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PROCEDURE FOR EVALUATING THE EFFECTIVE USE RANGE OF THE UNIFIED SPACE PLATFORMS

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In JSC "ISS" the task of evaluating the efficiency of using the previously developed unified platforms for the creation of a new spacecraft was solved in a more empirical way, by generalizing the reserve for existing developments and assessing opportunity and expediency of applying the existing reserve in the future (continuity of development). However, the methodological basis for solving this kind of problem has not been developed to this day. From this follows the conclusion about the urgency of developing a methodology for assessing the range of effective application of the unified space platform and the need for its implementation.

In this article, the methodical approach to problems of expediency of use of existing unified space platforms for creation of new space vehicles on their basis is considered. The sources of uncertainties arising in the design of space vehicles and the stages of choosing the optimal project under conditions of uncertainty are determined. This article describes such a design approach of space vehicles as a rational design. The main task of this approach is indicated. Also in the article the design parameters that determine the structural stability of the spacecraft are listed. A mathematical model of a spacecraft based on a unified space platform has been developed, which determines the dependence of design parameters on the characteristics of the payload.

The criterion of a space vehicle optimal design based on a unified space platform, defined as the ratio of the efficiency index to the cost index for the creation of a spacecraft, is formed. A methodology for assessing the range of effective application of unified space platforms has been developed. Approbation of the developed technique was carried out based on existing geostationary space communication apparatuses on the basis of a unified space platform "Express-1000NT", developed by JSC "ISS". Calculated data and graphical representations of effective application ranges of the unified space platform "Express-1000NT" are presented. Based on the results of approbation, it can be concluded that the developed methodology allows to asses properly the range of effective application of unified space platforms for communication satellites in the geostationary orbit.

Keywords: satellite, spacecraft, GEO, unified space platform, project model.

МЕТОДИКА ОЦЕНКИ ДИАПАЗОНА ЭФФЕКТИВНОГО ПРИМЕНЕНИЯ УНИФИЦИРОВАННЫХ КОСМИЧЕСКИХ ПЛАТФОРМ

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В АО «ИСС» задача оценки эффективности использования разработанных ранее унифицированных космических платформ (УКП) для создания нового космического аппарата решалась в большей степени эмпирическим путем, путем обобщения задела по существующим разработкам и оценкb возможности и целесообразности применения имеющегося задела в перспективе (преемственность развития). Однако методической основы решения такого рода задачи до сих пор разработано не было, bз чего следует вывод об актуальности разработки методики оценки диапазона эффективного применения УКП и необходимости ее внедрения.

Рассмотрен методический подход к проблематике целесообразности использования существующих унифицированных космических платформ для создания на их базе новых космических аппаратов. Определены источ-

ники неопределенностей, возникающих при проектировании космических аппаратов. и этапы выбора оптимального проекта в условиях неопределенности. Описан такой подход к проектированию космических аппаратов, как рациональное проектирование, обозначена главная задача этого подхода. Также перечислены проектные параметры, определяющие структурную устойчивость космического аппарата. Разработана математическая модель космического аппарата на базе унифицированной космической платформы, определяющая зависимость проектных параметров от характеристик полезной нагрузки. Сформирован критерий оптимального проекта космического аппарата на базе унифицированной космической платформы, определяемый как отношение показателя эффективности к показателю затрат на создание космического аппарата. Разработана методика оценки диапазона эффективного применения унифицированных космических платформ. Апробация разработанной методики проведена на основе существующих геостационарных космических аппаратов связи на базе унифицированной космической платформы «Экспресс-1000НТ» разработки АО «ИСС».

Представлены расчетные данные и графические изображения диапазонов эффективного применения унифицированной космической платформы «Экспресс-1000НТ». По результатам апробации можно сделать вывод, что разработанная методика позволяет корректно оценивать диапазон эффективного применения унифицированных космических платформ для спутников связи на геостационарной орбите.

Ключевые слова: космический аппарат, спутник, геостационарная орбита, УКП, космическая платформа, проектная модель.

Introduction. During a long period of space activity of JSC “ISS” a large number of spacecrafts (SC) of information support and their component systems and instruments have been developed. By doing so, a unified range of basic types of spacecraft (SCUR) was created, the modification of which allowed to create entire families of spacecraft for specific tasks and operating conditions quickly.

At the same time, a technical policy was developed to introduce new principles and approaches in the creation of information space technologies, the main idea of which is expressed in the integration of various functions on one spacecraft; a significant increase in the life of the spacecraft; increase of power capacity of the spacecraft; creation of devices operating in a vacuum and spacecraft with a leaky instrument compartment; creation of unified space platforms (USP), unified on-board support systems and unified on-board instruments; reduction in the cost of development by replacing physical developmental models of spacecraft with software models and the use of equipment and software developed for various projects (inter-project unification), etc.

However creation of a parametric series of unified space platforms is associated with the solution of the optimization task of increasing the output effect of the spacecraft created on their basis in the presence of functional redundancy of the USP with simultaneous reduction of the costs and terms of the spacecraft creation by minimizing the modifications of the USP.

When creating a parametric series of SCUR and USP for spacecrafts providing the information support, this task was solved in a more empirical way, by summarizing the reserve of existing developments and assessing the feasibility and expedience of applying the existing reserve in the future (continuity of development).

In this paper, a methodological basis for solving this problem is proposed.

A formal description of a spacecraft project. The design of the spacecraft is carried out using models containing a number of parameters that are random variables with known or unknown distribution laws [1].

The sources of uncertainty are random factors of utilization, incompleteness of the initial data for the design, due to the error in forecasting the main technical, technological, economic indicators, as well as the error in predicting the conditions for the project due to the long duration of its creation.

For such models, the task of choosing the optimal design of the spacecraft is transformed into the problem of choosing a solution under the conditions of uncertainty and is done by searching for such a project, which by taking into account the uncertainty in a number of parameters delivers the extremum of the objective function whenever possible.

As a result, the task of choosing the optimal project under uncertainty is solved in two stages:

– at the first stage, a project that satisfies the conditions and constraints that determine the permissible range of SC existence, that is the permissible design of the spacecraft is developed;

– at the second stage, the optimization of the parameters for the chosen criterion is carried out in a wide range of its existence, i. e, a quasi-optimal design of the spacecraft is selected.

At the same time, all restrictions on parameters should be satisfied with a high level of probability, which is a necessary and sufficient condition for the implementation of an acceptable project, that is ensuring its structural stability.

The procedure of optimizing the project serves as guidelines and boils down to isolating the range of valid parameters, in which the efficiency index is close to optimal. This approach to design is called rational design [1].

Rational design clarifies and supplements the fundamental principles of the system approach to the development of complex technical systems as follows:

– in the synthesis of the system structure options, it is necessary to start from the uncertainty ranges of all the parameters and if these ranges overlap, then the alternative is not considered;

– completeness of mathematical models of the system and modeling errors should take into account uncertainty ranges in parameters;

– when forming the optimization criterion, the quality indicators of the system are ranked according to the degree of their influence on the criterion, taking into account the reliability of their values;

– comparison of different project variants is carried out under identical conditions of uncertainty.

Thus, the main task of rational design is to provide conditions for the implementation of an acceptable project by ensuring that the critical parameters of spacecraft that are random variables are not exceeded by creating compensation mechanisms for these uncertainties ensuring a guaranteed existence of an acceptable project, i. e. structural stability of the spacecraft project in the whole range of possible realizations of random parameters.

When designing a spacecraft, the mechanism for parrying uncertainties is reduced to the creation of centralized reserves of spacecraft resources to parry uncertainties by its parameters and redistribution of these reserves as the project progresses.

The choice of the nomenclature of critical parameters is carried out on the basis of an analysis of the most significant limitations that are associated with the problems the SC is to solve:

– the solution of target tasks;

– control of the spacecraft operation;

– motion control of the spacecraft;

– control of the angular position of the spacecraft;

– maintenance of energy and heat balance;

– ensuring compatibility of the spacecraft with a launch vehicle.

According to the research made, the design parameters that determine the structural stability of a spacecraft (guaranteed satisfaction of constraints) include [1]:

– the mass of the spacecraft and the mass of the working body of the propulsion system (PS);

– the volume of the spacecraft in the folded position, the volume of the instrument cluster and tanks of the PS, the area of solar batteries and a radiator, the dimensions of the antennas;

– the eccentricity of the spacecraft mass center;

– the moments of inertia of the spacecraft in the folded and working positions;

– power consumption and heat release of the spacecraft.

At the same time, the mass, volume, power consumption of the spacecraft and its components are independent of the above nomenclature of parameters.

Therefore, in order to implement an acceptable project, it is primarily planned to manage the budget for the mass and energy consumption of the spacecraft in the permissible range of change, as well as the formation of a layout scheme for the spacecraft that is resistant to changes in the parameters of the spacecraft.

The limiting values of the mass and volume of the spacecraft are limited by the selected means of induction, and therefore the design of the spacecraft must be directed at their maximum use in order to increase the target efficiency.

Project model of the spacecraft with USP. One of the effective mechanisms for implementing an acceptable project is the use of a modular-type layout scheme of a spacecraft consisting of a payload module (PM) and a unified space platform (USP) for which the mass and energy budgets of the spacecraft are presented in the following form:

$$M_{\mathrm{SC}} = M_{\mathrm{P}} + M_{\mathrm{USP}},$$
$$W_{\mathrm{SC}} = W_{\mathrm{P}} + W_{\mathrm{USP}}, \quad (1)$$

where M_{SC} and W_{SC} – are mass and power consumption of the spacecraft; M_{P} and W_{P} – are mass and energy consumption of the PM; M_{USP} and W_{USP} – are mass and power consumption of the USP.

The budget of the spacecraft resources is formed on the basis of the maximum satisfaction of the payload requirements in the spacecraft resources (energy consumption mass, volume) in the form of a generalized payload mass M_{Pg} [1]:

$$M_{Pg} = M_{\mathrm{P}} + K_W \cdot W_{\mathrm{P}} = M_{\mathrm{P}} \cdot \alpha_{\mathrm{P}},$$
$$\alpha_{\mathrm{P}} = 1 + K_W \cdot W_{\mathrm{P}} / M_{\mathrm{P}}, \quad (2)$$

where α_{P} – is the coefficient of partial costs of the SC resources to ensure the needs of the payload; K_W – is the average coefficient of partial costs of the spacecraft mass for generating electricity and heat rejection, kg / W.

In this case, the generalized mass of the payload M_{GP} can be used to form the indicator of the spacecraft efficiency – the generalized coefficient of the partial costs of the spacecraft resources for the solution of the target task:

$$K_{\mathrm{P}} = M_{Pg} / M_{\mathrm{SC}} = K^0_{\mathrm{P}} \cdot \alpha_{\mathrm{P}}, \quad (3)$$

where $K^0_{\mathrm{P}} = M_{\mathrm{P}} / M_{\mathrm{SC}}$ – mass payload coefficient of a spacecraft.

Costs for carrying out development work on the development of a spacecraft (C_{DW}) according to the enlarged methodology are proportional to the costs for the manufacture of a spacecraft (C_M) [1]:

$$C_{DW} = K_{DW} \cdot C_M. \quad (4)$$

The value of the coefficient K_{DW} is determined by the novelty of the spacecraft being developed and its components, the volume of ground-based experimental testing of the spacecraft and its component parts, and is specified in the range 4–8. At the same time, for the spacecraft on the new USP $K_{DW} \approx 8$, and when using the borrowed USP $K_{DW} \approx 4$.

Costs for the manufacture of a spacecraft, as a combination of the costs of manufacturing its components and their integration into the spacecraft structure, depends on its target efficiency, reliability, mass, energy consumption, etc. Taking into account the fact that the mass of the spacecraft is limited by the power capabilities of the launch vehicle and is used to realize target tasks with a given efficiency and reliability, in design studies it is used as an equivalent to the cost of manufacturing the spacecraft [1]

$$C_M = C_{si} \cdot M_{\mathrm{SC}}. \quad (5)$$

The value of the specific indicator C_{si} is determined on the basis of the statistical data processing on SC-analogues.

Substituting equation (5) into equation (4), we obtain the functional dependence of the development work cost on the mass of the spacecraft.

$$C_{DW} = K_{DW} \cdot C_{si} \cdot M_{\mathrm{SC}}. \quad (6)$$

The obtained system of equations allows to formulate the criterion of the optimal SC project (objective function) of the scalar type, defined as the ratio of the efficiency index (M_{GP}) to the cost indicator for the creation of the spacecraft C_{DW}.

$$E_{\mathrm{SC}} = \frac{M_{Pg}}{C_{DW}} = \frac{K_{\mathrm{P}}}{K_{DW} \cdot C_{si}} = \frac{K^{0}{}_{\mathrm{P}} \cdot \alpha_{\mathrm{P}}}{K_{DW} \cdot C_{si}}. \tag{7}$$

Procedure for evaluating the effective use range of the USP. To create a modern spacecraft for various purposes in a sufficiently short time, it is advisable to use a unified space platforms (USP) [1–3].

The USP is intended for further installation and adaptation of the payload (P) on it and providing it with all the conditions for full-time operation and for the tasks set for the spacecraft.

It should be noted that in practice the application area of the USP without further development is very limited, which is due to the variability of payload (P) parameters (mass, power consumption, design), the use of different types of launch vehicles, operation orbits, etc. Therefore, there is often a need for modification and even substantial improvement of the USP for the specific characteristics of a spacecraft.

To exclude the need to improve the USP, it is worked on the limiting characteristics of the PM and the spacecraft as a whole. In this case, the target efficiency of the spacecraft (K_{P}) is somewhat reduced due to a reduction of the resources for the PM because of the availability of surplus resources for the USP.

Let us consider the case of the USP application developed for a basic spacecraft, for a new spacecraft with a smaller mass and energy consumption.

$$M_{SCb} = M_{Pb} + M_{\mathrm{USP}}; \quad M_{SCn} = M_{Pn} + M_{\mathrm{USP}};$$
$$M_{SCn} \le M_{SCb}; \; W_{Pn} \le W_{Pb}; \tag{8}$$

The use of the USP on the new spacecraft reduces the cost of the DW, which leads to an increase in its E_{SC} criteria. However, if the mass of the new spacecraft is different from the mass of the basic spacecraft (to a smaller side), the mass of its payload decreases and, accordingly, its efficiency decreases, which reduces its E_{SC} criterion. The range of effective application of the USP on the new spacecraft is determined by a relative dimensionless criterion (index "*b*" refers to the base spacecraft, and the index "*n*" to the new spacecraft).

$$\delta E = \frac{E_{SCb}}{E_{SCn}} = \frac{K_{Pb} \cdot K_{DWn}}{K_{Pn} \cdot K_{DWb}} \le 1{,}0\,. \tag{9}$$

For further research, we transform inequality (9) to the following form:

$$\frac{K_{Pn}}{K_{Pb}} \ge \frac{K_{DWn}}{K_{DWb}}. \tag{10}$$

We will carry out calculation of the coefficient K_{Pn} using the constancy of the USP mass for the base and new spacecraft:

$$K_{Pn} = \frac{M_{Pn} + K_W \cdot W_{Pn}}{M_{SCn}}; \tag{11}$$

$$M_{Pn} = M_{SCn} - M_{\mathrm{USP}} = M_{SCn} - (M_{SCb} - M_{Pb}).$$

Substituting the expression for M_{Pn} in the formula for calculating K_{Pn} we obtain:

$$K_{Pn} = 1 - \frac{M_{SCb}}{M_{SCn}} \cdot (1 - K_{Pb} + \delta_W)\,;$$
$$\delta_W = K_W \frac{W_{Pb} - W_{Pn}}{M_{SCb}}. \tag{12}$$

Substituting the equation for the calculation of K_{Pn} in inequality (10), we obtain a ratio for estimating the range of effective application of the USP (without its improvement):

$$1{,}0 \le \frac{M_{SCb}}{M_{SCn}} \le \frac{1 - K_{Pb} \dfrac{K_{DWn}}{K_{DWb}}}{1 - K_{Pb} + \delta_W}. \tag{13}$$

In the case of a connection between M_{Pn} and W_{P} (coefficient α_{P}), the expression for determining K_{Pn} and the mass ratios M_{SCb} / M_{SCn} will assume a different form:

$$K_{Pn} = \frac{M_{Pn}}{M_{SCn}} \cdot \alpha_{\text{ПН}} = \left[1 - \frac{M_{SCb}}{M_{SCn}}\left(1 - \frac{K_{Pb}}{\alpha_{\mathrm{P}}}\right)\right] \cdot \alpha_{\mathrm{P}}\,, \tag{14}$$

$$1{,}0 \le \frac{M_{SCb}}{M_{SCn}} \le \frac{1 - \dfrac{K_{Pb}}{\alpha_{\mathrm{P}}} \cdot \dfrac{K_{DWn}}{K_{DWb}}}{1 - \dfrac{K_{Pb}}{\alpha_{\mathrm{P}}}} = \frac{1 - K^{0}_{Pb} \dfrac{K_{DWn}}{K_{DWb}}}{1 - K^{0}_{Pb}}. \tag{15}$$

Approbation of the procedure for evaluating the effective use range of the USP. The verification of the developed procedure for evaluating the effective use range of the USP is carried out using the example of USP "Express-1000NT" for geostationary spacecraft. Evaluation of effective use range of the USP will be carried out at K_{DWn} / K_{DWb} = 4/8 = 0.5 for the two calculation options [11]:

– for dependent values of M_{P}, W_{P}, $\alpha_{\mathrm{P}} = 1 + K_W \dfrac{W_{\mathrm{P}}}{M_{\mathrm{P}}}$ using $K^{0}{}_{\mathrm{P}}$ (by formula (15));

– for independent values of M_{P}, W_{P}, using K_{P} and at δ_W = 0 (by formula (13)).

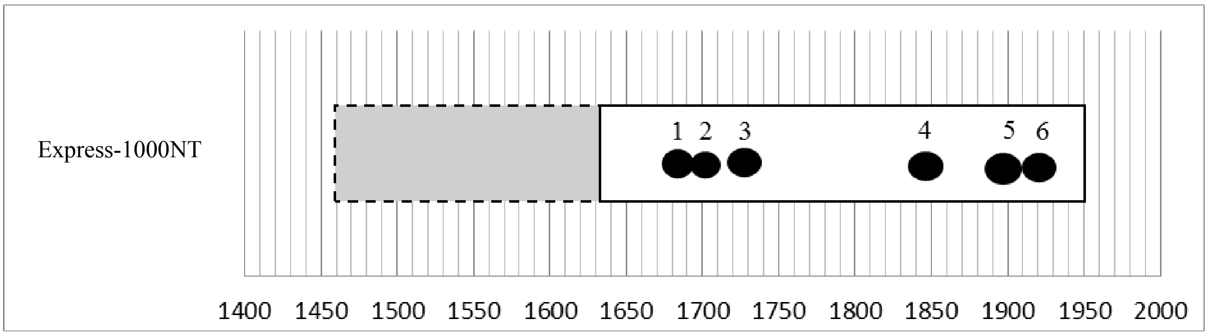
Calculated data are given in see table, graphical representations of the effective use ranges of USP "Ekpress-1000NT" are shown in see figure. The solid line denotes the use of $K^{0}{}_{\mathrm{P}}$, the dotted line indicates K_{Pb}. The points on the graph indicate the realized spacecraft on the basis of the USP:

1) "Express-AT1" (weight 1672 kg);
2) "KAZSAT-3" (weight 1704 kg);
3) "TELKOM-3" (weight 1725 kg);
4) "Yamal-300K" (weight 1847 kg);
5) " LYBID" (weight 1903 kg);
6) "AMOS-5" (weight 1929 kg) [12–15].

Conclusion. The results of the approbation allow us to make the conclusion that the developed procedure makes it possible to estimate the effective use range of unified space platforms for communication satellites in the geostationary orbit correctly.

Effective use range of the unified space platform “Express-1000HT”

№ п/п	Characteristics		Value
1	Platform type		E-1000NT
2	Basic satellite weight, kg	M_{SC}	1950
3	The maximum mass of the payload (P) (RTR + antennas), kg	M_P	500
4	Maximum payload power consumption, W	W_P	5900
5	Coefficient of energy efficiency, kg / W	K_W	0.048
6	Generalized payload mass	M_{Pg}	783.2
7	The coefficient of generalized payload	K_{Pb}	0.402
8	Payload coefficient	K^0_{Pb}	0.256
9	Coefficient of partial mass costs for payload power supply	α_P	1.566
10	The minimum mass of a new spacecraft using K^0_P	M_{SCn}	1633
11	The minimum mass of a new spacecraft using K_P и $\delta_W = 0$	M_{SCn}	1459



Effective use range of the unified space platform “Express-1000HT”

Диапазон эффективного применения УКП «Экспресс-1000НТ»

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