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ASSESSMENT OF PERSPECTIVES FOR THE ORBITAL UTILIZATION OF SPACE DEBRIS

Technogenic pollution of the near-Earth space by fragments of space debris of various sizes significantly limits the possibilities for implementing space activities and is a great danger to objects on Earth. Low orbits with heights up to 2000 km are particularly heavily clogged. The Inter-Agency Space Debris Coordination Committee recommends removing fragments of space debris from the area of working orbits. Currently, promising ways of space debris removal are considered: descent into the Earth's atmosphere, relocation to an orbit with a lifetime of less than twenty-five years, relocation to a utilization orbit, and orbital disposal. Orbital utilization considers space debris as a resource for the industry in orbit. The objectives of the article are to assess the perspectives for the orbital utilization of space debris and to develop a method for choosing the number and placement of safe recycling orbits in the area of low near-Earth orbits. The paper analyzes the prospects for the use of orbital utilization of space debris and the assessment of the possibilities of using orbital storage and subsequent reuse of dismantled space objects, instruments, and materials. A number of problems of planning and organizing the orbital utilization of space debris are formulated and solved. A method for determining safe orbits of space debris utilization in the area of low near-Earth orbits based on a criteria system developed. Using the developed method and software package, the possible orbits of space debris utilization in the area of low near-Earth orbits are determined. The lifetime of a space object in the utilization orbit, the stability of the orbit at a long time interval, and the energy consumptions for transferring the space object from the working orbit to the utilization orbit are estimated. The novelty of the obtained results lies in the development of a clustering technique for the orbits of utilized space debris objects and the development of a technique for selecting a possible orbit for the utilization of space debris in the area of low near-Earth orbits. The results obtained can be used in the planning and organization of the orbital utilization of space debris.

Keywords: *debris, removal, disposal, utilization, mathematical modeling.*

1. INTRODUCTION

Currently, the accumulation of space debris in near-Earth orbits is a significant problem. In accordance with the guidelines of the Inter-Agency Space Debris Coordination Committee (IADC) on the limitation of space debris in the near-Earth space, it is recommended to remove fragments of space debris from the working orbits' region. To implement the IADC recommendations on combating space debris, constructive measures are taken to prevent pollution of the near-Earth space, as well as active and passive methods of space debris removal from the area of working orbits. As a rule, space debris is removed to disposal areas in a higher altitude or a low earth orbit

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region. Space debris may be located in disposal areas for hundreds of years and does not impede the implementation of space projects. This method of removing debris reduces the risk of collisions in the source area but increases it in the disposal area. The space debris transferred to the region of low near-Earth orbits must have a lifetime of less than twenty-five years. When moving in a dense atmosphere, small fragments of space debris, as a rule, completely burn, unlike large ones, unburnt remnants of which can reach the Earth. Due to the large errors in predicting the movement of space debris fragments in the atmosphere, it is impossible to predict with sufficient certainty and in time the place and time of the fall of large fragments of space debris to the Earth. It is not possible to undertake the necessary measures to protect life and property.

At present, according to various estimates, about 7000 tons of space debris are in orbits. Low orbits with altitudes up to 2000 km are particularly badly clogged. It is estimated that the transfer of one kilogram of mass to a high orbit can exceed 10 thousand dollars. Most of the space debris consists of expensive specific equipment, devices, and materials used in the manufacture of rockets and satellites. In conditions of limited resources and the high consumption of their delivery into space, it is advisable to assess the perspectives for utilization of space debris and the subsequent use of equipment, devices, and materials dismantled from the failed satellites.

The utilization of space debris can bring several advantages. The economic benefit of utilization of space debris is the possibility of re-use it on the newly created space vehicles, in-service valuable equipment, devices, and materials. In addition, utilized space debris can also be used as a source of energy and working mass for the manoeuvres of a spacecraft. Regular utilization of space debris can significantly reduce the risks of collisions of operating spacecraft with space debris and the risks of falling of space debris fragments on the Earth. In connection with the above, it makes sense to consider the existing space debris as one of the types of near-Earth space resources [1—3]. It is assumed that some of the space debris can be stored and utilized directly in orbit. Well-chosen orbits of space debris utilization will not pose a significant threat to the functioning of a spacecraft.

2. FORMULATION OF THE PROBLEM

Assessment of the perspectives for orbital utilization of space debris requires a detailed study of a number of issues. They include: assessing the economic feasibility of utilizing fragments of space debris, developing utilization strategies, formulating requirements for service of space vehicles for implementing these strategies, assessment of technical, economic, law, and other aspects of such operations. The space debris utilization strategy includes the choice of spatial distribution and the number of orbital areas used for the utilization, the formation of a group of near ones in terms of the possibility of utilization of space debris fragments in orbit, the choice of priority for the utilization of space debris fragments.

The utilization of space debris involves the development of low-cost technologies for its collection and preservation in orbits. One of the possible utilization technologies involves the use of a service spacecraft, which, after the capture of the next space object, takes it to the utilization orbit. After some time, it returns for a new space object. The length of time a service spacecraft stays in a utilization orbit is determined by the difference in precession velocity of the utilization orbit plane and the orbit plane of the next utilized spacecraft. The flight is carried out at the moment of approximate coincidence of the longitude of the ascending node of the utilization orbit and the orbit of the object being utilized.

The utilization of large space debris requires the creation of a service spacecraft, which must be equipped with special means for conducting remote and contact operations with fragments of space debris. Currently, reusable orbital service space vehicles are considered as the most prospective for resolving this problem. Perspective areas of research on the creation of methods and means of the utilization of large-sized fragments of space debris are the creation of means of docking of service spacecraft with fragments of space debris and the development of service spacecraft for utilization of space debris fragments.

The work aims to assess the perspectives of the orbital utilization of space debris and to develop a method for choosing the number and spatial placement of safe orbits for utilization in the area of low near-Earth orbits.

3. CLUSTERING OF THE ORBITS OF SPACE DEBRIS FRAGMENTS

When planning the utilization of space debris, it is necessary to take into account the limited energy possibilities of a service spacecraft. In this connection, the problem arises of rationally splitting up a set of orbits of space debris fragments into subsets (clusters) of orbits that are available for utilization by a single service spacecraft. Each orbit of the space debris fragment should belong to only one cluster, and the orbits belonging to the cluster should be near in terms of energy consumptions for the interorbital transfer between them.

To date, a sufficiently large number of cluster analysis algorithms have been developed: hierarchical algorithms, non-hierarchical iterative algorithms, graph algorithms, fuzzy clustering algorithms, algorithms using neural networks, genetic algorithms [4, 7, 10]. To solve the problem of clustering orbits of a service spacecraft, it is rational to use the *k*-means clustering algorithm, which belongs to the group of non-hierarchical methods of cluster analysis [7]. The advantages of the *k*-means algorithm are the simplicity and speed of its use, clarity, and transparency of the algorithm. The disadvantages of the algorithm include the need to specify the number of clusters before clustering.

Let us represent the elements of the set of orbits of space debris fragments $X = \{x_1, x_2, ..., x_n\}$ in the form of their characteristic vectors. Later, we will fully identify the orbit with its characteristic vector, which is a set of orbital parameters. It is required to divide this set of orbits into k clusters S_1, S_2, ..., S_k. Each orbit should belong to one cluster only located at the smallest distance from this orbit. The distribution of the orbits in clusters must satisfy the criterion of optimality, expressed in terms of the distance $\rho(x_i, x_j)$ between any pair of orbits of the considered set. When splitting the original set X of orbits of space debris fragments into k clusters S_1, S_2, ..., S_k, it is proposed to apply an iterative algorithm of *k*-means that minimizes the sum of squares of distances from each point of the cluster to its centre. As a distance (metric) between the orbits $\rho(x_i, x_j)$, any non-negative real function can be used that is defined on the set X and satisfies the following conditions:

$$\rho(x_i, x_j) = 0 \text{ only when } x_i = x_j , \qquad (1)$$

$$\rho(x_i, x_j) = \rho(x_j, x_i) , \qquad (2)$$

$$\rho(x_i, x_j) \le \rho(x_i, x_k) + \rho(x_k, x_j) . \qquad (3)$$

When splitting the original set of orbits X into k clusters $S_1, S_2, ..., S_k$, an iterative algorithm *k*-means is used. It minimizes the sum of distances from each point of the cluster to its centre.

The action of the k -means algorithm comes down to a search:

$$\arg\min_{s} \sum_{i=1}^{k} \sum_{x \in S_i} \rho(x, \mu_i) , \qquad (4)$$

where $S = \{S_1, S_2, ..., S_k\}$, μ_i are cluster centres $i = 1, ..., k$, $\rho(x, \mu_i)$ are distances between orbit x and cluster centres μ_i .

In the sequel, a variable t is used to indicate the iteration step number. At the first step of the algorithm *k*-means execution, the initial values of the cluster centres μ_i^0 are determined. Arbitrary points of the orbit characteristics are chosen as the initial values of the cluster centres. In the next step, the orbits are distributed among the clusters.

All orbits are grouped into clusters, the distances to the centres of which are minimal

$$\forall x_i \in X, i = 1, ..., n : x_i \in S_j \Leftrightarrow j = \arg\min_{k} \rho(x_i, \mu_k^{(t-1)}). \qquad (5)$$

The next step is to recalculate the centres of the changed clusters.

$$\forall i = 1, 2, ..., k : \mu_i^{(t)} = \frac{1}{|S_i|} \sum_{x \in S_i} x . \qquad (6)$$

The process of calculating the centres and redistributing of the orbits continues until one of the conditions is satisfied: the cluster centres have stabilized, i. e., all orbits belong to the cluster to which they belonged before the current iteration or the number of iterations is equal to the maximum number of iterations.

An important step in the clustering of orbits of space debris fragments is the choice of a metric by which the proximity of the orbits is determined. This is due to the fact that the results of clustering can differ significantly when using different metrics. The choice of metrics is ambiguous, and this is the main difficulty. Most often, the Euclidean metric is used in clustering problems. Other standard metrics are also widely used: the square of the Euclidean distance, the distance of city blocks, and the Chebyshev distance. Along with the listed metrics, a number of other, less common metrics are also used [4, 7].

Attempts to cluster orbit space debris using standard metrics did not lead to positive results. In this connection, for clustering orbits of space debris fragments, it was proposed here to use a non-standard energy metric — delta-velocity of interorbital transfer between these orbits. The introduction of the energy metric made it possible to successfully cluster the orbits of space debris.

4. SELECTION OF UTILIZATION ORBITS

The selection of orbits of utilization was carried out using the following criteria: the annual catastrophic collision probability of a utilized spacecraft with space debris in a utilization orbit, the lifetime of a spacecraft in the utilization orbit, stability of the orbit of utilization over long time intervals, and energy consumptions for transferring the spacecraft from an initial orbit to the utilization orbit. The selection of orbits of utilization was carried out in the region of low Earth orbits. Near-circular orbits were considered as possible utilization orbits. The annual probability of a catastrophic collision with space debris was used as a criterion for the destruction of a spacecraft in the orbit of utilization. Catastrophic collisions are characterized by the complete destruction of the spacecraft, and non-catastrophic collisions are characterized only by the loss of its functionality. The condition for a catastrophic collision of a spacecraft with space debris is considered to be collisions with specific impact energy greater than 35...45 J/g [8, 12].

The selection of orbits suitable for utilization was carried out according to the criterion of the minimum possible annual catastrophic collision probability of the utilized spacecraft with space debris. To determine the annual catastrophic collision probability, the ESA MASTER-2009 model of space debris was used [5]. In constructing the space debris model, along with experimental data, statistical approaches, various collision and fragmentation models, as well as additional a priori information are widely used.

The ESA MASTER-2009 space debris model allows for a given orbit of a spacecraft with a cross-sectional area S to obtain an estimate of the annual probability of its collision with fragments of space debris, the dimensions of which are contained in the interval (d_1, d_2). To estimate the annual catastrophic collision probability of a spacecraft with space debris, the Poisson distribution is used:

$$P(S, d_1, d_2, N) = 1 - \exp(-N)\,, \qquad (7)$$

where P is the annual catastrophic collision probability of a spacecraft with space debris when moving in a given orbit, N is the annual number of collisions of a spacecraft with space debris with specific impact energy greater than 35...45 J/g.

To determine the average number of collisions $N(d_1, d_2)$, mainly statistical methods are used. Their use is due to the fact that for non-catalogue fragments of space debris, only distributions of size, mass, and orbital parameters can be specified.

The basis of statistical methods is the D. Kessler method [8, 11], which determines the average number of collisions $N(d_1, d_2)$ according to the formula:

$$N(d_1, d_2) = S \rho V_{rel} \Delta t\,, \qquad (8)$$

where S is the cross-sectional area, $\rho(d_1, d_2)$ is average concentration of space debris, V_{rel} is average relative velocity of the spacecraft and space debris, Δt is the time interval of the spacecraft movement in orbit.

The selection of orbits suitable for utilization was carried out using the predicted values of the annual catastrophic collision probability of the utilized spacecraft with the space debris. For forecasting, the ESA MASTER-2009 [5] and DRAMA [6] software packages were used.

The calculations were performed for a family of near-circular orbits with an eccentricity of 0.0001 and discretely varying altitude and inclination of the orbits. The longitude of the ascending node and the argument of perigee did not vary. The estimated calculations showed that the variation of these parameters has practically no effect on the annual catastrophic collision probability of a recycled spacecraft with space debris. The step of changing the orbit altitude is 100 km, and the step of changing the orbit inclination is 10°. During the calculations, it was assumed that the sizes of fragments of space debris are in the range from 0.01 m to 30 m, the cross-sectional area of the utilized spacecraft $S = 5$ m^2, the mass of the utilized spacecraft $m = 500$ kg, the specific energy of catastrophic destruction — 40 J/g.

Fig. 1 shows a graph of the annual catastrophic collision probability of utilized spacecraft with space debris in the low-Earth orbit region.

The graph in Fig. 1 makes it possible to estimate the annual catastrophic collisions probability in the region of low near-Earth orbits and highlight orbits with increased space debris. It can be seen from the graph that the maximum annual catastrophic collision probability of a spacecraft with space debris is reached in near-circular orbits with inclinations of 80°, 90°, 100°, 70°, and 60°. It is advisable to carry out the utilization of space debris in these orbits in the first place.

Fig. 2, Fig. 3 show graphs of the annual catastrophic collision probability of the utilized spacecraft for orbits with large quantity and small quantity space debris.

From the graphs in Fig. 2, Fig. 3 it can be seen that the curves of the annual catastrophic collision probability of spacecraft with space debris for orbits with the considered inclinations have a similar character. The absolute maximum of the annual catastrophic collision probability in height was reached at altitudes of ~800 km. The second and third clearly defined local maximums were reached at altitudes of 1400...1500 km. At an altitude of ~1700 km, a

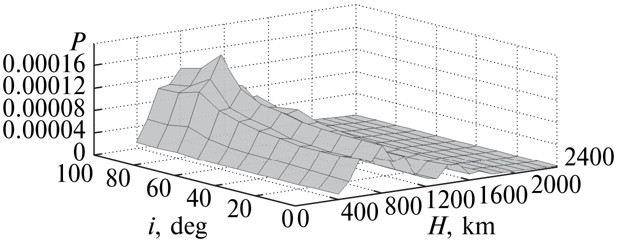

Fig. 1. Estimation of the annual catastrophic collision probability in the region of low near-Earth orbits

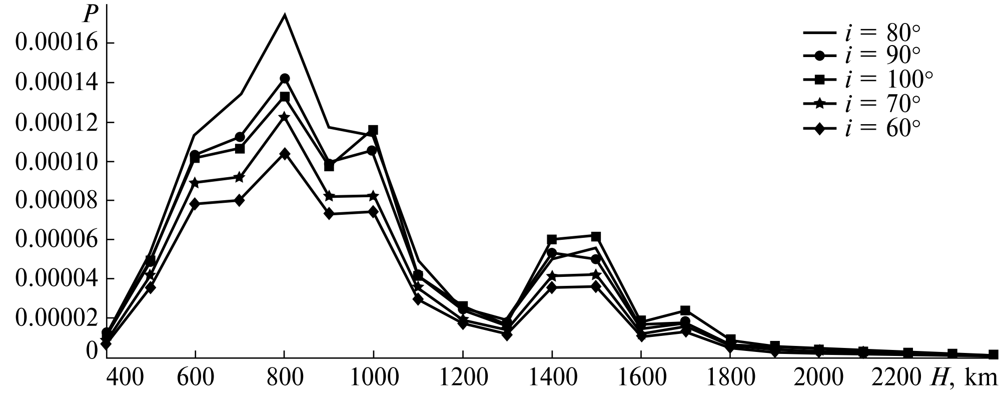

Fig. 2. Estimation of the annual probability of catastrophic collisions for orbits with large quantity of space debris

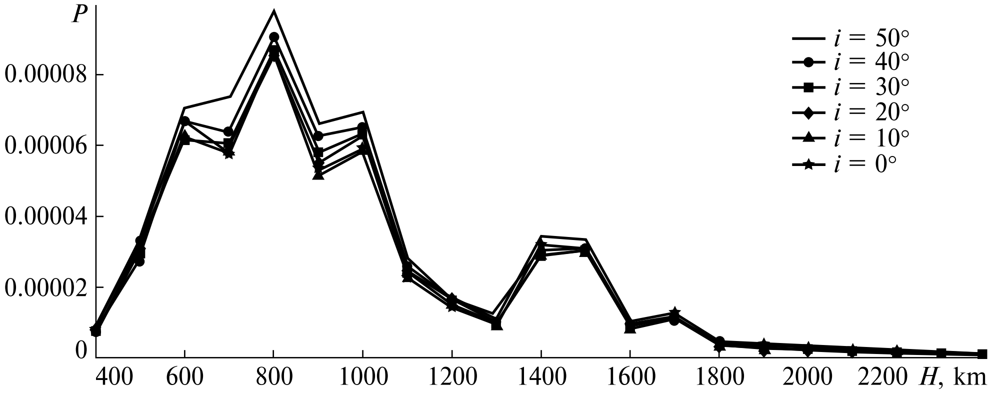

Fig. 3. Estimation of the annual probability of catastrophic collisions for orbits with small quantity of space debris

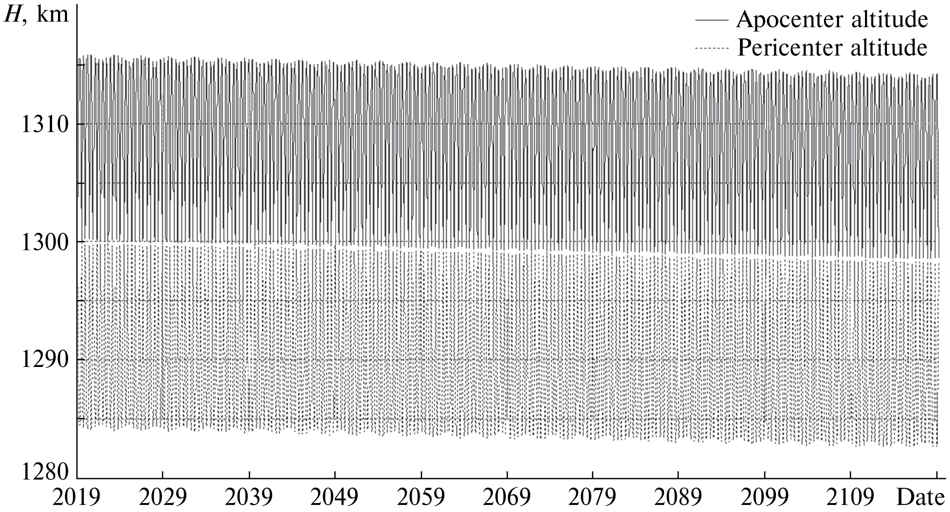

Fig. 4. Changing the apocenter and pericenter altitude H of the utilization orbit vs. time ($H^0_{me} = 1300$ km, $i_0 = 80°$, $e_0 = 10^{-4}$, $C_b = 0.006$, the beginning of the movement 01.02.2019)

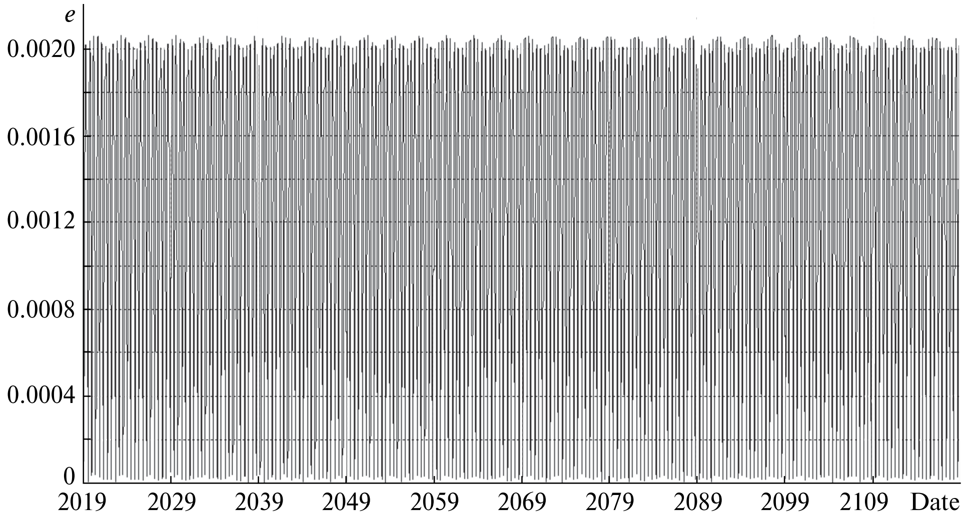

Fig. 5. Changing the eccentricity e of the utilization orbit vs. time ($H^0_{me} = 1300$ km, $i_0 = 80°$, $e_0 = 10^{-4}$, $C_b = 0.006$, the beginning of the movement 01.02.2019)

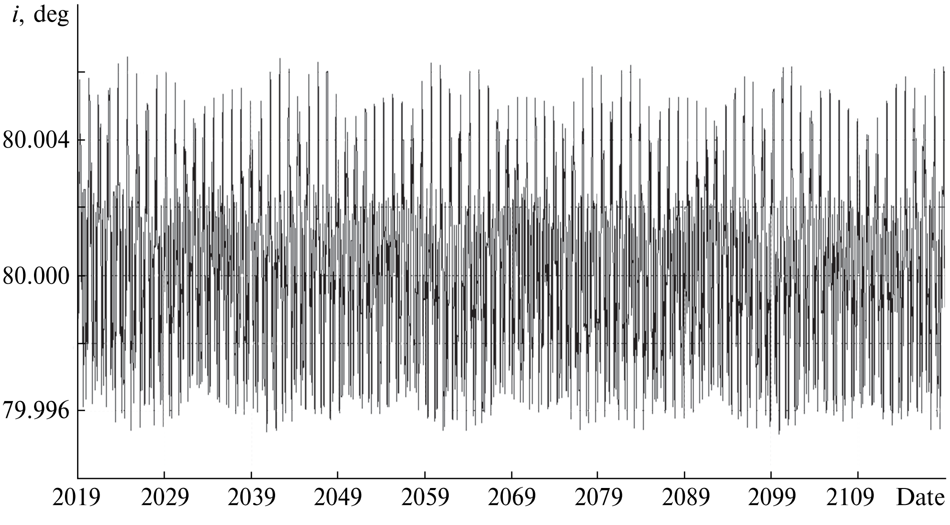

Fig. 6. Changing of inclination i of the utilization orbit vs. time ($H^0_{me} = 1300$ km, $i_0 = 80°$, $e_0 = 10^{-4}$, $C_b = 0.006$, the beginning of the movement 01.02.2019)

weakly expressed local maximum is realized. Local minimums were reached at altitudes of ~1300 km and at altitudes above 1800 km. As a result of the analysis performed, it is proposed to use near-circular orbits with mean altitudes of ~1300 km and above 1800 km as possible orbits for the utilization of space debris.

5. ASSESSMENT OF THE STABILITY OF UTILIZATION ORBITS

The estimation of the ballistic lifetime of spacecraft in the orbit of utilization and the stability of the utilization orbit over a long time interval was carried out using high-precision numerical prediction of their motion. To predict the motion, the DRAMA software package [6] was used, which implements a complete and accurate mathematical model of the perturbing forces acting on the spacecraft. The following forces were considered as such forces: forces arising due to the non-sphericity of the Earth's gravitational field and the force of aerodynamic drag of the atmosphere. As the analysis showed, the influence of other perturbing forces in determining the ballistic lifetime and evolution of the orbits of spacecraft that begin their motion in the orbits of utilization can be neglected.

In the DRAMA motion model, the gravitational potential of the Earth was used taking into account five harmonics of its decomposition in accordance with the GEM-T1 model of the gravitational field of the Earth [9]. The density of the atmosphere was determined according to the model of the atmosphere NRLMSISE-00. The indices of solar and geomagnetic activity used in this model corresponded to the FOCUS-1A data [8]. The spacecraft motion was predicted using the universal method of numerical integration of the corresponding differential equations [6], which has high computational efficiency in terms of accuracy and speed.

In the research, the ballistic lifetime and the evolution of spacecraft orbits in space after their transfer from working orbits to utilization orbits was estimated.

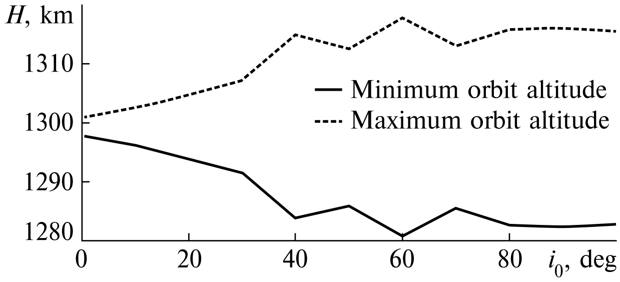

Fig. *7.* Changing of maximum and minimum altitude of utilization orbits vs. the initial orbit inclination (H_{me}^0 = 1300 km, e_0 = 10^{-4}, C_b = 0.006, the beginning of the movement of 01.02.2019)

As utilization orbits, we considered the use of the lowest near-circular orbits with initial mean altitudes of H_{me}^0 ~ 1300 km, H_{me}^0 ~ 1800 km and eccentricities $e_0 = 10^{-6}$ and $e_0 = 10^{-4}$ with orbital inclinations i_0 = 0°, 10°, 20°, 30°, 40°, 50°, 60°, 70°, 80°, 90°, 100°. In the calculations, the ballistic coefficient of the spacecraft assumed the following values: 0.004, 0.006, and 0.01 m^2/kg. The ballistic coefficient was calculated by the formula

$$C_b = \frac{C_d S}{2m},$$

where C_d is drag coefficient, S is the cross-sectional area, m is the mass of the spacecraft.

In addition, it was assumed that the beginning of the movement of a spacecraft in the utilization orbits accounted for 01.02.2019. The stability of the orbits of spacecraft that begin their motion in utilization orbit has been estimated for 100 years. The evolution of the orbits was studied in the time interval 2019—2119. The results of the calculations showed that for all considered variants, the predicted duration of the ballistic lifetime of spacecraft that begin their motion in the orbits of utilization exceeds 100 years.

Fig. 4—Fig. 6 show the results of the prediction of the evolution of the parameters of the spacecraft orbit, which begins its movement in a utilization orbit with a mean altitude of H_{me}^0 ~ 1300 km.

The graphs in Fig. 4—Fig. 6 demonstrate that changes of the apocenter altitude, pericenter altitude, eccentricity, and inclination of the considered orbit of utilization obey the oscillatory law, have a negligible small secular drift, and are stable over a long time interval. The results of the prediction of the evolution of the parameters of the orbit of the spacecraft, which begins its motion in utilization orbits with a mean altitude above 1800 km, look similar.

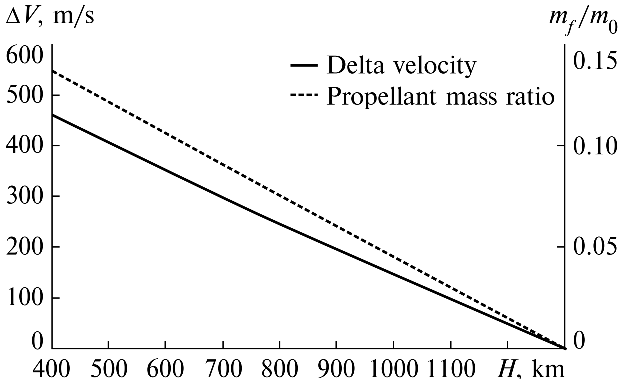

Fig. 8. Delta-velocity and propellant mass ratio m_f/m_0 required for coplanar transfer between near-circular working orbits of the altitude 400...1300 km and orbit utilization with mean orbit altitude H_{me} = 1300 km

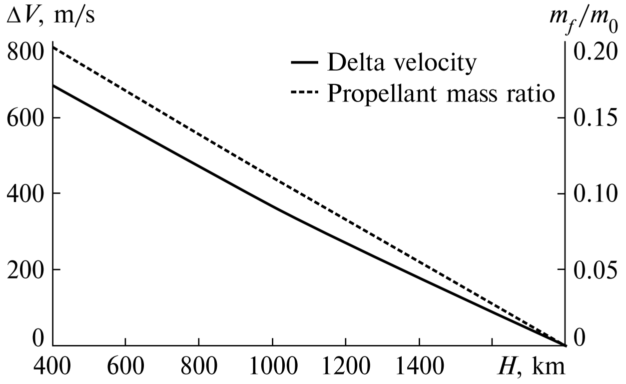

Fig. 9. Delta-velocity and propellant mass ratio required for coplanar transfer between near-circular working orbits of the altitudes 400...1800 km and orbit utilization with mean orbit altitude H_{me} = 1800 km

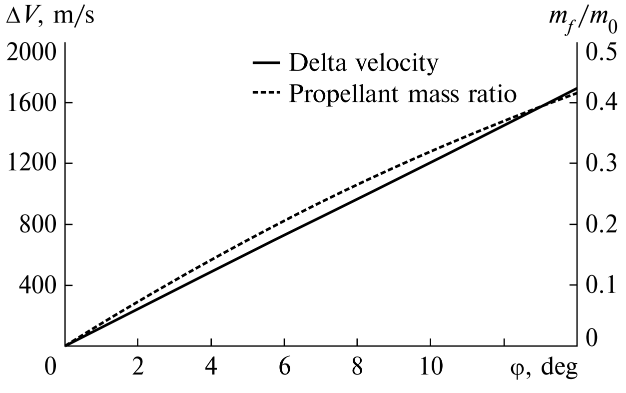

Fig. 10. Delta-velocity and propellant mass ratio required for rotation of the orbital plane (rotation altitude of the orbital plane = 1800 km)

Fig. 7 shows the results of an assessment of the dependence of the change of the maximum and minimum altitude of the utilization orbit over 100 years, depending on its initial inclination.

The graphs in Fig. 7 illustrate the significant dependence of the maximum and minimum altitudes of the orbit for utilization over 100 years from its initial inclination. The difference between the maximum and minimum altitudes of the utilization orbit reaches a maximum with an initial inclination of the orbit $i_0 = 60°$ and is ~36 km. The variation of the ballistic coefficient and eccentricity within the considered limits led to a slight change in the maximum and minimum altitudes of the utilization orbit over 100 years. (Change did not exceed 1 km).

As a result of assessing the stability of the orbits of spacecraft that begin their motion in the considered orbits of utilization, it was found that the maximum oscillations of the apocenter altitude and pericenter altitude over a period of 100 years did not exceed 20 km and 15 km, respectively. The eccentricity oscillations did not exceed 0.0021, and the inclination variations did not exceed 0.01°.

The obtained results indicate the sustainability for 100 years of orbit of utilization with mean altitudes of ~1300 km and ~1800 km.

6. ASSESSMENT OF THE ENERGY CONSUMPTION OF TRANSFERRING A SPACECRAFT FROM THE WORKING ORBIT REGION TO THE ORBIT OF UTILIZATION

The energy consumptions of transferring the spacecraft from the working near-circular orbits of the altitude range 400 km to 1300 km into the utilization orbit with a mean altitude of 1300 km and from the original near-circular orbit of the altitude range 400 km to 1800 km into the utilization orbit with a mean altitude 1800 km were estimated. To estimate the energy consumptions of interorbital transfers, the delta-velocity and propellant mass ratio for the transfer were used.

A tri-impulse interorbital transfer of a spacecraft from the working orbit to the utilization orbit was considered. First, a two-impulse coplanar Hohman transfer was carried out from the initial near-circular orbit to a circular orbit with a mean orbit radius equal to the radius of the utilization orbit. Then the plane of the resulting orbit was rotated to coincide with the plane of the orbit of utilization.

The propellant mass ratio for the transfer of the spacecraft to the utilization orbit was determined by the K. E. Tsiolkovsky formula:

$$\frac{m_f}{m_0} = 1 - \exp\left(\frac{\Delta V}{gI_{\text{sp}}}\right), \qquad (9)$$

where m_f is the required propellant mass for transfer the spacecraft to a utilization orbit, m_0 is the total mass of a charged transporting spacecraft and transported spacecraft, ΔV is delta-velocity of the orbital transfer to the utilization orbit, I_{sp} is the specific impulse of the propulsion system of the spacecraft, g is the acceleration of gravity.

At estimating the propellant mass ratio for the transfer of the spacecraft to the utilization orbit, it was assumed that the specific impulse of the propulsion system of the spacecraft was $I_{\text{sp}} = 320$ s.

Fig. 8—Fig. 10 show the dependences of delta-velocity and the propellant mass ratio required for spacecraft orbital transfer from the working orbits into the utilization orbit with a mean orbit altitude of 1300 km.

It can be seen from the graphs in Fig. 8—Fig. 9 that the spacecraft transfers from the working orbits to the utilization orbits may require from 0 to 0.2 propellant mass ratio.

From the graphs in Fig. 8—Fig. 10 it can be seen that the rotation of the orbital plane is energetically much more expensive than the change of the mean orbit altitude. Therefore, it is advisable to choose the number and inclination of the orbits of spacecraft utilization in such a way that the inclination of the orbits of the utilized spacecraft and the orbits of the utilization does not exceed 5 degrees.

7. CONCLUSIONS

The paper analyzes the perspectives for the use of orbital utilization of space debris for cleaning near-Earth space from technogenic pollution and assesses the possibilities of long-term orbital storage and subsequent reuse of devices, instruments, and materials dismantled from recycled spacecraft when solving problems of the further exploration of near-Earth space. There are formulated and solved a number of problems arising in the planning and organization of the orbital utilization of space debris. A technique has been developed for clustering of orbits of utilized space debris objects.

A methodology for determining safe orbits of space debris utilization in the area of low near-Earth orbits based on a formulated criteria system has been developed. The methodology includes: selection of a utilization orbit by the criterion of the minimum possible annual catastrophic collisions' probability of a utilized spacecraft with space debris, estimating the lifetime of a spacecraft in utilization orbit, assessment of the sustainability of the orbit of utilization over long time intervals and assessment of energy consumption for transferring the spacecraft from the working orbit to the orbit of utilization. Using the developed methodology and software package, possible orbits of space debris utilization in the area of low near-Earth orbits are determined. As utilization orbits, it has been proposed to use near-circular orbits with mean altitudes of ~1300 km and above 1800 km. The number and inclination of the utilization orbits are proposed to be chosen in such a way that the inclination of the working orbits of the spacecraft and the utilization orbits does not exceed 5 degrees. The results obtained can be used in the planning and organization of the orbital utilization of space debris.

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ОЦІНКА ПЕРСПЕКТИВ ОРБІТАЛЬНОЇ УТИЛІЗАЦІЇ КОСМІЧНОГО СМІТТЯ

Ріст техногенного забруднення навколоземного космічного простору фрагментами космічного сміття різного розміру істотно обмежує можливості реалізації космічної діяльності й становить велику небезпеку для об'єктів на Землі. Особливо сильно засмічені низькі орбіти з висотами до 2000 км. Актуальність забезпечення безпеки космічних польотів в умовах техногенного забруднення навколоземного космічного простору і зниження небезпеки для об'єктів на Землі при неконтрольованому входженні космічних об'єктів у щільні шари атмосфери і їхньому падінні на Землю стрімко зростає. Відповідно до керівних принципів Inter-Agency Space Debris Coordination Committee фрагменти космічного сміття рекомендується видаляти з області робочих орбіт. Зараз як перспективні способи видалення космічного сміття розглядаються: спуск у щільні шари атмосфери Землі, переміщення на орбіту зі строком життя менш ніж двадцять п'ять років, переміщення на орбіту поховання та орбітальна утилізація. Відповідно до концепції орбітальної утилізації космічне сміття розглядається як ресурс індустрії на орбіті. Метою статті є оцінка перспектив орбітальної утилізації космічного сміття та розробка методики вибору кількості й просторового розміщення безпечних орбіт утилізації в області низьких навколоземних орбіт. У статті проаналізовано перспективи використання орбітальної утилізації космічного сміття для очищення навколоземного космічного простору від техногенного забруднення та оцінено можливості тривалого орбітального зберігання й наступного повторного використання для розв'язку задач подальшого освоєння навколоземного космічного простору пристроїв, приладів і матеріалів, демонтованих з утилізованих космічних об'єктів. Сформульовано та вирішено ряд задач, що виникають при плануванні й організації орбітальної утилізації космічного сміття. Розроблено методику визначення безпечних орбіт утилізації космічного сміття в області низьких навколоземних орбіт. Методика базується на сформульованій системі критеріїв. З використанням розроблених методики та пакету програм визначено можливі орбіти утилізації космічного сміття в області низьких навколоземних орбіт. Оцінено тривалість життя космічного об'єкта на орбіті утилізації, стійкість орбіти утилізації на тривалих часових інтервалах і енергетичні витрати для переведення космічного об'єкта з робочої орбіти на орбіту утилізації. Новизна отриманих результатів полягає в розробці методики кластеризації орбіт об'єктів космічного сміття, що утилізуються, й розробці методики вибору можливих орбіт утилізації космічного сміття в області низьких навколоземних орбіт. Отримані результати можуть знайти застосування при плануванні та організації орбітальної утилізації космічного сміття.

Ключові слова: *космічне сміття, видалення, поховання, утилізація, математичне моделювання.*