Biuletyn Wojskowej Akademii Technicznej

https://biuletynwat.pl/

Vol. 73, No. 4, 2024

Small Satellites for Smart Operations The Case for Polish Autonomous Space Capabilities

Adam Sowa

Military University of Technology, Institute of Optoelectronics, 2 gen. S. Kaliskiego St., 00-908 Warsaw, Poland

* Corresponding author at: adam.sowa@wat.edu.pl

Article history:
Received: 2nd *December* 2024
Accepted: 2nd *April* 2025
Available on-line: 23th *May* 2025

Keywords: small satellites, satellite formations, military Space capabilities, satellite carriers

DOI: 10.5604/01.3001.0055.1247

Abstract. Small satellites, here referred to as SmallSats, are revolutionizing how we approach space missions by providing cost-effective, flexible and innovative solutions to conduct space operations. Smart satellite formations, due to significant advancements in satellite technologies, improved mission resilience, and cost efficiency, as well as flexibility and scalability, became a promising solution for a wide range of current and future Space missions. In military domain, sensor-to-shooter satellites are providing disruptive military technology, enabling rapid, precise, and flexible response capabilities. In this paper, it is asserted that, in the mid to long term, there is a need to develop dual-use autonomous Polish capabilities in support of procured space assets operating in low Earth orbit, especially at altitudes up to 800 km. Based on an analysis of trends in small satellites development and application as well as the advantages related to SmallSats formations, it is argued that these capability needs could be met by the use of smart SmallSats formations. Poland, as an emerging space nation, already has significant know-how, experience, expertise and Space heritage of hi-tech payloads to be used in building effective SmallSats Space capabilities. The approach has already been implemented in R&D project PIAST (Polish ImAging SaTellites) expected to achieve initial comprehensive Space capability. For a variety of reasons, autonomous launch capability for at least the smallest satellites is recommended. It is also recommended to further investigate if satellite carriers could be used as Mother Ships prepositioned in specified orbits and loaded with different SmallSats to be deployed in task force formations as needed. It is proposed that some important challenges, such as broadband inter-satellite communication, be overcome through the connectivity with NATO and EU Space infrastructures. Likewise, other problems could be solved or leveraged by the use of advanced NATO and EU Space assets, along with carefully selected commercial services.

1. Introduction

Small satellites, often referred to as SmallSats, are revolutionizing how we approach space missions by providing cost-effective, flexible and innovative solutions to conduct space operations. They allow small businesses and emerging space nations to participate in space activities. Any satellite with a mass below 500 kg is here considered a small satellite.

Miniaturization of space propulsion, onboard processing and control, as well as communication systems have transformed the space sector by allowing SmallSats to carry out complex tasks that were previously achievable only with larger spacecraft [1]. A transition to composite materials in space applications is ongoing, allowing spacecraft to be built from mechanically robust materials to protect them from high-velocity impacts [2]. Self-healing materials are also being explored to address damages incurred to spacecraft components due to impacts from space debris, atomic oxygen, vacuum, ultraviolet radiation and extreme temperatures so that spacecraft are more resilient, economical and have improved longevity [3].

Some advantages of small satellites include lower development and launch costs, as they are cheaper to build and send to space as secondary payloads, rapid deployment and operation in large constellations. They can serve as reasonably cheap platforms for testing new technologies and innovative concepts with reduced overall risk.

On the other hand, there are also challenges related to SmallSats, such as limited power budgets, payload capacities and lifespans, as well as antenna aperture size restrictions [1]. Complying with international laws, when it comes to synchronizing frequencies or collision avoidance and space debris mitigation requirements, may equally be a challenge.

In this paper, Polish general capability needs related to autonomous Space operations in the mid to long term are identified, and the use of SmallSats in a smart way for these kinds of operations in low Earth orbit is considered. Then, the advantages and challenges related to some chosen SmallSats formations, sensor-to-shooter satellites as well as transport options into Space are analyzed and summarized. It is further argued that the Polish capability needs, related to autonomous Space operations, could be met by the use of SmallSats smart formations. The approach implemented in R&D project to achieve initial comprehensive Space capability is presented.

2. Polish Capability Needs Related to Autonomous Space Operations

Satellites are crucial for military supremacy. They play essential role in a multitude of military applications, including intelligence, surveillance, target acquisition, reconnaissance, early warning, communications, and GPS. In the commercial sector, besides GPS and communications, they also cover bank transactions, the internet and weather monitoring.

These days, satellite systems are becoming more and more vulnerable to destruction by Earth-based anti-satellite weapons. They could also be disrupted by active jamming devices, directional lasers and kinetic systems in orbit and on Earth, or simply by collision with Space debris, which is increasing in number. The US, China, India and Russia have all demonstrated anti-satellite capabilities by hitting their own satellites in Space [4].

Therefore, the shift from large, single-purpose satellites toward groups of smaller and cheaper ones that can act in unison seems reasonable where possible and justifiable.

It is asserted that, in the mid to long term, there is a need to develop dual-use autonomous Polish capabilities in support of procured space assets in low Earth orbit (LEO), especially at altitudes up to 800 km. A low Earth orbit is an orbit around Earth with a period of 128 minutes or less (making at least 11.25 orbits per day) and an eccentricity of less than 0.25. These capabilities should allow for Space-to-ground and Space-to-Space operations, as well as protection and defence of high value Space assets, such as Polish Pléiades Neo satellites (Fig. 1).

Based on an analysis of trends in small satellites development and application, the use of SmallSats for these three types of Space operations in low Earth orbit is considered.

Of course, one can rightly argue that for example NATO permanent Joint Intelligence, Surveillance & Reconnaissance capability or initiatives like Alliance Persistent Surveillance from Space are strong enough contributors in support of NATO operations, but even in this case, space-based assets as a rule are to be owned and operated by Nations and possibly by commercial providers. The same is true for other Space capabilities to be used by NATO [5], [6], [7].

Fig. 1. Pléiades Neo satellite. Image credit: Airbus Defense & Space

In building useful and effective Space capabilities, the following challenges for the use of SmallSats Space assets should be analyzed, assessed and options considered: access to space, readiness, resilience, scientific, and industrial potential to design and build capable satellite platforms and payloads, as well as operational know how that is not trivial and difficult to acquire.

3. Constellations and Smart Satellite Formations

Constellations are large groups of satellites providing global coverage for services like observation, communication and navigation (Fig. 2).

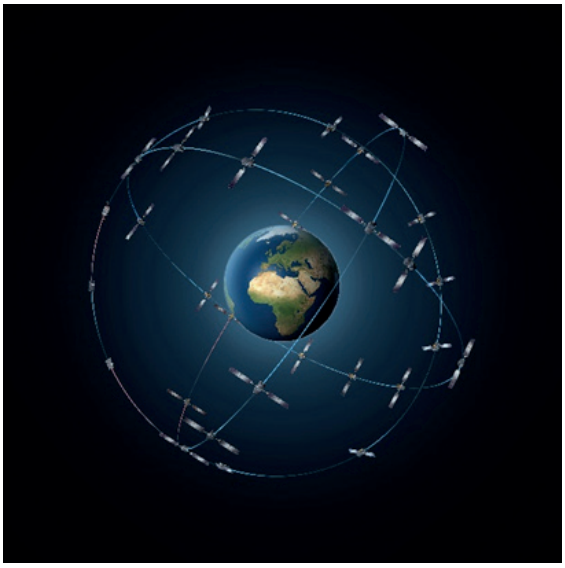

Fig. 2. Galileo constellation. Image credit: the European Space Agency

Smart satellite formations consist of multiple satellites operating in coordinated and adaptive configurations to achieve specific objectives. They utilize advanced technologies in communication, navigation, and control to dynamically adjust and optimize their positions and functions. Such formations enable capabilities beyond what a single satellite can achieve, including flexible reconfiguration and resilience through redundancy, enhanced functionality and spatial resolution, improved data collection and processing.

The following types of satellite formations are of special interest in this paper for analysis and consideration due to their useful characteristics described below.

- Trains: satellites following each other in the same orbital path with precise spacing, useful for time-sequential observations;
- Clusters: groups of satellites operating in close proximity, often in coordinated patterns to achieve specific observational or other stated goals;
- Swarms (Fig. 3): large numbers of small satellites with the ability to reconfigure dynamically.

Fig. 3. Satellite swarm for NASA's Starling mission. Image credit: Rocket Lab

The advantages of smart satellite formations are as follows:

1) Flexibility and scalability, as they can dynamically adjust to new mission requirements and can be scaled up or down as needed;
2) Redundancy and resilience: distributed systems are more robust to individual satellite failures, enhancing overall mission reliability;
3) Enhanced data quality and coverage: multiple satellites can provide more comprehensive and higher-quality data compared to single-satellite missions;
4) Cost efficiency: shared resources and coordinated operations can reduce mission costs.

There are also some challenges that should be addressed as well, such as:

1) Complex coordination, as maintaining precise formations and coordination among numerous satellites is technologically challenging;
2) Communication delays and bandwidth: ensuring reliable and high-speed communication links between satellites;
3) Collision avoidance: managing the risk of collisions within densely packed formations;
4) Power management: high data processing and communication demands require efficient power management systems.

4. Enhancing Military Capabilities by Sensor-To-Shooter Satellites

Sensor-to-shooter satellites are advanced military assets designed to streamline the process from threat detection to engagement. These systems integrate sensor data collection with rapid communication to shooter platforms, enhancing response times and operational effectiveness.

The key components and technologies needed for such a capability are: sensor satellites, communication infrastructure, shooter platforms, data processing & analytics, and command and control systems.

1) Sensor satellites are equipped with various sensors (optical, infrared, radar, radio communications or electronic signals interceptors) to detect and monitor targets, as well as to collect real-time intelligence, surveillance, and reconnaissance data. Examples include electro-optical satellites for high-resolution imagery and radar satellites for all-weather, day-night monitoring;
2) Communication infrastructure to secure high-bandwidth communication links to transmit data between sensor satellites and ground, aerial or sea-based shooter platforms. Utilizes RF and laser communication for rapid data transfer;
3) Shooter platforms include ground-based, aerial or sea-based weapon systems capable of engaging targets and range from missile defense systems and artillery units to fighter jets and drone swarms;
4) Data processing and analytics: onboard processing to filter and analyze sensor data and identify threats in real-time. AI and machine learning algorithms enhance target identification, classification, and tracking;
5) Command and control systems: centralized or distributed systems that coordinate the sensor-to-shooter loop to ensure seamless integration of sensor data with shooter platforms, enabling rapid decision-making.

Among the advantages of such systems are: rapid response, enhanced situational awareness, increased accuracy and operational flexibility.

1) Rapid response significantly reduces the time from target detection to engagement, enhancing operational tempo and effectiveness;
2) Enhanced situational awareness provides comprehensive, real-time awareness of the battlespace, improving decision-making and coordination;

3) Increased accuracy: real-time data and advanced analytics improve targeting precision, reducing collateral damage;
4) Operational flexibility supports various missions, from missile defense to counterinsurgency operations, and is adaptable to different threat environments.

The applications include: missile defense, allowing early detection and tracking of ballistic missiles and enabling timely interception; air superiority enhancing air defense; maritime security by tracking and engaging naval threats, including submarines and surface vessels, but also counter-terrorism, allowing monitoring and targeting terrorist activities and infrastructure.

The stated challenges are as follows:
1) Technical complexity related to developing and integrating advanced sensors, communication systems, and shooter platforms;
2) Cybersecurity to ensure the security and integrity of data and communication links against cyber threats;
3) High development and deployment costs, requiring significant investment;
4) Regulatory considerations pertaining to international regulations and ethical concerns related to the use of autonomous weapons systems and real-time surveillance.

5. Access to Space Options for Small Satellites

For small satellites to be highly effective, particularly when arranged in constellations and formations, each satellite has to be placed in a specific orbital plane and orbital position.

Currently, three main options are available to reach a specific orbit. The first is to employ a dedicated launch with a small launch vehicle. Plenty of small launchers are in development around the world, with few already operational. However, their cost per kilogram is predicted to be much higher than that of large launchers [8]. The second possibility is a rideshare option, where a satellite is transported by a large launcher together with other payloads to a general predetermined orbit. After separation, satellites need to be transferred to their specific orbits. This can be done in two ways: either by using satellite's own propulsion system or by a satellite carrier, also called a satellite dispenser or space tug. Satellite carriers, such as D-Orbit ION (Fig. 4), SHERPA, Firefly Aerospace SUV, Momentus Vigoride, MOOG OMVs are cargo spacecraft designed to accommodate several satellites with a total mass up to hundreds of kilograms and transport them into precise orbit and orbital position. Throughout a mission, they can release hosted satellites individually, changing orbital parameter between one deployment and the next.

In [8] it has been demonstrated that a satellite carrier is inherently less efficient than a group of autonomous satellites using their own propulsion, particularly for different orbits and large number of satellites. However, it is not always possible or convenient to provide small satellites, particularly the smallest ones (nanosats/ cubesats/ microsats) with comparable propulsion capabilities of a larger carrier, making the latter still a very attractive option in several situations.

Fig. 4. D-Orbit ION. Image credit: D-Orbit

Small launch vehicles are more expensive than rideshare options, but their costs impact only a part of total mission costs and can provide a higher responsiveness and frequency of launch opportunities for unserved orbits. A cost analysis also shows that, particularly for sophisticated small satellites, when the final orbit is far from the release one, a dedicated small launch vehicle can be cost competitive with the nominally much cheaper large launcher [8].

6. Building Useful and Effective SmallSats Space Capabilities

Poland is an emerging space nation already with significant know-how, experience, expertise and Space heritage of hi-tech payloads to be useful in building effective SmallSats Space capabilities.

Lower development and launch costs, rapid deployment and operation in smart formations, flexible reconfiguration and resilience through redundancy are the characteristics of great importance in building useful and effective SmallSats Space capabilities. Distributed systems are more robust to individual satellite failures. They can dynamically adjust to new mission requirements and can be scaled up or down as needed, enhancing overall mission effectiveness and reliability.

SmallSats can also serve as reasonably cheap platforms for testing new technologies and experimentation with innovative concepts, platforms and payloads reducing overall risk. This could speed up the development of scientific and industrial potential to design and build capable satellite platforms and payloads, as well as ground segment capability and operational know how that is not trivial and not easy to acquire.

These advantages of SmallSats Space assets justify the argument that the Polish capability needs, related to autonomous Space operations in mid to long term, could be met by the use of SmallSats smart formations in support of procured space assets, provided that the critical challenges are overcome.

However, it should be noted that some important challenges, such as broadband inter-satellite communication, could also be overcome through the connectivity with NATO and EU Space infrastructures. Other problems could be solved or leveraged by the use of advanced NATO and EU Space assets. Similarly, the use of carefully selected commercial services should not be excluded.

From a military standpoint, in Polish geopolitical reality, Space assets readiness is of importance, as is the assured launch of new satellites with the shortest possible "time to space". For a variety of reasons, autonomous launch capability for at least the smallest satellites should be considered a must.

Future missions could also require the use of additional SmallSat Space assets that may not be well specified ahead of time. To address this challenge, it is worth considering if satellite carriers like D-Orbit ION could be procured and used as Mother Ships prepositioned in specified orbits and loaded with different SmallSats to be deployed in task force formations as needed.

7. PIAST – Polish Imaging Satellites Project

The challenges related to design, production, launch and operation of Polish SmallSats constellation (Fig. 5) and formation have been addressed in R&D project PIAST (Polish ImAging SaTellites) by a consortium of Polish research centers, academia and industry.

As a result, a comprehensive satellite system (Fig. 6) consisting of a space segment with three satellites, ground station, mission control center as well as advanced data processing center is to be build and operated to allow for in-orbit capability demonstration and experimentation.

Fig. 5. PIAST satellites constellation.
Image credit: PIAST Consortium

The goal of PIAST project is to place in orbit a constellation of three satellites in order to perform optoelectronic Earth imaging and demonstrate a capability to acquire images with a 5 m ground resolution. SmallSats will conduct orbital maneuvers to demonstrate orbit change, formation forming, formation flying, and cooperation of satellites in performing tasks and experimentation both on Earth and in Space in LEO orbits at different altitudes. They will also demonstrate de-orbiting maneuvers at the end of the mission.

The satellites are designed to be agile, modular and scalable, with characteristics and functionalities useful in different military missions, such as inter-satellite communication and precision pointing. They are integrated in Poland and use technologies developed in Poland, including satellite platforms, propulsion system, AOCS, telescopes, laser rangefinder, and laser communication devices.

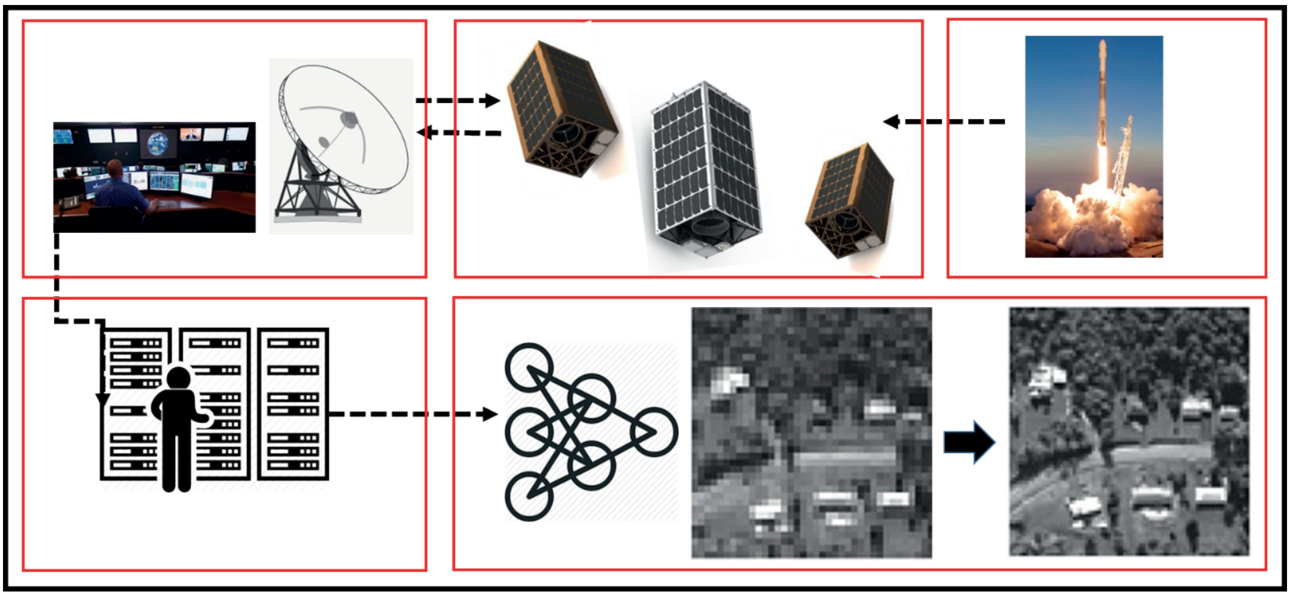

Fig. 6. PIAST comprehensive satellite system. Image credit: PIAST Consortium

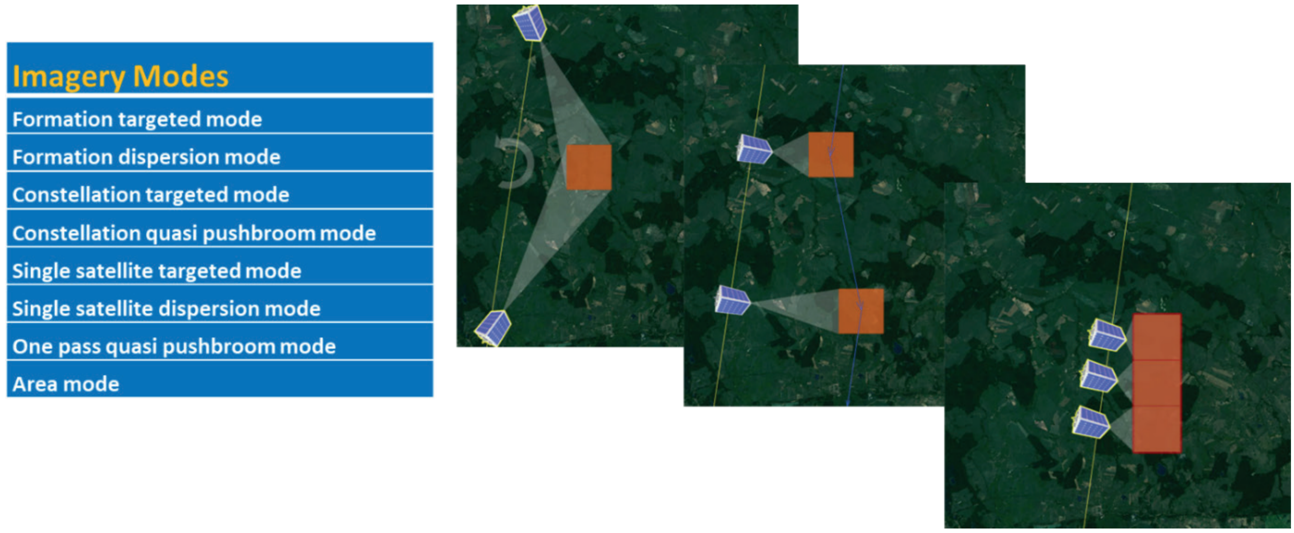

Fig. 7. PIAST constellation and formation imagery modes. Image credit: PIAST Consortium

The SmallSats constellation will be operated from Poland and from abroad through Ground Station as a Service functionality. Newly developed AI algorithms will take advantage of the numerical superposition of imaging data received from cooperating satellites, including simultaneous acquisition of pictures of the same area (Fig. 7).

In-orbit experimentation includes precision maneuvers, precision pointing capabilities and on-board satellite sensing devices, space to ground laser communication, satellite laser ranging, inter-satellite laser communication, as well as the use of ground laser for satellites detection and tracking.

The project has already resulted in the development of new technologies, know-how, testing and industrial capabilities, enabling the simultaneous production of multiple satellites and their relevant payloads. The concepts, solutions and technologies developed will be finally validated during Space mission.

8. Conclusions

Smart satellite formations represent a significant advancement in satellite technology, enabling enhanced data collection, improved mission resilience, and cost efficiency. The flexibility and scalability of these formations make them a promising solution for a wide range of current and future space missions. In military domain, sensor-to-shooter satellites are providing disruptive military technology, enabling rapid, precise, and flexible response capabilities.

In this paper, it is asserted that, in the mid to long term, there is the need to develop dual-use autonomous Polish capabilities in support of procured space assets operating in low Earth orbit, especially at altitudes up to 800 km.

Based on the analysis of trends in small satellites development and application as well as the advantages related to SmallSats formations, the paper showed that the Polish capability needs, related to autonomous Space operations, could be met by the use of SmallSats smart formations.

Poland, as an emerging space nation, already has significant know-how, experience, expertise and Space heritage of hi-tech payloads to be used in building effective SmallSats Space capabilities.

The challenges related to design, production, launch and operation of Polish SmallSats constellation and formation have already been addressed in R&D project PIAST (Polish ImAging SaTellites) by a consortium of Polish research centers, academia and industry. It is expected to achieve initial comprehensive Space capability.

For a variety of reasons, autonomous launch capability for at least the smallest satellites is recommended. It is also recommended to further investigate if satellite carriers could be used as Mother Ships prepositioned in specified orbits and loaded with different SmallSats to be deployed in task force formations as needed.

It is proposed that some important challenges, such as broadband inter-satellite communication, be overcome through the connectivity with NATO and EU Space infrastructures. Likewise, other problems could be solved or leveraged by the use of advanced NATO and EU Space assets, together with carefully selected commercial services.

Source of funding for the work
NCBR, DOB-SZAFIR/10/A/022/01/2021, *Nanosatellite reconnaissance constellation for optoelectronic imaging PIAST* [Nanosatelitarna konstelacja optoelektronicznego rozpoznania obrazowego PIAST] (Polish ImAging SaTellites).

Acknowledgements
The contributions to the PIAST (Polish ImAging SaTellites) project of the following consortium members from research centers, academia and industry are very much acknowledged: Military University of Technology (Institute of Optoelectronics, Faculty of Civil Engineering and Geodesy), Space Research Centre of the Polish Academy of Sciences, Creotech Instruments S.A., Łukasiewicz Research Network – Institute of Aviation, Scanway S.A., PCO S.A. a member of PGZ S.A. The necessary funding from NCBR, the Polish national R&D center, is acknowledged and appreciated.

I would like to express sincere gratitude and appreciation to all my outstanding colleagues from PIAST project team for their invaluable contributions and collaborative spirit allowing this project to happen.

Adam Sowa https://orcid.org/0000-0003-2726-9344

References

[1] Pelton J.N., Madry S. (Eds.), *Handbook of Small Satellites. Technology, Design, Manufacture, Applications, Economics and Regulation*, Springer, 2020, https://doi.org/10.1007/978-3-030-36308-6.

[2] Tserpes K., Sioutis I., *Advances in Composite Materials for Space Applications: A Comprehensive Literature Review*, MDPI, Aerospace, 2025, https://doi.org/10.3390/aerospace12030215.

[3] Incel J.C., Peerzada M., Mathews L.D., Pai A.R., Al-Qatatsheh A., Abbasi S., Yin Y., Hameed N., Duffy A.R., Lau A.K., Salim N.V., *Overview of emerging hybrid and composite materials for space applications*, Advanced Composites and Hybrid Materials, Springer, 6, 2023, https://doi.org/10.1007/s42114-023-00678-5.

[4] Wordsworth R., *The risks of a new Space race*, Geopolitical Futures, March 8, 2024.

[5] *NATO's overarching Space Policy*, 27.07.2019, NATO, https://www.nato.int/cps/en/natohq/official_texts_190862.htm?selectedLocale=en [accessed: 8.03.2024].

[6] *Joint Intelligence, Surveillance and Reconnaissance*, 7.03.2024, NATO, https://www.nato.int/cps/en/natohq/topics_111830.htm [accessed: 7.03.2024].

[7] *Allies launch strategic initiatives to enhance capabilities*, 9.07.2024,https://www.nato.int/cps/en/natohq/news_227472.htm#:~:text=The%20Alliance%20Persistent%20Surveillance%20from%20Space%20%28APSS%29%20programme,and%20at%20sea%20with%20unprecedented%20accuracy%20and%20timeliness [accessed: 9.07.2024].

[8] Barato F., Toson E., Milza F., Pavarin D., *Investigation of different strategies for access to space of small satellites on a defined LEO orbit*, Acta Astronautica, 222, 2024, 11–28.

Małe satelity w inteligentnych operacjach kosmicznych – polskie autonomiczne zdolności satelitarne to konieczność

Adam Sowa

Streszczenie. Małe satelity, zwane SmallSats, rewolucjonizują sposób, w jaki podchodzimy do misji kosmicznych, dostarczając opłacalne, elastyczne i innowacyjne rozwiązania do prowadzenia operacji satelitarnych. Inteligentne formacje satelitarne dzięki znacznemu postępowi w technologiach kosmicznych, zwiększeniu odporności misji i efektywności kosztowej, a także elastyczności i skalowalności, stały się obiecującym rozwiązaniem dla szerokiego zakresu obecnych i przyszłych misji kosmicznych. W domenie wojskowej satelity typu *sensor-shooter* dostarczają przełomowej technologii, zapewniając zdolności do szybkiego, precyzyjnego i elastycznego reagowania. W artykule stwierdzono, że w perspektywie średnio- i długoterminowej istnieje potrzeba rozwijania polskich zdolności autonomicznych podwójnego zastosowania w celu wsparcia pozyskanych zasobów kosmicznych działających na niskiej orbicie okołoziemskiej, zwłaszcza na wysokościach do 800 km. Na podstawie analizy trendów w rozwoju i zastosowaniu małych satelitów, a także korzyści związanych z formacjami SmallSats, argumentuje się, że te potrzeby w zakresie zdolności mogą zostać zaspokojone przez zastosowanie inteligentnych formacji SmallSats. Polska jako kraj z aspiracjami kosmicznymi ma już znaczący know-how, doświadczenie, wiedzę specjalistyczną i tzw. *Space heritage* w zakresie zaawansowanych technologicznie podsystemów satelitarnych, które mogą być wykorzystane w budowaniu efektywnych zdolności satelitarnych bazujących na SmallSats. Podejście to zostało już wdrożone w projekcie badawczo-rozwojowym PIAST (Polish ImAging SaTellites), który ma na celu osiągnięcie wstępnej kompleksowej zdolności kosmicznej. Z różnych powodów zaleca się zbudowanie autonomicznych zdolności wynoszenia na orbitę przynajmniej najmniejszych satelitów. Ważne jest również zbadanie i zweryfikowanie, czy satelity transportowe (*satellite carriers*, Space Tugs) mogłyby być używane jako statki-matki rozmieszczone wcześniej na określonych orbitach, będące nośnikami małych satelitów o różnym przeznaczeniu, które w razie potrzeby zostałyby użyte w formacjach zadaniowych zgodnie z bieżącymi wymaganiami. Proponuje się, aby niektóre istotne wyzwania, takie jak szerokopasmowa łączność międzysatelitarna, zostały przezwyciężone przez zapewnienie interoperacyjności z infrastrukturą kosmiczną NATO i UE. Podobnie inne problemy mogą być rozwiązywane lub lewarowane przez wykorzystanie zaawansowanych zasobów kosmicznych NATO i UE oraz starannie dobranych dostawców usług komercyjnych.

Słowa kluczowe: małe satelity, formacje satelitarne, wojskowe zdolności kosmiczne, transportery satelitów