Розглянуто один з шляхів очищення навколоземних орбіт від космічного сміття – відвід великогабаритних об'єктів, які являють небезпеку для космічної навігації та екології навколоземного простору, в щільні шари атмосфери Землі. Для його реалізації запропоновано комбінований метод з використанням реактивної двигунної установки й аеродинамічного вітрила. Двигунна установка забезпечує формування еліптичної орбіти відводу з перигеєм у верхніх шарах атмосфери, а аеродинамічне вітрило – поступове зниження швидкості за рахунок дії сили аеродинамічного опору. Показано, що поєднання активного й пасивного методів дозволяє частково компенсувати недоліки обох методів і реалізувати гарантований відвід об'єкта космічного сміття в щільні шари атмосфери з мінімальними витратами в заданий термін. При цьому ефективність запропонованого методу в багато чому залежить від стану верхньої атмосфери, яка є функцією сонячної активності, що змінюється з періодом 11 років.

Для визначення ефективних траєкторій руху об'єктів космічного сміття в верхніх шарах атмосфери вирішена задача про рух тіла в гравітаційному полі Землі з урахуванням динаміки атмосфери, а також з урахуванням циклів сонячної активності. Отримано залежності висоти перигею першого витка орбіти відведення, що забезпечує час існування не більше 25 років, і величини імпульсу швидкості, необхідного для формування орбіти відведення з низьких колових орбіт. Визначено енергетичні витрати на відведення об'єктів великогабаритного космічного сміття з врахуванням динамічно змінюваної атмосфери Землі. Проведено аналіз впливу сонячної активності на енергетичні витрати процесу відведення космічних об'єктів.

Результати роботи представляють практичний інтерес для розробки засобів комбінованого відведення великогабаритного космічного сміття з низьких навколоземних орбіт

Ключові слова: космічне сміття, гравітаційне поле, низька навколоземна орбіта, комбінований метод відведення, енергетичні витрати

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ANALYSIS OF BALLISTIC ASPECTS IN THE COMBINED METHOD FOR REMOVING SPACE OBJECTS FROM THE NEAR-EARTH ORBITS

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1. Introduction

At present, more than ten thousand various space debris objects move in low near-Earth orbits [1]. These include satellites that exhausted their service time, upper stages of carrier rockets, as well as fragments from explosions, destructions, and other emergencies.

The greatest potential danger of further increasing the amount of space debris is posed by unmanaged large-size space objects. These in the first place include defunct satellites and upper stages of carrier rockets, whose structures contain tanks with the remnants of fuel components, accumulating batteries, and other elements that are hazardous to destroy [2]. Destruction of such objects could lead to an even bigger complexity related to space debris.

One of the techniques to remove space debris is the removal of large-size objects in the dense atmosphere of the Earth where they would cease to exist [3]. However, the application of such methods requires careful planning of the motion trajectory of bodies because an incorrect decision increases the risks of hurting people and damaging objects of human life activities on Earth due to the fall of residues unburned in the dense layers of the atmosphere [4].

2. Literature review and problem statement

To date, a sufficiently large number of methods and technical solutions have been proposed for the removal of non-functioning spacecraft and their elements from the near-Earth orbits [5]. One of the most popular is the active method that uses jet propulsion systems. A given method makes it possible to ensure the guaranteed removal of an object within a specified time both in dense layers of the Earth's atmosphere and in higher orbit, including deep space. To implement a given method, tugs and various rocket propulsion systems are employed [6, 7], including thrusters [8, 9]. The disadvantage of this method is significant energy costs related to the need for fuel components to operate the systems that enable the removal process, which leads to the high cost of a particular implementation.

More economical is the passive method, which is based on the use of aerodynamic [10] or solar sailing devices [11] of various configurations. Disposal of space objects is ensured via the influence exerted on a target object by drag forces of the Earth's atmosphere and/or by pressure of sunlight. This method is easy to implement, requires no energy costs, but it has several limitations. The use of an aerodynamic sail is appropriate in orbits with a perigee altitude located in the Earth's atmosphere while a solar sail's effectiveness depends on the orientation of the plane of the orbit in the orthogonal direction on the Sun. The disadvantage of the method is that the removal process is long enough and can last for tens and even hundreds of years.

There are other schemes to remove space objects from the near-Earth orbits, which include the remote deceleration of an object. A given method is based on creating artificial atmosphere along the motion path of a target object by spraying chemical reagents, by influencing a target object in space debris with ionic radiation [12], by using generators of electric and magnetic fields, etc. [13]. However, a given method demonstrates low efficiency when removing large-sized space objects.

It is also possible to use cable systems. It has been proposed, following the end of the term of active existence in the near-Earth orbit, to deploy a special removal tool, which is located below the disposed object and is connected by a rope [14]. This approach is rather complex to implement, and requires working out specialized technical solutions.

Based on an analysis of existing space debris removal schemes, one can draw a conclusion on the feasibility of simultaneous use of a jet propulsion system and sail devices. Such a combination of active and passive means of removal makes it possible to partially compensate for the disadvantages of both methods and to implement the removal of space debris object to the Earth at minimal energy costs over tightly regulated time frame not exceeding 25 years.

At the same time, to develop the project means of the combined method of removal, it is necessary to determine energy costs on its implementation. That necessitates considering the ballistic aspects of the combined method taking into account the dynamically changing Earth's atmosphere.

3. The aim and objectives of the study

The aim of this work is to develop ballistic support for the implementation of the removal using a combined method.

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

– to design a schematic diagram for the combined removal of space objects from the near-Earth orbits;

– to develop a procedure for determining the removal scheme that would provide for the assigned lifetime of a coupler taking into consideration the minimization of energy costs by a jet propulsion system;

– to construct a mathematical model of the motion of a space object in the Earth's atmosphere during combined removal considering the dynamically changing solar activity;

– to simulate the removal of space objects from the near-Earth orbits using a combined method;

– to determine the impact of ballistic aspects on efficiency of the combined method of removal.

4. Schematic diagram of the combined method for removing space objects from the near-Earth orbits

Consider a combined scheme of disposing of large-sized space objects (SO) based on the link "means of removal – space object". A given scheme implies the use of a jet propulsion system and aerodynamic sail device (Fig. 1).

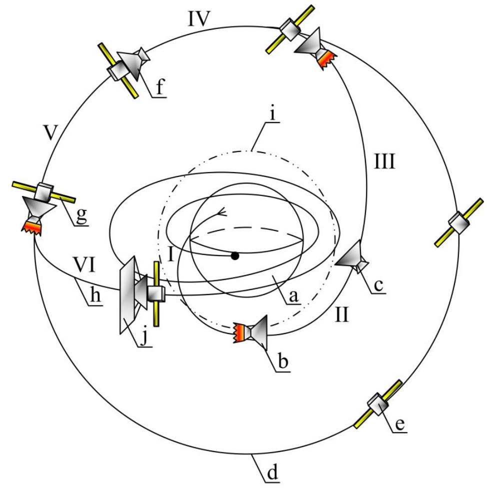


Fig. 1. Schematic of removal of large-size SO using a combined method: a – Earth; b – a means of removal with enabled jet propulsion system; c – a means of removal with disabled jet propulsion system; d – orbit of the disposed object; e – disposed object; f – link with disabled jet propulsion system; g – link with enabled jet propulsion system; h – disposal orbit; i – upper bound of dense layers of the Earth's atmosphere; j – link with aerodynamic sailed to sail

The scheme consists of the following specific sections: I – section of taking a means of disposing to the near-Earth orbit; II – passive section of flight of a means for removal with a reorientation towards SO; III – section to follow SO; IV – section to capture SO; V – section of reorienting the link, enabling a jet propulsion system, forming a disposal orbit; VI – passive section of link's flight to landing or termination of existence.

Determine the dependence of energy costs on removal, using a Tsiolkovsky formula and relations for the Goman transition [15]:

$$m_T(\nu_C) = m_0\left[1-\exp\left(-\frac{\Delta V}{9{,}80665\, I}\right)\right],$$

$$\Delta V = \sqrt{\frac{\mu}{h_H + R_e}}\left(\sqrt{\frac{2\tilde{r}}{\tilde{r}+1}}-1\right),\ \tilde{r} = \frac{h_\pi(\nu_C)+R_e}{h_H + R_e},$$

where m_T is the mass of propellant components, required to form a disposal orbit; m_0 is the mass of a link prior to enabling a jet propulsion system; h_{H} is the height of initial orbit; h_π is the disposal orbit's perigee height; I is the specific pulse of a jet propulsion system; μ is the gravitational constant; R_{e}=6,371.1 km is the average radius of the Earth; ν_{C} is the phase of solar activity at the time of removal start.

In a general case, the lifetime of an active-passive removal device based on a jet propulsion system and aerodynamic sail is a function of many variables

$$t_C = F\left(h_H, h_\pi, \sigma, \nu_C\right), \quad (1)$$

where σ is the ballistic coefficient of the link.

The schematic diagram of removal that provides for the assigned lifetime of link taking into consideration the minimization of energy costs by a jet propulsion system is represented in the form of an inverse problem using the following functional

$$\left[h_\pi, \nu_C\right]^T = \arg_{\substack{t_C \le t_{\max} \\ m_T \to \min}}\left\{F\left(h_H, h_\pi, \sigma, \nu_C\right)\right\}, \quad (2)$$

where $t_{\max}$ is the maximal lifetime of the link in the near-Earth orbit.

Solution procedure (2) consists of the following stages:

– the application of a Goman coplanar scheme of flights between two orbits, which is optimal in terms of energy costs;

– the construction of dependences of the link's lifetime on height of the initial orbit, the disposal orbit's perigee height;

– the determination of the disposal orbit's perigee height by minimizing the functional for each of the examined phases of solar activity

$$h_\pi\left(\nu_C\right) = \arg_{t_C \le t_{\max}}\left\{F\left(h_H, h_\pi, \sigma, \nu_C\right)\right\};$$

– the determination of the dependence of energy costs on a solar activity phase using a Tsiolkovsky formula and relations for the Goman transition;

– the minimization of functional

$$\nu_C = \arg_{m_T \to \min}\left\{m_T\left(\nu_C\right)\right\}$$

to calculate the phase of solar activity at the time of removal start.

5. Construction of a mathematical model of a space object motion in the Earth's atmosphere during a combined removal

To solve the set task, it is necessary to construct a mathematical model of the link motion considering the dynamically changing Earth's atmosphere.

Let us introduce assumptions:

– the link "a means of removal – space object" is a solid body;

– aerodynamic characteristics of the link for the three axes, associated with the body, are equal;

– only the translational motion of the center of mass of the link is considered;

– the Earth is the common earth ellipsoid WGS-84;

– the Earth's gravitational potential accounts for the effect of 2, 3 and 4 harmonics;

– the Earth's atmosphere is standard;

– the attraction of other celestial bodies and the pressure of sunlight are ignored;

– the index of geomagnetic activity is constant and equals 10.

Construct a mathematical model of the link motion on a removal orbit under the action of forces of attraction and the aerodynamic drag of the Earth's atmosphere. Consider differential equations of motion in the osculating orbital elements that take the form:

$$\left.\begin{aligned}
&\frac{dp}{dt} = 2\sqrt{\frac{p}{\mu}}TR,\\
&\frac{di}{dt} = \frac{WR\cos u}{\sqrt{\mu p}},\\
&\frac{d\Omega}{dt} = \frac{WR\sin u}{\sqrt{\mu p}\sin i},\\
&\frac{dl}{dt} = \sqrt{\frac{p}{\mu}}\left[S\sin u + T\left(\frac{p+R}{p}\cos u + \frac{R}{p}l\right) + W\frac{R}{p}h\operatorname{ctg} i\sin u\right],\\
&\frac{dh}{dt} = \sqrt{\frac{p}{\mu}}\left[-S\cos u + T\left(\frac{p+R}{p}\sin u + \frac{R}{p}h\right) - W\frac{R}{p}l\operatorname{ctg} i\sin u\right],\\
&\frac{du}{dt} = \sqrt{\frac{p}{\mu}}\left(\frac{\mu}{R^2} - W\frac{R}{p}\operatorname{ctg} i\sin u\right),
\end{aligned}\right\} \quad (3)$$

where p is the focal parameter; i is inclination; Ω is the longitude of ascending node; l and h are the Laplace parameters; u is the argument of latitude; S, T, W is the binormal and transversal disturbing accelerations; $R = p/\left(1 + l\cos u + h\sin u\right)$ is the geocentric distance to the link.

Determine disturbing accelerations included in (3). According to the assumptions made, accelerations will be determined as the geometric sum of accelerations of perturbation of the force of gravity of the Earth and the atmospheric drag force, that is :

$$\left.\begin{aligned}
&S = g_S + b_S,\\
&T = g_T + b_T,\\
&W = g_W + b_W,
\end{aligned}\right\} \quad (4)$$

where g_S, g_T, g_W are the radial, transversal, and binormal projections of the gravitational perturbations of the Earth's potential; b_S, b_T, b_W are the radial, transversal, and binormal projections of acceleration of the force of aerodynamic drag of the atmosphere.

Given the accepted normal gravitational potential of the Earth, we write:

$$\left.\begin{aligned}
&g_S = g_R + g_\omega \sin\varphi_e,\\
&g_T = g_\omega \sin i\cos u,\\
&g_W = g_\omega \cos i,
\end{aligned}\right\} \quad (5)$$

$$g_r = -\frac{\mu}{R^2}\left\{\begin{aligned}
&\frac{3}{2}\frac{a_e^2}{R^2}C_{2,0}\left(5\sin^2\phi_e - 1\right) +\\
&+\frac{5}{2}\frac{a_e^3}{R^3}C_{3,0}\sin\phi_e\left(7\sin^2\phi_e - 3\right) +\\
&+\frac{15}{8}\frac{a_e^4}{R^4}C_{4,0}\left[7\sin^2\phi_e\left(3\sin^2\phi_e - 2\right) + 1\right]
\end{aligned}\right\},$$

$$g_\omega = -\frac{\mu}{R^2}\left\{\begin{aligned}
&3\frac{a_e^2}{R^2}C_{2,0}\sin\phi_e - \frac{3}{2}\frac{a_e^3}{R^3}C_{3,0}\left(5\sin^2\phi_e - 1\right) -\\
&-\frac{5}{2}\frac{a_e^4}{R^4}C_{4,0}\sin\phi_e\left(7\sin^2\phi_e - 3\right)
\end{aligned}\right\},$$

$$\sin\varphi_e = \sin i\sin u,$$

where φ_e is the geocentric latitude; a_e is the large half-axis of Reference Earth Ellipsoid; $C_{2,0}$, $C_{3,0}$ and $C_{4,0}$ are the zonal harmonics of the Earth's gravitational potential.

Projections of the atmospheric drag force acceleration will be determined from expression

$$\left.\begin{aligned} b_S &= \sigma\rho V_O V_{OS}, \\ b_T &= \sigma\rho V_O V_{OT}, \\ b_W &= \sigma\rho V_O V_{OW}, \end{aligned}\right\} \qquad (6)$$

where ρ is the density of the atmosphere; V_{OS}, V_{OT}, V_{OW} are the radial, transversal, and binormal projections of relative velocity;

$$V_O = \sqrt{V_{OS}^2 + V_{OT}^2 + V_{OW}^2}.$$

Projections of relative velocity will be determined from ratios

$$\left.\begin{aligned} V_{OS} &= \sqrt{\frac{\mu}{p}}\left(l\sin u - h\cos u\right), \\ V_{OT} &= \sqrt{\frac{\mu}{p}}\left(1 + l\cos u + h\sin u\right) - \omega_e R\cos i, \\ V_{OW} &= \omega_e R\sin i\cos u, \end{aligned}\right\} \qquad (7)$$

where ω_e is the angular velocity of daily rotation of the Earth.

Density of the atmosphere is a complex function that depends on the height of a flight, solar activity index at a frequency of 2,800 MHz, an index of geomagnetic activity, direct ascension and declination of the Sun, as well as the Greenwich coordinates of the current position of the examined object.

Determine the latter

$$\left.\begin{aligned} x &= R\left(\cos(\Omega-\gamma)\cos u - \sin(\Omega-\gamma)\sin u\cos i\right), \\ y &= R\left(\sin(\Omega-\gamma)\cos u + \cos(\Omega-\gamma)\sin u\cos i\right), \\ z &= R\sin\phi_e, \end{aligned}\right\} \qquad (8)$$

where γ is the angle that defines position of the Prime Meridian relative to the direction towards vernal equinox.

Index of solar activity is conveniently represented as the Fourier series decomposition [16]. Approximate the statistics on average daily and weighted average, over 81 days, indexes of solar activity over the last two cycles by functions of the form

$$F_{10,7} = a_0 + \sum_{i=1}^{N_F} a_i \sin\left(m_i\omega\tau + \nu_i\right), \qquad (9)$$

$$F_{81} = a_0 + \sum_{i=1}^{N_F} a_i \sin\left(m_i\omega\tau + \psi_i\right), \qquad (10)$$

where $F_{10,7}$ is the average daily index of solar activity; F_{81} is the weighted index of solar activity over 81 days; τ is the number of days since 01.01.1987 a; ω, m, ν, ψ are coefficients (Table 1); N_F is the number of harmonics.

The initial conditions of motion:

At a time point following the braking pulse of velocity, the link "a means of removal – space object" moves on disposal orbit with the following parameters:

$$p_0 = \frac{2R_H R_\pi}{R_H + R_\pi}, \quad R_H = h_H + R_e, \quad R_\pi = h_\pi + R_e,$$

$$i_0 = i_H, \quad \Omega_0 = \Omega_H, \quad u_0 = u_H,$$

$$l_0 = \frac{R_\pi - R_H}{R_H + R_\pi}\cos u_H, \quad h_0 = \frac{R_\pi - R_H}{R_H + R_\pi}\sin u_H,$$

where i_H, Ω_H, u_H are the inclination, the longitude of an ascending node, and the argument of the perigee latitude of the initial orbit.

Table 1

Approximation coefficients of solar activity indices

i	$A\cdot10^{22}$	ω	m	ν	ψ
0	120.0	–	–	–	–
1	–52.8	0.001499	1	2.748076	2.671873
2	–11.9		2	1.129520	1.000345
3	–7.6		4	0.673236	0.461934
4	7.2		6	2.427329	2.073972

6. Results from simulating the removal of space objects from the near-Earth orbits using a combined method

Consider a ballistic analysis of the active-passive means of removal, executed on the basis of a jet propulsion system and aerodynamic sail.

Given:

– the link "a means of removal – space object" weighing 3 tons and whose ballistic coefficient is 0.001, 0.01 and 0.1 m^2/kg, which moves in a circular orbit with an inclination of (0 and 98.1 degrees) and a height of 300 to 1,500 km;

– specific thrust pulse of the jet propulsion system of a means of removal is 330 s.

Required:

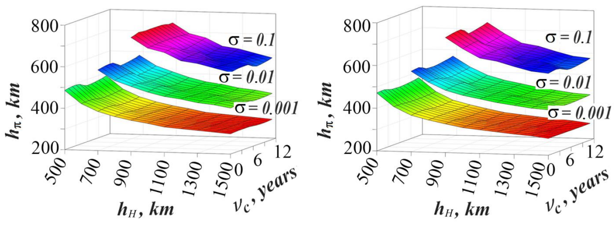
– to determine a velocity pulse, required to form a disposal orbit for the link with a lifetime not exceeding 25 years, which would take into consideration a change in the state of the atmosphere over an 11-year cycle of solar activity;

– to determine the minimal consumption of fuel components to ensure the removal taking into consideration a change in solar activity over an 11-year cycle;

– to determine a phase of solar activity, which ensures minimum energy costs for removal from low near-Earth orbits.

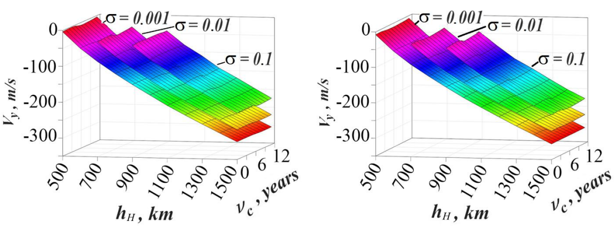
The phase of solar activity at the time point of the removal onset can be accounted for by choosing the appropriate removal date within the 24th cycle of solar activity, by selecting 11 points in time from 01.01.2009 00:00:00 to 01.01.2019 00:00:00 at an increment of one year.

The result of our simulation of the link's removal process using (3) to (10) is the derived dependences of the perigee height of the disposal orbit's first revolution, ensuring a lifetime not longer than 25 years (Fig. 2). Fig. 3 shows magnitudes for the velocity pulse, required to form a disposal orbit. Consumption of fuel components for the formation of a disposal orbit is shown in Fig. 4.



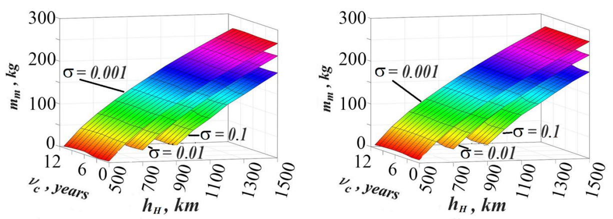
a b

Fig. 2. Dependence of perigee height of the first revolution h_{π} on the initial orbital altitude h_H and the phase of solar activity ν_c ν_C: *a* – i_H=0°; *b* – i_H=98.1°



a b

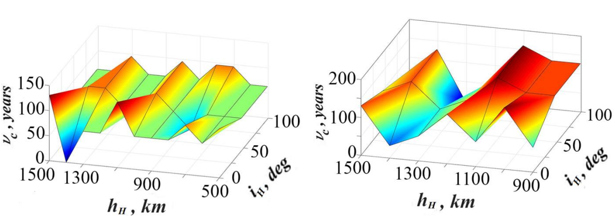
Fig. 3. Dependence of pulse velocity V_y on the initial orbital altitude h_H and the phase of solar activity ν_C: *a* – i_H=0°; *b* – i_H=98.1°



a b

Fig. 4. Dependence of fuel component consumption m_m on the initial orbital altitude h_H and the phase of solar activity ν_C: *a* – i_H=0°; *b* – i_H=98.1°

The result of solving a functional (2) is the following derived dependences of the phase of solar activity, ensuring the minimum energy costs for the removal of the link "a means of removal – space object" from circular near-Earth orbits, on height and inclination of the initial orbit (Fig. 5).



a b

Fig. 5. Dependence of the optimum phases of solar activity ν_C on the initial orbital altitude h_H and inclination angle of the initial orbit i_H: *a* – σ=0.001 m^2/kg; *b* – σ=0.1 m^2/kg

The results obtained demonstrate the impact of different ballistic aspects on the effectiveness of removing the examined object to the upper layers of the atmosphere.

7. Discussing the influence of ballistic aspects on efficiency of the combined method of removal

It follows from the above dependences that:

– the perigee height of the first revolution of the disposal orbit that provides a 25 years of lifetime, weakly depends on inclination of the initial orbit. Its values at minimum energy costs on removal in the range of the accepted initial conditions are: for σ=0.001 m^2/kg – 98...20 %; σ=0.01 m^2/kg – 90...30 %; σ=0.1 m^2/kg – 80–40 % of height of the initial orbit;

– the impact of a phase of solar activity on energy costs is a recurring in character. In the first approximation, it can be represented as a harmonic function with an amplitude that decreases in proportion to an increase in the height of the initial orbit. The amplitude of oscillations relative to the average value varies within ±4 %. In this case, the amplitude of velocity pulse oscillations relative to the average value does not exceed, for the ballistic coefficient of 0.001 m^2/kg, 2 m/s, for 0.01 m^2/kg – 3 m/s, for 0.1 m^2/kg – 4 m/s;

– energy costs for the removal from an equatorial orbit (inclination – 0 degrees) on average is 4–5 m/s lower than that for the Sun-synchronous (inclination – 98.1 degrees).

Based on data in Fig. 5, a minimum of energy costs for the formation of a disposal orbit with a lifetime of 25 years is observed for the phase of solar activity from 0° to 130°. The resulting minimum depends on height of the initial orbit and a ballistic coefficient (up to 4 years from the onset of the current cycle of solar activity).

In general, it can be argued that it is expedient, for the removal of large-size space debris objects from the low near-Earth orbits, to use the combined method based on applying both a jet propulsion system and an aerodynamic sail device.

Results of study [17] showed that the scope of application of the combined method is bounded below by the heights of orbits of 700–900 km depending on a ballistic coefficient. This scope is bounded at the top by the heights of 2,000–2,300 km, when consumption of fuel components for the combined removal becoming commensurate with a purely active method. In this case, the structure is complicated with an increase in the mass of a removal system due to an aerodynamic sail.

The prospects for further research include construction of a combined method for removal using thrusters and electrojet engines. In addition, it is of considerable interest to develop a design-ballistic support for the removal using auto-firing rockets-carriers [8], less costly, and environmentally friendlier, compared to conventional rocket-carriers.

8. Conclusions

1. We have designed a schematic diagram for the combined removal of space objects from the near-Earth orbits to ensure the removal of space debris objects within a specified time frame at minimal energy costs for a jet propulsion system.

2. We have proposed a procedure for implementing the combined removal scheme, ensuring the assigned lifetime of a space debris object and at minimum energy costs for a jet propulsion system.

3. A mathematical model has been constructed for determining effective motion trajectories of space debris objects in the upper layers of the atmosphere, which takes into consid-

eration the influence of atmospheric dynamics and cycles of solar activity, which made it possible to solve the problem on a body motion in the gravitational field of the Earth using the combined method for removing OS from low near-Earth orbits.

4. We have performed simulation of influence of the solar activity phase on energy costs. It is shown that such an influence is recurring in character, which in the first approximation can be represented as a harmonic function with an amplitude that decreases in proportion to an increase in the height of the initial orbit. In this case, the amplitude of oscillations relative to the average value varies within ±4 %.

5. It has been shown that energy costs for the removal from an equatorial orbit are, on average, 4–5 m/s lower than those for the Sun-synchronous. A minimum of energy costs for the formation of a disposal orbit with a lifetime of 25 years is observed for a solar activity phase from 0 to 130 degrees.

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