

# Restoration of the current signal from solar panels of AIST small spacecraft for estimate the parameters of the rotational motion

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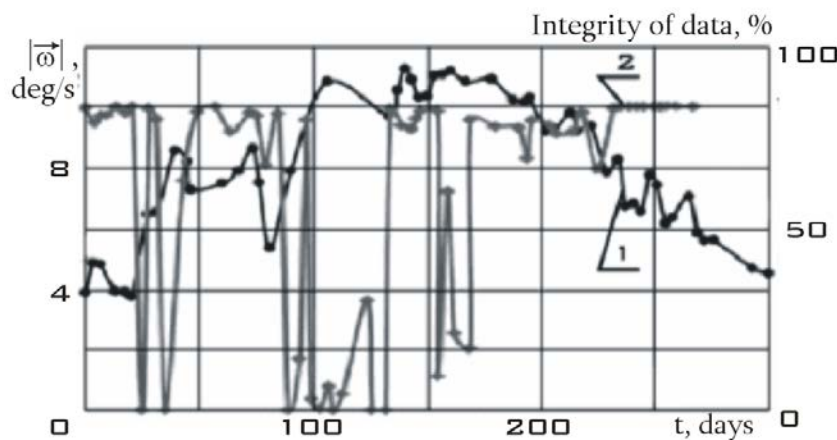
**Abstract.** The paper deals with the problem of estimating the rotational motion parameters of the prototype of the small spacecraft "Aist" using data on the current from solar panels. The spectral analysis of the signal is carried out. The continuous signal was restored by its discrete readings using the Kotelnikov series. The angular velocity of the rotational motion of the prototype of the small spacecraft "Aist" is estimated. A comparative analysis of the results with the results obtained by other authors. Conclusions are drawn about the changes in the parameters of the rotational motion of the prototype of the small spacecraft "Aist" during its orbital flight.

## 1. Introduction

To ensure the efficiency of solving problems facing a small spacecraft, it is necessary to control the angular velocity of its rotation. Small spacecraft, the structural and layout scheme of which contains large elastic elements (for example, solar panels), are operated in an oriented flight. The need for a constant orientation of solar panels relative to the Sun dictates the need to use a small spacecraft full-fledged system of motion control and orientation. An example of such small spacecraft can serve as "Aist-2D" [1]. In this case, the target range of angular velocity values is limited to a few hundredths of a second.

For the case of small spacecraft operation in non-oriented flight, limiting the angular velocity of rotation is also relevant. The quality of telemetry information transmitted from a small spacecraft directly depends on the angular velocity of rotation. So, in work [2] there is a graph illustrating the dependence of telemetry reliability on the angular velocity of rotation of a small spacecraft on the example of a prototype of a small spacecraft "Aist" (Figure 1). As follows from Figure 1, if the angular velocity of rotation exceeds 10 *deg/s*, then the quality of the telemetric information deteriorates markedly. Empty or bad sections appear in the data set, because the receiving antenna was unable to confidently receive the signal due to the high speed of the transmitter. Therefore, in small spacecraft that are operated in undirected flight, Executive bodies are also provided to ensure and control the target values of the angular velocity of rotation of the small spacecraft.





**Figure 1.** Dependences of the module of angular velocity (curve 1) and the reliability of telemetric information (curve 2) on time for a prototype of a small spacecraft "Aist".

When operating small spacecraft, various abnormal situations may arise related to failures of the main measuring instruments. The paper [3] describes the situation of transition of a small communications spacecraft to a state of uncontrolled rotation after an emergency situation. In his telemetry information, there were no data on the parameters of his rotational motion and the kinetic moment of the flywheel engines, which were used as the executive bodies of the system of orientation and control of orbital motion. With data current to the solar panels, the author of the work [3] has established that the module of the angular velocity of small spacecraft was within  $0.60...0.75 \pm 0.2$  deg/s. This made it possible to make a timely decision on the unloading of the kinetic moment of the flywheel engines.

During flight tests of the Munin nanosatellite, the magnetometer failure caused the information about the current collection from the solar battery to become more reliable data on the evolution of the small spacecraft around the center of mass [4].

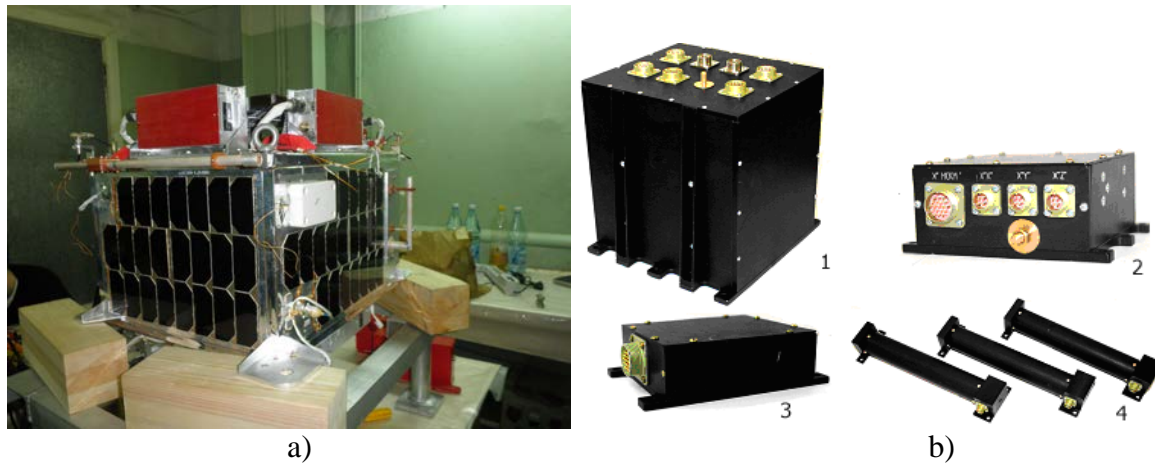
Thus, the use of current data is relevant in case of failure of standard measuring instruments in order to attempt to control the rotational motion of a small spacecraft during its partial operability.

There are situations when a small spacecraft has fulfilled the planned period of active existence. In this degraded battery. As a result, virtually all of the target and support equipment turned out to be inoperable due to the lack of the necessary power supply. However, telemetric information from the board of a small spacecraft at the same time continues to come. It also contains current data from solar panels.

This situation is typical for the flight and experimental samples of the small spacecraft "Aist" [5, 6]. These small spacecraft were operated in uncontrolled flight. Therefore, current data can serve not as primary information for monitoring the effectiveness of the orientation system and orbital motion control, but as a source material for estimating the parameters of the rotational motion of a small spacecraft. The study of the rotational motion of a small spacecraft under conditions of prolonged exposure to disturbing factors in the absence of control actions is of great interest. Moreover, the prototype of the small spacecraft "Aist" has been in orbit for more than four years in non-oriented flight mode [7].

## 2. Comparison of estimates of the angular velocity of rotation of a small spacecraft by various means

The standard measuring instruments for estimating the angular velocity of rotation of a small spacecraft "Aist" prior to the degradation of the battery on the flight and experimental samples of a small spacecraft were magnetometers (Figure 2 [8]), which, according to research [9], worked correctly. Since there were significantly more measurements for the prototype of the small spacecraft "Aist" than for the flight model of the small spacecraft "Aist", we will choose this device for further research.



**Figure 2.** Appearance of the prototype of the small spacecraft "Aist" (a) and scientific equipment MAGCOM (b): 1 – electronics unit; 2 – control unit electromagnets; 3 - magnetometer; 4 – electromagnets where.

The first stage of the work was the study of differences in the estimates of the angular velocity using the readings of magnetometers and current data from solar panels during the working life of scientific equipment and standard measuring instruments of the prototype of the small spacecraft "Aist". It is necessary to make sure that the estimates of the angular velocity from the current data are correct before using those periods of the active existence of a small spacecraft in which only current data were available.

Unfortunately, due to the nature of the measurements themselves, this verification can only be carried out to a limited extent. Since telemetry information was extremely saturated during the regular operation of scientific equipment, current data were recorded and transmitted to the Earth once a minute while the magnetometers operated, while the primary information processing algorithm from the magnetometers [10] generated measurements every 6 seconds. Therefore, the test could be carried out only in the frequency domain of  $0 \dots \pi/60 \text{ rad/s}$ . Figure 3 presents the results of a comparison of the angular velocity estimates using magnetometer sensors and current data from solar panels per channel for measurements 09.09.2014.

The evaluation of the angular velocity of rotation of the prototype of a small spacecraft "Aist" from measurements of the induction vector of the Earth's magnetic field was carried out according to the following formula [6]:

$$\vec{\omega}_i = \frac{\vec{B}_i \times \left( \dot{\vec{B}}_i - \frac{d\vec{B}_i}{dt} \right)}{B_i^2},$$

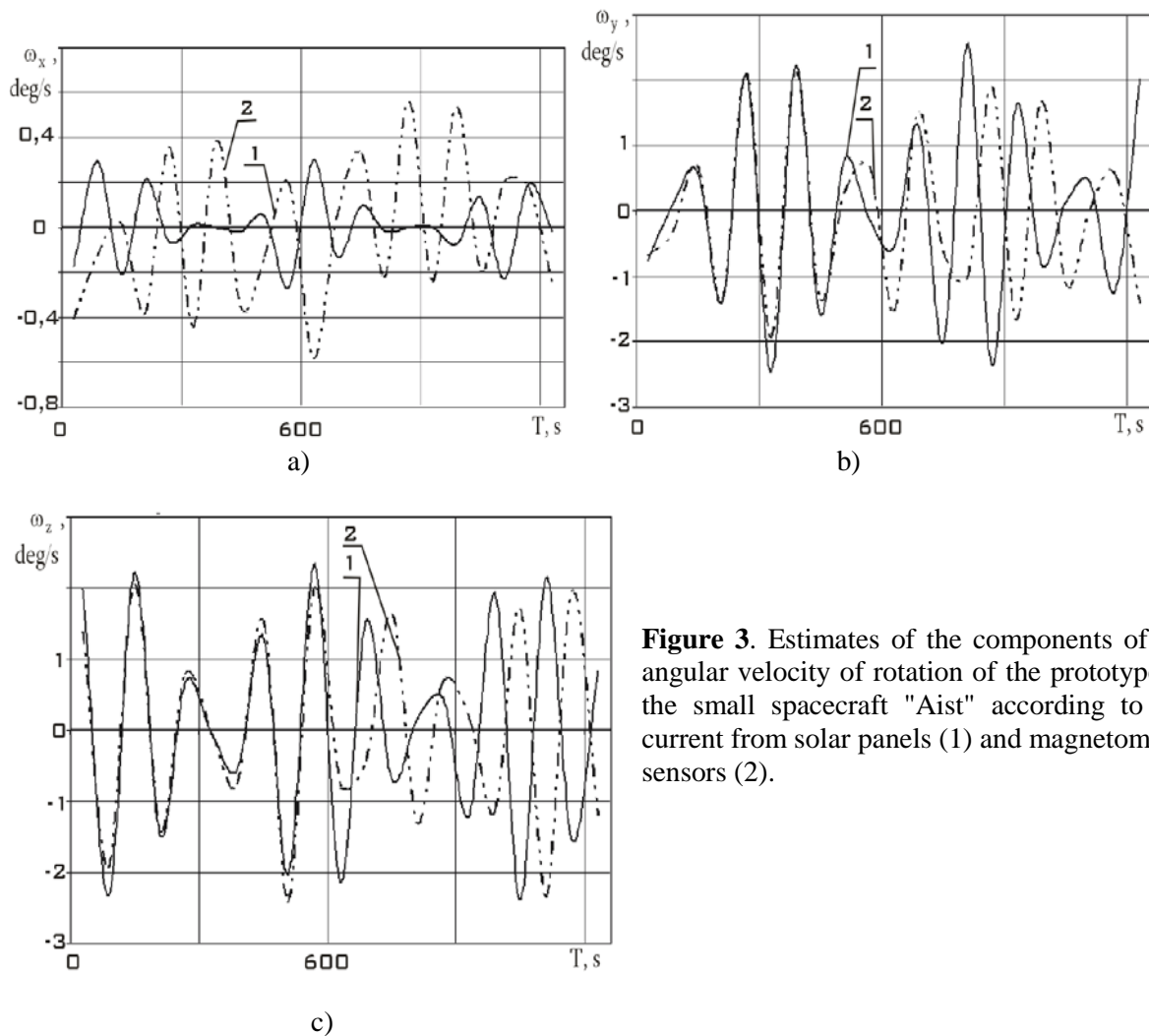
$\vec{\omega}_i$  is the vector of the angular velocity of rotation of the small spacecraft around the center of mass at

a time  $\frac{d\vec{B}_i}{dt}$  is the induction vector of the earth's magnetic field;  $\dot{\vec{B}}_i$  is the local derivative of the induction vector of the Earth's magnetic field in the small spacecraft related coordinate system, which is mainly due to the movement of the small spacecraft around the center of mass.

The evaluation of the angular velocity of rotation of a prototype of a small spacecraft "Aist" using current data from solar panels was carried out using the following formulas [4]:

$$\omega_{ki} = \frac{\arccos\left(\frac{i_{ki}}{i_{\max}}\right) - \arccos\left(\frac{i_{ki-1}}{i_{\max}}\right)}{t_i - t_{i-1}},$$

$i_{ki}$ ,  $i_{ki-1}$  is the measured values of the current at the time and, respectively;  $i_{\max}$  is the maximum value of the current, which is considered constant and the same for all faces of the small spacecraft "Aist";  $k = x, y, z$ .



**Figure 3.** Estimates of the components of the angular velocity of rotation of the prototype of the small spacecraft "Aist" according to the current from solar panels (1) and magnetometer sensors (2).

The analysis of dependencies in figure 3 shows that significant differences in the given time interval are observed only for the component of angular velocity  $\omega_x$ . However, it is noted in the paper [5] that the consistency of the two magnetometers of the prototype of the small spacecraft "Aist" over this measurement channel was unsatisfactory. However, the use of several different non-parametric shift criteria did not allow us to recognize the measurements of the first magnetometer by overshoot. As a result of the research, it was revealed that there was a discrepancy in the estimates of the angular velocity of rotation of a prototype of a small spacecraft "Aist", measured from different magnetometers for an angular velocity component  $\omega_x$ , in some cases, they differ more from each other than from evaluation using current data. Therefore, referring to studies [5], we can assume that, in general, the numerical characteristics of the angular velocity (expected value and variance) are

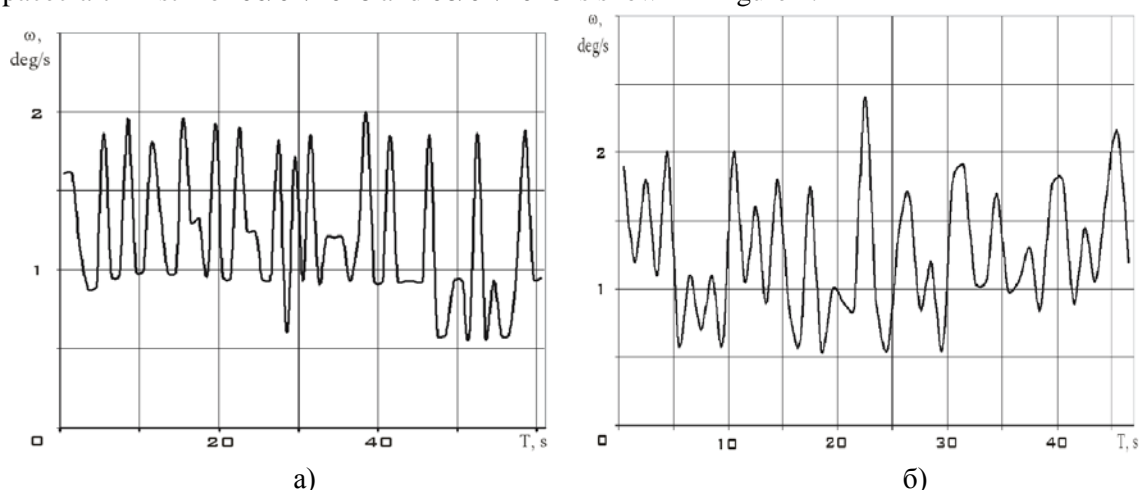
correctly estimated using current data from solar panels. In the works [10, 11] the evaluation of the angular velocity of rotation of the prototype of the small spacecraft "Aist" was carried out by other authors. In general, the results shown in Figure 3 are consistent with these estimates.

### 3. Estimation of the angular velocity of rotation of a small spacecraft from current data from panels.

After the degradation of the battery, the current data from the solar panels became the only source of primary information for estimating the angular velocity of rotation of the prototype of the small spacecraft "Aist". The standard measuring instruments, like other scientific equipment, did not function due to the absence of the required power supply. During this period, it was possible to realize the time interval between measurements 1 c, since the density of telemetry information was minimal. Thus, the frequency domain was extended to the segment  $0 \dots \pi \text{ rad/s}$ . However, there was another problem. The degradation of the battery led to the fact that the cycle of its charge-discharge is significantly reduced. After receiving a signal that the battery is fully charged, the solar panels are automatically disconnected from the charging circuit. At the same time, zero current was recorded in the telemetry data. As a result of this, the first telemetric data practically did not contain areas in which the current from all three panels facing the Sun would be non-zero. Often, one, two, or even all three panels were disconnected from the battery charging circuit. Estimation of the angular velocity in such areas is almost impossible.

This problem was solved as follows. Telemetry exchange sessions with a prototype of the small spacecraft "Aist" began with testing the functional status of scientific equipment. That equipment, which could work normally with power, was used to discharge the battery. The on-board computer was sent a command to turn on this equipment. She could not work properly, because the battery almost immediately discharged. However, there was also no signal that the battery was fully charged. Thus, it was possible to avoid automatic disconnection of solar panels from the battery charging circuit and to obtain telemetric data on the charging current in the amount necessary for their analysis. In this case, telemetry sessions were conducted only during the period when the small spacecraft was visible, which was about 10–15 minutes. It was not possible to record the telemetric information in the memory of the onboard computer and then transfer this data during the communication session.

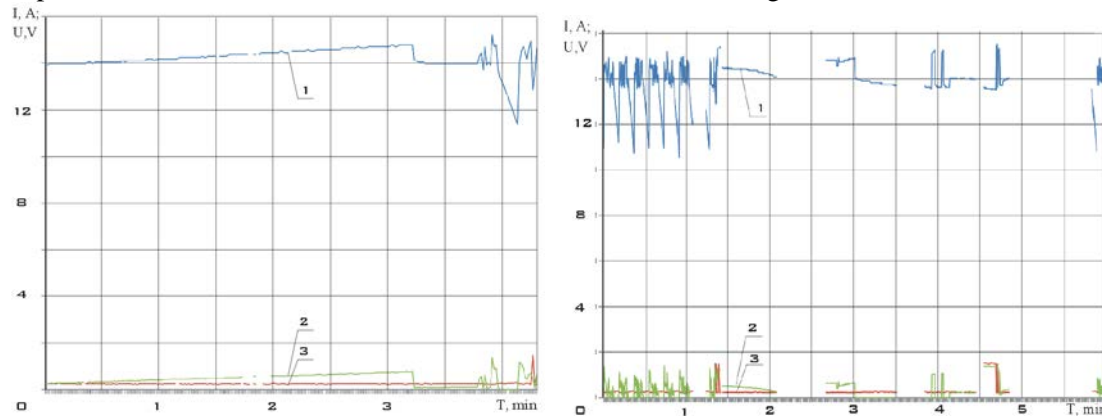
The evaluation of the module of the angular velocity of rotation of the prototype of a small spacecraft "Aist" for 06/01/2018 and 08/04/2018 is shown in Figure 4.



**Figure 4.** Estimates of the angular velocity module of the prototype of the small spacecraft "Aist" according to the current from solar panels 01.06.2018 and 04.08.2018.

As can be seen from Figure 4, in both cases there is a significant high-frequency component of the signal. From a physical point of view, its presence could be explained by the action of a periodic force, creating a moment around the center of mass of a small spacecraft. However, numerous studies of the

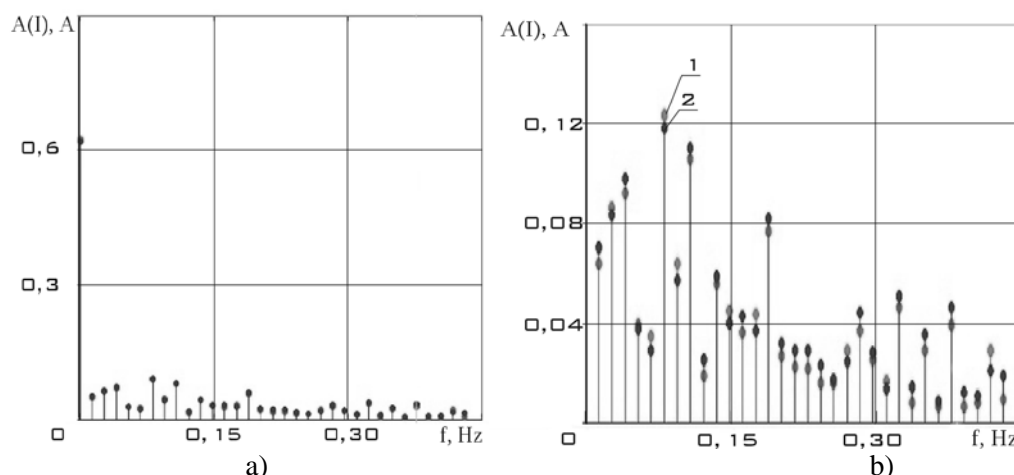
orbital motion of a small spacecraft do not confirm this. Then we can assume that the high-frequency component is a distortion of the signal. On the other hand, the current data were recorded in telemetry information with an accuracy of two decimal places. Fix it in the degradation of the battery has failed. An example of telemetric information on the operation of the power supply system of a prototype of a small spacecraft "Aist" for 01.06.2018 and 04.08.2018 is shown in Figure 5.



**Figure 5.** Data on the operation of the power supply system of the prototype of the small spacecraft "Aist" for 01.06.2018 and 04.08.2018: 1 - the potential difference of the onboard network; 2 - charging current from solar panels; 3 - current consumption of onboard equipment.

The smooth sections of the curves in Figure 5 correspond to the charging mode of the battery. Hop-change sites reflect the inclusion and attempts of scientific equipment to operate in accordance with the commands sent to the onboard computer of a small spacecraft during communication sessions. Gaps in the curves indicate the presence of erroneous sections in the telemetry information, associated mainly with the rotation of the signal transmitter relative to the receiver [13].

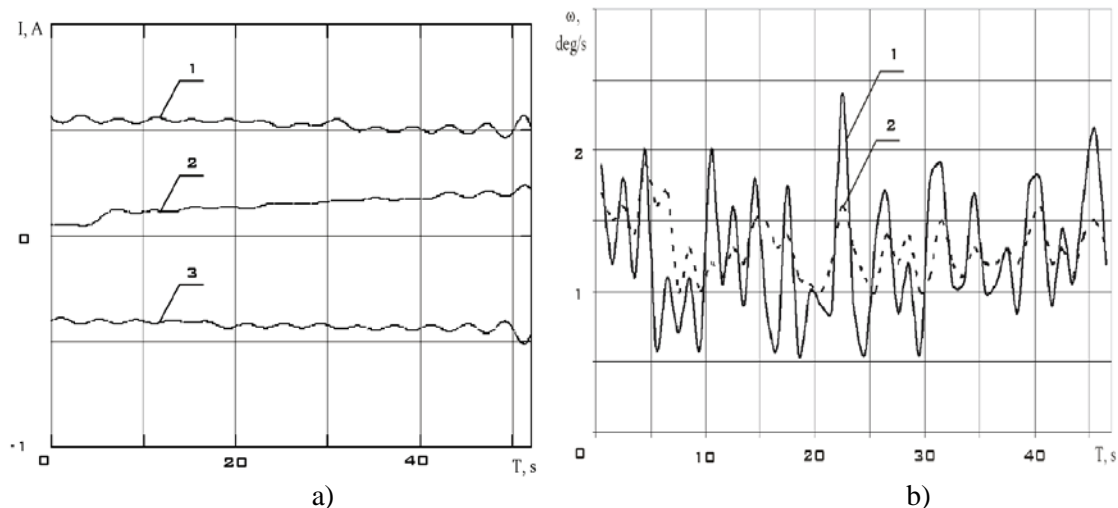
To get a continuous signal about the current, restore it near Kotelnikov [14]. Compare the spectra of the original discrete and reconstructed signal. For this purpose, we use discrete values of the continuous signal at points shifted by 0.25 with time. If the original signal contains samples  $i(t_1)$ , where  $t_1 = 0; 1; 2; \dots [s]$ , then to build the spectrum of the recovered signal we use  $i(t_2)$ , where  $t_2 = 0.25; 1.25; 2.25; \dots [s]$ . Since the Kotelnikov series at points  $t_1 = 0; 1; 2; \dots [s]$  completely coincides with the original discrete signal. Figure 6 shows the spectrum of the original and recovered signals for 04.08.2018.



**Figure 6.** Amplitude frequency characteristics of the initial discrete signal (1, lighter points) and the restored near Kotelnikov continuous signal (2, darker points) for the current ix from solar panels 04.08.2018: zero frequency; (b) increased fragment without zero frequency.

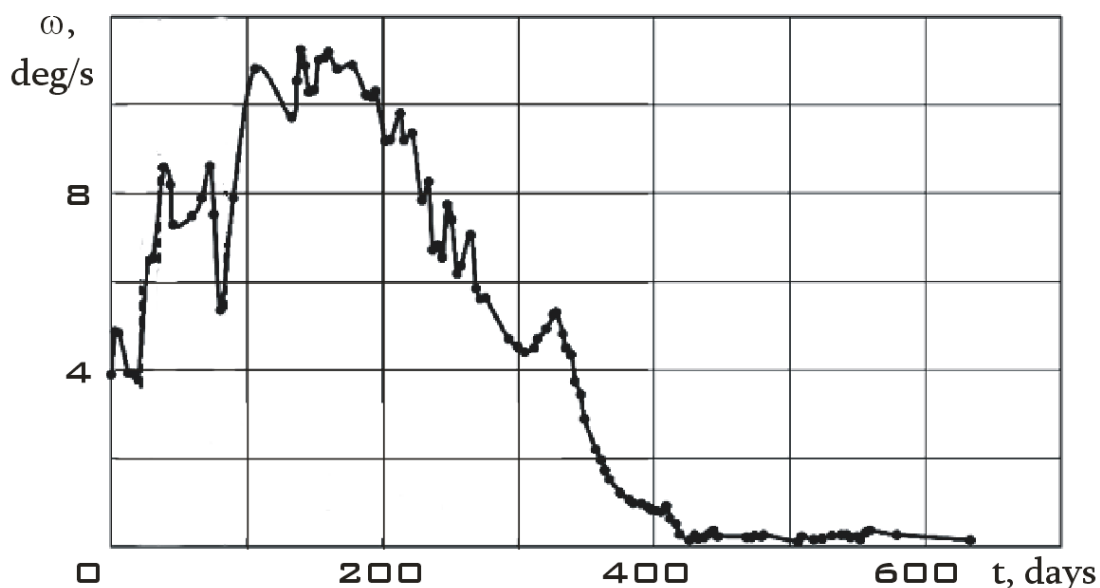


Figure 7 shows the reconstructed signal for currents, corresponding to Figure 4b, and a comparison of the estimates of the angular velocity modulus from discrete current counts from the panels and the reconstructed signal.



**Figure 7.** Recovered signals for the currents from the solar panels 04.08.2018 (a): 1 – current  $i_x$ ; 2 – current  $i_y$ ; 3 – current  $i_z$ . Estimation of the angular velocity module of the prototype of the small spacecraft "Aist" on the restored signal (b): 1 – on a discrete signal; 2 – on the restored signal.

As can be seen from Figure 7b, the high-frequency component has decreased significantly. Therefore, it was mostly a noise superimposed on the signal. Significant differences in Figure 7b can be explained by the low accuracy of the source current data, which was two decimal places at a maximum value of current 1. In general, the data obtained by the character are similar to the estimates of the angular velocity in the period of operation of standard measuring instruments. These assessments were performed and presented in the paper [11]. The average value of the angular velocity for the plot presented (Figure 7 b) is significantly lower than in the work [11]. However, even during the period of operation of standard measuring instruments, the researchers noted that after three unsuccessful attempts to reduce the angular velocity module by means of electromagnets, the prototype of the small spacecraft "Aist" gradually stabilized (Figure 8) [15].



**Figure 8.** Dependence of the angular velocity module of the prototype of the small spacecraft "Aist" in the period of performance of standard measuring instruments [15].

Estimates [11] were made at the beginning of the operation of a small spacecraft, where its angular velocity was still high. Studies have shown that after some stabilization (Figure 8), the prototype of the small spacecraft "Aist", most likely, no longer acquired a large angular velocity. At least, the available data on the current from the solar panels that can be processed, allow us to conclude that the angular velocity module of the prototype of the small spacecraft "Aist" hardly exceeded 5 deg/s during the data processing period from 15.05. on 08.08.2018.

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