The method of investigation of basic project parameters of the microsatellite with ammonia propulsion system by random search

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Abstract. A large number of basic project parameters of the microsatellite with ammonia propulsion system determines the relevance of the problem of their search by method of random scanning. The aim of the work is to create a methodology of selecting the basic project parameters of the microsatellite using a calculation program adapted to the chosen method of random scanning. The mathematical model for random project parameters selects the optimal mass of the microsatellite with a propulsion system based on complex relationships investigated parameters, providing a solution to the given task microsatellite maneuvering.

1. Introduction
In a number of national and foreign microsatellites (MS) are used ammonia corrective propulsion systems (CPS) because of the possibility of obtaining high values of the specific impulse of thrust of electrothermal microthrusters (ETMT) with minimal energy consumption, for example: MS "Ugatusat" (Russia), MS "BX-2" (China), MS "Microsat" (Ukraine) [1-3].

Among a large number of MS project parameters with ammonia CPS it is possible to allocate a limited number of the most important characteristics – the basic project parameters (BPP). The optimal selection of BPP with the solution of the problem of optimization of the objective function provides the performance of tasks of orbital maneuvering of MS with given characteristic velocity and with the minimum mass expenses.

In the practice of designing rocket and space technology in multivariate parametric studies successfully used methods of random search and, in particular, the method of random scanning (MRS) [4, 5].

The novelty and practical significance of the research is due to the fact that in the practice of designing MS with ammonia CPS, the MRS method allows the selection of BPP based on the analysis of a large number of their combinations with the preservation of quasioptimal target function [5-7].

2. Formulation of the problem
In General, the problem of analysis and selection of BPP MS with CPS when using MRS is formulated as follows: to determine the values of BPP \( \{X_1, X_2, ..., X_n\} \), which provide a minimum mass of MS with CPS at realization given characteristic velocity and satisfy the system of constraints \( \{a_i, b_i\} \) on BPP:

\[
m_{\text{opt}} = \min F(X_1, X_2, ..., X_n); a_i \leq X_i \leq b_i
\] (1)

The object of the study is MS with ammonia CPS with ETMT in the mass span of 30–50 kg.

The aim of work is to study the BPP MS with ammonia CPS with ETMT using MRS (Figure 1).

The target limitation in research is the problem of orbital maneuvering of MS, presented in the form of calculated reserves of characteristic velocity.
As an BPP is considered (Figure 1): temperature and pressure in chamber ETMT $T_K$, $P_K$, diameter of critical section of nozzle $d_k$, diameter of nozzle $d_c$. As a target function, mass of MS is taken, including the mass of the CPS with propellant and mass of adaptation means (MA) of CPS in MS (Figure 1). As a MA, considered system exhibition of thrust vector ETMT for end face circuitry of CPS installation (Figure 1).

![Figure 1. The scheme for the study BPP the MS with CPS with the help MRS.](image)

As basic CPS for MS weighing 30-50 kg is accepted CPS of constant diameter developed for the nanosatellite weighing 10 kg which characteristics are provided in the table 1 [7].

| Basic design CPS | Parameter | Value |
|------------------|-----------|-------|
| Propellant tank  | Construction mass CPS, kg | 2.28 |
| Electro valve    | Propellant tank mass, kg | 0.88 |
| ETMT            | Mass of the upper bottom, kg | 0.44 |
| Vaporizer       | Mass of the lower bottom, kg | 0.4 |
| Filling and drainage coupling | Pressure in fuel tank, MP | 1.9 |
| Pressure sensor | Propellant tank capacity, l | 0.917 |
| Pressure regulator | Volume of filled working fluid, l | 0.78 |
|                     | Volume of gas cushion, l | 0.137 |
|                     | Average value of ammonia filled, kg | 0.484 |

At a research of mass of MS the following cases can be considered:

$$m_{MS} = m_{MS}^{pred}; \Delta V_{char} = \Delta V_{char}^{pred}; m_{MS} = m_{MS}^{without\ CPS} + m_{CPS}; \Delta V_{char} = \Delta V_{char}^{pred}$$ (2)

In the first case the is solved problem of redistribution of mass of MS on the specified mass of CPS and mass of office systems, the target equipment and a design of MS. In the second case, the increase in the mass of MS due to the introduction of its composition CPS (adopted basic).

3. Theory

BPP MS studies are conducted using a calculation program developed on the basis of a mathematical model of MS with ammonia CPS and ETMT that meets the requirements of the MRS.

The mathematical model of ETMT includes parametric dependences for calculation of thrust ETMT $P_{ETMT}$ and specific impulse of thrust $I_{sp}$ through gas-dynamic functions of gas flow [1]:

$$P_{ETMT} = p_k \cdot F_{K} \cdot K_T; \tag{3}$$

$$K_T = \left( \frac{\lambda_k}{\lambda_k - 1} \right) \left( \frac{2}{k + 1} \right); \tag{4}$$

$$I_{sp} = a_{sp} \cdot K_{sp}; \tag{5}$$
\[
a_{kr} = W_{kr} = \sqrt{\frac{2k R^* T_k \lambda}{k+1}};
\]

\[
K_{\text{sp}} = \left( \frac{1}{\lambda_c} + \frac{1}{\lambda_c} \right) \left( \frac{k+1}{2} \right);
\]

\[
q(\lambda_c) = \frac{F_{kr}}{F_{kr}} = W_C \rho_C = \lambda_c \left( \frac{k+1}{2} \right) \left( \frac{1}{k-1} + \frac{1}{k+1} \lambda_c^2 \right);
\]

\[
\tau(\lambda_c) = \frac{T_C}{T_k} = \left( 1 - \frac{k-1}{k+1} \lambda_c^2 \right);
\]

\[
\pi(\lambda_c) = \frac{p_C}{p_k} = \left( 1 - \frac{k-1}{k+1} \lambda_c^2 \right);
\]

\[
T_C = T_k \left( \frac{p_C}{p_k} \right)^{\lambda_c};
\]

where \( K_T \) – dimensionless thrust ratio; \( K_{\text{sp}} \) – dimensionless ratio specific impulse thrust;

\( T_C, T_k \) – the temperature of the gas on the nozzle slice and in the ETMT chamber respectively; \( \rho_C, \rho_k \) – the gas density at the nozzle exit and the camera ETMT in the critical section of the nozzle, respectively; \( F_{kr}, p_k \) – the gas pressure at the nozzle cut and in the chamber ETMT respectively; \( F_C, p_C \) – squad of nozzle cut and critical cut of nozzle, respectively; \( W_C \) – gas flow velocity at nozzle cut;

\( a_{kr} = W_{kr} \) – gas flow velocity equal to the speed of sound in the critical section of the nozzle;

\( k \) – heat capacity ratio of gas; \( R^* \) – gas constant; \( M_g \) – molar mass of gas;

\( q(\lambda_c) \) – relative area of the critical section of the nozzle cut; \( \tau(\lambda_c) \) – relative temperature at nozzle cut; \( \pi(\lambda_c) \) – relative pressure at nozzle cut; \( \lambda_c = W_c / a_{kr} \) – relative velocity of gas flow at nozzle cut.

The interaction of mass characteristics of MS, thrust of ETMT, specific impulse, time of operation and number of ETMT inclusions is described by the expression \([1]\):

\[
V_{\text{char}} = -g_C l_{\text{sp}}^{\text{sp}} \ln \left[ \frac{m_{\text{ms}} - P_{\text{ETMT}} T^{\text{sp}} (N-1) - P_{\text{ETMT}} T^{\text{i}} N}{m_{\text{ms}} - P_{\text{ETMT}} T^{\text{sp}} (N-1) - P_{\text{ETMT}} T^{\text{i}} N} \right] - g_C l_{\text{sp}}^{\text{sp}} \ln \left[ \frac{m_{\text{ms}} - P_{\text{ETMT}} T^{\text{i}} N}{m_{\text{ms}} - P_{\text{ETMT}} T^{\text{i}} N} \right],
\]

where \( V_{\text{char}} \) – characteristic velocity MS with CPS; \( l_{\text{sp}}^{\text{sp}} \) – average specific impulse thrust ETMT when entering the mode; \( l_{\text{sp}}^{\text{i}} \) – average specific impulse thrust ETMT after entering the mode; \( P_{\text{ETMT}} \) – thrust ETMT; \( T^{\text{i}} \) – time of ETMT release to the mode; \( T^{\text{sp}} \) – ETMT operating time on the mode; \( N \) – the number of CPS inclusions.

The CPS weight-dimension model is constructed on the basis of basic CPS (Figure 2a) \([7]\). The mass of the CPS construction \( m_{\text{cps}} \) is presented in the form of:

\[
m_{\text{cps}} = m_{b}^{w} + m_{b}^{w} + m_{i}^{i} + m_{\text{aut}} + m_{\text{ma}}^{\text{CPS}},
\]

where \( m_{b}^{w}, m_{b}^{w} \) – mass of top (0.44 kg) and bottom (0.4 kg) of the tank; \( m_{i}^{i} \) – mass of a cylindrical part of the tank; \( m_{\text{aut}} \) – mass of automatic equipment of CPS (0.48 kg); \( m_{\text{ma}}^{\text{CPS}} \) – mass of adaptation means CPS (0.8 kg) (Figure 2b).

The mass of MA CPS in MS in the form of the system of movement of CPS in two mutually perpendicular directions for an exhibition of a thrust vector of ETMT is determined by a prototype method (CPS MS "Ugatusat").
Figure 2. 3D base model CPS (a) with system thrust vector Exhibition (b) and CPS with the changeable height of tank (c): 1 – the automatic equipment of CPS; 2 – propellant tanks; 3 – ETMT.

The weight $m_t'$ is determined by the expression (Figure 2c) (14):

$$m_t' = \rho_m H 2 \delta \pi (R + r),$$  \hspace{1cm} (14)

where $\rho_m$ – tank material density; $H$ – height of a cylindrical part of the tank; $\delta$ – tank wall thickness; $R$ и $r$ – external and internal radii of the cylindrical part of the tank.

The average daily energy consumption of CPS $N_{da}^{\text{CPS}}$ and the required average daily energy consumption of MS $N_{da}^{\text{req}}$ are determined by the dependencies:

\[
N_{da}^{\text{CPS}} = N_{da}^{\text{CPS}} N_c^{\text{CPS}} t_{\text{day}}^{\text{CPS}} / 24;
N_{da}^{\text{req}} = N_{da}^{\text{CPS}} + N_{da}^{\text{SOS}} + N_{da}^{\text{OKS}},
\]

where $N_{CPS}$ – the actual power of CPS; $C_{CPS}$ – number of CPS inclusions per day; $t_{\text{day}}^{\text{CPS}}$ – CPS unit on time; $N_{da}^{\text{SOS}}$, $N_{da}^{\text{OKS}}$ – average daily energy consumption of the orientation and stabilization system (SOS) and the onboard control system (OKS), respectively.

In the study of BPP, the required average daily energy consumption of MS $N_{da}^{\text{req}}$ is estimated. If $N_{da}^{\text{req}}$ is greater than the base average daily power consumption of MS $N_{da}^b$, then the mass of solar cells (CS) of the power supply system (SPS) increases by the amount of $dm_{\text{sp}}^{\text{CPS}}$:

\[
N_{da}^{\text{CPS}} = k_s^{\text{CPS}} (N_{da}^{\text{req}} - N_{da}^b),
\]

where $k_s^{\text{CPS}} = m_{da}^{\text{CS}} / N_{da}^{\text{CS}}$ – the ratio of mass loading on the average power of MS; $m_{da}^{\text{CS}}$ – the mass CS, ensuring $N_{da}^{\text{req}}$.

As the basic average daily power consumption of MS is accepted power consumption of 60 W.

Program for the calculation of the required reserve rate characteristic $V_{\text{char}}$ for the following tasks orbital maneuvering: prevent orbit insertion errors, maintain orbit parameters, facilitate interorbital maneuvering, insert SSV into disposal orbits [1]. For the calculation of reserves of the characteristic velocity $V_{\text{char}}$ MS with mass of 30–50 kg, the mid-section area $S_{\text{mid}}$, the aerodynamic coefficient $C_x$ are selected on the basis of statistical data depending on weight-dimension of MS.

Formation of variable values of BPP is carried out by generation of random numbers. Restrictions on BPP taken based on the implemented parameters for the MS type "Ugatusat" [1].

The set of values of the objective function is determined cyclically with the generation of new BPP at each step. The received set of values $m_{\text{MS}}$ is narrowed to quasioptimum area of criterion function – the mass MS with CPS and MA $\{m_{\text{opt}}^{\text{MS}}\}$. For this purpose, a numerical criterion is introduced – the restriction on the maximum mass introduced in the calculation program $m_{\text{MS}}^{\text{max}}$.

The quasi-optimal area of the target functions to be printed is determined by the condition (17):

$$\{m_{\text{MS}}^{\text{opt}}\} = \{m_{\text{MS}} - m_{\text{MS}}^{\text{max}}\}; \{m_{\text{MS}}^{\text{opt}}\} < 0.$$

If the condition (17) is met, the values of the objective function $m_{\text{MS}}^{\text{opt}}$ together with the BPP determining it are printed in the calculation program.

The flowchart of the calculation program is shown in Figure 3.
Figure 3. The flowchart of the program of parametrical researches CPS with ETMT on the basis of MRC.

The indicator of a shock adiabatic $k$, relative speed of a stream of gas on a cut of a nozzle $\lambda$, power costs of $N_T$ ammonia heating, decide on the help of subprogrammes Figure 4.

Figure 4. Flowcharts of subprogrammes of definition of an indicator of a shock adiabatic $k$ (a); determination of relative speed of a stream of gas on a nozzle $\lambda$ (b); definition of costs of power of heating of ammonia $N_T$ (c).
The indicator of a shock adiabatic is presented by a set \( k = f(T_k) \) and decides by methods of interpolation of function on one variable (Figure 4a) [8].

On the received dependences of a shock adiabatic on temperature change of relative speed of a stream of gas on a nozzle cut is received \( \lambda_s \) (Figure 4b).

Power costs of heating of ammonia are presented to ETM T by a set \( \frac{\text{ТК}}{\text{Тм}} = \frac{\text{Р}}{\text{Р к}} \) and decide by methods of approximation of functions on two variables (Figure 4c) [8].

4. Results and discussion

The results of the research are given for the following initial data: mass MS without KDU 30 kg, 40 kg and 50 kg. The necessary reserve of characteristic velocity is accepted by results of calculations for performance of coplanar transition between circular orbits of 500–700 km (108 m/c), 700–800 km (52 m/c). The results of the BPP MS with CPS study are presented in tables 2, 3.

**Table 2.** The results of the BPP MS with CPS studies method MRS to coplanar transition between circular orbits with \( H_0 = 500 \) km and \( H_h = 700 \) km

| Parameter | Value |
|-----------|-------|
| \( m_{\text{MS}, \text{without CPS}} \), kg | 30 | 40 | 50 |
| \( V_{\text{char}}, \text{m/s} \) | 108 | 108 | 108 |
| \( T_k, \text{K} \) | 672 | 647 | 656 | 642 | 675 | 630 | 667 | 658 | 604 | 592 | 619 | 622 |
| \( P_k, \text{MPa} \) | 0.04 | 0.02 | 0.02 | 0.03 | 0.01 | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 | 0.04 | 0.03 | 0.03 |
| \( d_s, \text{mm} \) | 0.8 | 0.8 | 1.1 | 0.9 | 0.9 | 0.8 | 1 | 1 | 0.6 | 0.8 | 0.8 | 0.9 |
| \( d_c, \text{mm} \) | 5 | 7 | 7 | 8 | 5 | 9 | 6 | 9 | 5 | 6 | 4 | 4 |
| \( m_{\text{MS}}, \text{kg} \) | 36.37 | 36.36 | 36.42 | 36.38 | 47.68 | 47.62 | 47.69 | 47.59 | 59.29 | 59.23 | 59.30 | 59.27 |
| \( m_{\text{CPS}}, \text{kg} \) | 6.37 | 6.36 | 6.42 | 6.38 | 7.68 | 7.62 | 7.69 | 7.59 | 9.29 | 9.23 | 9.30 | 9.27 |
| \( m_{\text{opt}}, \text{kg} \) | 2.088 | 2.085 | 2.116 | 2.090 | 2.819 | 2.789 | 2.825 | 2.762 | 3.725 | 3.692 | 3.725 | 3.715 |
| \( P_{\text{CPS}}, \text{gf} \) | 3.77 | 1.93 | 3.56 | 3.67 | 1.18 | 1.96 | 1.46 | 1.51 | 0.93 | 3.79 | 2.75 | 2.75 |
| \( l_{\text{opt}}, \text{s} \) | 165.6 | 166.1 | 163.4 | 165.5 | 164.2 | 166.2 | 164.2 | 168.2 | 155.4 | 155.8 | 154.5 | 154.9 |
| \( N_{\text{reg}}, \text{W} \) | 50.1 | 47.3 | 49.8 | 49.7 | 46.3 | 47.2 | 46.7 | 46.7 | 45.9 | 48.6 | 49.9 | 48.6 |

**Table 3.** The results of the BPP MS with CPS studies method MRS to coplanar transition between circular orbits with \( H_0 = 700 \) km and \( H_h = 800 \) km

| Parameter | Value |
|-----------|-------|
| \( m_{\text{MS}, \text{without CPS}} \), kg | 30 | 40 | 50 |
| \( V_{\text{char}}, \text{m/s} \) | 52 | 52 | 52 |
| \( T_k, \text{K} \) | 552 | 568 | 587 | 602 | 498 | 652 | 594 | 588 | 610 | 672 | 618 | 577 |
| \( P_k, \text{MPa} \) | 0.01 | 0.01 | 0.01 | 0.02 | 0.01 | 0.03 | 0.04 | 0.02 | 0.02 | 0.01 | 0.01 | 0.02 |
| \( d_s, \text{mm} \) | 0.7 | 0.9 | 1 | 0.9 | 1 | 0.8 | 0.8 | 1 | 0.8 | 1.1 | 0.9 | 0.8 |
| \( d_c, \text{mm} \) | 8 | 7 | 7 | 6 | 10 | 4 | 7 | 10 | 9 | 9 | 10 | 7 |
| \( m_{\text{MS}}, \text{kg} \) | 34.65 | 34.67 | 34.64 | 34.61 | 45.52 | 45.21 | 45.24 | 45.23 | 55.81 | 55.68 | 55.78 | 55.96 |
| \( m_{\text{CPS}}, \text{kg} \) | 4.65 | 4.67 | 4.67 | 4.61 | 5.52 | 5.21 | 5.24 | 5.23 | 5.81 | 5.68 | 5.78 | 5.96 |
| \( m_{\text{opt}}, \text{kg} \) | 1.126 | 1.131 | 1.118 | 1.097 | 1.611 | 1.430 | 1.455 | 1.447 | 1.769 | 1.702 | 1.753 | 1.855 |
| \( P_{\text{CPS}}, \text{gf} \) | 0.74 | 1.20 | 1.47 | 2.38 | 1.48 | 2.76 | 3.84 | 3.02 | 1.95 | 1.82 | 1.23 | 1.92 |
| \( l_{\text{opt}}, \text{s} \) | 153.2 | 152.3 | 154.2 | 155.9 | 142.4 | 159.3 | 157.8 | 158.2 | 162.9 | 169.2 | 164.1 | 155.1 |
| \( N_{\text{reg}}, \text{W} \) | 45.56 | 46.23 | 46.64 | 47.96 | 46.57 | 48.68 | 49.91 | 48.73 | 47.25 | 47.18 | 46.27 | 47.21 |
Analysis of the results of the studies shown in table 2 showed:

- for $m_{\text{MS} \text{without CPS}} = 30$ kg, the quasi-optimal domain of the objective function is: $m_{\text{opt}}^{\text{MS}} = 36.36 \ldots 36.42$ kg at $m_{\text{red}}^{\text{CPS}} = 6.36 \ldots 6.42$ kg for the following BPP range: $T = 642 \ldots 672$ K, $P = 0.02 \ldots 0.04$ MPa, $d_{\nu} = 0.8 \ldots 1.1$ mm, $d_{c} = 5 \ldots 8$ mm;

- for $m_{\text{MS} \text{without CPS}} = 40$ kg, the quasi-optimal domain of the objective function is: $m_{\text{opt}}^{\text{MS}} = 47.59 \ldots 47.69$ kg at $m_{\text{red}}^{\text{CPS}} = 7.59 \ldots 7.69$ kg for the following BPP range: $T = 630 \ldots 675$ K, $P = 0.01 \ldots 0.02$ MPa, $d_{\nu} = 0.8 \ldots 1.1$ mm, $d_{c} = 5 \ldots 9$ mm;

- for $m_{\text{MS} \text{without CPS}} = 50$ kg, the quasi-optimal domain of the objective function is: $m_{\text{opt}}^{\text{MS}} = 59.23 \ldots 59.30$ kg at $m_{\text{red}}^{\text{CPS}} = 9.23 \ldots 9.30$ kg for the following BPP range: $T = 592 \ldots 622$ K, $P = 0.01 \ldots 0.04$ MPa, $d_{\nu} = 0.6 \ldots 0.9$ mm, $d_{c} = 4 \ldots 6$ mm.

Analysis of the results of the studies shown in table 3 showed:

- for $m_{\text{MS} \text{without CPS}} = 30$ kg, the quasi-optimal domain of the objective function is: $m_{\text{opt}}^{\text{MS}} = 34.61 \ldots 34.67$ kg at $m_{\text{red}}^{\text{CPS}} = 4.61 \ldots 4.67$ kg for the following BPP range: $T = 552 \ldots 602$ K, $P = 0.01 \ldots 0.02$ MPa, $d_{\nu} = 0.7 \ldots 1.1$ mm, $d_{c} = 6 \ldots 8$ mm;

- for $m_{\text{MS} \text{without CPS}} = 40$ kg, the quasi-optimal domain of the objective function is: $m_{\text{opt}}^{\text{MS}} = 45.21 \ldots 45.52$ kg at $m_{\text{red}}^{\text{CPS}} = 5.21 \ldots 5.52$ kg for the following BPP range: $T = 498 \ldots 652$ K, $P = 0.01 \ldots 0.04$ MPa, $d_{\nu} = 0.8 \ldots 1.1$ mm, $d_{c} = 4 \ldots 10$ mm;

- for $m_{\text{MS} \text{without CPS}} = 50$ kg, the quasi-optimal domain of the objective function is: $m_{\text{opt}}^{\text{MS}} = 55.68 \ldots 55.96$ kg at $m_{\text{red}}^{\text{CPS}} = 5.68 \ldots 5.96$ kg for the following BPP range: $T = 577 \ldots 672$ K, $P = 0.01 \ldots 0.02$ MPa, $d_{\nu} = 0.8 \ldots 1.1$ mm, $d_{c} = 7 \ldots 10$ mm.

5. Findings and conclusions

On the basis of the developed settlement program the technique of the choice of BPP MS with ammoniac CPS with ETMT with the top face configuration of CPS with use of MRC is created.

The technique is worked out for MS in the mass range of 30–50 kg and can be extended to another mass range MS. The received set of BPP MS values allows to carry out their choice from positions of the solution of a multicriteria task with preservation of quasioptimum criterion function.

At change of the scheme of an arrangement of CPS in MS it is necessary to finish the MA CPS mass model as a part of MS.

References

[1] Blinov V N, Schalay V V, Zubarev S V, Kositsin V V, Ruban V I and Khodoreva E V 2014 Studies of electrothermal microengines of corrective propulsion systems for maneuvering small spacecrafts: monograph (Omsk: OmSTU Publishing House) p 264

[2] Bromaghim D R, LcDuc J R, Salasovich R M, Spanjers G G and Fife J M 2002 Review of the Electric Propulsion Space Experiment (ESEX) Program Journal of Propulsion and Power vol 18(4) pp 723 – 730

[3] Blinov V N, Vavilov I S, Kositsin V V, Lukyanchik A I, Ruban V I and Schalay V V 2016 Experimental Testing of Electrothermal Microthrusters with Autonomous Heating Elements for Orbital Maneuvering of Small Space Vehicles Indian Journal of Science and Technology vol 9 (19) p 10

[4] Batischov D I 1975 Search methods of optimal design (Moscow: Soviet radio Publishing House) p 216

[5] Zaharova E M and Minaschina I K 2014 Overview of multidimensional optimization methods Information process vol 14(3) pp 256 – 274

[6] Tkachenko I S 2011 Method of system analysis of the effectiveness of means of orbital inspection based on maneuvering small space vehicles: abstract dissertation (Samara: Samara State Aerospace University named S. P. Korolev) p 153

[7] Blinov V N, Vavilov I S, Kositsin V V, Lukyanchik A I, Ruban V I and Schalay V V 2018
Study of power-to-weight ratio of the electrothermal propulsion system of nanosatellite maneuvering satellite platform *Journal of Physics: Conference Series* **944** 012020

p 14

[8] Blinov V N, Vavilov I S, Kositsin V V, Lukyanchik A I, Ruban V I, Charushina E B and Schalay V V 2015 Assessment of energy costs for heating the working fluid during operation of the propulsion system on ammonia *Problems of development, manufacture and operation of rocket-space and aviation equipment: materials of the sixth All-Russia. sci. tech. Conf.* (Omsk: OmSTU Publishing House) pp 62 – 69