Multidimensional risk assessment of space critical infrastructures: the human factor

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Abstract: The paper presents some risks from outer space, elaborating on a risk profile for critical space infrastructure by presenting, in short, the problem of space weather phenomena, space debris and near-Earth objects. At the same time, the analysis also takes into account the development of anti-satellite weapons and other forms of space warfare. The main novelty of the scientific approach is the attempt to introduce a new paradigm in the field of critical space infrastructure, i.e. the human factor as a component that is currently missing from the literature. The analysis proves that the risk profile of the physical component is similar to the risk profile generated by the same spectrum of threats to the human component.

Keywords: risk assessment, critical infrastructures, space systems, multidimensional analysis.

Evaluarea multidimensională a riscurilor infrastructurilor critice spațiale: factorul uman

Rezumat: Lucrarea prezintă unele riscuri din spațiul cosmic, elaborând un profil de risc pentru infrastructurile critice spațiale, prezentând pe scurt problema fenomenelor meteorologice spațiale, a resturilor spațiale și a obiectelor din apropierea Pământului. În același timp, analiza ia în considerare și dezvoltarea armelor antisatelit și a altor forme de război spațial. Principala noutate a abordării științifice constă în încercarea de a introduce o nouă paradigmă în domeniul infrastructurilor critice spațiale, adică factorul uman drept componentă care lipsește în prezent în literatură. Analiza demonstrează că profilul de risc al componentei fizice – sistemul spațial – este similar cu profilul de risc generat de același spectru de amenințări la adresa componentei umane.

Cuvinte cheie: managementul riscurilor, infrastructuri critice, sisteme spațiale, analiza multidimensională.

1. Introduction

Modern societies depend, to a significant extent, on the continuous activity of critical infrastructures that ensure the necessary flow of essential goods and services. These goods and services include drinking water, electricity supply, information and communication technologies and waste management. The malfunctions can have serious and rapid repercussions on the population and its activities, and can affect other infrastructures through a domino effect. A large-scale power outage would also disrupt water distribution, rail transportation and telecommunications. Today's critical infrastructures are complex socio-technical systems, composed of a multitude of components, technologies, policies and social factors Much importance is given to the “infrastructural” part of critical infrastructures and less to the human factor. The so-called “critical infrastructures”, i.e. the power grid, the transport network and information and communication systems among others, are essential to maintain vital societal functions. If these critical infrastructures suffer disruptions of business continuity due to natural disasters, terrorism and criminal activity, both business and

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citizens have to deal with severe discomfort. At European Union level there were identified 11 sectors of Critical Infrastructures and 32 services. The influence of space-critical infrastructure (SCI) on the proper functioning of critical ground-based systems has progressed to the point where, in some cases, the space system has become an integral part of the system-of-systems. It should be noted a discrepancy between the level of development of the various SCIs, caused by the fact that technical and financial barriers to the construction of the SCI determine a prioritization of systems that offer the easiest functions to most users, leading to an extremely high marginal utility of each new units added to a space infrastructure. In turn, these systems are becoming increasingly critical, especially after the development of the private satellite industry has enriched the supply of services. Thus, critical terrestrial infrastructures are influenced by space ones in the form of command, control, coordination, communication and observation capabilities. These services can be accessed by a large number of users, even if they are offered by a limited number of SCIs. However, less is said about the astronauts that help maintaining the critical services. Therefore, this paper attempts to exemplify the risks and threats from outer space to critical infrastructures, extrapolating them for the astronauts on International Space Station.

Much literature focuses on the failure of infrastructures and not on the vital role that humans play in outer space's system of systems. Another branch of literature looks at worldwide efforts to improving resilience of critical infrastructures in order to withstand emerging threats, as well as unconventional attacks. However, some threats cannot be foreseen, while reducing all possible risks at the minimum possible level is not always cost effective.

2. Space critical infrastructures

Space-based capabilities provide support to military, commercial, and civilian applications. With more countries and commercial firms to participate in satellite construction, space launch, space exploration, and human spaceflight, the previous technological and cost barriers to space are falling down. Although these advancements are creating new opportunities, new risks for space-enabled services have emerged.

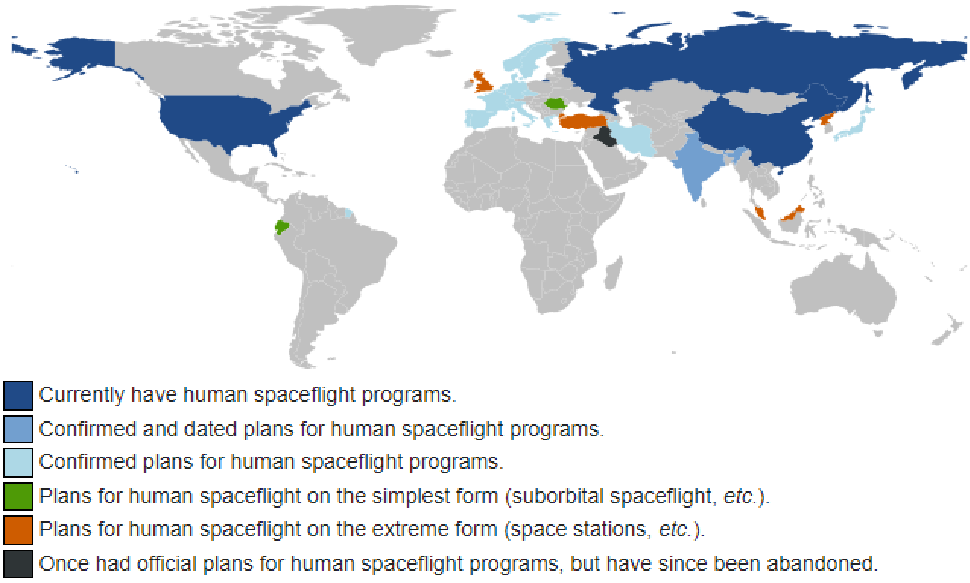
With the worldwide space setting changing quickly, also the worldwide rivalry is expanding with new participants acquiring new aspirations in space. Major innovative shifts, for example, digitalisation, miniaturisation, artificial intelligence or reusable launchers, are disrupting conventional plans of action in the space area. The European space sector needs to adjust to take advantage of business models in the space sector. In this specific circumstance, the Space Strategy for Europe, proposed by the Commission and advanced with the political directions of the Council and Parliament set a high desire for Europe to stay a space force and grasp the difficulties ahead (Botezatu et al., 2019).

However, political ambitions and investment in the area are not enough, Exposure of space infrastructures to the adverse outer environment could produce interruption of vital services. Precisely because the space critical infrastructures can be broken down into main three physical parts: the "space" segment, the "launch" segment, and "ground" segment. The satellites contain the payloads that will accomplish the primary mission, as well as a bus that provides the infrastructure for operating the payload. The launch vehicles transport the satellites to orbit. We argue that the human factor should also be taken into account because most of current space-based services are operated through and with people. The human component however is not considered in the academic and policy-related literature. Furthermore, the space design architecture encompasses a ground segment, i.e.gateways where data is downlinked from satellites as well as processing and distribution facilities that sets the raw data in the appropriate format and location for all users.

Finally, the launch segment can be relatively simple for a single satellite architecture, or very intricate for a many-satellite architecture. For space architectures with multiple satellites, the launch segment can receive significant attention, and plays an important role in mission risk reduction and constellation replenishment and maintenance strategies.

3. The human factor

Humans have been more connected with the space exploration missions and less to the well-functioning of critical infrastructures. In fact, this is the innovative bit of the current research article, an attempt to highlight the importance of humans in the process of protecting space and ground based critical infrastructures. From a historical perspective, human spaceflight programs have been conducted by Russia, the United States, China and by the American private spaceflight companies. While in the past, human spaceflight has typically been a government-directed activity, commercial spaceflight has gradually been taking on a greater role. Since the first private human spaceflight took place on 21 June 2004, commercial crew launches have operated since May 2020 (Hull & Johnsson, 2020). The image below presents the status of ongoing human spaceflight programs.



(source: NASA Astronaut Corps)

In this regard, the current paper looks at threats from space to critical infrastructure and attempts to formulate the argument that humans sent in space or that operate assets in space may be equally vulnerable. Therefore, the next section looks at the description of threats from space, then the paper will present its research methodology and main results, before drawing conclusions.

It is well known that the human body changes and transforms in the outer space environment. These changes could be grouped into:

1. Changes in the physical forces on and within the body brought about by a reduction in weight of the body's components;
2. Psychosocial changes induced by the long-term confinement of such a voyage without the possibility of escape;
3. Changes in the levels and types of radiation in the environment (White & Averner, 2001).

Human missions have exposed their crew members to transient radiation from solar particle events and to continuous radiation from high-energy galactic cosmic rays. The literature presents that protons and high-atomic-number energetic particles involved may exert sizeable biological effects even at low fluency, and there are considerable uncertainties associated with secondary particle effects (White & Averner, 2001).

In this regard, it is less known and experimented various health risks resulted from exposure to space radiation. One is definitely the induction of late-occurring cancers. However, damage to the central nervous system is also potentially a mission compromising event because of the possibility of cell loss from radiation damage affecting the functional integrity of the central nervous system (Vasquez, 1998). Nevertheless, more recent studies highlight the gaps to previously unknown mechanisms of radiation-induced cellular pathologies based on the communication between damaged and undamaged cells and the induction of unstable states that lead to late expression of genetic damage (Azzam et al., 2001). The above-mentioned literature argues that space radiation seems to be uniquely effective in causing such cellular changes.

4. Threats to space critical infrastructures

Space-based assets and systems are critical to ensuring security on Earth (security from space). At the same time, these assets need to be protected in the difficult environment of outer space (security of space). The adverse space environment as well as the inability to technically intervene in case of space systems failure, among other factors, is to be taken into account when discussing the protection of space infrastructures (Georgescu, et al., 2015). since November. 2, 2000, people have been orbiting our planet inside the International Space Station, bringing together science, technology and human innovation to enable new technologies and research breakthroughs not possible on Earth. Human explorers sent to live in space and to travel to other planetary bodies projects a captivating and alluring image. Yet they are exposed to the adverse space environment and this is our mission here to present few ideas that might be considered a starting point in looking more carefully at this problematic.

Critical space infrastructures are subject to a series of unique threats. At the same time, critical terrestrial infrastructures can be impacted by natural threats from space. Governance of such risks is possible only through the use of the capabilities offered by space-critical infrastructures. Thus, extraterrestrial space is a complex environment in which natural or anthropogenic threats work together to affect the functioning of critical space systems and encroach on the security of critical terrestrial infrastructures, through direct effects, or by spreading the disruption of other systems vulnerable to these threats.

The three specific space threats are cosmic meteorological phenomena, the impact with cosmic debris and the possibilities of impact with asteroids or comets of significant size.

Deliberate human threats to critical space infrastructure are numerous, diverse and highly effective. Their development dates back to the beginnings of space programs, which had an important military component and “dual-use” philosophy in the development of new technologies. Today, many space actors are developing anti-satellite capabilities or legitimate defense technologies that can be modified to become powerful anti-satellite weapons.

Space weather is a concept that describes ”variations in the Sun, solar wind, magnetosphere, ionosphere, and thermosphere, which can influence the performance and reliability of a variety of space-borne and ground-based technological systems and can also endanger human health and safety”. (Royal Academy of Engineering, 2013) Explosive eruptions of energy from the Sun that cause minor solar storms on Earth are relatively common in contrast to extremely large events (‘superstorms’) that occur sporadically, i.e. once every century. Most superstorms miss the Earth, while for those that do travel towards Earth, only half interact with Earth’s environments causing damage. (Royal Academy of Engineering, 2013).

Like the Earth's climate, space weather conditions are universal, and counteracting their effects can become a challenge. Space weather can occur anywhere from the surface of the sun to the surface of Earth. As a space weather storm leaves the sun, it passes through the corona and into the solar wind. When it reaches Earth, it energizes Earth’s magnetosphere and accelerates electrons and protons down to Earth’s magnetic field lines where they collide with the atmosphere and ionosphere, particularly at high latitudes. Thus, a naturally occurring phenomenon has the potential to cause substantial detrimental effects on the terrestrial economy and social well-being. Each component of space weather impacts a different technology.

A near-Earth object (NEO) is any small object whose orbit brings it into proximity with Earth. This includes about thirteen thousand near-Earth asteroids (NEAs), more than one hundred near-Earth comets (NECs), solar-orbiting spacecrafts and meteoroids, large enough to be tracked in space before striking the Earth. In fact, as of February 18, 2016, 13839 Near-Earth objects have been discovered. Some 880 of these are asteroids with a diameter of approximately 1 kilometer or larger. Also, 1681 of these NEOs have been classified as Potentially Hazardous Asteroids (PHAs). It is now widely accepted that collisions in the past have had a significant role in shaping the geological and biological history of the planet.

While the chance of a large object hitting the Earth is very small, it could produce destruction and loss of life. Taking only the asteroid population of the Solar System, this is divided into many sub-populations by the effects of gravity. Thus while all revolve around Sun, the vast majority is situated in the Main Belt between Jupiter and Mars. Jupiter’s gravity shapes and stirs the Main Belt, causing some asteroids to escape the Solar System entirely or sending others Sun-ward so that they might interact gravitationally with the Solar System’s inner quartet of planets. Some reach orbits that bring them close to Earth, and some of those eventually enter Earth’s atmosphere. (Portree, 2013).

Asteroids large enough to be visible that impacted Earth in the past, have been linked to mass extinctions.

Space debris is the collection of defunct man-made objects in space – old satellites, spent rocket stages, and fragments from disintegration, erosion, and collisions – including those caused by debris itself. When one piece collides with another, even more debris is released. Over more than half a century since the first artificial satellite was launched into space, human activity has progressed at a steady pace as the economic, military and scientific potential of areas near Earth has been discovered. Thus, in addition to the few space stations and over a hundred human missions, the need for research outside the Earth's gravitational field or atmospheric distortions, as well as the advantages of orbital satellite telecommunications, have led to the placement of entire constellations of artificial objects around the planet. with a special focus on areas of utmost importance.

At the level of preventive technological solutions for potential damage, we find the endowment with shields and additional propulsion resource of satellite systems. To avoid creating new waste, new collisions must be prevented, and satellites must be orbited at the end of their life. Launch vehicles must also re-enter the atmosphere without generating new waste. To reduce existing waste, there is no technological solution on the verge of implementation. The challenges are the need to coordinate the adoption of these measures by all spatial, private or national actors, and the generation of an administrative, legal and economic framework to stimulate the adoption and implementation of good practices, as well as investments in the technological means detailed above.

As of September 2020, there are over 128 million debris fragments from greater than 1 mm to 1 cm, 900 000 objects from greater than 1 cm to 10 cm, and 34 000 objects (ESA, n.d.).

The problem with space debris is not only reducible to one single collision between a piece of debris and a functional space system, but the cascade collision, also known as the Kessler Syndrome. This represents a scenario put forth by the NASA scientist Donald Kessler in the 1970s in which space becomes so overpopulated with debris that one collision set off larger chain reactions, eventually reaching a stage when navigation becomes impossible. With the greatest concentration of debris to be found at 750-800 km, traveling up to speeds of 28,163 km/h, the LEO is severely affected.

5. Research methodology

Risk assessment provides decision makers with a responsible understanding of the risks that could affect the achievement of objectives and the accuracy and efficiency of the controls already in place, providing a basis for decisions on the optimal approach to risk management. Within the present research demarche, the authors followed step by step the stages of risk management process, namely identifying, analyzing, evaluating and treating risks.

If we start from the hypothesis that the human factor is as vital when discussing space critical infrastructures as other technical networks, it results that threats from space we have mentioned in this article could be extrapolated to astronauts. By that, and without getting into medical discussions, we agree that space debris, near-Earth objects and radiation from the solar storms could impact astronauts or other humans sent to space. Therefore, tarting from these categories of threats, 10 risk scenarios were developed. They all considered that a scenario provides a way to communicate a common picture of future uncertainties and factors that may influence decisions that should be made now.

The following aspects were taken into account in the construction phase of the scenarios:

- we have as subject plausible descriptions, possible to take place in the future;
- the scenario regarding the incident must be presented schematically and included in gravity impact scales - depending on the availability of the data held in this phase;
- must be representative of the type of threat identified;
- it is necessary to be structured consistently and logically;
- it must be written clearly and coherently, in order to be understood and accepted by users and stakeholders;
- it must be sufficiently specific to allow a rapid assessment of the intervention capabilities required in the event of that event.

Scenario management for critical infrastructure protection must take into account the concept of risk, both as a cause and as an effect, on the one hand, but also through risk assessment methods, on the other hand.

The main objective of the present demarche is to establish if new elements could be embedded within Space Critical Infrastructure concept, as up to now in literature only physical component of space systems where assessed and catalogued as critical infrastructures and not the human component – the astronauts.

The following 10 scenarios were analyzed in terms of likelihood and impact:

- satellite failure due to natural causes;
- satellite failure due to human causes;
- temporary / total disruption of all satellite services due to the impact with targets in the vicinity of the Earth (NEOs – Near Earth Objects, asteroids, etc.);
- disruption of space services due to radiation generated by geomagnetic storms;
- locking / spoofing;
- occurrence of diseases on board the ISS / in space;
- software infrastructure failure;
- collisions with small and very small space debris (up to 10 cm);
- collisions with larger space debris;
- space war.

6. Results analysis

The formula used to estimate risks was:

$R = P \times I$

Where: R – risk; P - likelihood of occurrence for each scenario; I - impact, consequence.

Depending on the result obtained, the analyzed scenario can be in one of the three cases of risk classification:

- Red, unacceptable risk;

- Yellow, tolerable risk;
- Green, acceptable risk.

Also, as in (Bucovetchi et al., 2017) unacceptable level of risk generates a major discontinuity in the progress of the operational activity that triggers the need to implement additional means of protection, as well as procedures for emergency management that occurred in order to reduce the impact and immediate restoration of optimal operating parameters.

For better visualization of the results there was used TopEase, a software that embeds Object Oriented Programming concepts and help managers to have birds' eye view over the hole system. Furthermore, the system in question is perceived as a living one.

The visualization of the risk levels associated with the analyzed scenarios both for the spatial systems and for the human factor can be seen in figures 1 and 2.

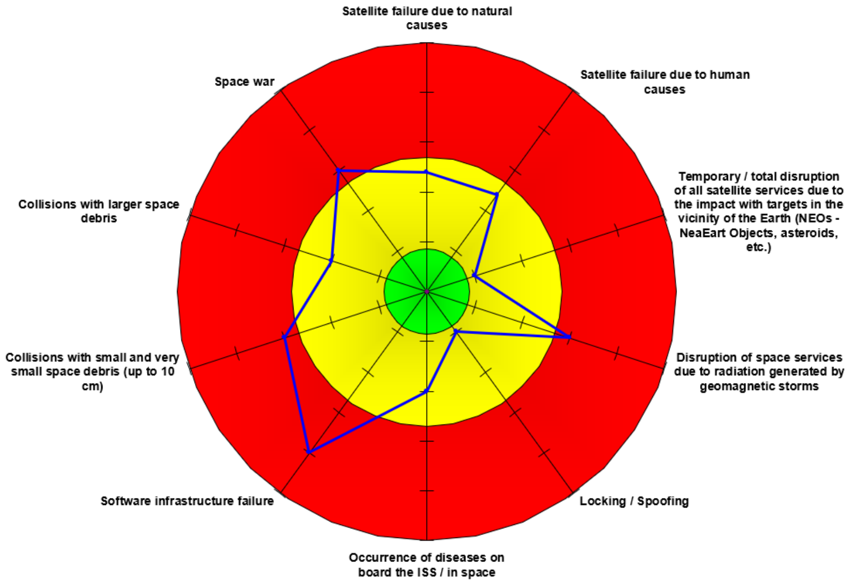


Figure 1. Risk profile for Space systems

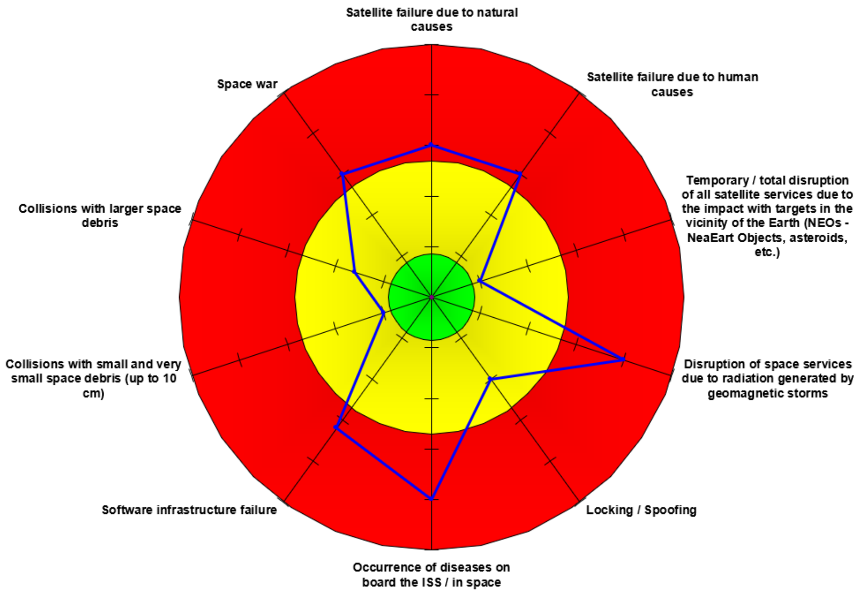


Figure 2. Risk profile for Human element

There is a great similarity between the two graphical representations, which may lead us to the conclusion that the astronaut can be included as a component of critical space infrastructure.

It should be noted that in the analysis presented only threats from outer space were considered, but both the astronaut and the physical components of space systems are also subject to threats from Earth, such as:

- the vulnerable points of the communication system can be exploited by malicious attacks to interfere with the proper functioning, which can even affect the human crew;
- in fact, no satellite can be repaired in space if it has been damaged.

7. Conclusions

Critical space infrastructure gathers multiple stakeholders, have an enormous amount of interaction with other vital sectors as well as to an outer space environment, and involve cutting edge technologies. Furthermore, integrating further functions implies more interaction, interfaces, new technologies to integrate, new risks to control, more requirements to verify, new skills to build, and so on. In conclusion, CSG can be used as approach for understanding critical infrastructures.

According to (Bucovetchi et al., 2019) "the main capabilities provided by Critical Space Infrastructures are navigation, positioning and timing (GNSS networks such as the US NavStar, Russian Glonass, Chinese Beidou and European Galileo), communications and remote sensing, the latter of which are especially important circumstantially, such as when Earth-based replacement systems are disrupted (undersea cables for communications etc.) or when there is a crisis or emergency situation whose management or alleviation depends on space services (Earth Observation of extreme weather phenomena)".

With human spaceflight becoming increasingly appealing to governments and private entities, humans in space are exposed to threats equally as the infrastructures. If we consider that humans are equally vital to the well-functioning of both space and ground infrastructures, then humans in space should be better considered as vital elements of this complex system of systems. From a medical perspective, the literature shows that for the experiences of the past 40 years of space-related research and health care, to manage effectively the health and related mission risks of future space explorers, it is not enough to separately address the loss of bone that occurs during a nearly weightless state, with its attendant increased risk of fracture, or the problems of increased cancer risk caused by the natural radiation that accompanies space flights away from low-Earth orbit. The protection of space critical infrastructures is important to incorporate the human factor, although this will not be easy; the problems and challenges that must be faced are many and great and have been discussed for several years. However, the decision makers should take this aspect into account for a better integrated perspective of connecting the Earth services with the outer space applications.

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Olga BUCOVEȚCHI received her BSc in Economic Engineering (2006) and PhD in Industrial Engineering (2014) from University Politehnica of Bucharest. Now she is assoc. prof. at University Politehnica of Bucharest. Her main research activities are in the fields of risk management, protection of critical infrastructures, education management and business continuity. Her research has addressed issues related to the interdisciplinary sciences, such as identifying threats and vulnerabilities, service availability, increasing security and building security strategies. She is actively involved in the development of key concepts in the field of resilience and critical infrastructure protection through involvement in national and international projects.

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