3. Calibration of Low-Temperature Infrared Thermometers // MSL Technical Guide 22. 2009. URL: https://pdfs.semanticscholar.org/408a/354c752a4124f68369fa671d93f5acfba7fc.pdf
4. Doslidzhennia pokhybky ultrazvukovykh vytratomiriv za umov spotvorenoi struktury potoku na osnovi CFD-modeliuvannia / Pistun Ye., Matiko F., Roman V., Stetsenko A. // Metrolohiya ta prylady. 2014. Issue 4 (48). P. 13–23.
5. Turkowski M., Szufleński P. New criteria for the experimental validation of CFD simulations // Flow Measurement and Instrumentation. 2013. Vol. 34. P. 1–10. doi: https://doi.org/10.1016/j.flowmeasinst.2013.07.003
6. Random Number Generation and Testing. URL: http://csrc.nist.gov/groups/ST/toolkit/rng/index.html
7. Kondrashov S., Opryshkina M., Matsak O. Kontrol metrolohichnoho stanu system z neliniynymy pervynnymy peretvoriuvachamy za dopomohoiu testovykh vplyviv // Metrolohiya ta prylady. 2015. Issue 2. P. 33–41.
8. Volodarskiy E., Koshevaya L., Dobrolyubova M. Otsenivanie kachestva mnogoparametricheskogo tekhnologicheskogo protsessa pri korrelyatsii ego pokazateley // Metrolohiya ta prylady. 2017. Issue 5. P. 20–24.
9. ISO\IEC 17025-2005. General requirements for the competence of testing and calibration laboratories. International Organization for Standardization, 2005.
10. Montgomery D. C. Introduction to Statistical Quality Control. 6th Ed. John Wiley & Sons, 2009. 754 p.

UDC 629.783
DOI: 10.15587/1729-4061.2019.168446

DETERMINING THE REGIONS FOR EFFICIENT USE OF ELECTRO-JET LOW-THRUST ENGINES

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Робота присвячена питанням визначення оптимальних областей використання двигунної установки для космічних апаратів на низьких навколоземних орбітах. Проведено аналіз запусків космічних апаратів за останні 5 років. В результаті аналізу запусків був обраний тип космічних апаратів, для якого будуть проводитися розрахунки – супутник дистанційного зондування землі на низькій навколоземній орбіті. Була вирішена задача визначення параметрів траєкторії руху космічного апарату, на який впливають зовнішні непостійні сили. За результатами аналізу зовнішнього впливу визначено можливі перспективні області застосування рухових установок космічних апаратів. Виконано порівняльний аналіз з масового критерієм ефективності застосування рухових установок на основі хімічних монокомполентних і електрореактивних двигунів для вирішення завдань підтримки параметрів кругової орбіти протягом тривалого часу.

Для висот орбіт нижче 300 км застосування рухової установки за результатами розрахунків виявилося неефективним через необхідність наявності великого запасу палива на борту і великої необхідної тяги двигуна. Для супутників на кругових орбітах з висотами від 350 до 450 км двигунна установка, яка використовує двигун на ефекті Холла ST-25 SETS, виявилася ефективнішою, ніж хімічна двигунна установка. Застосування хімічних двигунів для підтримки параметрів орбіти висотою вище 500 км буде краще електрореактивних через відносно невелику масу хімічної двигунної установки і достатнього ресурсу роботи двигунів для підтримки параметрів орбіти протягом значного часу.

Були отримані параметри рухової установки, що використовує двигун на ефекті Холла ST-25, для підтримки параметрів орбіт в різних діапазонах висот, сонячної активності і геометричних параметрів супутника. В результаті розрахунків було визначено необхідний ресурс роботи і запас палива для підтримки параметрів орбіти.

Отримані результати розрахунків можуть бути використані при розробці нових супутників і модифікації супутникових платформ

Ключові слова: динаміка польоту, низькі орбіти, електрореактивний двигун, монокомпонентний двигун, підтримання орбіти

1. Introduction

Among the components of a successful space mission is the accurate output to the target orbit and maintaining its parameters over the entire time of its active existence. This purpose is achieved by applying various types of engines: from those based on compressed gas to electric ones. Different orbits and missions necessitate maintaining and adjusting the orbit.

At the stage of design, it is important to select the proper type of engine for a satellite since many parameters would depend on a given propulsion system. These parameters include the starting mass and dimensions of a satellite, energy consumption, background radiation, working temperatures, and others.

Electronic database [1] contains basic characteristics for the satellites launched as of April 2018. Table 1 summarizes the distribution of satellites for orbits, which was acquired based on an analysis of data provided by a given resource.

Table 1

Number of launched satellites based on output orbits and years

Launch year	LEO	MEO	GEO
2018 (up to April)	95	10	13
2017	344	7	38
2016	96	10	37
2015	98	11	38
2014	93	17	34
2013	74	6	26

According to official data by NASA [2], 38 % of the total number of the launched satellites account for the exploration of the Earth, which testifies to considerable interest in research that involves satellites. Table 1 shows that the largest quantity of satellites is at low orbit (including solar-synchronous) whose characteristics include:

– a relatively short lifetime of a satellite;

– a gradually lowering altitude of the orbit and a change in its shape;

– the minimum orbiting time and distance to the Earth among all types of orbits;

– the greatest influence of the atmosphere on the orbital parameters of a satellite.

Paper [3] considered the motion of a spacecraft at the initial circular orbit with a height of 450 km. It is shown that at the level of solar activity of 125 sfu the time required to lower the orbit of the spacecraft by 100 km would be up to 450 days. The subsequent lowering would proceed even more intensively. One should, of course, consider that solar activity changes over time and the result obtained for the stable value of solar activity will not exactly match the reality. For various spacecraft with different mass-dimensional characteristics the results will vary, however, the trends will continue.

Decreasing the altitude of an orbit while maintaining the remaining characteristics unchanged would shorten the lifetime of a satellite or would require an increase in the total pulse of a propulsion system in order to maintain the orbit. One should also note that some satellites require a specific spatial position to solve their preassigned tasks. In such a case, the lowering of the orbit might prove unacceptable even over a long time while orbital parameters must be maintained.

To maintain orbital parameters, engines of various types could be used (chemical, electro-jet, etc.). Application of different types of engines is due to the existence of advantages and disadvantages of each type of engine. For further consideration and comparison, we have accepted the monopropellant engine BGT-X5 [4] and the Hall electrojet engine, which is the best in terms of the traction to power ratio among electro-jet engines [5], specifically ST-25 [6].

The tasks on maintaining spacecraft orbits' parameters are particularly relevant to spacecraft at low near-Earth orbits due to the significant impact from the atmosphere. The emerging developments in the field of engines construction for satellites broaden possible applications of propulsion systems aimed at addressing the challenges on maintaining orbits. Earlier studies did not consider newly created technical solutions. The relevance of the current work is due to the necessity of selecting a modern propulsion unit to maintain the low-orbit satellite parameters over a long time.

The tasks on maintaining the parameters for spacecraft orbits are particularly relevant at low-Earth orbits given the considerable aerodynamic effect of the atmosphere. Modern technologies in the field of creation of low-thrust engines extend the functionality and options for the use of small propulsion systems, thereby solving new, not previously achievable, tasks on maintaining the orbits' parameters. Studies that were conducted earlier do not give recommendations for choosing the type and parameters of propulsion systems that could maintain the parameters for low orbits.

Therefore, it is a relevant task to select the optimal variant of a propulsion system for various applications.

2. Literature review and problem statement

Prospects of using electric engines with high capacity are discussed in [7]. The paper considers the application of engines in telecommunication satellites, for orbital maneuvers aimed at outputting to the orbit and the disposal of space equipment that ceased operation. The output maneuvers include long-haul missions such as: output into a geostationary orbit, output into a lunar orbit, the orbit of Mars, and others. The paper addresses the application of engines with a power of 20 kW to perform appropriate maneuvers. The authors did not consider low-thrust engines and, therefore, did not define their scope of application.

Study [8] gives calculations of thermal fields in hollow cathodes. The calculation procedure could be used when designing cathodes for the Hall low-thrust engines. This study did not consider options for the subsequent use of engine with new cathodes.

Paper [9] addresses the electric jet propulsion systems (EJPS) that are needed to maintain the orbit of a spacecraft (SC), to output a spacecraft into orbit, and to implement interplanetary missions. The focus is not on choosing an engine for the mission, but rather selecting the engine parameters to match the specified characteristics.

Work [10] identifies the qualitative advantages of using the electro-jet engines of various types and describes in detail the selection of an alternative fuel for the Hall engine. The calculations provided comparative results for different fuel types. It is only natural that leaders in the rating list of a working body is Xenon – the working body of ST-25.

Paper [11] noted that one of the key areas in the application of Hall engines is to maintain the parameters for low orbits. A limited lifetime of satellites at low orbits, according to the authors, is due to the need to have a large reserve of fuel to maintain the orbit altitude. It is proposed, in order to reduce the fuel reserve, to capture particles from the rarefied atmosphere; however, no calculation of the mass effectiveness of such a method was provided.

Article [12] gives an assessment of areas where electric jet propulsion systems are used. However, it was assumed that at high circular orbits the required total thrust for satellites could be up to 5 N, and at high elliptical up to 2,000 N, which was in no way substantiated while significantly narrowing the scope of EJPS application. To direct satellites at low orbits, they calculated the mass of a fully-fueled propulsion system under different required summary pulses of the system. That article did not specify the sources of information based on which the authors acquired the mass of engines designs, as well as related elements (a storage system and a feeding system for a working substance, the power system). The authors did not consider the systems' energy balance, nor the technological aspects of fabrication.

Paper [13] shows that for low orbits the ratio of the maximum atmospheric density to the minimum, for a particular circular orbit, can be up to four times or more. In this case, the magnitude of variance increases with an increase in the orbit altitude. It is proposed in that paper to account for changes in atmospheric density by approximation using a Fourier series. At the same time, the paper indicates that the third harmonic of decomposition is associated with the description of an "atmospheric hump" ("bloating" along the isolines of density in the region of direct sunlight). The influence of the third harmonic of decomposition ranges from 2 % to 10 % depending on the location of an orbit relative to the plane of symmetry of the "atmospheric hump".

Works [14, 15] consider the use of electric engines to maintain the orbit altitude. The main adopted perturbing factor was aerodynamic drag. However, it is difficult to understand the reasons behind an abrupt increase in the lifetime of a satellite at a decrease in the specific pulse of the engine below 1,000 s; the physics of the process suggests otherwise. The disadvantages of the considered variants include the absence of change in solar activity during lifetime and the absence of link to the actual characteristics and masses of satellites.

Paper [5] compares different types of propulsion systems that can be used at small SC, with the specific examples showing the relationships between different characteristics of the propulsion systems for different purposes. The paper gives no preferences or recommendations for choosing a certain type of the propulsion system for solving particular tasks.

Study [16] reports an analysis of the applicability of various types of engines to maintain the orbit and orbital maneuvers; the authors derived energy characteristics for different variants of using propulsion systems. However, the improved level of technology, as well as sufficient miniaturization of electronics, have changed the assumptions for assessments and findings reported in [16].

Given the above, it follows that there are almost no sources that had examined the effectiveness of maintaining an orbit by different types of SC over a predefined time range by specific engines.

3. The aim and objectives of the study

The aim of this study is to determine the optimal range of maintaining the orbit parameters for spacecraft for which the application of electro-jet propulsion systems would be efficient for the mass criterion. That will make it possible to reduce the starting mass of a satellite or increase the mass of target hardware.

To accomplish the aim, the following tasks have been set:

– to perform a comparative analysis for the mass criterion of electro-jet and chemical propulsion systems used to maintain the orbit parameters for spacecraft;

– to determine the parameters for an electro-jet propulsion system in terms of altitude of rational use for various aircraft configurations.

4. Materials and methods to study the motion of a spacecraft

In the presence of small perturbing forces, the differential equations of disturbed motion can be written relative to the osculating orbital elements [17]. As such, we shall use the greater semi-axis of orbit *a*, eccentricity *e*, a longitude of ascending angle Ω, inclination of the orbit to base plane *i*, a pericenter argument (angular distance of the pericenter from ascending node) ω, the average anomaly M_0 at elementary epoch t_0. Orbital elements will be derived depending on the Earth gravitational parameter K, true anomaly *v*, a latitude argument *u*, the eccentric anomaly *E,* focal parameter *p*, the mean motion *n* and the radius-vector of a moving point *r.*

Write such equations in the form:

$$\frac{da}{dt}=2a^2 e\sin\nu\cdot S'+2a^2 pr^{-1}, \tag{1}$$

$$\frac{de}{dt}=2p\sin\nu\cdot S'+p(\cos\nu+\cos E)T', \tag{2}$$

$$\frac{d\Omega}{dt}=\frac{r\sin u}{\sin i}W, \tag{3}$$

$$e\frac{d\omega}{dt}=-p\cos\nu\cdot S'+(r+p)\sin\nu\cdot T'-er\sin u ctg i\cdot W', \tag{4}$$

$$e\frac{d\overline{M_0}}{dt}=\sqrt{1-e^2}\,(p\cos\nu-2er)S'-$$
$$-\sqrt{1-e^2(r+p)\sin\nu\cdot T'}, \tag{5}$$

where

$$S'=\frac{1}{K\sqrt{p}}S;\quad T'=\frac{1}{K\sqrt{p}}T;$$

$$W'=\frac{1}{K\sqrt{p}}W;\quad \overline{M_0}(t)=M_0(t)+\int_{t_0}^{t}\left(\frac{dM}{dt}-n\right)dt,$$

where *S*, *T*, *W* are the projections of disturbing acceleration, respectively, onto the direction of the radius-vector of a moving point, transversal, and normal to the orbital plane.

The motion of an object in a gravitational field of the Earth can be described using the gravity field models of varying degrees of accuracy [18]. For preliminary calculations, we accepted a model of the central gravitational field. In accordance with work [18], we accept the greater semi-axis of the ellipsoid of rotation to be equal to 6,378 km, the small semi-axis – to 6,356 km. Despite the apparent smallness in the magnitudes of semi-axes, accounting for differences in the heights of a circular orbit when calculating aerodynamic forces shows fluctuations in the changes of values for forces of the order of 20 %. Common accounting for differences in heights and diurnal change in the atmospheric density (especially upper layers) shows the ratio of the maximum to the minimum atmospheric density up to seven [13].

A spacecraft on the orbit is exposed to the rarefied atmosphere and radiation from the Sun and other sources. Paper [18] compared various models of the upper atmosphere, among which are Jacchia 71, DTM, and others. In accordance with the recommendations and conclusions from [18], the model of the atmosphere for calculations is accepted in line with GOST 25645.101 and GOST 25645.115. Solar activity is defined by GOST 25645.302. A Schatten algorithm [18] also makes it possible to derive the projected levels of solar activity in the long term, but has the disadvantage related to a substantial simplification of the model of the magnetic field of the Sun's poles.

We shall consider the solar radiation pressure in line with the procedure proposed in [18]. The normal component of the pressure on the surface with area S, which has a reflection coefficient ε, shall be determined from formula (6).

$$P_n = (1+\varepsilon) P_0 \cos\lambda, \tag{6}$$

where $P_0 \approx 4.56 \cdot 10^{-6}$ Pa is the average solar radiation pressure in the Earth orbit, λ is the angle between a normal to the surface and the incident radiation.

The above equations of motion are considered in the plane of an orbit; the SC motion is obtained by numerical integration using the Euler method. The calculation algorithm is as follows: set the starting position and the speed of a spacecraft, calculate the forces and disturbing accelerations, compute the position of a spacecraft in space over the subsequent time, recalculate the forces, and the computation is repeated. Simultaneously with the calculation of the trajectory using equations (1) to (6), one records the results obtained. Upon computing every 10 hours of flight, one adjusts the daily time of enabling a propulsion system. At a decrease in the mean altitude of the flight the engines operation time increases, and vice versa. To implement a given algorithm, we developed the software whose source data for calculations include the following SC parameters: thrust, launch mass, specific impulse of the engine, etc. At the output, we obtain the SC coordinates and a velocity vector at each time point during computation. The program created made it possible to calculate a trajectory when the engine is not running over the entire flight time or when it is idling. Parameters for solar activity and the associated parameters for the atmosphere can be either predefined or take predicted values depending on time.

Given a rather large volume of the calculation results, this article will provide only the basic parameters for a trajectory at key time points. We have performed test calculations for several satellites launched earlier, for which we know the output orbits and orbits at the time of the calculation. The results from solving the ballistic problem numerically and the SC position in the orbit coincided with sufficient accuracy (up to 5 %). The error in the calculation results is due to that we used as the source values for solar activity an approximate model with average values. If one disables the module of the atmosphere calculation, the dynamic problem is solved with an error less than 0.001 % (in comparison with the analytical calculation procedure reported in papers [14, 19]).

5. Determining the regions of rational use of chemical and electro-jet engines

To run an analysis, we have chosen the SC motion orbit close to circular. Parameters for the atmosphere were taken to match the equatorial plane of the SC motion. A circular orbit is possibly preferable, but in actual calculations this is a weakly elliptic orbit. The eccentricity of the orbit was on the order of 10^{-6} to 10^{-7} for all calculations.

The adjustment of an orbit over 24 hours is performed by enabling electro-jet engines for different periods. At lower flight altitude, the time of PS operation over 24 hours increases, at an increase relative to the desired value – reduced. Such a behavior of the system that maintains the altitude of an orbit was accepted based on the uncertainty in accurate prediction of a value for the parameters of solar activity and the atmosphere at any point in time. Such a control scheme produces slight deviations in a flight altitude from the required one. It is obvious that if one has exact data on perturbing forces they can be compensated for with sufficient precision; the trajectory parameters would be unchanged over time.

When solving the set problems, we used specific models of the electro-jet and chemical engines. As an electro-jet engine, we took the promising engine ST-25 based on a Hall effect [6]. As a chemical engine, we selected the currently applied monopropellant engine BGT-X5 [4] on the fuel AF-M315E. Basic characteristics of these engines are given in Table 2.

Table 2

Basic characteristics of the electro-jet ST-25 and the monopropellant engine BGT-X5

Title	ST-25	BGT-X5
Specific pulse, s	1,200	225
Thrust, mN	8	500
Used power, W	200	20
Efficiency, %	25	–
Mass of propulsion system, kg	6	1.5
Operation resource, h	5,000	0.3
Fuel consumption over operation resource, kg	12	0.25

Table 2 shows that the monopropellant liquid chemical engine BGT-X5 cannot match those values for the total pulse that are implemented at ST-25. However, the mass of the chemical engine is significantly less; for small SC that do not require large summary pulses it may prove to be the most appropriate solution. The main advantages of chemical engines include a greater thrust per unit mass of the engine, which makes it possible to swiftly change the parameters for a SC trajectory.

We shall analyze the motion of SC along a circular orbit when this orbit's parameters are maintained separately by each of the examined engines. Because the parameters of the atmosphere change over time, it is difficult to assign the exact time for an engine to start within 24 hours in advance, even considering the indicative value for the average solar activity [19]. Therefore, we shall prolong the time for the engine to start when SC is lower than the specified orbit, and shorten the engine operation time when the orbital altitude is above the required value.

To specify the problem, we accept the SC mass to be equal to 250 kg, the area of midsection – 2 m^2. The calculation results are given in Table 3.

An analytical comparison of the Hall and chemical engines shows that for altitudes lower than 450 km the use of the first type of engines is justified for the criterion of minimizing the mass of the system. For altitudes of about 500 km the advantage of the Hall engine in terms of the mass of consumed working substance is larger, however, the total weight of the propulsion system is inferior to the system at the chemical engine. However, for such low energy tasks the use of a propulsion system with a single engine BGT-X5 is not possible due to low resource of operation. To perform the task under consideration and to ensure the specified operational mode, it is necessary to apply a propulsion system, which includes more engines than a single engine BGT-X5.

Table 3

Fuel consumption for maintaining the orbit, kg

Orbit altitude and EJPS used	Time to maintain the orbit, years				
	1	2	3	4	5
550 km, based on ST-25	0.39	0.76	1.01	1.07	1.1
500 km, based on ST-25	0.76	1.37	1.8	1.95	2.07
450 km, based on ST-25	1.39	2.75	3.48	3.91	4.14
400 km, based on ST-25	2.74	5.78	7.59	7.76	8.68
550 km, based on BGT-X5	1.7	3.89	4.94	5.23	5.62
500 km, based on BGT-X5	3.45	7.38	9.72	10.19	10.35
450 km, based on BGT-X5	7.08	13.6	18.31	19.59	20.86
400 km, based on BGT-X5	13.62	27.03	37.73	38.57	43.15

A possible promising application of low-thrust engines is to use them at very low orbits (from 200 km to 300 km) as components of earth remote sensing satellites (ERS). SC function over a very limited period and quickly lose altitude at such orbits. By applying PS at such devices, their service life at a preset orbit can be prolonged to reach an economically justified term. Currently, such orbits are not used for ERS due to a short satellite lifetime at such orbits and their rapid transfer to the atmosphere. Such SC may be commonly used because a low orbit can significantly reduce the cost and simplify the design of optical systems; however, there remains the unresolved issue of a short satellite's lifetime.

To assess the required time of engine operation and the corresponding fuel consumption, one can use the assumption on that the engine should offset the disturbing impact of external forces. By equating the pulse of aerodynamic force to the pulse of the engine force, we obtained the engine operation time for different areas of the satellite cross section under different solar activity. We calculated the effectiveness of applying EJPS based on the engine ST-25 to maintain the orbit. At such altitudes (from 200 km to 300 km) the main impact on the SC orbit is exerted by the atmosphere, which in turn depends on the SC geometry and a flight mode. The source data for the calculation are as follows:

– the cross-sectional area of a satellite (midsection) is constant; it is accepted to be equal to 0.5 m^2;

– the drag coefficient (C_x) is adopted to be equal to 2;

– solar activity is adopted to be equal to 125 sfu.

The results from calculating the work of EJPS based on the engine ST-25, as well as its comparison with the EJPS on chemical fuel (based on the engine BGT-X5), are given in Table 4. It is obvious that applying such an engine at a spacecraft in order to maintain the altitude of a circular orbit within the range under consideration is highly unlikely. However, engines on the same type of fuel have similar characteristics and the results will not be radically different from those obtained for another engine on the same fuel components.

An analysis of the results reveals a fundamental possibility to use the engines ST-25 in order to maintain the low orbit parameters. For orbits at altitudes of up to 250 km the use of such an engine would not yield tangible benefits due to the necessity of long switching. Even for a minimum area of the spacecraft midsection of suitable power, the engine operation time at an altitude of 200 km is about 50 % of the flight time. Hence, for half the time, solar panels should spend energy on engine operation, rather than the target hardware. We should also note that fuel consumption to maintain orbital parameters would be commensurate to the resource of engine operation, which does not provide for a reserve in case of emergencies and uncertainty of initial parameters. The situation is slightly better for a 250 km altitude, however, for it, the fuel consumption for maintaining the orbit is rather high. When one considers that the actual cross-sectional area may exceed the minimal one by 5 times, we face a situation similar to the previous case under consideration. Using a propulsion system at the orbit of altitude 300 km and above can significantly prolong the lifespan of a spacecraft. These orbits are devoid of deficiencies specified for the orbits of altitudes 200 and 250 km.

Table 4

Characteristics of PS to maintain a low orbit

Orbit altitude, km	Total operation time of engine over 24 hours	Daily fuel consumption (ST-25), kg	Annual fuel consumption (ST-25), kg	Daily fuel consumption (BGT-X5), kg	Annual fuel consumption (BGT-X5), kg
200	22 hours	0.040	15	0.29	100
250	5 hours	0.009	3.5	0.04	27
300	100 min.	0.003	1.2	0.02	8.0

6. Results of calculating the required resource for an electro-jet propulsion system to maintain the orbit parameters

Given the above, one can draw a preliminary conclusion on that the greatest effect from using EJPS based on the EJE ST-25, in terms of the criterion for a minimum mass, would be achieved at altitudes from 300 km to 450 km.

In order to refine the characteristics for a propulsion system, we calculated the decelerating pulse that is created by the aerodynamic drag force acting on a spacecraft positioned at a circular near-Earth orbit under the assigned levels of solar activity. The calculation was carried out in line with the procedure described in [19]: we determined the motion velocity of the satellite and atmospheric parameters for the assigned flight altitude along a circular orbit and solar activity. Geometrical parameters used were standard for a given type of satellites. The results from calculating the decelerating pulse are shown in Fig. 1. The results from calculating average daily time of enabling the engine in order to maintain orbital parameters depending on the altitude and solar activity are shown in Fig. 2. Based on the characteristics for the propulsion system, we determined the annual fuel consumption (Fig. 3) and the required resource of engine operation (Fig. 4) to perform the tasks under consideration. Calculating the required amount of fuel was based on the condition for equality between the decelerating pulse and the pulse of the engine thrust. The required resource of operation is linearly related to the amount of fuel and is needed to estimate the feasibility of inducing a force pulse by the propulsion system.

The calculation results show that at solar activity close to maximum the engine operation time does not exceed 50 % of the time of the entire flight. For other variants, the total engine operating time is only a small fraction of the time a spacecraft is in orbit. When considering using a spacecraft for remote sensing of the Earth, we can assume that enabling an engine to maintain the orbit can be performed over the regions where the sensing is not carried out (for example, over oceans). Based on the calculation results, we can draw a conclusion on the efficacy of using engines for the selected range of heights. The chemical fuel consumption for such a task would be approximately 5 times larger than the consumption of a working substance for the electro-jet engine. The mass of the propulsion system is considered to consist of the masses of the engine, fuel, and related systems (for example, a system to feed a working body). The mass effectiveness of using different types of propulsion systems is estimated based on the total mass of the systems that it includes.

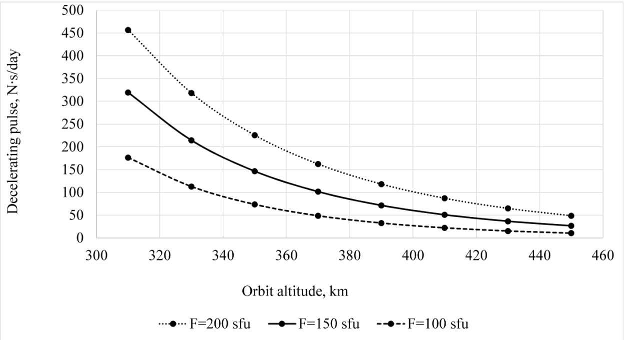

Fig. 1. Daily decelerating pulse of aerodynamic forces for the area of a spacecraft midsection of 2.55 m^2 at different average levels of solar activity

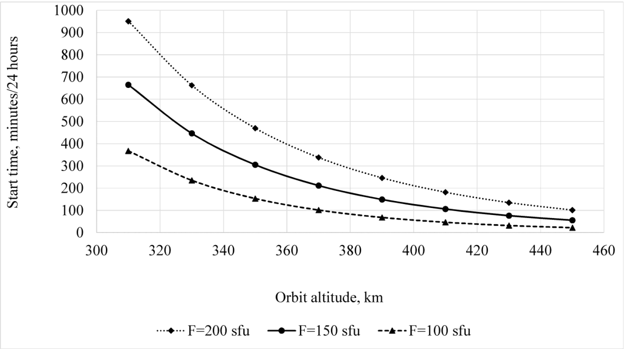

Fig. 2. Average daily start time of the engine to maintain orbital parameters for the area of a spacecraft midsection of 2.55 m^2 at different average levels of solar activity F

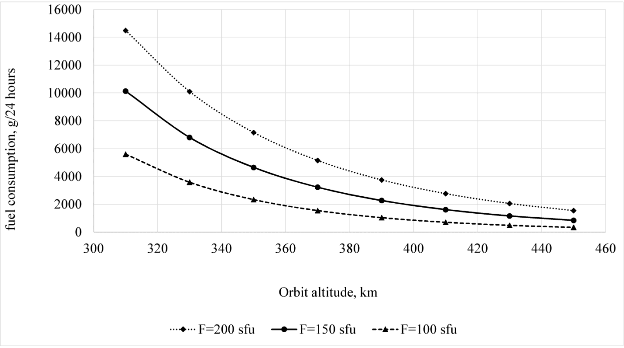

Fig. 3. Fuel consumption to maintain orbital parameters for the area of a spacecraft midsection of 2.55 m^2 at different average levels of solar activity F

For a propulsion system that employs the engine ST-25, the advantage of fuel reserve outperforms, completely and with a big margin, the large mass of the remaining systems. This indicates greater efficiency of the propulsion system with ST-25 in terms of a mass criterion compared to the propulsion system BGT-X5.

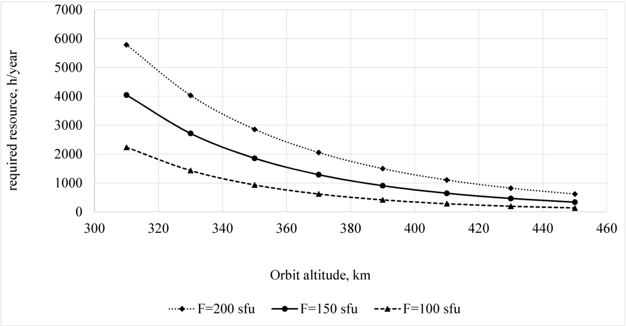

Fig. 4. The resource of engine operation required to maintain the orbit for a spacecraft midsection area of 2.55 m^2 at different average levels of solar activity F

It is expected that the system with an electro-jet propulsion system based on the EJE ST-25 will be used on spacecraft whose service time is longer than a year. We shall calculate the required fuel reserve and a resource of engine operation over 5 years in orbit within the specified range of heights. The calculation was carried out in accordance with the selected mathematical model of motion of a spacecraft. We assumed that the engine was enabled under a pulse mode. The total time of engine operation was chosen such that it would keep a spacecraft at the predefined altitude. Such a control over engine operation was selected in order to simulate parameters of the atmosphere that are not precisely defined in advance. Solar activity and the corresponding parameters for the atmosphere were forecast to launch a satellite at the end of 2020. Respective calculation results are given in Table 5.

Table 5

The required resource of engine operation and fuel consumption to maintain orbital parameters over 5 years

Orbit altitude, km	Fuel consumption, g			Operation resource, h		
	Midsection area, m^2					
	2.55	1.19	0.49	2.55	1.19	0.49
310	54,869	25,606	10,544	22,748	10,616	4,371
330	37,417	17,461	7,190	15,513	7,239	2,981
350	25,978	12,123	4,992	10,770	5,026	2,070
370	18,323	8,551	3,521	7,597	3,545	1,460
390	13,106	6,116	2,518	5,434	2,536	1,044
410	9,491	4,429	1,824	3,935	1,836	756
430	6,951	3,244	1,336	2,882	1,345	554
450	5,143	2,400	988	2,132	995	410

Table 5 shows that for most combinations of heights of the circular orbit and the geometries of spacecraft in the given orbits, the resource of a single engine ST-25 would be sufficient to perform the set task. For the case of the planned prolongation of the resource, it is possible to use the system that includes two identical engines. The use of such a system of dual-engines would make it possible to prolong the service time to the desired value and, if necessary, to increase the thrust of a propulsion system to perform a maneuver.

7. Discussion of results of studying the mass efficiency of applying propulsion systems to maintain orbital parameters

The results obtained are in good agreement with those reported in papers [14, 15]. Different approaches to estimating the mass and dynamic characteristics of spacecraft, employed in those papers, are based primarily on analytical procedures for assessing the impact of various external factors on orbital parameters. In addition, those papers applied the more precise aerodynamic coefficients for specific satellites. The differences are up to 5 %, which is negligibly small within the framework of the preliminary assessment.

Different methods to assign the source data in study [16] necessitated additional recalculation of the results obtained. The implicitly set required parameters and another statement of the problem do not make it possible to compare the results precisely; however, the results and conclusions are comparable.

Paper [19] outlined in detail the alternative approaches to solving problems on the orbital motion of spacecraft, including under the action of external forces, other than used in the current work. Among the described methods, analytical solutions make it possible to analyze the movement of an object under the influence of rather accurately assigned perturbations and to derive resulting formula to calculate the required magnitudes. In addition, paper [19] describes methods for solving numerically the differential equations of spacecraft flight dynamics, which provide similar solutions.

A more accurate accounting of atmospheric parameters is given in [13]. It has been shown that consideration of the Fourier series terms above 3 accounted for about 5 % of the total impact. Within the set problem, accounting for additional parameters considerably complicates the calculation algorithms and negligibly affects the result.

The results obtained in the current work could be applied when choosing propulsion systems for spacecraft, when there is a need and a possibility for using such systems for various combinations of spacecraft and their orbits. The results could be applied for spacecraft with a midsection area of 0.5 to 2.55 m^2, orbiting at heights from 200 to 600 km.

8. Conclusions

1. The result of our study is the identified mass characteristics for electro-jet and chemical propulsion systems for maintain the orbit parameters. For a height of the circular orbit to 300 km the use of a propulsion system can be difficult due to a large fuel amount required to maintain the orbit parameters over a long time. For the heights of a circular orbit from 350 km to 450 km the most effective solution based on the criterion of a minimum starting mass is the use of electro-jet propulsion systems, based, for example, on EJE ST-25. For altitudes above 500 km the use of electro-jet propulsion systems does not provide for a significant advantage over the chemical ones and could only be justified when a spacecraft performs additional orbital maneuvers.

2. We have determined the required resource of operation and the reserve amount of working fluid for a propulsion system based on the engine ST-25. To maintain the parameters for an orbit of spacecraft with a midsection area over 0.5 m^2 at altitudes of orbits from 300 to 450 km, it would suffice to have 5,000 hours of engine operational resource. The limit of applicability for the engine ST-25 passes through the heights of circular orbits from 300 to 390 km for different spacecraft configurations.

References

1. UCS Satellite Database. URL: https://www.ucsusa.org/nuclear-weapons/space-weapons/satellite-database
2. NASA Space Science Data Coordinated Archive, NASA's archive for space science mission data. URL: https://nssdc.gsfc.nasa.gov
3. Salmin V. V., Volotsuev V. V., Shikhanov S. V. Spacecraft preset orbital parameters control by means of thrusters // Vestnik Samarskogo gosudarstvennogo aerokosmicheskogo universiteta. 2013. Issue 4 (42). P. 248–254. URL: https://cyberleninka.ru/article/n/podderzhanie-zadannyh-orbitalnyh-parametrov-kosmicheskogo-apparata-s-pomoschyu-dvigateley-maloy-tyagi
4. BGT-X5 Green Monopropellant Thruster // Busek. URL: http://www.busek.com/index_htm_files/70008517E.pdf
5. Krejci D., Lozano P. Space Propulsion Technology for Small Spacecraft // Proceedings of the IEEE. 2018. Vol. 106, Issue 3. P. 362–378. doi: https://doi.org/10.1109/jproc.2017.2778747
6. SPS25 propulsion system. URL: https://sets.space/sps25/
7. Mission Scenarios for High-Power Electric Propulsion Space Propulsion 2018 / Mammarella M., Fusaro R., Andreussi T., Paissoni C. A., Viola N. et. al. // Conference: Space Propulsion 2018. 2018. URL: https://www.researchgate.net/publication/325119863_MISSION_SCENARIOS_FOR_HIGH-POWER_ELECTRIC_PROPULSION_SPACE_PROPULSION_2018
8. Pererva V. A., Karpovich E. V., Fedosov A. V. Development of penetration zone size prediction technique for hollow-cathode welding technology of spherical titanium tanks // Eastern-European Journal of Enterprise Technologies. 2016. Vol. 1, Issue 5 (79). P. 47–52. doi: https://doi.org/10.15587/1729-4061.2016.59790
9. Modern trends and development prospects of thrusters with closed electron drift / Zakharenkov L. E., Kim V., Lovtsov A. S., Semenkin A., Solodukhin A. E. // Conference: Space Propulsion 2018. 2018. URL: https://www.researchgate.net/publication/330116874_MODERN_TRENDS_AND_DEVELOPMENT_PROSPECTS_OF_THRUSTERS_WITH_CLOSED_ELECTRON_DRIFT

10. Initial investigation of alternative propellants for use with a low-power cylindrical hall thruster / Peter T., Dyer A., Ryan E., Garcia C. et. al. // In Space Propulsion 2018. 2018. 12 p. URL: https://eprints.soton.ac.uk/426412/
11. Development and experimental validation of a hall effect thruster RAM-EP concept / Andreussi T., Cifali G., Giannetti V., Piragino A., Ferrato E., Rossodivita A., Andrenucci M. // 35th International Electric Propulsion Conference Georgia Institute of Technology. 2017. URL: https://iepc2017.org/sites/default/files/speaker-papers/iepc-2017-377_ram_final.pdf
12. Yermoshkin Yu. M. Electric propulsions rational application range on the applied spacecrafts // Sibirskiy zhurnal nauki i tekhnologiy. 2011. Issue 2 (35). P. 109–113. URL: https://cyberleninka.ru/article/n/oblasti-ratsionalnogo-primeneniya-elektroreaktivnyh-dvigatelnyh-ustanovok-na-kosmicheskih-apparatah-prikladnogo-naznacheniya
13. Maslova A. I., Pirozhenko A. V. Izmeneniya plotnosti atmosfery pri dvizhenii kosmicheskih apparatov na nizkih okolozemnyh orbitah // Kosmichna nauka i tekhnolohiya. 2009. Issue 1. P. 13–18.
14. Ishkov S. A. Efficiency of using electric propulsion engines for the task of keeping in a near-circular orbit // VESTNIK of the Samara State Aerospace University. 2016. Vol. 15, Issue 1. P. 55–63. doi: https://doi.org/10.18287/2412-7329-2016-15-1-55-63
15. Ishkov S. A. Optimization of Design Parameters of Spacecraft Equipped with Electro Rocket Low-thrust Engine and Calculation its Applying Area at Low Earth Orbit // Procedia Engineering. 2017. Vol. 185. P. 239–245. doi: https://doi.org/10.1016/j.proeng.2017.03.306
16. Kontseptsiya ispol'zovaniya elektroraketnyh dvigateley na mikrosputnikah / Dron' N. M., Kondrat'ev A. I., Hit'ko A. V., Horol'skiy P. G. // Aviatsionno-kosmicheskaya tekhnika i tekhnologiya. 2008. Issue 9. P. 39–43.
17. Alpatov A. P. Dinamika kosmicheskih letatel'nyh apparatov. Kyiv: Naukova dumka, 2016. 487 p.
18. Montenbruck O., Gill E. Satellite Orbits: Models, Methods and Applications. Springer, 2005. 369 p.
19. Curtis H. D. Orbital Mechanics for Engineering Students. Butterworth-Heinemann, 2014. 768 p. doi: https://doi.org/10.1016/c2011-0-69685-1