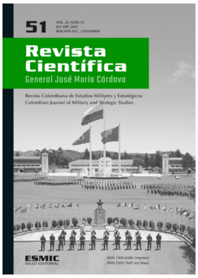

Revista Científica General José María Córdova
(Colombian Journal of Military and Strategic Studies)
Bogotá D.C., Colombia
ISSN 1900-6586 (print), 2500-7645 (on line)
Journal homepage: www.revistacientificaesmic.com

Weaponizing the edge of space? Progress and prospects of military high-altitude platforms

¿Armar los confines del espacio? Avances y perspectivas de las plataformas militares de gran altitud

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How to cite in APA: Šlebir, M. (2025). Weaponizing the edge of space? Progress and prospects of military high-altitude platforms. *Revista Científica General José María Córdova, 23*(51), 565-588. https://doi.org/10.21830/19006586.1483

Published online: July 1, 2025

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Revista Científica General José María Córdova
(Colombian Journal of Military and Strategic Studies)
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Volume 23, Issue 51, July-September 2025, pp. 565-588
https://doi.org/10.21830/19006586.1483

Weaponizing the edge of space? Progress and prospects of military high-altitude platforms

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ABSTRACT. High-altitude platforms are rapidly developing technology, but their role in the future of warfare has not yet been sufficiently explored. This paper attempts to address this gap by linking technology, doctrine, and future studies. The study offers a comprehensive overview of the distinctive characteristics of high-altitude airspace, the technological advancements in military high-altitude platforms, and their potential applications in future conflicts. It also identifies weaknesses in existing aerospace defense capabilities and emphasizes the need for a robust international regulatory framework. By framing high-altitude platforms as a disruptive technology and high-altitude airspace as a contested domain, the study contributes to the discourse on air and space power. Methodologically, the paper is based on a semi-systematic literature review, combined with future study techniques and supported by semi-structured interviews.

Keywords: air defense; air warfare; future of warfare; high-altitude platform; military operations; military technology

RESUMEN. Las plataformas de gran altitud son una tecnología en rápido desarrollo, pero su papel en el futuro de la guerra aún no se ha explorado lo suficiente. Este artículo intenta abordar esta brecha vinculando tecnología, doctrina y estudios de futuro. El estudio ofrece una visión general de las características distintivas del espacio aéreo de gran altitud, los avances tecnológicos en plataformas militares de gran altitud y sus posibles aplicaciones en conflictos futuros. También identifica las debilidades en las capacidades de defensa aeroespacial existentes y enfatiza la necesidad de un marco regulatorio internacional sólido. Al enmarcar las plataformas de gran altitud como una tecnología disruptiva y el espacio aéreo de gran altitud como un dominio en disputa, el estudio contribuye al discurso sobre el poder aéreo y espacial. Metodológicamente, el artículo se basa en una revisión bibliográfica semi-sistemática, combinada con técnicas de estudio de futuro y con el apoyo de entrevistas semiestructuradas.

Palabras clave: defensa aérea; guerra aérea; futuro de la guerra; plataforma de gran altitud; operaciones militares; tecnología militar

Section: Dossier • Research Article

Received: March 10, 2025 • Accepted: May 30, 2025

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Introduction

In 2023, a series of high-altitude, highly publicized airspace incidents occurred over North America. From February 4 to February 12, the U.S. Air Force shot down four high-altitude objects. U.S. authorities identified the first as a Chinese surveillance balloon. At the same time, the other three downed objects remained unidentified and were likely privately owned unmanned systems with no ties to foreign states. While China claimed that its balloon was a civilian weather balloon that had gone off course, the shootdown fueled ongoing diplomatic tensions between the U.S. and China. It led to increased scrutiny of unidentified aerial phenomena worldwide. In addition, the Chinese balloon incident captured the attention of aeronautical and military experts. First, the Chinese balloon flew at an altitude of about 60,000 feet (18 km), well above the altitude at which civilian and even most military aircraft operate (Mansoor, 2023). Second, it raised concerns about the military's ability to effectively detect, identify, and track relatively large but slow aircraft flying at such unusual altitudes (Smith, 2023). Third, a balloon with a low radar and thermal signature raised the question of how well standard air-to-air weapons are suited for such unconventional targets (Helfrich et al., 2023). Finally, the incident (re)raised the question of the boundary between airspace and (outer) space and the limits of state sovereignty (Hitchens, 2023).

All in all, the Chinese balloon incident has drawn attention to the militarization of "the edge of space," a volume of high-altitude airspace with unique physical and operational characteristics that can be exploited to gain a military advantage (Taylor et al., 2023; Bera, 2023; Trevithick, 2023; Liu, 2024). While the idea of using high-altitude systems to gain a warfighting edge is not new,[1] modern high-altitude platforms are a technology with the potential to revolutionize air warfare in the 21st century. Operating in high-altitude airspace but below the limits of outer space, these systems could offer a unique combination of characteristics bridging the gap between aircraft and satellites. Unsurprisingly, both the military and civilian sectors have shown interest in exploring the potential of high-altitude platforms for a wide range of applications, including reconnaissance, surveillance, communications, and even weapons delivery.

1 Toward the end of World War II, Japan used incendiary balloons called Fu-Go, which were designed to fly over the Pacific via the jet stream and wreak havoc in the U.S. From November 1944 to April 1945, approximately 9,000 Fu-Go balloons were launched, about 300 of which reached the continental U.S. and caused limited damage (Coen, 2014). Fu-Go balloons are the earliest examples of unmanned high-altitude devices used in combat. Although they did not fly high enough to be classified as high-altitude platforms by today's standards (their typical flight ceiling was between 30,000 and 40,000 feet, i.e., about 9–12 km), they certainly posed a challenge in terms of detection and interception. For a comparable British World War II balloon weapon project, albeit simpler in design and at a lower altitude, see Operation Outward (Peebles, 1991, pp. 52–57).

Aim and methods

Although high-altitude platforms are rapidly evolving and approaching technological maturity for widespread use, their role in the future of warfare is poorly understood and understudied. Literature investigating the future of warfare (Cohen et al., 2020; Gruszczak & Kaempf, 2024a; Hasanov et al., 2024; Rajagopalan & Patil, 2024), the future of air warfare technologies (Espitia Cubillos et al., 2020; Wills, 2015; Briant, 2023), the future of air power (Lambert, 2023; Sankaran, 2024), or the importance of air power in general (Olsen, 2018; Fedorchak, 2020; Baliž & Prebilič, 2024) tends to overlook their potential.

On the other hand, there is a substantial body of mainly technical knowledge on high-altitude platforms that demonstrates rapid technological advances. However, the research is limited in its recognition of military applicability (see, e.g., d'Oliveira et al., 2016; Gonzalo et al., 2018; Pelton, 2020) and has not yet provided sufficient insight into how this new technology will potentially alter the character of armed conflict. This study aims to fill this gap by building on existing research (Kirsch & Montagnier, 2019; Spencer, 2019; Horváth, 2021) and establishing a connection between technology, doctrine, and future studies. The study also aims to contribute to the discourse on high-altitude airspace as a contested domain and to inform on the evolving hybridization of air- and space-based military power.

Methodologically, this paper is based on a semi-systematic literature review and a combination of two future study techniques: visioning and forward-looking technology analysis. The paper also draws on five semi-structured interviews with subject matter experts.

In the first step, we conducted a semi-structured literature review. According to Snyder (2019), semi-systematic literature reviews are helpful when it is simply not possible or practical to analyze every single paper relevant to the topic. The semi-systematic approach is most useful in identifying "themes, theoretical perspectives, or common issues within a specific research discipline" (p. 335), making it well-suited for exploring relatively broad research questions. For this study, we initially conducted a literature search using predefined search terms in an academic library or database. We then supplemented the search with an additional database to ensure that a comprehensive range of relevant literature was captured.[2] In the next step, we expanded our search to include gray literature using a web search engine and an artificial intelligence chatbot.[3]

2 We searched the Digital Library of the University of Ljubljana (DiKUL). Since DiKUL provides access to content disseminated by all major scientific publishers and information services, it was chosen as the entry point for this search. We used the following search query without additional filters, except for the publication date of 2015 or later: (high altitude platform) OR (high altitude platform system) OR (high altitude platform station) OR (high altitude pseudo satellite) OR (atmospheric satellite) OR (high altitude long endurance) OR (high altitude airship) OR (atmospheric satellite). For further searching, we used the above query paired with additional search terms: (query as listed above) AND ((military) OR (intercept) OR (weapon) OR (targeting) OR (Karman line)). Lastly, we used Google Scholar with the same search queries.

3 Some sources were identified using the Google search engine or via the Gemini AI chatbot.

After identifying the relevant themes and findings, we tried to apply them to the future. In doing so, we methodologically entered what is commonly referred to as future studies. According to Gruszczak and Kaempf (2024b), contemporary debates regularly address the future of warfare, which has become “one of the most hotly debated topics amongst academics, militaries, and policymakers alike” (p. 1). However, how can we know what the future holds? We cannot because predicting complex future developments is limited. However, a variety of future techniques have been developed, not to claim that we can predict the future, but to help us to foresight and better prepare for the possibilities of the future (Heuser et al., 2024, p. 12). This paper draws on two techniques: visioning and forward-looking technology analysis. While the former is primarily concerned with exploring possibilities of desirable or undesirable change, the latter attempts to evaluate emerging technologies and their potential impact on the area of interest.

Our reflections on the future were methodologically intertwined with the insights gained from semi-structured interviews with five subject matter experts (see Moore, 2014, pp. 117–121).[4] The interviewees were asked to envision various scenarios of how high-altitude platforms might evolve, the potential consequences, and the factors that might accelerate or hinder the adoption of these systems. Although interviews can be a powerful source of information, it is essential to note that data from interviews generally lack reliability and generalizability and are biased by self-selection (Moore, 2014, pp. 125–126). Speaking of bias, the methods of future studies are also not immune to it. One of the most notable is confirmation bias, where researchers tend to favor information that confirms or reinforces their prior beliefs. This can lead to “blind spots” in research (Heuser et al., 2024, p. 16).

This research was supported in part by artificial intelligence tools. The following tools were used for the purposes listed: Gemini 1.5, 2.0, and 2.5 (brainstorming, literature search, wording, and syntax), DeepL (language editing and translations), and InstaText (language editing). In addition to the introduction, the article consists of five sections. First, the characteristics of high-altitude airspace are outlined. Next, a comprehensive overview of current and future military high-altitude platforms is provided. Then, the utility of these platforms is examined, followed by an exploration of the challenges of defending against them. In conclusion, the findings are interpreted in relation to the article’s aim.

4 We consulted with five subject matter experts, either in person or via email. We assured them anonymity so that they could freely express their views. We selected interviewees who were experts in the major topics covered in this paper, namely air navigation services, aircraft engineering, air defense, and military theory (two respondents covered the latter field). To mitigate subjective bias, we triangulated the experts’ responses with those from other sources. The interviews, therefore, are not directly referenced in the paper, as their primary role was to guide the research and refine the analysis rather than to serve as citable evidence themselves. This is because the information obtained was corroborated and integrated with other sources to ensure objectivity.

High-altitude airspace – a backgrounder

No fixed altitude line separates high-altitude platforms from conventional aircraft. A common criterion is the ability to operate at an altitude of 20 kilometers or above (see d'Oliveira et al., 2016, p. 249; Nikodem & Kaltenhäuser, 2020, p. 1037; Pelton, 2020; Horváth, 2021, p. 83; Liu, 2024, p. 198; ITU, 2025), while some sources suggest a boundary a few kilometers lower (see Alsahlani, 2017, p. 1; Staats, 2023). The limit may seem arbitrary, but several factors support it. First, in terms of classification, the airspace above flight levels 600–660 becomes either unclassified or uncontrolled.[5] Alternatively, it reverts to one of the less restrictive classes.[6] This means that high-altitude platforms operate in a volume of airspace with loose or no regulations.

Second, virtually all civil air traffic flies below 20 kilometers. While it may be practical for specific aircraft designs to cruise at or above this limit (e.g., supersonic airliners such as the retired Concorde and Tupolev-144 or the still-in-development Boom Overture), Eurocontrol data (2021) shows that there is little air traffic even above flight level 450 (approximately 14 km). Third, most high-performance military jets have a service ceiling between 15 and 20 kilometers, and military aircraft are rarely designed to reach altitudes a few kilometers above this range (Eurocontrol, n.d.; U.S. Air Force, n.d.). Fourth, relatively low wind speeds characterize altitudes around 20 kilometers, as they are located above jet streams and below faster, higher stratospheric winds. Consequently, aircraft require less power to counteract wind (Rajan et al., 2019, p. 2). Fifth, encapsulating all the previous points, the low air density in the stratosphere significantly reduces lift, limits engine performance, reduces protection from cosmic radiation, and poses challenges to pressurization. However, the lower region of the stratosphere generally enjoys relatively low winds. Apart from experimental or niche military designs, the physical properties of the atmosphere have thus made flying above 20 kilometers difficult and uncommon.[7]

5 A flight level is a measurement of altitude as determined by an altimeter set to the standard setting of 1013 hPa. Flight levels are used to separate aircraft in the higher parts of the airspace, as they eliminate the need for flight crews to adjust their altimeters to the local barometric pressure repeatedly. Therefore, flight level 600 approximates 60,000 feet (18.29 km), and flight level 660 approximates 66,000 feet (20.12 km), with the exact altitude of the flight levels varying according to the atmospheric pressure at a given time.

6 According to the scheme adopted by the International Civil Aviation Organization, airspace volumes are classified into one of seven classes (A, B, C, D, E, F, or G), with Class A being the most restrictive and Class G being the least restrictive. At high altitudes, airspace volume is either unclassified/uncontrolled (such as in Belgium and Luxembourg above flight level 660) or classified in one of the less restrictive classes, such as Class E (as in the U.S. above flight level 600) or Class G (as in Ireland above flight level 600) (AIM Belgium, 2025, ENR 1.4; Federal Aviation Administration, 2024, ENR 1.4; AirNav Ireland, 2025, ENR 2.2).

7 As of this writing, the highest altitude achieved in sustained horizontal flight by a manned heavier-than-air aircraft is 85,061 feet (25.93 km), set by a Lockheed SR-71A in 1976. The record for a manned lighter-than-air aircraft is held by the Strato-Lab balloon, which reached an altitude of 113,740 feet (34.67 km) in 1961. Although manned balloons have reached even higher altitudes, the crew mem-

On the other hand, there is no internationally agreed-upon boundary between airspace and outer space. Therefore, there is no clear limit to the altitude at which a system would be already considered a spacecraft.[8] Various approaches have been developed to potentially delineate airspace from outer space (Gangale, 2018), but the Kármán line remains the most influential concept in discussions about the boundary of space. According to this approach, the boundary lies "at the theoretical limit of airflight at an altitude where aerodynamic lift is exceeded by the centrifugal force" (UN Committee on the Peaceful Uses of Outer Space, 1970, p. 20). However, the Kármán line, although widely discussed and commonly referred to, only accounts for aerodynamic lift and does not consider aerostatic buoyancy, the upthrust that lighter-than-air designs use to float in the air (Gangale, 2018, p. 157). For this paper, high-altitude platforms encompass any aircraft that utilize either lift or buoyancy to operate at high altitudes for extended periods, typically above 20 kilometers but below the loosely defined boundary of outer space.

The debate about the legal limits of space, once considered theoretical, is becoming increasingly practical as technological developments bring to the fore the legal question of the highest altitude at which states can regulate flight operations under air law. In addition to new generations of high-altitude platforms, high-altitude airspace is of increasing interest due to the expansion of commercial spaceflight (both space- and earthbound), suborbital flight (including suborbital space tourism), the emergence of new high-speed passenger transportation concepts (such as hypersonic airliners), and the proliferation of new generations of weapon systems (such as hypersonic glide vehicles). We concur with Nikodem and Kaltenhäuser (2020, p. 1042) that high-altitude airspace will be populated by users with different needs, who may want to persistently stay or transit vertically and horizontally through it at vastly different speeds.

However, as Gangale (2018, p. 163) points out, it is doubtful that a sovereign state would allow the unregulated presence of high-altitude platforms over its territory, as this would forfeit the presumption of state sovereignty. States are reluctant to relinquish any part of their sovereignty and will likely argue that any superjacent high-altitude platform – no matter its altitude – is operating in their airspace, in which, according to the international air law, "every State has complete and exclusive sovereignty" (*Convention on International Civil Aviation*, 1947, art. 1). Some stakeholders have already recognized the need to regulate the

bers returned to Earth by parachute. Among the unmanned vehicles, the NASA Helios Prototype holds the aerodynamic record at 96,863 feet (29.52 km), and the Japanese BS 13-08 set the aerostatic record at 176,000 feet (53.64 km) (World Air Sports Federation, n.d.). As Gangale (2018, p. 164) concludes in this regard, the practical limit of usable airspace is approximately 53 km, although this could increase in the future.

8 As Gangale (2018, p. 83) summarizes, since the 1970s, altitudes proposed to delineate airspace from space have ranged from 60 kilometers (196,900 feet) to 100 nautical miles (185.2 km, or 607,600 feet). As the author argues, this range may "demonstrate where a consensus gut level of comfort lies" and "suggest a range of altitudes wherein a hard altitude might eventually be selected." However, international law does not define the boundaries of outer space or the altitude limits of national airspace.

so-called "higher airspace," "near space," "mesospace," "protozone" or "protospace" in order to mitigate risks and protect economic and military interests. Thus far, no agreement has been reached on establishing an international regime, although various proposals exist, such as the draft Convention on the Regulation of Near Space (Gupta & Sgobba, 2022).

The technology – a forerunner

Operating in high-altitude airspace is a feat achievable by specialized designs that push the limits of aeronautical technology.[9] In terms of aircraft, both heavier-than-air and lighter-than-air designs are feasible in the high-altitude domain in both manned and unmanned configurations. However, manned lighter-than-air aircraft are not discussed in detail below, as they have minimal military utility and offer less potential for disruptive change.

Manned heavier-than-air aircraft are a mature technology, and several fixed-wing designs can reach high-altitude airspace.[10] Although large leaps in their future performance are less likely than with unmanned systems, advances in areas such as aerodynamics, avionics, materials science, and propulsion systems continue to yield benefits. However, the high cost of developing and operating manned aircraft imposes inherent limitations, meaning their role will likely remain niche. While the Lockheed SR-71 reconnaissance aircraft, an iconic record holder mentioned above, was retired decades ago, other designs, such as the Lockheed U-2 reconnaissance aircraft and the Mikoyan MiG-31 supersonic interceptor, remain in service and have recently been modernized (Lockheed Martin, 2023; RuAviation, 2023).[11]

Nevertheless, manned high-altitude reconnaissance aircraft are likely to be phased out relatively soon because the value of their key attribute – flexibility – is diminished by the proliferation of both satellite-based and unmanned high-altitude platform-based sensors. For example, the last operational U-2s are due to be retired in 2026 (Cohen, 2023). Meanwhile,

9 A variety of terms have been used to describe aircraft flying at altitudes above 20 kilometers, which reflect either the aircraft's specific characteristics or general advancements in the field. These terms include "high-altitude platform station," "high-altitude pseudo-satellite," "high-altitude platform system," "high altitude powered platform," "atmospheric satellite," "high altitude aeronautical platform," "high altitude airship," "stratospheric airship," "stratospheric platform," and "atmospheric satellite." As d'Oliveira et al. (2016, pp. 249–250) note, the term "high-altitude long endurance" has also been used. However, it is generally more associated with unmanned aerial vehicles that have a service ceiling of about 18 kilometers. In this paper, we use the term "high-altitude platform" because it is generic and encompasses the essence of various technical designs.

10 When it comes to the ability of fixed-wing designs to reach high-altitude airspace, we must distinguish between two phenomena. On the one hand, several military jets can reach altitudes well above the lower limit of high-altitude airspace, but only by performing a zoom climb, which trades speed for altitude and is of limited operational utility. On the other hand, there are only a handful of manned aircraft specifically designed for service ceilings at these altitudes, which can, therefore, sustain horizontal flight. This section focuses on the latter.

11 According to official U.S. Air Force (n.d.) data, the U-2 has a service ceiling of over 70,000 feet (21.21 km). In contrast, the official Russian source lists the MiG-31's service ceiling at 20,600 meters (Ministry of Defense of the Russian Federation, n.d.).

their Russian counterparts, the Myasishchev M-55s, have reportedly even been considered for a service return; however, this is likely a stopgap measure to temporarily bolster Russian intelligence, surveillance, target acquisition, and reconnaissance (ISTAR) capabilities until unmanned replacements become available (Newdick, 2023; Overclockers, 2023).

On the other hand, manned high-altitude interceptors such as the MiG-31 are expected to remain in service for the foreseeable future and could also be replaced by next-generation designs under development, such as the PAK-DP (sometimes referred to as the MiG-41) (Nikolov, 2024). However, there is little reliable information on the progress of the PAK-DP development, which could potentially raise the operational ceiling for interceptor aircraft. The same applies to other sixth generation (multirole) fighters currently under development around the world. In the future, manned high-altitude fixed-wing designs may remain valuable because they continue to offer a unique combination of relatively high speed (whether high subsonic, supersonic, or perhaps one day hypersonic), a large payload (several tons of armament) and a human-in-the-loop. However, their endurance is and will remain limited.

The problem of limited endurance is being addressed by unmanned designs, some of which could soon transition from the prototype phase to mass production. One of the pioneers in the heavier-than-air category is Zephyr, a solar-powered, battery-backed unmanned fixed-wing aircraft originally developed by QinetiQ, later acquired by Airbus, and now manufactured by Airbus subsidiary AALTO. In 2018, Zephyr set a Guinness World Record for an unmanned fixed-wing aircraft by reaching an altitude of 74,114 feet (22.59 km) (Guinness World Records, n.d.).[12] In 2025, Zephyr broke its endurance record for unmanned aircraft with a 67-day nonstop flight in the stratosphere (AALTO, 2025a). According to the latest available timeline, AALTO expects its global entry into service in 2026 (Airbus, 2024; O'Grady, 2025).

The company has ambitious plans to have nearly 1,000 aircraft in the air within the next decade or so (Hoyle, 2023) and aims to keep aircraft airborne for at least a year (Weaver, 2019, p. 61). One of the sectors in which AALTO (2025b) markets its aircraft is defense, promoting a specific Zephyr C4ISR (Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance) solution. The company advertises the aircraft's low detectability, high survivability, low latency, and persistence as either a C4 (a combination of various radio communications or tactical data links, such as Link 16/22) or an ISR (image/data capture) platform.

With a cruise speed of about 12 knots indicated (which equates to about 45–60 knots true airspeed at high altitudes, depending on actual altitude and temperature), a total mass of about 65 kilograms, a payload of 8 kilograms, and a base price of about 5 million USD

12 An unofficial altitude record for a fixed-wing unmanned aircraft is attributed to the Helios Prototype, which was developed as part of NASA's Environmental Research Aircraft and Sensor Technology (ERAST) project. During a test flight near Hawaii in 2001, the Helios Prototype reached an altitude of 96,863 feet (29.52 km) and remained above 96,000 feet (29.26 km) for over 40 minutes (NASA, 2002).

(Weaver, 2019, pp. 61–62; Hoyle, 2023; Whiterow, 2024), the aircraft seems best suited for the military either as an IMINT (imagery intelligence), SIGINT (signals intelligence), or MASINT (measurement and signature intelligence) platform or as a C4I node. Plans are in place to increase the payload to 14 kilograms within a few years (SatteliteObservation, 2024) and 15–20 kilograms after 2029 (Bowden, 2024).

Other heavier-than-air high-altitude platforms under development that could technologically compete with Zephyr are ApusDuo (Mira Aerospace, n.d.), PHASA-35 (BAE Systems, n.d.), SULE (Swift Engineering, n.d.; sUAS News, 2024), Qimingxing 50 (Trevithick & Parken, 2022), La-252 (TopWar, 2024), Argus (Aviacija Rossii, 2024) and CSIR-NAL HAP (Venkatakrishnan, n.d.). Although it is challenging to synthesize the characteristics of these heavier-than-air, solar-powered, battery-backed unmanned platforms because they are in various stages of development, with varying amounts of publicly disclosed details and in part of different designs, their general characteristics appear to be as follows: wingspan of 15–50 meters, maximum takeoff weight of 40–150 kilograms, planned service ceiling exceeding 60,000 feet, and a payload of a few kilograms to about 15 kilograms (with plans to exceed this capacity in future versions). At least two companies are also working on a heavier-than-air high-altitude platform that is considerably larger (with a wingspan comparable to that of a wide-body passenger jet) and would have a larger payload allowance (up to 68 and 360 kilograms, respectively). However, such designs appear to be niche (Sampson, 2024; Skydweller, n.d.).

In the lighter-than-air category, Stratobus, an airship originally designed by Thales and now being co-developed by a consortium of partners under the EuroHAPS program (European Defence Fund, 2022), is attracting the most attention. Stratobus is a proposed unmanned, solar-powered, battery-backed airship that will have no rigid internal structure but will be inflated and maintained in shape by helium under super pressure. The concept envisions a 140-meter-long airship equipped with solar cells to power four propeller engines and carry a payload of up to 250 kilograms, capable of operating at altitudes of 18 to 20 kilometers. Like fixed-wing solutions, Thales plans for a one-year endurance, after which an airship will have to land for maintenance. Instead of immediately building the full-size Stratobus (expected to be built around 2030), the company is first developing a smaller, 60-meter-long demonstrator, which is currently under construction and is expected to make its first flight at the end of 2025 (Thales Alenia Space 2023; Masselin, 2024; SatteliteObservation, 2024).

Although there is no precise information on the planned flyaway price of a serial-produced airship, it is likely to be an order of magnitude higher than for fixed-wing, heavier-than-air solutions (Weaver, 2019, pp. 62–63). There is information circulating that the designers expect to increase the payload to up to 450 kilograms (CNIM Systèmes Industriels, n.d.), which is also an order of magnitude higher than that of most fixed-wing counterparts. The same applies to power generation, which will be in the range of several kilowatts, allowing for a relatively power-hungry payload. Projects currently competing with Stratobus include Ecosat (Capgemini, n.d.) and an already flight-tested Sceye (Sceye, n.d.). At the same time, several countries and companies have the opportunity to revive projects that were previously abandoned due to high costs and technological challenges.[13]

Additionally, China most likely also has a secretive high-altitude airship program, as suggested by satellite images of a giant hangar in northwestern China (Trevithick, 2024a) and photos of an unknown airship near the northern Philippine Island of Luzon (Trevithick, 2022). However, none of the projects are likely to reach the optimistic payloads of a few tons and about a dozen kilowatts of power generation that were envisaged in feasibility studies from decades ago (cf. Jamison et al., 2005, p. 21). Hybrid solutions that combine airship buoyancy with an aerodynamic lift are also being developed (Persechino & Baraniello, 2024), trading some of the airship payloads for increased maneuverability. The feasibility of missile-launched high-altitude airships is also being researched (Riboldi et al., 2022).

The least technologically complex high-altitude platforms are high-altitude balloons. Generally unmanned and filled with gas with low molecular mass (helium or hydrogen), these lighter-than-air aircraft are launched into the stratosphere, where they are exposed to winds that can carry them over great distances. High-altitude balloons are regularly used by meteorologists, hobbyists, and researchers, and have a rich military history.[14] They are even considered for large-scale reintroduction by advanced armed forces (Hitchens, 2024a; Saballa, 2024). However, an unsteerable balloon has obvious disadvantages.

For this reason, modern designs intended for military use typically feature a steering mechanism that enables controlled flight, usually by adjusting altitude and entering a prevailing wind of a different direction.[15] Although they are (optionally) steerable, high-altitude balloons have limited maneuverability compared to other types of aircraft. This can make it difficult to control their position or navigate in complex wind conditions. The most apparent advantages of using high-altitude balloons are their relative simplicity and, therefore, affordability. The cost of smaller, fully mission-equipped designs is as low as several thousand USD, while larger models can carry payloads of up to several tons (Piancastelli et al., 2023; NASA, n.d.). Although balloons can also be tethered to restrict their movement, the current world record of 9,032 meters suggests that tethering a high-altitude one may be impractical (CGTN, 2022).

13 For an overview of the most important past projects, see d'Oliveira et al. (2016, pp. 251–256).

14 In addition to the Fu-Go balloons mentioned above, Operation Genetrix is another notorious example. It was a large-scale U.S. Air Force balloon reconnaissance operation designed to overcome the lack of intelligence on the Eastern Bloc. In early 1956, under the guise of meteorological research, hundreds of unmanned balloons were launched and drifted by prevailing westerly jet streams over the Eurasian landmass, particularly the Soviet Union. Approximately ten percent of the gondolas (mission modules) were later successfully recovered either midair or from the surface (Peebles, 1991, pp. 162–190).

15 For a brief discussion of the maneuverability of the aforementioned Chinese balloon, see Bushwick (2023). For some of the technological solutions that enable altitude control, see Snizek (2024).

In closing this chapter, let us briefly revisit heavier-than-air fixed-wing designs, namely those powered by airbreathing engines. Although current market trends may suggest that solar-powered, battery-backed high-altitude platforms will supersede airbreathing designs, this is unlikely. There are at least two reasons why the development of air-breathing engine high-altitude platforms will continue. First, energy generation by solar cells is limited due to seasonal variations in daylight hours at high latitudes, which constrain the operational capabilities of solar-powered high-altitude platforms in the winter months or polar regions.[16] Second, chemical fuels have a higher energy density, which allows for heavier payloads, faster airspeeds, and higher operating altitudes.

This enables the development of aircraft with entirely different performance, as demonstrated by the long-retired Mach 3 and 95,000 feet (29.00 km) capable Lockheed D-21 U.S. strategic reconnaissance unmanned aerial vehicle (National Museum of the Air Force, n.d.). Little is known about its potential contemporary successors, though evidence suggests that China has an operational design, the WZ-8, with a somewhat similar performance (Lee, 2023). Other designs with supersonic or perhaps even hypersonic speeds are currently under development (Carlin, 2024; Hermeus, 2024; Trevithick, 2024b), in addition to subsonic platforms, such as the WZ-9 (Trevithick & Rogoway, 2025).

Military – the utilizer

High-altitude platforms have a variety of applications, including enhancing telecommunications networks and collecting surface observation and weather data. While the military has long recognized the operational value of high-altitude platforms (as discussed in previous chapters), legacy systems were impractical for widespread use despite being state-of-the-art for their time. However, the convergence of technological advances suggests that these limitations are being overcome, and high-altitude platforms, especially unmanned configurations, could become truly disruptive technology. Below, we outline potential future military applications of high-altitude platforms. We do not claim to be able to predict the future; instead, we aim to highlight some of the possibilities that lie ahead. This discussion will examine specific use cases and explore the expected benefits and limitations of each.

First, let us consider the realistic option of using high-altitude platforms as communication relays to extend the range of surface-based and airborne systems. In this case, one of the main advantages is the combination of a high vantage point and relative proximity to Earth. For instance, the free space path loss of a high-altitude platform used for communication is

16 One way to overcome this limitation is to use hydrogen-powered designs. Hydrogen has a high energy storage density that could enable year-round operation anywhere on Earth with multi-day endurance. For an example of such an aircraft, which is currently under development, see Leichtwerk AG (2025).

significantly lower than that of a satellite-based communication system.[17] However, the high altitude still allows line-of-sight communication to be established over a wide area, overcoming the terrain obstacles that limit terrestrial systems.

Deploying such unmanned platforms in large numbers in geostationary or quasi-geostationary position, with months or even years of endurance,[18] would make them a viable alternative to geostationary satellites. They would also enable repositioning and meeting dynamic user demand, as well as having low latency and facilitating easy upgrades after recovery. Additionally, they could be a reliable option for housing future sixth generation (6G) wireless communication nodes. However, operating relatively close to the ground (compared to satellites), their most significant limitation could be physical security, as high-altitude platforms are more susceptible to physical interference and jamming.

A second realistic scenario involves the use of high-altitude platforms for intelligence, surveillance, and reconnaissance (ISR) to provide optical, infrared, radar, or other data to augment existing surface, airborne, and satellite assets. While a comprehensive exploration of such applications is beyond the scope of this paper, we would like to highlight an option that could uniquely enhance existing capabilities. Namely, an interesting configuration of unmanned high-altitude platforms would house an airborne early warning (AEW) radar, an airborne ground surveillance (AGS) radar, or a combination of both.[19] This setup would offer several advantages.

First, the altitude itself would extend the radar's horizon, allowing it to detect low-flying and/or surface targets at greater distances. Second, an unmanned configuration reduces personnel exposure in non-permissive environments, as only the technical asset is at risk. Third, deploying such a radar on a long-endurance unmanned platform, such as a stratospheric airship, would dramatically improve on-station time compared to current manned AEW/AGS systems. While the technical complexities of powering, operating, and maintaining sophisticated radar systems must be addressed to design an operational aerostat configuration, current medium-altitude tethered AEW aerostats, such as those procured by Poland, suggest the possibility of a similar system at higher altitudes (TCOM, 2024). However, an aerostat that is less maneuverable than manned systems could pose a viable and high-payoff target for

17 As Gangale (2018, p. 162) illustrates, "all other things being equal, a satellite-based communication system orbiting at 358 kilometers, being at 10 times the distance of a [high-altitude platform] at 36 kilometers altitude, has 100 times the free space path loss". A geostationary satellite, located 1,000 times the distance of a high-altitude platform, has 1,000,000 times the free space path loss.

18 The concept of a permanent sky station is being explored. For an example of a proposed pseudo-permanent high-altitude platform, see JP Aerospace (2019).

19 China's new WZ-9 high-altitude long-endurance system is likely to be equipped with multiple radars capable of air and ground moving target indication, as well as synthetic aperture radar imagery (Trevithick & Rogoway, 2025).

the next generation of long-range, actively guided surface-to-air and air-to-air missiles being developed by several states.

The following realistic scenario involves the use of high-altitude platforms for electronic warfare. While electronic warfare encompasses a wide range of activities that use the electromagnetic spectrum to create offensive or defensive effects, countering GPS jamming has recently been highlighted as a task particularly suited to high-altitude platforms. Essentially, the platform would receive the GPS signal from the satellites and retransmit it to the surface at a much higher power, making it much more difficult for jammers to interfere with it (Welch, 2024). On the other hand, high-altitude platforms have already been envisioned as satellite navigation jammers, potentially disrupting communications between the satellite and the surface station (Otay et al., 2023). However, to effectively disrupt the transmission path, such an unmanned platform would need to be deployed in a geostationary or quasi-geostationary position, which could make it an easy target for the countermeasures described in the next chapter.

One relatively unexplored option is utilizing high-altitude platforms as kinetic weapons platforms, particularly when considering unmanned systems. Due to the limited payload and aerodynamic delicacy of solar-powered, battery-backed, heavier-than-air designs, these are likely to be less suitable for carrying bombs, missiles, loitering munitions, or directed energy weapons. This is less true for lighter-than-air designs, which can carry payloads of up to several hundred kilograms (for airships) or even tons (for balloons). However, while mounting ordnance on high-altitude lighter-than-air platforms is feasible, the practical benefits are questionable. Compared to conventional fixed-wing aircraft, the low airspeed negates any advantage in weapons range resulting from the high altitude at which the weapons are released. Furthermore, the altitude itself might offer little protection from enemy air defenses. Therefore, the likelihood of a successful weapons delivery would depend heavily on other factors, such as force multipliers.

Conversely, long-endurance, high-altitude aerostats could provide round-the-clock weapons stations at the edge of space, ready to be activated. If stationed in friendly or international airspace (12 nautical miles or more from a nation's coastline), these platforms would not violate international treaties.[20] Moreover, air-breathing high-altitude platforms will offer an entirely different set of weaponing possibilities, as their heavier payload generally allows for the carriage of more substantial ordnance. Ongoing projects suggest that some unmanned high-altitude hypersonic platforms under development are indeed intended as strike platforms, as evidenced by DARPA's (2025) interest in "technologies that allow weapons,

20 However, such deployments have worrying practical implications, as they could be perceived as provocative, exacerbating tensions and triggering conflict. For example, if armed with effective directed-energy weapons, high-altitude platforms could be deployed in proximity to enemy missile launch facilities, ready to fly in and shoot down ballistic missiles at the boost phase. Although this capability seems defensive, it could be seen as a first-strike enabler.

weapon bays and ejection systems to accommodate hypersonic separation from aircraft and flyout to the target" (p. 6). Such capabilities could revolutionize global strike operations and potentially alter the strategic balance.

High-altitude platforms could also serve as motherships, carrying and launching unmanned aerial vehicles (UAVs). This approach could significantly increase the operational range and endurance of unmanned aerial vehicles, especially of smaller models with limited onboard energy storage. Launching from above allows unmanned aerial vehicles to conserve energy that would otherwise be spent reaching the operational altitude. While these aircraft could be recovered and recharged for use in multiple sorties, this concept faces substantial challenges. The primary limitations are the limited power generation capabilities of high-altitude platforms and the difficulty of high-altitude docking, as the flight performance of smaller drones does not enable them to return to high altitudes. Consequently, a one-way launch-and-dispose operational model appears much more feasible. For example, the U.S. Army is considering using high-altitude balloons to carry and deploy drones tasked with disrupting or destroying enemy ground-based infrastructure, such as jammers or satellite control stations (Hitchens, 2024b). China is exploring a similar option of using high-altitude balloons (Trevithick, 2023) and is also working on airbreathing engine-powered fixed-wing motherships that could deploy up to 100 smaller drones (Nikolov, 2025).

When considering high-altitude platforms as either kinetic or non-kinetic weapons platforms, it is important to recognize that any offensive operation could potentially include high-altitude decoys. These decoys could mimic the signatures of more valuable assets, creating false targets to confuse enemy surveillance and targeting systems, saturating enemy defenses, depleting their resources, and disrupting their decision-making processes. The critical challenge would be to achieve an effective cost-benefit ratio. While the advantages of high-altitude decoys are obvious, their effectiveness would depend on achieving the target signature of the real assets. Theoretically, high-altitude platforms could also be used for other military missions, such as psychological warfare (e.g., leaflet campaigns), the covert insertion of special operations forces (as in high-altitude parachuting), logistics (e.g., covert airdrops of essential but light items) and attacks using weapons of mass destruction.

Driven by significant civilian interest (see GSMA, 2021; HAPS Alliance, 2024; Global Market Insights, 2025), high-altitude platforms also have substantial dual-use potential. Civilian applications are numerous and include providing widespread internet connectivity to underserved areas, conducting environmental research, and supporting disaster relief and recovery efforts. However, platforms operated by civilian entities could also be utilized for some military functions. Similar to space systems (see Ortega, 2023), high-altitude platforms can be envisioned as dual-use, service-oriented assets. Indeed, civilian high-altitude platforms are expected to offer capabilities that are attractive to the defense sector, facilitating their integration into civil defense or total defense policies. Unlike satellites, however, commercial high-altitude platforms will predominantly operate within national airspace, which is governed by principles of national sovereignty. This is in contrast to outer space, which is governed by a distinct body of international law emphasizing the peaceful use and non-appropriation of resources. Thus, the legal and regulatory frameworks addressing the dual-use nature of high-altitude platforms will differ from those applicable to space-based assets.

Ultimately, the adoption of a doctrine for the effective integration of high-altitude platforms into military operations will be crucial. The doctrine serves as a fundamental guide that codifies "how, for what, and why" resources are used (Angstrom & Widen, 2015, p. 5). Without it, effective integration of vastly different assets becomes nearly impossible. Given the current under-theorization of high-altitude platforms and high-altitude airspace in military thought (see, e.g., Staats, 2023), future doctrines must address challenges such as (re) defining mission types and operational roles, navigating legal complexities (including rules of engagement), establishing a clear command and control, ensuring seamless force integration, and detailing mission planning and airspace control. Doctrines must remain adaptable to evolving technologies to maximize the military utility of high-altitude platforms.

Aerospace defense – the protector

As technology advances, the threat posed by high-altitude platforms is growing. Current defense systems, designed primarily to defend against conventional aircraft or low-Earth-orbit satellites, are often ill-suited for the high-altitude domain. This creates a critical gap in defense capabilities that will need to be addressed by air defense, space defense, or, if unified under a single command, aerospace defense. Complicating matters further, defenders may face high-altitude platforms with very different kinematic characteristics and target signatures. This requires a multifaceted approach rather than a "one-system-fits-all" defense solution. To keep the discussion of aerospace defense concise and informative, we structured our analysis around key tactical battle management functions, including detection, identification, weapon allocation, and engagement, while excluding detailed consideration of potential dual-role capabilities of anti-satellite and anti-ballistic systems.[21]

Modern integrated air defense systems (IADS) fuse data from various sensors, with radars typically forming the core of detection and tracking. While plans are underway to deploy constellations of space-based and/or aerostat-based air surveillance systems (Newdick, 2024), surface-based radars are likely to remain the backbone of the sensor network for the foreseeable future. Adequate altitude coverage is as important as an instrumented range for

21 As Czajkowski (2024, p. 370) explains, most modern counter-space operations rely on non-destructive, easy-to-execute, and difficult-to-attribute modes of attack. Kinetic anti-satellite weapons, although potentially the most destructive, have not yet been widely deployed. Only four countries have tested dedicated kinetic anti-satellite weapons to date: the U.S., Russia, China, and India.

detecting threats at high altitudes. Modern military air surveillance radars typically specify detection up to 100,000 feet (around 30 km), which appears to be sufficient for most existing and near-future high-altitude platforms.

While this ceiling may be adequate at present, the development of a new generation of high-altitude platforms, including hypersonic ones, may require further technological improvements. However, some air surveillance radars are limited to elevation coverage of only 20 degrees (BAE Systems, 2020; Lockheed Martin, 2024). This means that such radars can only detect high-altitude platforms flying at an altitude of 100,000 feet at approximately 85 kilometers or more. Although overlapping coverage from adjacent radars can mitigate this limitation, it can also lead to target tracking complexities, particularly for smaller countries or isolated areas with only a few radar sites.

While target signatures can vary widely among different high-altitude platform designs, it is worth noting that engineers actively try to control detectability. For example, even solar-powered, battery-backed, heavier-than-air designs, while rather fragile, may support operations in non-permissive environments. Low-noise, low-temperature electric motors, coupled with a silent glide option, minimize acoustic and infrared signatures. Such aircraft also leave no condensation trails, making them difficult to detect visually. Furthermore, radar software may automatically filter them out if their ground speed is very low and even more so if they are built with a minimized radar cross-section (Spencer, 2019, pp. 40–42; Piancastelli et al., 2023; Renouard, 2024).

Once a potential intruder is detected, the next step, which is regularly carried out in peacetime, is to identify it visually before any further action is taken. This is primarily done by scrambling Quick Reaction Alert aircraft, typically jet fighters. These aircraft intercept the unidentified aircraft, establish visual contact, and report the bogey's type, nationality, registration, heading, speed, altitude, and any observed armament or unusual characteristics. This information is then relayed to command-and-control centers, allowing them to make decisions such as requesting further identification, issuing warnings, or escalating the response based on the assessed threat level (NATO, 2024). However, intercepting high-altitude platforms flying above the operational ceiling of jet fighters is a challenging task. While fighter pilots can attempt to gather information through visual observation from below or by doing a zoom climb, these methods are inherently limited.

The angle of observation is poor, and the difference in speed can be significant, making detailed identification difficult. If a zoom climb is performed, the observation window is brief, and the maneuver is potentially risky and fuel-intensive, especially when using afterburners. This may require the development of alternative tactics and, possibly, new technologies. One solution is to use electro-optical or infrared targeting systems (e.g., targeting pods), which can acquire, identify, and track targets at extended altitudes and ranges. Another option is the development of specialized high-altitude platforms that can reach and maintain position near the target. These platforms could provide persistent surveillance and detailed imagery, supplementing jet fighters and perhaps even serving as loitering (suicide) interceptors.

If a high-altitude platform were detected, identified, and assessed as a threat, countermeasures would need to be taken. Even in the case of a single intruder, the response may not be straightforward, particularly since there is no uniformly agreed-upon boundary between airspace and outer space and, therefore, no clear limit on the altitude at which a state has an enforceable right to act. This ambiguity could lead to escalation if a state misinterprets or overreacts to the presence of a high-altitude platform. Because there is no clearly defined boundary, action taken against a high-altitude platform could be perceived as a violation of another state's property.

Should the decision be made to engage the high-altitude platform, whether in peacetime, during a crisis, or in wartime, several considerations would come into play. The first of these is allocating the right weapons to engage the threat. While this may seem straightforward, it is a decision with complex implications. Simply put, the "right weapon" is not always the most advanced or the most powerful one. As Gangale (2018, pp. 384–386) notes in this context, since the late 1950s, advanced states have consistently maintained the ability to deny the use of airspace up to an altitude of approximately 30 kilometers.

Contrary to expectations, however, this attitude has not increased. Some early systems, such as the Nike Hercules, had a ceiling of around 45 kilometers, but only a few later developed surface-to-air missile systems exceeded 30 kilometers. This is primarily due to the decline of high-altitude reconnaissance missions, which have largely been replaced by satellite technology. Consequently, medium- to long-range surface-to-air and air-to-air missiles developed since the 1970s have typical ceilings of 24 to 30 kilometers, well above the operational ceilings of fighter aircraft and even most high-altitude platforms, but possibly barely at or even below the ceiling of next-generation high-altitude platforms. This means that air defense commanders would have to carefully weigh the cost-benefit ratio when allocating scarce and expensive high-altitude interceptors. Engaging with a weapon system with a significantly higher engagement ceiling than necessary could unnecessarily deplete limited interceptor stocks or reveal previously undisclosed capabilities. Failure to score a hit would not only waste munition but also provide the enemy with important intelligence about the system's performance envelope and possible weaknesses.

Furthermore, allocating an air defense system to engage a decoy would only exacerbate the problem. The engagement decision, therefore, requires a precise assessment of the circumstances, the target profile, and the available arsenal, along with its characteristics. To technologically address the challenge of engaging a large number of slow-moving high-altitude platforms, various economically viable weapon solutions are being considered, such as mini unmanned aerial vehicle interceptors (UAVI) powered by commercial microjet engines and armed with recoilless guns with airburst munitions (Piancastelli et al., 2023; Piancastelli et al., 2024).

Conclusions

The strategic advantage of air power is closely tied to technological innovation. Historically, controlling high-altitude airspace had limited military value due to technological constraints. Recent advances are rapidly altering this as high-altitude platforms approach widespread use. The high-altitude domain, with its unique physical and operational characteristics, is thus becoming a focal point in the development of military and civilian aircraft, with military high-altitude platforms poised to become a significant force multiplier. The primary advantages of using high-altitude platforms in military service appear to be operational flexibility, multipurpose utility, and cost-effectiveness. However, integrating them into effective force architecture will likely face initial challenges due to limited technological maturity, as well as issues related to doctrine and interoperability.

The technological landscape of military high-altitude platforms is diverse, including a variety of heavier-than-air and lighter-than-air designs in both manned and unmanned configurations. While manned fixed-wing designs remain relevant due to their speed, payload, and human-in-the-loop characteristics, unmanned platforms, particularly solar-powered, battery-backed fixed-wing aircraft, as well as airships and balloons, are increasingly favored due to their endurance and affordability. Engineered for endurance of up to a year and capable of carrying payloads of tens to hundreds of kilograms, these unmanned platforms could soon be utilized for a wide range of applications, including providing communications relays and surveillance, as well as electronic warfare and kinetic strikes, all while eliminating personnel exposure in non-permissive environments. In particular, the potential to deploy long-endurance high-altitude platforms as permanent weapon stations in international airspace poses a significant challenge to existing security paradigms. Coupled with the development of air-breathing hypersonic high-altitude platforms capable of delivering substantial ordnance, this could lead to a revolution in global strike operations, significantly altering the strategic balance. On the other hand, the need to counter a variety of very different high-altitude platforms, ranging from slow-moving balloons to hypersonic unmanned aerial vehicles, creates a complex problem for aerospace defense.

The proliferation of different high-altitude platforms is forcing a fundamental reassessment of established military doctrines and operational concepts. This involves not only technological adaptations but also a fundamental shift in strategic thinking, necessitating a reassessment of concepts such as sovereignty, airspace control, and deterrence, all of which are also promising areas for future research. Furthermore, the militarization of high-altitude airspace underscores the need for international dialogue and cooperation to prevent unintended escalation. The influx of diverse civil and military operators necessitates the establishment of a clear international regulatory framework, a goal that remains elusive. The current situation creates a vacuum in which competing national interests and technological advances could lead to instability and where the likelihood of misjudgment or misinterpretation of actions is high. However, developing a regulatory regime will require a concerted effort from various stakeholders, including militaries, governments, international organizations, industry, and academia. Practical cooperation between these various entities would be the best way to avert a potential high-altitude arms race.

Disclaimer

The author declares that there is no potential conflict of interest related to the article. Content generation tools by Artificial Intelligence were used for its preparation in the following way: Gemini 1.5, 2.0 and 2.5 (brainstorming, literature search, wording, syntax), DeepL (language editing, translations), InstaText (language editing).

Funding

This research was supported by Slovenian Research and Innovation Agency under grant P5-0206.

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