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Threats to Satellite Systems in the Earth Orbit

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Abstract:

A large number of satellites operate in Earth's orbit. These are satellites for Earth observation, navigation, meteorology and climate, communication, and many others. They perform tasks and provide services without which today's world would not function. All these satellites are highly vulnerable since there are different kinds of threats. They are primarily space debris and various natural threats such as near-Earth objects and space weather. In addition, there are also intentional, man-made threats which are divided into kinetic, non-kinetic, electronic and cybernetic. The article discusses the development of knowledge of individual types of threats and suggests/analyses possible ways how to recognize them and how to protect vital satellites from them.

Keywords:

satellites, satellite systems, threats, anti-satellite weapons, space weather, space management, space situational awareness, space debris

1 Introduction

Satellites performing very diverse tasks are installed in orbits around the Earth. The vast majority of them perform tasks without which our normal life could not function. For example, Earth observation (EO) satellites are vital for today an almost infinite number of different applications from precise farming, forest fire mapping, urban planning, thematic mapping, water pollution monitoring, to glacier movement measurement, archaeological site documentation or insurance risk assessment.

A very important application domain is, of course, defense and security, which includes conducting military and non-military operations, border control, supporting humanitarian operations, treaty verification (e.g. proliferation of weapons of mass destruction) and many others. Very important is the use within the imagery intelligence (IMINT), which assumes the use of special satellites with sensors providing very high resolution imagery in real time.

And equally vital are other satellites and constellations such as meteorological satellites, satellites of global navigation satellite systems (GNSS), communication

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satellites or scientific satellites that monitor solar activity or the state of the Earth's geomagnetic field. It is necessary to realize that all these satellites and satellite systems are vulnerable.

The term "space security" has been used since the beginning of the satellite era. It relates to guaranteed access to space and the ability to freely exploit space for various purposes. Traditionally, space security was defined in military terms in relation to the strategic balance between the United States and the Soviet Union. Since the end of the Cold War, a two-dimensional model of military and environmental dimensions of space security has developed. Today, however, it is necessary to consider the third dimension, which represents intentional, man-made threats [1]. Threats to satellite systems can therefore be divided into space debris, natural threats originating in space and intentional threats (Tab. 1).

The need to solve the problem of space debris in the Earth orbit is gradually becoming common knowledge, but not enough is said about the causes of the dramatic increase in its amount. However, in addition to natural dangers originating from space, remote sensing systems are also threatened by the increasing activities of some states aimed at deliberately endangering these systems, and not only their components in the Earth orbit.

Tab. 1 Threats to satellite systems in the Earth orbit

Threat	Threat type	Examples
space debris		non-functional and uncontrolled bodies in Earth orbit
natural threats	near-Earth objects	asteroids, comets
	space weather	solar eruptions, coronal mass ejections, solar wind, cosmic rays
intentional threats	kinetic	direct-ascent, co-orbital weapons
	non-kinetic	nuclear explosions in outer space, directed energy weapons
	electronic	jamming, spoofing
	cyber	monitoring data traffic, intercepting data, inserting false data, taking control of satellite

It is alarming how many of these anti-satellite means capable of disabling sensors or entire systems temporarily or permanently have been developed to date. These means are a threat not only to the space segment, i.e. satellites and their constellations in orbit, but also to the ground segment in the form of control and management centers and other infrastructure elements. Not only Earth observation satellites are at risk, but also satellites of global navigation systems, meteorological, communication, scientific and other satellites. It means all satellites on low Earth orbit (LEO), medium Earth orbit (MEO) and geostationary orbit (GEO). And of course, manned missions are also at risk.

To ensure safe and sustainable access to outer space for all, guidelines, principles and recommendations related to the management of outer space are formulated and issued, which are mainly initiated by the United Nations (UN). Other organizations are then involved in building space situational awareness and developing capabilities to detect, identify, catalogue and track objects in orbit around the Earth.

2 Space Debris

Space debris represents a significant and ongoing threat to the functioning of vehicles in the Earth orbit and to the sustainability of the space environment in general. The terms space debris, orbital debris or space junk collectively refer to all non-functional and uncontrolled bodies of various sizes that orbit the Earth at various altitudes. The main problem is the velocity of these bodies, which is up to 7.8 km/s (approximately 28 000 km/h), and especially their constantly increasing number [2].

Since the beginning of the space age in the 1950's, there has been more space debris in orbit around the Earth than functional satellites [3]. Until 2007, most space debris originated from explosions of upper stages of launch vehicles. By 2022, however, more than half of all objects catalogued came from three major events, which were China's anti-satellite weapon test and destruction of its own satellite in 2007, the accidental collision of the US Iridium communications satellite with Russia's malfunctioning Cosmos satellite in 2009, and Russia's destruction of its own satellite in 2021 [4]. Collisions in orbit, however, are gradually increasing, both accidental mostly caused by uncontrollable collisions of inactive bodies and fragments of space debris, and those formed intentionally as part of anti-satellite weapons tests. Examples are well-known cases of Russia, the USA, China or India shooting down their own satellites.

The number of space debris objects is constantly increasing not only due to these collisions, but also due to battery explosions, explosions of residual propellants and rapidly increasing number of space launches worldwide. In 2023, the models estimated more than 36 000 objects larger than 10 centimeters in size, 1 million objects between 1 and 10 centimeters (these are referred to as lethal nontrackable debris - LNT), and more than 130 million objects smaller than 1 centimeter (Tab. 2) [5]. Smaller objects are capable of seriously damaging satellites and their sensitive components, while larger fragments are capable of causing complete destruction of the satellite, which can lead to the creation of hundreds to thousands of new fragments.

Tab. 2 Number of debris objects in the Earth orbit

Size	≤ 1 cm	> 1 cm and ≤ 10 cm	> 10 cm
Number	130 000 000	1 000 000	36 500

In recent years, there has been a significant increase in the number of launches. The most significant change can be seen in the LEO, where the number of launches has increased tenfold by 2023 compared to 2000. The development in this area is manifested mainly by the launch of large constellations of satellites and the shift towards commercial operators. Several private entities have already started launching mega-constellations containing tens of thousands of satellites, especially communication ones. This is also related to the increase in the number of bodies returning to the atmosphere. A significant number of fragmentation events have been registered for a long time, with an average of twelve unintentional collisions or disintegrations of bodies occurring in orbit every year [3, 6].

The probability of collisions is increasing rapidly, and in the future there is a threat that access to orbit could be lost due to the amount of space debris. Kessler syndrome (also Kessler effect or collisional cascading) is a scenario from 1978 that predicts a density of objects in LEO so high that collisions between them can start a cascade in which each subsequent collision generates space debris, making further collisions ever more likely [7, 8]. The issue of space debris has been discussed for quite a long time, the first European conference on space debris was held in 1993 [9]. However, practical results are not yet visible.

It is already clear today that the number of space debris objects in orbit will increase in the future even if all launches were to be completely stopped, due to the expected increase in the number of fatal collisions. The grey line in Fig. 1 shows the result of LEO debris evolution simulation for the case of no further launches, therefore, it is appealed to follow the recommendations for the launch, operation and controlled termination of the operation of space bodies. In addition, it is necessary to develop active debris removal (ADR) technologies [6].

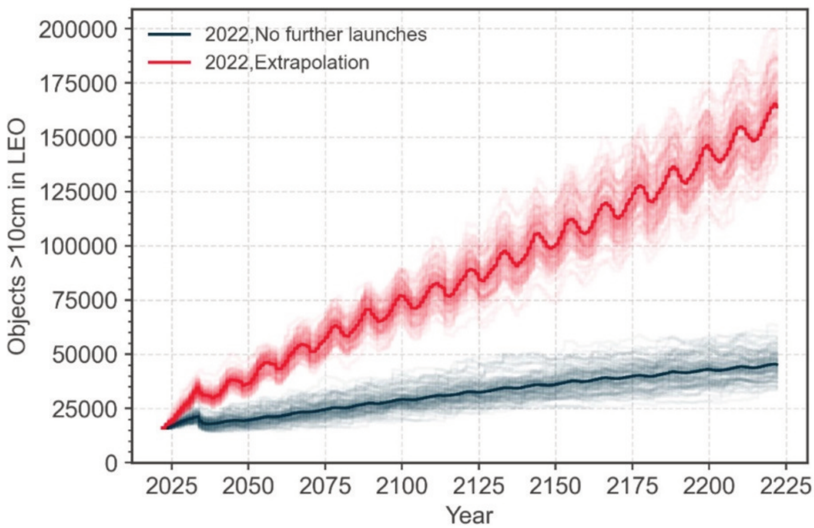

Fig. 1 Number of objects larger than 10 cm *in LEO in the simulated scenarios* [6]

3 Natural Threats Originating from Space

Natural hazards originating from space, i.e. threats to EO systems that are not based on intentional human action, can be divided into two categories – near-Earth objects and the influence of space weather.

3.1 Near-Earth Objects

Near-Earth objects (NEOs) are asteroids and comets ranging in size from a few meters to tens of kilometers that come close to the Earth in their orbits around the Sun and can potentially collide with the Earth. Their orbits were deflected close to the Earth by the gravity of nearby planets. Of the 600 000 known asteroids in our Solar System, more than 31 000 of them were classified as NEOs in 2023, that is objects orbiting less than 1.3 astronomical units (au) of the Sun. This means that they can come at least within 0.3 au – about 45 million km – of the Earth's orbit. Of these objects, almost 2 000 are classified as potentially hazardous objects (PHOs). These are objects over 140 meters in size that have a minimum orbital intersection distance of less than 0.05 au – about 7.5 million km – from the Earth's orbit [10-12].

3.2 Space Weather

Space weather (SWE) is a natural phenomenon that is the result of processes originating mainly in the Sun, but it also results from the nature of the Earth's magnetic field and atmosphere and our position in the Solar System. Space weather manifests itself, for example, in solar eruptions, coronal mass ejections, the solar wind or cosmic rays. Magnetic fields, radiation, particles, and matter ejected from the Sun interact with Earth's atmosphere and magnetic field to cause geomagnetic storms in Earth's magnetosphere. The solar wind is a continuous stream of mainly protons and electrons in a state known as plasma emitted at high speed from regions of the Sun's corona. Cosmic rays are represented by high-energy particles originating outside the Solar System.

Space weather can affect the performance and reliability of EO satellites as well as their ground infrastructure. With its manifestations, it can affect the passage of the signal through the ionosphere in such a way that there can be a complete loss of communication with the satellite. At times of increased Sun activity, the drag force on satellites increases. During normal solar activity satellites in LEO have to boost their orbits about four times per year to make up for atmospheric drag. When solar activity is at its greatest over the 11-year solar cycle, satellites may have to be maneuvered every 2-3 weeks to maintain their orbit.

Charged particles from the solar wind reduce the efficiency of solar panels, which are subject to degradation, and some subsystems may be physically damaged by ionizing radiation. The long-term impact of charged solar wind particles on the surface of satellites can affect their trajectories, while high-energy cosmic ray particles can damage or destroy spacecraft electronics [13-15].

4 Intentional Threats to Satellites

Deliberate threat to EO and other systems comes mainly from anti-satellite (ASAT) weapons and activities. Some activities or weapons are designed to temporarily put satellites out of service, but others can damage them permanently or destroy them completely. Some attacks can be conducted from the air, from LEO, or even from the ground.

The beginning of the development of the first anti-satellite weapons dates back to the very beginnings of the human space age, that is to the first years of the Cold War. The first artificial Earth satellite, Sputnik 1, was launched into space in 1957 by a Soviet R-7 intercontinental ballistic missile designed to carry nuclear warheads which was the impetus for the decision to develop means capable of countering objects in orbit.

The first test of an anti-satellite weapon was already carried out in October 1959 in the USA as part of the Bold Orion Operation. An anti-ballistic missile launched from the B-47 bomber guided itself toward the Explorer 6 satellite at an altitude of 250 km passing within 6.4 km of the target. If the rocket carried and detonated a nuclear warhead, the satellite would be destroyed [16].

Since then other types of weapons have been developed, tested and practically used. ASATs can be divided into several categories according to the principle of operation. The categories of ASATs are as follows: kinetic, non-kinetic, electronic, and cyber. Another possible specification of the types of these means can be, for example, whether they can threaten their targets from the ground, from the air or from orbit, whether or not they are of a physical nature, etc. [2, 4, 17].

4.1 *Kinetic Weapons*

Kinetic anti-satellite weapons include weapons with direct-ascent (DA-ASAT) and co-orbital weapons. Kinetic weapons generally destroy a target in orbit either by direct hit or detonation near the target. While direct-ascent weapons are guided missiles launched directly to destroy a target in orbit, co-orbital weapons are first launched into orbit around the Earth and then maneuvered close to the target where they can attack it by deliberate collision, explosion or even using robotic arms (Fig. 2).

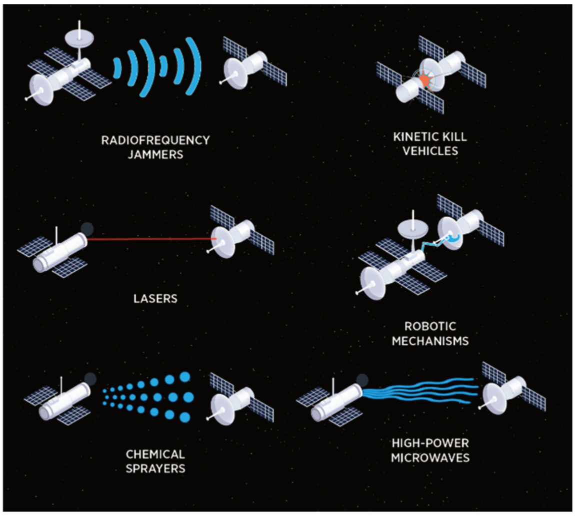

Fig. 2 Space based (co-orbital) ASAT weapons [4]

Direct-Ascent ASATs

The already mentioned US test from 1959 belongs to the DA-ASAT type. The first successful test of reaching a target in orbit was carried out by the Soviet Union in February 1970 with a Zyklon-2A rocket that exploded near the DS-P1-M (Tyulpan/Lira) satellite at an altitude of about 500 km and fragments from the explosion hit the satellite. In the USA, the first successful downing of a satellite was carried out in September 1985, when a guided missile launched from an F-15 destroyed the Solwind (P78-1) satellite at an altitude of 555 km.

It is alarming that even at a time when the effects of space debris on the safety of operating satellite systems in orbit and even on the safety of manned flights are known, there are other irresponsible activities that can have far-reaching consequences for the sustainability of space around Earth.

In January 2007, China deliberately destroyed its own malfunctioning FengYun-1C weather satellite in orbit at an altitude of 865 km using a ground-based medium-range ballistic missile. This resulted in up to 40 000 fragments, which have been a potential threat in heavily used orbits ever since (Fig. 3). Similar tests were supposed to take place in 2010, 2013 and 2014, but no further fragments were produced [18]. In April 2011, some fragments travelled past the International Space Station (ISS) at a distance of only 6 km. In January 2013, part of the fragments collided with the Russian BLITS satellite and destroyed it [19]. In 2019, it was estimated that at least 3 000 of all regularly monitored objects with the potential to compromise the safety of the ISS still came from this Chinese test.

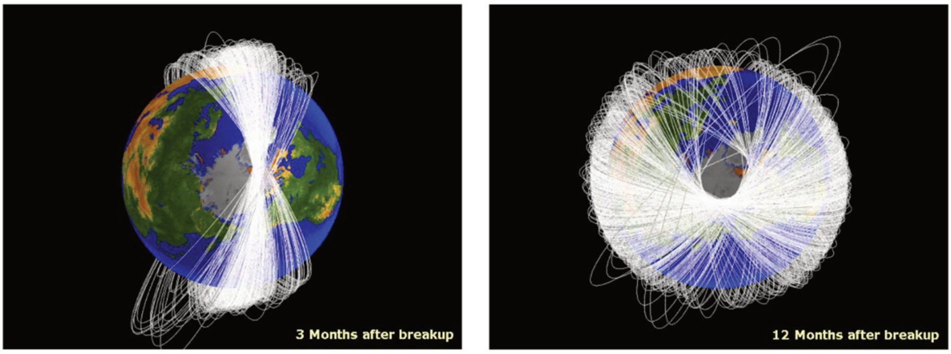

Fig. 3 Evolution of the Fengyun-1C satellite debris orbit planes after China ASAT test in 2007 [20]

Another case is the destruction of the malfunctioning spy satellite USA-193 at an altitude of 247 km by a cruise missile launched from a US Navy ship in February 2008.

India also joined the DA-ASAT tests when it used a ground-launched missile to destroy the Microsat-R satellite at an altitude of 300 km in March 2019 [21]. The test was to prove that India is as powerful a space power as the United States, Russia and China. Despite India's claimed safe approach to conducting the test, dozens of fragments were found to be orbiting at a perigee of approximately 200 km and an apogee of over 900 km, thus crossing the orbit of the ISS. Since the test was carried out, Indian fragments have already threatened some other functional satellites several times [22].

Even as recently as in November 2021, Russia used a DA-ASAT cruise missile to destroy its own malfunctioning Cosmos 1408 satellite in LEO at an altitude of 550 km. Subsequently, more than 1 500 traceable fragments and hundreds of thousands of smaller fragments were created and these have already clearly threatened the ISS and will probably orbit in LEO for decades [4, 23].

In recent years, the efforts of other states to join this group of great powers have been registered. Iran, North Korea, Australia, Japan, South Korea and some other states are trying to build capabilities and test DA-ASAT assets [4, 17].

Co-orbital ASATs

The first tests of co-orbital weapons were carried out by the Soviet Union in 1963 using R-7 intercontinental ballistic missiles. The method was based on launching a body into the same orbit in which the target was moving and approaching it in order to destroy it. Such operations require mastering the problem of autonomous approach of objects and are used today, for example, by inspection satellites when exploring other vehicles in orbit. So far, in addition to Russia, only the United States and China have presented advanced capabilities to perform autonomous rendezvous and proximity operations in orbit [2].

However, these capabilities potentially have other uses, such as removing larger objects of space debris, repairing satellites or refueling in orbit. One example of peaceful use for now is China's SJ-21 satellite, which in 2022 on GEO approached, docked with, and pulled the defunct Beidou G2 GNSS satellite into a higher orbit to allow a new satellite to occupy that position. After that, SJ-21 returned to its original position at GEO [17]. Another example is the planned mission of NASA's OSAM-1 (On-orbit Servicing, Assembly, and Manufacturing) satellite, which was renamed to Restore-L recently. The satellite should approach the EO Landsat 7 satellite in 2025, attach to it, refuel and transfer it to a new orbit [24].

The category of kinetic anti-satellite activities sometimes also includes physical damage or sabotage of the ground infrastructure of the satellite system.

4.2 Non-Kinetic Weapons

Non-kinetic anti-satellite weapons include, in particular, nuclear explosions in outer space and directed energy weapons. Some sources also include cyber attacks and jamming in this category.

Tests with nuclear explosions in space have been conducted since the late 1950's. In July 1962, the United States conducted the largest nuclear test in space, one of a total of five as part of Operation Fishbowl. The explosion occurred at an altitude of 400 km, approximately 1 500 km from Hawaii. In addition to significant atmospheric phenomena and serious disturbances on the ground infrastructure in Hawaii, due to the influence of the electromagnetic impulse, several American navigation satellites in orbit at an altitude of over 1 000 km, including satellites of Great Britain and the Soviet Union, were immediately or subsequently disabled. Similar tests were also carried out in operations Argus, Dominic and others. By 1963, when the Partial Test Ban Treaty (PTBT) was signed, the United States had conducted a total of 15 tests and the Soviet Union 7, all at altitudes between 22 kilometers and 540 kilometers [25-27].

Directed energy weapons include, for example, laser or microwave weapons. These devices can cause glare or total blinding of sensors, disruption of electronic equipment, damage or destruction of circuits, disruption of communications or interruption of power supply [e.g. 28, 29]. In September 2006, the media published information that one of the US military satellites was hit by a laser located on the territory of China [30].

4.3 Electronic Threats

The category of electronic threats includes activities referred to as jamming and spoofing. A jamming device disrupts communications between the ground infrastructure and an orbiting satellite by generating noise in the same frequency band that overloads the communication channel and blocks the transmission of information either in the direction from the Earth to the satellite or in the opposite direction from the satellite to the users.

Spoofing is an activity where an attacker tricks a receiver into believing that a fake signal produced by the attacker is the real signal it is trying to receive [17].

4.4 Cyber Threats

Cyber threats and attacks can target satellites, ground infrastructure, communication means and end-user equipment. Cyber attacks can be used to monitor data traffic, intercept data, or insert false or corrupted data into a system, resulting in data loss or service interruption. In extreme cases, there is even a risk of taking control of the satellite, which can lead to the interruption of communication or permanent damage to the satellite, for example by depleting the fuel supply or entering commands that would damage electronic systems or sensors [4, 17].

The term hacking is also used for such activities, i.e. malicious penetration into systems. These cases have most likely already occurred in the past. In 1998, an alleged takeover of the German ROSAT satellite was registered, which was destroyed after pointing the solar panels directly into the sun. In 1999, the case of taking control of one of the British SkyNet satellites and demanding a ransom was publicized. Then there are reliably documented cases from 2007 and 2008, when there was repeated interference or even a few minutes of full control and maneuvering of the NASA Landsat 7 and Terra EO satellites [31, 32]. Russia has periodically jammed GPS signals in several areas, including in Ukraine since its 2014 invasion and in northern Norway during NATO exercises there. Also Russian cyberattack on ViaSat communications satellite ground infrastructure that interrupted service to Ukraine and several European nations were reported since 2022 [33].

These cases are proof that satellites and their ground systems are really just computers running special software, but they often use common operating systems like Unix or Linux and are therefore just as vulnerable as any other computer.

5 Standards Related to Outer Space Management

All existing documents seeking to establish a responsible approach to outer space management are legally non-binding instruments, which also applies to documents issued by the UN. Nevertheless, it is important that similar standards of the UN and other organizations are issued, published and recalled. Only in this way is there any hope of preserving the sustainability of the near-Earth space for its peaceful use for the benefit of all.

5.1 United Nations

The first of the fundamental documents was the "Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies", also known as the Outer Space Treaty, which entered into force in 1967 [34]. The principle of free use and research of space is enshrined in Article I: "The exploration and use of outer space, including the Moon and other celestial bodies, shall be carried out for the benefit and in the interests of all countries, irrespective of their degree of economic or scientific development, and shall be the province of all mankind".

But the Outer Space Treaty is more than 50 years old, so in connection with the new dynamics of the use of space, especially commercial use, its limitations are becoming apparent. The treaty only established a minimum set of rules that each country must follow. Nevertheless, the provisions of the treaty also apply to what private companies do in space and they have ever-greater ambitions, which are no longer limited to simply launching satellites. At this time, there is no regulatory framework that allows governments to oversee private activities in space and ensure that these entities comply with the articles of the treaty [35, 36].

In 2019, the UN Committee on the Peaceful Uses of Outer Space (COPUOS) issued guidelines for the long-term sustainability of activities in outer space [37]. However, even these guidelines are not legally binding due to international law and compliance with them is voluntary. In 2022, the United Nations General Assembly approved a resolution calling to halt destructive testing of direct-ascent ASAT weapons as an urgent measure aimed at preventing further damage to the near-Earth space [38, 39].

5.2 Inter-Agency Space Debris Coordination Committee

Standards related to space management are also issued by other organizations. For example, the Inter-Agency Space Debris Coordination Committee (IADC), which brings together 13 national space agencies such as NASA, ISRO, CNES, JAXA and others, has been developing a set of recommendations aimed at reducing the amount of space debris since 2002. These recommendations should be taken into account during mission planning, design, manufacture and operation (i.e. launch, mission performance and subsequent disposal) of orbital stages of spacecraft and launch vehicles [3, 40]. The IADC also created the concept of protected regions around the Earth (Fig. 4) and formulated requirements for their future safe and sustainable use, especially with regard to the creation of space debris [40].

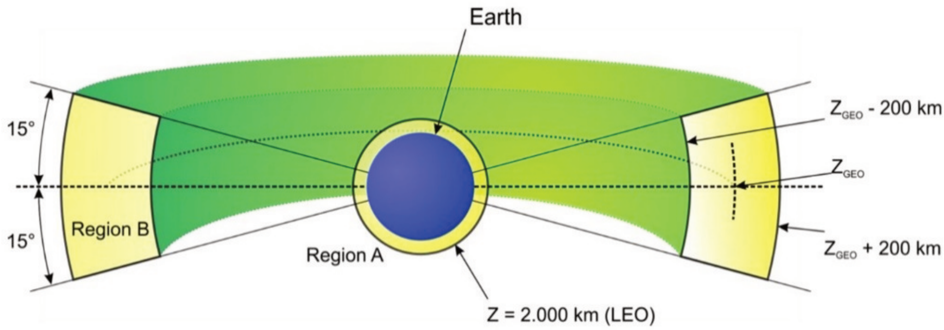

Fig. 4 Protected orbital regions [40]

5.3 European Union

In 2017, the European Space Agency (ESA) began publishing an annual report on the space environment. In it, ESA recommends the procedures that should be applied after the end of life of the systems in LEO, GEO and MEO [3].

In 2023, the “EU Space Strategy for Security and Defence” [41] was published. In it, space is designated as a strategic domain that is absolutely essential for preserving the strategic autonomy of the EU and its member states. This domain includes, in addition to the space environment, orbits and orbiting satellites and other systems, ground infrastructure including launch infrastructure, user infrastructure and cyber systems, as well as the related space industry sector. The strategy is dedicated to understanding the main space threats in the form of deliberate activities of other parties and proposes measures to strengthen the resilience and protection of space systems and services in the EU.

6 Space Situational Awareness

The only way to preserve the usability of near-Earth space is its continuous monitoring and building of Space Situational Awareness (SSA). SSA means knowledge of the space environment, including the exact location and function of space objects and the state of space weather. A number of organizations are involved in building the SSA, especially in developing the capabilities of detection, identification, cataloguing and constant monitoring of objects in the Earth orbit.

For example, the UN supports, through COPUOS, the creation and operation of other entities with the aim of improving international coordination of activities related to NEO. It supports activities in the framework of NEO detection and tracking, and it promotes international cooperation in the research of technologies and methods for diverting NEOs from the collision course and for increasing planetary protection [12].

NASA, through its Orbital Debris Program Office (ODPO), conducts near-Earth space monitoring. To do this, it uses ground-based radars and telescopes, sensors in orbit and other means. It is also involved in the development of measures to reduce the amount of space debris [42]. NASA's Center for Near Earth Object Studies (CNEOS) deals with calculating the orbits of asteroids and comets and their probability of impact on Earth. It also maintains a database of tens of thousands of known NEOs and their close approaches to the Earth's orbit, both back to the year 1900 and their prediction to the year 2200 [11].

The US National Oceanic and Atmospheric Administration (NOAA) conducts observations of various space weather phenomena and provides this data to various users in near real time. It compiles and provides reports on acquired data and space weather conditions. It generates forecasts for various types of space weather phenomena and the resulting impacts on Earth and human activities, and issues alerts and warnings [43].

The US Space Force operates several systems to track objects in orbit. These are, for example, the Space-Track or Space Fence systems for detecting, tracking and cataloguing more than 300 000 objects in LEO, MEO and GEO. These systems allow authorized users to obtain information about the exact parameters of the orbits of monitored objects [44, 45].

The European Union, through its agencies, is also dedicated to building and maintaining space situational awareness. For example, ESA has created the Space Safety Program (S2P), which includes space weather monitoring, early warning of asteroids on collision courses with the Earth, and other activities related to planetary protection [46]. To provide timely and reliable information and services related to space weather, ESA operates a service network, a coordination center and an online portal for space weather [47]. ESA also searches for, catalogues, tracks these objects within the NEO Coordination Centre (NEOCC), predicts their orbits and potential close approaches and, if necessary, issues warnings [10, 48].

The European Union Satellite Centre (EUSC) supports the decision making and actions of EU within its Common Security and Defence Policy and especially in the field of space. The center started operating the Space Surveillance and Tracking (SST) support office (EU SST Front Desk). This task was later assigned to the European Union Agency for the Space Programme (EUSPA). It uses a worldwide network of ground and satellite optical, laser and radar sensors for monitoring and provides several specialized services related to objects in Earth orbit to authorized users as follows [49, 50]:

- the Collision Avoidance Service consists in assessing the risk of collision between spacecraft and between spacecraft and space debris. For example, in the first half of 2021 alone, more than 7 000 close approaches in LEO, MEO and GEO were detected, of which almost 200 were classified as the High Interest Events. As a result, one of the GNSS Galileo satellites was forced to perform an evasive maneuver for the first time in March 2021,
- the Re-entry Analysis Service provides a risk assessment of the uncontrolled re-entry of manmade space objects into the Earth's atmosphere. This happens on average once every 3 days in the case of satellites or parts of launch vehicles, and in the case of pieces of space debris approximately every 30 hours,

- the Fragmentation Analysis Service provides detection and characterization of in-orbit fragmentations. On average, EU SST detects six fragmentation events per year.

The probability of collisions in Earth orbit is still increasing due to the increasing number of launches and the continued disintegration of bodies caused by mutual collisions, battery explosions and ongoing ASAT tests. It turns out that satellites are also vulnerable due to the non-existent mandatory safety standards required for the launch of new satellites; another problem is the insufficient security of older satellites [4, 31].

The complexity of this problem increases not only with regard to the growing number of launched bodies, especially in connection with the proposals for new mega-constellations of satellites. More and more bodies have the ability to maneuver in orbits, which has an impact on the need for coordination in case of collision avoidance operations [6]. Preparations are also underway to launch satellites capable of operating in swarms with their own autonomy, communicating and cooperating with each other, planning and executing autonomous maneuvers without the need to receive commands from ground operators [51]. Thus, the importance of continuous monitoring for increasing the safety of satellite operations, and not only EO satellites in LEO, is growing.

7 Conclusion

When considering the number of specialized missions of EO satellites, constellations of GNSS satellites or daily monitoring of meteorological satellites, it is clear how our life is strongly dependent on the uninterrupted provision of services of systems operating in Earth orbits. Additionally, the security of many nations is heavily dependent on satellites supporting security and defense applications, such as IMINT and others. And recently we came to the disturbing realization that all these systems are actually very vulnerable, not only from the direction of the outer space, but also from the hostile activities of man. Our reliance on space-based assets becomes a point of potential vulnerability. It follows that it is vital to seriously and urgently deal with the state of near-Earth space and the active and effective protection of satellites in orbit.

The question is to what extent current satellite service providers are addressing satellite security and resilience and to what extent it is sufficient. Today, it is no longer enough to have satellites that survive the launch and begin to fulfill assigned tasks in orbit; however what is needed, are defendable satellites.

The complexity, quantity and dynamics of various types of threats are constantly increasing. For the successful protection of satellite systems, it will be necessary to apply different approaches, for example threat-specific approaches, which represent immediate responses to newly identified threats, and systemic approaches, which will be more complex, long-term, but also more effective.

Research by a number of institutional and commercial space actors and their ambitious plans indicate where the road to better protection of satellite systems could go. Potential ways of addressing the challenge consist in cyber, physical and electromagnetic hardening; using of anti-jamming, radiation shielding, GPS authentication and detection and blocking of fake signals; exploiting secure chip architectures; using embedded security by design; rapid refresh of technologies; de-orbiting and replacing by more up-to-date systems; building of a hybrid system architecture, i.e. combining of satellites of different sizes; launching space surveillance satellite constellations for SSA; launching debris mitigation vehicles; launching permanent satellite robot fleets on LEO and GEO for in-orbit assembly, refueling, servicing and salvage, etc.

Despite all these planned solutions, it is apparently crucial to realistically prepare for the fact that losses of some space assets will inevitably occur in the future and we have to be prepared. But there is still hope that all parties, both institutional and commercial, will respect the Outer Space Treaty and other UN resolutions and guidelines and will approach their activities in Earth orbit responsibly so that near-Earth space remains usable on a long-term basis for the benefit of all humanity.

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