About some features of the distribution of relative accelerations in the vicinity of the satellite in the region of GEO orbits

A. S. Horbachova
Odesa National I.I. Mechnikov University,
Faculty of Mathematics, Physics and Information Technologies,
Department of Theoretical Physics and Astronomy
O. A. Bazyey
Odesa National I.I. Mechnikov University,
Faculty of Mathematics, Physics and Information Technologies,
Department of Theoretical Physics and Astronomy
Odesa National Maritime University,
Faculty of Shipbuilding, Information Technology and System Engineering,
Department of Mathematics, Physics and Astronomy,

ABSTRACT

Along with the development and achievements of cosmonautics, another type of objects in near-Earth space appeared - space debris. It poses a threat to satellites and future missions. According to the size, fragments of space debris are classified into four categories: 10 centimeters and more, from 1 to 10 centimeters, from 0.3 to 1 centimeter and less than 0.3 centimeters. It is spread over all Earth orbits and has selected areas of orbits with a greater concentration of them. This is explained by the events of intentional and unintentional destruction of satellites in the past. As a result of a number of such events, as well as the launch of satellites into near-earth orbit and the abandoning of spent rocket bodies, for almost 60 years in the field of GEO orbits, the number of fragments of space debris has reached almost 900. Several cases of destruction of working satellites and spent rocket bodies are already known. This poses an immediate threat to operating satellites in the field of GEO orbits. Therefore, there is a need to research the features of the space debris environment in the vicinity of the orbits of such objects. Along with the fact that space debris poses a threat to the future development of cosmonautics and modern achievements of the 21st century, these objects are of interest for modeling the movement of such objects in near-Earth space.

Key words: space debris, space vehicles, fragmentation, collision probability, computer simulation, celestial mechanics.

1. INTRODUCTION

The first artificial satellite of the Earth was launched into orbit on October 4, 1957. Since then, the active ”settlement” by spacecraft began, first of the near-Earth orbits, and then of the rest of the Solar system. In near-Earth space, their number began to grow rapidly. To put communications satellites into orbit or to study the planets and their satellites, it was necessary to use a launch vehicle. The launch vehicle worked out its resource and also remained in orbit. Along with the constant successes of mankind in the aerospace industry, frequent launches of spacecraft, the number of objects in orbit is continuously increasing [1]

As of 2022, about 6 340 missile launches have been carried out. The number of satellites that were launched into near-Earth orbit by these launches is about 14 710, of which 9 780 are still in orbit. Nevertheless, of the latter, about 7 100 satellites operate, and those satellites that no longer function are classified as space debris. [2]

Space debris is any type of space object created by man that is no longer in use. This may be either a no longer operating spacecraft, or a launch vehicle or fragments thereof, or any objects released by astronauts. [3]

The amount of space debris that is tracked and cataloged is about 32 500. Since 1961, more than 560 fragmentation events have been recorded in Earth orbit. Only 7 of them were associated with collisions, and other fragmentation events occurred due to explosions of spacecraft and the upper stages of launch vehicles. [2]

Fragments of space debris are not evenly distributed in near-Earth space. The area with the highest concentration of the number of debris is the orbital regions of LEO – 19 840. In other regions of orbits, fragments have the following distribution: MEO – 507, GEO – 893, GTO – 1 203 and HEO – 1 113. [2]

For near-Earth space, there is a classification of orbits by height. The main ones are as follows: [4]

LEO – low Earth orbits. Orbits with a height of perigee and apogee up to 2 000 kilometers;

MEO – medium Earth orbits. Orbits between LEO and GEO – value of perigee and apogee heights from 2 000 to 31 570 kilometers;

GSO – geosynchronous near-Earth orbits. Orbits with a perigee height and apogee of 35 586 to 35 986 kilometers and with an orbital period corresponding to the period of the Earth's rotation around its axis;

GEO – geostationary near-Earth orbits. Geosynchronous near-Earth orbits, which have the value of the inclination of the orbit to the equator plane from 0 to 25 degrees;

GTO - transition orbits in the region of GEO orbits. Orbits with a perigee height of up to 2 000 kilometers, an apogee height of 31 570 to 40 002 kilometers and an orbital inclination of 0 to 90 degrees;

HEO – highly eccentric orbits. Orbits with a perigee height of up to 31 570 and an apogee height of more than 40 002 kilometers.

The distribution of space debris by orbital regions is of a historical nature and is mainly associated with the testing of anti-satellite weapons and the events of the destruction of satellites by colliding with another satellite or with a fragment of space debris, or an explosion of a rocket body.

Thus, for more than 60 years after the launch of the first artificial satellite of the Earth, several hundred thousand different remnants of artificial celestial bodies have accumulated in near-Earth space. Cases of collisions of active satellites with space debris are no longer new. Moreover, many collisions with fragments of satellite fragments that were put into orbit in previous years, as well as explosions of rocket bodies, are recorded. [2]

2. CLASSIFICATION OF SPACE DEBRIS

The main source of information about space debris in near-Earth space is the US Space Observation Network (SSN), which tracks, compares and catalogs objects larger than 5-10 centimeters. Additional data is collected using radars and telescopes in several countries, including member states of the European Space Agency (ESA). Some observations are coordinated in general campaigns, for example, within the framework of the Inter-Agency Space Debris Coordinating Committee (IADC). Regarding smaller space debris, most of the information is obtained from the analysis of the impact of space debris on the open surfaces of spacecraft. [3]

There are several types of space debris:

- non-operating satellites that have expired;
- spent rocket bodies that were used to launch satellites;
- objects released during missions. For example, waste dumped from a spacecraft;
- fragments that were formed as a result of collisions, explosions or the failure of active satellites or larger debris. [3]

According to the US Space Surveillance Network (SSN), space debris can be classified based on its size and impact. The first category includes objects measuring 10 centimeters or more. Since space debris objects of this size can be tracked, it is possible to predict their collisions with satellites, and in some cases the satellite trajectory can be changed to avoid a collision. As of 2021, SSN tracks more than 27 000 objects of this size. [3, 4]

The next category is objects ranging in size from 1 to 10 centimeters. Objects in this range cannot be tracked, but they are large enough to destroy a satellite or rocket if space debris collides with the hull of a spacecraft. As of 2021, approximately 500 000 fragments larger than 1 centimeter have been registered at LEO altitudes. [3, 4]

Space debris ranging in size from 0.3 to 1 centimeter is the following category. These objects also cannot be tracked, and it is estimated that there are millions of them in the LEO orbit area. [3]

The last category of space debris includes objects less than 0.3 centimeters in size. It is estimated that there are about 10 million space debris objects less than 0.3 centimeters in the LEO orbit area. They, like objects up to 1 centimeter, pose a danger to existing satellites, but they can be effectively countered with the help of more advanced designs and protection of spacecraft. [3]

We also note the number of space debris objects, which was estimated using statistical models (MASTER-8, population 2021): about 36 500 space debris objects larger than 10 centimeters, 1 000 000 space debris objects ranging in size from 1 to 10 centimeters and 130 million space debris objects ranging in size from 0.1 to 1 centimeter. [2]

However, it should also be noted that more than half of the formed fragments of space debris could not be tracked and cataloged immediately after their formation, at least it took several to ten years. For example, two years after the fragmentation of the launch vehicle of the ”Transit 4A” satellite, about 70 % of the known fragments were cataloged, and in the event of the collapse of the carrier rocket of the ”NOAA 5” satellite, 63 % of the 159 known fragments. Thus, in 1971, ten years after the fragmentation of the launch vehicle of the ”Transit 4A” satellite, 80 % of the 298 known fragments were cataloged. These percentages of cataloged fragments are relevant as of 1997. [5]

3. PROGRESSION OF THE SPACE DEBRIS PROBLEM IN THE 21ST CENTURY

The problem of space debris did not arise in one year or several fragmentation events. It was preceded by a series of various kinds of events: from tests of anti-satellite weapons and the collision of two satellites in the area of LEO orbits to the explosions of the last stages of rockets left in the area of GEO orbits.

The only ASAT test conducted after 1985 was in 2007, when China launched a ballistic missile that destroyed the defunct ”Fengyun-1C” Chinese weather satellite at an altitude of 863 kilometers. Ten days after the test, the debris spread in orbit before the satellite exploded. Three years later, the debris was scattered much further, at altitudes from 175 to 3 600 kilometers. [6]

In February 2009, two satellites collided. One of them was an operating communication satellite ”Iridium-33” weighing 560 kilograms. Another was the inactive Russian communications satellite ”Cosmos-2251,” weighing 950 kilograms. When they collided at an altitude of 770 kilometers, both satellites were destroyed, resulting in large clouds of debris that move in orbits of these satellites. Over the next few months, more than 1 600 pieces of space debris were cataloged together. A 2010 analysis showed that about 20 % of them will remain in orbit for thirty years and 70 % of them will cross the orbit of the ”International Space Station” (ISS) until 2030. [6]

Thus, as a result of testing Chinese anti-satellite weapons and the collision of two satellites ”Cosmos-2251” and ”Iridium-33” the number of fragments of space debris that is being tracked increased by almost 30 %. [7]

In October 2012, the ”Briz-M” upper stage of the Russian rocket, which was in orbit with half-filled fuel tanks, exploded. As a result, at least 1 000 fragments were discovered. [6]

In the area of GEO orbits, as of 2010, only two explosions occurred, one of them is associated with the collapse of the American apparatus ”68081E Transtage 13” into three parts and the other with the battery explosion on the Russian satellite ”Ekran-2” . The latter did not lead to the disintegration of the satellite and the formation of fragments [7]. However, in recent years, the situation has changed qualitatively. In 2018, the ”Atlas 5 Centaur” upper stage fragmentation at an altitude of 29 017 kilometers. Fragmentation of ”Atlas 5 Centaur” occurred on August 30, 2018 at 22:03:49 UTC. This satellite was active and belonged to the United Launch Alliance. As a result of this event, as of the end of 2019, the number of space debris fragments is more than 400. As a result, this poses a significant problem in the field of GEO orbits [8]. In addition, in March and April 2019, two additional events of fragmentation of the upper stages of the ”Centaur” occurred [9, 10] Thus, the debris resulting from the three fragmentation events increased the number of all objects in the HEO and MEO orbit region listed in the catalog by 2 698 - this is more than 31 % of the total number of fragments in these orbital regions. [10]

It should also be noted that the discovered fragments of the ”Atlas 5 Centaur” upper stage move in the region of HEO orbits with a perigee height in the range of 5 270 – 17 850 kilometers and an apogee height in the range of 32 825 – 43 240 kilometers, thus intersecting the heights of all operating satellites of the Global Navigation Satellite System (GNSS). Thus, as a result of these events, 491 fragments of space debris were discovered and tracked. This led to a 25 % increase in the number of orbital debris tracked in the GTO orbit region. [8]

Characteristics of the problem

Consequently, many factors and events in the past have led to the current situation with space debris. As of April 1, 2022, the number of debris from the destruction of satellites has reached almost half of the recorded amount of payload, as shown in Table 1. In addition, approximately three out of every four payloads no longer work and represent a separate class of orbital debris. [10, 11]

Table 1.

Percentage of cataloged segments of artificial space objects in near-Earth space.

Source	Number of fragments ± 0.1 %
Abnormal events	2.2
Rocket bodies	8.1
Space missions	8.3
Payload	34.0
Destruction of satellites	47.4

Destruction of a satellite – destruction of an orbital payload, rocket body or structure. The destruction of a satellite can be accidental or the result of intentional actions, such as engine failure or a space weapon test, respectively. [11]

An anomalous event is the unplanned separation of one or more objects from the satellite, which remain practically intact. [11]

Space debris generated by space missions is the result of intentional ejection of objects, usually in small quantities, during normal operations in orbit. [11]

4. FEATURES OF MODELING THE MOVEMENT OF SPACE DEBRIS

At the same time, the problems of modeling the evolution of space debris have their own characteristics. There are several approaches. Depending on the area in which near-Earth orbits the simulation takes place, the fragments are considered differently. For their modeling in the field of LEO orbits, analytical and semi-analytical methods are used. In the first embodiment, for example, according to [12] the movement of orbital debris is modeled in terms of their spatial density. In this case, the continuity equation is used to propagate debris. The set of fragments of space debris is considered as a liquid. In the second version, for example, according to [13] in the SOLEM model created by them, integration is performed with averaging short-period perturbations. Otherwise, according to [14] in the FADE model created by them, differential equations of the first order are solved by the Euler method to describe the evolution of the environment of space debris. They describe the change in the number of debris over time, and collision statistics are modeled by the Monte Carlo method.

To simulate the evolution of space debris fragments in the GEO orbit region, numerical methods for integrating differential equations are used. For example, the Everhart method. In the model created [15] the integration of motion equations occurs by the 19th-order Everhart method over a period of 240 years. The perturbing accelerations from the asymmetry of the Earth's gravitational field (harmonics up to 27 order and degree inclusive), the pressure of sunlight, taking into account the shadow of the Earth, are taken into account, the Pointing-Robertson effect, atmospheric resistance, and lunar-solar impact. Calculations show that large values of the ratio of the middle section to the mass of space debris fragments lead to the passage of such objects through the regions of GEO orbits and GNSS satellites due to light pressure and the Lidov–Kozai effect [16]. This leads to long-period oscillations of eccentricity and inclination of orbits.

Thus, various methods for modeling the evolution of space debris fragments allow not only to predict their future distribution to solve the global problem of orbital debris, but also to identify new ones and confirm the already known subtle effects.

5. STUDY OF THE VICINITY OF THE SATELLITE IN THE AREA OF GEO ORBITS

In recent years, the likelihood of future fragmentations of spent stages of rockets and engines left in orbits of disposal, and the further evolution of their orbits, has become increasingly concerning. The vast majority of them were left with fuel. There are already known cases of fragmentation of such objects [2]. Disposal orbits are orbits into which spent spacecraft are left. For geostationary satellites, this is an orbit whose height is 200 kilometers higher than the height of a geostationary orbit [17]. Also according to the study [18], spent rocket bodies left in disposal orbits will cross the orbits of existing satellites if fragmentation occurs. Fragments of space debris with such orbits poses a potential threat to the existing satellites of the GEO orbit area. Therefore, there is a need to research the features of the space debris environment in the vicinity of the orbits of such objects. According to [19], for such calculations, it is possible to consider the movement of fragments of space debris relative to the satellite in its vicinity. Thus, the vector difference between the gravitational accelerations of the fragment and the satellite influenced by the Earth will be the perturbing acceleration. The relative motion of the fragment in the vicinity of the satellite occurs under the influence of perturbing accelerations. This will allow to create a spatial distribution of disturbing accelerations affecting fragments of space debris in the vicinity of the satellite's orbit. As a result, it will be possible to identify certain patterns of accumulation of space debris fragments, or their absence. Figure 1 shows the relative accelerations of test points in the vicinity of the satellite's orbit. The calculations are performed in the approximation of the geocentric problem of two bodies: the Earth and the test point. To simulate the motion of fragments in the vicinity of the selected satellite, the position of the test points was uniformly given using the parametric equation of the sphere. For these calculations, the Earth was considered as a material point. We also note that the graph was built in such a way that it immediately displays all possible values of two angles in one figure, which were used to set the positions of the test points. Therefore, some vectors may look like they intersect, but in fact they do.

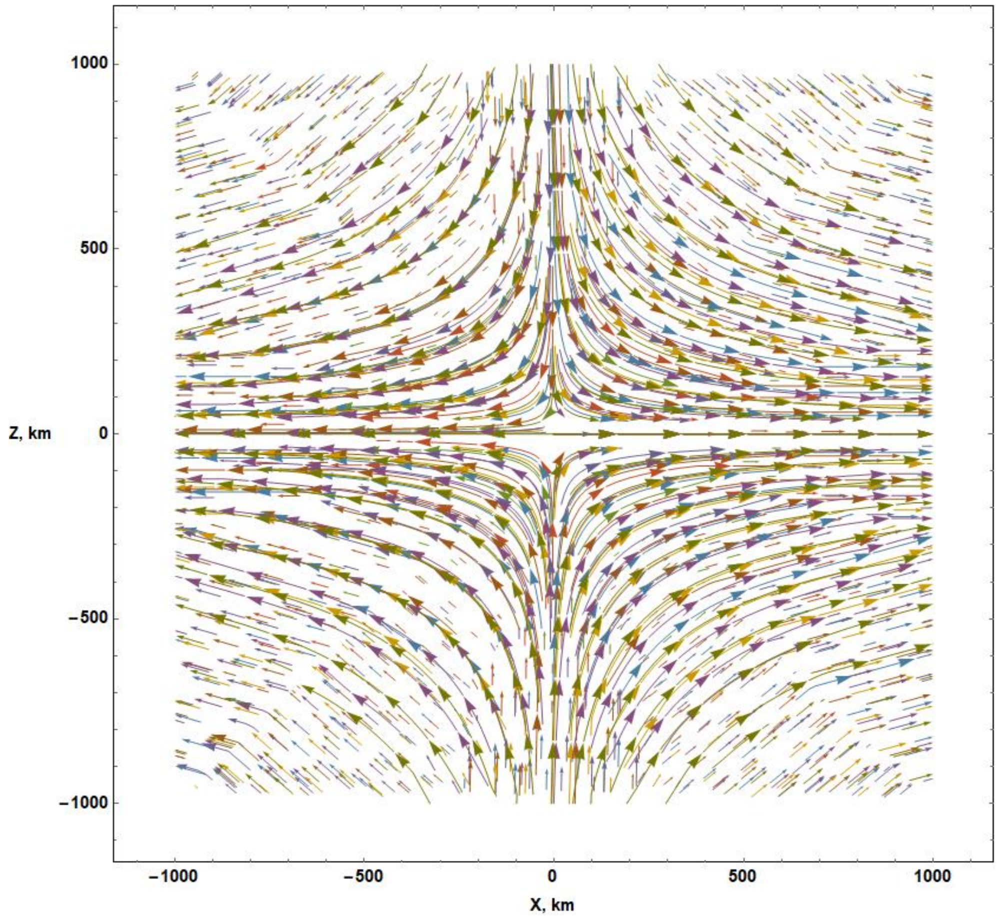

Fig. 1: Distribution in the satellite-centric reference system of relative accelerations of test points in the vicinity of the satellite's orbit.

6. MODELING

To research the vicinity of the satellite "Titan 3C Transtage R/B" was chosen. It has the following basic values of Kepler's orbital elements: orbital inclination to the equator plane – 1.9147 degrees, eccentricity – 0.0174266 and perigee and apogee values – 37 320 and 35 824 kilometers, respectively. The orbit of this satellite allows simulations of its motion and fragments in its vicinity, neglecting disturbances caused by the Earth's atmosphere, the magnitude of which for such an orbit is about 10^{-16} m/c^2 [20]. This acceleration is considered insignificant compared to the acceleration of the satellite to the Earth, whose magnitude varies from 0.44 to 0.01 m/c^2 [21]. The calculations are performed in the approximation of the geocentric problem of five bodies: the Earth, the Sun, the Moon, the satellite and the test point. Disturbing accelerations from the asymmetry of the Earth's gravitational field (harmonics up to 6 orders and degrees inclusive) are taken into account. The problem is solved by the numerical method of Everhart of the 15th order in Cartesian coordinates. The corresponding vectors of the states of the Sun and Moon are borrowed from the "JPL NASA" [22] web resource, and Kepler's elements of the satellite's orbit from the "SPACE-TRACK.ORG" knowledge base in TLE format [23]. Note also that then, using the "JPL NASA" resource, the necessary state vectors were obtained from Kepler's orbital elements. To simulate the motion of fragments in the vicinity of the selected satellite, the position of the test points was uniformly given using the parametric equation of the sphere. In Fig. 2, you can see in the satellite-centric reference frame the velocity distribution of test points in the vicinity of the satellite's orbit. Also, in Figure 2, different colors indicate the directions to the Earth, the Moon and the Sun. In the figure we can see some asymmetry of the velocity distribution of test points. However, this still does not allow us to conclude that there are certain patterns of accumulation of fragment of space debris, or their absence in the vicinity of the selected satellite.

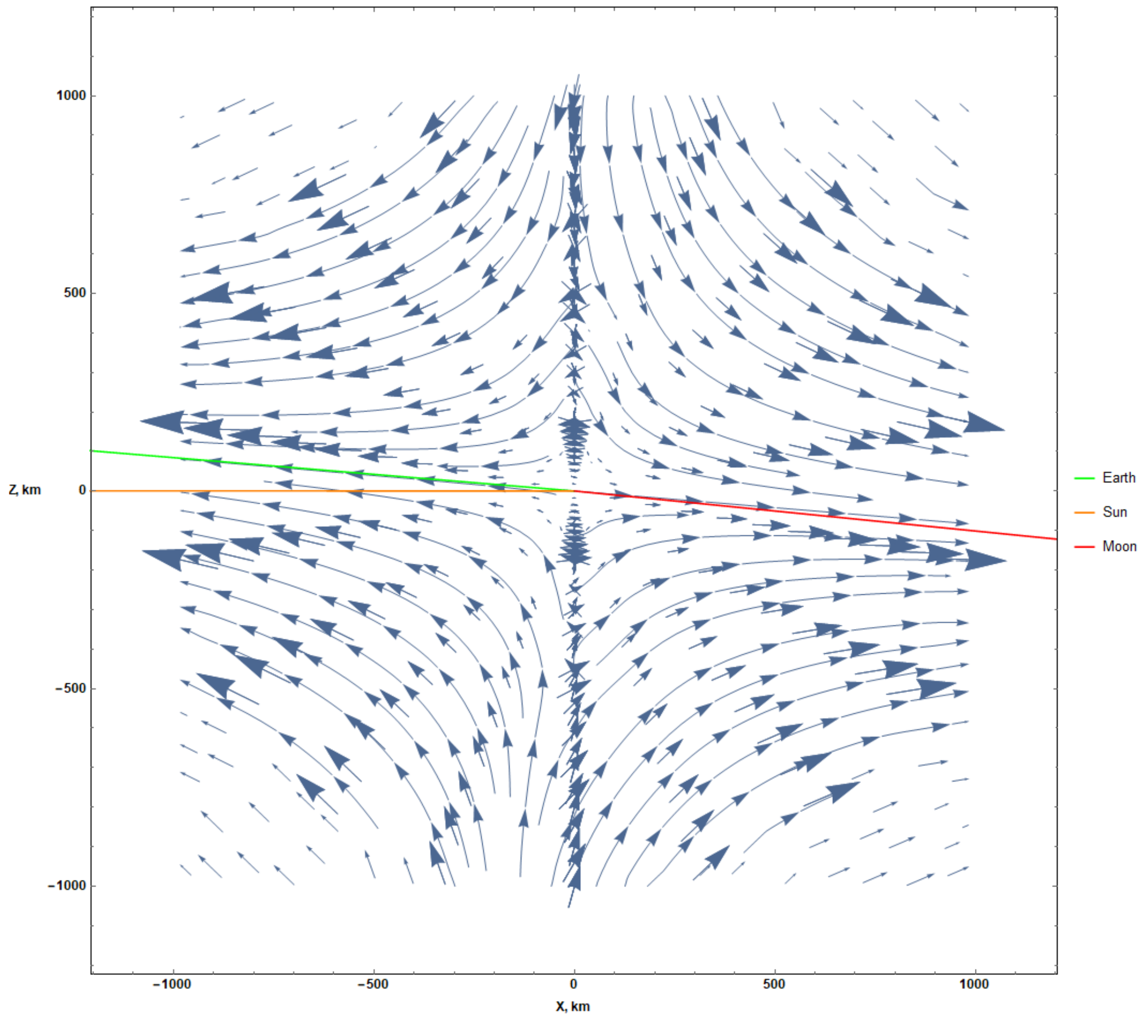

Fig. 2: Distribution in the satellite-centric reference system of the speed of movement of test points in the vicinity of the ”Titan 3C Transtage R/B” satellite orbit.

7. CONCLUSIONS

The distribution of the number and size of fragments of space debris has specific directions and areas. This is due to fragmentation events that occurred in the past. Since the launch of the first artificial Earth satellite, the region with the largest amount of space debris has been the region of LEO orbits, but since 2010 this situation has begun to change. This is due to fragmentation events of working satellites and the remaining last stages of rockets in the area of MEO and GEO orbits. In turn, this poses a danger to the operating systems of GNSS satellites, since these fragments will cross the orbits of satellites in the geostationary ring in the next few years. Such a situation is dangerous because in this case these satellites are at risk of collision with space debris.

Thus, in less than 100 years, the space around the Earth was filled not only with working satellites, but also with space debris. During this time, the problem of space debris generally appeared and grew from insignificant to become global.

Also, the motion in near-Earth space is of particular interest for modeling the evolution of space debris orbits. First of all, the created environment is a unique system of artificial space objects in the Solar System. Given the wide range of sizes of space debris fragments, from 10^{-6} to 10 meters, it becomes possible to study the effects of perturbations of various origins and age-related changes in orbital motion. According to [24] it is possible to draw an analogy between the movement of space debris in the area of LEO orbits and the movement of small planets in the asteroid belt. However, movement in space around the Earth has its own characteristics. The spatial density of space debris objects has a distinct direction by the inclination, eccentricity, and height of the orbit. In addition, some fragments of space debris form clouds, that is, areas with a greater concentration of such objects that move along such orbits that the satellite had before its destruction. Such features are explained by events of accidental or intentional destruction of satellites that occurred in the past.

Since fragments of space debris have an irregular shape, it becomes quite difficult to set such parameters as the ballistic parameter **γ** and the optical coefficient **κ** to model the evolution of their orbits. In turn, their small variation leads to a significant change in the orbits of space debris fragments. Depending on the values of parameters **γ** and **κ**, perturbation forces of various nature affect the movement of a separate fragment in different ways. Therefore, we considered a different approach to search for certain patterns of accumulation of space debris fragments, or their absence. According to the proposed method, for such calculations, it is possible to consider the movement of fragments of space debris relative to the satellite in its vicinity. As a result, this made it possible to isolate certain asymmetries in the velocity distribution of test points in the vicinity of the satellite "Titan 3C Transtage R/B". However, this still does not allow us to conclude that there are certain patterns of accumulation of fragments of space debris, or their absence in the vicinity of the selected satellite.

8. REFERENCES

[1] Chen Lei, Bai Xian-Zong, Liang Yan-Gang, Li Kebo. Orbital Data Applications for Space Objects. National Defense Industry Press, Beijing and Springer Nature Singapore Pte Ltd. 2017. P. E1.

[2] European Space Agency – Space Debris User Portal.

[3] Sylvestre Habimana, Parama Ramakrishna. Space debris: Reasons, types, impacts and management. *Indian Journal of Radio and Space Physics.* No 46. Vol. 1. March 2017.

[4] Bordovitsyna T. V., Aleksandrova A. G. Numerical modeling of the formation, orbital evolution, and distribution of fragments of space debris in near-Earth space. *Solar System Research*. Vol. 44, No. 3. June 2010. P. 238-251.

[5] Bade Anette, Reynolds Robert, Johnson Nicholas, et. al. Comparisons between orbital debris measurement data and modeling results: difficulties and special features. *Proc. SPIE 3116, Small Spacecraft, Space Environments, and Instrumentation Technologies.* Vol. 3116. October 1997. P. 208-218.

[6] Loretta Hall. The History of Space Debris. Space Traffic Management Conference 19. Roadmap to the Stars. 2014.

[7] Joseph N. Pelton. Space Debris and Other Threats from Outer Space. *Springer New York*. 2013. P. 84.

[8] Vladimir Agapov, Alexander Lapshin. Survey and follow-up strategies used in operation of aspos okp to gather observation data on GEO, HEO and MEO objects. ESA Space Safety Programme Office. 1-st NEO and Debris Detection Conference. 2019.

[9] T. Schildknecht, T. Flohrer, A. Vananti. Optical Surveys to Characterize Recent Fragmentation Events in GEO and HEO. First Int'l. Orbital Debris Conf. 2019.

[10] NASA. The Orbital Debris Quarterly News. Volume 26 – Issue 4.

[11] Phillip D. Anz-Meador, John N. Opiela, Debra Shoots, J.-C. Liou. History of On-Orbit Satellite Fragmentations, 15th edition. Technical Report. NASA. July 2018.

[12] Letizia Francesca, Colombo Camilla, Lewis Hugh. 2D continuity equation method for space debris cloud collision analysis. 25th AAS/AIAA Space Flight Mechanics Meeting. Williamsburg. 2015.

[13] Xiao-wei Wang, Jing Liu. An introduction to a new space debris evolution model – SOLEM. *Advances in Astronomy.* Vol. 2019. No. 1. May 2018. P. 11.

[14] Lewis H.G., Swinerd G.G., Newland R.J., Saunders A. The fast debris evolution model. *Advances in Space Research.* Vol. 44. No. 5. September 2009. P. 568-578.

[15] Kuznetsov Eduard. Dynamical evolution of space debris in vicinity of gnss regions. 7th European Conference for Aeronautics and Space Sciences (EUCASS). Milan, Italy. 2017.

[16] Prokhorenko Victoria. On the Dynamical Foundations of the Lidov–Kozai Theory. Astronomy Letters. No. 44. 2018. P. 49-66.

[17] Technical Report on Space Debris. UNITED NATIONS PUBLICATION Sales No. E.99.I.17

[18] Dr. Kim Luu and Dr. Chris Sabol. Effects of perturbations on space debris in supersynchronous storage orbits. AFRL/VSSS. October 1998

[19] Howard D. Curtis. Orbital mechanics for engineering students. Butterworth-Heinemann, 3, January 2014

[20] Karaush, E.A., Davlatov, Ruslan, Donchenko, Sergey, Gostev, Yu.V., Sokolov, Denis, Lavrov, Evgeny and Kharlamov, P.G.. (2020). Estimation of perturbing accelerations affecting the space gravitational wave antenna SOIGA-2. Izvestiâ vysših učebnyh zavedenij. Priborostroenie. 63. 907-920.

[21] Merritt, David. Gravitational N-Body simulations By Sverre J. Aarseth. General Relativity and Gravitation. Cambridge. May 2006. P. 413.

[22] JPL NASA online.

[23] SPACE-TRACK.ORG

[24] Rossi A., Anselmo Luciano, Cordelli Alessandro, et. al. Modelling the evolution of the space debris population. *Planetary and Space Science.* No. 46. 1998. P. 1583-1596.