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SAFETY ENGINEERING OF ANTHROPOGENIC OBJECTS

ORBITAL SATELLITE CONSTELLATIONS AND THE GROWING THREAT OF KESSLER SYNDROME IN THE LOWER EARTH ORBIT

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Abstract

The paper discusses the problem of the growing threat of orbital collisions – the Kessler syndrome in the Earth's lower orbit caused by orbital satellite constellations developed to provide broadband internet. It provides a theoretical context for the main argument by presenting the current data related to space debris in orbit, the concept of the Kessler syndrome and its application to orbital objects, the legal framework pertaining to the issue, mitigation programs and plans, and new orbital satellites constellations under development and how they contribute to the Kessler syndrome threat.
The main contribution of the paper is the carried out argument that the lack of a global legal system regulating the use of the Earth's orbit is a factor that strengthens the threat.

Key words: Kessler syndrome, satellite constellations, space debris, space debris models, space security

INTRODUCTION

The second decade of the 21st century has brought a dynamic and somewhat surprising development of the space industry. Since 1972 – the Apollo 17 crew mission to the Moon, the humankind has not left the safe environment of Earth's orbit, and for years the global space sector has been progressing in slow but steady pace run by a few largest space agencies like American NASA, European ESA, Japanese JAXA, and Chinese CNSA. The most significant achievement of the "old ways" of managing outer space exploration is the International Space Stations (ISS) that has facilitated more than 20 years of continuous crewed operations.

The situation started to change at the turn of the century when new generations of private entrepreneurs began to invest in and develop space technologies like rocket boosters, spaceships, and what most important for the subject of the paper – satellites and their constellations. This new shift is known among the space industry as "Space 2.0", and its emergence is dated around 2000-2002 when the companies like SpaceX, Blue Origin, and Virgin Galactic were established. (Pyle, 2019). The real change, however, came in 2012 when the first SpaceX commercial mission was successfully launched to the ISS (NASA, 2012).

Since then, the participation of the private sector in the space industry has skyrocketed, especially in the United States. Today, SpaceX is the only entity that provides reusable rockets (first stage and fairings) that is capable of vertical launch and landing. Their current flagship rocket – Falcon 9 has carried out 23 successful missions in 2020 (SpaceX, 2020) and another four are planned for December of that year (Weitering, 2020). Moreover, thanks to Crew Dragon spaceship developed by the company, Americans have regained this year the capacity of sending astronauts from their own soil after nine years of buying the seats on Russian Soyuz capsule. SpaceX is now in the process of building a communication satellites constellation that will be addressed and analyzed in the paper.

Nowadays, in the space industry, we witness a very productive cybernetic feedback look between the development of space technologies, the democratization of those technologies, and a substantial reduction of prices. The latter is even more significant if we compare the cost of launching cargo into orbit now and 20 years ago – Falcon 9 is over ten times cheaper than Space Shuttle (Jones, 2018). This, of course, directly translates into the mass and number of objects that we are able to put in the orbit viably. Once the constellations consisting of thousands of satellites were unthinkable, but in the current environment, they become a reality.

Space 2.0 also has brought new threats and challenges in the sphere of national and international security. The increase in launch capacity, among other factors, has led to progressive militarization and weaponization of space and new arms race (Bernat, 2019), which has also contributed to the growing numbers of orbiting objects.

The goal of the paper is to present the argumentation that the threat posed by the cascading collisions in the Earth’s orbit (Kessler syndrome) is becoming more severe due to the construction of orbital satellite constellations; the threat that presents a real danger for people during their EVAs and orbital infrastructure, which may bare immediate consequences for safety and security systems on Earth. In order to provide the theoretical context for the above claim, the following issues will be presented and discussed: (1) space debris, (2) the Kessler syndrome, (3) orbital debris models, (4) the legal issues related to space debris and mitigation actions against their proliferation, and (5) the planned and being currently developed orbital satellite constellations and how they contribute to the growing threat of the Kessler syndrome.

The paper does not provide either any new model of space debris evolution, not new mathematical estimates how orbital constellations increase the risk of cascading collisions – its contribution consists in the analysis of the existing data and demonstration that recent development of satellite internet technologies significantly increases the threat of orbital collisions, even more so due to the lack of global legal regulations.

1. Space debris

The Technical Report on Space Debris published by the United Nation Committee on the Peaceful Uses of Outer Space (COPUOS) defines space debris as "all manmade objects, including their fragments and parts, whether their owners can be identified or not, in Earth orbit or re-entering the dense layers of the atmosphere that are non-functional with no reasonable expectation of their being able to assume or resume their intended functions or any other functions for which they are or can be authorized" (UN, 1999, p. 2). European Space Agency (ESA) defines space debris in a similar manner – as "all the inactive, manmade objects, including fragments, that are orbiting Earth or re-entering the atmosphere" (ESA, 2017, p. 1). The definition formulated by the National Aeronautics and Space Administration (NASA) differs from the two above because, apart from human-made orbital objects, it includes into the space debris category the objects of natural origin (NASA, 2008, p. 22) – the meteoroids, i.e. "naturally occurring particulates associated with solar system formation or evolution processes. Meteoroid material is often associated with asteroid breakup or material released from comets" (NASA, 2008, p. 21). Orbital debris, according to NASA, should be understood as "artificial objects, including derelict spacecraft and spent launch vehicle orbital stages, left in orbit which no longer serve a useful purpose" (NASA, 2008, p. 21). For the purpose of this paper, which is the examination of the growing number of potential collisions (between natural and human-made objects) in the Earth's orbit, the NASA definition of space debris will be used.

According to ESA's data (last updated on Nov. 18 2020), since the launch of Sputnik 1 in 1957, there have been 5,990 rocket launches (excluding failures). The number of satellites these rockets have placed into Earth orbit is oscillating about 10,490, from which there are about 6,090 still in space. There are 3,300 satellites in the orbit that are still functioning. ESA estimated that the number of break-ups, explosions, collisions, or anomalous events that resulted in fragmentation is more than 550. ESA further reports that the total mass of all space objects in Earth orbit amounts to above 9100 tons and the number of orbital debris objects

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(approximated by statistical models) is the following – 34,000 objects greater than 10 cm, 900,000 objects from 1 cm to 10 cm, and 128 million objects from 1 mm to 1 cm (ESA, 2020a). Figure 1 depicts the growing numbers of space debris orbiting Earth.

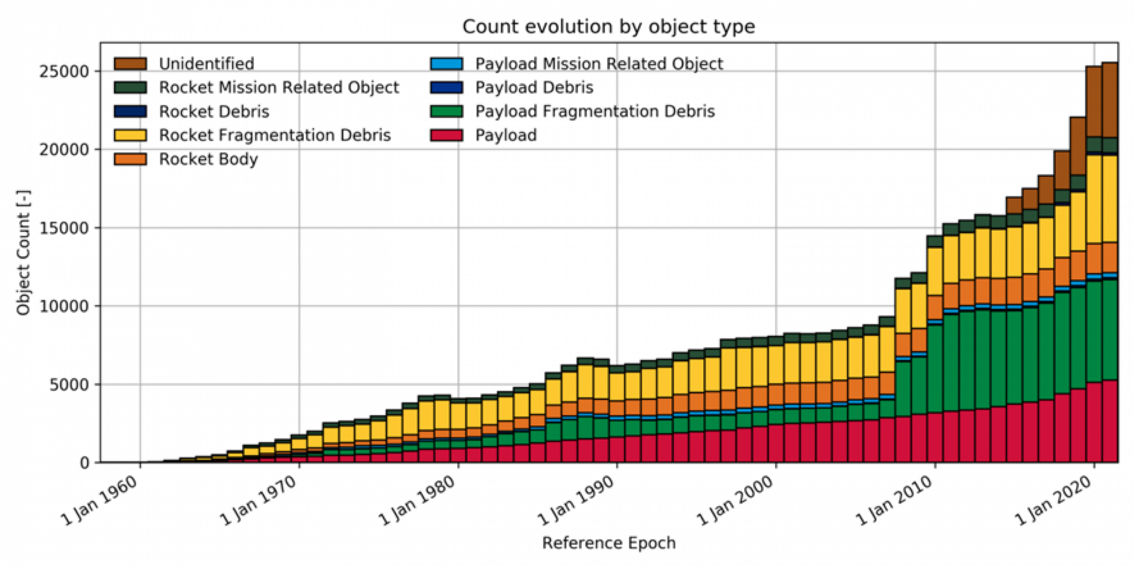

Figure 1. *Space debris by object type (Ibrahim, 2020)*

Two most important bodies monitoring space debris are NASA's Orbital Debris Program Office (ODPO) and ESA's Space Debris Office (SDO).

The number of space debris is on the rise. It stems from two facts. First, the number of satellite launches increases, and there is clear trend is that it will continue to do so (Fig. 1.) and every launch generates more debris (even so small as paint flake). The growing tendency is a consequence of both, the emergence of new actors in the space sector like SpaceX or Blue Origin (Space 2.0), and the growth and development of national space agencies. Secondly, we witness continuous miniaturization of satellites, what automatically translates into larger numbers of objects sent to the orbit.

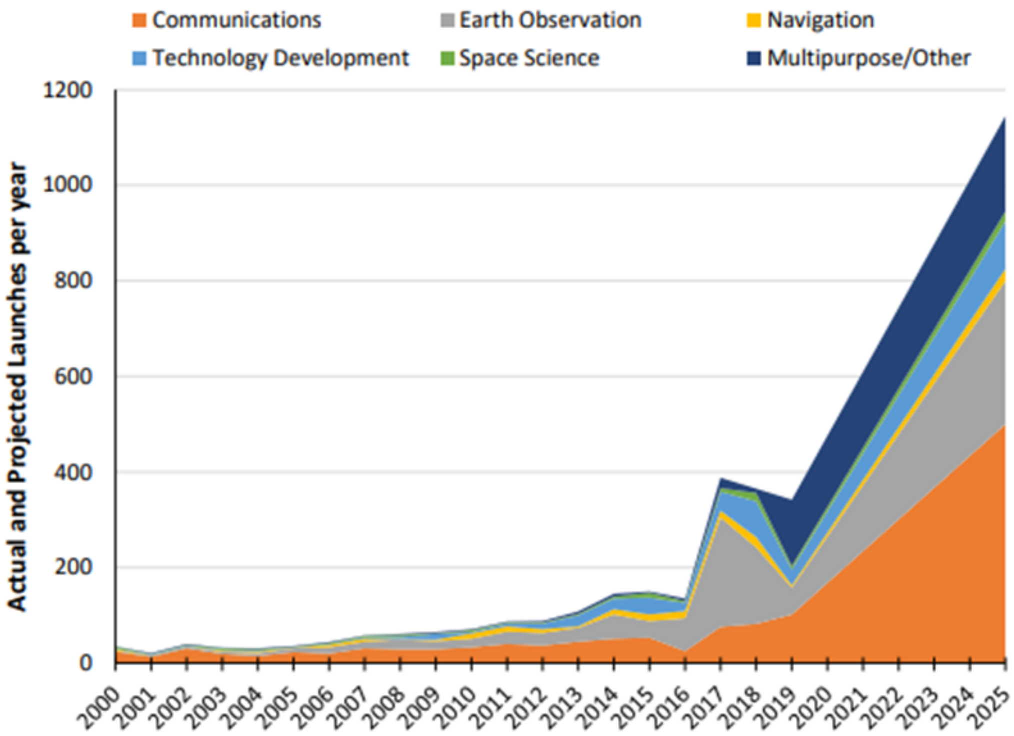

Figure 2. *Actual and forecast satellite launchers per year (NATO, 2020, p. 80)*

Using the criterion of the potential threat that space debris generate for potential target and the area of their impact area, they can be divided into three types, namely for (1) orbital operating objects and astronauts during extravehicular activity, (2) infrastructure and people on the surface of Earth, and (3) for future launches to the orbit (Bernat, 2018, p. 437).

2. The Kessler syndrome and space debris in the Earth's orbit

The concept of collisional cascading, later named the Kessler syndrome, did not originate to predict the interaction of orbiting space debris but it was developed by two astronomers – Kessler and Cour-Palais – to describe the process of ring formation around planets, the origin of meteoroids and meteorites from asteroids. In their 1978 paper, Kessler and Cour-Palais entitled *Collision Frequency of Artificial Satellites: The Creation of a Debris Belt* argued that satellite collisions "would produce orbiting fragments, each of which would increase the probability of further collisions, leading to the growth of a belt of debris around the Earth […]. The debris flux in such an earth-orbiting belt could exceed the natural meteoroid flux, affecting future spacecraft design" (Kessler, and Cour-Palais, 1978, p. 2673). In 2010, Kessler with the team published another paper, which, in more detail, defined the concept of orbital collisional cascading and presented its possible implications to future space operations. The Kessler syndrome, in the words of its intellectual father, can be summarized as follows:

> Fundamental orbital mechanics predict (with rare exceptions) that any two orbiting objects that pass through the same distance from the objects that they are orbiting about represent an unstable condition. The condition is unstable because the two objects will eventually collide and break up into a number of smaller fragments, creating an even larger number of objects sharing the same distance, and therefore increase the collision rate. The number and size of the smaller fragments depend on the collision velocity, which mostly depends on the orbital inclinations of the objects. (Kessler et al., 2010, p. 48)

The Kessler syndrome, in other words, is based on a simple fact that the more debris there are in orbit, the more collisions will occur and create more debris. Drmola and Hubik, who created a system dynamic model for orbital space debris, call it "reinforcing feedback loops" (2018, p. 30). In their paper, they provide an apt depiction of the process (Fig. 3).

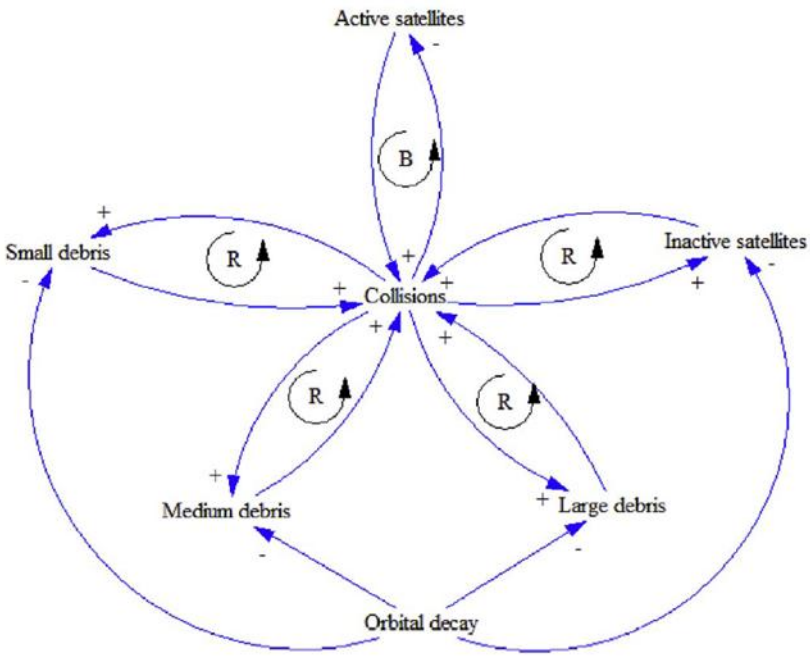

Figure 3. *Simplified causal diagram of space debris collisions, where "R" indicates the reinforcing feedback loops (Drmola, and Hubik, 2018, p. 30)*

Kessler and its team predict that in the specific regions of LEO there will be a slow but continuous growth in collision fragments that "will not stop until the intact population is reduced in number (2010, p. 2). The paper is concluded with a value-laden statement that in order to stop the growth of debris we should "obtain near 100% compliance with guidelines

[…] and, in addition, […] retrieve a number of objects that are already in orbit" (2010, p. 14); the invoked guidelines refer to the policies formulated in order to stop or mitigate the threat stemming from orbital object collisions.

3. Orbital debris models

There are several debris models developed by space agencies and academics. NASA currently runs two models – Orbital Debris Engineering Model, ORDEM 3.1 (NASA ODPO, 2019) and LEGEND (NASA, 2020). ORDEM, in a nutshell, is "is appropriate for those engineering solutions requiring knowledge and estimates of the orbital debris environment (debris spatial density, flux, etc.)" (NASA ODPO, 2019). LEGEND, on the other hand, is "a full-scale, three-dimensional, debris evolutionary model that is the NASA Orbital Debris Program Office's primary model for the study of the long-term debris environment projection" (NASA ODPO, 2020). Based on user-specified scenarios, the program is capable of providing multi-dimensional representations of the debris environment. Figure 4 shows "LEGEND-simulated historical LEO environment and results from three different future projection scenarios. Each projection curve is the average of 100 MC runs. The effective number is defined as the fractional time, per orbital period, an object spends between 200 km and 2000 km altitudes" (NASA ODPO, 2020).

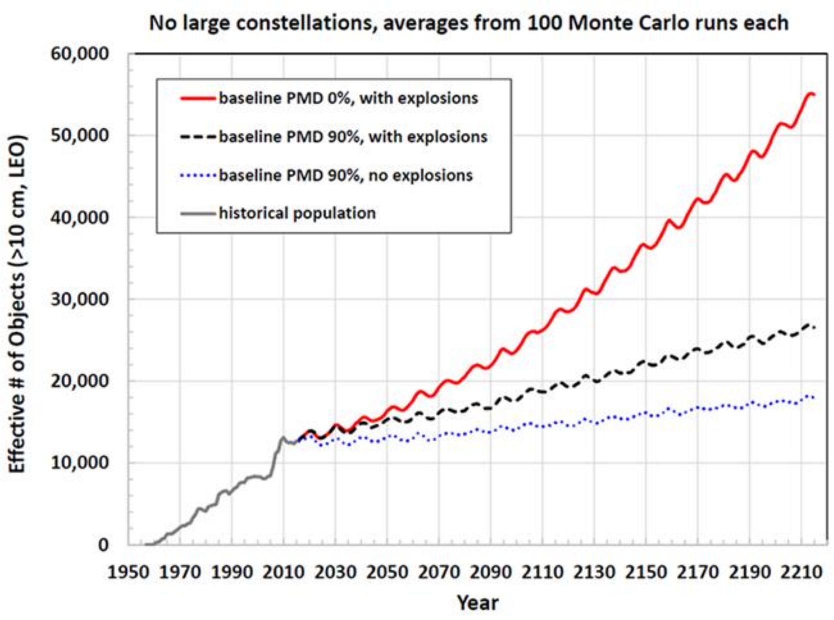

Figure 4. *LEGEND simulation for LEO environment with no large constellations (NASA ODPO, 2020)*

ESA has several programs, thanks to which it is able to monitor and predict the threats generated by orbital space debris. For space debris environment modeling two programs are the most important, i.e., MASTER – Meteoroid and Space Debris Terrestrial Environment Reference, Oriundo – On-ground risk estimation for uncontrolled reentries tool and PROOF – Program for Radar and Optical Observation Forecasting (ESA, 2020b). MASTER is the most ESA's most important tool for debris and meteoroid risk assessment. It covers "all debris and meteoroid sizes larger than 1 micrometer, and includes predictions of the space debris environment until 2050" (ESA, 2020b).

Whatever the morel and software used, the number of space debris grow at an increasing race (Fig. 1). There is a clear correlation between launch rate, which according to prediction will be growing year after year (Fig. 2), and the volume of space debris (Adilov et al., 2018, p. 81). Therefore, the threat generating by space debris collisions for people and infrastructure in orbit grows as well.

The above has been common knowledge for decades. Already in 2001, Kessler and Anz-Meador warned that "if the current intact satellite population is maintained, large regions of low Earth orbit will be unstable" (p. 272). In the last 20 years, the amount of space debris has significantly increased, and in consequence, the potential threat.

4. The legal context and mitigation actions against space debris proliferation

The UN Committee on the Peaceful Uses of Outer Space created a set of guidelines, which consist of the following postulates:

(1) Limit debris released during normal operations;
(2) Minimize the potential for break-ups during operational phases;
(3) Limit the probability of accidental collision in orbit;
(4) Avoid intentional destruction and other harmful activities;
(5) Minimize potential for post-mission break-ups resulting from stored energy;
(6) Limit the long-term presence of spacecraft and launch vehicle orbital stages in the low-Earth orbit (LEO) region after the end of their mission;
(7) Limit the long-term interference of spacecraft and launch vehicle orbital stages with the geosynchronous Earth orbit (GEO) region after the end of their mission. (UN, 2010, pp. 2-4)

It is worthwhile to notice that the above points are guidelines, not laws that would have to be complied with. The current situation is that space exploration and future exploitation is practically unlimited. It means that every state has total freedom to do what they want in terms of technology development, including space weapons and changing their national legal framework so they would allow, for example, future space mining. If there is one constraint still in force, it is a ban on placing nuclear weapons and weapons of mass destruction in orbit, which was established in the Article IV of the Outer Space Treaty from 1967 (UNOSA, 1967). There are many legal interpretations of what is prohibited by the Treaty, which is a consequence of the vague formulation of the Article, which reads the following:

States Parties to the Treaty undertake not to place in orbit around the Earth any objects carrying nuclear weapons or any other kinds of weapons of mass destruction, install such weapons on celestial bodies, or station such weapons in outer space in any other manner. (…) The establishment of military bases, installations and fortifications, the testing of any weapons and the conduct of military maneuvers on celestial bodies shall be forbidden. (UNOSA, 1967)

According to Boothby (2007), the Treaty unequivocally prohibits placing and keeping biological, bacteriological, chemical, and nuclear weapons in orbit. Bourbonniere and Lee (2008) argue that placing conventional weapons, even if they are equipped with nuclear drives, does not break the restriction imposed by the Treaty. They are also of the conviction that if the discussed weapons pass through the orbit on their ballistic trajectory, the law is not broken, although they add the statement that "while an activity that is prohibited by law should not occur, it is facile to argue that what is not prohibited by law should occur" (Bourbonniere & Lee, 2008, p. 901).

In practice, such a wide window of interpretation translates into almost unlimited freedom on the part of countries that have sufficient technological capacity to do so. In summary, (1) the law is unclear – the Treaty, to give one example, uses the notion of weapons of mass destruction, on which there is no consensus and its UNRCPD definition (1977) is too vague in respect to the number of potential victims; the latter is crucial in categorizing potential orbital kinetic bombardment systems as weapons of mass destruction, or not; (2) the United Nations and its agencies have not enough power to impose sanctions on the Treaty's violators.

In the case of space debris regulation, there is no even a legal equivalent to the Treaty of Outer Space – it has become a problem relatively recently. There are guidelines, not laws. Any undertaken mitigation programs are carried out out of the good will of the parties involved. In consequence, the amount of space debris in orbit is rapidly growing (Fig. 1.), and the mitigation programs and technologies are developed too slowly and are too small in scale.

5. Orbital satellite constellations and the growing threat of the Kessler syndrome

Space 2.0 – the new era of space exploration that we witness now in the 21st century means, in words of Buzz Aldrin, "moving human enterprise into space" (Pyle, 2019, p. xiv). The process of commercialization of outer space has already begun and is not limited to private companies providing technologies and services for national or international space agencies, as it was in the past. On the contrary, private companies from the space sector have now matured to carry out their own independent projects.

As for 2020, SpaceX is a company that serves as the best example – it launches satellites to the orbit, both for state and private contractors, it successfully realized two crew missions to the International Space Station, and is in the process of constructing Starlink satellite constellation that will provide high-speed internet access across the planet.

Each satellite weighs around 260 kg, is equipped with an ion propulsion system, autonomous collision avoidance system, and orbits Earth at approximately 540-560 km altitude (Starlink, 2020). At the beginning of November 2020, more than 860 Starlink satellites were orbiting the Earth (Jewett, 2020). Immediate plans include launching 12,000 satellites, but they assume a potential later extension to 42,000 (Henry, 2019a). Of course, SpaceX has employed, at least declaratively, all necessary measures to keep the space clean – the satellites are equipped with the deorbiting system, and in the event of inoperability of the propulsion system (Starlink, 2020). The orbital collisions are, however, inevitable. As it was shown before, the possibility of collisions grows with the number of orbital objects. Bastida Virgili with the team compared (2016, p. 154-155) orbital debris environment development without and with a large hypothetical constellation consisting of merely 1080 satellites, distributed across 20 orbital planes at 1,100 km altitude (Fig. 5).

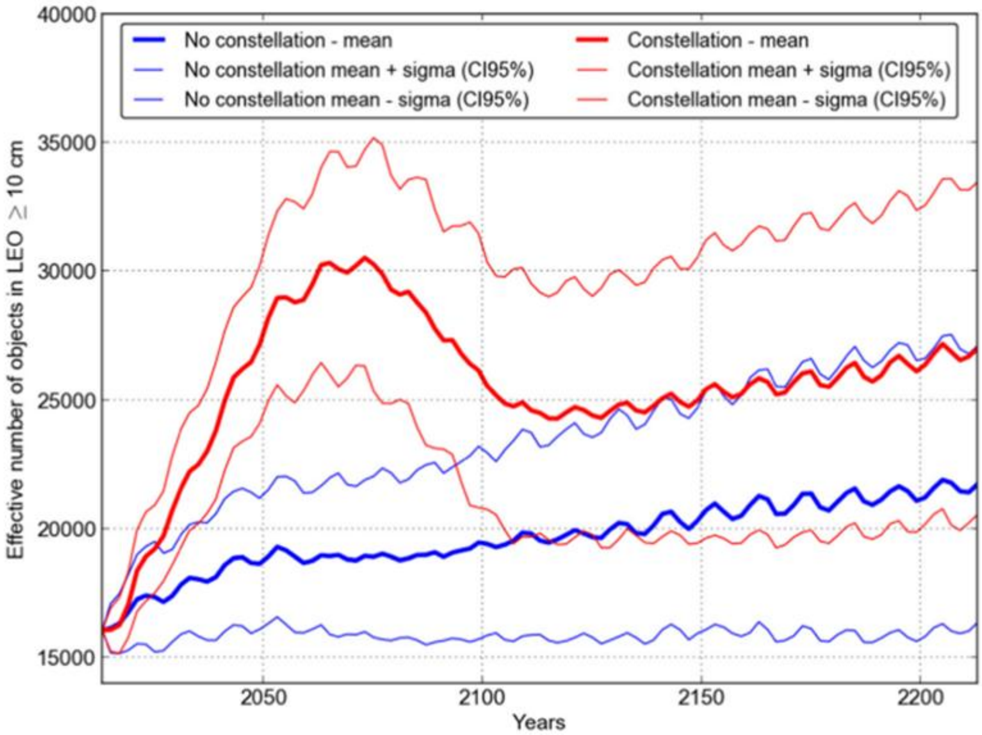

Figure 5. *Comparison of long term evolution of the number of objects in LEO with and without the constellation (Virgili et al., 2016, p. 155)*

It has to be noted that although SpaceX's Starlink is the only constellation that is being built in orbit, it is not the only one planned. There are at least a few initiatives aiming at the same goal – to construct internet infrastructure at the Earth's orbit. The planned Kuiper Systems LLC, which is a subsidiary of Amazon and intends to place 3,236 broadband satellites in the LEO, is one of Starlink's biggest competitors (Henry, 2019b). Now, there is even a rivalry between the two companies because Kuiper's lowest orbital shell is planned to be 590 km, with a tolerance of 9 km either above or below (Cao, 2020), which is the altitude of Starlink satellites. Moreover, the race for space in orbit is now at the beginning.

The outer space is vast. It increasingly becomes more cluttered with both operational satellites and space debris. The threat of collisions increases and no institution or body has enough power to license, coordinate and regulate what is sent to the orbit. The UNOOSA has not such power. National states decide what the companies from the space industry can launch to space. In the United States, which is most advanced in the area of private constellations, it is the Federal Aviation Administration (FAA) that issues the appropriate approvals. The race to put broadband internet satellites bears similarities to the gold rush – there are no rules, at the global level, apart from first-come, first-served.

CONCLUSION

The goal of the paper was to provide argumentation that there is a correlation between the development of orbital satellite constellations and the growth of the risk of orbital collisions. The latter, known as the Kessler syndrome, bring forth a real threat for orbital infrastructure, and in consequence many safety and security systems on the ground. All the data and models confirm that the amount of space debris in the low Earth orbit increases and it will continue to do so to even more extent due to currently built internet providing satellite systems that consist of unprecedented numbers of orbital objects.

The process seems inevitable because it is driven by profit and not limited by any international regulations. The technology development and that it will be able to provide broadband internet access to remote areas is undoubtedly a positive thing. One should remember, however, that the space around the Earth, although vast, is not unlimited and the access to it should be globally regulated. The current geopolitical situation makes it close to impossible. That is why the public, having gained knowledge about the situation, should put the pressure on national and international space agencies, as well as private companies that launch artificial objects into space. It seems that nowadays, the sense of global responsibility is the only option to efficiently mitigate the growing threat of the Kessler syndrome in the Earth's low orbit.

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