IAMD CoE's JOURNAL

Vol. 4 | May 2026
iamd-coe.org

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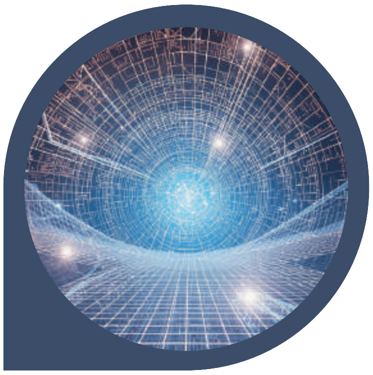


Editorial

As the Director of the Integrated Air & Missile Defense Centre of Excellence, it is both an honor and a privilege to welcome you all, to the 4th Annual IAMD COE Conference here in the beautiful island of Crete.

Having in mind the valuable experience that the Centre gained from our 3rd Conference during June last year, I strongly believe that this conference will also have the same success and would be beneficial for the whole IAMD community.

The Centre has managed to develop skills in all important fields of IAMD, with an active role and dedication to its mission, and to provide training and best practices, doctrines, analysis, and lessons learned in the demanding IAMD Domain.

This comes together with our motto "Act Knowing", a phrase of Pittacus (640 - 568 b.c), a Mytilenean General and one of the seven wise men of ancient Greece, which means to be fully aware of the situation before acting.

Since our previous conference in June 2024, the Center presented some significant achievements. Allow me to underline the most important of them:

- We have remained consistently engaged in education and training. Two iterations of the Surface-Based Air and Missile Defence Common Education and Training Program (CET-P) were conducted, bringing together sixty-one participants from nineteen nations. Additionally, at the request of the United Kingdom, a Mobile Training Team delivered a condensed version of the CET-P to thirty participants. Beyond these activities, the Centre's Subject Matter Experts have played a key role in coordinating and delivering education and training initiatives across the broader IAMD community.
- In parallel, the Centre has actively supported NATO entities in IAMD-related exercises, contributing to both the planning and execution phases.
- The IAMD COE has also undertaken significant studies and projects in collaboration with academic and research institutions. Notably, it has conducted advanced research on the Hypersonic Threat in cooperation with the Technical University of Crete. In partnership with the Institute of Computer Science/FORTH, the Centre developed a prototype Passive Radar System for drone detection and completed a study entitled "Countering Bio-Inspired Drones."
- Further supporting NATO efforts, the Centre successfully participated in workshops, conferences, and Innovation Challenges addressing topics such as "Counter Glide Bombs" and "Countering Fiber-Optic-Controlled FPV Drones," where its Subject Matter Experts had an active role. Importantly, the IAMD COE is also developing a Modelling and Simulation Laboratory to enhance NATO and Nations' Distributed Synthetic Training activities in the field of IAMD.
- In addition, the Centre has participated in a wide range of conferences, meetings, and exhibitions, further expanding its network of contacts to foster future cooperation with academia and industry. These efforts will be highlighted through the organization of our fourth Annual IAMD

Conference, dedicated to the theme:

"Future-Proof Capabilities in the Evolving Multi-Domain Synthetic Battlespace'

We are operating in an era where the speed of technological advancement, the blurring of domains, and the fusion of synthetic and physical battlespaces demand continuous adaptation. Future conflicts will not be confined to land, sea, or air, but will unfold in **cyber, space, and cognitive environments,** simultaneously and without warning.

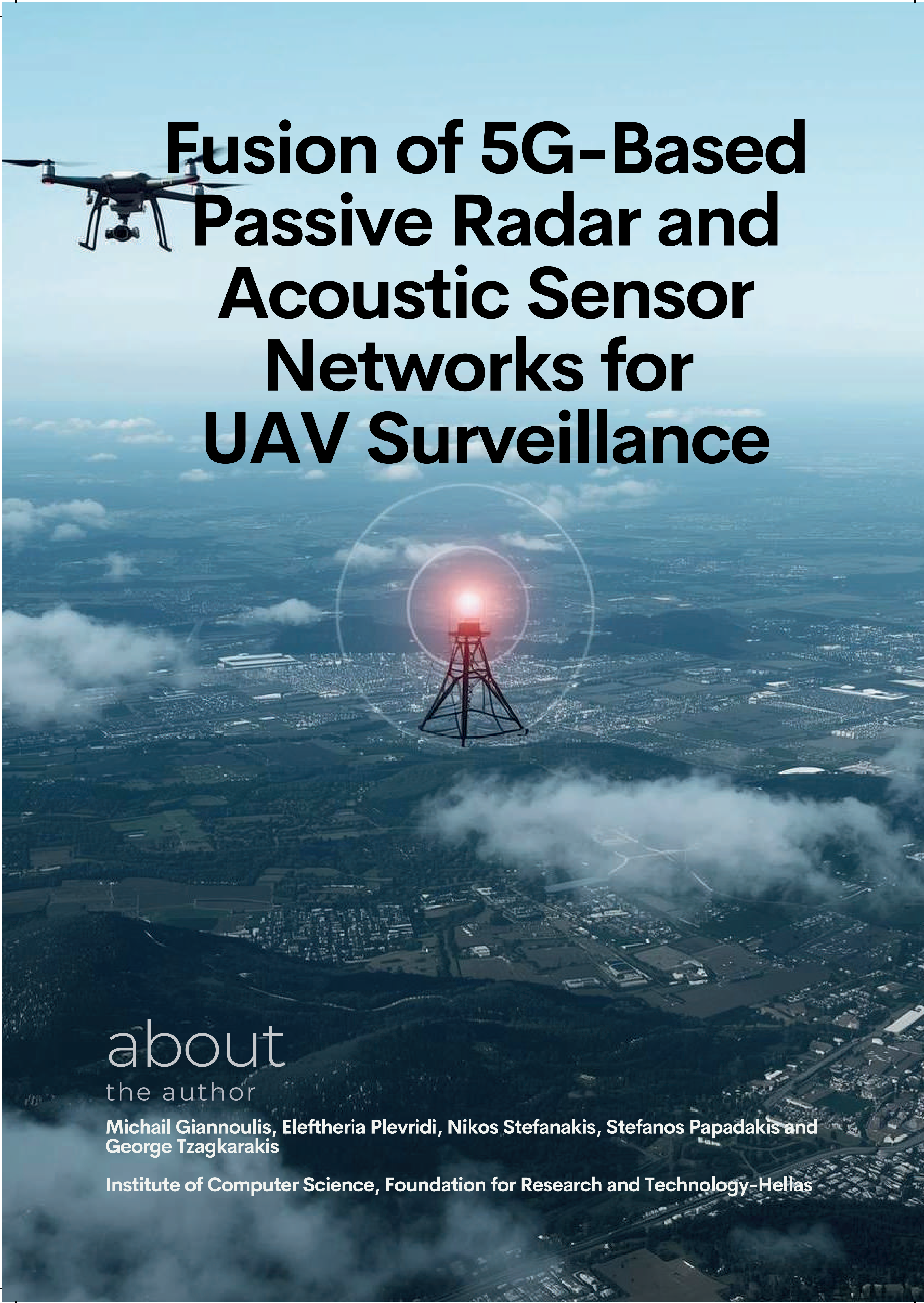
Synthetic Battlespace allows us to train, to test doctrines, and to evaluate capabilities before we are called to employ them in actual combat. In doing so, it becomes a vital tool in preparing our forces for the complexity of future warfare.
To remain credible, our forces must not only adopt advanced tools but also cultivate **doctrines, training, and interoperability** that allow us to foresee, adapt, and prevail in these complex environments.
Over the course of this conference, you will explore emerging technologies, operational concepts, and training solutions that will shape tomorrow's battlespace. Your deliberations will help forge a shared understanding of the path ahead—an understanding that is crucial if we are to ensure the **credibility and effectiveness of NATO's deterrence and defense posture.**
Sharing knowledge with our distinguished **speakers**, their capacity and expertise is valuable to all of us, as well as to ensure the success of the event.

I would also encourage all of you to be bold and even **provocative with your questions and interventions.** Only through challenging assumptions and testing ideas can we generate the kind of productive discussion that advances our collective understanding and strengthens our operational readiness.

Let me conclude by thanking each of you for your commitment, your expertise, and your presence here today. Together, we have the responsibility—and the privilege—of ensuring that our Alliance remains ready, resilient, and relevant in the face of tomorrow's challenges.

" Future conflicts will unfold in cyber, space, and cognitive environments,
the fusion of synthetic and physical battlespaces demand continuous adaptation"

Brig. General (OF-6)
Zacharias KOUTRAKIS GRC
IAMD COE DIRECTOR



Fusion of 5G-Based Passive Radar and Acoustic Sensor Networks for UAV Surveillance

about
the author

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Abstract:

The rapid proliferation of small unmanned-aerial vehicles (UAVs) is challenging air-space security, particularly in cluttered urban environments where line-of-sight sensing is intermittent. To address this problem, we introduce a fully data-driven surveillance architecture that fuses 5G-based passive radar system (5G-PRS) and a distributed acoustic sensor network (ASN) through deep-learning models and handcrafted signal processing pipelines. For the RF domain, a convolutional neural network (CNN) ingests raw 5G signal reflections and directly produces range–Doppler occupancy maps, jointly learning clutter suppression and target enhancement. Concurrently, a multi-branch audio transformer converts synchronized microphone streams into latent embeddings that capture micro-Doppler blade beats and broadband propulsion noise. A cross-modal fusion transformer with spatiotemporal self-attention then performs target association and state estimation. The end-to-end framework is trained with a composite loss that balances detection confidence, localization accuracy, and track continuity, while a self-supervised pre-training stage leverages large volumes of unlabeled 5G and urban-sound data to reduce annotation requirements. By exploiting existing 5G infrastructure and low-cost acoustics, and by letting neural networks learn optimal feature representations and fusion policies, the proposed system offers a scalable, spectrum-efficient path toward continuous UAV situational awareness without additional radio-frequency emissions or expensive bulky hardware components.

“ Where the eye is blind, the synergy of 5G and sound makes the invisible visible.”

1. Introduction

Unmanned Aerial Vehicles (UAVs) are vital in modern defence and security, offering efficient, flexible, and low-risk solutions for logistics, strikes, reconnaissance, and surveillance. Equipped with communication links, navigation systems, power modules, and advanced sensors, they support autonomous or semi-autonomous flight. However, their small size, agility, and low radar signature make them hard to detect with conventional methods. Optical and infrared sensors depend on visibility, while active radars compromise stealth by emitting detectable signals. In contrast, passive sensing uses existing signals to detect UAVs without additional emissions. Based on this approach, the AIRE5G framework was developed as a 5G-based Passive Radar System (5G-PRS), using reflected infrastructure signals to detect, classify, and track UAVs. Tests using synthetic data across various UAV types showed over 90% precision and recall, validating its effectiveness for surveillance. The envisioned extended system will also integrate acoustic sensors, forming a multi-layer sensing wall to improve detection of smaller drones and ensure functionality in radio-constrained environments. Supported by IAMD COE, AIRE5G aims to provide a flexible, data-driven detection platform for both civilian and defence applications.

2. Related Work

Modern drone-detection technologies (see Figure 2) can be grouped into four main categories: radio-frequency analysis, acoustic sensing, optical sensing, and radar systems, each with specific advantages and limitations. RF analysis systems (e.g., VERA-NG) intercept control or telemetry links between a drone and its operator. They are effective when communications are active but fail for autonomous or radio-silent drones. Acoustic systems (e.g., SKY-FORTRESS) identify propeller noise using microphone arrays; however, their performance degrades in windy, noisy, or long-range scenarios. Optical and electro-optical systems (e.g., Ultra FORCE 350-HD on Airbus H125) deliver high-resolution imagery but depend on visibility and lighting. Active radar systems (e.g., TRML4D, SPEXER) estimate range and velocity with high precision but require powerful emitters and are easily detectable. In contrast, AIRE5G offers a passive, stealthy, and cost-efficient alternative by using existing 5G transmissions. Moreover, the current architecture of AIRE5G is envisioned to be extended with acoustic sensing technology to mitigate the weaknesses of single modalities: acoustic sensors complement radar in line-of-sight gaps, while radar extends range and robustness. Together they will deliver radar-grade accuracy and stealth, at a fraction of conventional cost.

Figure 2. Representative detection systems: (a) VERA-NG; (b) SKY-FORTRESS; (c) Ultra FORCE 350-HD; (d) TRML4D/SPEXER

3. The AIRE5G Project

The AIRE5G project explores the convergence of 5G networks, passive radar sensing, and artificial intelligence for next-generation UAV surveillance. Specifically, it exploits ambient 5G signals for passive radar, eliminating the need for dedicated transmitters. AI-based models analyze reflected signals to detect and classify rotor-based UAVs in real time. The system is designed for scalability, with detection range and performance enhanced through hardware (and software) upgrades.

3.1 Architecture

AIRE5G employs a modular, software-defined architecture (see Figure 3) that processes real or simulated signals for drone detection. Receiver antennas feed signals to a Software-Defined Radio (SDR) front end, which performs filtering, synchronization, and baseband conversion. The processed data are transformed into Range-Doppler (RD) maps that visualize target movement.

These maps are analysed by the AI module, which detects and classifies UAV signatures. Optionally, our in-house simulator can generate synthetic signals to emulate various flight paths and propagation conditions, producing realistic RD maps. A graphical user interface (GUI) enables live monitoring of annotated RD images and system configuration.

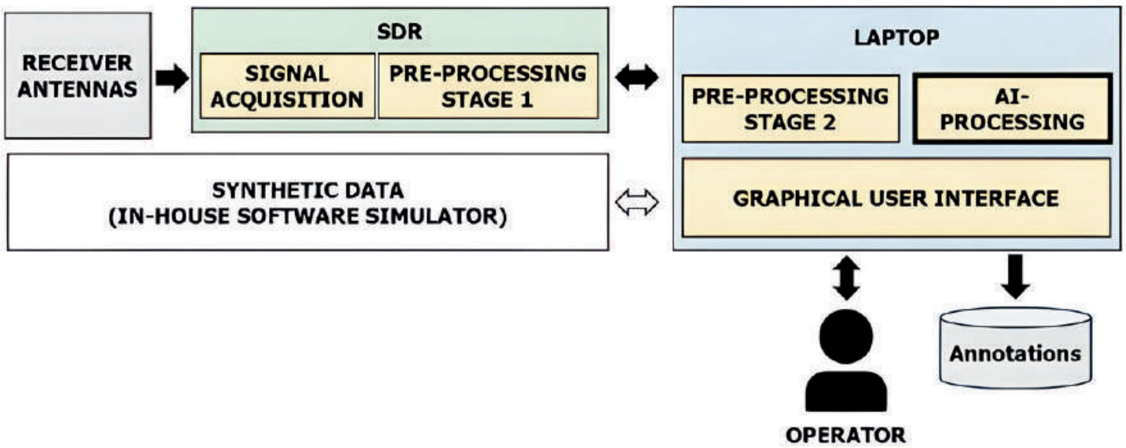

Figure 3. Overview of the AIRE5G system architecture

3.2 Actual Signal Data

In operational mode (see Figure 4), two passive antennas are used: a reference antenna that directly receives the 5G waveform from the base station and a surveillance antenna that records the same waveform after reflection from aerial targets. The system operates within the sub-6 GHz range (600 MHz - 3.5 GHz), depending on local 5G deployments. After synchronization and alignment, both signals undergo cross-correlation, decimation, and Fast Fourier Transform (FFT) operations to form RD images showing reflected energy as a function of range and Doppler. These images reveal micro-Doppler patterns generated by rotating blades and body movement.

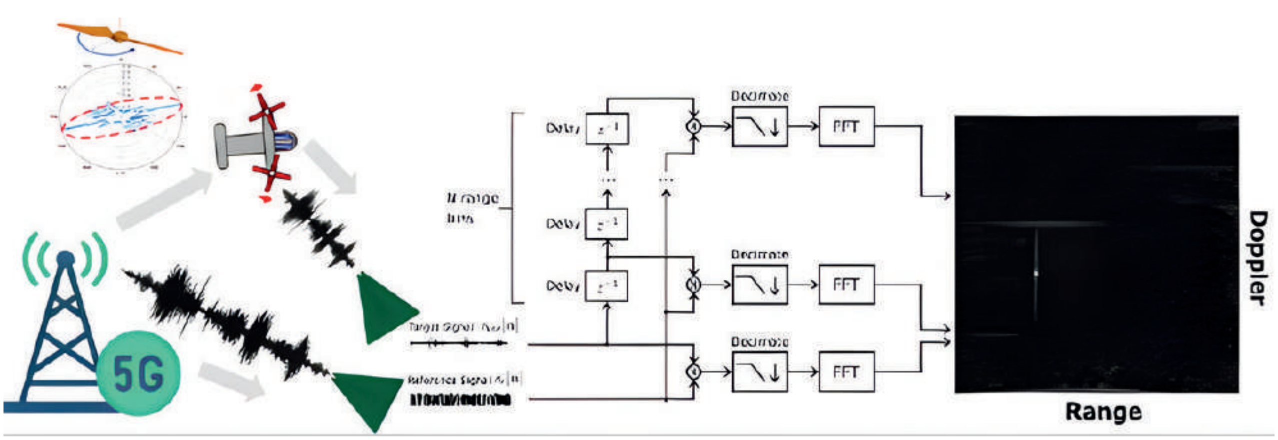

Figure 5. Simulation workflow of our in-house AIRE5G software simulator

3.3 Simulated Signal Data

Optionally, our in-house simulator (see Figure 5) reproduces the complete passive-radar chain. It generates synthetic reference and surveillance signals and processes them through cross-correlation and FFT transformations identical to those in operational mode. Users can configure parameters such as antenna geometry, UAV trajectory, altitude, velocity, radar-cross section (RCS), and carrier frequency. The simulator computes bistatic range, Doppler shifts, and received power, creating physically consistent datasets for AI training, validation, and system optimization.

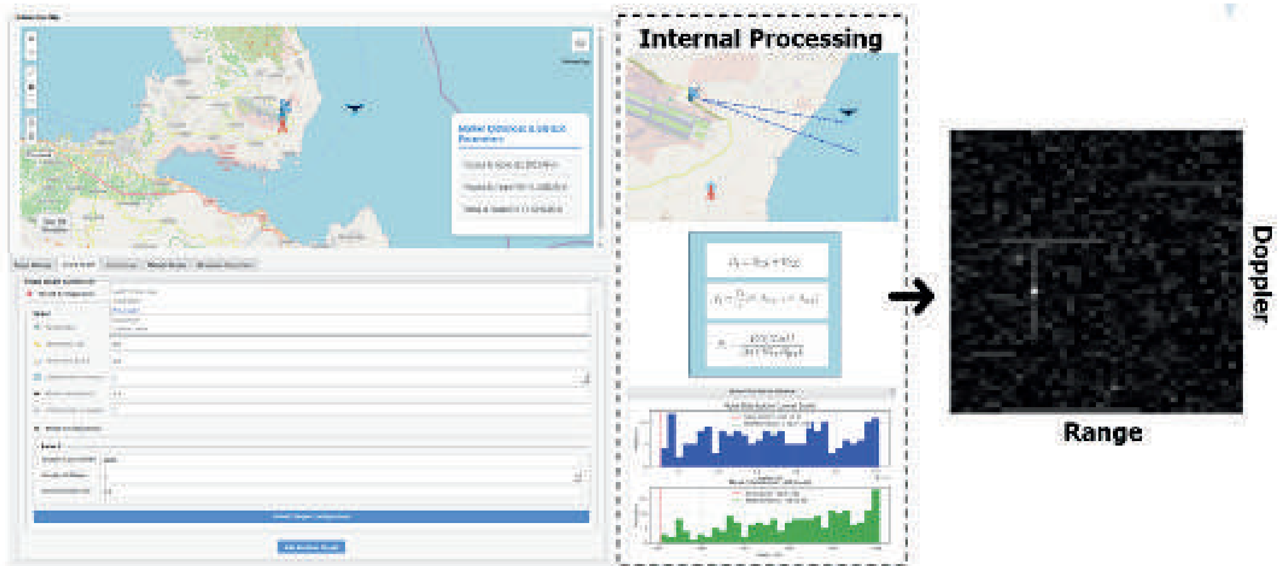

Figure 5. Simulation workflow of our in-house AIRE5G software simulator

3.4 AI-Processing

The AI module is built on a You Only Look Once (YOLO) architecture trained on RD images. Each image passes once through a unified deep network that extracts multi-scale spatial–spectral features and performs object detection. A backbone captures hierarchical features, and a neck module fuses them across resolutions (80×80, 40×40, 20×20), allowing detection of UAVs with varying size and dynamics. The dense prediction head outputs bounding boxes and confidence scores for each detected drone class. This one-shot inference enables real-time multi-target tracking, while transfer-learning mechanisms support adaptation to new frequency bands with limited data.

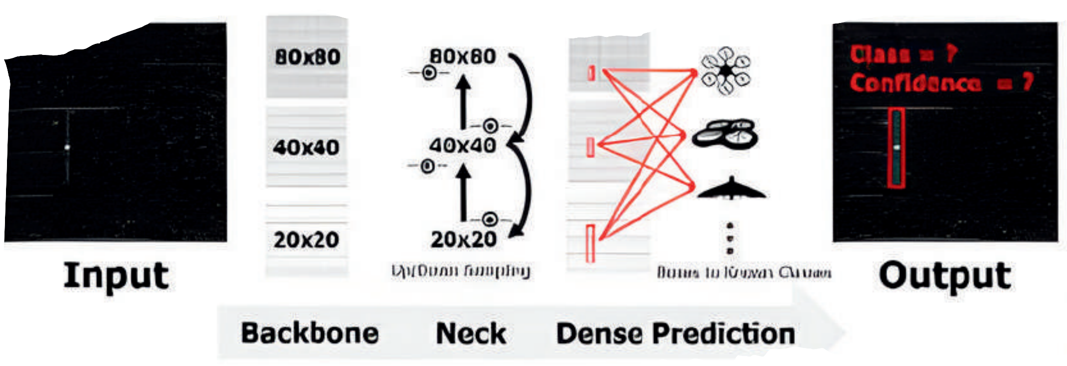

Figure 6. Deep learning pipeline for drone detection from RD maps

3.5 System Evaluation

The AIRE5G system is validated through simulated drone flights featuring quadcopters, hexacopters, and octocopters, as shown in Figure 7. Each platform was successfully detected and classified using a trained YOLO-based model. Precision rates of 90% per image demonstrated reliable discrimination across UAV categories. The average inference time was 120 milliseconds per frame, enabling near real-time performance. Detection range correlated with antenna specifications and the UAV's radar cross section (RCS): larger drones were detectable at greater distances, since smaller ones produced weaker reflections.

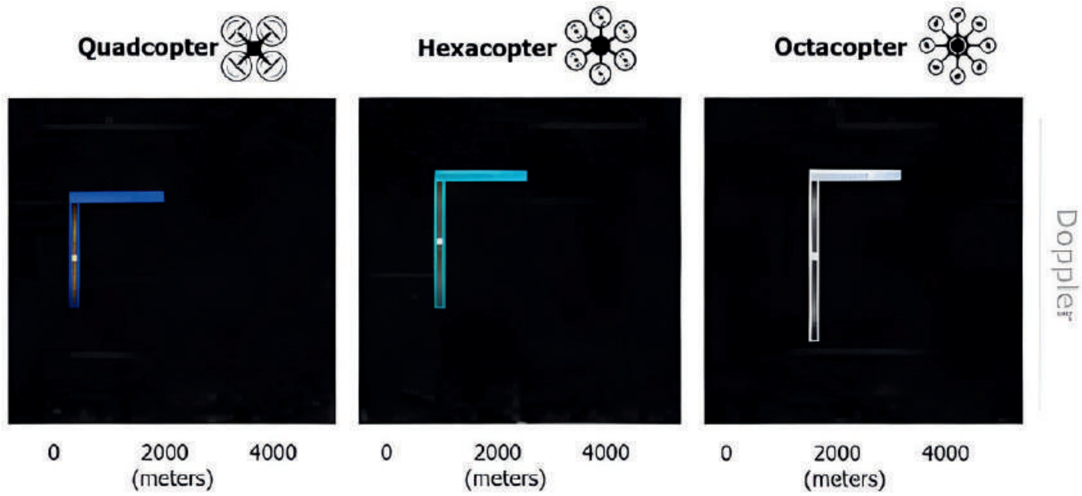

Figure 7. Detection outputs showing classified drone types on RD maps

4. The Envisioned Multi-modal System

The current AIRE5G system is a 5G-based passive radar for wide-area, long-range detection, but its performance can be limited by drone radar cross section and illumination geometry. To overcome these challenges, we propose integrating an Acoustic Sensing Network using AI-driven data fusion, as shown in Figure 8. Acoustic nodes detect propeller noise, enabling reliable tracking even when radar signals are weak or misaligned. Their low-cost, energy-efficient design allows dense deployment, expanding coverage from meters to kilometers. This envisioned multimodal approach will combine broad radar awareness with precise acoustic detection, ensuring scalable, stealthy, and resilient situational awareness across varied terrains and conditions.

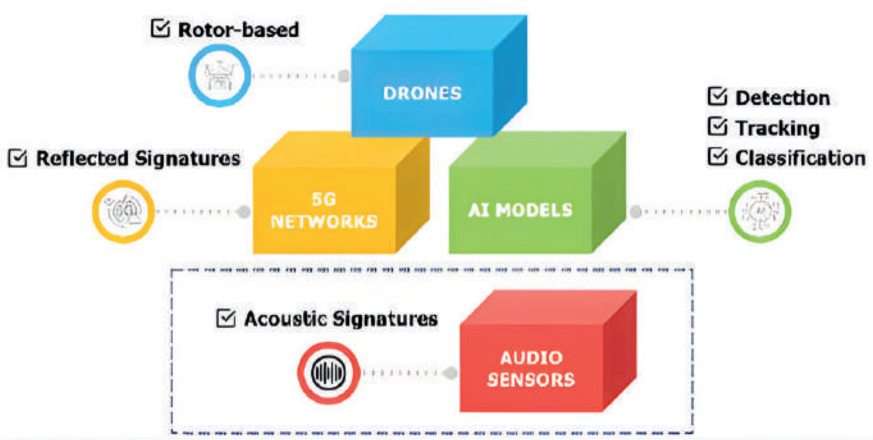

Figure 8. AIRE5G fusion system with new audio sensors module

4.1 A New Layer in Architecture

The addition of a new module extends the architecture by introducing an acoustic layer to the existing radar framework, as illustrated in Figure 9. This layer begins with audio acquisition from microphone arrays or directional sensors that capture sound pressure variations caused by drone rotors. Signals are transformed into time-frequency representations (e.g., Short-Time Fourier Transform, or spectrogram analysis) to highlight harmonic and modulation patterns characteristic of drones. Features such as spectral centroid, bandwidth, and modulation energy are then sent to the AI module for multimodal fusion. AIRE5G's modular design allows more modalities (e.g., optical or infrared) to be integrated with minimal reconfiguration.

Figure 9. A new acoustic layer added to the AIRE5G system architecture

4.2 Expected Surveillance Coverage

In realistic deployments, the existing Passive Radar System (PRS) can achieve a kilometre detection range, depending on the target's RCS and environmental conditions. In addition, the proposed extension using Acoustic Sensor Network (ASN) node is expected to cover approximately two hundred meters. To ensure continuous regional coverage, multiple PRS and ASN nodes can be deployed in overlapping zones. Operationally, a quadcopter (e.g., DJI Phantom 4) traveling at 20 m/s crosses 1000 meters in 50 seconds, while a hexacopter (e.g., DJI Matrice 600 Pro) at 16 m/s takes 62.5 seconds. These figures yield a reaction window of a minute for a single system node to detect and classify incoming threats.

5. Conclusions

The AIRE5G system is a flexible, intelligent, and cost-effective solution for passive UAV detection and situational awareness. Powered by advanced machine learning models, it supports self-training and continuous adaptation to new UAV targets, ensuring responsiveness to evolving threats. Designed for interoperability, the AIRE5G can be integrated smoothly with existing operational frameworks. With high precision and fast per-frame detection, AIRE5G offers a robust and scalable surveillance platform suitable for both civilian and defence applications. Furthermore, its software-defined, white-box architecture enables seamless upgrades and the integration of new sensing modalities (e.g., sound, optical) without hardware modifications on the existing modalities. Operating in the sub-6 GHz band, the Passive Radar System leverages existing signal transmissions for long-range, stealth monitoring. However, it faces two key limitations: reliance on signal availability, which may be lacking in some areas, and reduced effectiveness against targets with low radar cross-sections (RCS), such as small UAVs. To address these challenges, the envisioned Acoustic Sensor Network will provide dense short-range coverage using scalable, low-cost nodes.

Challenges of Unmanned Aircraft Systems Airspace Integration and their Potential for Enhanced Integrated Air and Missile Defence

about
the author

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Abstract:

This article examines the transformative potential and strategic necessity of using Unmanned Aircraft Systems (UAS) as red team aggressors to enhance European Integrated Air and Missile Defence (IAMD) capabilities. It argues that in an era where sophisticated aerial threats like autonomous systems and loitering munitions are proliferating, traditional training and engagement methods are becoming increasingly inadequate. Adopting UAS for adversary simulation offers a cost-effective, scalable, and highly realistic solution, enabling the replication of complex scenarios such as saturation and swarming attacks that are difficult and expensive to achieve with conventional assets, which can help to determine blind areas of actuation against real threats.

While the operational benefits are clear, the paper identifies airspace integration as the primary and most complex barrier to realizing the full potential of UAS. This challenge is multifaceted, encompassing a fragmented regulatory landscape between civil and military authorities, critical interdependent technical hurdles such as certified Detect and Avoid (DAA) systems, secure Command and Control (C2) links, and spectrum allocation, and unique military dilemmas that make collide operational stealth with civil aviation safety principles.

Overcoming these obstacles requires a concerted, multi-stakeholder effort, where the European Defence Agency (EDA) plays a pivotal role as a catalyst for collaborative development, standardization, and multinational training. These initiatives are strategically aligned with the European Commission's White Paper on Defence Readiness 2030, which prioritizes closing capability gaps in IAMD and drones. The article concludes that strategically integrating UAS into IAMD red teaming is an interesting cost-effective approach for building a more resilient, adaptive, and combat-credible European defence posture capable of meeting the evolving realities of the modern security landscape.

> " Transforming the adversary's greatest strength into our most critical training asset."

Labyrinth of the Sky: Overcoming the Challenges of UAS Integration in European Airspace

While the strategic and operational benefits of employing Unmanned Aircraft Systems UAS are – now more than ever – clear, their full potential can only be realised once they can operate routinely and safely in non-segregated airspace. Airspace integration stands as the primary barrier to unlocking the capabilities. For decades, military UAS have operated effectively, predominantly within the confines of segregated airspace or under highly restrictive authorisations. The fundamental challenge for Europe is to transition from this state of segregation to one of seamless integration within the continent's dense and complex civil airspace—a system designed entirely around the principles of manned aviation. This is challenge spans through complex regulatory frameworks, novel air traffic management concepts (with the good example of Single European Sky, U-space and Unmanned aircraft traffic management (UTM)), core technological hurdles, and unique military operational dilemmas.

Regulatory and Policy Complexity

The European regulatory landscape for UAS is a multi-layered framework that presents a significant hurdle to harmonised military operations. Civilian drones are subject to a comprehensive, risk-based EU framework implemented by EASA, established by Regulations (EU) 2019/947 and 2019/945, that categorises operations into three classes based on risk: 'Open' for low-risk, 'Specific' for medium-risk requiring prior authorisation, and 'Certified' for high-risk activities akin to manned aviation.

In stark contrast, the regulation of military drone use remains a national competency, falling under the remit of individual Member States. While Regulation (EU) 2018/1139 provides an "opt-in" clause allowing a Member State to apply the EU's civil aviation rules to its state aircraft, this is not mandatory, resulting in a fragmented regulatory landscape. This fragmentation severely hampers the cross-border military operations that are essential for both NATO and the EU's Common Security and Defence Policy (CSDP) missions. The EU Drone Strategy 2.0, a key policy document, explicitly acknowledges this friction and includes a flagship action (Action 15) aimed at aligning civil and military certification requirements where feasible, in order to foster greater synergy.

This dual regulatory system creates a fundamental impediment to the development of a truly unified European defence capability. The requirement for military UAS to navigate a patchwork of national rules for airworthiness, pilot licensing, and operational procedures when crossing borders introduces significant delays and administrative burdens. As an example, a rapid-deployment surveillance mission flying West to North-East Europe would face a complex, time-consuming series of legal approvals, negating the very speed and flexibility that make UAS such valuable military assets. This regulatory disunity is, therefore, an administrative inconvenience and a tangible operational vulnerability that undermines the principle of collective defence and the strategic ambitions outlined in documents like the EU's Strategic Compass. The push for harmonisation, facilitated by the EDA, is consequently a matter of core military effectiveness, and bureaucratic efficiency.

Technical and Interoperability Complexity

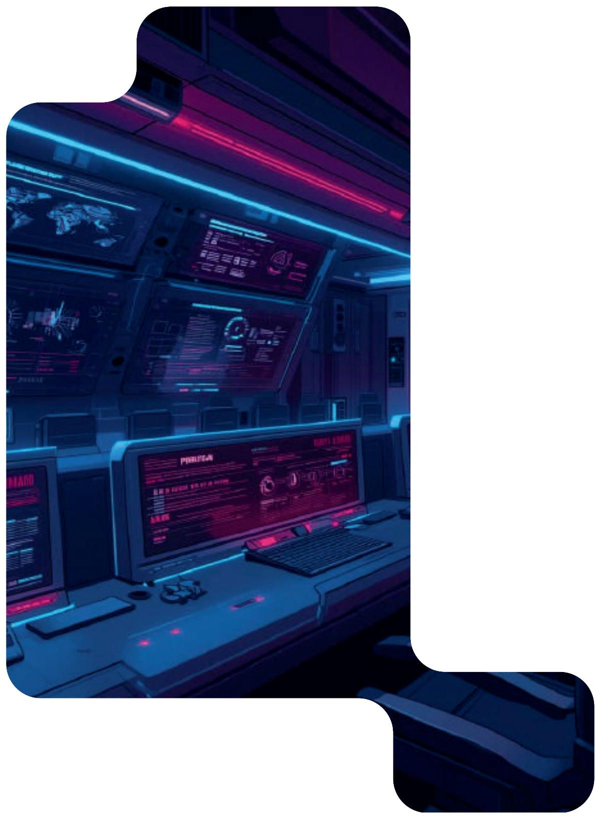
Beyond the overarching regulatory and airspace management frameworks, the integration of UAS hinges on overcoming several core technical and interoperability challenges.

Detect and Avoid (DAA) Systems

Arguably the single most critical technical barrier to routine operation in non-segregated airspace is the lack of a mature, certified Detect and Avoid (DAA) system. To operate safely, a UAS must be able to replicate a human pilot's fundamental ability to 'see and avoid' other aircraft and prevent mid-air collisions. DAA systems are designed to perform this function, using a suite of cooperative and non-cooperative sensors —such as radar, LiDAR, electro-optical/infrared (EO/IR) cameras, and ADS-B transceivers—to build a picture of the surrounding airspace, detect potential collision risks, and, if necessary, trigger autonomous avoidance manoeuvres. The primary challenge lies in developing a system that is sufficiently reliable, affordable for widespread adoption, and capable of meeting the stringent safety standards required for certification by aviation authorities like EASA. The EU is investing significantly in this area through the EDF, with specific calls (e.g., EDIDP-ISR-DAA-2019 and EDF-2023-DA-C4ISR-DAA) aimed at developing a standardised, qualified, and certifiable European DAA solution for both MALE and tactical UAS. This is complemented by SESAR projects like ERICA and IRINA – led by EUROCONTROL – which are validating DAA functionalities and the associated ATM procedures.

Command, Control (C2), and Communications Link Integrity

UAS are entirely dependent on robust and reliable data links for command and control (C2) and the transmission of payload data.These radio-frequency links are inherently vulnerable to both unintentional interference from other spectrum users and deliberate hostile actions such as jamming or spoofing. Because these links are essential for the "safety and regularity of flight," they must meet exceptionally high standards of integrity, availability, and security, akin to the communications used by traditional ATC. Besides advanced encryption and anti-jamming technologies, these links require coverage and access to dedicated and protected radio frequency spectrum.



Radio Frequency Spectrum Allocation

Secure and reliable C2 links require dedicated and protected radio frequency spectrum, which is a finite and increasingly congested resource. The allocation of spectrum is managed globally by the International Telecommunication Union (ITU) and at the national level by regulatory authorities. Within the EU, the European Commission works to coordinate and harmonise spectrum use to support the single market and prevent harmful interference.

Recognising its criticality for the future drone market, the EU Drone Strategy 2.0 includes a flagship action (Action 13) to "coordinate with other relevant EU actors a common approach with the aim of providing sufficient radio frequencies spectrum for drone operations".A tangible step in this direction is Commission Implementing Decision (EU) 2022/179, which harmonises the use of the 5 GHz band and explicitly permits UAS operations within the 5170-5250 MHz portion under specific technical conditions. However, there are considerable limiting factors, especially on the power of the transmitters, which needs to be very low power. This fact limits the usage of this portion of the spectrum to a few kilometres from the receiver/remote pilot station.

Cybersecurity and Resilience

As complex, networked, cyber-physical systems, UAS present a broad attack surface for malicious actors. Key vulnerabilities include hijacking the C2 link to seize control of the aircraft, spoofing GPS signals to divert it from its intended path or cause it to crash, or compromising the software of the ground control station to exfiltrate data or inject malicious commands. As UAS become more deeply integrated into networked military operations and civil infrastructure, their cybersecurity becomes a critical component of mission assurance and public safety. The EU's cybersecurity agency, ENISA, is actively studying and reporting on the evolving threat landscape, although specific public reports on military drone cybersecurity are limited. Building resilience against these threats is paramount. EDA-led projects such as USEXI (Unmanned Aircraft Systems Single European Sky Experimental Integration) are focused on developing critical enablers, including technologies for safe and autonomous navigation in GNSS-jammed or denied environments, a key aspect of operational resilience.

The dilemma of interconnected technical hurdles

These four technical hurdles—DAA, C2, Spectrum, and Cybersecurity—are deeply interdependent and must be addressed as an integrated system-of-systems problem. A technically perfect DAA system is spectrum is denied, preventing the avoidance command from ever reaching the aircraft. A secure, jam-proof C2 link is ineffective if it lacks access to sufficient, protected spectrum, forcing it to compete with other traffic and suffer from debilitating interference. And even with a flawless DAA and C2 link operating on protected spectrum, the entire system remains vulnerable if a sophisticated cyberattack can compromise the ground station's software or spoof the aircraft's navigation system.

Such technical hurdles lead to the need for compromises to allow for the operation of the UAS. In particular, airspace segregation, long bureaucratic processes of approval with the civil authorities and air navigation service providers, which lead to geographically- and time-limited permits to fly, and airspace operational safety cases. Consequently, regulatory approval and operational deployment are severely hampered, while aviation authorities and military certification bodies must evaluate and certify the entire safety and security chain as a holistic entity. This complex approach significantly extends the timeline for full integration, explaining why progress, despite notable advances in individual technologies, full integration remains incremental.

Military-Specific Integration Dilemmas

Beyond the technical challenges shared with civil aviation, military UAS integration faces a unique set of operational and doctrinal dilemmas. Military operations are, by their nature, dynamic, often unpredictable, and require flexible and rapid access to airspace. This operational imperative frequently conflicts with the more rigid, structured, and pre-planned nature of civil ATM.

A fundamental tension exists between the principles of civil aviation and the requirements of military effectiveness. Civil airspace safety is built on a foundation of cooperation and universal situational awareness, where all users are transparent and conspicuous through the use of transponders and, in the future, U-space e-identification services. Conversely, many military missions, particularly intelligence, surveillance, and reconnaissance (ISR) or operations in a pre-conflict environment, rely on stealth and the element of surprise. A military UAS broadcasting its precise location via ADS-B to comply with civil ATM requirements would simultaneously reveal its position, and potentially its mission, to any adversary with access to open-source flight tracking data. This creates a paradox where the very measures required for safe peacetime integration directly compromise the aircraft's utility in a crisis or conflict.

Resolving this paradox requires technical, fundamental doctrinal and procedural changes to UAS and the way we operate in a common airspace. The solution must involve new operational concept agreed upon by both civil and military authorities. This could include the development of dynamically reconfigurable airspace, as recommended in EDA-funded studies, which would allow for the temporary and flexible allocation of airspace for military needs. Another approach could be the establishment of "trusted" corridors where military UAS can operate under modified procedures. This, however, requires a level of dynamic civil-military ATM integration and mutual trust that is currently more aspirational than operational.

Furthermore, differing standards for military airworthiness and remote pilot certification must be reconciled with civil authorities to enable mutual recognition and a streamlined approach to UAS operations. EDA is actively developing harmonised procedures for military Remotely Piloted Aircraft Systems (RPAS) to fly as Operational Air Traffic (OAT) and within General Air Traffic (GAT) but the challenge of integrating them seamlessly remain as blocking points.

The Evolving Landscape of Air and Missile Threats and the Imperative for Advanced IAMD

The current security landscape is characterised by a rapid proliferation and increasing sophistication of aerial threats. This evolving environment encompasses a broad spectrum, ranging from advanced fighter aircraft and cruise missiles to low-observable UAS and emerging hypersonic technologies. Such a dynamic threat environment necessitates robust and adaptable Integrated Air and Missile Defence (IAMD) capabilities for multinational alliances to ensure collective security and territorial integrity.

A particularly challenging aspect of this evolving threat spectrum is the rapid advancement in autonomy and automation within UAS, coupled with the increased deployment of loitering munitions. These systems are no longer simple "drones"; they are capable of independent decision-making, complex behaviours, and extended endurance over target areas, which significantly complicates traditional IAMD efforts. Their unpredictable flight paths, ability to saturate defences, and potential for coordinated multi-vector attacks pose a novel threat that demands innovative countermeasures and ways of performing Training and Exercises (TREX). The proliferation of these lower-cost, high-impact threats presents a significant economic challenge for traditional, often expensive, IAMD systems. This dynamic creates an asymmetric cost-exchange ratio, where adversaries can deploy numerous affordable systems against high-value interceptors. Consequently, the strategic imperative for leveraging UAS in defence extends beyond technical testing to developing a cost-effective countermeasure to a potentially overwhelming volume of such threats, thereby enabling a more sustainable defence posture against massed autonomous attacks

The inadequacy of traditional ways of training against the unpredictability and complexity of autonomous systems, as well as saturation and swarming operations, highlights a fundamental need for more relevant and realistic training. Without the ability to simulate or – better yet – to replicate these advanced threats accurately, IAMD systems risk being prepared for a conflict environment that no longer reflects contemporary realities. This elevates the role of UAS from a mere cost-saving tool to a strategic enabler for maintaining a qualitative edge in an increasingly complex aerial battlespace.

UAS pose a considerable (real) threat, with examples of use in contemporary conflicts. As per the latest statistics, obtain from Ukraine in August 2026, almost 2/3 of Ukrainian neutralizations[1] of enemy assets were done using UAS. Furthermore, the invasion of Polish airspace on the night of 09 of September 2025 by 19 UAS serves as an indicator of the element of surprise and efficacy of these systems, which are very hard to identify, classify and engage/neutralize.

[1] It accounts for kills, destructions or impairments.

As a result, we propose a strategic adoption of UAS as a primary tool for red team aggressor replication in IAMD exercises. This approach would offer a cost-efficient and flexible alternative to traditional means, directly contributing to enhanced defence readiness and addressing the specific challenges posed by the next generation of aerial threats.

Unmanned Aircraft Systems as Red Team Aggressors: An Advantage for IAMD Preparedness

The utilization of UAS to replicate adversary aerial threats/red teaming in Integrated Air and Missile Defence (IAMD) TREX offers a compelling and multifaceted suite of benefits for multinational alliances. These advantages represent a significant paradigm shift from conventional ways of training.

Detailed Advantages of UAS in IAMD Red Teaming

● **Cost-Effectiveness:** UAS are demonstrably less expensive to procure, operate, and, crucially, more attritable, compared to manned aircraft or actual missile systems. This inherent cost efficiency enables more frequent and extensive training exercises within existing defence budgets, providing more opportunities to rigorously test IAMD systems and continuously train personnel.

● **Realistic and Diverse Threat Simulation:** Modern UAS and Remotely Piloted Aircraft Systems can be programmed and configured to emulate a wide array of threat profiles. They can simulate various speeds, altitudes, flight paths, and electromagnetic warfare signatures, offering a level of realism and diversity that is both difficult and costly to achieve with traditional assets. This adaptability is particularly crucial for preparing IAMD systems for emerging threats such as low, slow, and small targets, as well as the distinct and challenging operational patterns of loitering munitions, which can evade conventional radar systems and pose unique challenges to IAMD engagement timelines.

● **Enhanced Training and Evaluation:** UAS can provide consistent and repeatable threat, which are important for accurately evaluating IAMD system performance and operator proficiency. Furthermore, they can be equipped with sophisticated sensors and data links to deliver telemetry and performance data live for comprehensive post-exercise analysis. This facilitates a deeper understanding of system capabilities and limitations, enabling data-driven improvements.
● **Scalability and Complexity:** despite not replacing red aircraft and real high speed threats, UAS enable the simulation of highly complex scenarios that are often very expensive and logistically challenging to replicate using manned assets or live (aggressor) missiles. These scenarios can include coordinated and saturation attacks involving a large number of incoming threats (as observed in recent conflicts). Such complex scenarios are increasingly representative of potential real-world confrontations and are essential for robust IAMD validation.
● **Reduced Logistical Footprint:** UAS generally require less logistical support, including fewer personnel, less fuel, and less extensive maintenance infrastructure, compared to manned aircraft. This makes them easier to deploy and operate efficiently in diverse multinational exercise settings.

Utilizing UAS as a red team offers a paradigm shift in testing and training IAMD by providing a highly realistic, scalable, and cost-effective threat simulation - Figure 1. Drawing directly from lessons in recent conflicts where UAS have proven exceptionally effective, this approach allows IAMD systems to be challenged by the same low-cost, high-volume, and unpredictable attack profiles they are now expected to face. Unlike expensive and risk-averse manned aircraft, UAS can replicate swarming tactics and one-way attack vectors to truly saturate and stress an IAMD network's ability to detect, track, prioritize, and engage multiple targets simultaneously. This “affordable realism” enables more frequent and robust training exercises, allowing for the discovery of critical vulnerabilities in sensors, command and control, and effector capabilities before they can be exploited in a real-world engagement.
While cost-effectiveness is a significant advantage, a strategic value of UAS in IAMD red teaming lies in their capacity to enable scenarios that are otherwise difficult to set with traditional assets. This represents an interesting shift in the value proposition, moving from primarily cost-reduction to capability-enhancement, making UAS indispensable for adapting to a modern and effective IAMD posture. UAS can nimble the system development, doctrine refinement, and personnel training, which is crucial for adapting to the fast-evolving threats posed by AI-driven autonomous systems and other emerging technologies. It enables a continuous feedback loop for improvement.

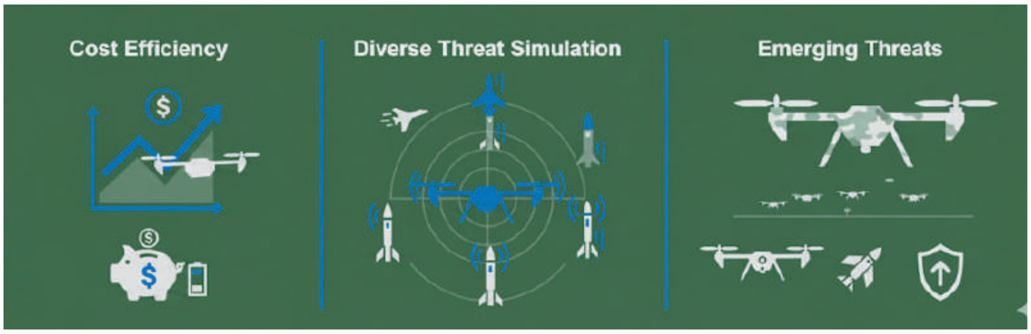


Figure 1 – Summary of the benefits of using UAS for read teaming IAMD

The European Defence Agency's Role in Advancing UAS and IAMD

The European Defence Agency is uniquely positioned to act as a catalyst and coordinator for the integration of UAS as red team aggressors within European IAMD capabilities. Its mandate and collaborative framework make it an indispensable actor in this critical defence transformation, cf. Figure 2.

Figure 2 – EDA's collaborative development and procurement initiatives.

Key Avenues of EDA Contribution

● **Facilitating Collaborative Development and Procurement:** The EDA promotes and supports collaborative projects among Member States for the development and procurement of advanced capabilities. This collaborative approach is designed to lead to significant economies of scale, ensure critical interoperability across national systems, and foster the combined security and defence efforts. EDA has developed Priority Implementation Roadmaps (PIR) to concretely address the EU Capability Development Priorities. Additionally, an IAMD Letter of Intent drafted by EDA was signed by 19 Member States. An IAMD Concept Paper was also developed to foster collaborative opportunities and shared with NATO as a read-ahead of the NATO IAMD Conference. A prime example of such collaboration in the broader UAS domain is the EDA's support for the European medium-altitude long-endurance UAS programme, the "EURO-MALE," via OCCAR.

● **Promoting and Supporting Multinational Training and Exercises:** The EDA plays a crucial role in integrating UAS into both existing and new multinational training exercises, via its unit, dedicated to Operations, Training and Exercises. This comprehensive support encompasses the planning, execution, and detailed analysis of such exercises. The EDA leverages its extensive expertise in critical areas such as military airworthiness and the complex airspace integration requirements for UAS (within the Single European Sky Unit). Furthermore, initiatives like the EDA's support for Test and Evaluation (T&E) centres could also be expanded and specifically tailored to address UAS-based IAMD testing against advanced autonomous threats.

● **Enhancing Interoperability:** Through its central role in EU Capability Development priorities implementation, EDA can significantly contribute to the fundamental interoperability of IAMD systems and operational procedures among Member States – and allied nations in coordination with NATO. This is a critical prerequisite for effective joint and combined operations against the diverse and technologically evolving threats of today and tomorrow.

● **Support for EU Defence Industry:** The EDA is also directly supporting the EU Defence Industry by delivering calls for tenders on specific and important UAS-related technology and air traffic integration enablers. Furthermore, it supports the European Commission in drafting European Defence Fund (EDF) calls and in the revision of the multi-annual planning of the EDF. Early June EDA organized an Air Superiority Industry Workshop to share and discuss PIRs with industry, and especially the IAMD one.

● **Bridging the "Valley of Death":** As highlighted in EDA's operational experimentation campaigns, the Agency plays an important role in helping to transition promising UAS technologies from advanced development stages into practical operational use for IAMD testing. This function ensures that innovative solutions successfully reach the warfighter, addressing real-world capability needs.

● **Alignment with NATO:** The EDA actively collaborates with NATO to align efforts on UAS development. This alignment spans key axes, including airspace integration of military UAS, the development of advanced technologies for UAS (especially in the field of autonomy, e.g., artificial intelligence and flight in GNSS denied environments, and baseline taxonomy, with projects like USESXI, UASRESOLVE and SAPAS), military UAS risk assessment (MUSRA), and the support to NATO STANAG on Training of Remote Pilots (ATP 3.3.8.1) and STANREC on Autonomy Guidelines.

The EDA's extensive coordination with a wide array of stakeholders including, the MS, EDTIB, EU Commission, EASA, EUROCONTROL, national authorities and standardization bodies for the "safe integration of military UAS into general air traffic (GAT)" highlights the intricate and complex interplay between technological development, regulatory frameworks, and operational realities, cf. Figure 3. This demonstrates that technical solutions cannot exist in a vacuum. Successful integration and operationalization of advanced defence technologies like UAS require a multi-stakeholder and multi-domain approach that transcends purely military considerations. Policy, regulation, and airspace management are equally critical to operationalize these capabilities effectively and safely across multinational environments, underscoring the need for integrated governance and collaboration.

By leveraging UAS, the EDA can enable its MS to conduct more rigorous, frequent, and cost-effective assessments of their IAMD capabilities. This strategic approach allows for the preservation of valuable missile stockpiles for actual operational use, while still achieving high-fidelity training and system validation against the most challenging modern threats.

Figure 2 – EDA's collaborative development and procurement initiatives.

Strategic Alignment with European Commission's Defence Readiness 2030: Drones, Counter-Drones and IAMD

The European Commission's White Paper on Defence Readiness 2030 outlines an ambitious vision for a more capable, resilient, and technologically advanced European defence posture. The strategic utilisation of UAS for IAMD red teaming, and more broadly, the entire effort to overcome the challenges of their integration, robustly aligns with several key objectives articulated within this important document. Successfully navigating the labyrinth of airspace integration is not merely a niche aviation issue; it is a prerequisite for achieving the high-level strategic goals set forth by the Commission.

The White Paper explicitly identifies the need to close critical capability gaps, with "air and missile defence, alongside drones and anti-drone systems" mentioned as a priority area. UAS-based red teaming directly addresses this imperative by providing a robust means to identify weaknesses and validate the effectiveness of IAMD systems. The specific phrasing in the White Paper is highly significant, as it recognises drones both as a threat to be defended against and as a versatile tool for defence, highlighting a sophisticated and pragmatic understanding of modern aerial warfare.

Furthermore, investing in the development of advanced UAS and the complex systems required for their integration significantly contributes to strengthening the EDTIB. EDA-facilitated collaborative projects can foster the growth of European industry and strategically reduce dependencies on non-EU suppliers for vital training, testing, and operational capabilities. This directly supports the White Paper's goal of ensuring the EDTIB is more competitive, resilient, and technologically sovereign. The EDA's role in aggregating demand towards joint procurement directly reflects the White Paper's call for Member States to "spend better, work together, and prioritise European companies".

Finally, the entire endeavour resonates with the White Paper's ambition to harness disruptive technologies for defence advantage. UAS, particularly those incorporating advanced autonomy, represent a rapidly evolving field. Employing them for threat replication and integrating them into the airspace actively drives innovation in cutting-edge areas such as artificial intelligence, advanced sensors, and resilient communications. Ultimately, the overarching aim of the White Paper is to enhance European defence readiness. Realistic, frequent, and complex IAMD training, enabled by fully integrated UAS, profoundly contributes to this goal by ensuring that personnel are better prepared, systems are thoroughly vetted, and doctrines are continually refined based on empirical data.

Conclusion

The strategic adoption of Unmanned Aircraft Systems (UAS) as red team aggressors is seen as an considerable improvement and a fundamental necessity for the future of European Integrated Air and Missile Defence (IAMD). The contemporary security landscape is increasingly defined by a proliferation of sophisticated, autonomous, and low-cost aerial threats that render traditional training methods dangerously outdated. As this article has argued, UAS offer a transformative solution by providing an unparalleled combination of **cost-effectiveness, scalability, and realistic threat replication**—from elusive, slow-moving targets to complex saturation attacks—which is essential for rigorously validating the IAMD systems of today and tomorrow.

However, the path to leveraging this full potential is impeded by significant, interconnected challenges. The primary obstacle remains the complex task of **airspace integration,** a multifaceted problem encompassing fragmented regulatory frameworks, critical technical hurdles like certified Detect and Avoid (DAA) systems, and unique military dilemmas that conflict with civil aviation principles. Successfully navigating this labyrinth is both a technical and strategic challenge.

Overcoming these barriers requires a concerted, multi-stakeholder effort, where the **European Defence Agency (EDA)** serves as a crucial catalyst for collaboration, standardization, and innovation. By aligning with the high-level objectives of the European Commission's Defence Readiness 2030, these initiatives directly address critical capability gaps in IAMD and drones while strengthening Europe’s industrial base. Ultimately, while the journey is complex, the strategic imperative is clear: integrating UAS into IAMD red teaming is **paramount** for building a more resilient, adaptive, and combat-credible European defence posture, ensuring that the Alliance is prepared not for the conflicts of the past, but for the evolving realities of the modern aerial battlespace.

Simulation of a Mach-7 Waverider in Off-Design Conditions

about
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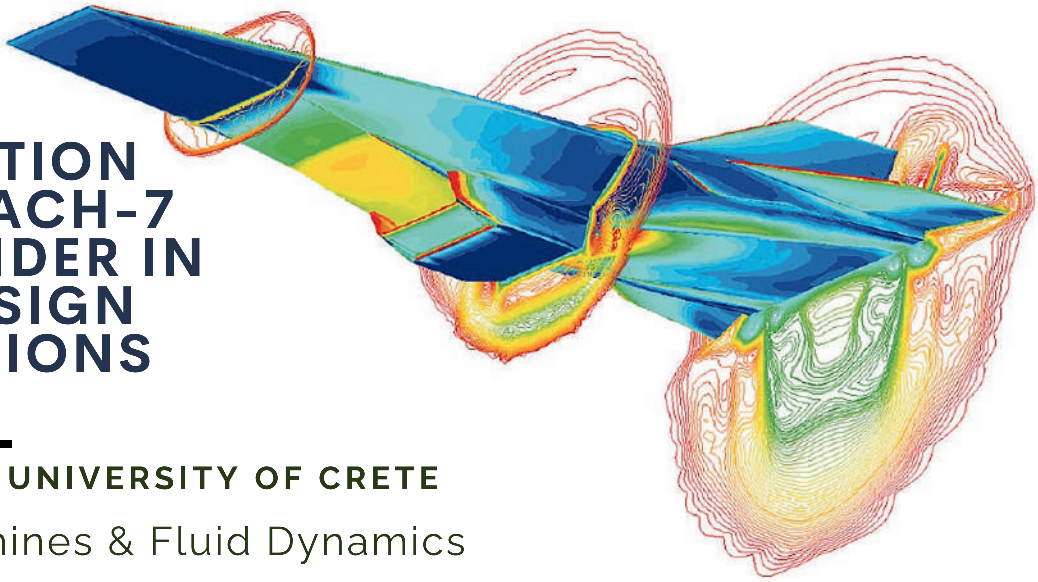

SIMULATION OF A MACH-7 WAVERIDER IN OFF-DESIGN CONDITIONS

TECHNICAL UNIVERSITY OF CRETE

Turbomachines & Fluid Dynamics Laboratory

Abstract:
This study investigates the performance of a Mach-7 waverider under off-design conditions through detailed simulations.
Two distinct off-design scenarios were analyzed, revealing that the waverider maintained robust aerodynamic performance, despite the deviations from optimal conditions.
The simulations employed advanced computational fluid dynamics (CFD) techniques to evaluate the aerodynamic efficiency of the vehicle. Results indicated that the waverider performed admirably, without severe losses in aerodynamic efficiency.
These findings underscore the resilience and adaptability of the waverider design, providing valuable insights for future hypersonic vehicle development and operational flexibility.

Introduction

The waverider is a prominent concept in hypersonic vehicle design, known for its superior aerodynamic efficiency at high speeds. Originally conceived in the 1960s [1], waveriders leverage shockwave structures to produce lift, minimizing drag and enhancing overall performance. These characteristics make them ideal candidates for applications such as hypersonic reconnaissance, rapid transportation, and spaceplane operations.
The focal point of this study is the simulation of a Mach-7 waverider in off-design conditions, a critical aspect given the practical operational environments where deviations from ideal flight parameters are inevitable. Hypersonic flight presents unique challenges, including extreme aerodynamic heating, high dynamic pressures, and complex shockwave-boundary layer interactions. Designing vehicles capable of maintaining performance in such regimes necessitates robust simulation and analysis techniques.

While significant research has been conducted on waverider performance at design conditions [2, 3, 4, 5], there is a relative paucity of data on their behavior under off-design scenarios. This gap is particularly significant given that real-world operations seldom adhere strictly to optimal flight conditions. Hence, understanding the performance of waveriders in off-design conditions is crucial for their practical application and reliability.
In this work, we focus on a Mach-7 waverider, a vehicle designed for sustained flight at seven times the speed of sound. The choice of Mach 7 is pertinent, as it represents a critical regime in hypersonic travel, balancing technological feasibility and performance demands. The study aims to simulate the waverider's performance in distinct off-design conditions, providing insights into its aerodynamic behavior and potential adaptability. The off-design conditions examined in this study involve variations in altitude and angle of attack.

The waverider was originally designed for an altitude of 90 km, optimized for this specific high-altitude environment to achieve maximum aerodynamic efficiency. The first off-design condition simulates flight at an altitude of 45 km and a speed of Mach 6.2. Under these conditions, the calculated lift-to-drag (L/D) ratio was found to be less than one, indicating a significant deviation from optimal performance. This scenario helps us understand the waverider's performance in a mid-altitude environment where atmospheric density is higher and the aerodynamic forces differ markedly from the design specifications. The second off-design condition examines flight at an altitude of 30 km with a 2-degree angle of attack and a speed of Mach 6. In this case, the L/D ratio was computed to be 1.463. This scenario provides insights into the vehicle's performance at a lower altitude, with a small deviation in the angle of attack, simulating a realistic operational condition where slight adjustments in flight parameters are necessary.

To conduct these simulations, we employ advanced computational fluid dynamics (CFD) tools, leveraging high-fidelity models to capture the complex interactions between the waverider and the hypersonic flow field. CFD has become an indispensable tool in hypersonic research, offering detailed insights into flow phenomena that are often challenging to measure experimentally. Our simulations provide a comprehensive analysis of aerodynamic forces, pressure distributions, and thermal loads under off-design conditions. The simulations for the 90 km altitude, where the atmosphere is rarefied, were conducted using the DSMC solver SPARTA [6] while simulations for the off-design altitudes were conducted using SU2 solver [7].

By exploring the performance of a Mach-7 waverider in off-design conditions, this work aims to bridge the knowledge gap in hypersonic vehicle behavior under non-ideal scenarios. The insights gained from this study are expected to inform the design and operation of future hypersonic vehicles, enhancing their robustness and operational flexibility in practical applications.

Results

This section presents the outcomes of the computational simulations conducted to evaluate the performance of the waverider under the aforementioned off-design conditions. More specifically, the study focuses on two different altitudes, 45 km and 30 km, and variations in angle of attack at Mach 6. These off-design conditions were chosen to assess the vehicle's aerodynamic and thermal behavior in environments deviating from its optimal design altitude of 90 km.
The simulations provide comprehensive insights into the Mach number distribution, pressure and temperature fields, turbulent viscosity, and heat flux around the waverider, elucidating its adaptability and performance robustness under these challenging scenarios.

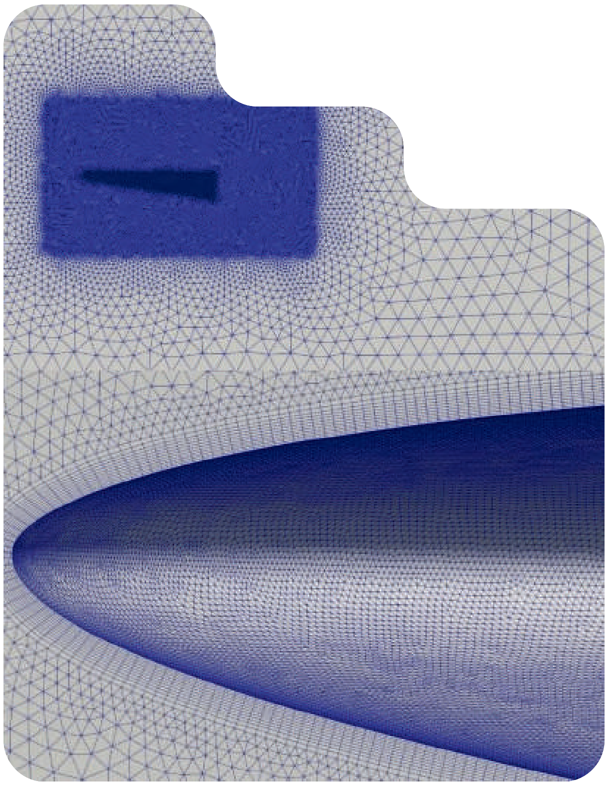

Figure 1. Computational grid overview.

Figure 1 provides an overview of the computational grid used for the simulations. A very dense surface grid was constructed on the vehicle's solid surface to allow for a detailed description of the geometry and the accurate simulation of the related flow phenomena.

The unstructured (hybrid) computational grid comprises of 54,484,085 elements and 15,732,524 nodes. While solving the Navier-Stokes equations requires fewer computational resources compared to the Direct Simulation Monte Carlo (DSMC) method, it is not without significant challenges. Solving the extended Navier-Stokes equations to accommodate reacting flows in thermochemical non-equilibrium conditions at high Mach numbers is particularly demanding. These equations form a complex system of interconnected nonlinear partial differential equations (PDEs), and their iterative solution can present numerous convergence issues. Consequently, multiple attempts may be necessary to achieve a converged solution.

Figure 2 depicts the velocity magnitude on the symmetry plane (top) and Mach number contours (bottom) at a plane parallel to the vehicle, for an altitude of 45 km. The contours highlight the flow acceleration around the waverider, with a clear visualization of the shockwaves formed at the leading edges. The Mach number distribution indicates significant deceleration as the vehicle interacts with the denser atmosphere at this altitude. The interaction with the denser atmospheric layers results in more intense shockwave-boundary layer interactions, which are critical for understanding the aerodynamic performance under these conditions.

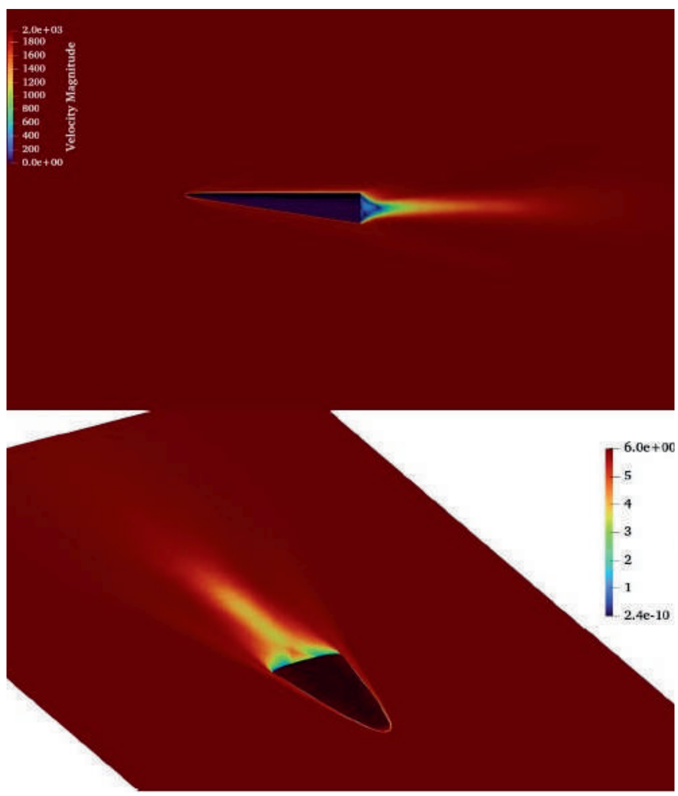

Figure 2. Velocity and Mach number contours, at an altitude of 45 km.

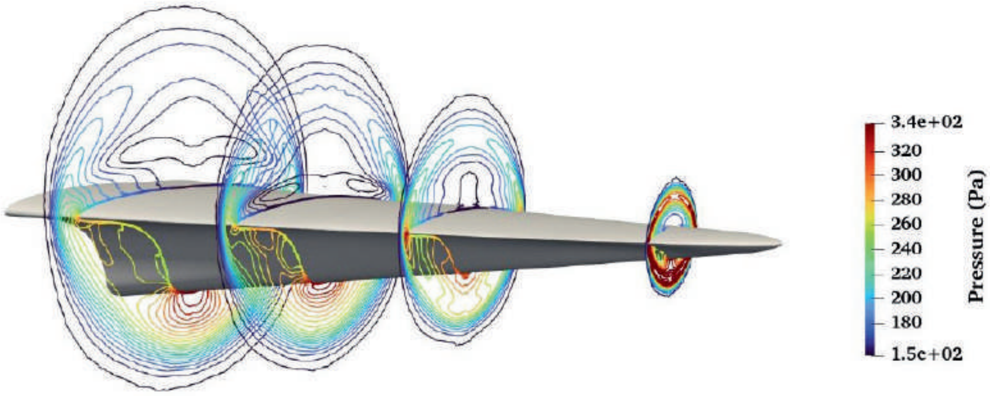

Figure 3. Contours of static pressure at various planes normal to the symmetry plane at an altitude of 45 km.

Complementing the Mach number contours, **Figure 3** shows the static pressure contours at various planes normal to the symmetry plane at an altitude of 45 km. These contours illustrate the pressure distribution around the vehicle, revealing high-pressure regions at the lower surfaces. This pressure differential is essential for generating lift and maintaining aerodynamic stability. The pressure gradients observed are indicative of the intense aerodynamic forces acting on the vehicle, which are critical for ensuring its structural integrity during high-speed flight.

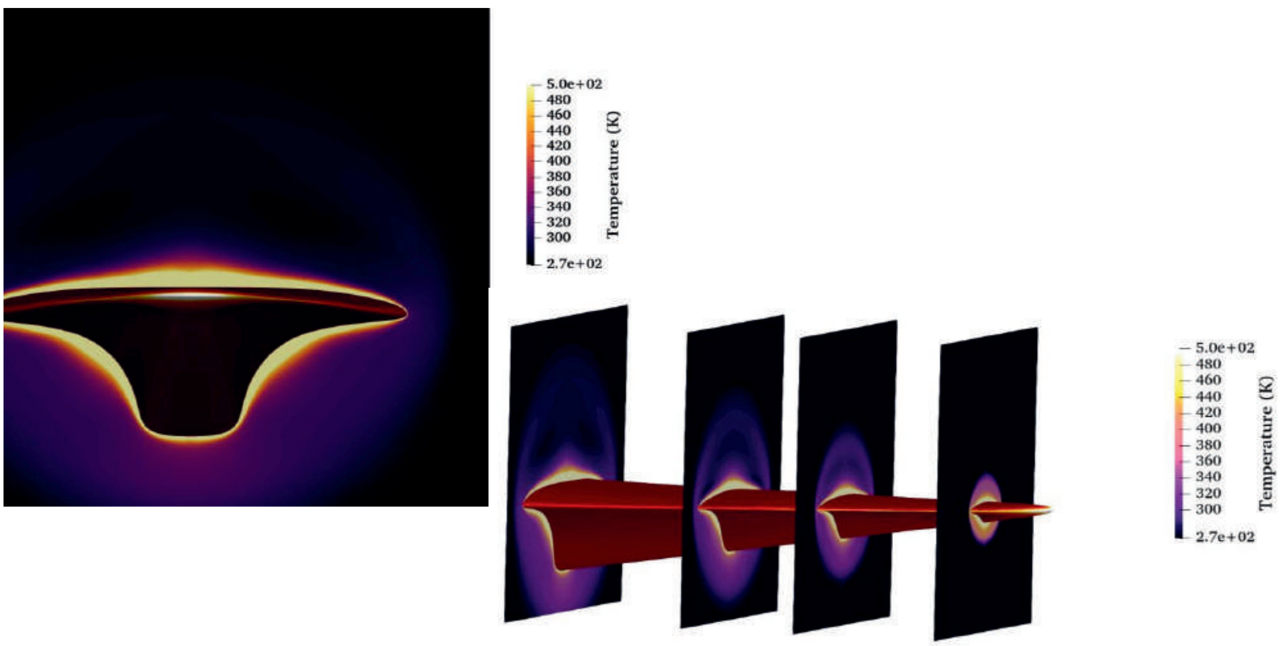

Figure 4. Temperature field around the vehicle at different planes normal to the vehicle's axis (top) and at a plane normal to the vehicle's axis, at an altitude of 45 km.

Further details of the thermal environment are captured in **Figure 4**, which depicts the temperature field around the vehicle at different planes normal to the vehicle's axis (top) and at a plane normal to the vehicle's axis, at an altitude of 45 km. The temperature distribution is crucial for understanding the thermal loads experienced by the waverider. The results show significant heating near the leading edges and lower temperatures in the wake regions, consistent with shockwave heating effects.

Expanding on this, **Figure 5** offers a volumetric three-dimensional rendering of the thermal trace at 0.0 degrees angle of attack at an altitude of 45 km. This perspective view provides a comprehensive visualization of the thermal footprint of the waverider, highlighting regions of intense heating and the overall thermal environment surrounding the vehicle. This volumetric rendering is particularly useful for identifying hotspots and understanding the overall heat distribution patterns, which are critical for effective thermal management.

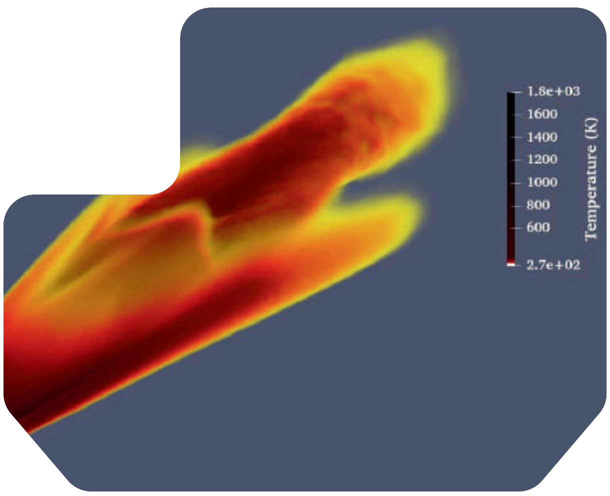

Figure 5. Volumetric three-dimensional rendering of the thermal trace at 0.0 AoA, at an altitude of 45 km (perspective view).

Transitioning to a lower altitude, **Figure 6** illustrates the Mach number contours at an altitude of 30 km on the symmetry plane (top) and a plane normal to the vehicle's axis. The contours at this lower altitude show a similar pattern of shockwave formation and flow deceleration, but with more pronounced effects due to the increased atmospheric density. This increased density at lower altitudes results in stronger shockwaves and higher aerodynamic heating, which are key considerations for vehicle performance and thermal protection.

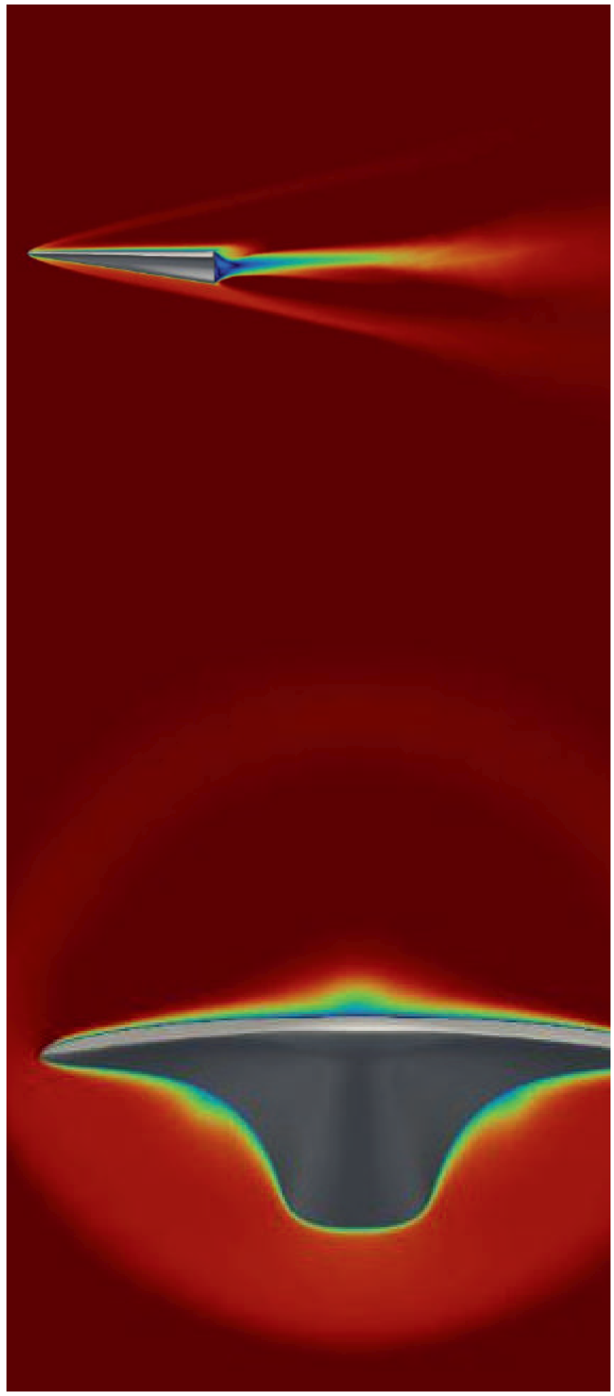

Figure 6. Mach number contours at an altitude of 30 km on the symmetry plane (top) and at a plane normal to the vehicle's axis.

Figure 7 combines the visualization of turbulent viscosity downstream with the pressure distribution around the vehicle at a plane normal to the vehicle's axis, at an altitude of 30 km. This combined view provides insights into the interaction between pressure forces and turbulent effects, which are critical for vehicle stability and control.

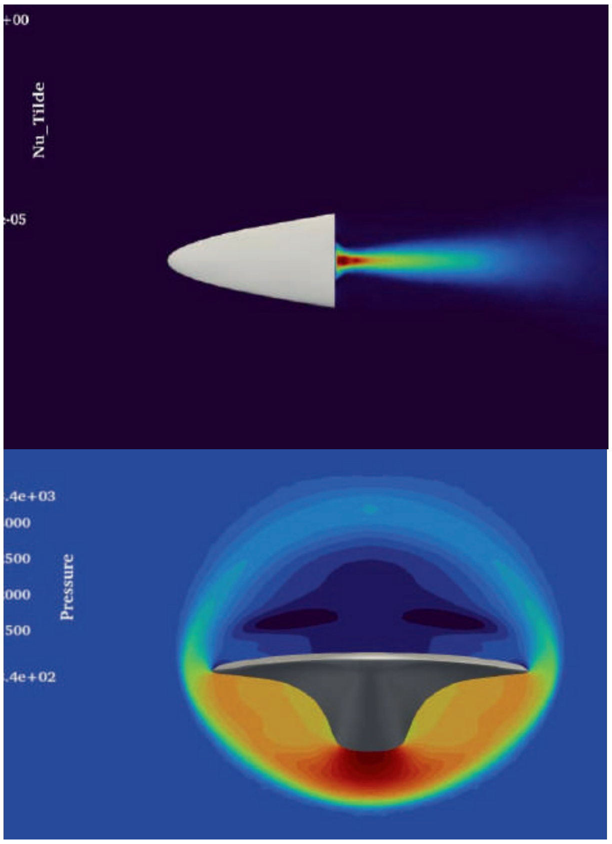

Figure 7. Turbulent viscosity downstream (top), and pressure distribution around the vehicle, at a plane normal to the vehicle's axis (altitude 30 km).

To further assess the aerodynamic forces acting on the waverider, **Figure 8** depicts the pressure contours on the vehicle's surfaces, at an altitude of 30 km. This detailed pressure mapping helps in optimizing the aerodynamic design for enhanced performance and efficiency.

To understand the thermal stresses experienced by the vehicle, Figure 9 depicts the temperature distribution at the symmetry plane, while Figure 10 illustrates the heat flux distribution at the symmetry plane, at an altitude of 30 km. These figures highlight the thermal gradients experienced by the vehicle, with significant heating occurring near the stagnation points and cooler regions in the vehicle's wake. This distribution is critical for understanding the thermal protection requirements for the waverider. Effective thermal management is essential to prevent structural damage, due to high-temperature exposure. The colormap has been adjusted for clarity, with the maximum heat flux value recorded as 255.376 kW/m². The highest temperature occurs around the vehicle's nose, reaching a maximum temperature of 1910.82 K. The minimum temperature observed at the back surface of the vehicle is approximately 1200 K, reflecting the thermal complexity of the flow field. Accurate heat flux and temperature predictions are vital for developing materials and coatings that can withstand the extreme thermal environment of hypersonic flight and support the thermal management.

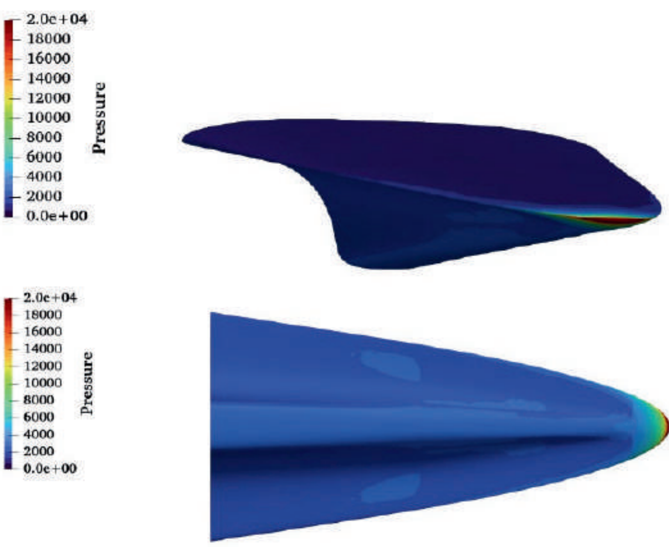

Figure 8. Pressure contours on the vehicle's surfaces (altitude 30 km).

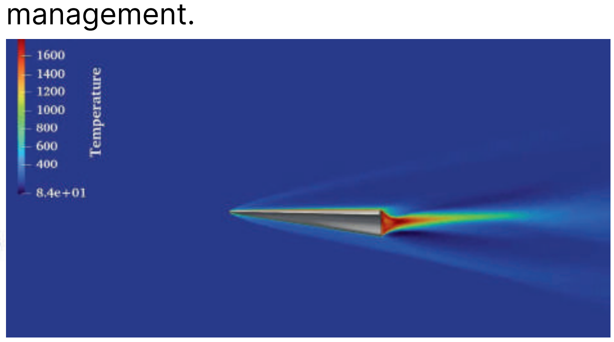

Figure 9. Temperature distribution at the symmetry plane (altitude 30 km).

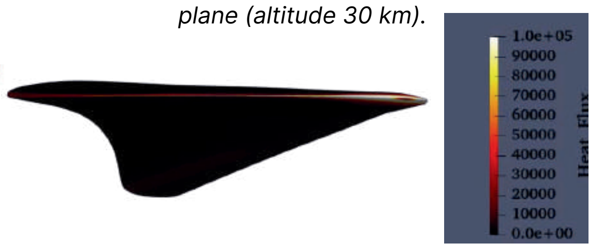

Figure 10. Heat flux distribution on the surface (altitude 30 km).

Conclusions

This study investigated the performance of a Mach-7 waverider under off-design conditions through detailed computational simulations. By examining the aerodynamic and thermal behavior of the waverider at altitudes of 45 km and 30 km, and varying the angle of attack at around Mach 6, we have gained valuable insights into the vehicle's robustness and adaptability in non-ideal operational environments. The simulations revealed that the waverider maintains significant aerodynamic efficiency even when operating outside its design altitude of 90 km. The detailed analysis of Mach number distributions, pressure and temperature fields and heat flux provided a comprehensive understanding of the vehicle's performance under different conditions. Notably, the pressure and thermal gradients observed highlight the critical areas requiring attention for structural integrity and thermal protection.

Future work will focus on enhancing the fidelity of the simulations by incorporating chemical reactions and non-equilibrium effects. These factors are crucial for accurately predicting the behavior of hypersonic vehicles in realistic operational environments. By addressing these additional complexities, we aim to further refine our understanding of waverider performance and contribute to the development of more resilient and efficient hypersonic technologies.

Acknowledgements

This study was funded by the Integrated Air and Missile Defense Centre of Excellence (IAMD COE) under contract number 22-10 “Analysis of the related Physical Phenomena and Aerodynamic Performance of Hypersonic Vehicle(s) and possible ways of exploiting those data in order to improve Surveillance Capabilities”. The authors would also like to thank the UKTC and EPSRC for computational time on the UK supercomputing facility ARCHER2 via project EP/R029326/1.

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Angelos G. Klothakis was born in Chania, Greece in 1985. He successfully finished his undergraduate studies in the School of Producton Engineering & Management, Technical University of Crete, Greece, in 2010 and his postgraduate studies in Producton Systems, in the same School, in 2015.

He is currently working for his Ph.D. Thesis in the same School, enttled “On the solution of high Mach number flows”. He has been a researcher since 2020 in a joint research project entitled "Mult-scale Modeling of Unsteady Shock-Boundary Layer Hypersonic Flow Instabilities," funded by the Office of Naval Research (ONR) and conducted by the University of Illinois at Urbana Champaign.

Train as you fight reinvented.

Synthetic Environment Exploitation to Enhance NATO IAMD Capabilities.

about

the author

Maj Gen Nikolaos MAKRYGIANNIS (Ret.)

Former IAMD COE Director

ABSTRACT

NATO Integrated Air and Missile Defense (IAMD) is essential for credible deterrence and defense in an era of increasingly complex air and missile threats, from UAVs to hypersonic missiles. To enhance IAMD capabilities, there is a critical need to integrate these efforts into Multi-Domain Operations.

This integration should leverage emerging and disruptive technologies to adapt to a future operational environment characterized by multi-region and multi-dimensional challenges—physical, virtual, and cognitive. Cultivating a military culture within NATO that promotes excellence in these areas is paramount.

INTRODUCTION

Persistent preparation in today's military landscape requires a Synthetic Environment, utilizing advanced modelling and simulation (M&S) to pinpoint improvement areas, foster trust in new capabilities, and support leadership development through wargaming and experimentation. Frequent, realistic training through live, virtual, and constructive (LVC) venues is crucial for conserving resources while enhancing combat realism and multi-domain readiness and to facilitate the development of innovative and collaborative solutions.

The IAMD Center of Excellence (COE) has explored relevant M&S initiatives across NATO nations, identifying modern training methods, including Serious Games and advanced extended reality (XR) technologies.

The COE aims to serve as a knowledge hub, fostering the development of a NATO IAMD simulated battle network while highlighting associated risks and opportunities for stakeholders, including in NATO HQs, NATO Command Structure (NCS), NATO Force Structure (NFS), scientific organizations, and other COEs. This collaborative approach is essential for advancing digitalization in line with the Warfare Development Agenda.

The envisioned transformation of NATO IAMD capabilities is central to the IAMD COE's Power of Work (POW) 25, as approved recently by its Steering Committee. By fully exploiting M&S capabilities across its transformational pillars, the COE seeks to engage with operational and tactical units to utilize the synthetic environment regularly, thereby reinventing NATO's IAMD, training, capabilities development, interoperability, and overall effectiveness.

ANALYSIS

On Going NATO Nations M&S Programs (FASF/HAF/RAF/USAF)

The transition of NATO Air Forces from fourth to fifth-generation fighter aircraft reflects the increasing complexity and cost of modern air combat. As these advanced aircraft become scarce high-value assets, maximizing their sortie effectiveness and training value has become a pressing challenge. This situation is exacerbated by the rising costs of operational flight hours, making it crucial for air forces to manage their resources effectively.

To address the need for Air-to-Air (A2A) and Air-to-Ground (A2G) training, many air forces are increasingly turning to private Red Air services and enhancing their simulation capabilities. The evolution towards a more integrated training environment involves utilizing "common synthetic environments" that allow for non-proprietary and interchangeable training systems. These developments enable aircrews to engage in mission rehearsals and test new weapons in a LVC multi-domain framework.

FASF – AIR WARFARE CENTER/Distributive Mission Operations Center (DMOC)

In this context, the French Air Warfare Center (AWC) and its Distributed Mission Operations Center (DMOC) in Mont De Marsan are at the forefront of these innovations.
Their L-16 LVC system, known as "Jeannette[1]", has been operational since 2018, providing a range of valuable services that enhance mission training and operational readiness. The DMOC facilitates everything from simple missions to complex Combined Air Operations (COMAO) and international exercises, such as VOLFA.

Moreover, the ongoing "Massive Network Simulation" program aims to develop in serious games software advanced part-task trainers for various fixed-wing and rotary platforms, all interconnected with the Jeannette system. This initiative not only supports national training needs but also promotes interoperability with established networks like CFBL NET[2] and emerging multinational training environments in Europe and across the Atlantic.

Picture 1. French AWC/DMOC – LVC - MNS

[1] CS GROUP: JEANNETTE, CS GROUP'S L16 TRAINING SYSTEM AT THE CORE OF THE INTERNATIONAL TOBRUQ LEGACY 2020 EXERCISE - CS GROUP
[2] Combined Federated Battle Laboratories Network (CFBL NET) (CFBLNet Public Site - APAN Community)

In the DMOC, SYNAPSE[3]'s experienced reservist weapons instructors collaborate to enhance training effectiveness. Their roles range from mission planning and airboss duties to running flight animations and conducting thorough debriefings. A key focus is on capturing performance data and statistics, leveraging the expertise of data scientists to provide actionable insights that support the operational requirements of the French Air Force.

HAF - Hellenic Air Tactics Center (HATC)/ Synthetic Training SQN (STS)

The Hellenic Air Force (HAF) has made significant strides in synthetic training through its Hellenic Air Tactics Center (HATC). A dedicated team has successfully developed ten F-16 tactical simulators, eight part-task trainers[4], and a Joint Terminal Attack Controller (JTAC) simulator, all designed to enhance tactical training mainly for Airmen. These systems operate within a cohesive tactical environment and are actively utilized during HATC courses and the annual INIOCHOS live exercise.

Picture 2. HAF HATC/STS M&S Capabilities

By collaborating with allied capabilities (UAWC/ABTC & FASF), HATC has enhanced its synthetic training environment, ensuring << day 1>> interoperability with NATO systems and allowing for efficient coordination with other synthetic environments.

Participation in NATO's RAFL 24-Virtual exercise (Jun 24), the first NATO Virtual rehearsal, marked a significant milestone in digital transformation for the alliance, preparing for future live exercises (OCT 24 in Greece).

HATC is also expanding its synthetic training capabilities with the development of an electronic warfare (EW) training environment and a Live-Virtual-Constructive (LVC) operations center. This center will integrate live platforms via Link-16[6], facilitating a more comprehensive and adaptable training approach.

Plans include extending synthetic training capabilities to HAF combat wings and other branches of the Hellenic Armed Forces, driven by advancements in virtual reality technology and compatible software. These initiatives aim to continually improve training outcomes and operational readiness.

Picture 3. VR/MR devices exploitation in Military/Civilian AVIATORS Training.

[3] A private company contracted by FASF (Expertise combat collaboratif , Entrainement des forces, Simulation).

[4] For Instructors, pilots or Air Battle Managers.

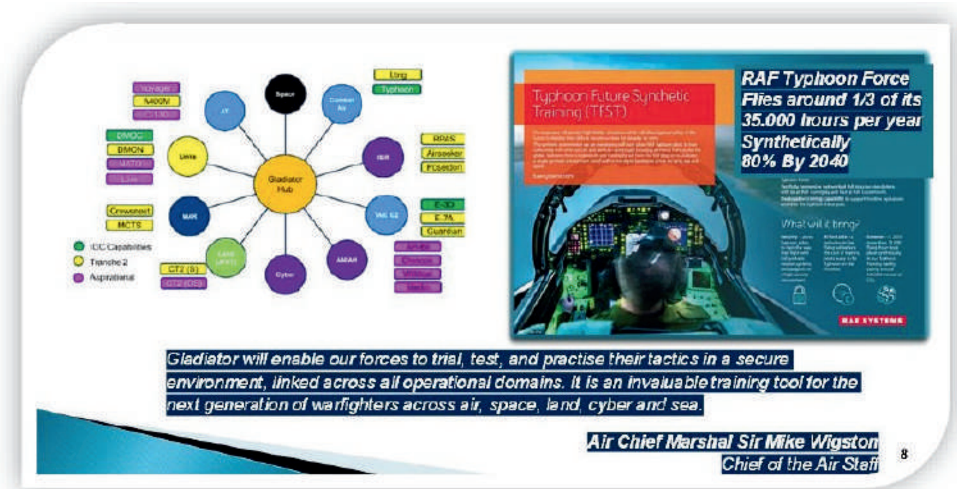
[5] E.g to UAWC/5 th CTS “Spartan Warrior” and ABTC “Athena Warrior” SYNTHEX.

[6] Voice communications among participants through existing Radio/Voice Over IP capabilities.

RAF - GLADIATOR, UK, Air Battlespace Training Centre (ABTC)

The new Gladiator training capability at ABTC - RAF Waddington - represents a significant advancement in synthetic training systems. This world-leading facility connects various synthetic training devices to a central hub, enabling collaborative training across Land, Maritime, and Air domains in a safe and secure environment.

The scale and security of this training are unprecedented in Europe, and future expansions will integrate Space and Cyber capabilities, enhancing connectivity with Allies and Partners. Air Chief Marshal Sir Mike Wigston highlighted the importance of Gladiator in preparing the next generation of warfighters across all domains.



Picture 4. Gladiator - ABTC

Importantly, Gladiator complements live training rather than replacing it, ensuring that training activities are conducted in the most effective settings. The UK Ministry of Defence has invested over £220 million in BAE Systems to deliver high-fidelity simulators[7] specifically for Typhoon pilots, further solidifying Gladiator's role in advanced synthetic training.

USAF – USN /VVTC & JSE

The Air Force Warfare Center at Nellis Air Force Base is advancing its Virtual Test and Training Center8 (VTTC), which provides a sophisticated platform for pilots and crews to train together using a variety of simulators in a controlled environment. This initiative not only enhances pilot training but also explores the integration of synthetic scenarios with live flying operations at the Nevada Test and Training Range.

The “vision” is for all the Air Force’s latest-generation aircraft to have a device that connects to the VTTC campus, and moreover to connect the newest platforms to the Joint Simulation Environment (JSE), a government-owned, non-proprietary modeling and simulation environment.

The JSE, initially established at the Naval Air Warfare Center Aircraft Division features a network of simulators, including eight F-35 and four F-22 cockpits, all designed to replicate actual aircraft systems precisely. This facility supports the simulation of complex mission scenarios with thousands of threats sourced from the latest intelligence models. It allows for the integration of various adversarial elements, such as enemy aircraft and advanced weaponry, along with electromagnetic, infrared, and cyber threats.

[7] Together with highly secure, state of the art, training facilities at RAF Coningsby in Lincolnshire and RAF Lossiemouth in Moray.

The JSE serves as a critical training tool, having already trained over 1,000 F-35[8] pilots, incorporated as well into the formal curriculum for weapons schools. This training environment is seen as vital for preparing pilots for real-world combat situations against peer adversaries. Department of Defense plans are in place to extend this high-fidelity simulation capability to additional Navy and Air Force facilities, with a fully operational JSE, complete with F-35 and F-22 cockpits, expected at Nellis AFB by 2028.

Picture 5. AWC/VTTC - JSE

Comprehensive NATO IAMD Training Environment

Considering that NATO IAMD must be multi-national by design, not aspiration, such integration demands a comprehensive multi-national training environment, including an open architecture network, command and control, tactical data links, shared doctrine and operating procedures. The baseline must remain "train as you fight" being as close as possible to the real operational environment. To that end, innovative ways of training are to be further developed, to complement live training in multi-domain operations, with most of the participants being in their operating environment-almost everyone besides the pilots[10] who will mainly connect through a simulated cockpit.

Proprietary simulators, however, each created by the manufacturer of the platform itself with inherent modeling, security, and latency limitations, make it expensive and time-consuming to link together multiple platforms and test new threat paradigms.

and latency limitations, make it expensive and time-consuming to link together multiple platforms and test new threat paradigms.
Integrated LVC training solutions could be developed and through standardized distributed simulation protocols to enable realistic tactical mission training, both at national and multinational levels, with a higher impact on the multinational coalition operations.

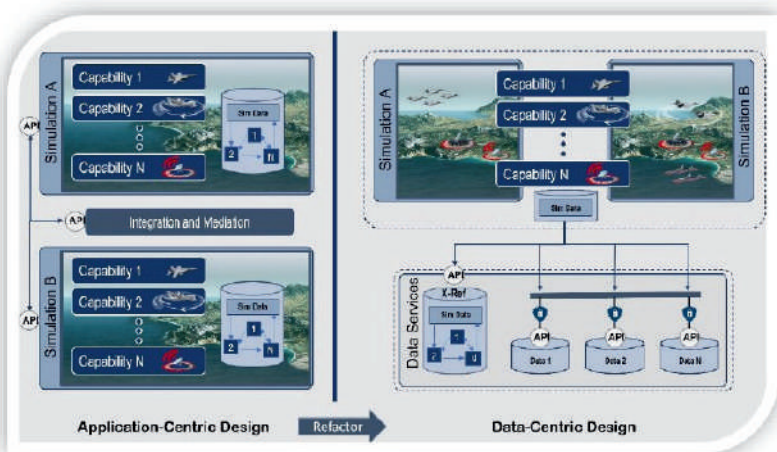
The urgency of the shift to the synthetic environment is multifaceted, including adversary observation capabilities, current range limits, the need to integrate multiple platforms with high operating cost, airspace capacity including environmental considerations, and that some training and test aspects cannot be efficiently taken place in a live environment. Adversary observation means everything from weapons testing to new tactics, techniques, and procedures (TTPs) can now be seen, particularly by opponents' satellites passing overhead.

[8] In early 2022, instructor and student pilots from the US Air Force (USAF) Weapons School used the JSE for a sprawling training exercise. They executed 32 defensive counter-air missions, each eight F-35s against up to 20 [adversary] threats, unimagined exercise in any other live or simulated environment.

Current ranges are also too limited for modern air warfare, as rehearsals needed require multiple aircraft and standoff distances in hundreds of miles, making it almost impossible to put all those assets together in one piece of sky, considering the cost of such setups as well. Moreover, the increased use of synthetic training will help with more efficient airspace exploitation[13] in addition to reducing the current carbon footprint[14] of live training. Finally, and more importantly, modern 5th gen platforms cannot be efficiently exploited[15] faced with poorly simulated Red Air adversaries (e.g F-16, and threat emulators), restricting needed Fighter Pilots advanced and realistic training, consequently undermining the pilots' Fighting Spirit.

When you pair all of those together, to enable effectiveness and performance you're almost left with no choice but to start executing some of this high-end, advanced test, training, and tactics development concerning IAMD effects in the synthetic environment, delivering cost[16], time, enhanced realism[17] and sustainability benefits over live training, enabling IAMD fighters, including fifth generation pilots, to acquire the skills they need to exploit the IAMD capabilities in the multi domain operation context to the maximum extent. Easier said than done, to achieve such effectiveness, in a NATO environment several parameters should be faced;

among others, various levels of security and interoperability (as the need for correlated terrain/targets), the integration of other domain M&S effects including cyber and space, intellectual proprietary rights and conflicting interests by industry, national procurement procedures, lack of the needed workforce to efficiently run suggested capabilities in parallel with live ops, and critically, the institutionalization of the synthetic training, maybe the most difficult task at hand, as the transition to synthetic training will likely face resistance due to organizational inertia, necessitating strategic change management approaches.



Picture 6. US shifting to a data-centric enterprise

[9] Many other IAMD fighters from C2 ABM, RTOs, to most SBAMD units, including navy units, might be connected to the envisaged training environment through a LINK (e.g J-REAP C).
[10] Instead starting from operational requirements.
[11] To be trained in an unfamiliar environment before deployment is crucial.
[12] E.g Single European Sky capacity increase.
[13] Support the European Green Deal and climate neutrality by reducing CO2, NOx and Noise emissions - for Eurofighter almost 9.6 tonnes of carbon saved by every synthetic flight.
[14] Cannot be "tricked".
[15] Economies of scale for NATO IAMD - Immense cost reduction measured long term in Billions €.
[16] Often, the operators in a synthetic environment underline a true sense of fear as they're getting punished if they make mistakes tactically.

Moreover M&S data should be treated as Strategic Asset[19], as a data-centric enterprise not only will provide shorter integration times and more readily available training opportunities to conduct Joint training exercises and mission rehearsals, but in addition will fuse research and experimentation to support capabilities development, and wargaming to enhance decision making from the political to the tactical level.

IAMD COE Supporting Role

The IAMD COE is strategically positioned to transform IAMD training within NATO, aligning with the Alliance Warfare Development Agenda, addressing ongoing challenges and enhancing cooperation among allies, by supporting the development of a NATO Synthetic Training Network across multiple services and domains to facilitate joint training, research, experimentation, and wargaming, thereby strengthening IAMD capabilities.

As a central hub, the IAMD COE will share insights on existing solutions and promote research and analysis while engaging with relevant stakeholders. A critical aspect of this transformation involves enhancing Modeling and Simulation (M&S) capabilities, with a new facility set to open in 2025[20]. This facility will enable remote connectivity to various LVC environments through the CFBL Net and VoIP.

Building robust relationships with the Operational and Training Community in locations like Souda Bay and leveraging the Synthetic Environment will further enhance collaborative training efforts. Support from NCIA and engagement with the M&S COE and the NATO DST WG will help streamline wargaming initiatives, minimizing duplication of efforts, while fostering innovation in experimentation within synthetic environments. This includes exploring concepts related to Unmanned Aerial Systems (UAS) and Hypersonic threats, which are vital for developing effective IAMD capabilities.

An operational state-of-the-art VR Tactical Simulator will provide interoperability with existing LVCs and serve as a Part Task Trainer for both Blue and Red Air scenarios. This initiative will enable valuable data capture for mission analysis and rehearsal, and support studies on the application of VR/MR devices in IAMD missions, particularly for fighter pilot training, in response to NATO Requests for Support. Through these efforts, the IAMD COE aims to significantly enhance NATO's defensive posture in the evolving threat landscape.

Picture 7. IAMD COE envisioned IAMD M&S Ecosystem

[17] As described in the Modelling and Simulation (M&S) US Government Reference Architecture (GRA) for Synthetic Training.
[18] To achieve this goal, data should be visible, accessible, understandable, trusted, and interoperable at the user's security level while securing that data when created, curated, and shared within the training environment to accelerate training with precision, speed, and scale (overall vision of US GRA).
[19] Space, air, maritime, land, cyber, and from the electromagnetic spectrum.
[20] By Greece, IAMD COE Framework Nation.

CONCLUSION

The evolving landscape of Integrated Air and Missile Defense (IAMD) necessitates a transformative approach to capabilities, leveraging advanced technologies and fostering a culture of innovation within military alliances. The integration of LVC environments is essential for preparing forces to meet modern multi-domain challenges effectively.

Key elements for this transformation include:

• Digital Transformation: Embracing modern technologies, including commercial off-the-shelf solutions, to enhance training efficiency and realism in IAMD operations.
• Collaboration and Networking: Building trust and cooperation among allied forces through persistent engagement in LVC environments, facilitating shared experiences and learning opportunities.
• Human Capital Investment: Developing expertise and training personnel who can manage complex synthetic exercises, ensuring effective planning and execution.
• Operational Requirements: Addressing the challenges in defining clear operational needs within the rapidly changing military landscape, where traditional approaches may not suffice.
• Innovative Solutions: Encouraging creative problem-solving and collaborative initiatives to adapt to emerging threats and technologies, thus enhancing overall readiness.
• Stakeholder Engagement: Involving various levels of military and political stakeholders to drive a unified approach to capability development and operational integration.

The IAMD Center of Excellence aims to be a pivotal hub for these efforts, promoting the transformation of IAMD capabilities while navigating relevant complexities. The transition to a more integrated, synthetic training environment is not just a logistical or technological challenge but a strategic imperative for NATO. It requires a concerted effort to align policies, overcome institutional resistance, and prioritize interoperability and security to fully realize the benefits of multi-national training initiatives.

The potential for improved operational effectiveness, cost efficiency, and environmental sustainability makes this shift essential for future readiness in complex multi-domain operations. By focusing on these areas, NATO can position itself to capitalize on significant projected benefits, reinforcing its defensive posture in an increasingly complex global security environment.

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