SPECIFIC FEATURES OF MATHEMATICAL AND EXPERIMENTAL MODELING OF COMBINED HEAT TRANSFER IN THE APPARATUES OF REMOTE PROBING OF THE EARTH

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INTRODUCTION

In the present paper the results of the development of the schematic diagram and the specific features of calculation of the basic elements of the thermal regime provision system (TRPS) for the target-oriented equipment (TOE) of a spacecraft (SC) for remote probing of the Earth BelKA (fig.1) are presented. Initially it was contemplated to create TOE as an autonomous mono block with its own TRPS, connected with SC only by information and power channels.

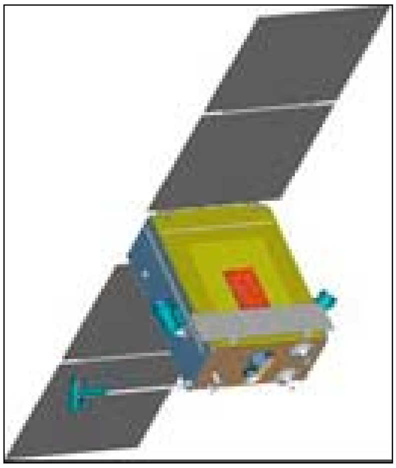

Fig. 1 General view of SC and TOE

In selecting the basic scheme of the thermal regulation system it was necessary to take into account the requirements as to the provision of the reliability of TOE, according to which the temperature drop over the basic elements of optical systems must not exceed ±2^{o}C with consideration for changes in the ambient radiation situation and at different initial and boundary-value conditions that determine the complex radiative-conductive heat transfer in the elements of the TRPS of the TOE.

1. THE BASIC DIAGRAM OF TRPS AND THE SPECIFIC FEATURES OF THE THERMAL REGIMES OF TOE

The target-oriented equipment of BelKA is an autonomous monoblock (Fig. 2) that includes two optical digital devices, assembled on a frame, for remote probing of the Earth (a panchromatic survey system (PSS) and a multizonal survey system (MZSS)), two electronic blocks of focal plane (one for each optical device), and an on-board information system (BIS). The monoblock has an autonomous thermal regime provision. As is known, the TRPS is intended both for removing the excess heat that releases during on-board equipment operation for the purpose of keeping the temperature variation of TOE elements in permitted limits and of compensating heat losses through the open apertures of the optical devices and for providing permanent and homogenous temperature of the latter within the above indicated rather rigid limits. The principle of operation of the TRPS is based on sustaining the thermal balance, averaged by orbital period of SC revolution, for each basic elements of the TOE by releasing excess heat through the radiators and apertures. The deficit of heat when the operation of the radiator causes superfluous cooling of the element is compensated with regulated heaters (in Fig. 2 they are painted light-brown).

The TRPS scheme for the SC (Fig. 3) was suggested and realized in which to decrease energy consumption by the heaters the possibility was used of smoothing the peak heat loads during the operation of electronic blocks at the expense of the thermal accumulating ability of the massive electronic blocks of the focal plane due to their heat capacity.

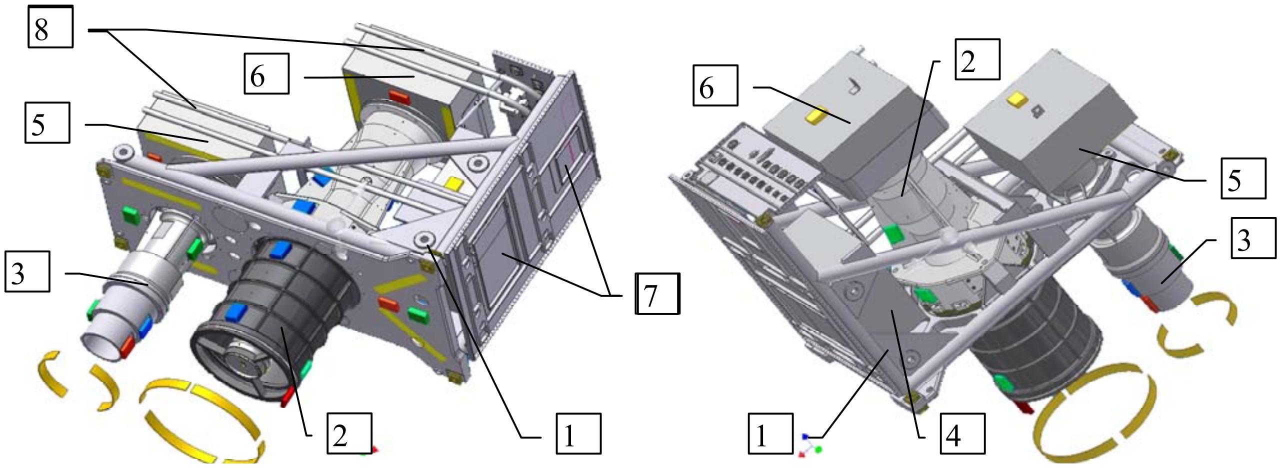

Fig. 2. External view of the target-oriented equipment monoblock (objectives blends with thermal buffers are removed). 1) monoblock frame, 2) PSS, 3) MZSS, 4) BIS, 5, 6) electronic blocks of focal plane (BFP), 7) TRPS radiators, 8) TRPS heat pipes, 9) cable coupling receptacles panel

The admissible temperature range of the electronic blocks is an order of magnitude higher than for the optic elements which allowed one, by installing special thermal resistors (pos. 2 in Fig. 3) between the zone where a regulating heater is placed and the portion of the block connected by heat pipes or conduction coupling with the radiator, to maintain the temperature of the zone 5-7 degree lower than that of the optics elements in the waiting regime of flight. This difference is sufficient for the temperature of the cooled portion in which the electrical power of the operating electronics is dissipated not to rise above the inadmissible one for optical elements in the course of the working session. Such an approach has made it possible to substantially decrease the surface areas of the radiators and correspondingly reduce the heat deficit. If during the stand-by period for electronic blocks the radiators lose heat excessively, it is compensated by the operation of the corresponding regulating heaters. In order to compensate heat losses through apertures and to sustain a more homogenous temperature for the most cooled optic elements near the apertures thermal buffers are located near of them which are devices similar to blends with controlled heaters on them. The choice of the size of the blends as well of their quantity, location and power of the heaters , installation of controlling probes was the subject of modeling of heat exchange in the BelKA equipment.

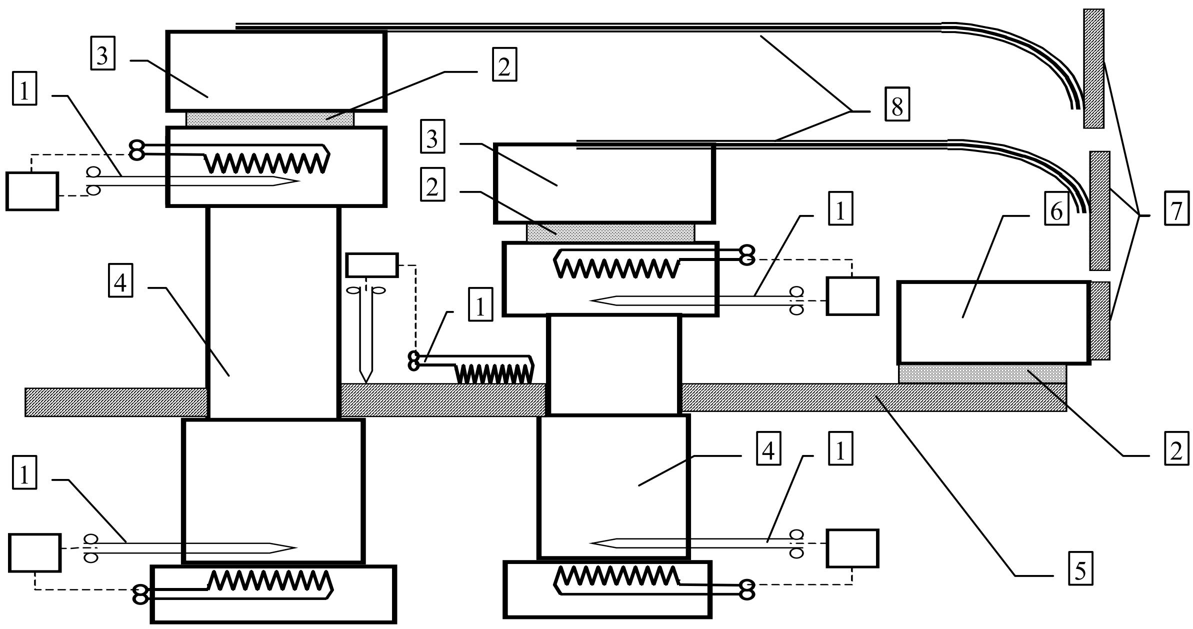

Fig. 3. Basic diagram of the HRPS of the TOE monoblock

(Location of five controlling sets of TRPS is shown: (1) heater, thermal probe and controller: at apertures, on the frame and on the TOE BFP; three thermal separations (2): between electronic blocks BFP (3) and optical devices (4), between frame (5) and BIS (6); three TRPS radiators (7) and heat pipes (8))

2. SPECIFIC FEATURES OF THE MATHEMATICAL MODEL OF THERMAL PROCESSES IN THE MONOBLOCK OF THE TOE

In calculation of the thermal processes in spacecraft usually the method of lumped parameters is used [2-4]. The essence of the method is that the entire modeled block is divided into separate discrete elements in such a way that the temperature of each element may be considered in some approximation homogenous and changing only in time. These can be separate, single relatively isolated units or parts of the block or, if the description is not precise enough, they may be divided further into several elements. According to the above, every k-th element is assigned with the single time-dependent value of temperature T_k and its average heat capacity C_k is determined according to the mass of every material composing it m_{ki} and its specific heat capacity c_{ki}:

$$C_k = \sum_{i=1}^{M_k} c_{ki} m_{ki} \ , \tag{2.1}$$

where M_k is the number of different materials in each element. Each of the elements is in conductive (heat conduction) and radiative (radiation) thermal interaction with other elements.

Conductive heat transfer between a pair of contacting elements numbered i and j is determined by the heat transfer coefficient α_{ij} according to the relation that prescribes a heat flux from the *i*-th to the *j*-th element proportionally to the temperature difference between them.

$$q_{ij}^c = \alpha_{ij}(T_i - T_j) \, . \tag{2.2}$$

The coefficient of heat transfer between a pair of elements is determined by the effective areas of the cross sections of these elements perpendicularly to heat flux direction between them S^c_i, S^c_j , the heat conduction coefficients of the materials of both elements λ_i and λ_j, and by the distance from the contact surface to corresponding mass centers l_i , l_j:

$$\alpha_{ij} = \frac{1}{\dfrac{l_i}{\lambda_i S_i^c} + \dfrac{l_j}{\lambda_j S_j^c}} \, . \tag{2.3}$$

This formula results from the law of summation of successively connected thermal resistances from the centers of masses of the elements to the contact surface, where the thermal resistances are defined as

$$R_i = \frac{l_i}{\lambda_i}, \qquad R_j = \frac{l_j}{\lambda_j}, \qquad R_{ij} = \frac{1}{\alpha_{ij}} \, . \tag{2.4}$$

If there is no ideal thermal contact between the elements (for instance, there is a gasket , no tight fitting and so on), then the additional contact resistance R^c_{ij} is introduced into (2.3):

$$\alpha_{ij} = \frac{1}{\dfrac{l_i}{\lambda_i S_i^c} + \dfrac{l_j}{\lambda_j S_j^c} + R_{ij}^c} \, , \tag{2.5}$$

For instance, in the case of a gasket between the elements the additional thermal resistance is expressed as

$$R_{ij}^{c} = \frac{d}{\lambda_c S_{ij}}, \tag{2.6}$$

where, d is the gasket thickness , λ_c is the thermal conductivity of the gasket material, and S_{ij} is the gasket area.

Heat transfer by radiation. A heat flux between two elements due to radiative heat transfer between them is described by the relation

$$q_{ij} = \varepsilon_{eff} A_{ij} \sigma \left(T_i^4 - T_j^{\,4} \right), \tag{2.7}$$

where σ is the Stefan-Boltzmann constant, ε_{eff} is the effective emissivity of the element surface, and A_{ij} is the dimensional mutual angle factor between the surfaces that describes the relative intensity of radiation heat transfer between them. This coefficient is defined as

$$A_{ij} = A_{ji} = S_i F_{ij} = S_j F_{ji}, \tag{2.8}$$

Here S_i and S_j are the areas of the emitting and mutually visible surfaces of the corresponding elements and F_{ij} is the dimensionless angle factor that describes the portion of heat flux emitted from the i-th surface and incident on the j-th surface. The last equation sign in (2.8) follows from the reciprocal relation for the angle factors [4]. Calculation of angle factors between the elements of curved surfaces is a rather complex part in modeling radiative heat transfer, since apart from the usually tedious procedure of calculation of the factors themselves it is necessary that their matrix should satisfy certain requirements such as reciprocal relation (2.8) and the condition of the balance between factors for a set of the surfaces that form a spatially closed system (resulting from the requirement of balance of the heat fluxes[4]). For this reason, for complex configurations, when many coefficients are to be calculated approximately, there may appear the necessity in iteration procedure to fit the entire matrix to meet these requirements. To calculate angle factors in some typical configurations of mutually emitting surfaces the formulas given in [1] were used.

Some of the specific features of the model are due to the presence of EIHTR. Heat transfer of open EIHTR of the TOE elements with the surfaces of the SC is described by a relation similar to Eq. (2.7) with the only difference that the j-th temperature is the average temperature of the inner surfaces of the SC T_{SC}. To calculate the heat flux from the elements of closed EIHTR to the inner surfaces of the SC the following formula was applied:

$$q_{i0} = \frac{1}{r_e} S_i^{Э} (T_i - T_S), \tag{2.9}$$

where, r_e is the specific (per area unit) thermal resistance of the EIHTR of TOE (according to the specifications, its value was adopted equal to about 10 (m^2 K/W).

In addition to the heat fluxes caused by heat transfer between the elements, some of them are influenced by fluxes from outside (Earth, SC elements, outer space) that here must be considered as given functions of time Q^0_i (t) dependent on the orbital trajectory of the SC and its orientation.

An important element of the mathematical model of the thermal processes occurring the monoblock of TOE is the modeling of the thermal regulation system. It is accepted that regulation is realized by the control system according to the following algorithm : "if the probe temperature decreases below the lower limit of admissible temperatures $T_s - \Delta T_0$ and a heater is not switched on , it is switched on and remains switched on until the probe temperature exceeds the upper limit of the admissible temperatures $T_s + \Delta T_o$; if the probe temperature increases above $T_s + \Delta T_0$ and the heater is switched on , it is switched off and remains switched off until the probe temperature falls lower than $T_s - \Delta T_0$ ".

With this regulation algorithm the heater power cannot be given as a determined function of temperature, since in the temperature range ($T_s - \Delta T_0$, $T_s + \Delta T_0$) the heater may be both switched off or switched on depending on its prehistory. Since for numerical realization of the mathematical model a universal computational packet was used with standard procedures for solving differential equations, direct programming of this algorithm inside the standard procedure turned out impossible. For this reason, for modeling a dynamic model has been developed similar to the trigger model, and the procedure of computation of thermal processes occurring in the monoblock was modified in a such way as to include this model.

The mentioned modification comes to the following. Each module of the mathematical model that includes a controlling feedback for a thermally stabilized element is supplemented with one other dynamic variable H(t) and an evolution equation for it. This variable varies in the range of [0, 1] and has the meaning of a portion of heat power emitted in the controlling heater of its nominal value. The evolution equation for H has the form

$$\frac{dH}{dt} = F(H, T_k), \tag{2.10}$$

where k is the number of computational element on which a temperature probe of TRPS is fixed , T_k is the temperature of the k-th element, and the function F is defined as

$$F(H,T) = \begin{cases} -Hb_r & \text{если} \quad T > T_s + \Delta T_0 \\ -(H-1)b_r & \text{если} \quad T < T_s - \Delta T_0 \\ -Hb_r & \text{если} \quad T_s - \Delta T_0 \le T \le T_s + \Delta T_0 \quad \text{и} \quad H \le 0{,}5 \\ -(H-1)b_r & \text{если} \quad T_s - \Delta T_0 \le T \le T_s + \Delta T_0 \quad \text{и} \quad H > 0{,}5 \end{cases}. \tag{2.11}$$

Here b_r is the fitting parameter for the calculating algorithm and has the value close to 0,5. Moreover, the TRPS heater power controlled by the probe fixed on the k-th element is given as a function of time as follows:

$$q_{CTP}(t) = P_c H(t), \tag{2.12}$$

The essence of the dynamic system (2.10), (2.11) can be most clearly clarified if one considers its following physical interpretation. The dynamic variable H (t) can be interpreted as the coordinate of a material point having no mass and moving in a viscous medium under the action of a potential force. The potential, the gradient of which (force) is described by function (2.11) depends in addition to the coordinate H also on the external parameter T (in our case this is the controlling temperature).

When $T > T_s + \Delta T_0$, it has the form of a parabolic potential well with a minimum at the point H = 0, therefore at this temperature the system is at rest at the point with the coordinate H = 0. When $T < T_s - \Delta T_0$, the function F has the form of the potential well with a minimum at the point H = 1, therefore the system is at rest at this point.

When $T_s - \Delta T_0 < T < T_s + \Delta T_0$, the potential represents two parabolic potential wells with minima at the points H = 0 and H = 1, "sewed " at the point H = 0.5. In such a system, the point is mainly motionless in one of the potential wells (that is, H has a value of 0 or 1). When the temperature parameter crosses one of the limit values of the given temperature range, the well that corresponds to the state in which the system must not be at this temperature disappears and the point under the action of the force arising as a result of this rearrangement of the potential point shifts during a short period of time into the other well if it was not there before. Such a behavior completely corresponds to the required algorithm that describes the control of the TRPS heaters.

The parameter b_r has the meaning of the steepness of potential wells and is the fitting parameter that controls the rate of the transition process. As a result, according to (2.12) the heating power of thermal stabilizing element takes the value of 0 or P_c, which corresponds to the state the switch being on or off.

To calculate the thermal processes and optimize the TRPS structure of TOE on the basis of the method of lumped parameters [1, 2] a mathematical model of the thermal processes in the TOE monoblock has been developed, which is characterized by the following main features:

- the model reflects the entire configuration of the monoblock as presented in Figs. 2 and 3 and includes its main components: the frame, both optical devices with their TRPS, the focal plane of optical devices with corresponding TRPS, the on-board information system and TRPS of the monoblock frame . The model reflects the principal conductive and radiative thermal mutual links between the components ;

- the model is constructed on the module principle: individual components of the monoblock are modeled by relatively independent program modules. They can be adjusted and tested independently of the others. The modules have ports for transferring data to model connections between the monoblock components and the influence of outside conditions. After the adjusting of the modules, the model is assembled by creating an assembled program block with adjusted connections between the ports of individual modules and with consideration for external influences;
- in the model a rather detailed division of the monoblock components into computational components is used, which permits ensuring its information capability and adequacy;
- the model includes a universal block for calculation of external thermal loads on the TOE elements for orbital and inertial SC orientation in its orbit.

3. SCHEMATIC DIAGRAM OF THE IMITATION OF THE ORBITAL CONDITIONS FOR THE TOE OF BelKA

In creating the apparatuses for remote probing of the Earth the results of the modeling of TPRS must be confirmed by thermal vacuum tests on ground-based TOE units.

For this purpose, at the Laboratory of Porous Media of the A.V. Liukov Heat and Mass Transfer Institute an experimental bench was created permitting one to imitate the thermal regimes of TOE characteristic for orbital flight of the Belarusian spacecraft . The bench consists of a barochamber with a total volume of about 10 m^3, equipped with radiation screens-imitators, a cryogenic cooling system, and measuring, data collection and control systems (Fig. 4).

Fig. 4. TRKI-4m nitrogen tanks and the fixtures of the system of cooling of barochamber screen-imitators of the HMTI for thermal vacuum tests of the TRPS TOE of BelKA

The test barochamber has to be equipped with thermal elements that imitate radiative fluxes to the SC elements not protected by insulation. Such elements are aperture orifices of optical devices and TRPS radiators. Due to the given SC orientation regime, these elements during the entire revolution are not subjected to direct radiation from the Sun and experience only the influence of the Sun rays reflected from the Earth on that part of the orbit, where the lighted portion of the planet is seen from the SC. The TRPS radiators also experience the influence of thermal radiation from the back side of the Sun collector whose calculated temperature during the entire circuit is known. Detailed imitation of the influence of radiation on the SC would require the creation of:

a) an imitation model of the intrinsic emission of the earth’s disc seen from irradiated elements in the solid angle of the same magnitude as that of the Earth from the orbit;

b) an imitation model of the flux of the Sun radiation reflected by the Earth from its lighted portion with consideration for the lighted zone phases;

c) cryogenic screens that imitate radiation conditions of open space thermal radiation;

d) an imitating model of the thermal radiation of the Sun collector back side on the TRPS SC radiator;

e) a control system of relative orientation of the radiated elements and radiation imitators from the surrounding space that models the SC orientation relative to the Earth and Sun on the orbit during the entire circuit.

However, the situation in our case is simplified by the fact that the SC orientation on the orbit is comparably simple so that, for instance, the solid angle of the surface earth disc seen from the TRPS radiator and its angle factor remain constant in value during the entire circuit and only the direction of radiation flow is changed. Still another simplification as concerns the radiators is the fact that for them only the general thermal balance is essential rather than the distribution of the heat flux over the surface. Moreover, due to specific coating the radiator surface is little sensitive to reflected solar radiation. Since the coefficient of solar radiation absorption for the radiators coating is rather small (A_0 = 0.12), the fraction q_s of solar radiation in the total heat flux absorbed by a radiator (from the Earth and from the Sun collector) can be calculated according to formula (3.1) as

$$q_S(t) = \frac{A_0\varphi_2\left(\frac{\pi}{2},\omega t\right)aS_0}{A_0\varphi_2\left(\frac{\pi}{2},\omega t\right)aS_0 + \varepsilon_0\varphi_1\left(\frac{\pi}{2}\right)\frac{(1-a)}{4}S_0 + \varphi_{\text{рад}}\varepsilon_0\sigma T_{\text{б}}(t)^4}, \tag{3.1}$$

where α is the Earth albedo , S_0 is the solar constant, ω the angle velocity of orbital revolution, t the time, ε_0 the emissivity of the radiator , σ the Stefan-Boltzmann constant, T_b the temperature of the battery, φ_2, φ_1, and φ_{rad} are the angle factors relative to the radiator respectively of the portion of the seen earth disc lighted by the Sun, of the entire seen earth disc, and of the battery. Calculations have shown that a maximum fraction of solar radiation in the heat flux to the radiator does not exceed 12%, whereas the average, for period of revolution, fraction composes only 4% . This means that there is no need in detailed modeling of the effect of reflected solar radiation on the radiator and that the heat flux conditioned by this influence may be taken into account with specially temperature correcting model of the element that simulates the thermal radiation of the Earth.

Based on these calculations, a screen was developed (Fig. 5) that imitates the effective thermal influence on the radiators of the TOE thermal regulation system, equivalent to Earth radiation, Sun collector radiation, and that of the open space . According to calculations (cycle diagram is given below), for the cooling screen from ambient temperature to minimal (T = 183 K), nitrogen was used flowing from motionless cryogenic screen. The heating of the imitator is provided by KH 220-1000-6 halogen emitters and is controlled by temperature and heat flux probes.

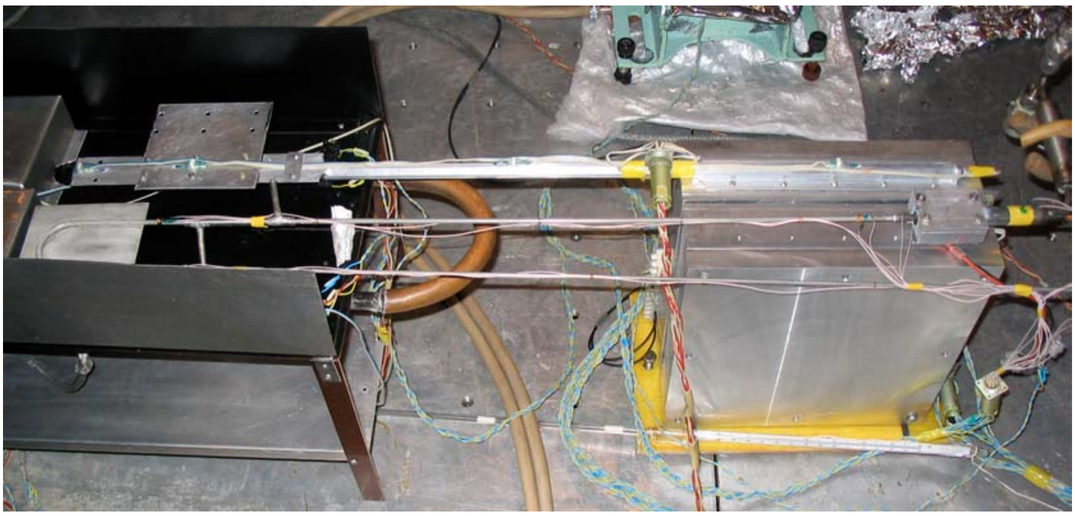

Fig. 5. Radiation screen-imitator of radiation on TOE TRPS radiators (1) and BFP mass size model (2) with heat pipes (3)

For imitation of the open space radiation on objectives a cryogenic fixed screen is used (Fig. 6) cooled by liquid nitrogen. On the concave side of the screen, the width, height, and the depth of which compose 815x900x640 mm, a special coating is applied with a high emissivity ($\varepsilon_{\theta} \geq 0.93$) . The supply of the cooling agent to the cryogenic screen is made from TRKJ-4m nitrogen tanks . The enthalpy of vaporized nitrogen is utilized in the trap for system protection from oil vapor penetration into the chamber. This scheme ensures practically uniform surface temperature equal to the liquid nitrogen boiling temperature (T = 100 K)

Fig. 6. Cryogenic (fixed) screen for imitation of the open space radiation i (1) and the cryogenic trap (2)

Modeling of radiative fluxes to the aperture orifices of the TOE optical devices is more complicated because they are oriented on the orbit in a such way that the Earth angle factor φ_1 relative to them changes during the circuit from a maximum value of $\varphi_1^{max} = 0.857$ to a minimal one of $\varphi_1^{min} = 0.12$. This occurs because the seen earth disc shifts relative to the aperture plane and on some portions appears beyond the “horizon” . The direction of the radiative flux changes so that radiation falls on different portions of the blends and optical elements. Such specific features must be modeled by an imitation system for heat fluxes. This means that the imitator of the radiation fluxes of the Earth must be motionless so that its angle factor relative to the aperture orifices could change in correspondence with the graph in Fig. 7.

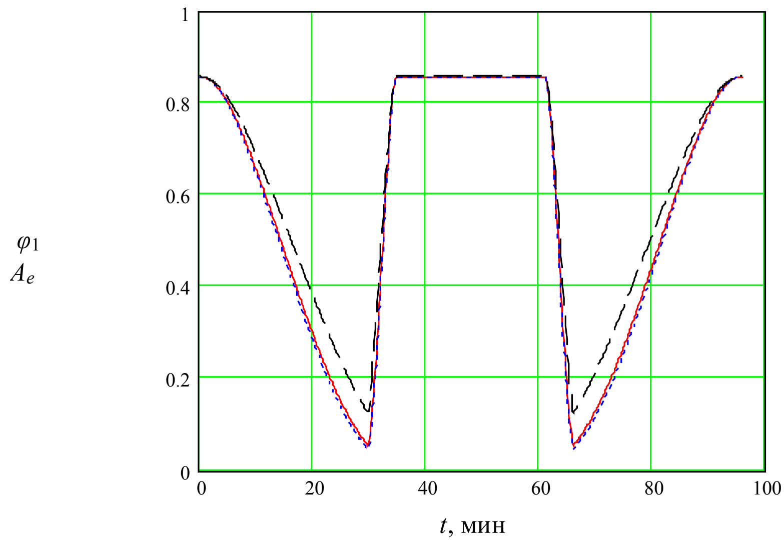

Fig. 7. Comparison of the angle factors of the Earth (solid line), of the screen in the case of the orientation similar with the Earth relative to the aperture plane at each moment of time (dotted line), and of the screen with corrected orientation (dash-dotted line) .

A rotatable radiation screen (Fig. 8) that emits in the infrared spectral range represents a segment of a cylindrical surface 660x840x180mm; it is located coaxially with the fixed cryogenic screen. It simultaneously imitates the radiation from the Earth composed of the intrinsic and reflected radiation and a change in the SC orientation relative to the Earth during its motion in the orbit.

Fig. 8. Rotatable screen-imitator of terrestrial thermal radiation on the aperture orifice of the TOE optical devices

The revolving device of the rotatable screen is based on a DSI-200-3 step motor , SMC-3000a controller, and SPS-5A power supply source. As technological heating elements, three rows of halogen lamps are used working at lowered voltage for preventing overheating in vacuum. They are installed near the cord plane on the concave side of the screen parallel to the generatrix of its cylindrical surface. The radiation from the lamps is directed onto the object by reflectors composed of three plane elements. The radiation intensity corresponding to the infrared load from the seen Earth’s surface is regulated by the temperature of the screen-imitator. The temperature, in its turn, is determined by the thermal balance caused as a result of the heating of the screen concave surface by incident radiation from the lamps and cooling due to its secondary emission from both surfaces to the ambient. On switching off of the heating lamps, as a result of radiation heat exchange of the outer surface with the fixed cryogenic screen, this temperature quickly falls, which permits one to control it according to calculation cycle diagrams in the necessary limits – from 250 to 340 K.

During the whole cycle of thermal vacuum tests an automatic system that controls the test object, barochamber, screen-imitators, and the apparatus for data collection realizes continuous control and registration of the execution by the imitators of external thermal influences on the given cycle diagram with required precision. To measure temperature, thin film platinum probes are used. Radiant heat fluxes are controlled by heat flow probes of original construction. The control system (program) ensures continuous recording of information on an electronic carrier and representation, on the monitor screen in real time regime, of given and realized cycle diagram parameters of TOE functioning in different regimes in orbital conditions.

To attain successful ground experimental adjustment of the on board optical-electronic apparatus of “BelKA”, the possibility of modeling, in the barochamber with the aid of prepared imitators, of different regular and extreme regimes of thermal vacuum test corresponding to the orbital flight conditions was verified. The sum test time composes from 96 min (one circuit) to several days and includes the following stages: pumping out of the barochamber to the needed vacuum, cooling of the cryogenic screens system by liquid nitrogen, attainment of a quasi-stationary thermal regime by the test object, execution of flight task, measurement of main characteristics, heating of the cryogenic screens , and chamber depressurization.

Below, calculated and experimental cycle diagrams are given for the working survey regime (Fig. 9). It is obvious that the developed apparatuses practically exactly reproduce the natural laws governing the change in the characteristic temperature and turning angles that correspond to the orbital flight conditions of “BelKA” and on-board TOE exploitation. Negligible difference was observed only for the temperature of rotatable screen at deflection angles close to $\pm 90^{o}$.

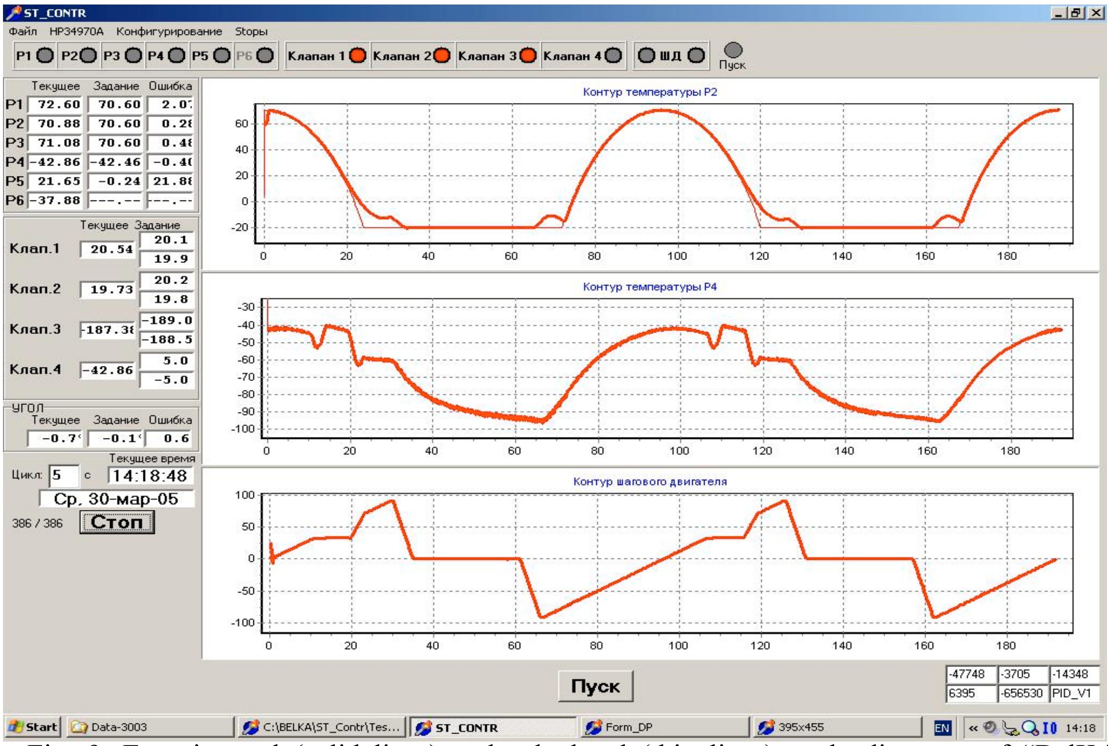

Fig. 9. Experimental (solid lines) and calculated (thin lines) cycle diagrams of “BelKA” orbital flight conditions thermal imitators (two circles, survey regime) on the display of a controlling computer

4. RESULTS OF MATHEMATICAL SIMULATION OF THERMAL PROCESSES IN THE TOE MONOBLOCK

At a preliminary stage of modeling, thermal calculations with different variants for the TOE monoblock constructive realization were conducted on the basis of which the optimal constructive parameters of the TRPS elements were determined. After this, when the mono block construction was finally formed, the numerical simulation of the thermal regimes in different conditions of testing of the mathematic model for balance (Fig. 10) as well orbital flight orientation (Figs. 11–16) was performed.

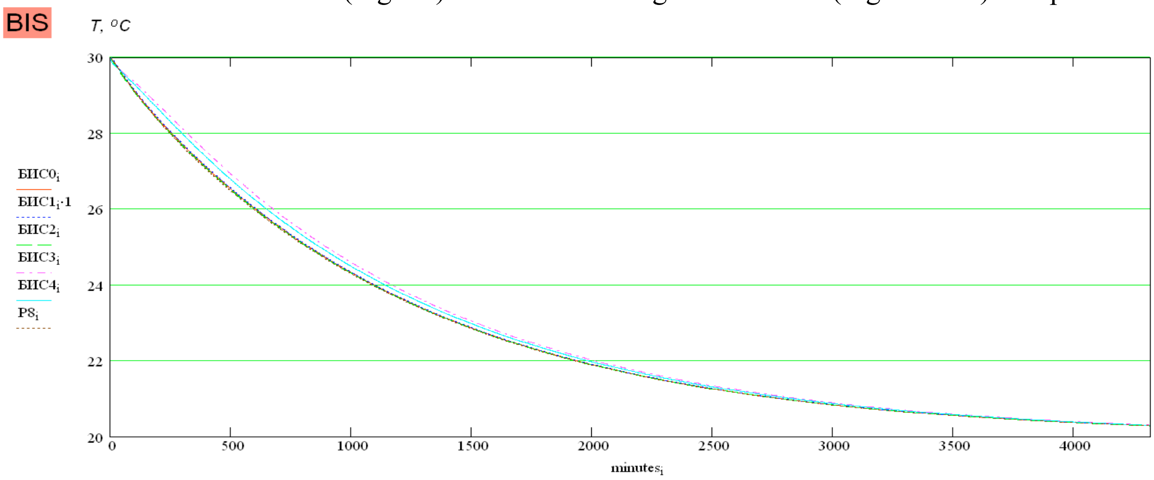

Fig. 10. Testing of the mathematical model for balance. The monoblock BIS elements temperature at zero power of heat emission and exchange of all external flows with heat transfer with the ambient at a temperature of 20 °C . Initial temperature is 30 °C

In Figs. 11 a, b the calculation results are given for the case of 24 h flight with a “cold start”. In this test, the initial temperature was given for all the elements to be equal to 0°C, and all external fluxes on the elements were determined by flight in duty regime with the orbital SC orientation and heat transfer with SC body temperature of 0°C. It follows from the data presented that the temperature of all the elements are established with small oscillations about some average values during approximately 400-900 minutes from the inception of the reading for different blocks.

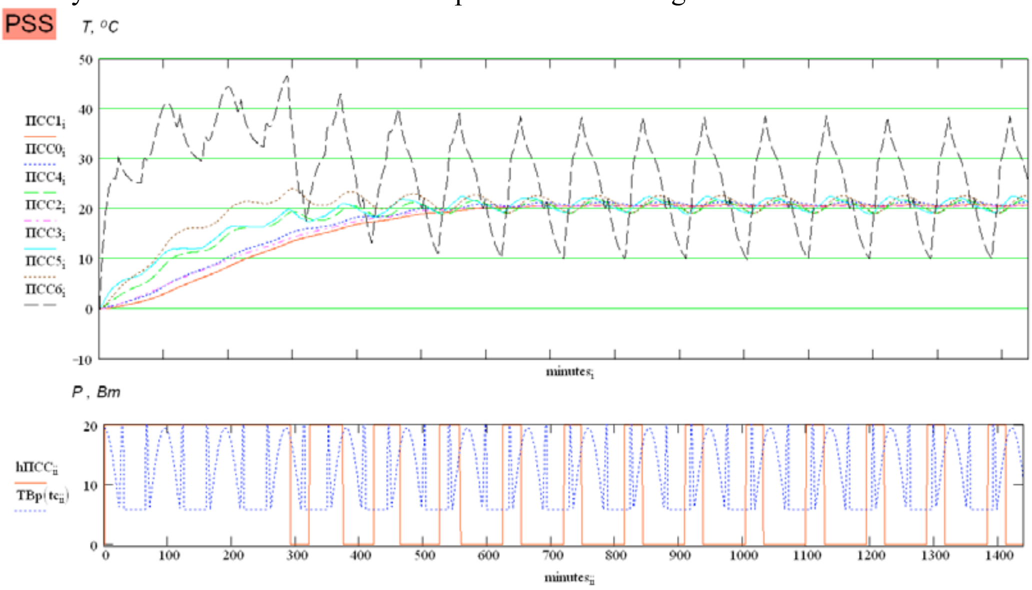

Fig. 11 a. Emergence of the thermal regime to a stable state after a “cold” start. The temperature of the PSS module elements. On the lower diagram there is the cycle diagram of TRPS heaters, PSS thermal buffer and external flow in aperture (flow minimum corresponds to the shadow period)

The operation of the TRPS heaters is modeled by control function (2.11) in which it is accepted that $\Delta T_0 = 0{,}5\ ^{o}C$.

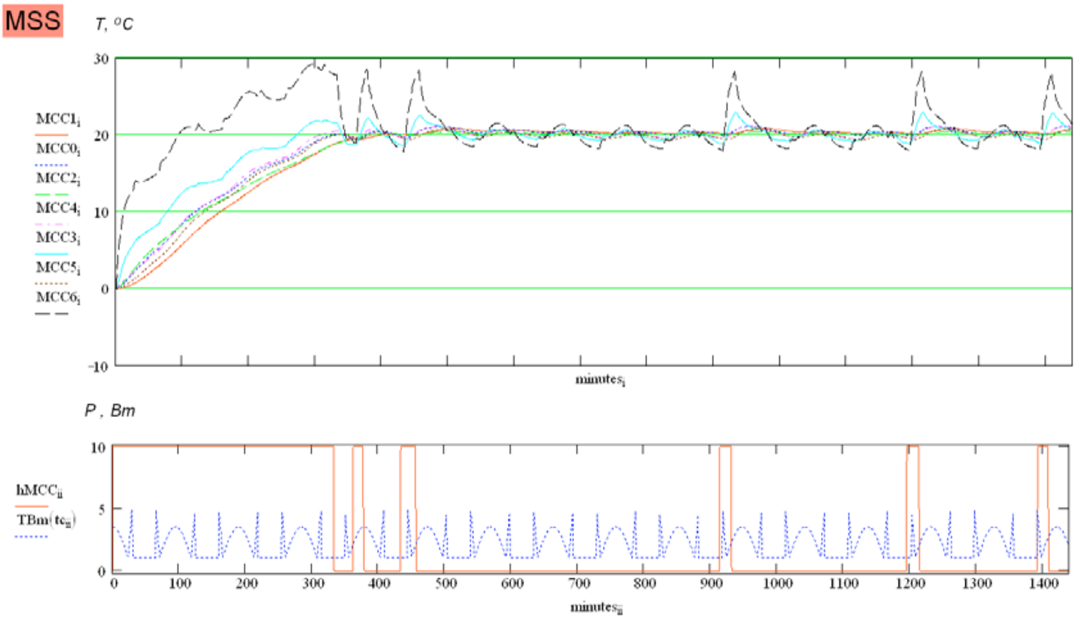

Fig. 11 b. Emergence of the thermal regime to a stable state after a “cold” start. The temperature of the MZSS module elements. On the lower diagram there is the cycle diagram of TRPS heaters for thermal buffer and cycle diagram of external flows in the aperture

In Fig. 18 calculation results are presented for the cases of 24 h flight after a “hot” start. In this test, the initial temperature was given equal to 30 ^{o}C for all elements, then all external fluxes on the elements were determined by flight in duty regime with SA orbital orientation and heat transfer with SC body temperature of 30 ^{o}C.

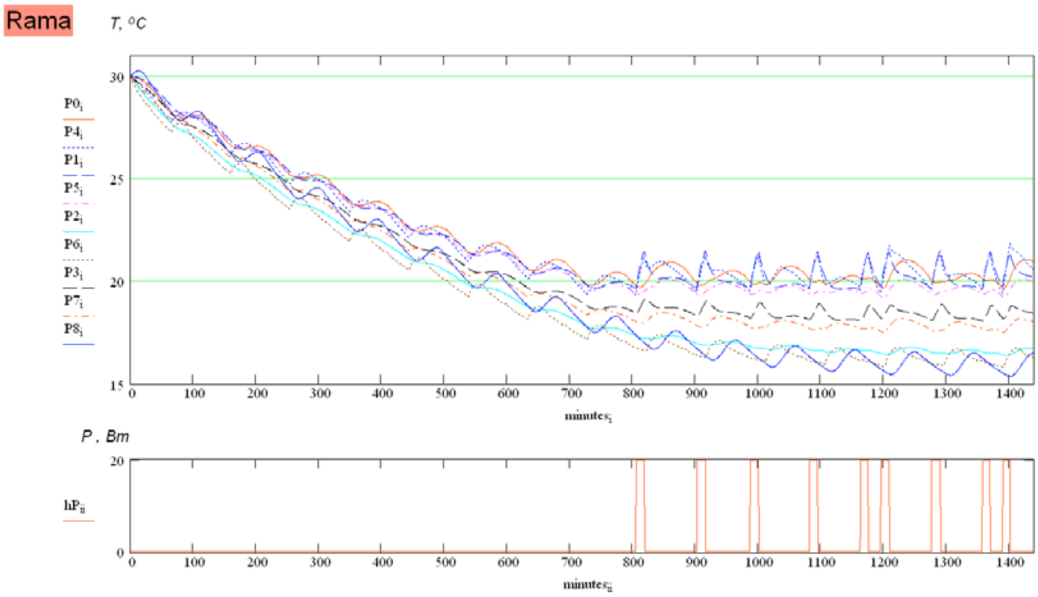

Fig. 12. Emergence of the thermal regime to a stable state after a “hot” start . Temperature of frame module elements. Initial temperature of SC module elements is 30°C. On the lower diagram there is the cycle diagram of the operation of the frame TRPS heaters

Unlike the “cold” start, the temperatures of the elements are established also with small oscillations about some values, but already during approximately 700-1200 minutes from the inception of the reading for various blocks. The average power of the operation of the TRPS heaters is seemingly lower.

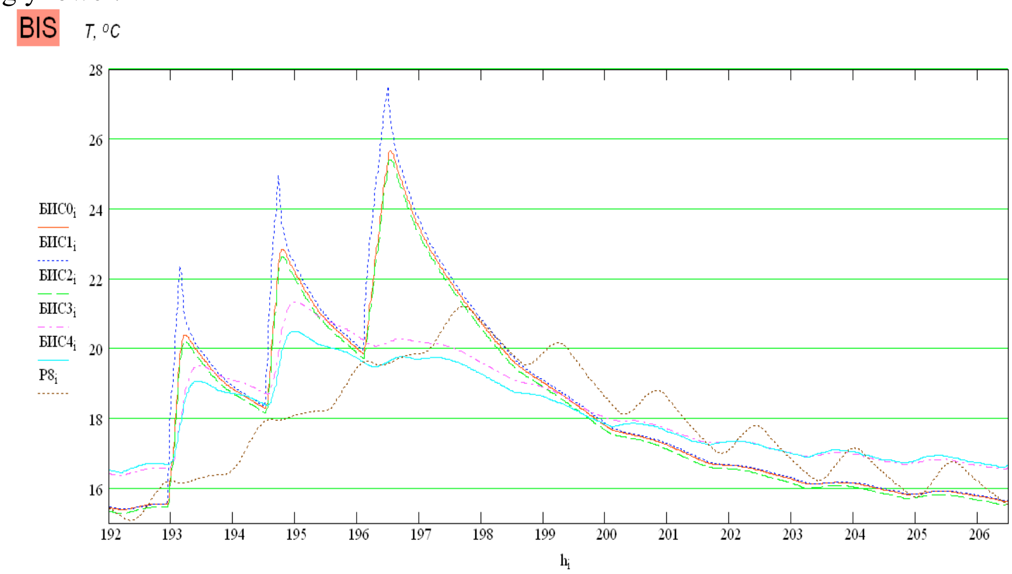

Fig. 13. The first 9 circuits after TOE switching on and the beginning of flight with a series of work séances that began from the stable duty regime at normal temperature of the SC body. The temperature of the BIS module elements. The working regime, orbital orientation, SC body temperature $T_{SC} = 20\ ^{o}C$

In Fig. 13 calculation results are presented at the same conditions as in the previous figures but for the working regime (series of two survey séances and one séance of data transfer during 24 h). The calculations were performed for the case of the regime attained during about 8 days of flight after the first circuits from the inception of the reading. From these data it follows that the principle of accumulation of the heat, emitted during working séances, is used in the accepted thermal regulation scheme is realized successfully due to heat capacity of the cooled components of the electronic blocks. The temperature rise during working séances nowhere exceeds the given temperature range in thermal stabilization and in a such way the TRPS is capable of keeping this temperature for the thermal stabilized zones of the SC. The average power of the heaters is seemingly lower than in the previous cases and still there is stock for power decrease.

In Fig. 14 the calculation results are presented for the thermal regime for a more thermally sressed case with temperature inside the SC body of + 40°C. In an unstable regime here one may observe only a small (1-2 °C) increase in the limit temperature of the frame elements which does not affect the meeting of the technical requirements. But the emission of power of the heaters on the frame practically stops. The total average power of all the heaters decreases approximately to 40% of the nominal value.

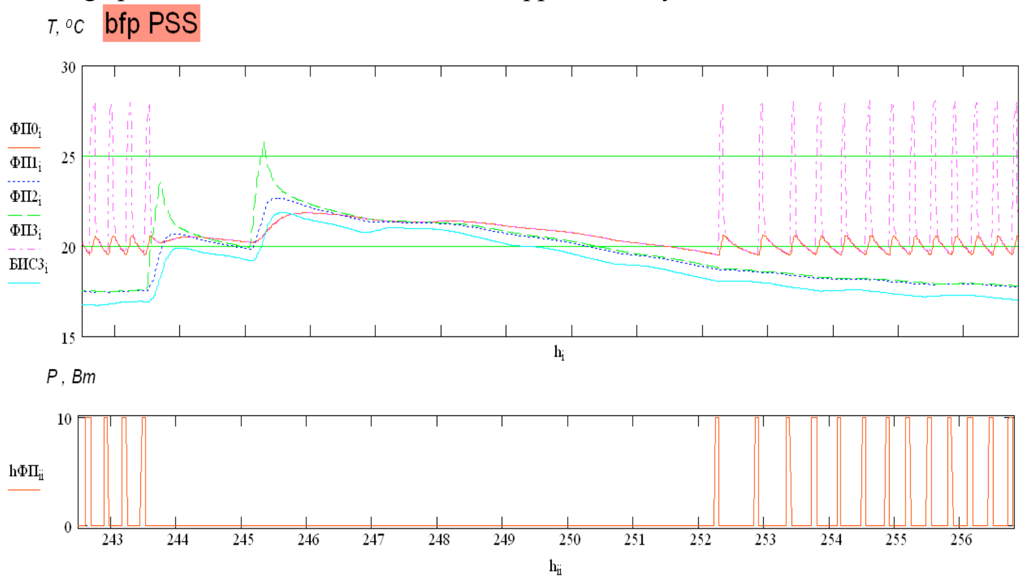

Fig. 14. The first 9 circuits of flight with a series of work séances beginning from stable duty regime with hot SC body. The temperature of BFP module elements. The working regime, orbital orientation, the temperature of the SC body T_{SC} = 40°C. On the lower diagram there is the cycle diagram of operation of TRPS heaters for BFP PSS

In Figs. 15–16 calculation data are presented for the working regimes (two survey séances and one transmittance séance during 24 h) for the case of the thermal regime established during about 8 days of flight with SC inertial orientation after the first three circuits from the beginning of the day for the “hot” case (Fig. 15) and “cold” case (Fig. 16) of the SC body. The temperature regimes satisfy the technical requirements.

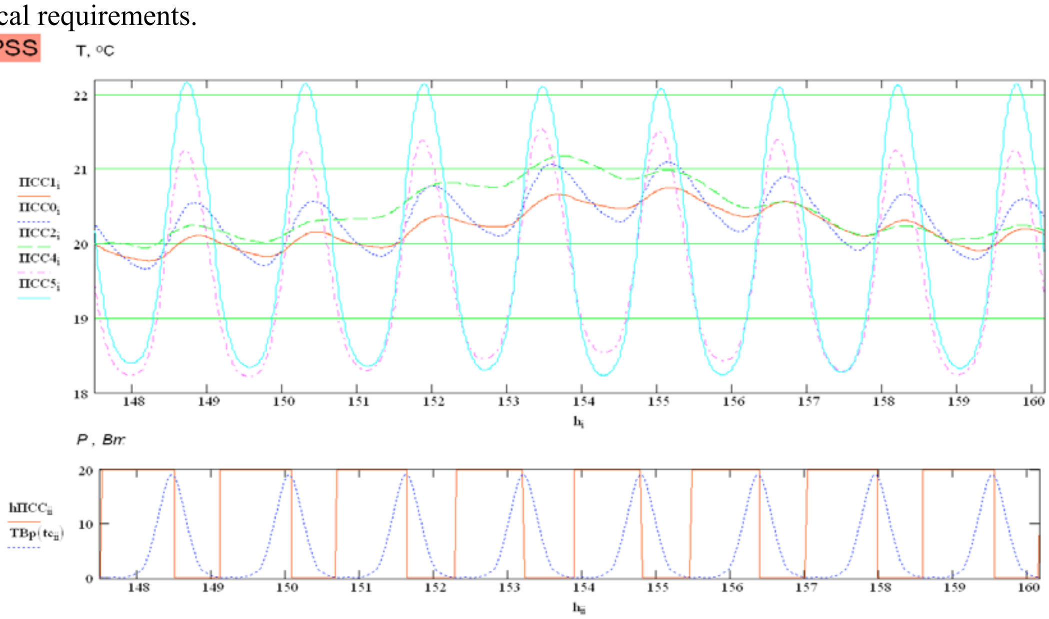

Fig. 15. The first 8 circuits of flight with a series of working séances that begin from the stable regime with the hot SC body. The temperature of PSS module optical elements. The working regime, inertial orientation, SC body temperature T_{SC} = 40°C

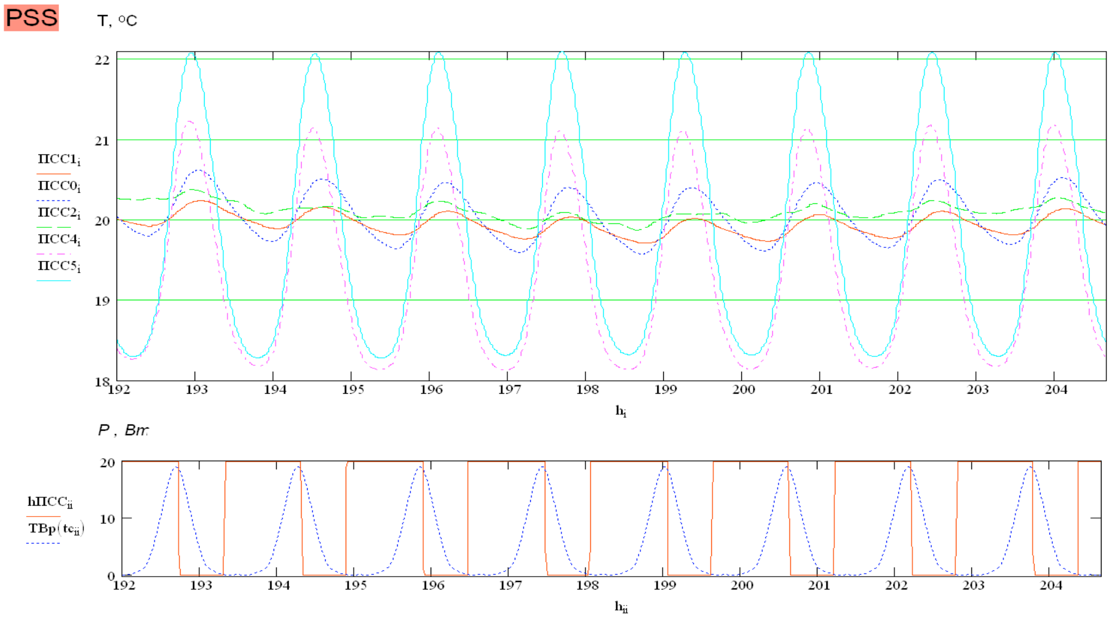

Fig. 16. The first 8 circuits of flight with a series of working séances beginning from the stable regime with a cold SC body. The temperature of PSS module optical elements. The working regime, inertial orientation , 8 circuits in a stable regime , SC body temperature T_{SA} = -10 °C

The thermal calculations on the basis of the presented model and their comparison with the results of ground tests have shown that the accepted scheme of thermal regulation and chosen constructive parameters provide a possibility of satisfying the technical requirements for the thermal regime providing in the module orbit of target-oriented equipment for spacecraft of remote probing of the Earth BelKA.

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