Evaluation of calibration accuracy of magnetometer sensors of Aist small spacecraft

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Abstract. In the paper the technique of estimation of calibration accuracy of magnetometer gauges by the example of an Aist small spacecraft is stated. According to the measurement of the Earth's magnetic field in the orbital flight of a small spacecraft, the parameters of its rotational motion around the center of mass are estimated and primary information is generated for the magnetic actuators of the orbital motion control system. Therefore, calibration of the magnetometer sensors at the ground test stage is essential for the successful execution of the flight program. The technique can be used at the stages of ground and flight tests of magnetic field measuring instruments.

1. Introduction
The wide use of small space vehicles determines their rapid development at the present stage. The main advantages of small spacecraft are the speed of the mission and the low cost of the project. Small spacecraft can be launched by dozens with the help of a single carrier rocket. However, the dynamics of the orbital motion of small spacecraft has not yet been studied to the same extent as the spacecraft of other classes [1]. On the other hand, the use of an expensive orientation system can completely eliminate the advantages of small spacecraft. Thus, for the orientation of the small spacecraft for remote sensing of the Earth "Aist-2D", an expensive orientation system was used, including star sensors and flywheel motors [2]. For small space vehicles for scientific and technological purposes, this way will lead to a reduction in the mass of scientific equipment and a significant increase in the cost of implementing the program. Therefore, for a number of space projects, a more accessible version of a small spacecraft, for example, Aist-1, is needed.

Interest in such platforms has greatly increased after the successful launch of the flight and prototype of the Aist small spacecraft [3]. A full-fledged rotational motion control system was not provided for these devices. However, it was possible to reduce the angular velocity of their rotation around the center of mass. This is necessary for the successful implementation of gravitationally sensitive processes in the internal environment of the spacecraft [4]. The estimation of the rotational motion parameters of the flight and experimental samples of the Aist small spacecraft was carried out on the basis of measurements of the Earth's magnetic field by the sensors of the magnetometer [5]. The decrease in the angular velocity was realized by means of the magnetic executive organs of the scientific equipment of MAGKOM [6]. As the primary information for these executive bodies, the measurement data from one of the magnetometer sensors were used. To effectively use such algorithm to reduce the angular velocity, it is necessary to have correct measurement data. Therefore, it is
necessary to develop methods for monitoring the operation of measuring instruments, beginning with
the stage of ground tests [7].

The operational experience of flying and prototypes of the Aist small spacecraft showed that this
issue was not given much attention. Therefore, at the stage of post-flight analysis, it became necessary
to investigate the reasons for the shift of the averages values of the measurement data of the
corresponding channels of two different sensors of the magnetometer. One of the possible reasons for
this shift could be the calibration of these sensors, carried out at the stage of ground tests.

2. Materials and methods
Scientific equipment MAGKOM was developed by the specialists of the Institute of "Space
Instrument Engineering" of Samara University and consisted of the elements presented in Figure 1 [6].

![Scientific equipment MAGKOM](image)

**Figure 1.** Scientific equipment “MAGKOM” (cited by [6]): a – block of electronics; b – control unit
of electromagnet; c – three-component magnetometer; d – electromagnet.

In addition to the traditional method of estimating the accuracy of direct measurements of the
corresponding channels, for example, by examining the overlap of confidence intervals, etc., an
estimate of the accuracy of indirect measurements is proposed. As such measurements, it is possible to
use the angles between the sensor construction axes for stand-alone ground tests. At this stage of
testing, scientific equipment is not arranged in a spacecraft, but can be arbitrarily positioned relative to
one another. It is at this stage that the sensors of the magnetometer are calibrated.

For this procedure, the following algorithm is proposed.
1. Place the magnetometer sensors on the test bench.
2. Carry out direct measurements of the angles between the construction axes of the sensors.
3. Conduct direct measurements of the magnetic field by means of sensors.
4. Determine the direction cosines of the magnetic field induction vector.
5. Calculate the angles between the construction axes of the sensors.
6. Assess the significance of the differences between direct and indirect measurements.
7. Make conclusions about the correctness of sensor calibration.

This approach will improve the reliability of calibration of sensors and avoid a number of possible
errors in the measurement data at the stage of operation of a small spacecraft.

3. Investigation of the calibration accuracy of the sensors of the flight sample of the Aist small
spacecraft
To assess the accuracy of the calibration, the autonomous tests performed on August 24, 2008 (Figure
2) were used. From the consideration, the first 240 s, in which the test stand was set up, were
excluded. When testing the flight sample of an Aist small spacecraft, the only criterion for the
accuracy of calibration was the statistical coincidence of the moduli of the magnetic field induction
vectors measured by two different sensors (curves 1 and 2 in Figure 2). Analysis of individual measurement channels was not carried out. However, the magnetization of the elements of the test bench can affect the measurements by individual channels. In this case, the correspondence of the modules can be preserved. Therefore, let us implement the algorithm proposed in the previous section.

Figure 2. Results of autonomous tests of magnetometer probes of scientific equipment MAGKOM: 1 and 2 - modules of magnetic field induction vectors, measured respectively by sensors 1 and 2; 3, 5 and 7, are the components of the magnetic field induction vector (respectively $B_z$, $B_y$, $B_x$) measured by sensor 1; 4, 6 and 8 are the components of the magnetic field induction vector (respectively $B_z$, $B_y$, $B_x$) measured by sensor 2.

Let us calculate the angles between the corresponding measurement channels of different sensors of the magnetometer. At the stage of operation of the prototype of the Aist small spacecraft, the following correspondence was realized:

$$B_x[1] - B_x[2], B_y[1] - B_y[2], B_z[1] - (-B_z[2]).$$

Direct measurements of the angles gave the following results:

$$\alpha_1 = \angle(i_1; i_2) = 10^0 \pm 0.5^0; \quad \alpha_2 = \angle(j_1; j_2) = 17^0 \pm 0.5^0; \quad \alpha_3 = \angle(k_1; k_2) = 27^0 \pm 0.5^0. \quad \text{The estimation of these angles by means of the measurement data is shown in Figure 3, where the first 240 s are excluded.}$$

Estimation of the accuracy of indirect measurements was carried out with the aid of differentials. If:

$$\beta_i[1] = \angle(i_i; B_i) = \frac{B_i[1]}{\sqrt{B_x[1]^2 + B_y[1]^2 + B_z[1]^2}},$$

then:

$$|\Delta \beta_i[1]| \leq \frac{\partial \beta_i[1]}{\partial B_x[1]} |\Delta B_x[1]| + \frac{\partial \beta_i[1]}{\partial B_y[1]} |\Delta B_y[1]| + \frac{\partial \beta_i[1]}{\partial B_z[1]} |\Delta B_z[1]|.$$

(1)

According to the developers of scientific equipment, the accuracy of measurements of both sensors of the magnetometer is the same:
\[ \Delta B_i [1] = \Delta B_i [1] = \Delta B_i [2] = \Delta B_i [2] = \Delta B_i [2] = 0.5 \mu T. \]

In this case:
\[
\frac{\partial \beta_{i1}}{\partial B_{i1}} = \frac{B_i [1] B_i [1]}{\sqrt{B_i [1] + B_i [1] + B_i [1]}}; \\
\frac{\partial \beta_{i2}}{\partial B_{i2}} = \frac{B_i [1] B_i [1]}{\sqrt{B_i [1] + B_i [1] + B_i [1]}}; \\
\frac{\partial \beta_{i3}}{\partial B_{i3}} = \frac{B_i [1] B_i [1]}{\sqrt{B_i [1] + B_i [1] + B_i [1]}}.
\]

Let us estimate the error in measuring each angle using expressions analogous to (1). In the case of correct measurement, vectors \( \vec{B}_1 \) and \( \vec{B}_2 \) may differ randomly by the measurement error. Therefore, the angles measured previously directly can be estimated as follows:
\[
\hat{\alpha}_1 = |\beta_{i1} - \beta_{i2}| = \angle (\vec{i}_1; \vec{B}_1) - \angle (\vec{i}_2; \vec{B}_2);
\]
\[
\hat{\alpha}_2 = |\beta_{i1} - \beta_{i2}| = \angle (\vec{j}_1; \vec{B}_1) - \angle (\vec{j}_2; \vec{B}_2);
\]
\[
\hat{\alpha}_3 = |\beta_{i1} - \beta_{i2}| = \angle (\vec{k}_1; \vec{B}_1) - \angle (\vec{k}_2; \vec{B}_2).
\]

**Figure 3.** Results of direct and indirect measurements of the angles between the construction axes of the corresponding measurement channels of two different magnetometer sensors: 1, 2, 3 – confidence bands of the direct measurement (\( \alpha_1, \alpha_2 \) and \( \alpha_3 \), respectively); 4, 5, 6 – results of the indirect measurement \( \alpha_1, \alpha_2 \) and \( \alpha_3 \), respectively.
The results of the evaluations shown in Figure 3 show that the confidence intervals of direct and indirect measurements of the angles between the construction axes of the respective measuring channels of two different magnetometer sensors completely overlap. Therefore, it is possible to conclude that the sensors are calibrated correctly not only by the modulus of the magnetic induction vector, but also by each measurement channel.

4. Conclusion

Thus, as a result of the studies carried out, the following conclusions can be drawn.

1. In a number of cases, for example, in the case of a non-optimal operation of the magnetic actuators, the existing ground testing program is not sufficient to find the reasons for this work. Therefore, it is necessary to return to the stage of ground tests at the post-flight efficiency analysis stage of the tasks that were assigned to the spacecraft. At the same time, the required information may not be fully preserved or the existing test methodology does not allow obtaining unambiguous answers to some questions.

2. The proposed assessment of the accuracy of calibration of each measurement channel allows one, at the testing stage, to almost completely eliminate the inaccuracy of calibration as a possible cause of a decrease in the quality of primary information to reduce the angular velocity of rotation of the spacecraft around the center of mass with the help of magnetic actuators.

3. The numerical simulation shows the correctness of calibration of each channel of the magnetometer sensors of the flight sample of the Aist small spacecraft. This conclusion is confirmed by the correct operation of the magnetic executive bodies of this apparatus, a report on which is presented in [5].

4. For the prototype of the Aist small spacecraft, where ineffective work of magnetic actuators was observed, the calibration data were not preserved. Therefore, the inaccuracy of the calibration of the magnetometer sensors can not be excluded as the reason for the inefficient operation of the magnetic actuators.

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