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# From the launch of the first satellite to the global problem of space debris

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Along with the development and achievements of cosmonautics, another type of object 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. Space debris is spread over all Earth orbits and has selected areas of orbits with a greater concentration. This is explained by the events of intentional and unintentional destruction of satellites in the past. As a result of a series of such events, as well as the launch of a certain class of satellites into Earth orbit for almost 60 years, the probability of space debris colliding with a satellite has increased 7 times in the area of LEO orbits. Collision probability estimates were $10^{-9}$ in 1966, and in 2024 the estimate increased to $10^{-2}$. So, in 2013, these estimates were 0.0005, and in 2020 it is already 0.001. The increase in the probability of a collision in 2020 and in the years from 2020 to 2024 is associated with the launch of the "Starlink" constellation of satellites. There are already several cases of the close passage of the "Starlink" satellite constellation with active satellites and the need to perform maneuvers to avoid collisions. Thus, not only has the number of maneuvers to avoid space debris increased, but also the need to avoid collisions with other satellites. At the same time, measures adopted to reduce and remove space debris are already being applied. In order to predict the future space debris environment more effectively and remove the most dangerous objects, a number of models of the evolution of the space debris environment have been created. They make it possible to simulate various scenarios of an increase in the number of objects in near-Earth space and to consider the possibilities and degree of necessity of their removal. 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 their movement in near-Earth space. However, if the state of the space debris problem is not qualitatively changed in the coming years, there is a threat in the next 50 years to lose the achievements of the space sphere over the past almost 60 years.

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## 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 (Chen et al., 2017).

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 (ESA – Space Debris User Portal).

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 (Habimana and Ramakrishna, 2017).

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 (ESA – Space Debris User Portal).

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; HEO, 1 113 (ESA – Space Debris User Portal).

For near-Earth space, there is a classification of orbits by height. The main ones are as follows (Bordovitsyna and Aleksandrova, 2010):

- 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 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, the first recorded collision of two artificial objects in near-Earth space was the collision of debris from the third stage of the "French Ariane" rocket with the "French Cerise" spacecraft during its launch in 1996 (Guo, 2021).

We should note that a few years before that, there was general discussion about the problem of space debris and about the fact that this problem exists. In accordance with UN General Assembly resolution 48/39 of 10 December 1993: the clause on space debris was included in the consideration of the Scientific and Technical Subcommittee at its thirty-first session in February 1994. In 1999, the report "Technical Report on Space Debris" was published, which includes the following parts: methods of observation of fragments of space debris, analysis of this data and prediction of the impact of these objects on spacecraft; simulation of space debris environment and assessment of collision risks; proposing measures to prevent the formation of space debris (United Nations, 1998). In the following years, basic principles were developed to reduce the amount of space debris. These are now known as the "Recommendations for Reducing the Level of Space Debris." They are supplemented and developed, but they are, as before, recommendations that may or may not be followed (Ansdell, 2010).

However, already in the 21st century, the collision of satellites, their intentional and unintentional destruction brought the problem of space debris to a qualitatively different level. In December 2009, the world's first conference on the problem of space debris removal was held (Ansdell, 2010).

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 (ESA – Space Debris User Portal).

## 2 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 (Habimana and Ramakrishna, 2017).

There are several types of space debris (Habimana and Ramakrishna, 2017):

- 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.

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 (Habimana and Ramakrishna, 2017; NASA – Space Debris and Human Spacecraft).

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 (Habimana and Ramakrishna, 2017; NASA – Space Debris and Human Spacecraft).

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 (Habimana and Ramakrishna, 2017).

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 (Habimana and Ramakrishna, 2017).

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 (ESA – Space Debris User Portal).

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 (Anette et al., 1997).

## 3 How did the problem arise

### *3.1 The appearance of space debris in the 20th 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.

Nevertheless, the launch of the first artificial satellite of the Earth – "Sputnik-1" did not begin the accumulation of space debris in the near-Earth space. The main part of the launch vehicle remained in orbit for only two months, and the main module of the satellite burned in the atmosphere a month later. However, the long-term problem began to grow shortly thereafter. "Vanguard-1", the second satellite launched by USA, was launched into orbit in March 1958 and stopped radio transmission after six years. It is still orbiting Earth in the MEO orbit region. The other two "Vanguard" satellites launched in 1959 are inactive, but remain in similar orbits (Hall, 2014).

The "West Ford" project was carried out by the MIT Lincoln laboratory for the U.S. Air Force in the early 1960s. The goal of the project was to create an 8 kilometers wide, 40 kilometers thick band of tiny copper wire segments in an orbit close to the polar orbit as a passive radio reflector for military communications. At the first deployment attempt in October 1961, the payload was not distributed as planned. In the end, seven small objects were catalogued as orbital debris due to a failed attempt (Hall, 2014).

A second attempt to deploy the "West Ford" project in May 1963 brought a payload of 480 million copper needles, each 1.8 centimeters long and 0.00178 centimeters in diameter. Only one quarter to half of the needles dissipated as planned. Most remained in blocks that were more resistant to decay. In the end, 144 clusters from this attempt were identified and cataloged. Forty-six of them were in orbit in 2013 (Hall, 2014).

Between 1968 and 1985, the USA and the USSR tested ASAT anti-satellite weapons. By 1990, as a result of twelve such tests, 7 percent of the recorded orbital debris was obtained (Hall, 2014).

In the last American test of ASAT in 1985, the rocket destroyed a faulty American satellite, which was located at an altitude of 525 kilometers. By January 1, 1998, all but 8 of the 285 space debris had burned in the atmosphere (Hall, 2014).

The explosion of the "Ekran-2" satellite in the GEO orbit area occurred on June 23, 1978 due to battery rupture. Another event of fragmentation in the GEO orbit area is the explosion of the "Titan 3C Transtage" satellite, which generated about 20 fragments on February 21, 1992 (Flury, 1995).

In July 1996, already mentioned, the French satellite "French Cerise" was damaged by a fragment of space debris from a "French Ariane" rocket that exploded 10 years ago in 1986 (Kondratiuk et al., 2016; Guo, 2021).

### *3.2 Increasing the number of space debris in the 21st century*

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 (Hall, 2014).

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 (Hall, 2014).

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% (Pelton, 2013).

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 (Hall, 2014).

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 (Bordovitsyna and Aleksandrova, 2010). 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 (Agapov and Lapshin, 2019). Also, in March and April 2019, two additional events of fragmentation of the upper stages of the "Centaur" occurred (Schildknecht et al., 2019; Anz-Meador, 2022). 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 (Anz-Meador, 2022).

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 (Agapov and Lapshin, 2019).

## 4 Characterization 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 (Anz-Meador et al., 2018; Anz-Meador, 2022).

**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 (Anz-Meador et al., 2018).

An anomalous event is the unplanned separation of one or more objects from the satellite, which remain practically intact (Anz-Meador et al., 2018).

Space debris generated by space missions is the result of intentional ejection of objects, usually in small quantities, during normal operations in orbit (Anz-Meador et al., 2018).

### *4.1 Probability of collision*

Along with the increase in the number of fragments of space debris, estimates of the probability of collision of satellites in orbit with these objects also change (Fig. 1). Also, changes in the approach to the analysis of observed collisions and improvement of modeling methods affect the change in these estimates.

The following estimates illustrate this change (Hall, 2014):

1966: probability of collision with "Gemini 8" space capsule during its 10.7 hour flight $= 2.3 \times 10^{-9}$;

1967: probability of collision with "Apollo" spacecraft during one year in orbit $= 11.2 \times 10^{-4}$;

1970: probability of collision with the "Skylab" space station during an eight-month mission $= 2.27 \times 10^{-4}$;

1971: probability of collision with the space station "Skylab" = 2–3% within a ten-year period according to the calculations of one source, according to another – up to 8% within ten years;

1981: probability of collision between any two objects is 6% per year, or 1 collision every 17 years. Comparing this estimate with the estimate in 1976 – 1.3% per year (1 collision every 77 years) allows us to predict that by 1998 the frequency of collisions will be from 0.24% per year to 1% per year (1 collision every 1–4 years);

1990: collision probability between orbiting satellites and space debris from $10^{-7}$ to $10^{-4}$ per year in LEO orbits and from $10^{-12}$ to $10^{-7}$ per year in GEO orbits;

1997: probability of an object (space debris or meteorite) entering a $2 \times 5$ kilometers $\times 2$ kilometers maneuvering area around an artificial satellite during 9.7 days in orbit is 86%. There is a 60% chance that the "Space Shuttle" window will be replaced after the mission;

2007: probability of debris larger than 1 centimeter to collide with an active satellite in LEO orbits once every 5–6 years (17–20% per year) before the destruction of "FY-1C," but once after its destruction every 3–4 years (25–33% per year);

2010: probability of space debris collision with a satellite in LEO orbits doubled between 2006 and 2009 due to the "FY-1C" ASAT test and the collision between the "Iridium-33" and "Cosmos-2251" satellites. The explosion of the "Briz-M" upper stage in 2012 also increased the probability of a collision;

2013: probability of a collision between a spacecraft and space debris larger than 1 centimeter is 1 time every 1.5–2 years (50–67% per year).

Five years later, with the launch of the "Starlink" satellite constellation, the probability of an orbital collision increased. According to estimates (Haicheng et al., 2022), the probability of collision of space debris with the "Starlink-61" satellite, which belongs to the "Starlink" satellite constellation, has the following values: 2020 – 0.001, 2021 – 0.005, 2022 – 0.009, 2023 – 0.017 and in 2024 is 0.014. To calculate the probability of a collision, it was assumed that the mass of the space debris fragment is more than 0.1 kilograms and the size exceeds 1 centimeter. The indicated collision probabilities exceed the red warning threshold of $10^{-4}$ (Haicheng et al., 2022). Thus, NASA divided the probability threshold of evasive maneuvers into a yellow threshold with a value of $10^{-5}$ and a red threshold with a value of $10^{-4}$. When the collision probability exceeds the red threshold, an evasive maneuver is performed. When the collision probability is higher than the yellow threshold, evasive maneuvers will be performed without compromising the mission objective (Sun et al., 2020). Thus, the probability of collisions of the "Starlink-61" satellite with space debris increases almost linearly every year and has a high probability of catastrophic collisions. As you can see, Fig. 1 illustrates this change well. A sharp increase in collision probability estimates in 2020 is due to the launch of the "Starlink" constellation of satellites.

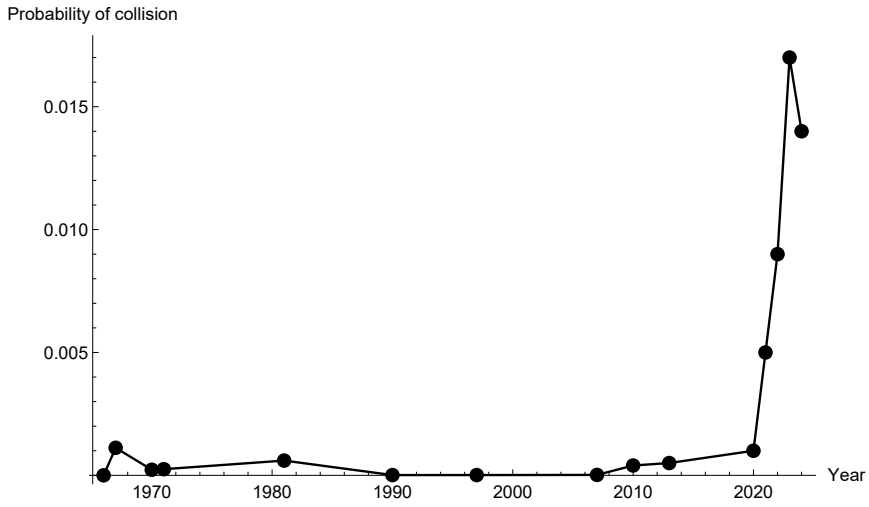



**Figure 1** Change over time estimates of the probability of collision of space debris with operating satellites in the region of LEO orbits.

### *4.2 Collision avoidance*

Along with the fact that estimates show an increase in the probability of collisions of active satellites with space debris, the number of maneuvers used to avoid these debris also increases. Thus, the launch of the satellite may be delayed if its launch trajectory intersects with the likely trajectory of tracked orbital debris. For example, at the end of June 2014, there was a three-minute delay in the launch of an Indian rocket with satellites from four countries (Hall, 2014).

In addition, orbiting satellites that can adjust their trajectory can maneuver to avoid collisions with orbital debris. More than 100 such maneuvers were registered in 2010 alone. In April 2012, thanks to tracking the movement of space debris, it was possible to avoid collision of the Russian "Fermi" satellite with orbital debris. In 2013, 29 collision avoidance maneuvers were performed thanks to NASA (Hall, 2014).

The "International Space Station" (ISS) also has to maneuver to avoid collisions with space debris. From 1999 to 2014, the ISS performed 19 collision avoidance maneuvers. For example, on October 27, 2014, the ISS avoided a collision with a piece of space debris from the "Cosmos-2251" satellite. In several other cases, the approach to space debris was detected too late to perform an evasive maneuver, and the crew aboard the ISS hid in a safe location. As a result, a number of its components were damaged on the ISS, including heat radiators, solar panels and a window (Hall, 2014).

Not only space debris, but also other operating satellites pose a collision threat to spacecraft. So, the European Space Agency (ESA) had to maneuver the Aeolus satellite in 2019 to avoid a potential collision with the "Starlink-44" satellite. There were also cases of a close pass of one of the "Starlink" satellites with the Chinese "Tiangong" space station. The first incident occurred on July 1, and the second on October 21, 2021. As a result, the "Tiangong" space station was forced to maneuver to avoid a collision. Thus, the constellation of "Starlink" satellites also directly affects the operation of other spacecraft in the area of LEO orbits and poses a threat to the formation of space debris (Sun et al., 2020).

Thus, as the amount of orbital debris increases, the number of maneuvers performed to avoid collisions increases. Note that according to estimates (Habimana and Ramakrishna, 2017), satellite operators may have to increase the number of evasive maneuvers by five times more in 2059 than in 2019. Since each maneuver requires fuel, this shortens the active life of the satellites or requires additional fuel to be put into orbit, thereby increasing the cost of the launch and the amount of space debris.

## 5 Solving the problem

### *5.1 Measures to reduce and remove space debris*

Along with this, measures were taken to reduce space debris. There are two ways to reduce the amount of space debris: mitigation and removal. Mitigation refers to preventing the formation of new space debris, while removal refers to either natural removal by atmospheric combustion or active removal by artificial systems. NASA has developed the world's first initial set of guidelines for preventing the creation of space

debris (Ansdell, 2010). In turn, the Inter-Agency Space Debris Coordinating Committee (IADC) continued this work in 2002 and issued an updated set of guidelines in 2007 entitled: Guidelines for Space Debris Reduction. The guidelines were called "non-binding." However, such standards were adopted by the UN General Assembly in December 2007. These guidelines have the following seven components (Pelton, 2013):

1. To limit the emission of space debris during the normal operation of the spacecraft;
2. Minimize the probability of satellites leaving the operational state during the operational stages;
3. To limit the probability of an accidental collision in orbit;
4. Avoid deliberate destruction of satellites and other similar actions;
5. Minimize the probability of fragmentation of satellites after the mission as a result of explosions of its fuel blocks;
6. To limit the long-term presence of the upper stages of spacecraft and launch vehicles in the area of LEO orbits after the end of their operation;
7. Reduce the long-term threat from finding defunct spacecraft and spent rocket stages in geosynchronous Earth orbit.

The work carried out by NASA (Liou and Johnson, 2007) to simulate the active removal of orbital debris over the next 200 years showed that some fragments of space debris are more dangerous than others, since they are more likely to cause collisions, which will create new space debris. These more dangerous objects have a mass of between 1 000 and 1 500 and between 2 500 and 3 000 kilograms; inclinations of orbits from 70 to 75, from 80 to 85 and from 95 to 100 degrees; and orbital altitudes from 800 to 850, 950 to 1 000, and 1 450 to 1 500 kilometers. Simulations showed that the annual removal of only five of these objects will significantly affect the further state of the space debris problem (Ansdell, 2010).

General concepts of developed space debris removal systems, as of 2021, include electrodynamic cables, solar sails, drag devices, orbital vehicles, and space lasers (Sapaty Peter, 2021). All of them have their advantages and disadvantages, which makes it difficult to find a single system. For example, several electrodynamic cables weighing about one hundred kilograms each could be launched as a secondary payload to reduce the amount of space debris in low Earth orbit for five years. However, they only work with objects larger than ten centimeters in size, and attaching them to orbital debris using conventional robotics can be prohibitively expensive to achieve (Ansdell, 2010).

### *5.2 World software development*

Along with the introduced principles for reducing the number of space debris fragments, it is also necessary to have an idea not only about which fragments are better to remove, but also to have predictions about the future of near-Earth space. Such forecasts can be built on the basis of models of the evolution of the space debris environment. Beginning in the late 1970s, the first simplified models of fragmentation and subsequent evolution were developed, which included lower-order terms in the Earth's gravitational potential and atmospheric resistance. By the late 1980s, NASA had begun a series of EVOLVE program developments, which for the first time used

Monte Carlo processing to estimate the occurrence and dynamics of future fragments. The latest version of the model included a new evolution model and a selection of pairs of collisions by type: intact-to-intact, intact-to-fragment, fragment-to-fragment. However, EVOLVE remained a one-dimensional model for calculating collisions. This limited the accuracy of collision pair calculations, as only the type of pair could be identified, not individual objects (Krisko, 2007).

Next, three-dimensional models were developed: LEGEND and DAMAGE. LEGEND included orbital evolution and fragmentation models and the latest EVOLVE model in the LEO orbit region, as well as a geosynchronous orbit evolution model. The main goal was to predict the growth of the amount of space debris as a result of the launch of satellites into orbit and their fragmentation in the future (Krisko, 2007). The DAMAGE model can also simulate historical and future pieces of space debris around 10 centimeters in size using a Monte Carlo approach. Historical and future fragmentation events are modeled using the NASA Standard Decay Model, and potential sources of space debris, with the exception of objects associated with space missions, are not considered. (Lewis et al., 2009).

In early 2012, Center National d'Etudes Spatiales (CNES) decided to focus on developing an orbital debris evolution model to predict the persistence and evolution of the space debris environment. Already at the beginning of 2013, MEDEE was developed. It was created to provide the ability to rerun any simulation by changing some parameters in the initial model or different conditions acting on the space debris environment. This is due to the need to study the sensitivity of the model to the initial conditions. MEDEE is able to track the collision probability over time of any space object present in the space debris environment, and therefore compile a list of desired objects that should be removed from the space environment (Dolado-Perez et al., 2013).

Here are other created models of space debris: DELTA, LUCA and NEODEEM. The DELTA model was developed by QinetiQ for the European Space Agency (ESA). It allows us to design the space debris environment for all regions of the Earth's orbits in the future (Martin et al., 2004). The LUCA model is used for long-term simulations of the space debris environment. To take into account the perturbation accelerations caused by atmospheric resistance, studies of the U.S. Navy were used. Namely, the distribution of the density of the atmosphere (Radtke et al., 2015). The NEODEEM model analyzes the orbital evolution of each object and takes into account future satellite launches, collisions and fragmentation of debris, and de-orbiting of satellites after operation. The space debris environment evolution model NEODEEM was jointly developed by Kyushu University and JAXA to simulate the dynamics of space objects over time in near-Earth space and space debris objects larger than 10 centimeters in size (Kawamoto et al., 2018).

In general, the models mentioned take into account such perturbation accelerations as the perturbation caused by the influence of the Sun and the Moon, the pressure of sunlight, the resistance of the atmosphere and from the asymmetry of the Earth's gravitational field (harmonics of different order and degree), and also include various models of the Earth's shadow.

According to (Dolado-Perez et al., 2013), the difference between the LEGEND, DELTA, and MEDEE models is manifested in the differences in the 200-year prediction of the number of fragments, some of their orbital elements, and the density of

orbital debris. Thus, the number of fragments of orbital debris larger than 10 centimeters in the area of low Earth orbits as of 2200 according to the MEDEE model will have a value of 17 000, the DELTA model – 21 000, and the LEGEND model – 24 000. Such forecasts are necessary to imagine the scale of the problem (Anz-Meador et al., 2018).

Therefore, as of 2022, the main models of the evolution of space debris include: the LEGEND model from the National Aeronautics and Space Administration (NASA), the DAMAGE model from the United Kingdom Space Agency (UKSA), the MEDEE model from the Center National d'Etudes Spatiales (CNES) , the DELTA model from the European Space Agency (ESA), the LUCA model from Technische Universität Braunschweig, the NEODEEM model from Kyushu University and the Japan Aerospace Exploration Agency (JAXA) (Wang and Liu, 2018).

We should also note that not only models of the evolution of space debris have been developed, but also complex tools for analyzing the compliance of the future launch of a space vehicle with the standards for preventing the formation of space debris. First of all, these tools will already include models of the evolution of space debris. For example, the tool developed by ESA is DRAMA (debris risk assessment and mitigation analysis). DRAMA is based on the MASTER model, the DISCOSweb database, the ORIUNDO model and the PROOF observational program. MASTER allows you to estimate the flow of debris or meteorites spreading to a spacecraft in an arbitrary Earth orbit. DISCOS is a source of launch information, object registration information, launch vehicle description, spacecraft information (e.g., size, mass, shape, mission objectives, owner), and orbital data history for all unclassified objects, which can be tracked, numbering more than 40 000 objects. The ORIUNDO model is used to assess the risk of uncontrolled recurrences for the Earth's surface. The program for radar and optical prediction of observations PROOF provides not only statistical characteristics for space debris, but also other parameters for observations of artificial space objects (ESA – Space Debris User Portal).

Let us note some of the parameters that DRAMA can analyze for any space mission: the impact of the flow of space debris fragments and meteorites (in user-defined modes), the frequency of collision avoidance maneuvers for a given spacecraft, and the acceptable level of risk for a specific project and the fuel requirements for transfer to and from the various planned orbits (ESA – Space Debris User Portal).

### *5.3 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, and, 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 (Letizia et al., 2015), 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 (Wang and Liu, 2018) in the SOLEM model created by them, integration is performed with averaging short-period perturbations. Otherwise, according to (Lewis et al., 2009) 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 (Kuznetsov, 2017), 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, allowing for the shadow of the Earth; the Pointing–Robertson effect, atmospheric resistance and lunar–solar impact are taken into account. 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 (Prokhorenko, 2018). This leads to long-period oscillations of eccentricity and inclination of orbits.

Thus, various methods for modeling the evolution of space debris fragments allow us to not only 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.

## 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 is 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 (Rossi et al., 1998), 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

the 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 $\boldsymbol{\gamma}$ and the optical coefficient $\boldsymbol{\kappa}$ 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 $\boldsymbol{\gamma}$ and $\boldsymbol{\kappa}$, perturbation forces of various natures affect the movement of a separate fragment in different ways.

Therefore, the environment of space debris has its own characteristics of detection, modeling and distribution in near-Earth space. In turn, it complicates the process of removing fragments of space debris that pose a threat to operating satellites and future space missions. The proposed methods and already adopted measures are unique for cosmonautics. Along with this, according to forecasts of 2006 (Liou and Johnson, 2007), after half a century it will no longer be possible to launch a spacecraft in the area of LEO orbits, if the current situation with the launches of artificial Earth satellites continues. After all, according to forecasts of the development of this environment, the moment of a cascading increase in the number of fragments of space debris may come. This possible development of this environment was first noticed by Donald J. Kessler. Kessler's syndrome suggests that the number of such objects will increase to such an extent that it will no longer be possible to put a single spacecraft into orbit even to remove fragments of space debris (Kessler et al., 1978). Thus, the untimely solution of this problem will have catastrophic consequences both for the development of the space sphere and for other technological achievements of the 21st century. Yes, the problem of habitation of near-Earth space and the spread of fragments of space debris is still of global importance.

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