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Requirements of Modern Air Defence

Ivan Boban[1]

ABSTRACT

Modern air defence systems are facing accelerated development of ballistic, hypersonic, and unmanned threats that increasingly surpass the capabilities of traditional defensive technologies. This paper analyses the main challenges posed to air defence by ballistic missiles and various categories of unmanned aerial vehicles. Through case studies from Ukraine, Israel, and the Gulf War, it illustrates the limited effectiveness of existing defence systems, particularly against sophisticated threats. Special attention is given to the concepts of air defence saturation through drone swarms and the economic implications of such tactics. In the final section, technological solutions for future defence are presented, including a multi-layered orbital sensor architecture, directed energy weapons, and electronic warfare systems. The paper concludes that the future effectiveness of air defence will depend on the ability to integrate various technologies into flexible and economically sustainable defence systems.

KEYWORDS: *air defence, ballistic missiles, unmanned aerial vehicles, hypersonic weapons*

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[1] Ministry of Defence of the Republic of Croatia, ivan.boban10@gmail.com

Introduction

Modern air defence is confronted with dynamic and increasingly complex challenges driven by rapid technological advancement and evolving security threats. While traditional systems were primarily focused on neutralizing enemy aircraft, today's reality demands responses to two increasingly serious threats – ballistic missiles and unmanned aerial vehicles. Ballistic missiles, due to their high velocity, increasingly complex flight trajectories and potential to carry conventional or nuclear payloads, pose an existential risk to critical infrastructure and strategic targets. Their detection and interception are complicated by factors such as steep impact angles, reduced reaction time and the emergence of modern hypersonic missiles capable of manoeuvring, which further highlights the limitations of existing systems as evident in the war in Ukraine and Iranian attacks on Israel. On the other hand, unmanned aerial vehicles have redefined the concept of asymmetric warfare. From inexpensive commercial drones used for reconnaissance to swarms of autonomous unmanned aircraft capable of overwhelming targets through coordinated strikes, these platforms enable the mass saturation of airspace at minimal cost. Their widespread use from the war in Ukraine to conflicts in the Middle East exposes the vulnerabilities of traditional air defence systems.

The key challenges of modern air defence lie not only in the technical ability to detect and neutralize these threats but also in the integration of multi-layered systems, rapid response capabilities and adaptation to hybrid scenarios in which ballistic missiles and unmanned aerial vehicles are employed simultaneously. This paper analyses how global and national systems must transform their operational paradigms through the synergy of advanced technology and intelligence capacities for early warning. By examining real-world examples, the objective is to explore the possibilities and limitations of contemporary solutions and to highlight critical guidelines for future development.

Ballistic Missiles: Technical Characteristics and Challenges for Air Defence

Ballistic missiles represent one of the most complex challenges for modern air defence systems. Their trajectory is divided into three phases: boost (launch using a rocket booster), midcourse (free flight, often at high altitude or outside the atmosphere for longer range systems) and terminal (high speed descent through the atmosphere). Based on their range, ballistic missiles are commonly categorized as SRBM (300 km to 1000 km), MRBM (1000 km to 3000 km), IRBM (3000 km to 5500 km), and ICBM (over 5500 km) (Missile Defence Advocacy Alliance [MDAA], 2018). During the first two phases of flight, a missile, particularly an ICBM, can reach speeds exceeding Mach 20. In the terminal phase, due to the denser layers of the atmosphere, air resistance causes deceleration, but the missile still travels at supersonic or even hypersonic speeds. This dynamic significantly shortens the time available for defensive response, especially if detection occurs only in the terminal phase (Ali, 2021).

In addition to speed, one of the key challenges lies in flight geometry. Ballistic missiles such as the 9M723 Iskander employ a steep impact angle of nearly 90° in the terminal phase, thereby entering the radar dead cone, a zone where radars are unable to track the target due to limitations in the elevation angle of the antenna. This effectively allows the missile to approach the target undetected in the final phase (Dziczkaniec, Noga, Matysek, Uminski, 2024). Modern ballistic missiles do not follow classical ballistic trajectories, instead they perform manoeuvres during flight. For example, the aforementioned 9M723 Iskander is capable of manoeuvring at forces exceeding 30 G (Center for Strategic and International Studies [CSIS], 2024a), which is often beyond the capabilities of conventional interceptors. Furthermore, it can alter its trajectory by up to 70 km horizontally (Dziczkaniec et al., 2024), complicating interception during the terminal phase. Systems such as the GMD (Ground-based Midcourse Defence) lack sufficient flexibility to counter such threats, as they mostly rely on predictable trajectories (Ali, 2021). In addition, some ballistic missiles release decoys during flight creating a cloud of several dozen false targets that saturate radar systems and mimic the radar signatures of actual warheads (Li, Jin, Li, 2023).

Hypersonic Missiles: A Technological Shift in Modern Warfare

The definition of hypersonic missiles is still not unambiguously established. A speed exceeding Mach 5 is considered hypersonic and by that standard, any missile surpassing this velocity could be classified as a hypersonic missile. In that case, hypersonic projectiles would not currently represent a significant technological shift in modern warfare, given that virtually all ballistic missiles reach hypersonic speeds in their initial phases, primarily due to their high apogees and the reduced air resistance at those altitudes. The characteristic that sets modern hypersonic projectiles apart from others is their ability to manoeuvre during flight in order to evade enemy air defence and to maintain hypersonic speed in the terminal phase.

According to their flight profile, modern hypersonic missiles can be divided into several categories.

- Hypersonic Glide Vehicle (HGV): these are primarily launched using intercontinental ballistic missiles (ICBMs), which lift them into the upper layers of the atmosphere. After the launch phase, the HGV separates and enters a glide phase, using its aerodynamic shape to manoeuvre. Due to their high speed and ability to make sudden changes in direction, HGVs complicate detection and interception by enemy air defence systems. Such systems are most often strategic in nature and their primary purpose is the delivery of a nuclear warhead. An example of such system is the Russian Avangard which is launched using the intercontinental missile RS-28 Sarmat. After separating from the carrier rocket, the HGV itself has a range of about 6000 km and flies at a speed of Mach 20+, changing altitude and direction to avoid interception (Center for Strategic and International Studies [CSIS], 2024b). Although hypersonic glide vehicles are often associated with intercontinental ballistic missiles and nuclear use there are examples that deviate from this pattern. Chinese DF-17 system is launched from mobile medium-range platforms and has been developed primarily for conventional use (Center for Strategic and International Studies [CSIS], 2024c), thereby applying the HGV concept in regional, non-nuclear scenarios.
- Hypersonic air-launched ballistic missile: a type of missile in which the initial phase of flight is achieved through its own propulsion, while the later

part follows a quasi-ballistic trajectory. This trajectory is characterized by a relatively low flight profile or a flight path similar to that of traditional ballistic missiles with the added capability of unpredictable manoeuvring. The Kh-47M2 Kinzhal is a true example of a hypersonic air-launched ballistic missile. This type of missile has been used relatively intensively in the war in Ukraine, with its primary launch platforms being the MiG-31K and TU-22M3 (Center for Strategic and International Studies [CSIS], 2024d), while in the near future launches will likely also be possible from SU-34 aircraft (TASS, 2023a). During its quasi-ballistic flight it reaches a maximum speed of over Mach 10, while in its final phase during its descent toward the target its speed decreases due to increased air density and due to the missile's own manoeuvring, which results in a loss of kinetic energy. The Kinzhal can be considered as an air launched version of Iskander-M ballistic missile system, from which it evolved.

- Hypersonic ballistic missile: they are launched from ground-based systems using powerful propulsion systems and after the completion of the boost phase, they continue to move in free fall along a ballistic trajectory. The main characteristics include long range, high kinetic energy upon re-entry into the atmosphere and among more modern systems the capability of manoeuvring during terminal phase. Examples of such systems include the Iranian Fattah-1 and the Russian Oreshnik.
- Hypersonic cruise missile: cruise missiles use a continuously operating engine and sophisticated navigation systems to maintain a stable, controlled flight at relatively low altitudes. Their aerodynamic profile allows for high precision and flexibility in route selection and flying at low altitudes further complicates radar detection. Currently, the only operational example of this type of hypersonic missile is the 3M22 Zircon.

Effectiveness of the Patriot System Against Scud Ballistic Missiles During the Gulf War

According to Postol (1991), during the Gulf War, Patriot PAC-2 system was presented as a revolutionary defence against Iraqi Scud missiles. Initial claims by the U.S. military and the manufacturer Raytheon indicated a 96% interception success rate. However, subsequent analyses particularly by Israeli experts, revealed a significantly different picture. For example, in Israel, 17 Scuds were reported as intercepted, but less than 20% of the warheads were actually destroyed. The cause of this discrepancy lay in the definition of interception success. The system registered a successful hit whenever a missile detonated near the target, even if the warhead was not destroyed. This meant that impacts on fuel tanks or debris were also included in the statistics, resulting in a distorted perception of the system's effectiveness.

The Iraqi Scuds were unstable and tended to disintegrate at altitudes between 15 and 20 km. This flaw became a challenge for the Patriot system. It identified multiple fragments (fuel tanks or fuselage sections) and lost track of the actual target, the warhead. Patriot's radar automatically targeted larger fragments, while the smaller and more aerodynamic warhead often passed undetected. During attacks on Israel, the system misidentified debris as threats, resulting in the launch of 28 missiles at only 5 Scuds, and on the night of January 25, six Patriot batteries in Tel Aviv launched 27 missiles against 7 Scuds (Postol, 1991). In addition, Patriot missiles were optimized for slower targets, which led to delayed detonations when engaging the faster Scuds.

As a result of all these issues, the development of a new variant of the Patriot system followed designated PAC-3, which represents a technological evolution of the PAC-2 version. The new version is optimized specifically for intercepting ballistic threats, integrating more advanced sensors and hit-to-kill technology in an effort to address the challenges posed by modern ballistic missiles.

War in Ukraine

The war in Ukraine represents the first major conventional conflict after a long period of relative peace, revealing numerous strengths and weaknesses of certain systems and methods of warfare including aspects of air defence. In this section, we analyse the effectiveness of Ukrainian air defence in intercepting ballistic missiles, based on available statistical data published on August 20, 2024. It is important to note that the data is based on an official release by the Ukrainian Ministry of Defence. As Ukraine remains in an active conflict, the interpretation and relevance of this data must be approached with a certain degree of caution.

Table 1. Interception rate of Russian missiles in Ukraine

Missile	Launched	Intercepted	Interception rate
S-300/S-400	3008	19	0.6%
KH-555/101	1846	1441	78.1%
KH-25/29/31/35/58/59/69	1547	343	22.2%
Iskander-M/KN-23	1300	56	4.3%
Kalibr	894	443	49.6%
KH-22/KH-32	362	2	0.6%
P-800 Onyx	211	12	5.7%
Iskander-K	202	76	37.6%
KH-47M2	111	28	25.2%
Tockha-U	68	6	8.8%
KH-35	15	1	6.7%
3M22 Zircon	6	2	33.3%

Source: Ukrainian Ministry of Defence; Defence Express, 2024

Table 2. Interception rate of Russian missiles by type

Type	Launched	Intercepted	Interception rate
Ballistic missile	4849	111	2.3%
Cruise missile	4721	2318	49.1%

Source: Table 1.

Analysis of the presented tables clearly indicates a significant disparity in the effectiveness of Ukrainian air defence when intercepting ballistic versus cruise missiles. According to official Ukrainian data, by mid-August 2024, Russia had launched nearly an equal number of ballistic and cruise missiles. However, the interception rate for cruise missiles was 21 times higher than that achieved against ballistic threats. These results are not unexpected given frequent statements by senior Ukrainian officials who emphasize that ballistic targets pose a considerable challenge for their systems and that Ukrainian air defence cannot consistently or effectively respond to such attacks (TASS, 2023b; Meduza, 2022).

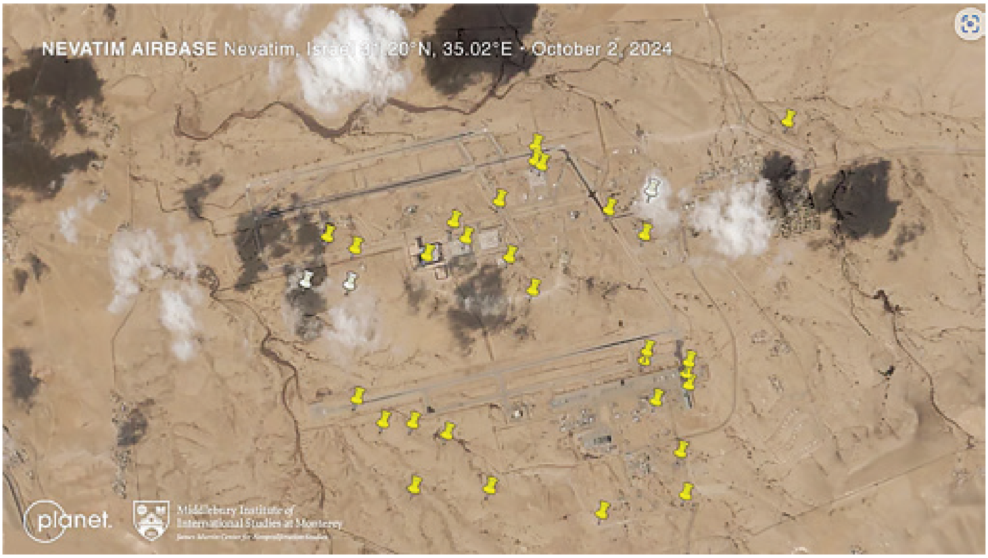
Particularly noteworthy is the comparison of interception effectiveness between the KH-22/32 missiles and the hypersonic KH-47M2 Kinzhal. Both missiles are air-launched and have a similar quasi-ballistic flight profile, but Kinzhal possesses twice the maximum speed, more advanced guidance systems and the capability for intensive manoeuvring in the terminal phase of flight. Therefore, it is surprising that Ukrainian data shows a significantly higher interception rate for the Kinzhal compared to the KH-22/32. These figures contradict statements by the spokesperson of the Ukrainian Air Force, Yuri Ignat, who has stressed that the Kinzhal is a significantly more challenging target than the KH-22 (Frontier India, 2023). A possible explanation is that Ukrainian forces prioritize targeting the Kinzhal and according to a report by the Kiel Institute of Economy, they often launch between 16 and 32 Patriot missiles to intercept a single Kinzhal (Wolff, Burilkov, Bushnell, Kharitonov, 2024). Considering the cost of approximately 4 million dollars per interceptor and the limited annual production of only 500 missiles, such an approach is not sustainable in the long term (Kubo & Kelly, 2024). Another possible explanation is offered by former Russian Defence Minister Sergei Shoigu, who stated that Ukrainian forces often misidentify launched missiles resulting in reports of Kinzhal interceptions that did not actually occur (Sputnik News, 2023).

Nonetheless, regardless of these potential uncertainties in identifying the specific type of missile, presented data clearly illustrates how all forms of ballistic threats remain a substantial challenge for modern air defence systems.

Israel and Iran

On October 1, 2024, Iran launched approximately 200 ballistic missiles, primarily medium-range Shahab-3s and first-generation hypersonic missiles at targets in Israel. This mass attack represented a serious test for Israel's multi-layered air defence system, which includes Iron Dome, David's Sling, Arrow-2, Arrow-3, and several U.S. Navy destroyers equipped with the AEGIS system (Youvan, 2024). In the context of a mass strike, radar systems can become overwhelmed by the sheer number of simultaneous targets, leading to radar saturation and delays in the prioritization and launching of interceptors (Ibid.). The hypersonic variants further complicate the task with their manoeu-

Figure 1. Identified Iranian missile impacts at Nevatim Airbase



Source: Brumfiel (2024)

vres in the terminal phase of flight, which accordingly increases the likelihood of breaching defences. While Iranian reports claimed a very high success rate, Israeli officials stated an equally high interception rate. Nevertheless, analysis of satellite imagery and videos recorded during the attack clearly confirms that a significant number of missiles penetrated Israel's air defence. For instance, no fewer than 32 impacts were identified at the Nevatim Airbase, which houses Israeli F-35 aircraft (Brumfiel, 2024).

The subsequent Twelve-Day War in June 2025 provided another test of layered air and missile defence over Israel. According to some sources, Iran fired 574 ballistic missiles and Israeli officials claimed that only 49 missiles impacted on populated areas, Israeli infrastructure and bases (Cicurel, 2025). Implying interception rates above 90%. However, the widely cited figure that US and Israeli forces intercepted 273 missiles Iran launched refers to the 322 missiles they chose to engage yielding an 85% success rate, whereas measured against all launches the share of missiles physically destroyed in flight is closer to one half, with the remainder either malfunctioning or landing in open areas (Ibid.). This methodological choice, based on Israeli reported data, means that interception figures are difficult to independently verify and could possibly overstate performance of the defensive systems.

Israel’s initial surprise strikes on Iranian nuclear and missile infrastructure sharply reduced Tehran’s ability to mount a single, concentrated retaliatory mass strike, easing part of the burden on the defensive layer. The defensive “umbrella” combined Iron Dome, David’s Sling and Arrow-2/3 with forward-deployed US Patriot and THAAD batteries and Aegis destroyers equipped with SM-3, augmented by limited French and Arab contributions (Ibid.). Even so, US and Israeli officials concede that defending against roughly 500 Iranian missiles consumed around a quarter of US THAAD and SM-3 stocks and hundreds of high-end Israeli interceptors in less than two weeks, leaving Israel running low on anti-ballistic missiles (Lair, 2025).

These attacks confirm that, although the Israeli air defence systems are among the most sophisticated in the world and cover a relatively limited geographical area, ballistic and hypersonic threats continue to pose undeniable challenges. It is essential to continue the development of new technologies and mechanisms to ensure that air defence remains one step ahead of the rapid advancement of ballistic missile capabilities.

Future Solutions in Countering Ballistic Threats

In the context of growing threat posed by advanced ballistic and hypersonic missiles the demands of modern air defence are increasingly shifting toward the development of a multi-layered, integrated and highly responsive architecture of sensors and interceptors. One of the most significant proposals involves the establishment of an orbital network of sensors deployed across various orbits, from low Earth orbit (LEO), through medium Earth orbit (MEO), to geostationary (GEO) and highly elliptical orbits (HEO). Such a layered architecture would provide complementary global coverage and ensure system resilience in the event of an attack on a specific orbital layer (Karako & Dahlgren, 2023a).

A key technological component of this future defence is the development of advanced space-based sensors capable of continuous tracking of high-speed and manoeuvrable targets including the provision of so-called fire-control quality tracks for guiding interceptors. Particularly noteworthy is the HBTSS (Hypersonic and Ballistic Tracking Space Sensor) program which aims to enable precise and uninterrupted tracking of hypersonic and ballistic threats in real time (Karako & Dahlgren, 2023b). Sensors on high-altitude unmanned aerial vehicles provide an additional layer of early warning and tracking, especially useful in regional scenarios where orbital coverage is not yet sufficient (Karako & Dahlgren, 2023a).

In terms of interceptors, new models featuring multi-object kill vehicles (MOKVs) and flexible propulsion configurations are being proposed, expanding engagement space and enabling sequential multiple intercepts ("shoot-look-shoot") (Karako, Williams, Rumbaugh, 2020). Particular focus is also being placed on the possibility of interception during the boost phase, while the projectile is still ascending, considering concepts such as directed energy weapons, space-based interceptors, and forward-deployed platforms (Karako, Williams, Rumbaugh, 2020).

Although these proposed solutions are becoming increasingly technologically feasible, it is important to emphasize that most remain largely in the conceptual and experimental stages. Implementing such an architecture brings with it a series of challenges, including the extreme complexity of managing a sensor and interceptor network, the need for a high level of interoperability and very high financial costs (Karako & Dahlgren, 2023a). Additionally, operational integration among different military branches and allies, as well as institutional coordination, represent further obstacles that must be addressed in order for the vision of an effective and adaptable defence system to be realized. At the same time, the majority of these concepts are primarily focused on countering high-end strategic ballistic threats. Their extreme unit cost and likely production constraints suggest that they will be reserved for a limited set of critical targets and cannot provide an answer to scenarios in which an adversary can launch hundreds or even thousands of SRBMs.

Unmanned Aerial Vehicles as a Challenge to Modern Air Defence Systems

Unmanned aerial vehicles (UAVs) have rapidly evolved into a key component of modern warfare. Their mass availability and technological advancement represent a significant shift in the threat paradigm faced by air defence systems. Unlike traditional combat aircraft or missiles, various types of drones can be produced cheaply and in large numbers allowing even less technologically advanced actors to pose a serious threat to highly sophisticated and expensive air defence systems. The use of UAVs on the battlefield exemplifies a classic asymmetric threat. One of the main reasons is the stark cost disparity, a relatively inexpensive drone can challenge and potentially neutralize military equipment that is exponentially more costly. For example, Geran-2 (Russian modified version of the Iranian Shahed-136), a loitering munition or "kamikaze" drone extensively used by Russia in the war in Ukraine, has been estimated by some sources to cost only around USD 35,000 per unit (Hollenbeck, Altaf, Avila, Ramirez, Sharma, & Jensen, 2025). However, given the increasingly expanded production capacities associated with Geran-2 drones (Luxmoore & Lytvynenko, 2025), actual cost per drone may be even lower. Their low cost enables the frequent launch of mass swarms, which both depletes and overwhelms air defence systems. On the other hand, interceptors such as modern surface-to-air missiles are significantly more expensive. For instance, guided missiles like the American Patriot can cost several million dollars per unit (Evstifeev, 2024). UAVs have thus emerged as a weapon of attrition, forcing defensive forces to either expend costly munitions or risk drone penetration to the target.

Typology of Unmanned Systems

Unmanned aerial vehicles encompass a wide range of systems from miniature quadcopters to large strategic UAVs. For the sake of simplicity they can be classified into three basic categories.

- Heavy UAVs: larger long-range, high-altitude UAVs capable of carrying substantial payloads. This category includes so-called MALE/HALE UAVs (Medium/High Altitude Long Endurance) such as the American MQ-9 Reaper and RQ-4 Global Hawk or the Turkish Bayraktar TB2. These systems are designed for reconnaissance and precision strikes using guided bombs or missiles often operating at significant distances from the operator.
- OWA (one-way attack) or Kamikaze drones: one-way attack unmanned aerial vehicles that carry a warhead and crash into the target, destroying themselves on impact. These so-called loitering munitions combine characteristics of drones and missiles. Examples include the Iranian Shahed-136

(Geran-2) or smaller tactical munitions such as the Russian Lancet drone or the American Switchblade. Their role is to carry out single-use attacks and they serve as cheaper, albeit less capable, alternatives to cruise missiles and guided bombs.

- FPV (first person view) drones: mini and micro drones piloted by an operator via real-time video feed. These are most often commercial quadcopters equipped with improvised explosives. They are used for close-range tactical strikes with high precision, though they have limited range and battery life.

This classification is simplified and in practice there exists a continuum of UAV sizes and roles. Nevertheless, the categories outlined above help distinguish the primary functions and challenges each type poses to air defence systems.

Limitations of Heavy UAVs

Large or heavy UAVs were originally developed as an extension of air power capable of loitering over the battlefield for extended periods while conducting surveillance or precision strikes with guided munitions. However, experiences from recent conflicts have revealed significant shortcomings in this class of UAVs. Firstly, these are highly expensive systems. For example, a single Reaper with associated equipment and armaments is valued at over USD 50 million (U.S. Air Force, 2020), while even smaller platforms like the TB2 cost several million dollars. Secondly, the production of such complex platforms is limited as they require advanced electronics, sensors, and trained operators, which means they cannot be quickly replaced in the event of losses. Their principal vulnerability lies in contested airspace dominated by enemy air defences. If an adversary possesses a layered air defence system, a heavy UAV becomes an easy target due to its size, limited manoeuvrability and relatively low speed. In the early phase of the war in Ukraine in 2022, Bayraktar TB2 drones achieved some success against armoured columns. However, as Russian air defence established a multi-layered protective network, including missile systems and electronic warfare capabilities, TB2 losses increased sharply (Shoaib, 2023) and according to Russian sources, total number of Baryaktar TB2 drones shot down surpassed 100 units (Leonkov, 2025). Already by mid-2022, Ukrainian forces had begun using them less frequently due to the higher risk of shoot downs and their declining operational effectiveness. A similar fate befell large American UAV near sophisticated air defences. In 2019, Iran shot down a U.S. Global Hawk valued at around USD 176 million (Law, 2019), demonstrating that even the most advanced unmanned aircraft are not immune to well-organized defence systems. Heavy UAVs are particularly vulnerable to enemy electronic warfare (EW) as their communication links with ground control stations can be jammed or disrupted. In a conflict between near-peer adversaries, heavy UAVs no longer enjoy the strategic freedom they had in low-intensity conflicts. Given the high costs and loss rates their role becomes questionable. Their operational usefulness is limited to environments where enemy air defence and aviation are inactive, making them unsuitable for highly contested airspace. In such scenarios, the focus shifts toward more numerous, lower-value platforms that can be more easily sacrificed.

OWA UAVs and Air Defence Saturation

One-way attack drones (OWA), also commonly referred to as kamikaze or suicide drones, have emerged as an effective and economical substitute for cruise missiles in numerous scenarios. These drones loiter in the vicinity of a target before diving and detonating like a guided missile. Their growing popularity stems from several factors such as low cost, long range and tactical flexibility. In recent times, the most well-known example of this type is the Geran-2, which has a range of approximately 2,000 km and carries a warhead of about 40 kilograms. Statistics show that from September to December 2024, Russia launched more attack drones at Ukraine than in the previous 23 months combined (Hollenbeck et al., 2025), and the trend of mass drone launches has continued into 2025. Geran-2 drones are used both for attacking targets and for saturating air defence systems. Their sheer numbers flood radar screens and force defending forces to expend valuable missiles on relatively inexpensive threats (Ibid.). Kamikaze drones are therefore deliberately used to exhaust air defence systems and even when shot down in large numbers the defence pays a high price through the depletion of interceptors and reduction of stockpiles.

Russian doctrine in the war in Ukraine heavily relies on this attrition strategy. Typically, a wave of low-cost unmanned aerial vehicles (such as the Geran-2) is first launched toward infrastructure targets, forcing Ukrainian air defence to activate its missile and anti-air artillery systems across multiple locations simultaneously. Once defences are exposed and partially depleted dealing with drones, a second wave of more precise and expensive munitions (ballistic and/or cruise missiles) is launched against selected targets. Through this “swarm–then–strike” tactic, the attacker maximally exploits the advantages of low-cost drones. Ultimately, even if only a small percentage penetrates the defence and hits its target, the attack is cost-effective as the resulting damage outweighs the expense of the strike.

FPV Drones: Precision and Quantity

FPV drones represent a micro-level unmanned threat but with a disproportionately large effect at the tactical level. These are typically small quadcopters operated by a user through a first-person video feed. They are equipped with improvised explosives such as grenades, shaped charges, or similar lethal payloads and are used for precise short-range attacks, usually within a few kilometres of the operator. Their main advantage lies in their exceptional precision thanks to real-time video guidance, the operator can direct the FPV drone precisely to a target’s weak point.

However, FPV drones also have clear limitations. Their reliance on radio signals for control and video transmission makes them vulnerable to electronic jamming. With sufficiently powerful electronic warfare systems signal can be easily disrupted, causing the drone to lose control and crash before reaching the target (Pultarova, 2025). One proposed solution is the use of fibre optic FPV drones which are immune to electronic warfare systems. However, this introduces new constraints, particularly in terms of mobility. Additionally, the range of FPV drones is limited due to the need to maintain signal integrity, it rarely exceeds a few kilometres and battery life typically supports only 10 to 15 minutes of flight. In the case of drones using fibre optics, range is determined by the length of the cable. This means FPV drones are applicable primarily at the tactical frontline level to support units in direct contact with the enemy, but not for deep strikes into enemy rear areas.

Despite these limitations, FPV drones have proven extremely effective, as quantity becomes a quality of its own. A drone’s frame, motor, and electronics can be procured on the commercial market for a few hundred to a few thousand dollars. Operator training is quick and soldiers can be made combat-ready to use FPV drones in a short period. As a result, warring sides are capable of fielding hundreds or even thousands of FPV drones on the battlefield simultaneously. In 2024, for example, Ukraine launched a procurement program for 10,000 advanced drones equipped with AI components with the specific goal of saturating the battlefield with these systems (Bondar, 2025). According to some estimates, total domestic production of small drones in Ukraine reached into the millions annually (Ibid.). A similar trend is seen in Russia, which is mass-converting commercial drones for FPV attacks and training large numbers of operators at the small-unit level.

The key advantage, therefore, becomes the sheer number of available drones. Even if air defence systems jam or shoot down a large portion of them, a certain percentage inevitably penetrates the defences and delivers its strike. FPV drones have established themselves as precise, expendable assets that significantly increase infantry firepower, while their quantity further strains defensive systems at all levels.

Future Counter UAV Defence

In light of the aforementioned threats, modern air defence systems must adapt to a new reality. Relying solely on kinetic interceptors has proven both insufficient and economically unsustainable in the face of mass drone swarm attacks. As Evstifeev (2024) notes, when confronted with swarms of micro and mini drones, air defence systems quickly become overwhelmed, expensive missiles are rapidly depleted and neither in quantity nor cost can all drones be intercepted by missile systems alone. A transition toward a layered counter-drone defence combining diverse technologies is therefore essential.

– Electronic Warfare (EW): jamming and takeover systems already represent the first line of defence. Strong jammers of GPS signals and control frequencies can cause attacking drones to veer off course or crash. Additionally, systems for cyber takeover of UAVs are being developed, which could redirect enemy drones, potentially even turning them against their original operators. In the current war, there have already been instances where electronic measures have downed more drones than conventional kinetic systems. EW offers a relatively low-cost defence as a single jamming system can cover a wide area and simultaneously affect multiple drones.

- Directed energy systems: they are increasingly emerging as a promising solution for close-range air defence. Lasers can physically disable UAVs instantly and at minimal cost with each "shot" amounting to little more than the consumption of electrical energy. The U.S. and Israel are actively testing prototypes. For example, the American mobile DE M-SHORAD system (mounted on a Stryker armoured vehicle) combines a 50-kW laser with an automatic cannon and missiles in a unified counter-drone turret (Ibid.). Although laser systems are dependent on atmospheric conditions and are therefore less effective at longer ranges it is likely that laser weapons will gradually assume the role of close-range defenders of key assets against drone attacks, once technical challenges related to cooling and power supply are resolved.
- Active countermeasures and new interceptors: in addition to lasers, there is growing demand for more affordable kinetic interceptors specifically adapted to unmanned aerial threats. One solution lies in short-range missile systems such as 70 mm laser-guided rockets APKWS II, which cost around USD 35,000 per unit. This is significantly less than multimillion dollar Patriot missiles, yet they can effectively destroy drones within a few kilometres of range (Ibid.). A similar approach is being pursued by Russian forces with the development of a specialized variant of the Pantsir air defence system designed for counter-drone operations. The new version, Pantsir SMD-E, is equipped with 48 smaller and more cost-effective TKB-1055 very short-range missiles, instead of the standard 12 type 57E-6 missiles (Trevithick, 2024). Additionally, traditional air defence artillery is being enhanced with smart munitions. Programmable 30–57 mm rounds are under development capable of air-bursting near the UAV and releasing a cloud of ball bearings to increase the likelihood of striking small targets. Systems such as the German Oerlikon Skynex or the American M230LF mounted on the Stryker allow one smart projectile to replace a dozen conventional ones offering a clear economic advantage (Evstifeev, 2024). Also, various types of interceptor drones are also being developed. These are small unmanned aerial "hunters" that autonomously track enemy drones and neutralize them through collision or net deployment. Speaking of sensors, an additional line of development is the use of distributed acoustic detection networks. Ukraine's Sky Fortress system illustrates this approach through a nationwide grid of several thousand low-cost passive acoustic sensors that detect the characteristic sound of Geran OWA UAVs

and provide targeting data to mobile gun and MANPADS teams (Decker, 2024).

In the future, effective drone defence will likely depend on the integration of all these elements into a layered system. The key is finding a cost-effective approach. Expensive interceptors should be reserved for larger and more dangerous targets, such as ballistic and cruise missiles or combat aircraft, while swarms of small drones should be countered through a mix of electronic warfare, laser weapons, and lower-cost kinetic means. It is clear that the era of exclusively kinetic air defence is coming to an end and a new era of hybrid interception systems is emerging where rapid algorithms, directed energy and smart munitions confront swarms of increasingly intelligent and numerous unmanned aerial vehicles.

NATO Integrated Air and Missile Defence in the Missile Age

NATO already fields a sophisticated form of integrated, multi-layered air defence in the shape of the NATO Integrated Air and Missile Defence System (NATINAMDS). NATINAMDS is a 24/7 network of national and NATO sensors, command and control nodes and weapon systems under SACEUR’s authority, designed to provide a shield against aerodynamic and ballistic threats across the Alliance’s airspace (NATO, 2025). In terms of sensing, data fusion and C2, the system is highly mature consisting of airborne early warning, space and ground-based radars and standardised Air C2 architectures; all this gives NATO forces excellent situational awareness and rapid information sharing. NATINAMDS also connects air-based air defence (ABAD) with a layered ground-based air defence (GBAD) architecture that spans very-short and short-range systems (e.g. Stinger, Mistral, Gepard-type platforms), medium-range systems such as NASAMS or IRIS-T SLM and long-range surface-based air and missile defence assets like Patriot and SAMP/T complemented by Aegis Ashore sites and Aegis equipped surface combatants providing upper tier ballistic missile defence (NATO, 2024).

However, much of this upper layer remains fundamentally optimised for a relatively small number of high-end strategic ballistic threats, rather than for sustained campaigns involving large salvos of modern SRBMs and massed

OWA UAVs. The Aegis BMD architecture, for example, relies heavily on exoatmospheric, hit to kill SM-3 interceptors designed to defeat medium and intermediate range ballistic missiles in their midcourse phase, with smaller numbers of endoatmospheric SM-6 interceptors available for terminal engagements. Depressed, quasi-ballistic trajectories such as those flown by Russian Iskander-M or North Korean KN-23 missiles spend most of the time in the lower atmosphere and therefore are not best suited for interception by exoatmospheric systems. In addition, the annual production of high end exoatmospheric interceptors is extremely limited. Grieco, Slingbaum and Walker (2024) note that two US Navy ships expended roughly a year's worth of SM-3 production in a single day while intercepting Iranian ballistic missiles bound for Israel, underlining that these weapons are inherently strategic assets that cannot sustain prolonged high-intensity use.

Fixed Aegis Ashore sites, while offering persistent coverage, are also static and therefore increasingly vulnerable in an era where cheap FPV and long-range autonomous drones can be used for covert sabotage of high value targets deep in the rear. Ukraine's recent Operation Spiderweb, which destroyed or damaged dozens of Russian long-range bombers at multiple air bases using truck launched drones operating from Russian territory, illustrates how previously safe strategic assets and infrastructure can be systematically hunted by low-cost unmanned systems once their location is known. Similar vulnerabilities would apply to any inadequately protected, above-ground missile defence site. Beyond these structural issues, many other GBAD systems within NATINAMDS have only limited or uncertain effectiveness against the most modern manoeuvring ballistic threats and almost all suffer from insufficient and constrained production capacity, making it doubtful that they could sustain interception rates required in a prolonged peer conflict.

Medium-Term Solutions: Rebuilding Magazine Depth and Industrial Capacity

The emerging environment can be increasingly characterised as a "missile age" or an era of high precision aerial warfare, in which the opening weeks of a conflict are dominated by the mass employment of ballistic and cruise missiles, UAVs and loitering munitions. Grieco's (2024) analysis of Chinese missile threats to US air bases in the Indo-Pacific is illustrative. Under conservative assumptions, PLARF runway attacks would exhaust US and Japanese missile defence interceptors within the first 24 hours, closing runways to fighter operations for roughly 12 days in Japan and about two days in Guam and other Pacific locations, while closing tanker operations for more than a month in Japan. Even doubling the number of Patriot and THAAD interceptors in theatre still leaves the defender running out of missiles within as little as 56 hours, with only modest reductions in runway closure times. Grieco further estimates that the current US stockpile of around 1,200 Patriot interceptors and roughly 500 THAAD interceptors would likely be expended within a few days in a high-intensity campaign, highlighting a structural imbalance between offensive missile inventories and defensive magazines.

NATO's own IAMD policy recognises the need to strengthen "surveillance, interceptors and command and control" and explicitly links this to the broader defence planning and industrial base agenda (NATO, 2025). Yet in the medium term, there is no quick solution to the magazine depth problem. Significantly increasing production of complex SAM and BMD interceptors requires major investments, workforce expansion and the partial reorientation of defence and industrial capacity away from post-Cold War paradigms focused on expeditionary counter-insurgency operations. Present production volumes, and corresponding stockpiles, remain largely calibrated to limited contingencies, not to months long, high-intensity peer conflict. Grieco's findings therefore strongly suggest that, at least for the coming years, neither NATO nor the United States can simply "buy" their way out of the problem of massed missile salvos through more of the same high-end, expensive interceptors. Any serious medium-term solution must thus prioritise rebuilding interceptor inventories, expanding manufacturing capacity and rebalancing cost-exchange ratios, while accepting that this will necessarily be a multi-year effort rather than something that can be solved in a matter of months.

Short-Term Solutions: Dispersal, Hardening and Tactical Reconfiguration

Given these constraints, a number of measures can and should be pursued in the near term using existing forces and infrastructure. First, Cold War habits of concentrating large numbers of aircraft, GBAD assets and personnel on a limited number of major bases and hubs must be abandoned. Offensive long-range strike capabilities have matured to the point that no realistic level of air and missile defence can guarantee very high interception rates over a prolonged period. Survivability therefore depends on dispersal and redundancy. Grieco's modelling shows that dispersing US aircraft and personnel across JSDF bases and selected civilian airfields, combined with faster runway repair techniques, can reduce fighter and tanker closure times by up to 60–70%, even though it cannot eliminate disruption entirely. For NATO, this logic implies a systematic effort to pre-plan and resource dispersal to military and, where politically feasible, civilian airfields, along with hardened and redundant logistics nodes, fuel and munitions storage and C2 facilities.

Second, wherever practicable, critical functions should be moved underground or into heavily hardened structures before a crisis, including command posts, key communication nodes, maintenance facilities and high-value stocks of interceptors and spare parts. Modern precision weapons, including ballistic missiles and OWA UAV swarms, pose a particular danger to exposed, above-ground infrastructure in the operational and even strategical rear.

Third, at the tactical level, GBAD units themselves require much more robust close-in protection against OWA UAVs and FPV drones. High-end SAM launchers, radars and command vehicles must be surrounded by "guardian" elements equipped with MANPADS, short range anti-aircraft guns, mobile EW teams, counter-FPV teams and small, networked mobile air-defence groups. Finally, in conditions of saturation, the burden on C2 and fire control becomes extreme. Enhancing training and drill within existing NATO Air C2 structures and gradually integrating new and developing AI-based tools into Threat Evaluation and Weapon Assignment (TEWA) processes, offers one of the few realistic ways to accelerate decision making. In combination, such short-term doctrinal, organisational and infrastructure adjustments can significantly increase the resilience and sustainability against the types of high-volume missile and UAV campaigns that current stockpiles of interceptors alone are unlikely to defeat.

Conclusion

The analysis of modern air defence reveals an increasingly evident divergence between the technological capabilities of offensive systems and the defensive systems attempting to counter them. The evolution of ballistic and hypersonic missiles significantly reduces the effectiveness of conventional air defence solutions. Simultaneously, the widespread and low-cost use of unmanned aerial vehicles confirms the transformation of the battlespace toward a reality in which quantity often outweighs quality. In this context, the requirements for modernizing air defence are no longer limited to the technical refinement of interceptors, but rather demand the development of integrated, multi-layered architectures that combine kinetic, electronic, and directed energy means. A multi-layered, integrated and responsive defensive architecture leveraging advanced sensors, artificial intelligence, and new interceptor technologies is becoming a necessity rather than an option. There is a particularly pressing need for the implementation of orbital and aerial sensor networks capable of early detection and precise tracking of highly manoeuvrable threats. However, the implementation of such systems faces a range of operational, logistical, and financial challenges, especially in terms of ensuring long term cost-effectiveness and strategic resilience.

The future of air defence depends not only on technological superiority but also on the ability to strategically adapt, cooperate and build systems capable of responding to dynamic, multi-vector and increasingly accessible aerial threats in real-world conflict scenarios. It is important to emphasize that the advancement of offensive means is developing along two distinct trajectories. On the one hand, highly sophisticated systems such as ballistic and hypersonic missiles, and on the other, the mass employment of inexpensive drones whose main strength lies in quantity. Accordingly, modern air defence must evolve in both directions simultaneously. While advanced orbital sensors, artificial intelligence and precision interceptors are indispensable for countering high-end missile threats, defending against swarms of drones requires simpler, more robust, and cost-effective measures such as artillery, programmable ammunition or laser weapons. Only an integrated, multi-layered system that combines missile, artillery, electronic warfare and directed energy components can provide credible and sustainable protection in the complex threat environment of the future.

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Ivan Boban

Zahtjevi suvremene protuzračne obrane

SAŽETAK

Suvremeni sustavi protuzračne obrane suočeni su s ubrzanim razvojem balističkih, hipersoničnih i bespilotnih prijetnji koje sve češće nadilaze mogućnosti tradicionalnih obrambenih tehnologija. Ovaj rad analizira glavne izazove koje za protuzračnu obranu predstavljaju balistički projektili te različite kategorije bespilotnih letjelica. Kroz analizu slučajeva iz Ukrajine, Izraela i Zaljevskog rata prikazuje se ograničena učinkovitost postojećih obrambenih sustava, osobito protiv sofisticiranih prijetnji. Posebna pozornost posvećena je konceptima zasićenja protuzračne obrane rojevima dronova i ekonomskim posljedicama takvih taktika. U završnom dijelu rada predstavljena su tehnološka rješenja za buduću obranu, uključujući višeslojnu orbitalnu arhitekturu senzora, oružja usmjerene energije i sustave elektroničkog ratovanja. Rad zaključuje kako će buduća učinkovitost protuzračne obrane ovisiti o sposobnosti integracije različitih tehnologija u fleksibilne i ekonomski održive obrambene sustave.

KLJUČNE RIJEČI: *PZO, balistički projektili, bespilotne letjelice, hipersonično oružje*