

SPACE DOMAIN AWARENESS AND CRITICAL SPACE INFRASTRUCTURES: IMPLICATIONS FOR AIRSPACE GEOPOLITICS

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Abstract: *This interdisciplinary scientific article explores the dynamic intersection of Space Domain Awareness (SDA) and Critical Spatial Infrastructures (CSI), as well as their far-reaching implications for airspace geopolitics. With the increasing reliance on space assets and the growing interest in space exploration, ensuring a comprehensive understanding of the space domain becomes crucial for safeguarding critical spatial infrastructures and maintaining regional geopolitical stability. This article delves into the challenges and opportunities arising from the interplay between SDA and CSI, shedding light on the complex relationships that shape airspace security and geopolitics.*

Keywords: *Space Domain Awareness, Critical Space Infrastructures, Airspace Geopolitics, Space Assets, Surveillance and Tracking, Space Situational Awareness, Geopolitical Stability, Space Security*

1. INTRODUCTION

The utilization of space for civilian, commercial, and military purposes has experienced a spectacular rise, revolutionizing the way we interact with the world and driving significant advancements in technology and science. This exponential growth has brought about an ever-increasing dependence on space assets, making them indispensable to modern society. Those Space Infrastructures (SI) that are *critical* integrators for other strategic domains include a wide array of space-based assets and ground-based facilities, and have become the backbone of numerous essential services that impact virtually every aspect of human life [1].

Space assets play a pivotal role in providing vital services such as global communication, precise navigation systems, real-time weather monitoring, and reconnaissance for national security and defense. From satellite-based communication networks facilitating instant global connectivity to Global Positioning System (GPS) satellites enabling accurate location-based services, the seamless functioning of these critical spatial infrastructures is vital for supporting economic activities, ensuring public safety, and enhancing military capabilities [1, 2, 3, 4].

However, the rapid growth of space activities has led to an increasingly congested and contested space domain [5]. The proliferation of satellites and other space debris has significantly heightened the risk of collisions, posing a serious threat to existing space assets [6]. Additionally, advancements in technology have given rise to new challenges, including potential cyber-attacks and electromagnetic interference that could disrupt the normal functioning of critical spatial infrastructures [7].

The vulnerability of these assets to both natural hazards, such as solar storms and cosmic radiation, and human-made hazards, such as intentional satellite disruptions or space-based aggression, demands urgent attention.

To safeguard the integrity and functionality of these crucial infrastructures, effective Space Domain Awareness (SDA) has become an imperative. Space Domain Awareness involves the continuous monitoring, tracking, and understanding of objects and activities in space [8, 9]. By maintaining situational awareness of the space domain, space agencies and governments can identify potential threats, anticipate collisions, and respond promptly to any anomalies or suspicious activities. Timely detection and response are essential to mitigating risks and ensuring the safety and security of critical spatial infrastructures.

Therefore, the focus on Space Domain Awareness, particularly when considered in a broader correlation with Critical Spatial Infrastructures, has grown significantly. An integrated approach that combines technological advancements, international cooperation, and policy frameworks is essential to addressing the multifaceted challenges posed by the growing space activities. By fostering collaboration among spacefaring nations and organizations, we can collectively enhance Space Domain Awareness and promote responsible space practices to mitigate potential conflicts and safeguard critical spatial infrastructures for the benefit of all humanity. This article aims to explore the complex relationships between Space Domain Awareness and Space Critical Infrastructures, shedding light on their implications for airspace geopolitics and the broader global landscape.

2. UNDERSTANDING SPACE DOMAIN AWARENESS (SDA)

This section provides an in-depth analysis of Space Domain Awareness (SDA), a critical component in comprehending the dynamic and complex environment of the space domain. SDA involves a comprehensive set of technologies, methodologies, and data sources utilized to monitor, track, and analyze objects and activities within space. By continually observing and evaluating objects such as satellites, spacecraft, debris, and potential threats, SDA plays a pivotal role in enhancing the safety and security of space critical infrastructures and other space assets [8, 9].

A key aspect emphasized in this section is the paramount importance of space situational awareness in space (SSA) operations. SDA enables stakeholders to maintain real-time awareness of the space environment, including the precise location, trajectory, and characteristics of space objects. This heightened awareness is indispensable for space agencies, governments, and private entities to make informed decisions regarding satellite launches, orbital maneuvers, and mission planning, thus minimizing the risk of collisions and optimizing space asset utilization.

Surveillance and Space Situational Awareness (SSA) activities and network of organizations are pivotal players in bolstering the effectiveness of SDA. These organizations continuously collect data from a variety of sources, such as ground-based radars, space-based sensors, and satellite tracking networks. They consolidate this information to create accurate and up-to-date catalogs of space objects, identifying potential conjunctions and collision risks, and providing essential early warnings for potential space debris-related hazards.

Romania has played a pivotal role in the EU Space Surveillance and Tracking (SST) Partnership [10], demonstrating a proactive commitment to enhancing space situational awareness and bolstering the region's capabilities in space domain monitoring.

As a member of the European Union and a participant in space-related activities, Romania has actively engaged in collaborative efforts to advance the SST initiative. Through participation in joint projects, data-sharing agreements, and technological advancements, Romania has contributed valuable insights and resources to support the EU's objective of fostering a safer and more secure space environment. By leveraging its expertise in aerospace research and technology, Romania continues to make significant strides in the field of Space Domain Awareness, making essential contributions to the EU's collective efforts to track and monitor space objects, prevent collisions, and address potential threats to critical space infrastructure. As the SST Partnership evolves, Romania's active involvement reaffirms its commitment to international cooperation and proactive space governance, further cementing its position as a key player in European space endeavors.

The exponential growth of space debris presents one of the most pressing challenges for SDA [11]. Discarded rocket stages, defunct satellites, and other fragments pose significant risks to operational spacecraft and critical spatial infrastructures. This section delves into the complexities of tracking and monitoring space debris, including the assessment of potential conjunctions between objects. Advanced algorithms and computational models are crucial for predicting and mitigating potential collisions, as well as for devising optimal collision avoidance strategies to safeguard valuable space assets.

In light of these challenges, the need for effective SDA frameworks becomes evident. Collaborative efforts between governments, international space agencies, and private industry are vital for sharing data and expertise, thus fostering a robust SDA ecosystem. Additionally, investments in research and development are essential to enhance the accuracy and scope of SDA capabilities, promoting the sustainability of space activities and reinforcing the protection of critical spatial infrastructures.

Overall, this section underscores the vital role of SDA in shaping the future of space exploration and utilization. The integration of advanced technologies, methodologies, and surveillance systems within the realm of SDA enhances our ability to navigate the increasingly congested and contested space domain. By effectively managing space debris, mitigating collision risks, and promoting collaborative frameworks, SDA paves the way for the secure and prosperous growth of critical spatial infrastructures and the broader space industry.

3. CRITICAL SPACE INFRASTRUCTURES AND AIRSPACE GEOPOLITICS

This section delves into the profound significance of critical spatial infrastructures (CSI), which comprise a diverse array of space-based assets and ground-based facilities. CSI play a pivotal role in modern societies, enabling crucial functions such as global communication, precise navigation, climate monitoring, earth observation, and national security operations. As an indispensable backbone of various economic sectors, disruptions to these infrastructures can have far-reaching consequences that extend beyond individual nations and can impact the global community.

The analysis begins by examining the economic ramifications of potential disruptions to CSI. Given the immense reliance on satellite-based communication and navigation systems in the global economy, any interruptions in these services could lead to severe financial losses and hamper international trade. Disruptions in earth observation and climate monitoring capabilities could also adversely affect agriculture, disaster management, and environmental protection efforts, with dire consequences for both developed and developing nations.

Moreover, disruptions to critical spatial infrastructures can have significant societal impacts. Emergency response systems that depend on satellite-based communication might suffer delays or incapacitation during crises, potentially leading to increased casualties and damage. Additionally, disruptions in satellite-based internet services could adversely affect education, healthcare, and disaster relief in remote and underserved regions.

From a military perspective, the vulnerability of CSI raises concerns regarding national security. Space-based assets play a critical role in military operations, including reconnaissance, communication, surveillance, and missile warning systems. Any hostile actions against these assets could severely undermine a nation's defense capabilities, leading to potential regional destabilization or escalation of conflicts.

The geopolitical implications of airspace control and surveillance further underscore the significance of critical spatial infrastructures. Nations strategically leverage their spatial assets to gain advantages over rivals, asserting dominance in specific regions and projecting power globally. The ability to monitor adversaries' activities through space-based surveillance provides valuable intelligence, shaping military and diplomatic decisions. As a result, airspace geopolitics emerge as a complex interplay of national interests, alliances, and potential flashpoints, influencing the dynamics of international relations.

Given the increasing militarization and commercialization of space, it becomes imperative for nations to safeguard their critical spatial infrastructures and maintain their access to space for peaceful purposes. International cooperation and adherence to space law play crucial roles in managing airspace geopolitics, preventing conflict escalation, and fostering space sustainability. Consequently, understanding the intricate interdependencies between critical spatial infrastructures, airspace geopolitics, and international relations is vital for navigating the challenges and opportunities presented by the space domain in the 21st century.

4. THE CONFLUENCE OF SDA AND CSI: SECURING AIRSPACE GEOPOLITICS

The third section delves into the dynamic interplay between Space Domain Awareness (SDA) and Critical Spatial Infrastructures (CSI) and their combined role in maintaining regional airspace geopolitics. By understanding and harnessing the synergies between these domains, nations can bolster their capacity to safeguard essential assets in space and on the ground.

Enhanced space domain awareness plays a pivotal role in strengthening the protection of critical spatial infrastructures against an array of emerging threats. Space-based aggression is an escalating concern, as nations seek to gain a competitive edge by targeting adversaries' satellites or deploying anti-satellite capabilities. An in-depth understanding of the space domain's dynamics and constant surveillance can enable timely response and deterrence measures, reducing the vulnerability of critical space assets to potential acts of aggression.

Additionally, the increasing dependence on interconnected networks and information technologies exposes critical spatial infrastructures to cyber-attacks. Hostile actors might attempt to disrupt satellite communications, compromise ground-based systems, or manipulate data to cause widespread chaos and disruptions. Combining space domain awareness with robust cybersecurity measures can build resilience and mitigate the impact of cyber threats, ensuring the continuity of critical services and preserving regional stability.

Moreover, the section addresses the significance of mitigating electromagnetic interference (EMI) within the space domain. The proliferation of space assets and the rise of mega-constellations introduce challenges related to radio frequency interference. Ensuring uninterrupted access to radio frequency spectrum is crucial for the optimal functioning of critical spatial infrastructures and avoiding clashes between satellite systems. A comprehensive space domain awareness approach helps identify and address EMI sources, enabling effective spectrum management and reducing potential conflicts between space operators.

Furthermore, the confluence of SDA and CSI necessitates international collaboration and information sharing among nations to foster collective security in the space domain. As space becomes more congested and contested, the need for cooperation and transparency becomes increasingly apparent. Sharing tracking data, conjunction assessments, and other relevant space-related information can facilitate improved situational awareness, reducing the risks of accidental collisions or misunderstandings between space actors [12].

Promoting responsible space behavior and adherence to international norms and agreements is also a critical aspect of securing airspace geopolitics. Encouraging all spacefaring nations to abide by guidelines such as the United Nations Space Debris Mitigation Guidelines or the Code of Conduct for Outer Space Activities can promote responsible and sustainable space practices, minimizing the generation of space debris and the potential for space-related conflicts.

In conclusion, the confluence of Space Domain Awareness and Critical Spatial Infrastructures offers significant opportunities for enhancing airspace geopolitics and space security. By leveraging advanced technologies and fostering international cooperation, nations can effectively protect their critical space assets from emerging threats, bolster regional stability, and ensure the sustainable use of space resources for the benefit of humanity. A proactive and collaborative approach will be pivotal in navigating the challenges of an increasingly complex and interconnected space domain.

CONCLUSIONS

In the face of ever-increasing space activities and the growing importance of space assets in diverse sectors, the interplay between Space Domain Awareness (SDA) and Critical Spatial Infrastructures (CSI) emerges as a complex and multifaceted domain that significantly impacts airspace geopolitics. As nations endeavor to bolster their space capabilities and protect their strategic interests, it becomes imperative to grasp the intricate dynamics at the intersection of SDA and CSI. This understanding is vital for fostering regional stability and ensuring the sustainable utilization of space resources.

With the escalating utilization of space for communication, navigation, remote sensing, and national security, the protection of critical spatial infrastructures becomes a top priority for governments and organizations alike. These infrastructures comprise an amalgamation of space-based assets, ground stations, data centers, and associated networks, all playing pivotal roles in facilitating modern life. Yet, they face a range of potential risks, including collisions with space debris, cyber-attacks, intentional interferences, and natural space phenomena. Effective Space Domain Awareness plays a critical role in mitigating these risks by providing real-time data on the location and behavior of space objects, facilitating early warning systems, and guiding collision avoidance measures.

The link between SDA and CSI further extends to airspace geopolitics, where nations assert control over their territories and airspace to safeguard their interests. Geopolitical rivalries in the space domain can manifest in disputes over orbital slots, spectrum allocation, and the positioning of critical spatial infrastructure facilities. Heightened international competition in space exploration and exploitation underscores the significance of airspace control and surveillance, with strategic advantages at stake for nations possessing advanced SDA capabilities.

To navigate the intricate challenges and seize the opportunities arising from the interdisciplinarity of SDA and CSI, international cooperation stands as a paramount principle. Collaborative efforts among nations can facilitate the sharing of space situational awareness data, intelligence, and best practices, promoting collective security and reducing the risk of misunderstandings or conflicts in the space domain. Establishing clear policy frameworks, agreements, and norms of behavior for space activities can bolster predictability and promote responsible behavior, fostering an environment conducive to peace and cooperation.

Furthermore, technological advancements play a crucial role in enhancing SDA capabilities and bolstering the resilience of critical spatial infrastructures. Research and development efforts should focus on innovative sensing technologies, artificial intelligence, and data analytics to improve space object tracking and situational awareness accuracy. Emphasizing the standardization and compatibility of space-based systems can promote interoperability and data exchange among different nations and organizations, thereby fostering a safer and more secure space environment.

Ultimately, the successful convergence of SDA and CSI can contribute to ensuring regional stability, averting potential airspace conflicts, and fostering the sustainable and peaceful utilization of space resources for future generations. By recognizing the interdependence of these fields and prioritizing international collaboration, policy coherence, and technological innovation, the global community can navigate the evolving landscape of airspace geopolitics while safeguarding critical spatial infrastructures in an increasingly interconnected and space-dependent world.

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