A Perspective on Training and Education for Space Domain Awareness in Military Space Operations

Simone Caso, Simon Spronk
Royal Netherlands Aerospace Centre (NLR),
Amsterdam, The Netherlands,
simone.caso@nlr.nl, simon.spronk@nlr.nl

ABSTRACT

Space domain awareness (SDA) is a critical component of modern military space operations, encompassing the ability to detect, track, and characterize objects in Earth's orbit, as well as understanding the various effects and factors that influence activities within the space domain. This includes both human-made objects (e.g., satellites, debris, and spacecraft) and natural space phenomena (e.g., space weather and its operational impact). The evolving challenges in the space domain, such as the increasing congestion of orbital pathways and the rise of potential adversarial actions, require a workforce that is not only technically proficient but also adept in operational strategy. A major milestone was reached in 2019 with NATO's adoption of a Space Policy, officially recognizing space as a distinct operational domain alongside land, air, sea, and cyberspace. Meanwhile, the establishment of space forces such as the United States Space Force (USSF), further underlines the growing strategic importance of space.

With the expansion of space activities and increasing reliance on space-based infrastructure, the number of military personnel involved in space operations has naturally grown. These developments have led to a significant increase in educational initiatives and training programs tailored to the unique demands of the space domain. Consequently, the space sector today is vastly different from the landscape of a decade ago, with more rapid advancements and a growing need for specialized expertise in areas such as space situational awareness (SSA) and satellite operations. Accordingly, this paper explores the educational and training methodologies for SDA, with an emphasis on innovative approaches to improve learning effectiveness and operational preparedness. By exploring a 'training needs analysis' (TNA) and a 'training media analysis' (TMA) through a literature-based approach, this paper aims to identify essential skills and determine the most effective educational and training modalities.

ABOUT THE AUTHORS

Simone Caso works as an R&D engineer at the Royal Netherlands Aerospace Centre (NLR) in the Training and Simulation department. He holds a PhD in Behavioural and Movement Sciences and he is a visiting researcher at the Vrije Universiteit Amsterdam. His research primarily focuses on military space applications, with an emphasis on educational and training purposes, as well as the integration of cutting-edge technologies. Simone's work explores how to enhance training simulations through advanced technologies and how these can be applied to military operations and other complex environments. His interests also extend to improving human performance in high-stakes settings using data-driven approaches and innovative methods.

Simon Sponk works as R&D engineer at the Royal Netherlands Aerospace Centre (NLR) in the Training and Simulation department. He Holds an MSc in Aerospace Engineering. His work includes contributing to the L1b in-flight calibration efforts of earth observation instruments OMI and TROPOMI. In addition work on the L2 data processing of Sentinel-5, and has recently shifted to focus on the simulation of air- and spacecraft. Through his work he attempts to create innovative technical solutions and provide insight in how air and space assets can be best used to approach problems in both a military in civilian context.

A Perspective on Training and Education for Space Domain Awareness in Military Space Operations

Simone Caso, Simon Spronk
Royal Netherlands Aerospace Centre (NLR),
Amsterdam, The Netherlands,
simone.caso@nlr.nl, simon.spronk@nlr.nl

INTRODUCTION

Since the launch of Sputnik 1 in 1957, space has become an essential domain for national security. As the Cold War progressed, early military applications, such as reconnaissance, laid the groundwork for space militarization. Later, the first Gulf War (1991) marked the true operational integration of space-based capabilities, including the global positioning system (GPS), intelligence, surveillance, and reconnaissance (ISR), and communications. Over the years, as reliance on the space domain grew, maintaining awareness of activities within this domain has become increasingly critical to ensuring its security and functionality (Coletta & Pilch, 2009; Hays, 1994; Lambeth, 2004). The space domain of today, especially with the expansion of proliferated low Earth orbit (pLEO) missions, represents an affected shift from what existed even a decade ago as the number of satellites has increased 700% in that time frame. With the increasing use of small satellites, pLEO (2000 km from earth or less) has become a critical area of interest for military operations. This expansion highlights the rapidly evolving landscape of space, where new challenges and opportunities continue to emerge. As such, the need for space domain awareness (SDA) has grown substantially.

Modern SDA expands on traditional space situational awareness (SSA)[1] by addressing emerging threats such as anti-satellite (ASAT) weapons, spy satellites, space debris, and space weather (di Mare, 2025). With developments such as the EU Space Surveillance and Tracking (SST) program and the expansion of European, and more broadly, North Atlantic Treaty Organization (NATO) military space activities, there is a growing need for dedicated education and training programs to prepare military personnel for an increasingly contested and congested space environment. Accordingly, this perspective paper explores the current and potential educational and training methodologies for SDA, emphasizing innovative approaches to enhance both the learning experience and operational readiness of military space personnel. It begins with an overview of SDA, including its historical development and contemporary challenges. Next, through a 'training needs analysis' (TNA), the paper identifies the skills and knowledge required for operational profiles (e.g., satellite operators) engaged in SDA-related tasks. Complementing this, a 'training media analysis' (TMA) examines the technologies and tools that could enhance education and training efforts.

TNA and TMA are phases of a systematic and phased approach to develop training solutions (e.g., the aviation dedicated approach of the Royal Netherlands Aerospace Centre (NLR)[2], see *Figure 1)*. Particularly, TNA[3] is the first step in developing an effective training program. It focuses on identifying the knowledge, skills, and competencies individuals need to perform their roles effectively; and it provides insight into the difficulty, importance, and frequency of skills, supporting the development of training that progresses from simple to complex scenarios (Gould et al., 2004). This involves analyzing operational tasks and job roles to determine what kind of training is required, for whom, and why. This phase ensures that trainings are aligned with both organizational goals and operational requirements. The training design phase focuses on developing the actual training content and structure. This includes designing lessons, exercises, scenarios, and assessments, without making final decisions on the training media (see Van Merriënboer et al., 1992). The third phase is the TMA[4] which determines the most suitable methods and tools for delivering the training as designed. This includes evaluating various formats such as simulators, virtual reality (VR), serious gaming, and others. In practice, these phases are executed with subject matter experts, for example through interviews focused on specific skills and competencies required for a given role (e.g., those of an SDA analyst). However, this paper

[1] The European Space Agency (ESA) defines SSA as comprising three main areas: space surveillance and tracking (SST) of objects in orbit; space weather monitoring, which focuses on solar and geomagnetic conditions that affect systems and safety; and near-Earth object (NEO) detection of potentially hazardous asteroids or comets.
[2] See https://www.nlr.org/training/.
[3] See https://www.nlr.org/training/training-needs-analysis-tna/.
[4] See https://www.nlr.org/training/training-media-analysis-tma/.

aims to make a start with the TNA and TMA phases for developing SDA training, based on literature only. Therefore, it is worth noting that future work will need to include in-depth workshops with SDA analysts, and the TMA will have to be completed with input from the training design phase. Finally, the paper discusses the challenges and opportunities related to both current and future SDA educational and training methods, as well as the integration of advanced technologies into training frameworks to better prepare personnel for the demands of the evolving space domain.

Figure 1. NLR Training Processes

SPACE DOMAIN AWARENESS

SDA is essential for maintaining the safety, security, and sustainability of space operations. While traditional SSA focuses on the capabilities such as tracking "space" objects, monitoring space weather, and detecting near-Earth objects, SDA extends this by integrating these capabilities with contextual understanding (e.g., intent assessment, behavioral analysis, and threat prediction) across interconnected space systems (Holzinger & Jah, 2018). Since 1957, more than 5250 launches have placed over 21000 satellites into orbit. As of 2024, around 23000 objects remain in orbit and are regularly tracked by systems, such as the United States Space Surveillance Network[5]. These include active satellites, inactive satellites, and various forms of space debris. Accordingly, roughly 11000 of these are still operational satellites, while the rest, though still tracked, are no longer functioning and are considered debris (Froehlich, 2019). Some of these debris occurred both intentionally and unintentionally. For example, in 2007 China altered the balance of space warfare by launching an SC-19 ASAT missile at its own weather satellite Fengyun-1C. Around 15000 pieces of debris were detected from this event, while hundreds of thousands of smaller debris particles, too small to track but still hazardous, were released into low Earth orbit (LEO) (Kan, 2007). Another notable event occurred in 2009, when the American Iridium 33 satellite (active) collided with the Russian Kosmos 2251 satellite (deactivated), marking the first publicly confirmed collision between two intact satellites (Fateev et al., 2009). A third collision event occurred in 2019, when the Indian Space Research Agency (ISRO) conducted a mission named "Mission Shakti", using a ballistic missile to destroy an Indian satellite in LEO. The claim was made that by selecting this specific satellite at such a low altitude would limit the creation of space debris as most of it would decay within 45 days (Kosambe, 2019). Meanwhile, a more recent event was the Russian anti-satellite missile test in 2021, showing how Russia is also developing inspector satellites and ASAT weapons (Defensie, 2022). Lastly, although the National Aeronautics and Space Administration (NASA) classifies the Russian satellite Cosmos 2576 (launched in 2024) as a satellite with unknown purposes[6], it is not beyond the realm of possibility that this development marks the next step in the militarization of space through the arming of spacecraft (BBC News, 2024).

Both intentional and unintentional incidents, combined with the rapid growth of space activities, such as Starlink's mega constellations, have led to an annual increase in collision risks, threatening the long-term sustainability of space operations. As a result, SDA was developed to provide a broader knowledge of the domain than SSA covered (di Mare, 2025). Consequently, NATO transitioned from SSA to the adoption of SDA, reflecting the increasing need for a more comprehensive understanding of the space domain to support strategic and military objectives. Thus, rather than being entirely separate knowledge domains, SDA encompasses and builds upon SSA, providing a more integrated and operationally relevant perspective for planners and decision-makers (Grest, 2022). From a technical prospective, SDA data is typically compiled from various sources, including space surveillance networks and multinational and commercial systems, creating a "space catalog" that informs military, intelligence, commercial, and public stakeholders about the space environment. This integration of data enhances awareness in specific operational situations by supporting timely assessments and enabling coordinated action when necessary. Practically, SDA integrates several capabilities, including SST, space weather, and space intelligence. SST is responsible for detecting,

[5] The Space Surveillance Network is a system operated by the United States Space Surveillance Network to track and monitor objects in space. It includes surveillance satellites, radar systems, and telescopes and its primarily focused is tracking space debris, satellites, and other man-made objects orbiting Earth.
[6] See https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=2024-092A.

cataloging, and aiming the sensor in the correct place to re-detect a certain object. Space weather focuses on solar activity and its impact on spaceborne and ground-based systems through variations in the (upper) atmosphere, while space intelligence involves collecting and analyzing data to identify unknown satellites and assess their operational status, capabilities, and intentions, whether collaborative or hostile (Holzinger & Jah, 2018; Jah, 2016). This information is primarily examined by satellite operators or possibly SDA analysts.

SDA is crucial for identifying risks and threats to space systems, enabling appropriate countermeasures to enhance resilience (Holzinger & Jah, 2018). Accordingly, the United States Space Force (USSF) recommended a $100 million increase in their 2024 budget compared to the previous year. Specifically, the USSF intends to focus SDA spending on geosynchronous orbit (GEO)[7], as this orbit is strategically important as the government's most valuable communication and surveillance satellites operate there (Katalyst Space Technologies, 2024). Meanwhile, smaller countries such as the Netherlands, are also directing their investments towards SDA through their space force and/or command - in this case, the Defense Space Security Centre (DSSC) (Otten, 2024). Every space command has its defined roles, especially depending on its size. For large space commands such as the USSF, the SDA analyst role exists. However, in smaller space commands, this role could likely be integrated into the role of satellite operators. Therefore, considering the coming years, where space commands are still new and several countries do not have any, the paper examines the role of the satellite operator, who is also involved in SDA activities (i.e., SDA analysts). The next section of the paper explores the skills and competencies essential for this role.

EXPLORING TRAINING NEEDS ANALYSIS

Knowledge Required and Competencies Basis

Military satellite operators working in SDA are part of a specialized workforce tasked with securing and maintaining the functionality of space systems. Their responsibilities range from tracking space objects and managing satellite systems to making real-time decisions that protect both military and civilian assets (Lambakis, 2024). The competencies required for satellite (SDA) operators include a range of technical, analytical, and leadership skills, essential for effective operations in an increasingly contested and congested space environment. For instance, these operators must possess advanced technical knowledge, cybersecurity expertise, analytical proficiency, leadership abilities, cross-disciplinary collaboration skills, and an understanding of space-related policies and strategies (Alliger et al., 2004; Frostman et al., 2007; Li & Melin, 2023; Soto, 2023). See Table 1 for an overview of the possible knowledge and skills of operators.

Satellite (SDA) operators require technical expertise in space operations, including space surveillance, satellite management, and space traffic control. Proficiency in operating space and ground-based sensors and tracking systems is essential for detecting and predicting the behavior of space objects. A foundation in physics, engineering, and orbital mechanics, including satellite trajectories, orbital decay, and collision avoidance, as well as sensor operations such as radar, optical, and infrared tracking is fundamental for interpreting sensor data and devising effective response strategies. Further, they must also be skilled in SST, which involves detecting, cataloging, and aiming the sensor in the correct place to re-detect a certain object (Zhang et al., 2024). Moreover, as space-based assets become increasingly integral to national security, cybersecurity skills are important. Operators must protect these assets against cyber threats (e.g., hacking and electronic warfare). This responsibility includes maintaining secure communication channels and ensuring the resilience of data-sharing platforms vital to both military and civilian operations (Hills et al., 2022).

Analytical and decision-making abilities are also needed to deal with the dynamic nature of satellite operations. Operators must rapidly interpret real-time data from multiple sources to make informed decisions, enabling them to predict and mitigate threats to space assets. Key analytical tasks include data fusion (i.e., integrating information from various sources) and threat identification (i.e., classifying potential hazards like space debris or adversarial satellites). Operators also need to monitor solar activity, understand its impact on satellite operations, and predict the effects of space debris to ensure sustainable operations (Frostman et al., 2007). Leadership, collaboration and mission command skills are essential, particularly for those in supervisory roles. These individuals must oversee operations in high-pressure environments, guide teams and ensure that operations align with broader defense strategies. Effective

[7] GEO is a region approximately 35786 km above the Earth's equator where satellites orbit at the same rotational speed as the Earth, making them appear stationary from the ground.

leadership in SDA requires resilience, problem-solving skills, and the ability to foster collaboration within diverse teams. Furthermore, operators must collaborate across disciplines, working effectively with military personnel, international allies (e.g., NATO), and commercial entities (e.g., SpaceX). Clear communication across technical domains is necessary to achieve mission objectives and foster cooperation in complex operational contexts (Li & Melin, 2023; Soto, 2023). Meanwhile, operators should be familiar with space law, policies, and military strategies governing space operations. Finally, the specific competencies required can vary depending on the organization. For instance, the DSSC currently manages three satellites, while the USSF manages more than 100 (Otten, 2024; Skibba, 2024). Thus, the required competencies may differ from one space command (or space force) to another.

In a previous survey study (Caso et al., 2024), the authors identified possible knowledge gaps in military space operations, with SDA being one of the topics studied. In that study, SDA was analyzed as an umbrella term for SSA, space traffic management (STM), and space weather. SSA was identified as the topic with the highest demand for education, with respondents expressing a strong desire for further education in this area for their daily work. Both SSA and STM, as well as space weather, showed significant gaps between the current knowledge and the knowledge which the respondents wanted to acquire. Consequently, SDA educational and training programs should address these competencies, in order to prepare operators for their roles and to adapt to the evolving challenges in the space domain.

Table 1. Knowledge and Skills of Satellite (SDA) Operators

Category	Knowledge areas	Core skills
Space Surveillance	- Orbital mechanics (e.g., collision avoidance strategies) - Tracking systems - Cataloging Resident Space Objects (RSOs)	- Operating (space-based and ground-based) tracking sensors - Analyzing object trajectories - Using SST software tools for orbital predictions
Safety of Flight	- Collision risk assessment - Conjunction Data Messages (CDM) processing	- Maneuver planning (e.g., collision avoidance) - Conjunction mitigation
Orbital Behavior	- Satellite and Space domain behavior patterns and anomalies - Maneuver analysis (e.g., detection techniques)	- Rapid data interpretation and classification - Using tools to model and simulate orbital adjustments - Classifying objects and behaviors based on historical data and trends
Cybersecurity	- Cyber threats (e.g., hacking or electronic warfare) - Secure communication protocols and encryption standards - Techniques for safeguarding tracking and data-sharing	- Breach detection - Network resilience - Implementing robust measures for SDA software and hardware
Analytical Proficiency	- Data fusion techniques (e.g., for diverse datasets) - Threat assessment and identification methodologies - Real-time analytics from SSA tools	- Rapid analysis - Analyzing large volumes of data under time pressure - Predictive modeling
SDA Tools Development	- Traffic management tools - Operational procedure development - Emerging trends in SDA software and system capabilities	- Testing technologies and refining SDA tools to improve performance
Leadership, Mission Command and Team Collaboration	- Team dynamics - Communication strategies (for technical and non-technical audiences) - Organizational priorities and mission objectives for SDA	- Decision-making and problem-solving in leadership roles - Facilitating effective communication
Policy & Law	- Space law frameworks, including treaties and agreements (e.g., Outer Space Treaty). - Policies and strategies governing space operations and SDA activities - Ethical considerations in space operations	- Applying knowledge of space law and policies to operational decision-making - Advising teams on compliance with international standards and regulations - Contributing to policy development for space sustainability

Current Educational and Training Programs

Overall, foundational knowledge can be acquired through structured classes and courses, which are effective for building a knowledge base. In the aforementioned survey (Caso et al., 2024), the author identified the current educational courses and trainings (e.g., military exercises) related to space operations, with SDA being one of the key topics. These courses include the Fundamentals of Space Operations Course at the DSSC, the NATO School Oberammergau Space Course, the NATO Space Support Coordinator Course, the Space Weather Course provided by the Royal Netherlands Air Force (RNLAF), the Advanced Air/Space Power Course by the Defensie Academie (NLDA), the Fundamentals of ISR Course at the NLD-MoD, the Fundamentals of Space Operations Course at the Netherlands Ministry of Defense, and the Advanced SSA Course at the ESA. Lastly, the study investigated training and military exercises that, rather than solely aiming to improve knowledge (i.e., the educational aspect), focused on enhancing skills. Among the topics, only SSA and space weather showed significant differences between the current and desired level of skills. In terms of exercises, three military space exercises were mentioned by the survey respondents: Global Sentinel by the USSF, the NATO Exercise Steadfast Jupiter and CWIX, and the French Space Command exercise AsterX. Thus, if SDA is considered to encompass SSA, this broader scope implies that existing education and training programs, often designed primarily for SSA, may no longer be sufficient. There is a clear need to expand training to address the additional cognitive, technical, and strategic skills required for effective SDA. The next section explores various educational and training (media) tools that could support this development.

EXPLORING TRAINING MEDIA ANALYSIS

Technological tools

Different types of knowledge and skills call for different training approaches. For instance, declarative knowledge (e.g., understanding systems and terminology) may benefit from e-learning and traditional instruction, while procedural skills (e.g., system operation, response execution) are better trained through simulations. Higher-order cognitive competencies, such as decision-making, and analytical thinking, require more immersive and interactive tools, such as serious games or scenario-based training. A recent review by Laamarti et al. (2024) highlighted the growing role of such digital media in military education and training. In the context of SDA, several tools have emerged to support the development of domain-specific competencies. One example is the use of serious games to support the development of 'analytical proficiency' (see *Table* 1). Games have proven useful in military settings by providing dynamic and immersive learning experiences. By combining simulations and gamified platforms, military personnel can practice strategic thinking, decision-making, and situational awareness in a controlled, risk-free environment (Laamarti et al., 2024). These tools bridge the gap between theoretical knowledge and practical application, exposing individuals to realistic scenarios that replicate battlefield conditions or complex operational challenges (Cruz-Cunha, 2012; Smith, 2010). For example, Auria's Battlespace Operational Readiness Game contributes to Space Command and Control (C2) operator training by providing mobile, cost-effective, and engaging learning modules. It enhances skill retention through single- and multiplayer campaigns, rewards, and instructor access to performance data. The game supports SDA objectives by preparing operators to detect, track, and assess both natural and artificial objects in Earth orbit, while maintaining readiness to act in contested space environments. As far as is known, this is currently the only game designed specifically to support SDA skill development.

Emerging technologies such as extended reality (XR) tools like VR create immersive environments that improve situational awareness and decision-making skills (Boyce et al., 2022; Caso, 2024). VR can immerse trainees in realistic orbital scenarios, while AR overlays critical information onto physical simulations, bridging the gap between theory and practice (Fahnestock, 2020; Jenkins et al., 2018; Stouch et al., 2023). These technologies provide safe and cost-effective training in high-risk environments to develop competencies such as the 'orbital behaviors' and 'safety of flights' (see *Table 1*). For example, the NLR VR-SSA tool that allows users to select satellites (see *Figure 2),* date, time, speed (see *Figure 3*), and other factors for educational purposes.

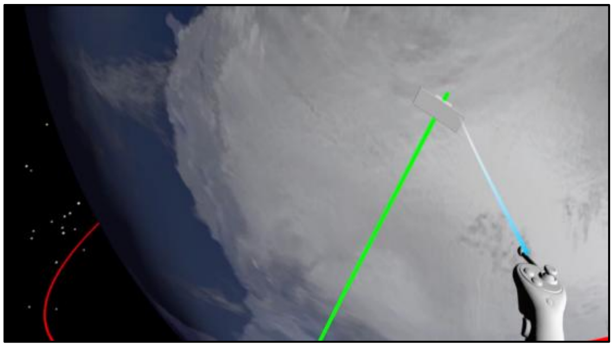

Figure 2. The Selection of a Satellite

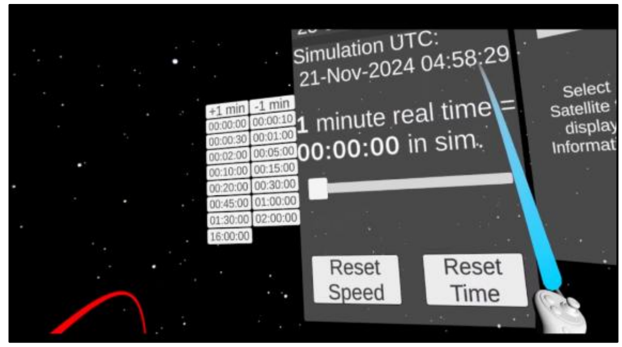

Figure 3. Selection Possibilities

The data visualized in the VR tool are sourced from ARGUS, a NLR SSA tool. It utilizes available data sources (e.g., Spacetrack) to monitor orbital events and provides advanced functionalities such as space object characterization, rendezvous and proximity operations (RPO), an automated warning system, and 3D visualization capabilities. One of the core applications of ARGUS is orbit calculation. Using collected data in the form of two-line elements (TLEs), it computes the orbital parameters of each tracked object. By projecting the orbits of selected space objects, information can be gained into their behavior and the impact of the space environment. Moreover, ARGUS enhances understanding of the maneuvering capabilities and mission characteristics of space objects by predicting positions and comparing them with actual TLE data. This allows for the identification of operational trends or deviations from expected behavior, enabling the prediction of anomalies and potential avoidance maneuvers or RPO activities.

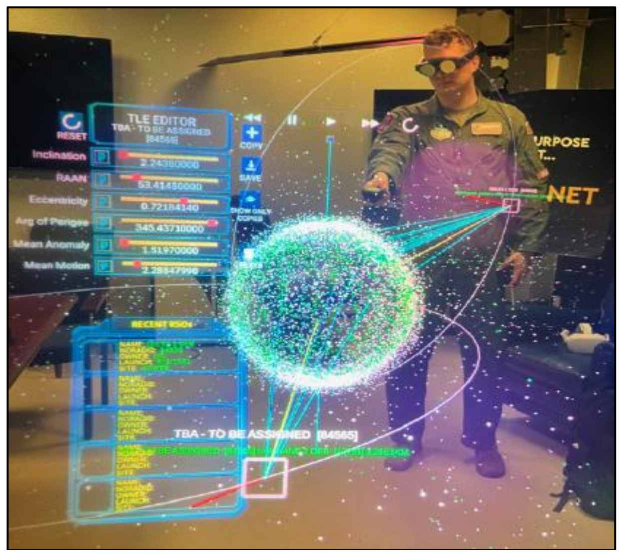

Figure 4. Stouch et al., (2023) AR SSA Tool

In addittion, Jenkins et al. (2018) and Stouch et al. (2023) developed an AR tool for space operators to enhance spatiotemporal understanding for proximity-based hazard assessments, maneuver planning, and scenario evaluations (see *Figure 4*). Similarly, Fahnestock (2020) explored the use of VR as an effective tool for training complex concepts within the USSF. Hence, XR could be used to educate satellite (SDA) operators by simulating satellite orbits, collision risks, and debris tracking, enhancing their ability to assess and respond to space threats in real-time. Moreover, XR technologies can also replicate real-world conditions, where satellite operators must quickly synthesize data from multiple sensors and satellites to make informed decisions. These immersive simulations provide valuable experience without the risks of live operations (Stouch et al., 2023).

XR could be integrated for educational, training and other psychological purposes (e.g., team coordination, communication and collaboration) within a space research facility (SRF) and space operations center (SpOC) (e.g., see the example of the Defense Advanced Research Projects Agency).[8] Related to this, NLR is currently developing these research and training facilities to support research and provide training, with the goal of integrating simulation systems (see *Figure 5*). Part of the SRF is a SimCell in which virtual satellites and larger constellation of satellites and space weather conditions can be simulated; the operations center part of the research facility can operate these virtual satellites in combination with real satellites. Also, connections with higher level training facilities can be established. Thus, satellite operators could be trained in SDA operations using both simulated and real data. Meanwhile, these practical training sessions could be integrated with theoretical classes or other education and training methods. In this regard, Caso et al. (2024) underlined that a balanced combination of these methods ensures a comprehensive educational and training experience. For example, trainees might begin with classroom sessions to develop theoretical knowledge, progress to XR-based simulations to acquire practical skills, and culminate with operations in the SpOC.

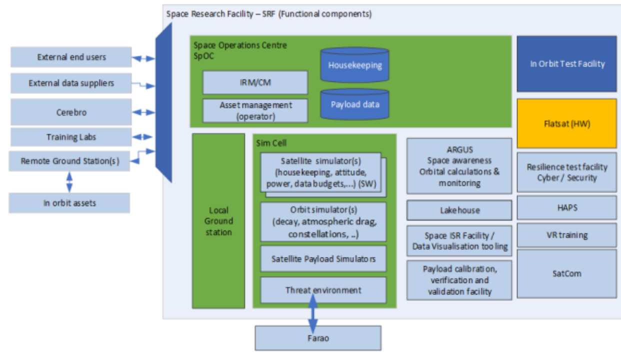

Figure 5. NLR Space Research Facility framework

Figure 6. NLR Battle lab Cerebro

Hence, a SpOC environment could be used for one-domain operations (i.e., the space domain) to train satellite (SDA) operators. To prepare these operators for multi-domain operations (MDO), training could be done via battle lab simulators. For example, NLR is conducting research on how to facilitate this through its battle lab Cerebro (see *Figure 6).* Cerebro is an environment in which concepts for military operations, for air and space power and information-driven operations are developed, tested, and evaluated. Specifically, it consists of a dedicated space for conducting tactical human-in-the-loop simulations, a C2 area from which the operational level of the simulation can be operated, and a control/observation room for (de)briefings, analysis, and to maintain a general overview during a simulation exercise (Knobbout, 2023). To train satellite (SDA) operators in MDO, the following training scenario may be considered. An unknown vessel appears to be performing suspicious maneuvers in the North Sea, in an area where underwater cables are present. In response, the Navy requires ISR imagery to gather more information. This would necessitate coordination between intelligence operators (in the intel or the space command, dependently on the defense structure of the country) and maritime defense forces. Simultaneously, a satellite, possibly from the same country as the vessel, is maneuvering close to the defense "ISR" satellite, with a high likelihood of attempting to blind or otherwise interfere with its operations. In such a scenario, intelligence operators, satellite (SDA) operators, and other Navy personnel would need to collaborate closely to ensure mission success. A battle lab could therefore facilitate such educational and training scenarios.

Technological applications

Lastly, technological applications such as artificial intelligence (AI) and machine learning could be applied to media tools like VR for educational and training purposes. For example, AI could generate educational or training scenarios for VR systems (e.g., satellite collision scenarios). Related to this, the Slingshot Aerospace company creates AI-driven training agents[9] that consists of dynamic adversaries which promote advanced course-of-action development by providing realistic, creative, and challenging opposition. This stimulates the trainees to develop innovative tactics, techniques, and procedures. Further, it challenges trainees with dynamic, evolving threats, enhancing their ability to respond effectively in real-world situations (Slingshot Space, 2024). Therefore, AI-powered systems facilitate real-time analysis of orbital data, allowing trainees (e.g., operators) to practice predictive analytics for collision avoidance and anomaly detection. This would allow the trainees to train in skills such as those in the categories 'space surveillance', 'orbital behavior', and 'analytics proficiency' (see *Table 1*). In addition, AI could generate (simulated) data to educate and train operators in 'realistic' scenarios. Accordingly, integrating machine learning algorithms and

[8] See https://www.youtube.com/watch?v=MXxoE4Y3s8s&t=207s.
[9] Threat agents are simulated adversaries or opponents used in training scenarios to replicate potential challenges and foster preparedness.

AI into training environments enables personalized feedback, optimizing the learning process for SDA education and training (Essa et al., 2023; Kaswan et al., 2024). Data (learning) analytics could involve the (automatic) collecting and analyzing data on trainees' performance to identify strengths, weaknesses, and trends (Kumar & Kumar, 2018).

To analyze data and utilize AI and machine learning effectively, personnel need to be educated and trained in the use of these applications for their work (Pedro et al., 2019). Much of SDA data-analysis is performed manually by analysts. As a result, this provides the opportunity to leverage applied machine learning. Accordingly, here analysts could be educated to interpret data generated by machine learning tools like Katalyst's ARC software, enhancing their ability (such as those in the category 'analytical proficiency', see *Table* 1) to assess SDA scenarios in real-time (Katalyst Space Technologies, 2024). To conclude, each tool and possible educational and training method present unique opportunities and challenges. Thus, the next section covers these challenges and opportunities, focusing on the educational and training tools mentioned.

CHALLENGES AND OPPORTUNITIES

While advanced tools promise significant benefits for education and training, their integration into current SDA training programs may present several challenges. The selection of appropriate training media is influenced by multiple factors, including resource availability (e.g., facilities and budgets), health and safety considerations (Doolani et al., 2020) validity (Tarnanas et al., 2013) and fidelity (Rompapas et al., 2021; Stoffregen et al., 2003). During the TMA as well as in the quality assurance phases (see *Figure 1*), careful evaluation of fidelity and validity is undertaken to align with the specific demands of training goals. The effectiveness of simulation-based training is determined or influenced by many factors, for example the quality of instructors, fidelity, and validity. These latter two aspects influence how well the training outcomes correspond to real-world task performance (Gray, 2019). Validity refers on how accurately a simulation measures or replicates the actual task execution (Stoffregen et al., 2003). Fidelity, meanwhile, represents the extent to which a simulation mirrors real operational systems and environments, including its ability to evoke cognitive, emotional and behavioral responses akin to those experienced in real scenarios. Additionally, it includes physical, psychological, emotional, and ergonomic aspects; each reflecting how realistically a simulation replicates sensory input, cognitive demands, task performance, emotional engagement, and physical movements (Harris et al., 2021; Ijsselsteijn et al., 2004). It is important to note that the level of fidelity must be carefully tailored to the specific learning objectives. Meanwhile, high fidelity is not always necessary, and the selection of fidelity levels should align with what is most effective for achieving the desired outcomes. This approach is referred to as targeted fidelity**,** where fidelity is aligned with training needs to ensure effectiveness without unnecessary complexity or cost. Incorporating this concept into the TMA phase helps balance realism and efficiency, ensuring that training remains relevant while making optimal use of available resources.

In order to develop effective simulations, it is important to examine a range of fidelity and validity metrics, as well as ensure scenario realism (Harris et al., 2021). For instance, to determine the validity of training tools, several methodologies may be used, such as the use of metrics, surveys and interviews for studying the user experiences; and behavioral observations for assessing performance metrics through observations and notational analysis (e.g., video behavioral analysis) (Howie & Gilardi, 2021; Kamińska et al., 2019; see Caso, 2025; Caso et al., 2025). In addition, metrics could also be generated using a stealth approach (see Shute 2011). For example, eye-tracking technology integrated into VR could provide valuable data about the information acquisition and processing. In this regard, in space operation centers, eye-tracking could be used to analyze gaze patterns and pupil dilation, contributing to enhanced training outcomes. A relevant example from the aviation sector is the Dutch Defense's INSPECT[10] project, which eye-tracking technology was used for training military air traffic controllers. Hence, by evaluating and optimizing fidelity and validity, educational and training programs could leverage advanced simulation technologies to make realistic and effective learning environments. These innovations not only improve knowledge and skill acquisition but also ensure that personnel are better prepared for the complexities of operational tasks. Nevertheless, very high-fidelity simulations of spacecraft behavior remain limited, since each satellite is essentially custom built. Accurate performance data is often only available once the spacecraft is operational, which constrains the development of training scenarios prior to launch.
However, high upfront costs for simulation systems may limit accessibility, particularly for smaller organizations. Here, collaborative efforts among government agencies, academic institutions, and industry partners could address

[10] See https://www.nlr.org/newsroom/nieuws/training-through-the-eyes-of-an-air-traffic-controller/.

these obstacles. For instance, initiatives such as NATO's joint military exercises and others such as the NATO Space Centre of Excellence, SDA TAP Lab[11] as well as the European Defense Fund (EDF) and Europe Defense Agency (EDA) projects[12] highlight the potential for resource sharing and interdisciplinary cooperation (Caso et al., 2024). Yet, the scalability of simulators like XR could provide long-term cost efficiency, making them feasible for broader adoption. These technologies could be used for purposes beyond education and training, such as recruitment. For instance, the VR ICARUS application (see Twigt et al., 2025) was originally developed to educate and train engineers, it is now also utilized for recruitment purposes. Lastly, as technology evolves at an increasingly rapid pace, it is important to integrate lifelong learning strategies (Dunlap & Grabinger, 2008), such as ongoing professional development, regular training updates, and access to current resources, into the TNA and TMA phases. For example, Apple Inc. developed recently the Apple Vision Pro. Personnel may undergo updated training on what these technologies could provide for their education and training. These strategies ensure that military personnel could continuously update their knowledge in the latest technological advancements.

CONCLUSION

The increasing importance of SDA in national security necessitates innovative educational and training methodologies for military personnel. This paper explored the current and potential approaches to enhance the learning experience and operational readiness of military space personnel. Using a literature-based approach to explore training needs and training media, this study identified skills and knowledge required for satellite (SDA) operators involved in SDA-related tasks, and examined various technologies and tools that can enhance education and training. The integration of emerging technologies and applications such as XR, AI, and machine learning can provide immersive and interactive educational and learning experiences, particularly in the Space Operations Centres and battle lab simulator environments. However, a full TNA and TMA, including a careful evaluation of fidelity and validity, are crucial to ensure that simulation-based training will be effective. To address the challenges associated with implementing these technologies, collaborative efforts among government agencies, academic institutions, and industry partners could facilitate resource sharing and interdisciplinary cooperation. Ultimately, effective education and training programs for SDA require a balanced combination of theoretical knowledge, practical skills, and innovative technologies. By leveraging these approaches, military organizations can enhance the operational readiness of their personnel and ensure the safety, security, and sustainability of space operations.

REFERENCES

Alliger, G., McCall, J. M., Albany, N., Mesa, A., Garrity, M. J., Beer, C. L., & Tossell, L. C. (2004). Cross-divisional analysis of competency-based training requirements for the air and space operations center (AOC). *Proceedings of the 26th Interservice/Industry Training, Simulation & Education Conference*, 1–11.

BBC News (2024, May 22). *US says Russia likely launched anti-satellite weapon.* BBC. https://www.bbc.com/news/articles/cq55ww5j7e2o.

Boyce, M. W., Thomson, R. H., Cartwright, J. K., Feltner, D. T., Stainrod, C. R., Flynn, J., Ackermann, C., Emezie, J., Amburn, C. R., & Rovira, E. (2022). Enhancing Military Training Using Extended Reality: A Study of Military Tactics Comprehension. *Frontiers in Virtual Reality*, *3*, 754627. https://doi.org/10.3389/frvir.2022.754627.

Caso, S. (2024). Emerging technologies in military space operations: Current applications and future research for educational and training purposes. *International Journal of Training Research*, 1–16. https://doi.org/10.1080/14480220.2024.2431482.

Caso, S. (2025). *Enhancing the Understanding of Perceptual-Motor Skills through Video Notational Analysis: A Video Notational Analysis of Visual Exploration, Team Communication, and Creativity in Elite Soccer*. [PhD-Thesis - Research and graduation internal, Vrije Universiteit Amsterdam]. https://doi.org/10.5463/thesis.1154.

Caso, S., Furley, P., & Jordet, G. (2025). Using video-notational analysis to examine soccer players' behaviours. *International Journal of Sport and Exercise Psychology*, 1–21. https://doi.org/10.1080/1612197X.2025.2477165.

[11] SDA TAP lab is a collaborative tech accelerator for U.S. companies, academia, federally funded research and development centres, industry experts and the USSF which they team together to solve critical SDA challenges. See https://sdataplab.org/.

[12] European Defence Fund (EDF) projects are European Union programs that supports the development of defense capabilities and technologies among European companies from the European countries. Whereas, EDA acts as a catalyst, promotes collaborations, launches new initiatives and introduces solutions to improve defense capabilities

Caso, S., Tanis, T., & van Kleef, A. (2024). *A Review on Education and Training Needs for Military Space Operations*. I/ITSEC, Orlando, FL.

Coletta, D. V., & Pilch, F. T. (Eds.). (2009). *Space and defense policy*. Routledge.

Cruz-Cunha, M. M. (Ed.). (2012). *Handbook of Research on Serious Games as Educational, Business and Research Tools:* IGI Global. https://doi.org/10.4018/978-1-4666-0149-9.

Defensie, M. van. (2022, November 25). *Defensie Ruimte Agenda (Ned en Eng)—Publicatie—Defensie.nl* [Publicatie]. Ministerie van Defensie. https://www.defensie.nl/downloads/publicaties/2022/11/25/defensie-ruimte-agenda.

di Mare, A. (2025, February 3). *The role of space domain awareness*. JAPCC. https://www.japcc.org/essays/the-role-of-space-domain-awareness/

Doolani, S., Wessels, C., Kanal, V., Sevastopoulos, C., Jaiswal, A., Nambiappan, H., & Makedon, F. (2020). A Review of Extended Reality (XR) Technologies for Manufacturing Training. *Technologies*, *8*(4). https://doi.org/10.3390/technologies8040077.

Dunlap, J. & Grabinger, S. (2008). Preparing Students for Lifelong Learning: A Review of Instructional Features and Teaching Methodologies. Performance Improvement Quarterly. 16. 6 - 25. https://doi.org/ 10.1111/j.1937-8327.2003.tb00276.x.

Essa, S. G., Celik, T., & Human-Hendricks, N. E. (2023). Personalized Adaptive Learning Technologies Based on Machine Learning Techniques to Identify Learning Styles: A Systematic Literature Review. *IEEE Access*, *11*, 48392–48409. https://doi.org/10.1109/ACCESS.2023.3276439

Fahnestock, M. (2020). *Air Force Orbital Mechanics / Space Operations Training in Virtual Reality*. 1–7.

Fateev, V., Sukhanov, S., Khutorovsky, Z., & others. (2009). Collision prediction for LEO satellites. Analysis of characteristics. *Proceedings of the 2009 Advanced Maui Optical and Space Surveillance Technologies Conference*, 1–4.

Froehlich, A. (2019). The Right to (Anticipatory) Self-Defence in Outer Space to Reduce Space Debris. In A. Froehlich (Ed.), *Space Security and Legal Aspects of Active Debris Removal* (Vol. 16, pp. 71–92). Springer International Publishing. https://doi.org/10.1007/978-3-319-90338-5_5.

Frostman, D., Henley, R., Morris, M., Mosbach, R., & Pimentel, B. (2007). A Competency-Based Approach to the Development of Space Professionals. *AIAA SPACE 2007 Conference & Exposition*, 6030.

Gould, D., Kelly, D., White, I., & Chidgey, J. (2004). Training needs analysis. A literature review and reappraisal. *International Journal of Nursing Studies*, *41*(5), 471–486. https://doi.org/10.1016/j.ijnurstu.2003.12.003.

Gray, R. (2019). *Virtual environments and their role in developing perceptual-cognitive skills in sports* (pp. 342–358). https://doi.org/10.4324/9781315146270-19.

Grest, H. (2022). *National Military Space Operations Centres- Requirements on National Centres with Respect to NATO Needs*.

Harris, D. J., Buckingham, G., Wilson, M. R., Brookes, J., Mushtaq, F., Mon-Williams, M., & Vine, S. J. (2021). Exploring sensorimotor performance and user experience within a virtual reality golf putting simulator. *Virtual Reality*, *25*(3), 647–654. https://doi.org/10.1007/s10055-020-00480-4.

Hays, P. L. (1994). *Struggling towards space doctrine: US military space plans, programs, and perspectives during the cold war*. Fletcher School of Law and Diplomacy (Tufts University).

Hedlund, E. (2017). Team Learning and Leadership in Multinational Military Staff Exercises. *Armed Forces & Society*, *43*(3), 459–477. https://doi.org/10.1177/0095327X16667088.

Hills, G., Baldasare, J., Henry, W., & Connell, W. (2022). A customized approach to cybersecurity education for space professionals. *MILCOM 2022-2022 IEEE Military Communications Conference (MILCOM)*, 160–165.

Holzinger, M. J., & Jah, M. K. (Eds.). (2018). Challenges and Potential in Space Domain Awareness. *Journal of Guidance, Control, and Dynamics*, *41*(1), 15–18. https://doi.org/10.2514/1.G003483.

Howie, S., & Gilardi, M. (2021). Virtual Observations: A software tool for contextual observation and assessment of user's actions in virtual reality. *Virtual Reality*, *25*(2), 447–460. https://doi.org/10.1007/s10055-020-00463-5.

Ijsselsteijn, W., De Kort, Y., Bonants, R., Westerink, J., & de Jager, M. (2004). *Virtual Cycling: Effects of immersion and a virtual coach on motivation and presence in a home fitness application*. University of Nottingham.

Jah, M. (2016). *Space surveillance, tracking, and information fusion for space domain awareness*. NATO STO-EN-SCI-292.

Jenkins, M., Bird, L., & Catto, G. (2018). *Increased Space Situation Awareness through Augmented Reality Enhanced Common Operating Pictures* (p. 46). The Advanced Maui Optical and Space Surveillance Technologies Conference. AMOS conference. https://ui.adsabs.harvard.edu/abs/ 2018amos.confE.46J.

Kamińska, D., Sapiński, T., Wiak, S., Tikk, T., Haamer, R. E., Avots, E., Helmi, A., Ozcinar, C., & Anbarjafari, G. (2019). Virtual Reality and Its Applications in Education: Survey. *Information*, *10*(10). https://doi.org/10.3390/info10100318.

Kan, S. (2007). *China's anti-satellite weapon test*. CRS Report for Congress. Order Code RS22652.

Kaswan, K. S., Dhatterwal, J. S., & Ojha, R. P. (2024). AI in personalized learning. In *Advances in Technological Innovations in Higher Education* (pp. 103–117). CRC Press.

Katalyst Space Technologies (2024). *Space Domain Awareness* [Online post]. https://www.katalystspace.com/space-domain-awareness.

Kosambe, S. (2019). Mission Shakti aka Project XSV-1: India's First Anti-Satellite Test (ASAT). *Journal of Aircraft and Spacecraft Technology*, *3*(1), 172-182. https://doi.org/10.3844/jastsp.2019.172.182.

Knobbout, J.J. (2023). *Virtualized Simulation for Military Concept Development and Experimentation: The Cerebro Battle Lab, a Case Study*. I/ITSEC, Orlando, Florida.

Kumar, K., & Kumar, V. (2018). Advancing learning through smart learning analytics: a review of case studies. *Asian Association of Open Universities Journal*, *13*(1), 1-12.

Laamarti, F., Eid, M., & El Saddik, A. (2014). An overview of serious games. *International Journal of Computer Games Technology*, *2014*(1), 358152.

Lambakis, S. (2024). Space sensors and missile defense. *Comparative Strategy*, *43*(1), 1–57. https://doi.org/10.1080/01495933.2023.2295235.

Lambeth, B. S. (2004). A Short History of Military Space. *Air Force Magazine*.

Li, J., & Melin, J. (2023). *Developing U.S. Space Force Organizational Culture with Future-Facing Intention* [Online post]. https://www.rand.org/content/dam/rand/pubs/perspectives/PEA500/PEA575-1/RAND_PEA575-1.pdf

Otten, D. (2024). *Space Domain Awareness. Space, dat is oud nieuws!?* https://vovklict.nl/intercom/2020/3/58.pdf

Pedro, F., Subosa, M., Rivas, A., & Valverde, P. (2019). Artificial intelligence in education: Challenges and opportunities for sustainable development. *UNESCO, Paris, France.*

Rompapas, D., Rodda, C., Brown, B. C., Zerkin, N. B., & Cassinelli, A. (2021). Project Esky: An Open Source Software Framework for High Fidelity Extended Reality. *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems*. https://doi.org/10.1145/3411763.3451804.

Shute, V. J. (2011). Stealth assessment in computer-based games to support learning. *Computer games and instruction*, *55*(2), 503-524.

Skibba, R. (2024). The Space Force Is Launching Its Own Swarm of Tiny Satellites. *Space Development Agency*. https://www.sda.mil/the-space-force-is-launching-its-own-swarm-of-tiny-satellites/.

Slighshot Space. (2024). [Online post]. https://www.slingshot.space/missions/training-education.

Smith, R. (2010). The Long History of Gaming in Military Training. *Simulation & Gaming*, *41*(1), 6–19. https://doi.org/10.1177/1046878109334330.

Soto, M. (2023). *A Qualitative Analysis Into Space Force Leadership Development* [PhD Thesis]. University of Arizona Global Campus.

Stoffregen, T., Bardy, B., Smart, J., & Pagulayan, R. (2003). *On the Nature and Evaluation of Fidelity in Virtual Environments* (pp. 111–128). https://doi.org/10.1201/9781410608888.ch6.

Stouch, D., Guarino, S., Duggan, D., Latiff, S., Hyland, R., & Brady, K. (2023). Immersive Space Operations Training in Extended Reality. *Immersive Space Operations Training in Extended Reality*. In Interservice/Industry Training, Simulation, and Education Conference (I/ITSEC), Orlando.

Tarnanas, I., Schlee, W., Tsolaki, M., Müri, R., Mosimann, U., & Nef, T. (2013). Ecological Validity of Virtual Reality Daily Living Activities Screening for Early Dementia: Longitudinal Study. *JMIR Serious Games*, *1*(1), e1. https://doi.org/10.2196/games.2778.

Twigt, D., Mathot, L., Den Exter, E., Lahkwani Daswani, M., Brouwer, S., Vos, C., Caso, S., Ten Hove, P. (2025). *ICARUS – Virtual Reality based training for Assembly, Integration and Testing. SmallSat, Amsterdam, NL.*

Van Merriënboer, J. J. G., Jelsma, O., & Paas, F. G. W. C. (1992). Training for reflective expertise: A four-component instructional design model for complex cognitive skills. *Educational Technology Research and Development*, *40*(2), 23–43. https://doi.org/10.1007/BF02297047.

Zhang, Z., Zhang, G., Cao, J., Li, C., Chen, W., Ning, X., & Wang, Z. (2024). Overview on Space-Based Optical Orbit Determination Method Employed for Space Situational Awareness: From Theory to Application. *Photonics*, *11*(7), 610. https://doi.org/10.3390/photonics11070610.