UDC 629.78: 629.036
Doi: 10.31772/2587-6066-2018-19-3-489-496

**For citation:** Yermoshkin Yu. M., Volkov D. V., Yakimov E. N. [On the concept of all electric propulsion spacecraft]. *Siberian Journal of Science and Technology.* 2018, Vol. 19, No. 3, P. 489–496. Doi: 10.31772/2587-6066-2018-19-3-489-496

**Для цитирования:** Ермошкин Ю. М., Волков Д. В., Якимов Е. Н. О концепции полностью электрического космического аппарата // Сибирский журнал науки и технологий. 2018. Т. 19, № 3. С. 489–496. Doi: 10.31772/2587-6066-2018-19-3-489-496

# ON THE CONCEPT OF ALL ELECTRIC PROPULSION SPACECRAFT

Yu. M. Yermoshkin*, D. V. Volkov, E. N. Yakimov

JSC "Academician M. F. Reshetnev "Information Satellite Systems"
52, Lenina Str., Zheleznogorsk, Krasnoyarsk Region, 662972, Russian Federation
*E-mail: erm@iss-reshetnev.ru

*Over the past several years the concept of the so-called "all electric propulsion spacecraft" has gained popularity among both customers and developers of geostationary (GEO) spacecraft; this issue is being actively discussed. The main advantages of the concept are the following: decreasing the mass of spacecraft and increasing its economic efficiency by means of pair orbital injection. There are some illustrative cases of implementation of this concept by American, European and Russian companies. However, specialists interpret the content of the concept in different ways. That causes the problems connected to the development of the conceptual design of spacecraft. It is therefore very important to consider the concept in more detail, to compare various points of view in order to form understanding reflecting its essence the most accurately. At the same time, on the basis of the available examples, it would be feasible to analyze the advantages and disadvantages of this concept in comparison with other approaches to the construction of propulsion system of spacecraft. In the article we offer to interpret the concept as "All electric propulsion spacecraft". This interpretation allows to understand its content unambiguously by the specialists of both Russian and Western Technical Schools. We offer to define "All electric propulsion spacecraft" as an apparatus that does not have in its composition an apogee engine unit that is chemically fuelled. It has to execute manoeuvres on geostationary orbit raising, orbit correction and momentum wheel unloading by electrical propulsion only. We have shown that with the existing level of excellence of the equipment this concept does not have any advantages over the concept of separate propulsion subsystems for the correction and orientation by total mass as well as by the level of reliability.*

*Keywords: all electric propulsion spacecraft, apogee thruster, propulsion subsystem, electric propulsion engine, orbit raising.*

# О КОНЦЕПЦИИ ПОЛНОСТЬЮ ЭЛЕКТРИЧЕСКОГО КОСМИЧЕСКОГО АППАРАТА

Ю. М. Ермошкин*, Д. В. Волков, Е. Н. Якимов

АО «Информационные спутниковые системы» имени академика М. Ф. Решетнёва»
Российская Федерация, 662972, г. Железногорск Красноярского края, ул. Ленина, 52
*E-mail: erm@iss-reshetnev.ru

*В последние несколько лет среди заказчиков и разработчиков геостационарных космических аппаратов (КА) набрала популярность и активно обсуждается концепция так называемого полностью электрического космического аппарата. Подчеркиваются преимущества данной концепции в части снижения массы КА и повышения экономической эффективности за счет парного вывода на орбиту. Имеются конкретные примеры ее реализации американскими, европейскими и российскими компаниями. Вместе с тем, ее содержание трактуется специалистами по-разному, из-за чего возникают проблемы, связанные с формированием облика космических аппаратов. Поэтому представляется важным рассмотреть эту концепцию более подробно, сопоставить различные точки зрения с тем, чтобы выработать понимание, более точно отражающее ее суть. Одновременно на основе имеющихся примеров и проектных оценок целесообразно провести анализ преимуществ и недостатков данной концепции по сравнению с другими подходами к формированию двигательных систем КА. Предложена трактовка понятия полностью электрического космического аппарата, позволяющая однозначно понимать его содержание специалистами как российской, так и западной технической школы. Предложено определить полностью электрический космический аппарат как аппарат, не имеющий в своем составе апогейной двигательной установки на химическом топливе. Он должен выполнять маневры по довыведению на геостационарную орбиту, коррекции орбиты и разгрузке маховиков* *системы ориентации с использованием только электрореактивной двигательной системы. Показано, что при существующем уровне совершенства оборудования данная концепция не имеет преимуществ перед концепцией раздельных двигательных подсистем для коррекции и ориентации как по суммарной массе, так и по уровню надежности.*

*Ключевые слова: полностью электрический космический аппарат, апогейный двигатель, двигательная подсистема, электрореактивный двигатель, довыведение.*

**Introduction.** The appearance of the new concept of "All electric spacecraft" has caused considerable controversy among specialists about the benefits and drawbacks of this concept of constructing spacecraft propulsion subsystem. The substantive content of these discussions is often hampered by discrepancies in understanding of the term in contrast to the clear-cut concept of "Propulsion subsystem". Therefore there is a need to raise two interdependent issues and respond to them. The issues are the following: a) clarifying the content of the concept of "All electric propulsion spacecraft"; b) assessing the advantages and disadvantages arising from the use of this concept while designing and operating GEO spacecraft. The article is devoted the consideration of these issues.

**Clarifying the content of the concept of "All electric propulsion spacecraft".** We can translate the English term "All electric propulsion spacecraft" into Russian, but the most accurate translation according to the meaning would be "spacecraft with electro jet propulsion subsystem solving any tasks". A simplified version close to word-for-word translation and the most widespread is "All electric propulsion spacecraft". Let's consider the meaning of this term that comprises a certain approach to the construction of propulsion subsystem of GEO spacecraft.

In considering the issue, it should be noted that historically, there are two different technical schools dealing with the concept of launching spacecraft into geostationary orbit. The Western School (that some American and European companies adhered to from the very beginning) involves initial launching of a satellite into elliptical geotransfer orbit with the further raising into geostationary orbit with the help of the own apogee engine unit of a satellite. The engine unit of a satellite is called "apogee" because it produces master impulse at orbit apogee. Specialists used only two-component systems with rather high thrust (hundreds of pound feet in order of magnitude) that allowed to perform apogee maneuvers at an optimal point of orbit and to obtain quite acceptable characteristics of engines in terms of economic efficiency (specific impulse). The main advantage of this approach was the speed of the execution of manoeuvres. Rather high engine thrust allowed to perform a manoeuvre during the limited period of time – not more than several days. That reduced to the minimum the dose obtained by a satellite while passing through radiation belts and allowed to put a satellite into operation as quickly as possible. One more important competitive advantage of the approach was the possibility to use launch vehicles of different types. It helped select the most convenient options with regard to the price and other points. Thrusters used remaining fuel after the completion of manoeuvres for the orbit correction during operational lifetime of the spacecraft and for the creation of control moments while maintaining satellite orientation in space.

While implementing the concept, it is necessary to place in spacecraft the propulsion subsystem with massive tanks of oxidizing agent and fuel, with inflation system and other necessary attributes; in this, the mass of the fuelled propulsion subsystem unit is 40–50 % of the launch mass of spacecraft.

In contrast to the Western Technical School, the Soviet (Russian) school comprised the launch into geostationary orbit on the so-called "direct" scheme: using a separate Booster that has some properties of spacecraft but it is actually a part of a launching vehicle. To some extent, a Booster may be considered as an upper stage of a launch vehicle. In such a conception there is no apogee engine unit as a component of spacecraft. Orbit correction and the creation of control moments are carried out during the spacecraft lifetime by on-board subsystems on the basis of low thrust, both two-component and single-component electric propulsion thrusters [1]. In this, in the latter case, developers can significantly reduce the mass of a fuel due to the high economical efficiency of electric propulsion that are generally used for correcting the orbit of spacecraft.

The evolution of the western approach was that specialists began to apply electric propulsion, in particular, ion propulsion, for correcting orbits of geostationary spacecraft in north-south direction (the correction of inclination of the orbit or north-south station keeping).

In this, the apogee engine unit in spacecraft was maintained, the correction of the longitude (West–East) and the performance of control moments continued to be carried out by the two-component liquid-fuelled low thrusters on the rest of the fuel of the apogee engine unit. In particular, the spacecraft on 601HP platform base with the use of the XIPS-13 thrusters were developed by Boeing [2]. The development of the concept comprised the application of more powerful ion thrusters XIPS-25 in spacecraft on Boeing 702 base platform not only for the correction of orbital inclination but for the partial performance of the maneuver of orbit raising as well [2; 3]. Four ion thrusters were installed on the revolving platforms that provided thrust in the direction of orbital speed in the mode of raising, and in the mode of orbital correction – in the directions "North–South" and "West–East" (fig. 1). In this, in the mode of orbital raising the engines operated at maximum power 4.2 kW, and in the mode of orbital correction – on half-power 2.1 kW. As the engines were installed on the moving platforms (drives), during the operation it was possible to generate control moments in order to unload momentum wheels of orientation systems. It allowed to considerably save the fuel for the attitude control thrusters that were on board the spacecraft together with the apogee engine unit.

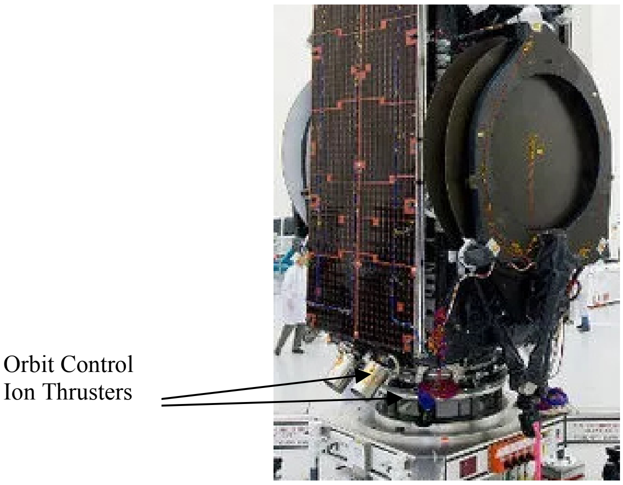

Fig. 1. The location of orbit control thrusters on board spacecraft built on Boeing 702SP platform base

Рис. 1. Размещение двигателей коррекции на КА, построенном на базе платформы Boeing 702SP

The next considerable evolutionary step in the construction of propulsion system of GEO spacecraft was a complete rejection of the apogee propulsion. In this version being implemented in the spacecraft created on Boeing 702SP platform base, the electrical propulsion subsystem took up the challenge of orbital raising [4]. It allowed to significantly decrease the mass of the fuelled propulsion subsystem and the satellite in whole. This, in turn, gave the possibility to perform pair launches using one launch vehicle that allowed to considerably reduce the cost of the injection of spacecraft into orbit. But it caused the increase of the period of raising operation to 7–9 months owing to fundamentally low thrust of an electrical propulsion. However, in the opinion of western specialists, the advantages of the concept outweigh the disadvantages. With its help, only for the European operator EUTELSAT three spacecraft were manufactured – EUTELSAT 115 West B″ EUTELSAT 117 West B (both on Boeing 702SP platform base), EUTELSAT 172B (on EUROSTAR-3000 base) [5]. These satellites were put into operation. The duration of orbital raising was from 4 to 6 months. On the satellite called EUTELSAT 172B the Russian-made thrusters called SPD-140D with a power of 4.5 kW were first used. The interest in the satellites of this type is increasing in the world.

We can note that the evolutionary development of the concept of the apogee engine unit with higher significance of electric propulsion in solving the problem of orbital raising led to the qualitative leap – total rejection of the chemically fuelled apogee propulsion; it generated the concept of “all electric propulsion spacecraft”. In western specialists' understanding, the lack of the chemically fuelled apogee propulsion is an essential feature of this concept.

There is, however, an additional issue concerning attitude control thrusters. If correction thrusters are installed on the drives that allow to decline a thrust vector from the line passing through the centre of spacecraft masses, there is every reason to impose the task of creating control moments to the correction engines as well and to completely refuse to use attitude control thrusters. In this case the concept of all electric propulsion spacecraft will be carried to its logical conclusion, i. e. in this case spacecraft will not have any other thrusters apart from electric propulsion thrusters, and they will solve two different functional tasks: moving the  center of spacecraft’s mass of and control its angular position.

However, the following circumstance hinders such ultimate realization of the “all electric propulsion spacecraft” conception: there are so called initial attitude modes of spacecraft and modes of ensuring survivability when the use of attitude control system with momentum wheels is difficult or impossible. Attitude control thrusters are necessary in this case. However, since impeded power balance is possible for the current modes, the use of electric propulsion is difficult due to their high energy consumption. Therefore, an additional independent engine subsystem providing the creation of control moments arranged along the three axes of spacecraft is necessary for such cases. The choice of the thruster type for such a subsystem depends on the preferences of designers and can be quite broad – from simple nozzles on a cold gas or heated nozzles to mono-fuel or two-component low-thrusters.

Generally when speaking about the advantages of the concept of “all electric propulsion spacecraft” this issue is neglected and it is considered to be of secondary importance and not worthy of special attention. It is interesting to note that if this concept is interpreted in this way, all spacecraft developed by JSC “ISS” starting from 1982 and equipped with electrically orbit correction propulsion subsystems and mono-fuel attitude control subsystems can be considered as “all electric propulsion spacecraft”. A. Vnukov and his co-authors repeatedly pointed to it in publications [6].

The question is, how to interpret the concept of "all electric propulsion spacecraft" correctly and unequivocally so that the specialists of both Russian and Western Technical Schools understand it equally? The following approach is possible: if we take into account the fact that the term "all electric propulsion spacecraft" was invented in the Western Technical School, the use of the interpretation of the term in the form in which it was formed in the Western specialists' view will be logical, i. e. it is logical to mean by this term a kind of spacecraft with an electrically propulsion subsystem without chemically fuelled apogee propulsion. The issue concerning the auxiliary attitude control propulsion is not considered. This approach implies the rejection of the ultimate interpretation of the term "all electric propulsion spacecraft", which excludes the presence of any other engine subsystems on board, except the electrical propulsion subsystem.

If we agree with the proposed definition, the meaning of the term or the concept of "all electric propulsion spacecraft" will be unambiguous for everyone. In addition, there will be freedom in choosing the type of auxiliary attitude control propulsion subsystem, which in any case is necessary on board spacecraft and the fact of its existence excludes the possibility of applying the ultimate interpretation of the "all electric propulsion spacecraft" conception

**Evaluating the advantages and disadvantages of the versions of the concept of "all electric propulsion spacecraft".** Let us suppose that the proposed interpretation of the concept "all electric propulsion spacecraft" is adopted. It is possible to modify it, in this case we give the auxiliary attitude control subsystem a little more advanced functions, i. e. we assign to it the tasks of creating control moments not only in some separate operating modes of a satellite, but during its entire service life as well. This approach, in particular, has been applied to all spacecraft developed by JSC "ISS" [6; 7]. We have evaluated the advantages and disadvantages of "all electric propulsion spacecraft" concept in comparison with the extended version applied on the products of JSC "ISS", which have been taken as a base. We have taken the following baseline data for the assessment:

– the need for the total impulse for various tasks with respect to the general stock are: orbit raising and orbit correction – 98 %, orientation during the service life including the period of the initial modes and the period of the modes of ensuring survivability – 2 %;

– the base scheme includes the propulsion subsystem of orbit raising and correction of the orbit and the attitude control propulsion subsystem;

– the orbit control and orbit raising propulsion subsystem consists of 6 perspective plasma engines of KM-75 type [8], a modified version of power processing unit (PPU) suitable for powering two thrusters simultaneously, a xenon feed unit and a xenon storage unit developed by JSC "ISS" [9];

– the attitude control propulsion consists of 8 thruster units with mono-fuel K50-10 thrusters [10], storage and feed unit.

In all the versions in which we do not use mono-fuel thrusters, cold xenon nozzles powered from the common xenon tank create control moments in the initial modes and modes of ensuring survivability.

In the version of hard-mounted correction thrusters, we have increased their number to ten to create control moments along three axes, taking into account the thrusters of orbit raising. In the version of the correction thrusters installed on rotary devices (drivers), the thrusters are used both in the mode of orbit raising and in the orbit correction mode with simultaneous creation of control moments. We have reduced the number of engines to the lowest possible – four. We have taken into account the mass of the rods, drives and its control units.

The main criterion for evaluating the versions is the total mass of fueled propulsion subsystems. Additional criteria are operational reliability and easy control. The mass estimate for different design versions of the propulsion subsystems is presented in table.

The results presented in the table show that the base design version of the satellite propulsion system (consisting of two independent subsystems: orbit control and orbit raising subsystems based on plasma thrusters and attitude control subsystem based on a monopropellant thrusters) has a significant advantage over other versions. We obtained similar results when carrying out project evaluations for other types of plasma engines and other types of PPU. This result suggests that at the present stage generating of control moments for the orientation of spacecraft by plasma orbit control thrusters is possible but it is irrational, since it requires a significant increase in mass in comparison with the version of two independent propulsion subsystems. The results of design estimates are unexpected as, at first sight, a system based on single, universal, very economical and reduced to a minimum number of thrusters must have the lowest mass. However, many calculations that we have carried out taking into account the attendant factors, the available data on the masses of the blocks of propulsion subsystems and prototypes of new equipment suggest otherwise. The reason is that in order to implement the versions using the electrical propulsion in creating control moments, it is necessary to increase the number of thrusters or install them on drives and rods, which together with their control units have a sufficiently large mass. In addition, it is necessary to take into account the mass of the auxiliary cold gas-reactive subsystem with the reserve of the fuel mass. We note that papers [11; 12] demonstrate that the version with fixed orbit control thrusters on the levers relative to the center of mass proved to be lighter than the base version, but this result was received without taking into account the xenon mass consumption for orbit raising and disturbing torques compensation at this stage.

We should note that the pessimistic estimates of the increase in mass for the implementation of versions different from the basic one are characteristic for the current level of perfection of the design of the equipment being used. But, if some lighter devices of controlling thrust vector appear, we can significantly reduce the mass of the driven version.

**The total mass of geostationary satellite propulsion subsystems for the different design versions**

| Design version | Difference from the base scheme, kg |
|---|---|
| The scheme with ten fixed correction units based on KM-75 using modified PPU | +32 |
| The scheme with four correction units based on KM-75 on four rods with uniaxial drives using modified PPU | +71 |

In order to comprehensively evaluate the feasibility of applying this or that concept, we have considered other aspects of the versions of engine subsystem constructions. Operational reliability of the system is one of the most important issues. It is necessary to compare the evaluation of reliability of the system with the combination of functions of orbit and attitude control with the reliability of the original scheme with separate propulsion subsystems of ones.

We have determined the reliability of the original system of $R_{INIT}$, by the following expression:

$$R_{INIT} = R_{CP} \cdot R_{ACP}, \qquad (1)$$

where $R_{CP}$ – reliability of the of correction propulsion; $R_{ACP}$ – reliability of the attitude control propulsion.

The reliability of the system with the combination of the functions R' is similarly defined by the expression:

$$R' = R_{AUX} \cdot R_{UNI}, \qquad (2)$$

where $R_{AUX}$ – reliability of the auxiliary propulsion for operation in the initial modes and modes of ensuring survivability; $R_{UNI}$ – reliability of the universal propulsion subsystem of orbit and attitude control

The reliability of the auxiliary propulsion subsystem in the first approximation can be comparable (equal to or slightly higher) with the reliability of the attitude control propulsion subsystem in the original version. Thus, the reliability of the system with the combination of functions depends on the second component – the reliability of the universal propulsion subsystem. Obviously, its reliability is lower than the reliability of the orbit control subsystem in the original version, since the composition of the subsystem and the structural scheme of reliability are more complicated. Most likely, the reliability of a system with the combination of functions is comparable or lower than the reliability of the original scheme with two independent engine subsystems.

To confirm this assumption, we have obtained a numerical estimate of the reliability for a specific version of the propulsion subsystem. It is possible to do it, for example, for the scheme with the fixed correction thrusters on the body of the spacecraft considered in [11]. This paper considers only the problem of orbit correction with the simultaneous creation of control moments without orbit raising. We have chosen the diagonal placement of 4 thrusters (fig. 2) as a base scheme of the orbit control propulsion subsystem.

Fig. 3 shows the structural scheme of reliability for this design of the propulsion subsystem.

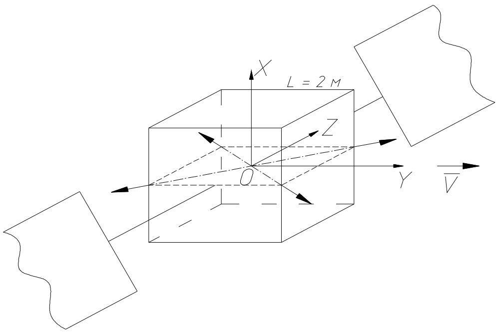

Fig. 2. Coordinate system and nominal thrust directions of orbit correction thrusters in the base scheme

Рис. 2. Система координат и номинальные направления выдачи тяги двигателей коррекции орбиты в базовой схеме

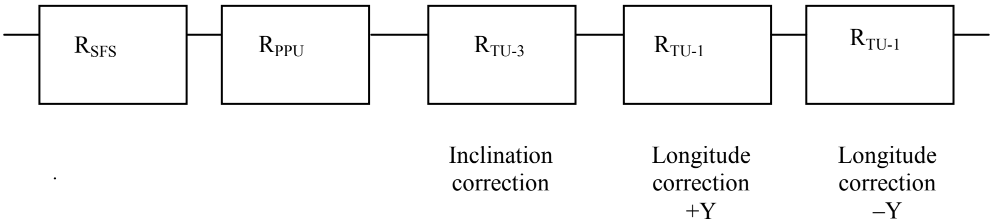

Fig. 3. Propulsion subsystem reliability scheme for the base version:
$R_{SFS}$ – reliability of xenon storage and feed system (storage unit and feed unit); $R_{PPU}$ – reliability of power processing unit; $R_{TU\text{-}3}$ – equivalent reliability of a scheme fragment for the correction of orbital inclination at triple reservation of the thruster units; $R_{TU\text{-}1}$ – equivalent reliability of a scheme fragment for longitude orbit correction in plus or minus directions at single reservation of the thruster units

Рис. 3. Структурная схема надежности подсистемы коррекции для базового варианта:
$Р_{СХП}$ – ВБР системы хранения и подачи ксенона (блок хранения и блок подачи ксенона); $Р_{СПУ}$ – ВБР системы преобразования и управления (СПУ); $Р_{ДК\text{-}3}$ – эквивалентная ВБР участка схемы для коррекции наклонения при трехкратном резервировании двигателей коррекции; $Р_{ДК\text{-}1}$ – эквивалентная ВБР участков схемы для коррекции долготы в направлении «плюс» или «минус» при однократном резервировании (дублировании) двигателей коррекции

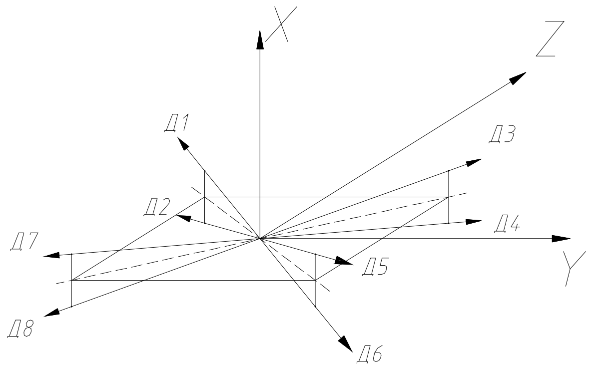

Fig. 4. The location of orbit control thrusters using hard attaching on the SC structure

Рис. 4. Размещение двигателей коррекции в схеме с неподвижным закреплением двигателей на корпусе КА

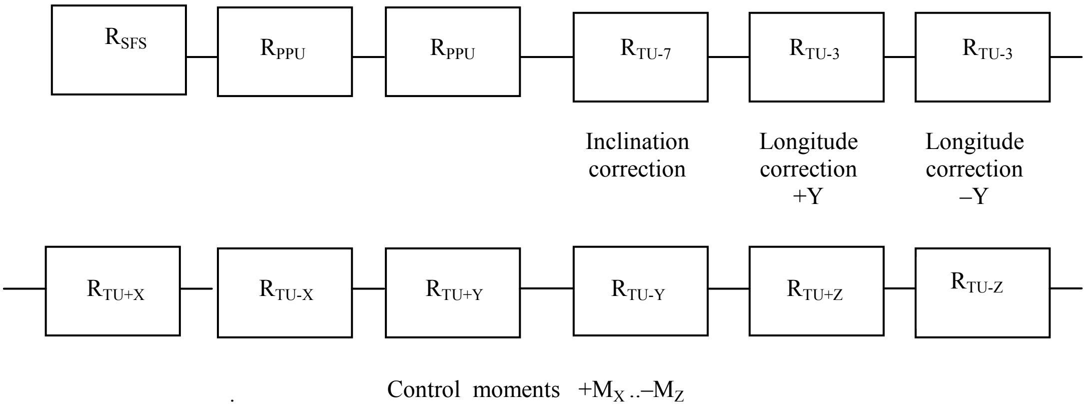

Fig. 5. The scheme of reliability of propulsion subsystem for the version with the combination of functions: $R_{SFS}$ – reliability of xenon storage and feed system (storage unit and feed unit); $R_{PPU}$ – reliability of power processing unit; $R_{TU\text{-}7}$ – equivalent reliability of a scheme fragment for the correction of orbital inclination at sevenfold reservation of the thruster units; $R_{TU\text{-}3}$ – equivalent reliability of a scheme fragment for longitude orbit correction in plus or minus directions at triple reservation of the thruster units; $R_{TU+X\ldots\text{-}Z}$ – equivalent reliability of scheme fragments for control moment creation at series-parallel reservation of thrusters

Рис. 5. Структурная схема надежности двигательной подсистемы с совмещением функций: $P_{СХП}$ – ВБР системы хранения и подачи ксенона; $P_{СПУ}$ – ВБР СПУ; $P_{ДК\text{-}7}$ – эквивалентная ВБР участка схемы для коррекции наклонения при семикратном резервировании двигателей коррекции; $P_{ДК\text{-}3}$ – эквивалентная ВБР участков схемы для коррекции долготы в направлении «плюс» или «минус» при трехкратном резервировании двигателей коррекции; $P_{ДК\pm X\ldots Z}$ – эквивалентные ВБР участков схемы при последовательно-параллельном резервировании двигателей коррекции для создания управляющих моментов

The article also represents the diagonal placement of eight engines in pairs with small (approximately 1°) deviations of the thrust lines relative to the center of mass to create control moments (fig. 4).

Engines work in pairs to create "pure" control moments of a certain sign on a certain axis, while a symmetrically located pair duplicates the selected one. Due to the lack of estimations of the reliability probability of the PPU for powering two engines, we have applied two similar PPU with the ability to power one thruster. The estimates of the reliability for such a device are known. If we take into account our assumptions, the structural scheme of the reliability of the propulsion subsystem with the combination of functions will have the form shown in fig. 5. Obviously, this scheme looks more complicated than the one shown in fig. 3.

The calculation using the above-mentioned structural schemes taking into account the known values of the reliability of the constituent elements shows $R_{INIT} \approx 0.9775$ for the initial scheme, and $R' \approx 0.9769$ for the scheme with the function combination, i. e. the reliability of the original version with independent propulsion subsystems is actually slightly higher, although the difference is observed only in the third decimal place.

For the version with the installation of orbit control thrusters on the drives, the structural scheme of reliability obviously must be different and it must take into account the reliability of the drives including mechanical components, electronic control units and flexible units for xenon feed. Probably the total reliability for such a scheme will roughly correspond to the version with fixed installation of the thrusters, that is, slightly lower than the original scheme contains.

The above-mentioned formal conclusions about the reduced reliability of the propulsion subsystem with the combination of functions are illustrated by using a simple example: if we assume that the electrical propulsion subsystem is completely or partially out of order, the problem of control moments creating is either not solved at all, or it is solved extremely limitedly by the auxiliary subsystem on a cold gas.

We should note that the inoperability of electrical propulsion can occur both as a result of internal and external causes. One of the main external reasons is the limitation of power consumption. So, in case of the failure in the orientation of spacecraft, it is actual to create control moments for its reconstruction. But in the non-orientable state, the orientation of solar cells is also disturbed, so the generation of electric power is reduced. The chemical battery capacity is limited. If in this case we use electrical propulsion, which are fairly powerful consumers of energy, for orientation, the problem of ensuring the survivability of spacecraft becomes very critical. In the case of the presence of two independent propulsion subsystems, even in case of disorientation, the thrusters creating control moments remain operational, since the energy necessary for their operation is enclosed in fuel itself.

Thus, to ensure the operational reliability and survivability of spacecraft, the concept of two independent propulsion subsystems (attitude control and orbit control) is preferable. With a certain arrangement of the attitude control thrusters, they can also be used to produce an orbit corrective impulse. In particular, certain SC of JSC "ISS" after the end of their service life in the presence of a residual fuel were taken to the disposal orbit by the orientation thrusters.

Thus, to ensure flexibility in application, the concept of two independent propulsion subsystems is useful as well. In this case, the algorithms for their use are completely separated from each other. That is, the program of ignition of orbit control thrusters is completely unrelated to the algorithm of attitude control thruster's ignition for momentum wheels unloading. Each correction session consists of one ignition of a thruster that is selected to output an impulse in a certain direction. If correction thrusters are used to create the control moments, the algorithms influence each other, therefore, for example, if the thrusters are fixed, the number of their ignitions in the correction session can increase to 6–8 [13; 14]. This complicates planning of corrections, as well as it puts additional demands on the resource of the thrusters according to the number of ignitions.

**Conclusion.** We have examined the essence of the concept of "all electric propulsion spacecraft". We can offer the following definition of this term: a spacecraft without an apogee propulsion system on chemical fuel, equipped with an electrical propulsion subsystem. This definition does not include the presence of any auxiliary propulsion subsystem onboard the spacecraft to provide initial orientation modes after separation from the upper stage and modes of ensuring survivability. We have shown that without such an auxiliary subsystem of orientation, the construction of the propulsion system of "all electric propulsion spacecraft" is impossible, therefore in its "pure form" with only electrically reactive thrusters this concept cannot be realized.

We have evaluated the advantages and disadvantages of the versions of the of "all electric propulsion spacecraft" propulsion subsystems in comparison with the version of two independent subsystems – for orbit control and attitude control of spacecraft. We have demonstrated that with the existing level of mass perfection of equipment, the concept of two independent propulsion subsystems has the advantage over other versions by total mass, operational reliability and ensuring survivability of the spacecraft, as well as for flexibility in application. The estimates of the mass of competing versions should be clarified in the development of more advanced thrust vector control devices.

## References

1. Popov G., Kim V., Murashko V. et al Electric Propulsion Subsystem Development and Application in Russia. 3rd International Conference "Spacecraft Propulsion". Cannes, France, October 10–13, 2000, 9 p.

2. Chien K., Hart S., Tighe W. et al. L-3 Communications ETI Electric Propulsion Overview. 29th International Electric Propulsion Conference. IEPC-2005-315. Princeton University. Oct. 31–Nov. 4, 2005, 16 p.

3. Lev D., Myers R.V., Lemmer K. M. et al.. The Technological and Commercial Expansion of Electric Propulsion in the Past 24 Years. 35th Electric Propulsion Conference. IEPC-2017-242. Georgia Institute of Technology. USA, October 8–12, 2017, 18 p.

4. De Tata M., Frigor P., Beekmans S. et al. SGEO Electric Propulsion Subsystem Development Status and Future Opportunities. 33rd International Electric Propulsion Conference. IEPC-2013-144. The George Washington University, USA, October 6–10, 2013, 11 p.

5. Casaregola C. Electric Propulsion for Station Keeping and Electric Orbit Raising on Eutelsat Platform. 34th International Electric Propulsion Conference, IEPC-2015-97. Kobe-Hyogo, Japan, July 4–10, 2015, 6 p.

6. Vnukov A. A., Rvacheva E. I. [Backgrounds and trends of all-electric propulsion geostationary satellites creation for the operation in geostationary orbit]. *Vestnik SibGAU*. 2014, No. 4(56), P. 140–146 (In Russ.).

7. Volkov D. V., Yermoshkin Y. M., Yakimov Y. N. [The application of propulsion subsystems of experimental design bureau "Fakel" on spacecraft developed by JSC "ISS"]. *Elektroreaktivnyie sistemy OKB "Fakel"* [Electric propulsion of EDB "Fakel"]. Kaliningrad, 2010, P. 113–119.

8. Lovtsov A. S., Tomilin D. A., Muravlev V. A. Development of High-Voltage Hall Effect Thrusters at Keldysh Research Centre. 68th International Astronautical Congress (IAC), Adelaide, Australia, September 25–29, 2017, 5 p.

9. Yermoshkin Y. M., Zhitnik Y. N, Ladygin A. P. [Development of the storage and feeding equipment for the spacecraft electric propulsion subsystems at JSC “ISS”]. *Materialy XIX mezhdunar. nauch. konf. “Reshetnevskie chteniya” posv. 55-letyu Sib. Gos. Aerokosm. Univers. ch. 1 pod red. Loginova Yu. Yu.* [Materials of the XIXth Intern. Scientific Conf. “Reshetnev readings” devoted to the 55th anniversary of SibGAU named after M. F. Reshetnev]. Ch. 1. Krasnoyarsk, November 10–14, 2015, P. 153–156 (In Russ.).

10. *Produktsiya OKB “Fakel”. Dvigatel K50-10.1* [The production of the experimental design bureau “Fakel”. Thruster K50-10]. Available at: http://www.fakel-russia.com/k50-10.html (accessed 18.12.2017).

11. Yermoshkin Yu. M., Raevsky V. A, Urusov V. M. [Geostationary spacecraft attitude and orbit control by motionless orbit control thrusters]. *Vestnik SibGAU*. 2009, No. 4 (25), P. 100–105 (In Russ.).

12. Yermoshkin Yu. M., Raevsky V. A, Urusov V. M. [Orientation and correction of the orbit of geostationary spacecraft: the scheme with the installation of correction thrusters on drives]. *Vestnik SibGAU*. 2010, No. 4 (30), P. 102–105 (In Russ.).

13. Ganzburg M. F., Kropotin S. A., Murashko V. M. et al. [The results of ten-year operation of electric thrusters within two telecommunication spacecraft Yamal-200 in the geostationary orbit]. *Space engineering and technology*. 2015, No. 4(11), P. 25–39 (In Russ.).

14. Ostrovsky V. G., Sukhov Yu. I. [Development and operation of electric thrusters and electric propulsion systems at the experimental design bureau-1 – TsKBEM – NPO “Energia” – RSC “Energia” named after S. P. Korolev (1958–2011)]. *Raketno-kosmicheskaya tekhnika. Trudy*. 2011. Ser. XII., Iss. 3–4, P. 122–127 (In Russ.).

### Библиографические ссылки

1. Electric Propulsion Subsystem Development and Application in Russia / G. Popov [et al.] // Spacecraft Propulsion : 3rd International Conference (Cannes. France. 10–13 October 2000).

2. L-3 Communications ETI Electric Propulsion Overview / K. Chien [et al.] // 29th International Electric Propulsion Conference. IEPC-2005-315 (Princeton University. Oct. 31 – Nov. 4. 2005). 9 p.

3. The Technological and Commercial Expansion of Electric Propulsion in the Past 24 Years / D. Lev, [et al.] // 35th Electric Propulsion Conference. IEPC-2017-242 (Georgia Institute of Technology. USA, October 8–12, 2017). 18 p.

4. SGEO Electric Propulsion Subsystem Development Status and Future Opportunities / M. De Tata [et al.] // 33rd International Electric Propulsion Conference. IEPC-2013-144 (The George Washington University, USA, October, 6–10, 2013). 11 p.

5. Casaregola C. Electric Propulsion for Station Keeping and Electric Orbit Raising on Eutelsat Platform // 34th International Electric Propulsion Conference, IEPC-2015-97 (Kobe-Hyogo, Japan, July 4–10, 2015). 6 p.

6. Внуков А. А., Рвачева Е. И. Предпосылки и перспективы создания полностью электрореактивных космических аппаратов для работы на геостационарной орбите // Вестник СибГАУ. 2014. № 4(56). С. 140–146.

7. Волков Д. В., Ермошкин Ю. М., Якимов Е. Н. Применение двигательных установок ОКБ «Факел» в составе космических аппаратов ОАО «ИСС» // Электрореактивные системы ОКБ «Факел». Калининград, 2010. С. 113–119.

8. Lovtsov A. S., Tomilin D. A., Muravlev V. A. Development of High-Voltage Hall Effect Thrusters at Keldysh Research Centre // 68th International Astronautical Congress (IAC) (Adelaide, Australia, 25–29 September, 2017). IAC-17-C4.4.4. 5 p.

9. Ермошкин Ю. М., Житник Ю. Н., Ладыгин А. П. Разработка в АО «ИСС» оборудования для хранения и подачи рабочего тела электрореактивных двигательных подсистем КА // Решетневские чтения : материалы XIX Междунар. науч.-практич. конф., посвященной 55-летию Сиб. гос. аэрокосмич. ун-та имени академика М. Ф. Решетнева : в 2 ч. Ч. 1 / под общ. ред. Ю. Ю. Логинова ; Сиб. гос. аэрокосмич. ун-т. Красноярск, 2015. С. 153–156.

10. Продукция ОКБ «Факел». Двигатель К50-10.1 [Электронный ресурс]. URL: http://www.fakel-russia.com/k50-10.html (дата обращения: 18.12.2017).

11. Ермошкин Ю. М., Раевский В. А., Урусов В. М. Проведение ориентации и коррекции орбиты геостационарного КА: схема с неподвижным закреплением двигателей коррекции // Вестник СибГАУ. 2009. Вып. 4 (25). С. 100–105.

12. Ермошкин Ю. М., Раевский В. А., Урусов В. М. Проведение ориентации и коррекции орбиты геостационарного КА: схема с установкой двигателей коррекции на приводах // Вестник СибГАУ. 2010. Вып. 4 (30). С. 102–105.

13. Итоги десятилетней эксплуатации электроракетных двигательных установок в составе двух телекоммуникационных космических аппаратов «Ямал-200» на геостационарной орбите / М. Ф. Ганзбург, [и др.] // Космическая техника и технологии. 2015. № 4(11). С. 25–39.

14. Островский В. Г., Сухов Ю. И. Разработка, создание и эксплуатация электроракетных двигателей и электроракетных двигательных установок в ОКБ-1-ЦКБЭМ-НПО «Энергия» – РКК «Энергия» им. С. П. Королева (1958–2011 г.) // Ракетно-космическая техника: Труды. Сер. XII. Королев : РКК «Энергия», 2011. Вып. 3, 4. С. 122–127.