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Earth's Magnetic Field Measurements Data Accuracy Evaluation on Board of the Small Spacecraft "AIST" Flight Model

A.V. Sedelnikov, A.S. Filippov, T.A. Ivashova

Samara National Research University

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Abstract

The article suggests a data accuracy test of Earth's magnetic field measurements performed with the magnetometer scientific instrument MAGKOM. The measurements were carried out on board of a small spacecraft "AIST" flight model starting from April 20, 2013 up to May 20 of the same year. The test is based on checking stationarity of the vector magnitude of the magnetic induction average value with unlimited measurement information volume increase. With the help of the proposed test, it is possible to arrive at conclusions about magnetometers operation correctness, and to assign the weight of various measurement channels when they are combined.

Keywords: Magnetometer, small spacecraft, measurements accuracy test;

1. Introduction

Earth's magnetic field measuring during the orbital flight of a spacecraft is produced with various purposes. Most often they are used as primary information to estimate the parameters of spacecraft motion around the cog. This information is necessary to control a spacecraft orbital motion [1-3], to evaluate the microacceleration level in the working area of technological equipment [4-7], to spot characteristics of the gravity-sensitive processes behavior in their implementation on board spacecraft [8-9] etc. Therefore, the task of Earth's magnetic field measurements data accuracy evaluation is an important and urgent task for measuring equipment monitoring at the operations phase of a spacecraft.

To solve this problem, various tools are used. In the paper [1] the problem of small spacecrafts stabilizing by measuring the Earth's magnetic field using engine flywheel is solved. The paper [2] also liquid rocket thrusters for spacecraft orientation is used. For small spacecrafts there are restrictions on the use of effectors of the control system [10]. Therefore, the solutions proposed in papers [1] and [2] are not always suitable for small spacecrafts. Especially when it comes to small spacecraft without a complete control system for orbital motion by classification [10]. A vivid example of the applicability of solutions [1] and [2] is the Aist-2D small spacecraft. From the perspective of the author of the paper [10], such small spacecrafts are practically in no way inferior to spacecraft of the middle class and are unlikely to find a mass application in view of the high cost of realizing their mission.

However, we should soon expect a massive use of small spacecraft in various areas of research. The most promising application, according to the authors [4, 10] are space technologies. At the same time for the successful implementation of technological processes, it is necessary to comply with the requirements for micro-acceleration [8]. These requirements are associated not only with the design of the smallest spacecrafts (this is detailed in [6]), but also with the quality of the measurement data. Thus, the proposed in the work [5] a method of reducing accelerations can be used in view of evaluations [4] and features of measuring only for small spacecraft type Aist-2D with a complete traffic control system [9].

For example, the authors of the works [3, 11] compare the significance of the magnetic field measurement data differences with the Earth's magnetosphere standard model. This comparison allowed the authors to conclude that the measuring equipment operated correctly onboard of the flight and technological samples of AIST and to detect significant differences between measurements of two different magnetometers. The results of the tests performed that the magnetometer No. 1 data differs from the magnetosphere standard model wider than the magnetometer No. 2 data for both small spacecrafts.

So, the authors decided not to consider the magnetometer No. 1 data in small spacecrafts motion estimation around the cog.

The detailed statistical studies of the measuring equipment operation accuracy on the technological sample of the Aist small spacecraft are performed in the paper [12]. They include the verification of the correspondence between the measuring channels of two different magnetometer sensors, the confidence spans

* Corresponding author e-mail: axe_backdraft@inbox.ru.

superimposing of corresponding measuring channels monitoring, the study of the statistical hypotheses of the significance of the differences between the numerical parameters of the measuring channels. Based on the analysis, the authors draw conclusions about measuring equipment operation accuracy and the presence of an average sampled value significant shift of the corresponding measuring channels.

The general approach of these works can be considered the data analysis that was run based on measurements on separate channels. The integrated test is proposed by the authors involving the research of the Earth's magnetic field vector magnitude dynamics rather than its individual components. Such approach supplements the statistical studies proposed in the works and allows us to make valid conclusions about the operation accuracy of on-board the earth's magnetic field measuring equipment.

2. Materials and methods

The subject of this study is Earth's magnetic field, the means of measuring, which are the part of the scientific equipment of MAGKOM (figure 1).

The spacecraft on board of which the MAGKOM scientific equipment operates is the flight model of the Aist small spacecraft (figure 2).

It was launched on April 19, 2013 as a hitchhiker payload with the spacecraft of middle class "Bion–M" No. 1 launch into orbit 21.04.2013 the Aist small spacecraft flight model was separated from the injection module (in-out box) and began an autonomous flight in a near-circular orbit with the height of approximately 575 km high. The service life of the Aist small spacecraft flight model is 3 years. Currently, the center for receiving and processing information of the Samara National Research University was named after Academician S.P. Korolev is still receiving the signal from this small spacecraft. The main characteristics, goals and objectives of this small spacecraft mission are presented in work [3] in details.

For processing, the primary information from the magnetometer sensors were used (figure 1d). It was a time series. For example, the measurements performed on 29.04.13 are shown in figure 3 for the first sensor and in figure 4 for the second sensor.

Three-component magnetometers (figure 1d) during optimal operation had a rated accuracy of $\pm 0{,}5\ \mu T$ and made measurements of the earth's magnetic field at 6 s intervals. The scientific equipment MAGKOM nuanced characteristics are performed in the paper [13].

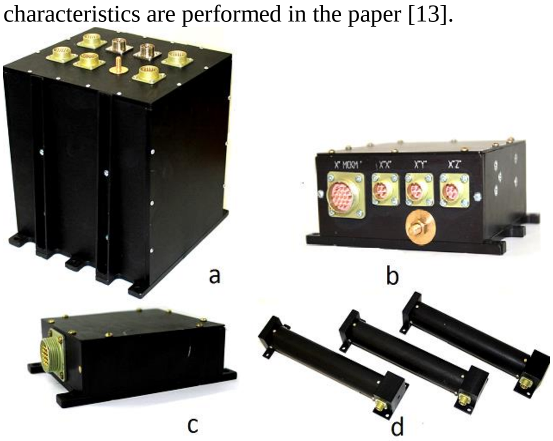

Figure 1. Scientific equipment MAGKOM (cited according to [11]): a-electronics unit; b- control unit for electromagnets; c- three-component magnetometer; d- electromagnets

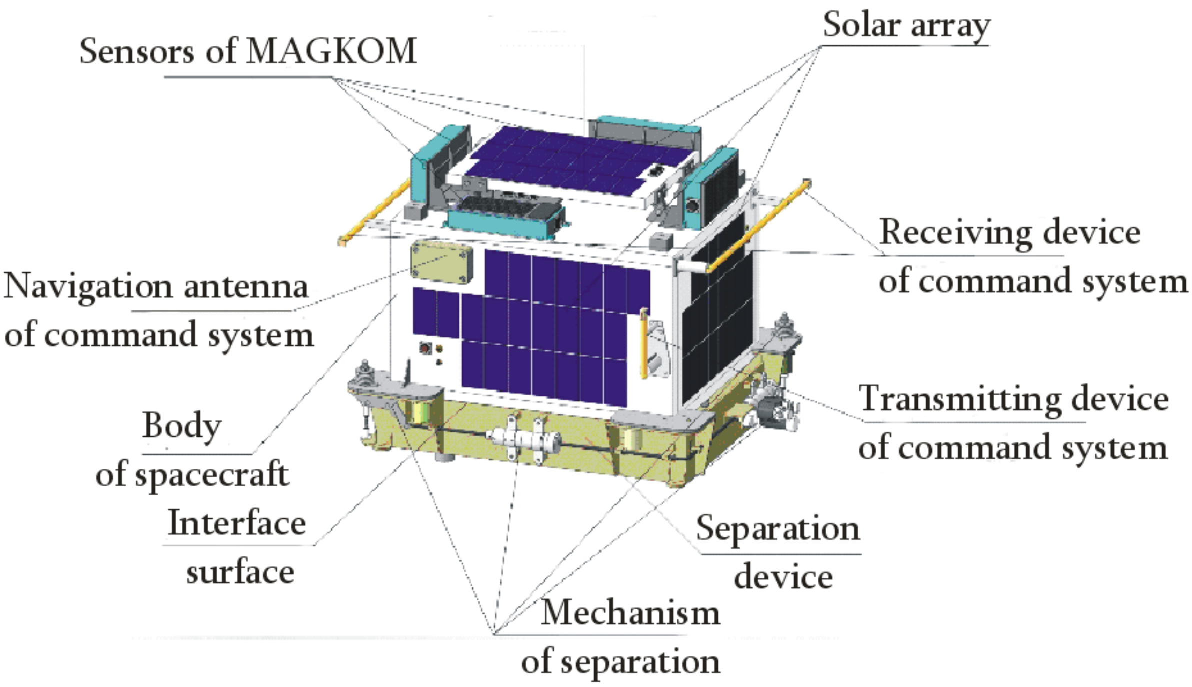

Figure 2. General view of the Aist small spacecraft flight model

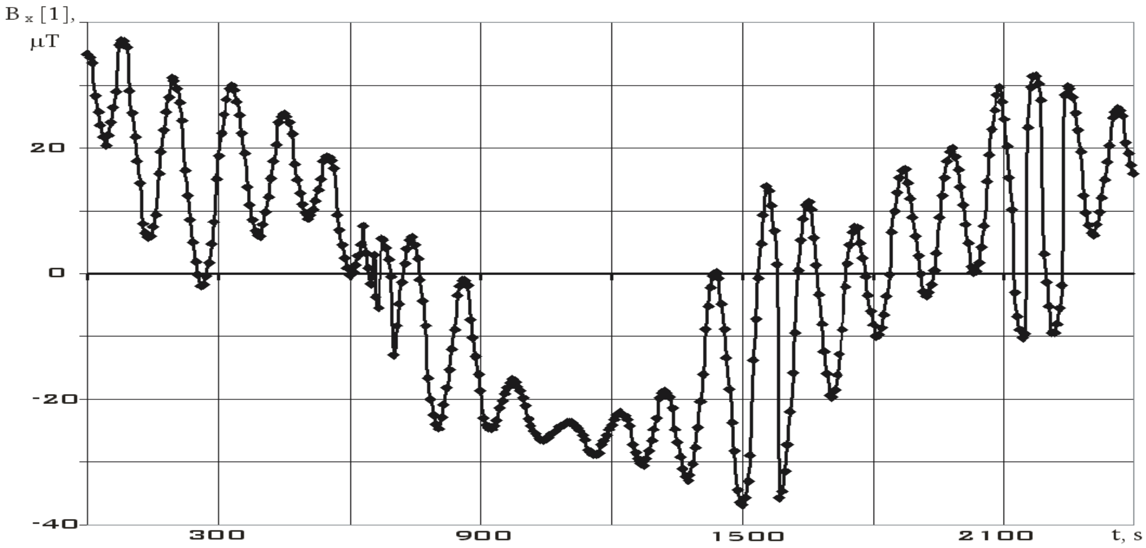

Figure 3a. The Earth's magnetic field measurements data form the sensor No. 1 on the channel $B_x[1]$ 29.04.2013

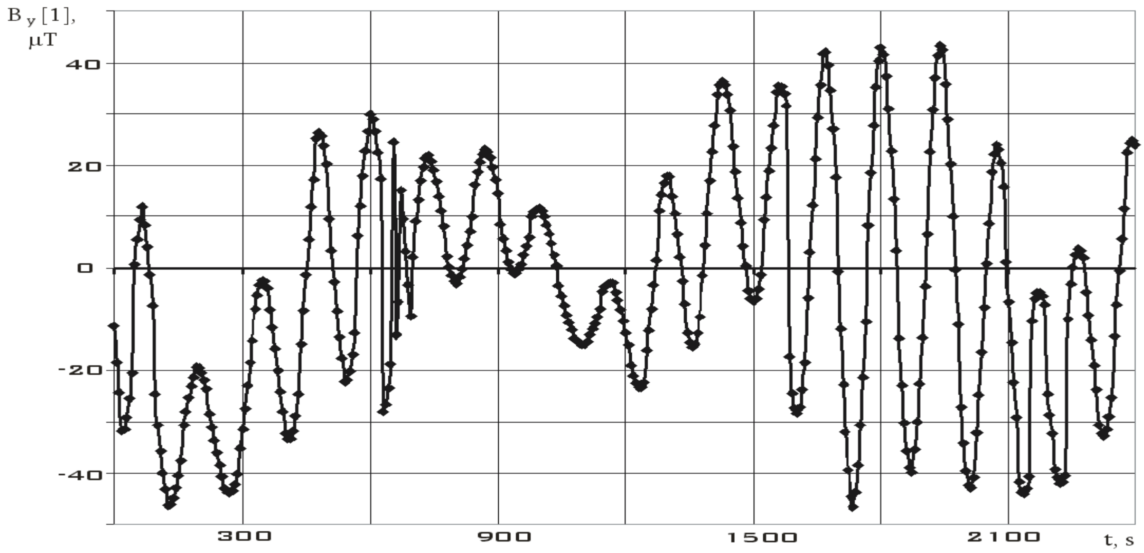

Figure 3b. The Earth's magnetic field measurements data from the sensor No. 1 on the channel $B_y[1]$ 29.04.2013

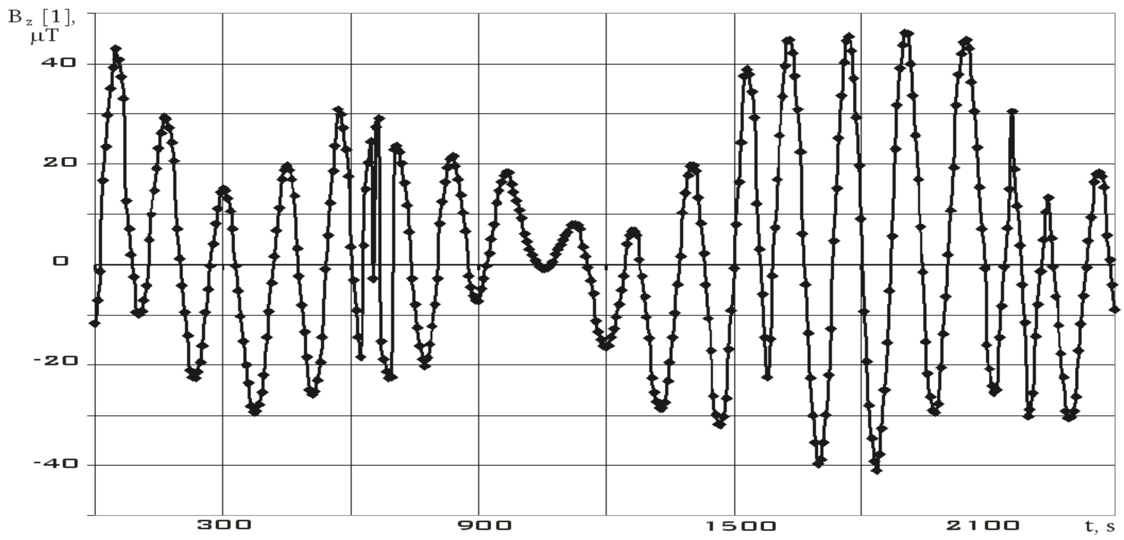

Figure 3c. The Earth's magnetic field measurements data from the sensor No. 1 on the channel $B_z[1]$ 29.04.2013

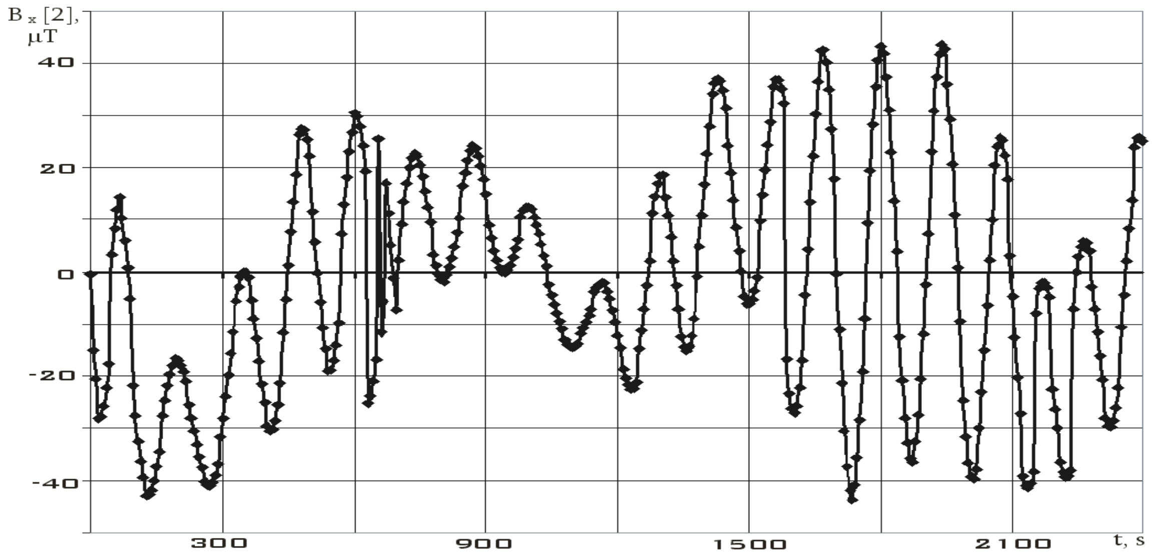

Figure 4a. The Earth's magnetic field measurements data from the sensor No. 2 on the channel B_x[2] 29.04.2013

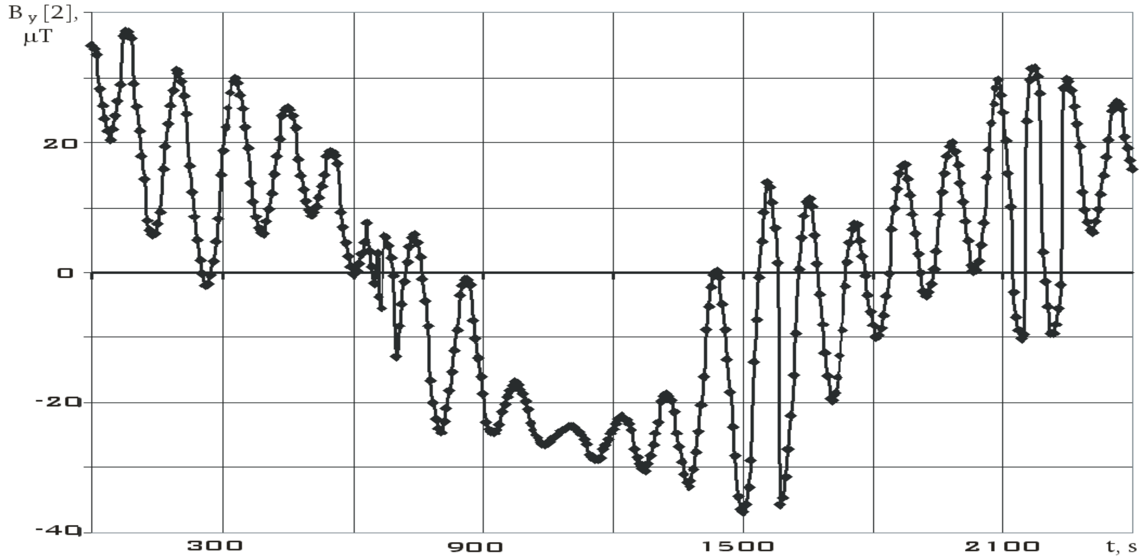

Figure 4b. The Earth's magnetic field measurements data from the sensor No. 2 on the channel B_y[2] 29.04.2013

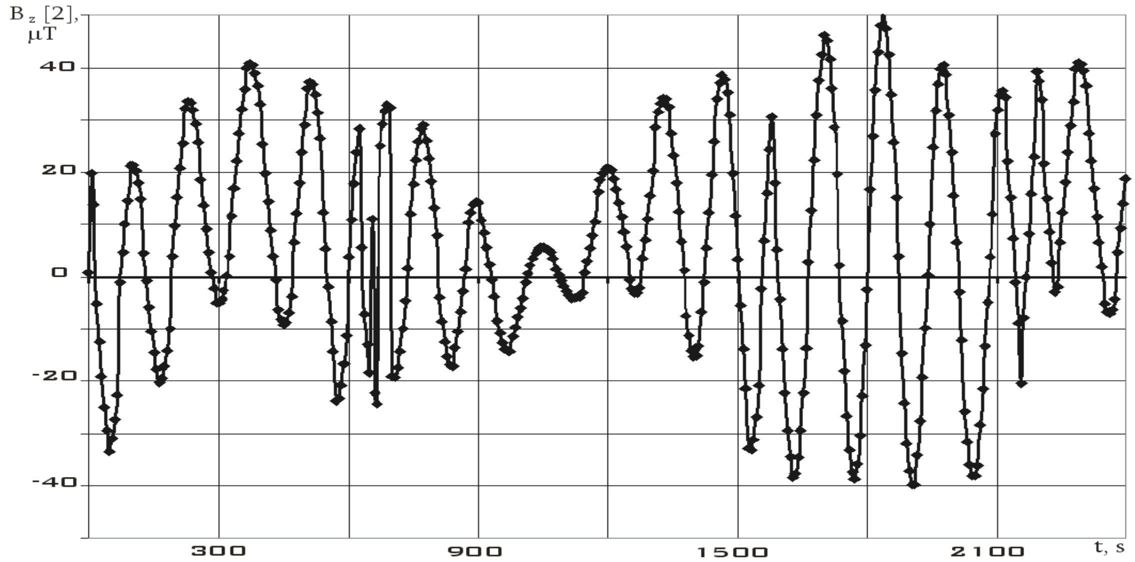

Figure 4c. The Earth's magnetic field measurements data from the sensor No. 2 on the channel B_z[2] 29.04.2013

While processing of measurement data, time series ejections, mostly associated with incorrect transmission, reception or telemetric information decryption, have been removed.

3. Integral accuracy validation test

The test assumes the modulus of the Earth's magnetic field induction vector analysis, calculated from measurements using magnetometers. The test is based on the following considerations:

3.1. Stationarity condition.

As first approximation, the modulus of the Earth's magnetic field induction vector average value along the orbit of the spacecraft can be regarded as permanent. Especially when it comes to measurements carried out in a relatively short period of time. The orbit of the spacecraft in this time interval should not vary significantly. In case of orbit variation, the test can be applied to the series of measurements before and after the variation separately. For higher accuracy testing, one can abandon the premises of the average value stationarity and use, for example, the global magnetic field model WMM 2005 to estimate the time history of the induction module average volume along the spacecraft's orbit over a measurable time interval.

3.2. The condition of representativeness.

During one measurement session, the spacecraft makes several turns or measurement sessions are selected in such a way that the orbit sections with the different values of the induction module meet uniformly in the total sample. The magnetic field of the Earth has fundamentally different characteristics at the poles and the equator (figure 5). If you select measurement sessions performed in part 1 or part 2, then the average value of the induction module will be overestimated. Appropriately, the choice of measurement sessions from part 3 or part 4 will result in a lower average value. Because of measurement sessions mismatching, the stationarity condition may be violated. Indeed, let us imagine that we have successively 100 measurements from part 1, part 2, part 3 and part 4. Without disturbing the time history of measurements, we provide the total sample from them. In this case, the average value for the first 100 sessions will be conservative, then the value will be decreased by adding part 2 measurement data, it will become conservative again after the addition of the part 3 data and finally decreased by adding the part 4 data.

In this case, testing the significance of changes in the induction module hypothesis can come to good. However this significance may not be related to the measurements, but may result from the incorrect arrangement of separate measurement sessions into the total sample. In this case, to properly form a common sample, you should evenly distribute the measurement data of part 1, part 2, part 3 and part 4, disturbing the measurements time history.

3.3. The property of consistency.

The increase of measurement sessions number in the total sample, subject to the condition of representativeness under measuring equipment correct operation condition, must serve to come sample average of the magnetic induction module arbitrarily close to its steady-state value adopted within the framework of the stationarity condition:

$$\lim_{n\to\infty}\left(\left|\vec{B}\right|-\left|\vec{B}\right|\right)=0\,, \qquad (1)$$

where $\left|\vec{B}\right|$ – the average value of the induction module along the spacecraft orbit, $\left|\vec{B}\right|$ – the sample average of the induction modulus, n – number of measurements.

And the variance of the sample average should also arbitrarily come to decrease:

$$\lim_{n\to\infty} D\left|\vec{B}\right|=0 \qquad (2)$$

Thus, the estimated mean $\left|\vec{B}\right|$ of the induction module along the spacecraft's orbit under measuring equipment correct operation condition can be considered as a consistent bias in small samples (figure 6).

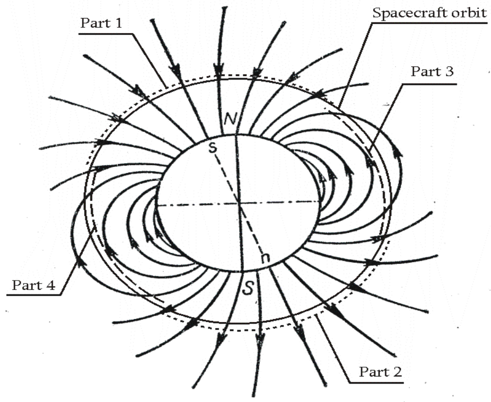

Figure 5. Scheme of the magnetic field lines of the Earth

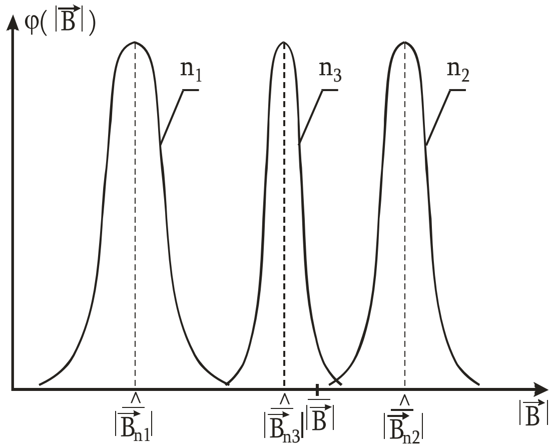

Figure 6. A qualitative illustration of the consistency property ($n_1 < n_2 < n_3$)

To use the integral test, the following algorithm is proposed:

1. Checking the time interval for measuring the stationarity condition.
2. Receding the initial measurement data outlier.
3. Calculating the modulus of the Earth's magnetic field induction vector from measurements.
4. Analyzing the spacecraft position in orbit at the time intervals when measurements were being taken.
5. Arranging the total sample of measurement data taking into account the condition of representativeness.
6. Verification the consistency of estimator condition of the modulus of the magnetic induction vector average orbital value from measurement data.
7. Estimating of the statistical analysis accuracy.
8. Forming the conclusions about the measuring equipment operation accuracy.

4. The results of checking the measuring equipment operation accuracy of the Aist small spacecraft flight model

To estimate the measuring equipment operation accuracy, the data obtained during the measurement sessions were used and the basic parameters of which are presented in Table 1.

Checking the time intervals of measurements according to paragraph 1 of the algorithm shows that only for the measurement session on 29.04.2013, the spacecraft performed less than one turn. Therefore, the measurements data validation integral test might be well-adjusted for the measurement sessions presented in Table 1. Outlier indicated in the third and the fourth columns of Table 1 were receded from the total sample in accordance with paragraph 2 of the algorithm. The calculation of the magnetic induction vector modulus provided the results presented in figure 7.

Table 1. The basic parameters of the Earth's magnetic field measurement sessions samples

Date	Volume of sample	Outlier		Turns number at a measurement session	Total sample volume	
		Sensor 1	Sensor 2		Sensor 1	Sensor 2
27.04.2013	1150	1	1	1,2	1149	1149
29.04.2013	400	0	1	0,6	1549	1548
10.05.2013	1350	0	0	1,7	2899	2898
14.05.2013	2350	1	2	2,6	5248	5246
16.05.2013	1699	221	228	2,1	6726	6717
20.05.2013	1750	42	41	2,3	8434	8426
27.04.2013	1150	1	1	1,2	1149	1149
29.04.2013	400	0	1	0,6	1549	1548

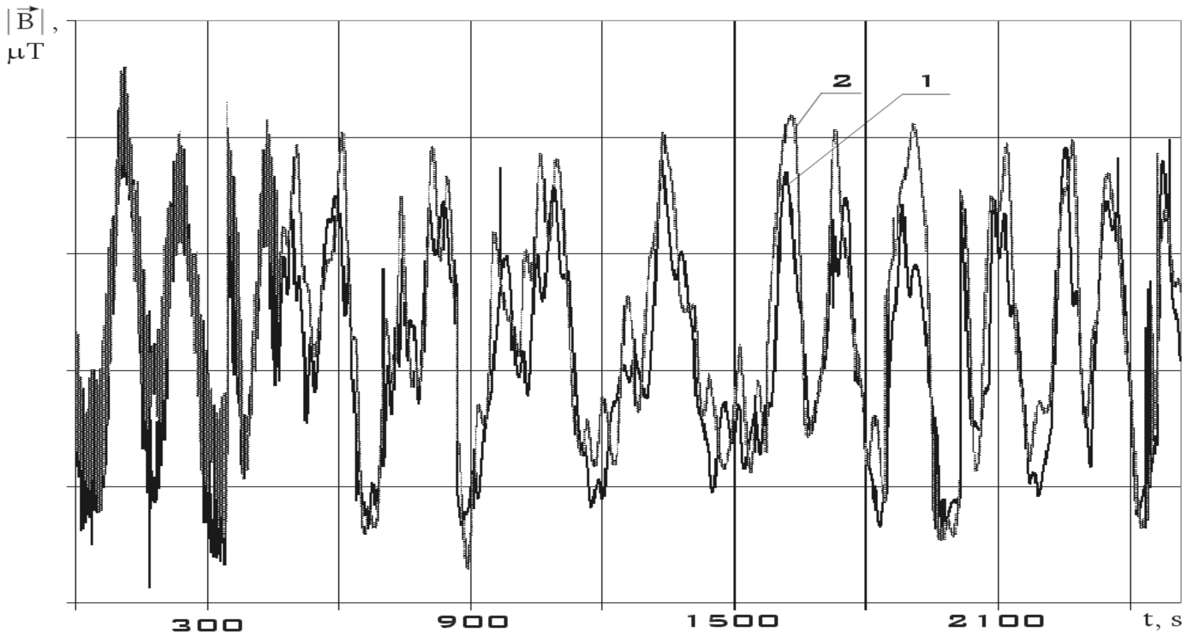

Figure 7. The modulus of the Earth's magnetic field induction vector on the measurements data 29.04.2013: 1) sensor No. 1; 2) sensor No. 2

To arrange the total sample, we will take the easiest rout without breaking the time history of measurements. We obtain the total sample by successive docking of the measurement sessions data given in Table 1. Let us check the consistency of estimator condition of the modulus of the magnetic induction vector average orbital value from measurement data using the expressions (1) and (2). The behavior patterns of an average value and of the total sample variance are shown in Figures 8 and 9.

Analysis of the obtained relationship shows that the sample variance decreases while the sample number increases. So, for $n = 1000$ the average orbital value of the Earth's field magnetic induction vector modulus can be represented as $|\vec{B}| = 33{,}2 \pm 4{,}5\ \mu T$ (Sensor No. 1) and $|\vec{B}| = 35{,}0 \pm 3{,}8\ \mu T$ (Sensor No. 2), and for $n = 8000$ – $|\vec{B}| = 31{,}7 \pm 1{,}9\ \mu T$ (Sensor No. 1) and $|\vec{B}| = 34{,}3 \pm 1{,}7\ \mu T$ (Sensor No. 2). This fully corresponds to figure 6, showing the average orbital value consistency of estimator. Since the measurement sessions have been carried out in a monthly time interval the average orbital value in this interval can be considered stationary. In this context the analytical error does not exceed the measurement error which is $\pm 0{,}5\,\mu T$ according to the developers of the measuring equipment. So, it is a fair assumption that both sensors on the Aist small spacecraft flight sample in the considered measurement sessions are operated correctly. The variation between measurement data (figure 8) is not discussed by the authors of the article. One of the possible reasons for this variation is the effect of the battery operation [12, 14, 15] that requires more careful analysis.

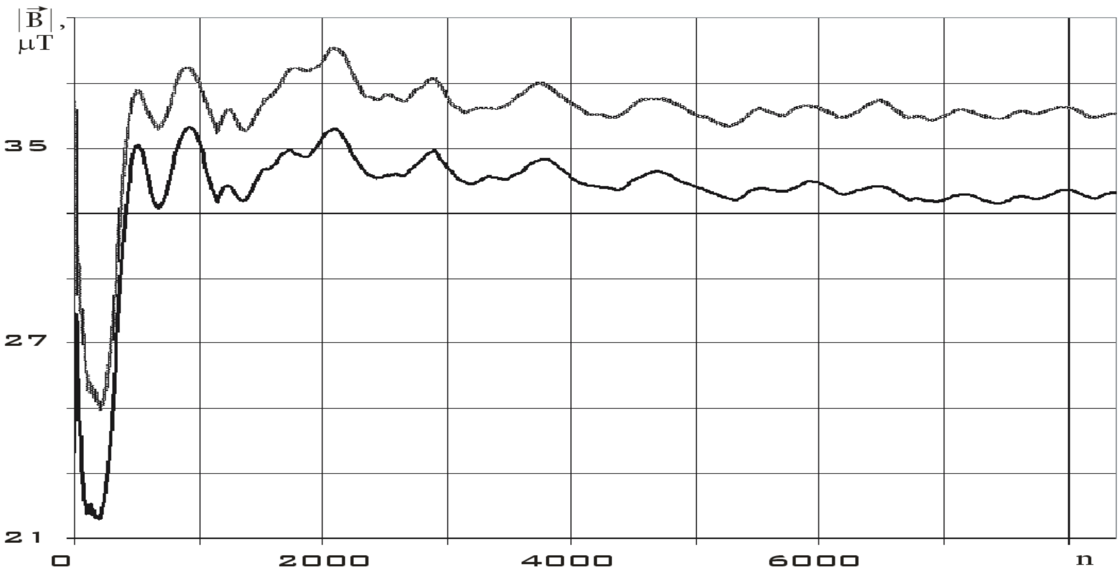

Figure 8. The behavior pattern of a total sample average value for the sensor No. 1 (the upper curve) and for the sensor No. 2 (the lower curve)

Figure 9. The behavior pattern of the total sample variance for the sensor No. 1 (the upper curve) and for the sensor No. 2 (the lower curve)

Conclusions

1. The advantage of the presented test is its integration that lies in all measuring channels validation at once. This saves time spent on analysis, and simplifies the test performance. However it is impossible to identify what measurement channel gives in correct data. The test is used successfully in the case of smooth operation of all measuring instruments for assigning the separate measurement channels weight when implementing joint processing of measurement data.
2. While arranging the sample volume of measurement data, measurement chrono sequence disarrangement may not allow to date the moment of the measuring instrument failure accurately. To solve this problem, it is necessary to test hypotheses of homogeneity of separate measurements samples. In this case, the series of measurements for part 1, part 2, part 3 and part 4 (figure 5) should be sorted and the hypothesis of homogeneity should be checked only within one of the parts.
3. The failure test can not only be a result of measuring equipment failed operation, but also with activating of other spacecraft equipment during the measurement session that can be significantly affected the magnetometer sensors readings. Therefore the proposed test can state the significance of the spacecraft operation systems and equipment impact on Earth's magnetic-field measurement with onboard tools.
4. The presented results of the time period since 20.04.2013 to 27.04.2013 show that onboard Earth's magnetic-field measuring equipment of the Aist small spacecraft flight sample operated perfectly.
5. A comparative analysis (benchmark analysis) of two sensors measurements shows that in the total sample while keeping the measurement sessions chronosequence of the second sensor sampling variance is lower than the first sensor. This suggests that more accurate evaluation of the magnetic induction vector components by means of a second sensor. The authors of [3] came to the same conclusion, that made further evaluation of the spacecraft evolution parameters around the center of mass center only on the basis of the second sensor measurements.

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