On the results of processing of the telemetry data received from the “AIST” small satellite constellation

I.S. Tkachenko[1], **S.L. Safronov**[1], **I.V. Kaurov**[1], **M.A. Ivanushkin**[1], **S.S. Volgin**[1]

[1]Samara National Research University, Moskovskoe Shosse 34A, Samara, Russia, 443086

Abstract. The article presents the result of processing of the telemetry data obtained from the “AIST” small satellite constellation. The results of processing telemetry data, obtained during emergency situations onboard of the satellites were presented. The Influence of the light-dark cycle on the power balance of the satellites were considered. The factors affecting the thermal regime of spacecraft were considered, recommendations for improving the thermal management system were formulated.

1. Introduction

Small satellites (SS) of the “AIST” family (developed as a joint project between Samara university and JRSC “Progress”) were designed to conduct studies of the near-Earth space. In particular, measurements of the magnetic field of the Earth and characteristics of micro particles of natural and artificial origin, that are colliding with the detectors of the “METEOR” scientific payload (SP). The “AIST” satellites are unsealed, they have no motion control systems and perform a non-oriented flight. There were two “AIST” SS produced. The first one was launched on April 14th 2013 from the Baikonur cosmodrome (radio call sign ICA: RS-43as). The second one was launched on December 28th 2013 from the Plesetsk cosmodrome (radio call sign ICA: RS-41at). After the initial three month of flight tests both satellites were taken into operation, which still continues

The process of operation of a SS is inextricably linked with the receipt, processing and analysis of telemetric information (TMI). The TMI shows the state of the onboard system of the satellite. The DOKA-B equipment, installed on the “AIST” SS, performs the sensors’ scanning for the platform and the payload, records the obtained data onto the power-independent data storage unit and transmits it during the communication sessions with the ground control station (GCS).

After the TMI has been processed and analyzed, the operational program for the SS is developed, the operation commands are formulated into a communication session plan that is going to be sent to the GCS in order to be transmitted to the SS [1].

The main objectives of this work is to analyze the volume of TMI accumulated during the operation of an SS to determine the causes of emergency situations, clarify the methods for calculating the energy balance and conducting ground thermal vacuum tests of unpressurized SS.

2. Emergency situation analysis

Emergency situations (ES) that occur in the process of the satellite’s operation due to the influence of the space factors, design flaws or manufacturing errors, could lead to failure of the SS systems. Equipment failures of an automatic system drastically change its structure and could lead to satellite’s failure states that hinder its performance [2].

TMI is analyzed in order to counteract the ES through detection of potential vulnerabilities in SS hardware and software. The analysis is also useful for refinement of satellite control techniques.

The analysis procedure consists of two stages. At the first stage, a search is carried out for inadmissible values of the parameters that are chosen as the ES main indicators for the “AIST” SS. Table 1 lists these parameters and ranges of acceptable values.

Table 1. List of analyzed parameters.

Parameter	Unit	The range of acceptable values
System voltage	*B*	10.0...15.5
System current	*A*	0.0…6.0
Solar panel current	*A*	0.0...6.0
Power and Telemetry Controller Modes	*bit*	xxxx0x0x
Receiver current	*A*	0.0...3.0
Transmitter current # 1	*A*	0.0...3.0
Transmitter current # 2	*A*	0.0...3.0
User navigation equipment current	*A*	0.0...3.0
Time generator’s current	*A*	0.0...3.0
MAGCOM payload’s current (main power bus)	*A*	0.0...3.0
MAGCOM payload’s current (backup power bus)	*A*	0.0...3.0
Temperature sensor #1 - #16	*°C*	-40.0...+60.0
Control modes	*bit*	xx00xx00

On the second stage, the SP with the same type of behavior of the monitored parameters and the causes of their occurrence are determined using technical documentation on the SS.

The TMI analysis allowed to identify three main failure types that can lead to ES:

- failure due to insufficient replenishment of energy reserves;
- failure due to incorrect operation of SP;
- failure due to exposure to heavily charged particles (HCP).

Information on the origins of the ES allows to evaluate their frequency of occurrence. As shown on figure 1, almost 40% of all the ES are caused by the lack of energy due to the SS battery degradation.

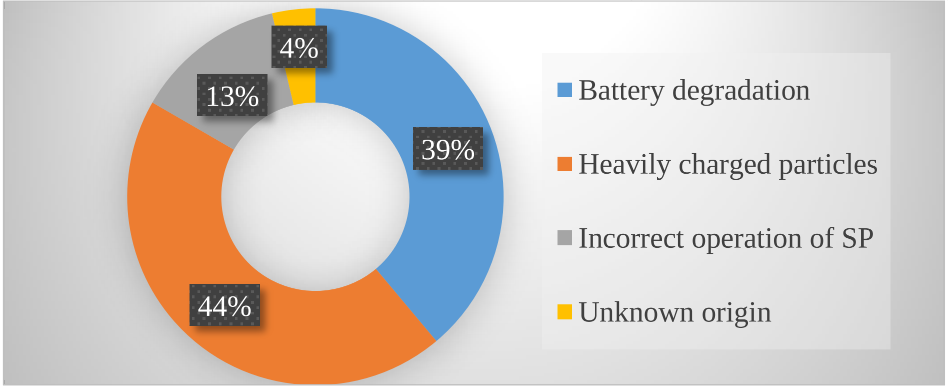


Figure 1. Nature of the ES emergence onboard of the "AIST" SS.

Battery degradation (loss of capacity) is a natural process. Depending on the type of battery, temperature conditions during operation and the number of charge-discharge cycles degradation can occur abruptly or gradually. In the case of nickel-cadmium batteries installed on the “AIST” SS, degradation occurred evenly, reducing the capacity to 42% of the nominal value after five years of operation for the AIST RS-41at, and to 59% for the AIST RS- 43as after 5.5 years.

Emerging failures, associated with insufficient replenishment of energy reserves, hinder the work of SP and disrupt the program of experiments.

It was experimentally established that the main reason for this type of ES is the method of calculating the energy balance used to plan the work of the platform and SE, which does not take into account the capacity of the battery that changes over time.

It was decided to enhance the initial method for calculating the energy balance in order to reduce the number of ES of this type and increase the operating time of the SE, by taking into account seasonal changes in the SS illumination conditions in orbit and their effect on the capacity of the battery.

3. Analysis of the light and shade situation and energy balance planning in the context of energy constraints

Ensuring the energy balance in the operation of the science equipment (SE) is an important task in the event of a shortage of electricity on board the spacecraft, which can be caused both by the degradation of the onboard systems and by the space factors.

In order to solve the task of maintaining the SS power supply system (PSS) in working conditions in the event of power shortage, by designing a program for planning the energy balance, a modeling of the light and shadow situation in the “AIST” SS orbits was carried out. The modeling of the light and shade conditions, carried out in the SGP4 orbital model [3], provides information on the amount of time that the SS is illuminated by the sun in its orbital motion.

As a result of modeling the light and shade conditions, the values of the length of the shadow-free areas were obtained (from 17 to 23 days). Their presence exerts a significant load on the thermal control system (TCS) of the “AIST” SS, causing overheating of the platform and SE. Sections with a maximum average daily duration of the shadow (36 minutes per turn for both “AIST” SS) have the greatest impact on the TCS, and lead to insufficient replenishment of the capacity of the battery, if the SE was active during this period.

The purpose of planning an energy balance onboard of a satellite is to fulfill the condition that the total amount of power consumed does not exceed the available capacity onboard. Such a condition can be represented as follows:

$$\sum_{i=1}^{n}\left(P_{SE_i}\cdot\Delta t_{SE_i}\right)\leq\left(P_{PSS}-P_{AP}\right)\cdot\Delta t_{progr}+\Delta Q_B\cdot U_{bs}, \tag{1}$$

where P_{SE_i} – power, drawn by SE on the *i*-th time interval in the program of the SE operation, [*W*]; P_{PSS} – power of PSS, [*W*]; P_{AP} – average power of the PSS, [*W*]; Δt_{SE_i} – duration of the *i*-th time interval, [*hour*]; Δt_{progr} – total duration of the SE work program, [*hour*]; ΔQ_B – available capacity of the battery, [*A·hour*].

In order to maintain a reserve of the battery charge, when calculating the energy balance, the minimum allowable capacity is proposed to be taken as $Q_B^{\min}=5{,}1\ A\cdot hour$.

The procedure for planning the energy balance was formulated as follows: after obtaining the TMI the first order of business is to determine the actual PSS parameters (battery capacity and the average power of the PSS); then, based on the developed model, the light and shade durations should be calculated for the next 24 hours of flight, the expected average power of the PSS and the amount of battery capacity left after the execution of the daily flight program. The flight program is only transmitted to the SS after the condition (1) is satisfied. If it is not, the Δt_{SE_i} parameters should be reduced and the calculations should be carried out once more for the corrected parameters.

As a result of applying the refined method of calculating the energy balance, an increase in the time of uninterrupted operation for both of the “AIST” SS increased from 1.5 to 4.2 hours during shadeless periods and from 50 minutes to 2.2 hours during turns with an average shade duration for the “AIST”

RS-43as, as the state of the battery on the “AIST” RS-41at only allows operation of the SE during the shadeless periods of the orbit.

In addition, the updated method allowed to exclude the appearance of ES caused by insufficient replenishment of energy reserves, since it includes calculations based on actual information about the parameters of the satellites’ power supply systems.

4. Analysis of the thermal regime of the “AIST” small satellites

Satellites of the “AIST” series are fitted with a passive thermal control system based on thermal pipes that are located inside of the honeycomb panels of the satellite’s body, thermal pads between the equipment and the panels of the SS and film heaters (FH). Heat is discharged through the edges of the SS hull, the thermal balance is controlled by the command and control navigation system in automatic mode. Temperature sensors, both control and measuring in the amount of 48 pcs. placed on the thermoplates of the SS installation, and on the honeycomb panels, in close proximity to the elements of the photovoltaic array. The location of the sensors on the external surfaces of the SS is shown in figure 2 [4].

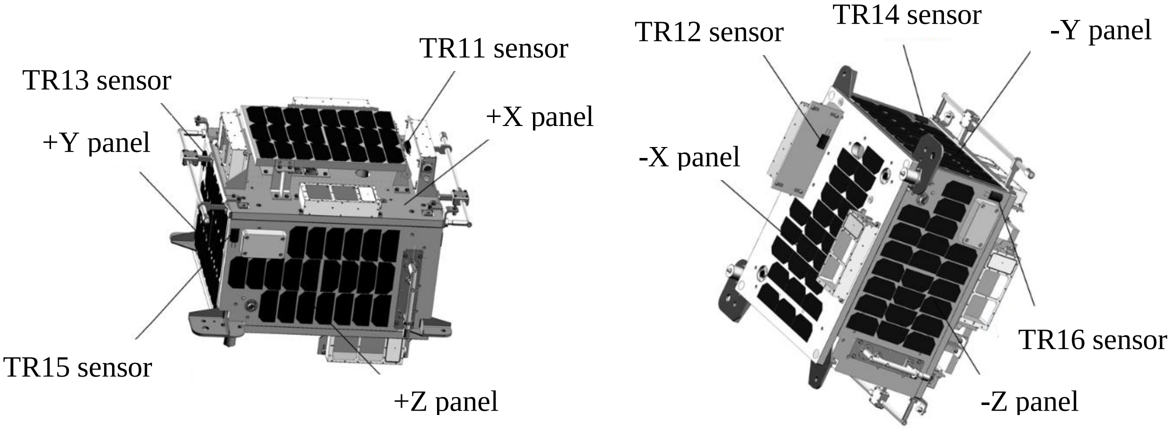


Figure 2. Location of temperature sensors on the external surfaces of the satellite.

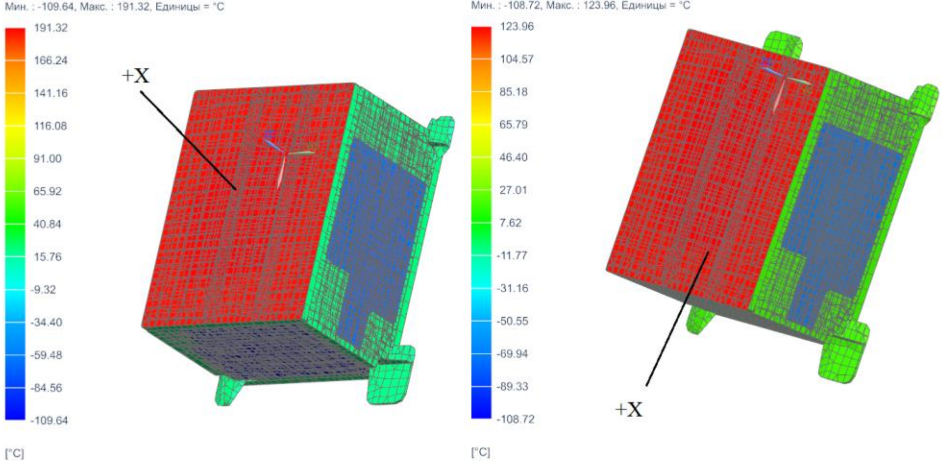
To ensure the thermal balance of the MCA shell on the external surfaces of the panels free of the photovoltaic elements, the thermal radiation characteristics are provided as $A_S \leq 0.2$, $\varepsilon \leq 0.1$, on the inner surfaces the degree of blackness $\varepsilon \geq 0.85$ is ensured. Thermal radiation characteristics of the photovoltaic elements $A_S = 0.86$, $\varepsilon = 0.84$.

As can be seen from figure 2, the + X panel has design features that affect its heat balance. The surface of the panel + X does not have photovoltaic elements (PVE) they are brought out on a separate panel of smaller dimensions installed with the help of brackets.

From the indications of the TR 11 sensor (installed on the outer surface of the + X panel) it was concluded that the absence of PVE on the + X panel plays a significant role on its heat balance. The temperature on the outer surface, due to the fact that $\frac{A_s}{\varepsilon} = 2$ increases rapidly and can reach 95-100 ° C in the illuminated part of the orbit. When the SS goes into the shade, the panel also quickly cools due to the fact that some of the heat through the heat pipes goes inside of the SS, the other part is distributed to other panels and goes through the brackets to the solar panel installed on the + X panel, so the panel can be cooled to minus 40 °C. According to preliminary calculations and conducted thermal vacuum tests of this should not occur.

Thermovacuum tests were carried out on the TVU400-05 experimental station of the experimental base of the JSRC “Progress” in 2012 in order to confirm the calculations of the thermal balance of the ICA “AIST” [5]. The thermal effects of outer space were simulated by screens having a degree of blackness ≥ 0.9 and cooled in the process of testing with liquid nitrogen to a temperature of minus 180 (± 10) ° C. Based on a comparison of the available data on the thermal vacuum tests and TMI data obtained with the GCC, it can be concluded that there is a discrepancy between the predicted and the observed temperature on board the SS. The revealed discrepancy could be attributed to inaccuracies in the simulation of flight conditions, in particular the magnitude of the heat fluxes. First of all, the assumptions relate to the TVU400-05, which, to create a heat flux, incorporates only infrared radiation simulators, which were used to create the net effect of external heat fluxes. In order to carry out tests that are closest to the conditions of outer space, the installation should contain simulators of the Sun. Otherwise, it is necessary to increase the power and time of exposure to simulators of infrared radiation. Thus, the approach to conducting thermal vacuum tests requires more detailed study and refinement.

The outer surface of the aluminum honeycomb, including the panel + X, was subjected to chemical polishing treatment during the manufacturing process. It was suggested that this type of coating is one of the reasons for the systematic overheating of the SS hull. To confirm this hypothesis, a thermal mathematical model of the “AIST” SS was built using the Siemens NX software package with the integrated NX Space Systems Thermal Simulation module [6]. Figure 3 presents an example of the thermal calculation of the + X panel, aimed at identifying the most suitable coating for the outer surface of the “AIST” SS. Figure 3a shows the + X panel, which has a surface that has been chemically polished, and figure 3b shows the + X panel, which has a surface coated with an EKOM-2 thermal control coating.



a) b)

Figure 3. Thermal model of the “AIST” SS: a – chemical polishing of the +X panel; b – EKOM-2 thermal control coating of the +X panel.

With the same initial data and orientation of the SS panel + X on the Sun, the maximum temperature value in the case of chemical polishing is higher by 67 ° C.

The simulation results demonstrate that the use of the ECOM-2 thermal control coating for the treatment of the external surfaces of the SS “AIST” hull panels is more preferable in order to ensure uniform heat distribution over the MCA surface.

Throughout the entire period of operation, especially in the shadowless periods, the “AIST” satellites overheat and function in such a state for long periods of time. This is confirmed by the TMI. Figure 4 shows the readings of the TR1, TR10 and TR16 sensors installed on the –Z panel for 2014 for the RSA-41a. The TR1 sensor is installed on the inside of the panel, next to the electromagnet (EM) of the MAGKOM system, the TR10 is also located on the inside of the panel on the plate holding the battery, TR16 is fixed on the outside of the panel.

After analyzing the graphs obtained from TMI of the temperature sensors, it can be seen that the temperature of the external panels of the SS did not fall below 10 ° C, the upper limit of the temperature readings was within + 65 ° C (maximum value + 83 ° C), except for the panel + X. The temperature of the panel + X, as mentioned earlier, is significantly different from the other panels. Its maximum temperature reached almost 100 ° C, and the minimum - 60 ° C. As for the internal temperature of the apparatus, it also varies from +10 to + 65 ° C. Battery unit and the block of radio equipment had a temperature from +10 to + 63 ° C.

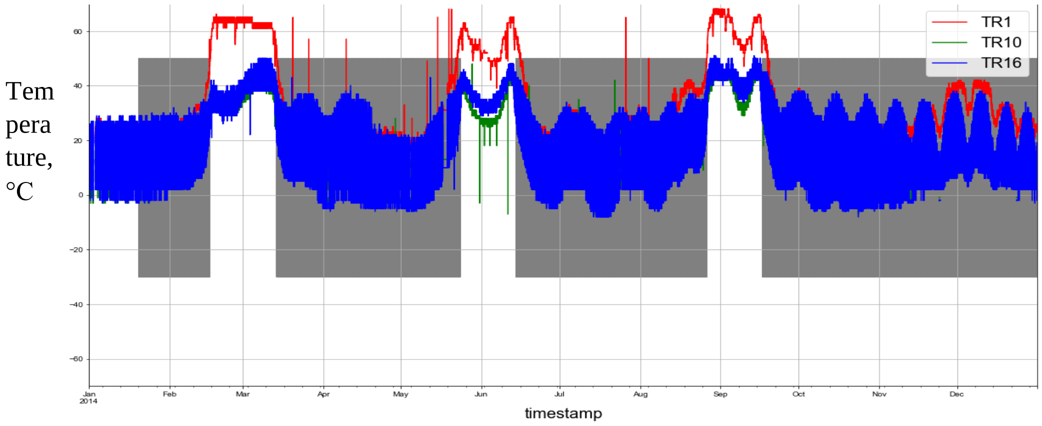


Figure 4. Readings of the TR1, TR10 and TR16 thermal sensors, mounted on the -Z panel of the "AIST" RS-41at small satellite.

Estimation of average temperatures along the edges of both devices shows that the SS "AIST" (RS-43as) that is operating in orbit with an inclination of 64.9 ° heats up by 3-5 ° C higher than the "AIST" (RS-41at), located in a polar orbit with an inclination of 82.4 °.

The telemetry analysis allows to make the following conclusions:

1. when conducting thermal vacuum tests that serve to verify the calculations, it is necessary to more accurately simulate the operating conditions and increase the power of infrared emitters, the introduction of solar simulators working in the optical range of the spectrum to ensure that heat flux close to real;
2. additional measures to dissipate heat from the SS are necessary for future use of the "AIST" platform:
    - increase the surface area for heat removal by transferring the photovoltaic arrays to folding external panels;
    - change the surface coating of the satellite to a coating with more suitable thermal radiation characteristics, which allow to remove and reflect as much heat as possible while staying on the Sun and keep it warm when in the shade;
    - increase the heat removal from the onboard equipment to the thermal boards;
    - ensure heat transfer by heat pipes between adjacent panels;
    - reduce the speed of SS rotation, or ensure its oriented flight.
3. the results of the analysis confirm the possibility and efficiency of using TMI data to improve the ground-based experimental testing of small satellites.

5. Conclusion

An analysis of TMI acquired during operation of the "AIST" SS constellation was carried out. It allowed to identify emergency situations onboard of the satellites and to point out inaccuracies in the original method of power balance calculation.

The influence of light and shade conditions on the PSS of the satellite was implemented into the power planning algorithm, allowing to increase the satellite's payload operation time and exclude ES caused by power shortage.

Modeling of the thermal modes of the satellite and comparing the results obtained with the TMI readings allowed us to determine a more suitable coating for the honeycomb panels, eliminating systematic overheating, identify the shortcomings of the thermal vacuum testing methods, and make recommendations for improving the thermal control system of the "AIST" small satellite.

6. References

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