RISK AND RESILIENCE IN LIGHT OF SPACE DEBRIS THREAT

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ABSTRACT

The role of space sector is rapidly changing from pure scientific missions to an active player in the future economy. The growing volume and variety of data and signals affect the down-stream (ground-based) systems' reliable operation. The current commercial/industrial model transformation in the Space sector increases the system's complexity, creates risks and hides vulnerabilities. This fosters the research on the sociotechnical resilience concept development. The Organization for Economic Co-operation and Development (OECD) recommends applying principles of resilience to emerging threats. Space debris threat can be considered as an emerging risk. In other words, it is a threat that keeps relevant stakeholders awake at night. A large number of risk reports is dedicated to resilience properties in the electricity, nuclear, transportation and other sectors, and space sector is out of focus. The purpose of this article is to harmonize the resilience assessment methods across space sector in order to improve the organizational capacity to identify and address the threat and produce suggestions for its good governance. It is shown that a lack of consistency in defining "how resilience is applied and measured" limits its effectiveness. Harmonization is especially important in light of increasing public awareness.

Keywords: catastrophe scenario; decision support; governance; resilience; risk management; space debris.

1. INTRODUCTION

Nowadays, business models depend on reliable and high quality space asset operation for a variety of purposes. The space asset loss may overall have global impacts, and the impact can go beyond the borders of a certain country who owns the satellite. One can compare effects with those observed during the pipeline loss, which carries oil/gas belonging to a country far away from the mining place; albeit this case mainly reflects physical interdependency. If the functions of the lost asset cannot—at least in short term, be substituted—it results in systematic failures across other critical infrastructures that have been constructed in interconnected way for increasing their robustness. This fact drives the awareness growth even in non-spacefaring nations. Nevertheless, industries, whose operation does not rely on space systems, are less concerned even in spacefaring nations.

Almost every critical infrastructure relays on space assets' reliable operation. The inter-infrastructure failure scenarios are presented in Table 1. Four critical infrastructure operational states are distinguished: local or widespread degradation, local or widespread outage. Three scenario are represented in case of global navigation satellite system (GNSS), communication (COMM) or meteorological (METEO) satellites loss. All of them correspond to the worst-case scenario. The number of small-satellites is rapidly growing as well as the number of functions they carry; currently, terrestrial critical infrastructures do not have strong interdependencies with them. However, the situation is swiftly changing with the appearance of satellite mega-constellations.

The paradigm shift in risk management of ground-based infrastructure towards a more resilient society poses this question that "how should the space infrastructure assessment procedures be adapted?". The scope of resilience covers many disciplines such as technical, economical, social, and policy-related. For instance, the concept of transportation system resilience was studied in [4], the organization management in [13], social, community and ecological systems in [3, 9].

The strategic goal "resilience of space infrastructure and services" was set by the European Union Institute for Security Studies (EUISS) [11]. The motivation of this paper lies on the need to present the study of space infrastructure resilience with respect to its technical characteristics, functions, and hazards.

2. RESILIENCE IN THE VIEW OF SPACE-BORNE INFRASTRUCTURE

Space systems are designed for functioning in the most hostile environment among known ones. Nevertheless, the marginal productivity constraint is the main factor which determines characteristics of New Space assets. It means that the function is provided with the

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Table 1. Terrestrial critical infrastructure disruptions caused by the loss of multiple space assets loss

State	**GNSS**	**COMM**	**METEO**
Local degradation	Healthcare Water supply Food industry Research facilities Energy sector	Chemical industry Nuclear industry Transport Finance Healthcare Research facilities Food industry Energy sector	Chemical industry Nuclear industry Transport Finance Healthcare Research facilities
Widespread degradation	–	–	–
Local outage	Transport Chemical industry Nuclear industry	–	Water supply Food industry
Widespread outage	Finance ICT	ICT	Energy sector

minimum number of required satellites. Therefore, each satellite becomes a highly vulnerable asset. This fact even heightens its cruciality. In general, the reliability requirement of an asset is determined by the degree of its influence on the systems security. However, the uniqueness of each mission complicates the uniform reliability protocol implementation. The total mass, composition material and construction procedure limitations, driven by the cost-reliability criteria, are unique for each mission. The common understanding of space debris threat is the first step in improving the sectors resilience.

The criticism of over-protected system design, construction and maintenance triggered the resilience concept popularization. It is known that a small increase in the protection level may require a large amount of additional costs. In other words, achieving desired protection level is normally not cost-effective in relation to the actual hazards. In contrast to risk assessment, which measures a potential loss associated with certain uncertainties, resilience is a much wider concept. Resilience (or resiliency) originates from the Latin word resilio which literally means “to jump back” [6]. In 1973, C. S. Holling defined resiliency as a measure to the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables [1]. After Holding, numerous interpretations of resilience have been developed. A general definition of resilience is given by the United Nations Office for Disaster Risk Reduction (UNDRR). According to the UNDRR, resilience is “the ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management” [14].

Adding the resilience concept to the modeling procedure gives more realistic results. In addition to being reliable, space infrastructures should also be resilient to catastrophic events. It is emphasized in [10] that a resilient system is able to absorb lessons for adapting its operation and structure to prevent or mitigate the impact of similar events in the future. A resilient system is specified as a system of **four “R”**: robust, redundant, rapid, resourceful. The risk management framework covers resilient improvement in the time of event occurrence, response and restoration period [5].

While critical infrastructure operators, owners and governments agree on the need of resilience building, the views on the levels of resilience may differ. The governing philosophies and policy documents vary significantly in resilience assessment. The need to consider resilience across a broad spectrum of categories, including physical and information systems infrastructure as well as cognitive and social systems and frameworks is emphasized in [2]. It is particularity of interest to see how the Committee on the Peaceful Uses of Outer Space (COPUOS) and the United Nations Office for Outer Space Affairs (UNOOSA) apply the principles of resilience to the emerging threat of space debris for a good governance of this issue in the coming years. For studying this, we employed the use of resilience matrix framework to compare temporal and spatial scales of resilience across COPUOS, UNOOSA Scientific and Technical Subcommittee (STS), and Legal Subcommittee (LSC) from their published annual reports after millennium based on the criteria. The resilience matrix framework was introduced in [7].

The resilience concept is an emerging topic. It is worth mentioning that there were no mention of the Resilience keyword in the treaties, conventions, and agreements made in the Old Space era including Outer Space Treaty (1967), Rescue Agreement (1968), Liability

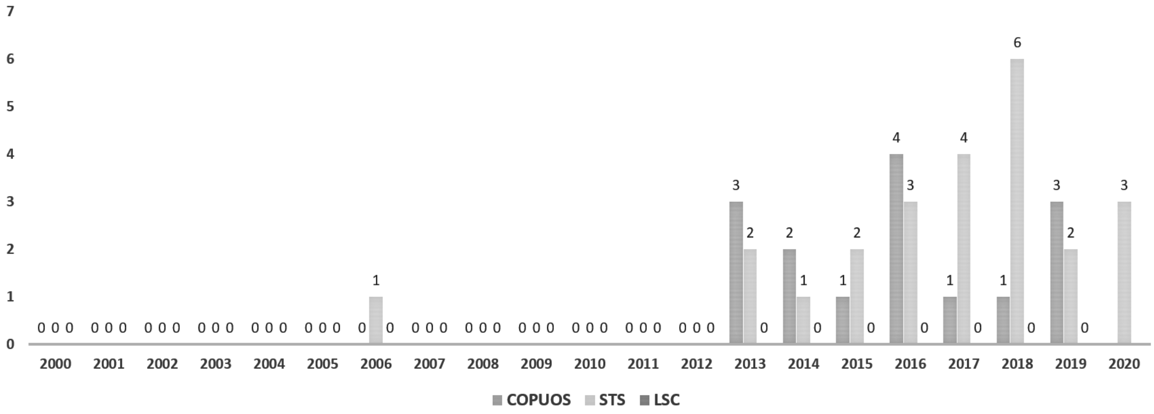

Figure 1. Appearance of the keyword "Resilience" in any form in COPUOS and UNOOSA (sub-) committees annual reports after millennium (adopted from [8]). The horizontal axis is year and the vertical is the frequency of appearance.

Convention (1972), Registration Convention (1975), Moon Agreement (1979). This shows that resilience was practically out of focus those days (Figure 1).

UNOOSA publications on space debris along with European Code of Conduct for Space Debris Mitigation (EU), Inter-Agency Space Debris Coordination Committee (IADC) Space Debris Mitigation Guidelines, International Telecommunication Union (ITU)s Recommendations, International Academy of Astronautics (IAA)s Study on Space Traffic Management were scored for direct and indirect inclusion of temporal and spatial stages of resilience. The four temporal stages of resilience, i.e. plan, absorb, recover and adapt are defined as the following:

- plan defines the steps taken by organizations to prepare critical functions and features of their operation for a universe of potential threats;
- absorb comprises the capability of a system or organization to absorb the consequences of an acute shock or extended stress without breaking and maintaining a certain degree of function;
- recover includes the time and resources needed for the system to recover its functionality post-shock;
- adapt includes the capacity of an organization or system to learn and improve its capacity to absorb and recover from shocks based upon past experience.

Each publication was also scored based on the three primary spatial domains of resilience, including the physical, informational, and social aspects of resilience defined as the following:

- physical showed that resilience was assessed within the context of physical infrastructure;
- information revealed that resilience was discussed with regard to information flows and data moving up the system;
- social showed that resilience was applied within the context of societal action and making society agile in the face of shock.

The outcome of this analysis is mapped in Figure 2. The resilience matrix shows that while all facets of resilience are considered across the collection of all (sub-)committees of UNOOSA and other international space debris related organizations, most focus is placed upon the prepare temporal stage on all three spatial domains, with a focus on information. Likewise, the contents of the prepared guidelines does not consistently address the latter temporal important stages of resilience, absorb, recover and adapt. One notable exception is the work of COPUOS which covers all temporal and spatial domains. This shows that COPUOS is serving as a knowledge broker helping to share and push forward the strategic thinking of resilience concept [8].

3. CONCLUSIONS

The concept of critical infrastructure resilience with respect to space threats is mainly focused on terrestrial critical infrastructures, especially about space weather impact on power grids , which is the backbone of modern critical infrastructures [12]. One of the main challenges for implementing the principles of resilience is the limitation and the scarcity of historical data. Despite the fact that the impact of threats on space assets was observed in the past, the revolutionary change in operation procedures and performance assessment algorithms make it difficult to correlate the events. Extreme events of the past may not lead to extreme consequences in the present and the other way around. It is proposed to develop a common resilience assessment methodology using the World Bank's recommendations for managing environmental disasters [15], as follow:

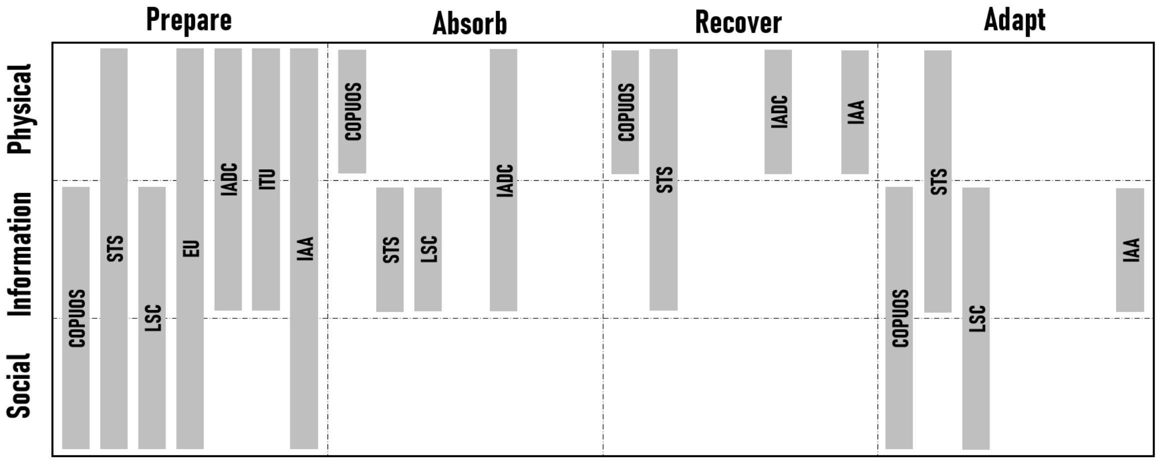

Figure 2. Resilience matrix showing the direct temporal (plan and prepare for, absorb, recover from, and adapt) and spatial (social, information, physical) domains of resilience for space debris related publications of COPUOS and UNOOSA (STS, LSC), European Code of Conduct for Space Debris Mitigation (EU), IADC Space Debris Mitigation Guidelines, International Telecommunication Union (ITU)s Recommendations, International Academy of Astronautics (IAA)s Study on Space Traffic Management (adopted from [8])

- make information on disaster risk easier to access;
- take preventive measures;
- provide adequate infrastructure and public services to reduce vulnerabilities;
- build institutions that permit public oversight of disaster preparedness and disaster response.

The World Bank's recommendations may also be applied for the space sector. Another difficulty drawn from the scarcity of historical data is that the actions for recovery phase planing are stepped behind compared to other phases of risk management.

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