution of the initial, calculated magnetic field and their deviations.

Figure 2 shows circular diagrams of the distribution of the initial, calculated magnetic field and their deviations for spacecraft mathematical model in the form of two dipoles.

Based on this model, we calculate the spacecraft magnetic moment as the sum (8) of the magnetic moments of the dipoles

$$M = \begin{bmatrix} -0.1237 & 0.92 & -0.2348 \end{bmatrix}$$

and magnetic field

$$BM = \begin{bmatrix} 3.0273 & 23.2437 & -2.5901 \end{bmatrix}$$

at the installation point of the onboard magnetometer. The simplest solution to the problem of compensating the initial satellite magnetic moment is to place this one compensating dipole with a magnetic moment

$$MC = \begin{bmatrix} 0.1237 & -0.92 & 0.2348 \end{bmatrix}$$

opposite to the satellite moment. Even with the location of this compensating dipole at the origin of the spacecraft coordinates, the magnetic field induction

$$BM = \begin{bmatrix} 1.6155 & 2.2043 & 2.615 \end{bmatrix}$$

at the point of installation of the magnetometer decreases by a factor 6.23. The location coordinates of this compensating dipole calculated from the condition of minimizing the resulting magnetic field at magnetometer installed point. Optimal position coordinates of the compensating dipole

$$P1 = \begin{bmatrix} 0.5 & 0.5 & -0.5 \end{bmatrix}$$

and at the same time the induction level at the installation point of the magnetometer

$$BM = \begin{bmatrix} 0.8903 & 0.5576 & 0.5736 \end{bmatrix}.$$

Thus, due to the installation of a compensating dipole at the optimal point, the magnetic field induction module at the magnetometer installation point decreased by 3.15 times compared with the magnetometer installation in the middle of the spacecraft and decreased by 19.8 times compared to the satellite without compensation. A more accurate compensation of the spacecraft magnetic moment is achieved by placing two compensation dipoles with magnetic moments

$$MC1 = \begin{bmatrix} -1.8404 & 0.4147 & -0.1316 \end{bmatrix},$$

$$MC2 = \begin{bmatrix} 1.9641 & -1.3347 & 0.3664 \end{bmatrix},$$

whose location coordinates in the spacecraft space are calculated by minimizing the magnetic field at onboard magnetometer installation point taking into account design constraints. Note that in the work [3] the spacecraft model was accepted as adequate to real measurements when 29 dipoles were taken into account, and when “only” 26 dipoles were taken into account, the spacecraft magnetic field model was insufficiently adequate to real measurements.

7. Conclusions

Computational technology for prediction and control by orbital spacecraft magnetic cleanliness based on geometric inverse magneto static problem solution with consideration of magnetic characteristics uncertainty to improve the spacecraft magnetic cleanliness and its controllability in orbit developed.

Geometric inverse problem solution reduced to vector game solution with COMSOL Muliphysics software calculated payoff vector. Game solution calculated based on heuristic optimization algorithms from Pareto-optimal solutions taking into account binary preference relations local games solutions.

Results of prediction and control by «Sich-2» microsatellite family for ensuring microsatellite magnetic cleanliness based on developed computational technology presented.

Declaration on Generative AI

The author(s) have not employed any Generative AI tools.

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