Transforming Joint Air and Space Power

THE JOURNAL OF THE JAPCC

Edition 42 | 2026

Joint Air Power Competence Centre


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Editorial

Welcome to the 42nd edition of the JAPCC Journal. Continuing with our Annual Theme, *Air Power at the Edge: Securing NATO's New Frontiers,* this edition returns to a question underpinning every capability we field: how do we prepare the people who will operate at that edge, and the architectures connecting them? Capability is bounded less by what the Alliance can buy than by what it can crew and connect. Aircrew, controllers, and the command and control (C2) arrangements that bind them set the rate at which everything else becomes useful.

We open with departing reflections from our Executive Director, Lt Gen Thorsten Poschwatta, whose stewardship has shaped this Centre's contribution to Joint Air and Space Power. Major General Marios Bantouvas then describes the Hellenic International Flight Training Centre as a shared Allied training asset. In 'How to Train Your Pilot', a companion piece sets a deliberate marker: however capable synthetic environments become, live flying and the guide by instructors' real-time judgment cannot be replaced.

Our Transformation and Capabilities section examines where our structures must change to keep pace with technology. Colonel Kevin 'Tread' Anderson explores the seams between the North American Aerospace Defense Command (NORAD) and NATO command and control in the High North, where two architectures must function as one. Major Eric Yuan then considers the requirements for the future aerial refuelling fleet, and James Black and Stuart Dee from RAND Europe discuss the promise and the barriers to fielding Directed Energy Weapons. Subsequent articles highlight the decryption risk quantum computing poses to Air C2, and the promise and limits of optical satellite communications.

Our authors then turn to integration. One traces how Tactical Air Control Parties must evolve into multi-domain teams employing small uncrewed systems and electronic warfare. Another argues for Artificial Intelligence as the means to fuse sensor data at the tempo Integrated Air and Missile Defence now demands. A third makes the case that Live, Virtual, and Constructive (LVC) infrastructure must be built for interoperability from the outset rather than retrofitted later. It sits alongside 'How to Train Your Pilot': that piece asks where LVC belongs in the pipeline, this one how it should be built.

Our Out of the Box contribution looks back to look forward. It analyses the first year of the invasion of Ukraine through Russian helicopter losses, and what they suggest about the cost of adapting too slowly.

Taken together, these contributions describe an Alliance that must think as quickly as it fields. That is the standard the JAPCC sets for itself, continuing the discussion at our forthcoming *Joint Air and Space Power Conference.*

This edition also introduces dedicated International Standard Serial Numbers (ISSNs) for the print and online Journal, strengthening its publication identity and discoverability. We invite you to share your views through our new Reader Feedback Survey. Scan the QR code on page 86 and help us shape future JAPCC publications.

Vito Cracas
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The Journal of the JAPCC welcomes unsolicited manuscripts.
Please email submissions to: **contact@japcc.org**

We encourage comments on the articles in order to promote discussion concerning Air and Space Power. Current and past JAPCC Journal issues can be downloaded from: **www.japcc.org/journals**

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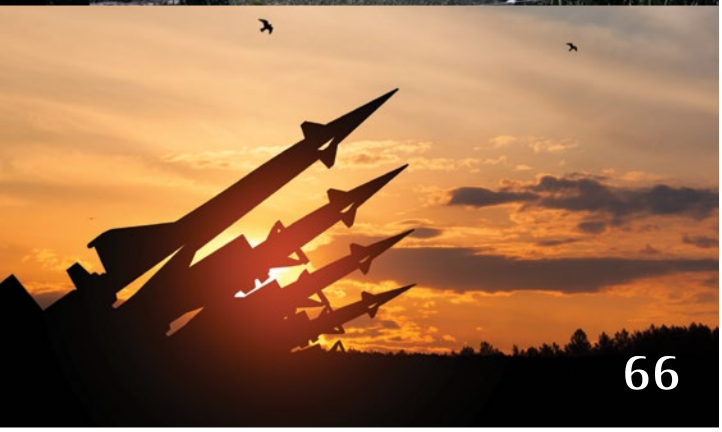

Out of the Box

Inside the JAPCC

Book Reviews

Imprint

Transforming Joint Air & Space Power:
The Journal of the Joint Air Power Competence Centre (JAPCC)

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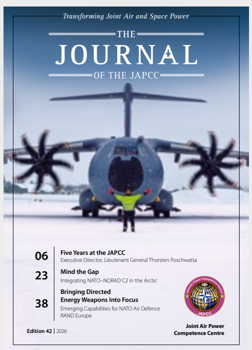
Purpose
The JAPCC Journal aims to serve as a forum for the presentation and stimulation of innovative thinking about strategic, operational and tactical aspects of Joint Air and Space Power. These include capability development, concept and doctrine, techniques and procedures, interoperability, exercise and training, force structure and readiness, etc.

ISSN 3136-5418 (Print)
ISSN 3136-5426 (Online)



Cover Illustration: Set against the demanding Arctic environment, ground personnel work alongside an A400M aircraft in deep snow, reflecting the challenges of sustaining air operations in extreme conditions. The scene highlights readiness, resilience, and the ability to generate combat air power from austere and contested locations. Aligned with JAPCC's mission, the image reinforces the importance of Agile Combat Employment, adaptability, and effective support to NATO air operations across the increasingly strategically significant High North.

[M] © Zentrum Luftoperationen PAO

Reflections on Five Years at the JAPCC

Strategic Change, Alliance Adaptation, and the Enduring Relevance of Joint Air and Space Power

By Lieutenant General Thorsten Poschwatta,
Executive Director of the Joint Air Power Competence Centre

In the past five years, the world has changed with a speed and intensity few would have predicted. When I assumed my duties as Executive Director of the Joint Air Power Competence Centre, we were still operating in a strategic environment shaped largely by crisis management, expeditionary operations, and an often-optimistic belief in a stable European security order. That assumption no longer holds. Strategic competition has returned to the forefront, deterrence and defence have reclaimed their central place in Alliance thinking, and the air and space domains have proven, once again and unequivocally, to be decisive from the very first moments of any conflict.

The return of large-scale war to the Euro-Atlantic area has been the defining shock of this period. Alongside it, the rapid proliferation of long-range precision fires and uncrewed systems, the weaponisation of space and cyberspace, and an accelerating pace of technological change driven by autonomy, artificial intelligence, and data dominance have collectively reshaped the strategic landscape. At the same time, NATO has grown, strengthened its posture, and renewed its collective commitment to credible deterrence and defence. This dynamic, of increasing challenge and renewed resolve, has fundamentally reshaped the context in which the JAPCC operates.

'The JAPCC will remain not only relevant, but indispensable, as the Alliance continues to adapt to an increasingly contested and complex strategic environment.'

For the JAPCC, these developments have not merely increased our workload; they have sharpened our relevance. Our mission to provide independent, forward-looking military advice on Joint Air and Space Power has become more essential than ever. Over the past five years, the Centre has evolved from serving primarily as a catalyst for transformation to acting as a bridge between operational urgency and long-term adaptation. Whether through concept development, analytical studies, doctrinal inputs, or our conferences and publications, the JAPCC has consistently sought to anticipate what the Alliance will need next – not what was needed yesterday.

Crucially, this has been a collective effort. The strength of the JAPCC lies in its multinational team of experts, drawn from many nations, services, and backgrounds, united by intellectual curiosity, professional rigour, and a shared commitment to the Alliance. I have been privileged to work alongside officers and civilians who were willing to challenge assumptions, speak uncomfortable truths, and translate complex problems into actionable insights for decision-makers. Their professionalism and dedication have been the true constant throughout a period of profound change.

As I now retire, I do so with confidence in the future of the Centre and gratitude for the people who make it what it is. The JAPCC is well positioned to continue shaping NATO's thinking on Joint Air and Space Power in an era where speed, integration, and resilience will define success. The challenges ahead are daunting, but they are matched by the talent, experience, and commitment within this organisation.

I extend my sincere thanks to our Sponsoring Nations, our partners across NATO commands and nations, and to all who have engaged with and supported the work of the JAPCC over the past five years. It has been both an honour and a privilege to serve in this role. I leave convinced that the JAPCC will remain not only relevant, but indispensable, as the Alliance continues to adapt to an increasingly contested and complex strategic environment. ●

ABOUT THE AUTHOR

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T-6A and M-346A aircraft in formation, representing the progression from basic to advanced fast-jet training at HIFTC.

The Hellenic International Flight Training Centre

A Strategic Enabler of NATO Air Power

By Major General Marios Bantouvas, Hellenic Air Force,
Commander of the Hellenic Air Training Command
& Lieutenant Colonel Athanasios Sdrakas, Hellenic Air Force, JAPCC

Pilot training has become a strategic determinant of combat air power. The technology of warfare has advanced rapidly, but training systems have not always evolved at a commensurate pace with modern aircraft systems. In contested airspace shaped by sophisticated Integrated Air Defence Systems (IADS), pressure in the electromagnetic spectrum (EMS), and integrated cyber- and space-enabled effects, the decisive factor is no longer the aircraft alone. Air forces must generate pilots capable of operating effectively in multi-domain, sensor-rich, and electronically contested environments. Pilot training, once viewed primarily as a national responsibility for producing sufficient aircrew, now has direct implications for Alliance

NATO Flight Training Europe (NFTE) provides a multinational framework for improving pilot training capacity, standardisation, and interoperability across the Alliance. Here, T-6A aircraft fly during formation training, developing core airmanship and handlingskills in Phase 2 at HIFTC.

readiness, interoperability, and combat credibility. Throughput, standardisation, and interoperability directly influence how rapidly NATO can generate credible combat air power.

This operational shift has increased the strategic relevance of the Hellenic International Flight Training Centre (HIFTC) at the 120 Air Training Wing (ATW) in Kalamata. It has evolved from a national training hub into an asset of Alliance-wide training relevance. On 3 April 2025, the NATO Flight Training Europe (NFTE) Steering Board formally certified the 120 ATW as a Pilot Training Centre during its 11th meeting in Cagliari, Sardinia. Today, the 120 ATW delivers the full spectrum of undergraduate and advanced fast-jet training. Phase 2 pilot candidates train on the T-6A Texan II before transitioning into Phase 3 and Phase 4 advanced and Lead-In Fighter Training on the M-346A. This flying training is supported by a Ground-Based Training System (GBTS), which includes simulators, mission-planning tools, computer-based instruction, and debriefing systems that allow students to rehearse, analyse, and refine tactical performance before and after flight. Together, these elements create an integrated, fighter-relevant training pipeline aligned with contemporary operational requirements across all training phases.

From National Asset to Strategic Infrastructure

The 120 ATW has long been a cornerstone of the Hellenic Air Force (HAF) pilot training system. The introduction of the T-6A in the early 2000s modernised basic training, while advanced jet training had relied on the T-2E Buckeye for decades. As fleet numbers declined and legacy aircraft aged, the transition away

The M-346A provides advanced fast-jet training at 120 ATW, bridging basic training and operational fighter employment.

from the T-2E offered an opportunity for more than a platform replacement. It enabled a shift from traditional 'stick-and-rudder' pilot training toward preparing aircrew to operate modern weapons systems in complex combat environments.

Kalamata's location supports that evolution. Consistently favourable weather conditions reduce disruption and improve syllabus predictability, offering an advantage for nations seeking reliable schedules and stable throughput. In practical terms, predictable flying days matter because capacity shortfalls often emerge not from single-point failures, but from cumulative training delays across a pipeline.

Training for the Realities of Modern Air Combat

Fourth- and fifth-generation platforms increase the cognitive demand placed on pilots. Modern air combat requires early mastery of sensor fusion, information management, and tactical decision-making under time pressure. Training systems that delay exposure to this complexity risk transferring the burden to frontline units. The Hellenic Air Force addresses this requirement by focusing on two critical elements of the training system: people and equipment.

The quality of the instructor cadre is central to the effectiveness of the training pipeline. At Kalamata, serving HAF officers with fighter aircraft backgrounds deliver instruction in the M-346, bringing a current operational perspective into the simulator, cockpit, and debrief. This human dimension ensures that advanced platforms and synthetic tools produce consistent, fighter-relevant learning outcomes rather than mere technical familiarity.

'Training capacity is no longer merely a domestic matter; it is a shared enabler of Alliance deterrence.'

If instructors provide the operational logic of the training system, the M-346 and its associated synthetic environment provide the means to apply it at the required level of tactical realism. The M-346 Block 5+ provides a credible bridge between basic flight training and operational fighter employment. Its avionics architecture and cockpit design replicate core logic elements of modern combat aircraft, enabling trainees to practise mission-system management as well as flight manoeuvring. The focus shifts from 'how to fly' to 'how to manage combat effects' within a system-of-systems

M-346A Full Mission Simulator.

environment. At the 120 ATW, advanced phases of the M-346A are delivered through a validated syllabus supported by integrated training devices, all assessed against NATO standards. Live flying and the live, virtual, and constructive (LVC) environment generate tactical complexity by combining live aircraft, simulators, and synthetic threats or entities within a common training scenario. This allows live sorties to interact with virtual adversaries, surface threats, and supporting assets, expanding realism while preserving cost-efficiency and safety. For air forces with limited access to dedicated adversary aircraft or expansive training airspace, such synthetic integration significantly increases training depth and flexibility.

Synthetic Training as Core Capability

Modern air forces no longer treat simulation as a mere supplement. The integration of fifth-generation aircraft and advanced munitions and sensors requires the flexibility that the synthetic environment provides. Training at Kalamata introduces complexity progressively, so that pilots build systems knowledge, procedural discipline, and tactical coordination in a deliberate learning progression.

Computer-Based Training (CBT) reinforces systems knowledge. Simulator-Based Training (SBT) enables procedural and multi-ship practice. High-fidelity Full Mission Simulators (FMS) rehearse complex tactical coordination between crews. These capabilities operate as layers within a single, coherent training architecture. The GBTS supports the M-346A syllabus through classroom instruction, computer-based learning, simulator training, and mission preparation. The Mission Planning and Debriefing System (MPDS) ensures continuity between design and outcome.

Synthetic training in the M-346A is not limited to ground-based tools, but is also integrated into live flying to build tactical competence in the live environment. Its Embedded Tactical Training System (ETTS), an on-board training capability of the aircraft, allows

High-fidelity Full Mission Simulators provide realistic mission rehearsal while enhancing crew coordination and operational readiness.

selected tactical events, simulated sensors, weapons, and computer-generated threats to be represented during the sortie. This gives students a more demanding training environment without requiring every aircraft, emitter, or threat system to be physically present in the airspace. Recorded data can then be used during the debrief to compare performance with the planned training objectives.

The HIFTC can therefore reserve live flying hours for tasks requiring the physical environment, while replicating more demanding scenarios earlier in training than was previously acceptable. The outcome is not simply cost efficiency; it is a more effective and more consistent training pipeline, an essential feature in an era of increasing pilot demand.

Integration into NATO Flight Training Europe

The integration of the HIFTC into the NFTE framework is more than an expansion of NATO's training capacity; it represents an Alliance-level effort to evolve how NATO generates combat-ready pilots. NFTE addresses fragmentation in pilot training across the Alliance by increasing capacity while improving interoperability and standardisation. Accreditation of the 120 ATW as an NFTE campus confirms compliance with NATO standards for safety, infrastructure, and instructional quality. More importantly, it positions Kalamata as a node within a networked training architecture rather than as a stand-alone national facility.

Across the Alliance, European air forces are modernising their combat fleets with advanced platforms such as the F-35, Eurofighter, Rafale, and upgraded F-16 variants. This increases the demand for high-quality pilot training at a time when many national training systems face structural constraints. Within this environment, a scalable campus inside the NFTE network provides resilience, surge capacity, and strategic depth. Training capacity is no longer merely a domestic matter; it is a shared enabler of Alliance deterrence.

Interoperability as a Training Output

The strategic value of the HIFTC extends beyond technical pilot production. By training multinational cohorts under a common syllabus and instructional culture, the model embeds interoperability from the earliest stages. Pilots who share mission-planning processes, debriefing standards, and tactical logic require less adaptation when integrated into combined formations. Interoperability becomes a reflex rather than a corrective measure applied later during operational service. In an era of multinational air policing, integrated air defence, and coalition expeditionary operations, such early convergence is a critical instrument for strengthening Alliance cohesion.

A Scalable Platform for the Future

The HIFTC was designed with expansion in mind. Additional aircraft, expanded simulator capacity, and scalable instructional architecture together create the basis for higher training output without altering the underlying training philosophy. In the near term, this scalability primarily supports growth in undergraduate and advanced fast-jet training. Over time, however, deeper networking with other European synthetic training nodes could enable more advanced forms of distributed mission rehearsal and multinational scenario-based training without requiring large-scale deployments. Such developments would reinforce standardisation not only doctrinally, but also practically. For NATO, this scalability matters. Rising demand for qualified aircrew coincides with fiscal pressures and force-structure adaptation. A resilient, expandable training node in Southern Europe strengthens long-term force generation planning.

Conclusion

The HIFTC represents more than a national modernisation effort. It is a strategic contribution to NATO's collective air power ecosystem. Built upon the heritage of the 120 ATW, the centre integrates an advanced training fleet, and a comprehensive synthetic training architecture within the NFTE framework. Its favourable operating environment, high availability rates, and fighter-relevant instructional design create a training system aligned with the demands of contemporary air warfare. As the operational environment becomes increasingly multi-domain and data-driven, the HIFTC demonstrates how national initiative, Allied cooperation, and technological integration can converge to produce interoperable mission-ready aircrew. In doing so, it contributes not only to Greece's national defence transformation, but to the collective readiness, and credibility of NATO air power in the decades ahead. ●

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Major General Marios Bantouvas is the Commander of the Hellenic Air Training Command (HATC), where he is responsible for the selection, training, and education of Hellenic Air Force personnel. He graduated from the Hellenic Air Force Academy in 1990 as a Second Lieutenant and has since completed a broad range of operational, instructional, and joint professional military education, including the Supreme Joint War College, Joint and Operational Electronic Warfare courses, and advanced instructor and command training. Throughout his career, he has held senior command and staff appointments across the Hellenic Air Force, with a strong focus on air defence, training, and personnel policy. His assignments include Director of the HAF General Staff Training Directorate, Director of the HAF General Staff Personnel Branch, and Commander of the 350 Guided Missile Wing. He has also served at the NATO Joint Air Power Competence Centre (JAPCC) in the SEAD-EW domain. Major General Bantouvas has accumulated more than 3,600 flight hours and has flown F-5 and F-16 aircraft.

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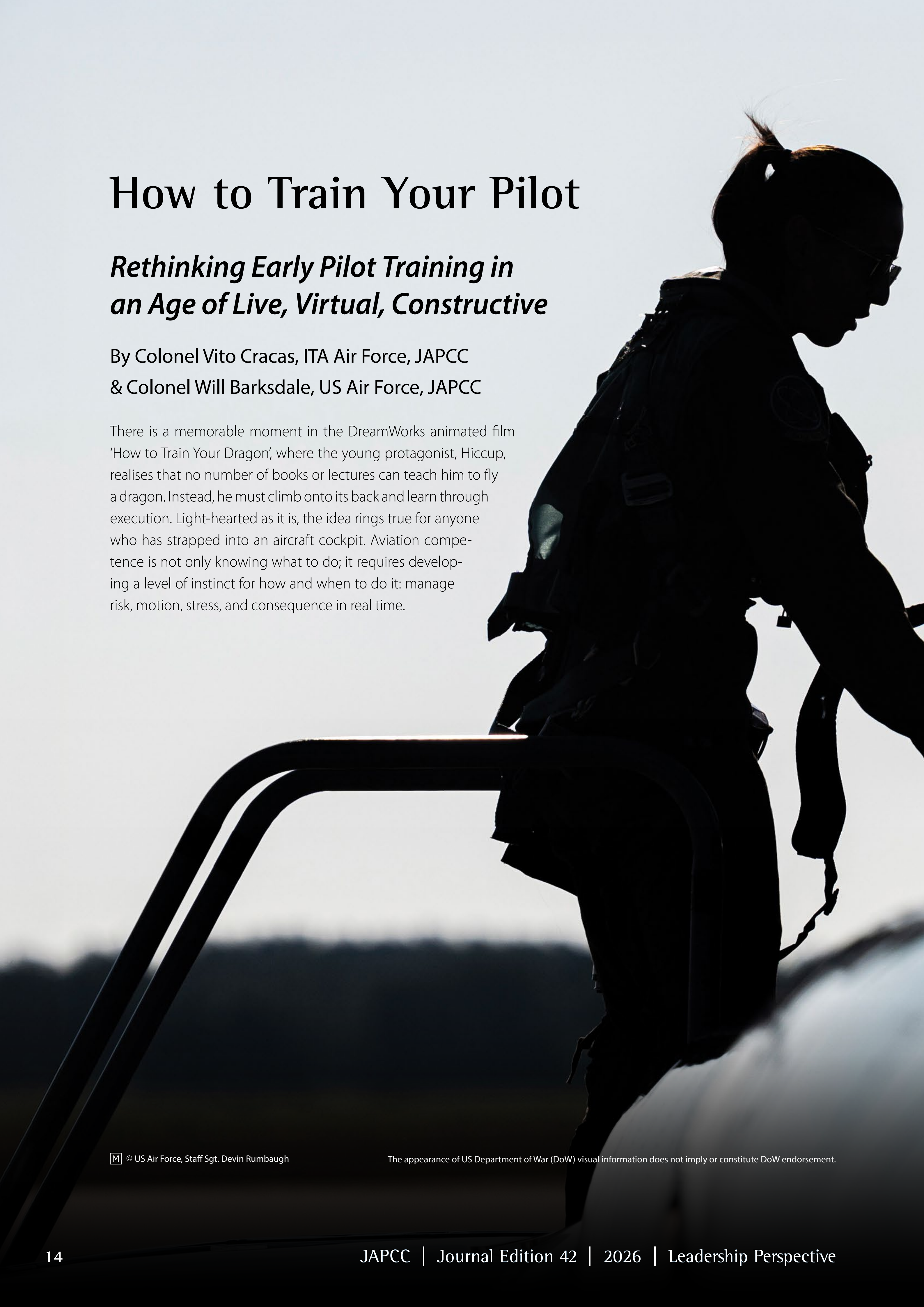
How to Train Your Pilot

Rethinking Early Pilot Training in an Age of Live, Virtual, Constructive

By Colonel Vito Cracas, ITA Air Force, JAPCC
& Colonel Will Barksdale, US Air Force, JAPCC

There is a memorable moment in the DreamWorks animated film 'How to Train Your Dragon', where the young protagonist, Hiccup, realises that no number of books or lectures can teach him to fly a dragon. Instead, he must climb onto its back and learn through execution. Light-hearted as it is, the idea rings true for anyone who has strapped into an aircraft cockpit. Aviation competence is not only knowing what to do; it requires developing a level of instinct for how and when to do it: manage risk, motion, stress, and consequence in real time.



M © US Air Force, Staff Sgt. Devin Rumbaugh

A full-mission simulator delivers striking realism; however, the terrain below is still projected, not felt.

Simulator technology did not impact the world of Hiccup, but NATO has firmly established simulator technology in Allied nations' pilot training systems. NATO air forces have invested heavily in modernisation: more capable aircraft, better simulators, and more coherent multinational coordination. The live, virtual, and constructive (LVC) environment is a powerful complement to live flying – not a replacement. NATO nations cannot afford to sacrifice the proficiency gained in live-fly training. If we reduce foundational flying experience in favour of synthetic efficiency, we risk producing pilots well-versed in tactical theory yet vulnerable in the basics that keep them alive.

Despite modern trainers, sophisticated simulation environments, and strong multinational training programmes, the most common causes of military aviation fatalities have not changed. Pilots are seldom lost in combat. Instead, mishaps most commonly occur due to spatial disorientation, loss of situational awareness, misapplied emergency procedures, and Controlled Flight Into Terrain (CFIT). These are not tactical failures; they are failures of airmanship, judgement, and embodied skill. As we examine NATO's training future, we must modernise without losing sight of a foundational truth: before a pilot can fight, they must first learn how to fly.

Modernising Flight Training

Nations must solve several conflicting problems: growing and retaining a proficient pilot force, upgrading and expanding their fleets, and doing both within tight budgets. Across NATO, annual flying hours per pilot vary widely, but many nations suffer from underfunding flying hours for pilots once they leave initial training, letting their hard-earned skills wither.[1] To compound the problem, NATO fleets are growing either older or smaller, as legacy aircraft age out and many nations convert to smaller numbers of exquisite, high-cost systems like the F-35 Lightning II. This leaves NATO's military leaders to decide how best to allocate limited resources across growing, training, and equipping their pilot forces.

Given these factors, the prospect of trading live flight hours for simulation is a topic of serious discussion.

An ENJJPT student pilot flies a T-6A Texan II during a training sortie near Sheppard Air Force Base, Texas. About 200 student pilots earn their wings at ENJJPT annually after a 55-week, three-phased training regimen.

Air forces acquire and operate simulators at significantly lower cost, and they can provide training for basic tasks without the burden of bad weather, airspace coordination, or the maintenance and logistics footprint that aircraft require. They provide a valuable supplement to live-fly training, and Allied pilot training schools have accordingly begun modernising both aircraft and simulator capabilities to improve the integrated LVC training environment. Several nations have replaced legacy trainers with digitally compatible platforms. The US Air Force (USAF) is introducing the Boeing–Saab T-7 to replace the T-38C, aligning training with fifth-generation combat aviation. Italy built a pipeline around Leonardo's M-345 and M-346 and established the International Flight Training School (IFTS), a partnership between Aeronautica Militare and Leonardo. France re-centred its system around the Pilatus PC-7 and PC-21; Greece uses a mix of Beechcraft T-6A and Leonardo M-346.[2] These modern trainers normalise glass cockpits and support constructive simulation, allowing air forces to download enhanced software for advanced syllabi. This includes instruction in Basic Fighter Manoeuvres (BFM), Advanced Combat Manoeuvring (ACM), and basic Beyond Visual Range (BVR) tactics. These enhancements represent genuine progress. But the risk is subtle and significant: efficiency can become a substitute for experience, and digital proficiency can be mistaken for airmanship.

Solo flight is the first time a student truly accepts responsibility for the aircraft. Until then, many students unconsciously assume the instructor is a safety net who can always fix any problem. That illusion disappears when the student taxis out, lines up, and takes off alone. Airmanship accelerates dramatically in those moments.

Nations have made substantial advances in simulation and LVC technologies, transforming how air forces prepare pilots for increasingly complex operational environments. Modern full-mission simulators now replicate high-fidelity cockpits with realistic sensor, weapon, and threat models, allowing aircrew to

NATO air forces are investing heavily in modern trainers and multinational programmes. The harder question is whether the pipeline behind them still teaches pilots to fly first.

rehearse scenarios that would be unsafe or prohibitively expensive to conduct in live flight. Concurrently, LVC creates scalable and repeatable tactical environments across geographic borders. These systems expand capacity, improve tactical training quality, and reduce strain on aircraft fleets. They have become indispensable for advanced mission training, particularly in dense threat scenarios. Yet none of this changes what pilots still must learn in a real cockpit, in the earliest phases of a pilot's career.

At the Alliance level, several multinational training enterprises are emerging. NATO Flight Training Europe (NFTE), established in 2021, coordinates an ever-growing network of training campuses to provide cost-effective, standardised instruction for jet, helicopter, and remotely piloted systems. NFTE matches national demand with available capacity, optimising throughput and reducing duplication across a resilient multinational ecosystem.[3,4] Among the campuses feeding this network, Italy's IFTS now trains pilots from multiple Allies, and in some ways is becoming similar to NATO's long-established Euro-NATO Joint Jet Pilot Training Programme (ENJJPT) in the USA. Additionally, the Hellenic International Flight Training Centre (HIFTC), also featured in this journal edition, serves as a training hub for NATO and international air forces. Impressive as this growth is, it answers a narrower question than it appears to. These programmes solve for capacity and standardisation. They say nothing about whether the pipeline is teaching pilots the right things in the right order, which is the question the accident data actually answers.

The Core Issue: Back to Basics

The uncomfortable truth is that enhanced capabilities are coming at the cost of basic airmanship. Early phases exist to build habits that keep pilots alive when the cockpit becomes busy, an emergency interrupts departure, or weather closes in. Students must face spatial disorientation, unusual attitudes, and workload saturation under supervision while piloting a real aircraft before encountering them tactically. They must make decisions under stress, manage fear, and trust instruments when senses lie. These skills cannot be replicated in a simulator-heavy syllabus – and assuming they can is precisely where airmanship is lost.

The water soaking that marks a first solo at IFTS – a small, universal ritual across Allied flight lines, and a reminder of what all the hours of training are ultimately for.

Simulators remain essential for replicating emergencies and reducing risk and cost, but they cannot fully reproduce the physiological and psychological stresses of real flight: compounding factors of g-forces, airsickness onset, sensory cues, or the pressure of manoeuvring over real terrain with genuine consequences. In a simulator, students know an instructor can freeze or reset the scenario; in an aircraft, there is no reset. Junior pilots, in particular, learn differently when errors carry genuine risk.

The pressure to produce aviators faster is real. But efficiency cannot come at the expense of survivability. Data on fatal accidents point to fundamentals, not advanced tactics, as the killers of young pilots; these fundamental skills are built through early, frequent, live flying.

Fly Early, Fly Often

If most fatal accidents stem from foundational weaknesses rather than tactical gaps, the implication is straightforward: keep early phases rich in real-world experience. Simulation should support those phases, not replace them.

The phased approach NATO uses in pilot development is deliberate, from initial screening through operational conversion and post-combat ready training. In practice, these three phases steadily build core skills: visual manoeuvring, instrument procedures, formation flying, edge-of-envelope handling, and disciplined cockpit management. These are the skills that keep a pilot alive during every departure, area manoeuvring, recovery, and diversion. Teach them early; practise often; reinforce relentlessly – in real aircraft. Frequency matters. Long gaps between flights erode confidence and slow learning. A reasonable target to build momentum without overwhelming the student is approximately three to four training events per week, sorties or simulators. Quality suffers when we cram too many complex events together, just as it suffers when weeks pass between flights.

Aircraft progression matters too. Reducing aircraft types and moving students quickly onto advanced trainers only works if performance steps are manageable. Moving a student with only 100 hours in a basic single-engine propeller aircraft straight to a high-performance jet, such as an M-346 or T-7, may look efficient on paper, but it ignores the psychological and cognitive leap involved. Proper risk management is necessary for success. There is a reason driving schools do not train new drivers in supercars: the platform itself can become the problem before the student is ready to exploit it. An alternative path uses a basic propeller aircraft for screening and fundamentals, then a basic jet or advanced turboprop with similar systems, and then an advanced jet. Where possible, staying within the same manufacturer family can reduce transition costs and cognitive load through cockpit commonality. NATO nations offer several examples of these paths. They each work, but how deliberately nations implement them is what makes the difference.

Finally, we must defend solo sorties. Solo flight is the first time a student truly accepts responsibility for the aircraft. Until then, many students unconsciously assume the instructor is a safety net who can always fix any problem. That illusion disappears when the student taxis out, lines up, and takes off alone. Airmanship accelerates dramatically in those moments. Cutting solo time may shorten a syllabus on paper, but it removes our most potent tool for building confidence and effective pilot skills.

If safety and readiness are serious aims, the non-negotiables are clear: early phases rich in live flying, sensible airframe progression, sustained tempo, and sufficient solo opportunities. Everything else, including LVC, advanced tactics, and synthetic sophistication, should be built atop that bedrock, not substituted for it. None of it works, though, without the people who teach it.

The Human Factor: Passion, Judgement, and the Instructor's Role

Flying is a human performance discipline. Aircraft, simulators, and syllabi provide structure, but instructors shape pilots into professionals capable of handling stress, managing risk, and making sound decisions when the unexpected occurs. The human element – and traits like judgement, temperament, and motivation – remains central to producing safe, capable aviators. A simulator can run a scenario script; it cannot replicate an instructor's real-time judgement, or the trust a student learns to place in another human being when the risk is real.

'The pressure to produce aviators faster is real. But efficiency cannot come at the expense of survivability.'

Instructor pilots are the custodians of airmanship, transmitting habits and attitudes that manuals and videos cannot capture. Students rarely appreciate how much the instructor is compensating, anticipating, and protecting them. Good instructors let students make mistakes and test their limits, withdrawing supervision progressively until the student's own judgement and confidence are what keep them safe.

Young pilots often feel immense pressure: to perform, not to fail, to meet the standard. Human-centred moments help balance that pressure and sustain the motivation needed to progress through a demanding pipeline. In an era of metrics, digital tools, and expanding simulation, maintaining this human connection is not a luxury; it is part of the job.

Many experienced instructors use simple techniques to keep students motivated and connected to the joy of flying. One example is giving a student a few minutes at the end of a sortie, when objectives are complete and the aircraft is safely configured, to simply fly. No tasks; no scripts; no evaluation. This free time is not formal policy, nor universal practice, but it reminds students why they chose this profession. A few minutes of unstructured flight can provide a psychological boost that carries them through the toughest stretches of training.

Conclusion

NATO's pilot training is modernising rapidly. But modernisation that displaces foundational airmanship trades one vulnerability for another. The accidents that claim pilots' lives overwhelmingly stem from gaps in basic flying skills, not tactical shortcomings. LVC will continue to expand, and it should. But modernisation must not erode the foundation on which survivability depends. Early training should be rich in live flying, steady in tempo, progressive in challenge. It must build the judgement, confidence, and airmanship that later phases rely upon – all guided by instructors whose real-time judgement no simulator can replace. Before NATO trains pilots to fight and win, it must ensure they learn to fly and live. ●

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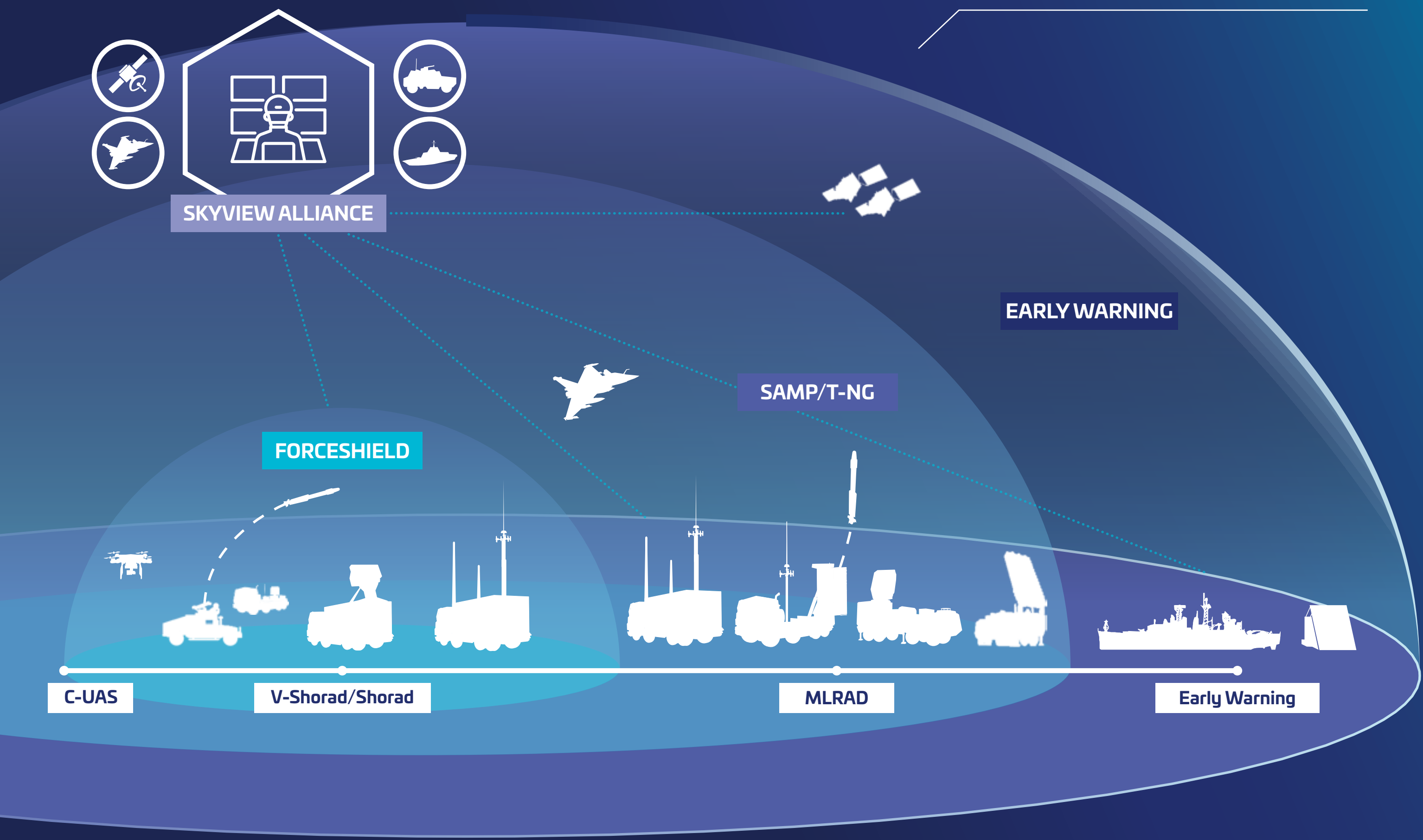

West of the Greenland-Iceland-UK gap, the Alaska NORAD Region and the Canadian NORAD Region feed their tactical pictures to NORAD Headquarters. East of it, the Combined Air Operations Centre at Bodø is the primary tactical air command and control node for a northern flank assigned in its entirety to Joint Force Command Norfolk.

Mind the Gap

Integrating NATO and NORAD C2 Across the Arctic

By Colonel Kevin 'Tread' Anderson,
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On 12 February 2026, Swedish Air Force JAS-39 Gripens departed Iceland for Greenland to join Royal Danish Air Force F-35s and German Typhoons in Operation Arctic Sentry, NATO's first Enhanced Vigilance Activity (eVA) dedicated to the High North. Yet as the formation crossed the Greenland-Iceland-United Kingdom (GIUK) gap, it also crossed an invisible boundary dividing the Arctic battlespace between NATO and North American Aerospace Defense Command (NORAD), a seam increasingly vulnerable to the speed and complexity of modern threats.[1]

For decades this seam has been both practical and convenient, a result of distinct operational requirements and intentional political choices. On one side of the gap, NORAD provides a centralised aerospace architecture

A Russian Su-35 flying inside the Alaskan Air Defense Identification Zone (ADIZ) passes dangerously close to a US Air Force F-16 from Eielson AFB, Alaska. While rare, such incidents reflect increasing tensions in the Arctic.

to secure a vast 8,000-kilometre approach. On the other side, NATO relies on a federated air defence structure to defend the European High North stretching from the GIUK gap to the Barents Sea. Over time, this boundary did not merely separate two areas of responsibility (AORs); it created parallel command and control (C2) ecosystems operating on separate networks and under distinct legal authorities.[2] Although strategic warning data is exchanged across the Atlantic, the pathways connecting the two systems are still optimised for an era of subsonic aircraft and ballistic trajectories. This leaves underlying tactical networks legacy-bound: slow, dependent on manual handoffs, and oriented vertically rather than horizontally.[3]

The operational environment has evolved. Hypersonic, highly manoeuvrable, and low-observable platforms can exploit any friction between the two organisations, compressing decision timelines and demanding rapid coordination across a battlespace whose two separate command ecosystems were never designed to operate together seamlessly. This article argues that NATO and NORAD must bridge this C2 seam not by erasing its political foundations, but by building the unified deterrence architecture the current threat demands. Achieving this requires progress across three pillars: the technical infrastructure to share data at machine speed, the institutional frameworks to align command culture and legal authorities, and the training opportunities that allow operators to work proficiently across the boundary. To make that case, the article maps the current Arctic C2 architecture, examines the barriers driving divergence between the commands, and offers recommendations to achieve seamless deterrence across the Arctic.

NORAD: The North American Shield

Established in 1957, NORAD is a bilateral organisation charged with safeguarding the North American continent through three primary missions: aerospace warning, aerospace control, and maritime warning. Operationally, NORAD divides the northern theatre into two regional command sectors split along the Alaska-Canada border. The Alaska NORAD Region (ANR) is directed by the 611th Air Operations Center (AOC) at Joint Base Elmendorf-Richardson, Alaska, where it is co-located with Alaskan Command and the 11th Air Force. The 1 Canadian Air Division (1 CAD) manages the Canadian NORAD Region (CNR) from Canadian Forces Base (CFB) Winnipeg, Canada. Sector-level tactical operations are executed by 22 Wing, Canadian Air Defence Sector (CADS) at CFB North Bay, Ontario. Both feed their tactical pictures back to NORAD Headquarters at Peterson Space Force Base (SFB) in Colorado Springs. Peterson SFB is also home to US Northern Command (USNORTHCOM), the overarching combatant command responsible for wider coalition coordination with Allies and partners.[4]

On its far western boundary, NORAD-NORTHCOM interfaces directly with US Pacific Command (USPACOM) across the Bering Strait. While this western boundary divides two geographic combatant commands, their close interoperability is anchored by shared national authorities, procurement lines, and synchronised doctrinal C2 goals, permitting seamless, automated, machine-to-machine connectivity.

NATO's Arctic Overhaul

Across the GIUK gap, the command structure transitions from a binational homeland defence mandate to a multilateral collective defence framework. NATO's model differs fundamentally from NORAD's centralised architecture. Rather than a single unified command, NATO's northern flank leverages a federated design that navigates sovereign national architectures, differentiated networks, and complex legal authorities. This framework balances multinational unity of effort with national sovereignty over sensors and weapons systems in the High North.

In 2025, NATO executed an extensive restructuring of its northern flank, reassigning the entire Arctic AOR to Joint Force Command (JFC) Norfolk and bringing the security interests of the seven Arctic Allies under a coordinated joint headquarters. In tandem with this geographic consolidation, NATO recently opened a dedicated Combined Air Operations Centre (CAOC) at Bodø Armed Forces Base in Norway. As the primary tactical air C2 node for the northern sector, CAOC Bodø orchestrates regional air policing, maritime surveillance, and large-scale exercises such as those under the Arctic Sentry umbrella.[5]

Between these two architectures lies Greenland. As both a North American island and a self-governing territory of Denmark, Greenland sits within NATO's political footprint, but its radar arrays at Pituffik Space Base send data directly into NORAD's early warning architecture. While Denmark has not formally incorporated Greenland into the NORAD framework, its unique trilateral arrangement extends NORAD's air defence perimeter to the edge of the Euro-Atlantic, marking the practical location where two parallel command structures meet.[6]

The Space Between

While NORAD and NATO monitor their respective geographic flanks, a complex space infrastructure orbits above. Buckley SFB, Colorado, home to Space Delta 4, serves as the primary global hub for processing and sharing overhead persistent infrared (OPIR) and other tracking data with both organisations. NORAD consumes this missile warning data in near-real-time through the Integrated Tactical Warning/Attack Assessment (ITW/AA) architecture. NATO then receives a filtered feed via the Shared Early Warning System

(SEWS II), which sanitises, geographically filters, and sends data into the Control and Reporting Centre System Interface (CSI) over secure network, via the Joint Range Extension Application Protocol (JREAP).[7]

The data flow is not entirely unidirectional. European Allies contribute national space-based ISR through multilateral pooling arrangements such as the Allied Persistent Surveillance from Space (APSS) initiative and France's Multinational Space-based Imaging System (MUSIS) programme. In addition, nascent independent warning capabilities such as the EU-funded Odin's Eye initiative are maturing. As European space capacity grows, NORAD will gain coverage and redundancy that US and Canadian architecture alone cannot provide. Today, NORAD's integrated, automated warning architecture is more mature than NATO's federated equivalent, but that gap is closing. Enhancing integration across the seam is therefore beneficial to both organisations.

While this data-sharing arrangement functions reliably under permissive, steady-state conditions, the cross-seam pipeline remains optimised for strategic early warning rather than dynamic tactical control. It lacks the horizontal, machine-speed pathways required to

pass high-fidelity tracking data directly between the 611th AOC, the CADS, and CAOC Bodø; it is precisely this gap that the converging threat environment is beginning to expose.[8]

Converging Threats, Diverging Seams

The Arctic is no longer a frozen buffer zone. Climate change is opening transit corridors that were once impassable; Sino-Russian cooperation is deepening across the region; and the accession of Sweden and Finland has pushed NATO's frontier further north than at any point in the Alliance's history. The polar region has become an arena of active competition, and the weapons that define it do not respect organisational boundaries. Hypersonic systems, low-observable cruise missiles, and containerised strike weapons compress decision timelines and demand coordination at machine speed. Consider a hypersonic glide vehicle detected west of Greenland with the potential to strike either North America or Europe. The threat will traverse both NORAD and NATO monitoring zones within minutes, yet delays from manual data translation, geographic filters, or gateway mediation consume decision time that cannot be recovered.[9]

Denmark and Sweden perform a training mission over the Faroe Islands as part of eVA Arctic Sentry.

As the threat environment rapidly converges, Allied C2 across the NATO-NORAD seam is at risk of technical and structural divergence. The United States and Canada are rapidly modernising toward Combined Joint All-Domain Command and Control (CJADC2), which links sensors, decision-makers, and shooters into a common automated ecosystem at machine speed.[10] Meanwhile, much of Euro-NATO remains anchored to legacy infrastructure, such as older network gateways and unmodernised Link 16 terminals that cannot support the bandwidth and multi-netting requirements of modern combat. NATO's Federated Mission Networking (FMN) framework is designed to bridge this gap by linking national systems through common standards. However, FMN is not a network itself, and its effectiveness depends on consistent implementation across dozens of sovereign nations.[11] Uneven adoption of the ten-year FMN spiral roadmap will delay theatre-wide integration. Compounding this, CJADC2 and FMN are not inherently compatible; gateway-mediated exchanges between them introduce latency into the tactical kill web. If these gaps are not closed, software deployment on the North American side risks outpacing Allied procurement cycles, creating a multi-tiered Alliance in which some partners are effectively isolated from the common ecosystem.

This technical divergence is worsened by an institutional expertise gap. NATO has historically under-resourced the human and organisational component required to manage advanced tactical networks. NATO currently lacks a centralised datalink integration office, a body responsible for managing network configurations, synchronising cryptographic updates, and ensuring Allied systems can talk to one another during a crisis. Without it, network coordination defaults to fragmented national solutions, producing C2 delays early in recent exercises and operations.[12] This shortcoming extends to the operator level as well, where the Alliance has no advanced Level 4 training pipelines within Europe for Joint Interface Control Officers (JICOs), leaving the European theatre reliant on a single training source in the United States.

Finally, both commands lack realistic training in denied, disrupted, intermittent, and limited environments. Scenarios tend to be stovepiped within NORAD or NATO, rarely involving cross-boundary target tracking and handoff. Rather than forcing networks to fail realistically, planners rely on administrative 'white cards' to simulate away friction.[13] This precludes primary, alternate, contingency, and emergency (PACE) plan validation and masks operational limitations across the transatlantic seam.

Closing the Gap: A Three-Part Strategy

To reconcile the diverging seam between NORAD and NATO, both organisations must execute a coordinated strategy that synchronises technical solutions, institutional structures, and operational exercises.

Pillar 1: Technical Solutions

Before the Alliance can achieve cross-seam interoperability, it must address hardware shortcomings, disparate data architectures, and the Arctic's harsh environmental constraints. Modernisation requires a pragmatic hardware baseline that connects existing systems into automated, machine-to-machine pathways, without requiring a costly fleetwide replacement.

The first priority is a tiered datalink upgrade. Aircraft and ground systems already equipped with older Link 16 terminals should keep them, provided they are upgraded to meet current cryptographic and aeronautical standards. Assets requiring higher bandwidth, such as advanced fighters, airborne early warning platforms, and key C2 nodes, should receive a full upgrade to modern systems like Multifunctional Information Distribution System Joint Tactical Radio System (MIDS JTRS). This upgrade would support faster, more flexible network configurations, including Tactical Targeting Network Technology for rapid sensor-to-shooter connections.[14] While a fully modernised NATO fleet will assure optimised efficiency, this tiered approach meets the requirement for effective cross-seam C2.

The second priority is a permanent NORAD-NATO data bridge: a shared mission partner environment (MPE) where both organisations' systems can automatically

The Northern Lights over the North Atlantic, as seen from HDMS Esbern Snare, Standing NATO Maritime Group One flagship.

pass data rather than relying on manual, point-to-point transfers. Instead of a unidirectional, US-managed pipeline, this architecture should be co-developed, drawing on existing US programmes such as the Secret and Below Releasable Environment (SABRE) while integrating natively into NATO's own network standards.[15] In practice, tracking data from Canada's new Arctic and Polar Over-the-Horizon radars, expected to be online by 2029, would flow into NORAD's cloud-based command system before automated gateways convert and push that data at machine speed directly to CAOC Bodø.[16]

Finally, the Arctic's atmospheric and ionospheric conditions are among the most disruptive on Earth, frequently degrading satellite communications at high latitudes. Both commands are responding by spreading their communications across multiple orbital bands, offering resilience when one altitude is degraded. The next step is consolidating these diverse assets into a single architecture that switches automatically between backup pathways without human intervention.[17]

Pillar 2: Institutional Collaboration

Software and hardware upgrades are inherently limited without the organisational frameworks and legal agreements required for implementation. The recommendations below are not calls to dissolve existing policy boundaries or override national sovereignty. They are proposals to work deliberately within those boundaries to manage the risk and friction those boundaries generate at the operational level. Taken together, they address the cultural, relational, and governance dimensions of cross-seam integration.

The first recommendation is to establish a classified information-sharing compact among the Arctic Seven NATO nations. The primary intent of such a compact is cultural: shifting institutional mindsets from a need-to-protect to a need-to-share philosophy. Such an arrangement should begin by developing a shared threat assessment among the Arctic Seven nations. This compact could progress these allies toward a political and legal framework that expands data releasability to build a comprehensive recognised operating picture of the entire Arctic. Aligning legal authorities across sovereign nations is admittedly the hardest dimension of this effort, but it is also the most important, as technical solutions will continue to stall at policy boundaries.

Second, while JFC Norfolk's Arctic Sentry framework has improved theatre-wide synchronisation, the Alliance still lacks a dedicated operational-level exchange between the ANR, CADS, and CAOC Bodø. A rotating annual forum among the three AOCs would give senior leaders and operational staff a dedicated venue to discuss cross-seam procedures, align future requirements, and build the institutional relationships that no amount of technical connectivity can substitute for.

Finally, as part of NATO's broader modernisation imperative under Allied Command Transformation (ACT), NATO and NORAD should establish an Advanced Tactical Data Link Integration Office. This office would manage cross-seam network configurations, synchronise cryptographic updates, and ensure technical alignment between CJADC2 and FMN on future software development. This would provide the permanent integration authority between technical modernisation and institutional governance that currently exists nowhere in the Alliance structure.

Pillar 3: Operational Training and Exercises

Where Pillar 2 focuses on organisational alignment and relationship building, Pillar 3 addresses the practical proficiency of the operators who must execute cross-seam missions. Technical architecture and institutional frameworks are only as effective as the people trained to use them under pressure.

The most immediate gap is Europe's absence of advanced datalink training infrastructure. NATO should establish a JICO training facility accredited to teach the Level 4 'Multi-Tactical Data Link Management' curriculum, replicating the standards of the US Joint Staff J6 Joint Interoperability Division Training Centre (JID-TC). Without this capability in theatre, the European flank will remain dependent on a single training source in the United States.[18]

Equally important is the quality of training operators receive once certified. Multinational exercise planners should abandon the administrative 'white cards' that simulate away network failures and atmospheric anomalies. When a cross-seam datalink drops or an ionospheric event severs a connection, forces should troubleshoot in real time. These degradations are the most valuable stress tests available for diagnosing interoperability issues before a real crisis occurs.[19]

NORAD and NATO should also increase the frequency and ambition of cross-seam tactical training: deploying fighters to opposite AORs to cross-train in homeland defence and air policing missions, executing Agile Combat Employment (ACE) concepts during Arctic-focused iterations of Red Flag-Alaska, and flying profiles that force live, cross-boundary targeting handoffs between controllers on both sides of the seam. The objective is shared procedural fluency that survives the friction of a real contingency.[20]

Finally, the Alliance should invest in a transatlantic Distributed Mission Operations (DMO) network dedicated to live, virtual, constructive (LVC) training between AOCs. Interconnecting existing North American and European virtual environments would allow battle managers in Alaska, Canada, and Norway to routinely practise cross-seam intercepts without the cost of cross-Atlantic aircraft deployments.[21]

Conclusion: Deterrence at Machine Speed

While the ice in the Arctic thaws, geopolitical tensions in the High North will continue to harden. For decades, the NATO-NORAD seam served as the mechanism by which the Alliance balanced operational deterrence with political sovereignty. The emergence of peer threats now demands a new approach that speeds integration by embedding interoperability, while guarding sovereignty. Hypersonic and low-observable systems demand a reassessment of how organisations share data, build institutions, and develop operators capable of managing the Arctic battlespace. The aircraft participating in Arctic Sentry may cross the GIUK gap in minutes, but their command architectures still do not. Until NATO and NORAD can exchange information and coordinate decisions with equal speed, the seam running through the Arctic will remain an operational vulnerability that adversaries can exploit. ●

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Evolving Aerial Refuelling for Contested Airspace

By Major Eric Yuan, US Air Force, School of Advanced Study of Air Mobility

Modern air campaigns are inherently dependent on the operational reach of tanker fleets. For decades, the Alliance designed an air operating model around the assumption that High Value Airborne Assets (HVAAs) could operate within safe sanctuaries in the rear echelon. Today, the proliferation of sophisticated Anti-Access/Area Denial (A2/AD) strategies, long-range interceptors, low-cost one-way effectors, and uncrewed systems has shattered the illusion of sanctuary.[1] It is now essential to explore alternative methods of air refuelling. These could include a hybrid fleet of large-capacity and smaller tankers capable of operating in higher-threat environments, or the integration of uncrewed assets to reduce overall mission risk. Consequently, Allied nations must fundamentally reassess their approach to aerial refuelling design by pivoting towards a combined approach that retains heavy volumetric capacity while introducing innovative, survivable options to deliver fuel inside contested environments.

Strategic Path Dependency

To understand the vulnerabilities of the current fleet, we must briefly examine how early technical choices shaped its development. The foundations of modern aerial refuelling were built upon military experimentation that pushed the boundaries of aviation endurance and range. Examples include the 1929 test flight that remained aloft for over 150 hours and the 1949 non-stop flight that circumnavigated the globe.[2] Modern aerial refuelling operations developed during the 1950s, driven by then US Strategic Air Command (SAC) and its requirement for global reach to achieve

A KC-135 refuels a stealth bomber. Even the B-21 Raider's range, persistence, and combat effectiveness depend on tanker support reaching it.

strategic deterrence. Ultimately, the immense fuel requirements of nuclear bombers forced the US Air Force (USAF) down a divergent path from its European Allies, a choice that permanently shaped the architecture of its aerial refuelling capability.

Early engineering choices reflected rational design trade-offs based on distinct operational necessities. The USAF designed the refuelling boom to satisfy the high-volume and high-speed fuel delivery demands of its massive strategic bomber fleet. The refuelling boom is hydraulically operated to transfer approximately 4,000 litres of pressurised aviation fuel per minute to a single receiver. The boom design prioritised offload velocity above all, while budgetary constraints required the USAF to standardise across its fighter and support fleets.[3,4] Meanwhile, the probe-and-drogue system remains prominent among many Allied nations and US naval aviation, as its flexible hose and drogue design allows a single heavy tanker to simultaneously refuel a two-ship fighter formation. Despite a slower offload rate of roughly 1,100 to 1,500 litres per minute, it also offers greater flexibility and lower acquisition costs.[5] As refuelling methods continued to evolve on both sides of the Atlantic, aerial refuelling became increasingly associated with particular platforms rather than the operational effect itself.

These design choices yielded the current tanker fleet, dominated by large commercial-derivative aircraft such as the Boeing KC-135 and Airbus Multi-Role Tanker Transport (MRTT).[6] Although efficient in terms of raw fuel payload and flight hour costs, these platforms feature massive radar cross-section and sluggish flight characteristics, leaving them uniquely vulnerable to threats.

The Evolving Operational Environment

While the refuelling tanker design paradigm has not drastically changed since the 1950s, the same cannot be said for the modern battlespace. Advanced A2/AD postures and long-range effectors have transformed the operating environment. Contemporary threats to refuelling tankers are no longer confined to localised surface-to-air missile engagement zones. Peer adversaries have developed a web of overlapping kinetic and non-kinetic threat layers that threaten every element of an airborne strike package, including command, control, and logistics nodes. Chief among these threats are ultra-long-range active radar-guided air-to-air missiles, such as the Russian R-37M and the Chinese PL-15. These 'HVAA killers' are designed to bypass fighter screens entirely, targeting low-manoeuvrability platforms from ranges exceeding 200 kilometres.[7]

New threat vectors, such as hybrid warfare and proliferation of drone technology, have also eroded safe sanctuary. Even remote main operating bases across

An A330 Voyager simultaneously refuels a Eurofighter Typhoon and a Tornado using the probe-and-drogue system, highlighting the flexibility and efficiency of multi-aircraft refuelling.

Europe and the Middle East are now vulnerable to low-cost, long-range one-way effectors, subversion, and sabotage. Tankers are forced to operate from further rear orbits because of advanced long-range threats, often at the expense of on-station time and offload capacity. The usable fuel offload, absent meaningful force extension plans, diminishes rapidly at the forward edge, constraining Allied combat persistence and making an air campaign more costly and more difficult to plan.

True Strategic Cost

The evolving peer threat environment has led modern acquisition programmes to heavily favour fifth-generation fighters and low-observable bombers designed to penetrate hostile territory.[8] However, this creates a dangerous imbalance by modernising the combat platform while neglecting the total strike package. This force design strategy only succeeds if the tanker can manoeuvre to the precise location required to accomplish its mission. If an adversary's threat networks prevent refuelling assets from accessing the battlespace, this further jeopardises the mission by increasing the risk to strike assets. As the evolving threat landscape pushes required stand-off distances even further out, this capability mismatch between tankers and receivers becomes a critical vulnerability. Today, the most pressing constraint on Allied air power is no longer the performance of the fighter or bomber fleet, but the availability, reach, and range of the refuelling tanker. The true cost of delivering a strategic effect must be calculated as the sum of all systems required to achieve it. Allied nations must recognise that the survivability of the aerial refuelling fleet is functionally inseparable from the lethality of the strike force.

Future Adaptations and Creative Solutions

Aerial refuelling is not a platform; it is a capability. The evolving operational landscape requires that NATO nations reassess their legacy approach of using large, refitted commercial platforms as the standard. NATO Aerial Refuelling Doctrine classifies tanker aircraft as HVAAs, a justified but overly general classification that limits creative solutions for future air-to-air refuelling (AAR).[9] While broadly accurate for heavy tankers like the Boeing KC-46 and MRTT, the HVAA classification creates the false perception that all tanker aircraft are converted from large commercial variants and constrains discussions of novel solutions to the paradigm of large, high-volume assets. Additionally, technological advances in uncrewed systems and autonomous collaborative platforms (ACP) offer future options. Decoupling tankers from HVAA provides nations with more scalable AAR alternatives, beyond the handful of costly and vulnerable platforms, and creates a more resilient, distributed logistics network.

An A-10 Thunderbolt II receives fuel using the probe-and-drogue method during an AAR exercise over a desert landscape.

Other types of aircraft, such as the Lockheed C-130, Embraer C-390, and even the Boeing F/A-18, can be configured with aerial refuelling capability. They either have dedicated variants or offer ground-configurable solutions that add tanker capacity without new acquisition programmes and logistics support pipelines, and give commanders mission optionality outside of a single, dedicated role. For instance, the HC-130 is a modified USAF special mission platform that uses an established system to provide dedicated aerial refuelling support to Joint Personnel Recovery (JPR) missions. It has different performance characteristics than traditional heavy tankers, brings with it an additional suite of communications and troop transport capability, and can operate in higher-risk environments than other heavy tankers. Although these aircraft offer refuelling capability to the battlespace, their limited fuel capacity and high-risk mission complexity have largely kept them away from steady-state mission profiles as prescribed by Air Refuelling Doctrine.

Allied nations should explore expanding non-traditional aerial refuelling capability, such as configuring existing combat aircraft to conduct AAR on demand. An improved version could include advance fourth- or fifth-generation fighter aircraft, or even legacy assets modified with internal and external fuel storage and offload capability. Although tactical aircraft have limited fuel offload capacity, the ability to provide even limited range and endurance extension to combat aircraft could result in a significant operational difference. In sufficient quantity, these aircraft could execute a distributed AAR concept of employment, working a pre-planned or dynamic hub-and-spoke system to deliver fuel closer to the target area.

Another means of granting more flexibility for forward AAR is dual-mode optionality for current and future receiver aircraft. Most receivers are configured for either boom or probe-and-drogue AAR, not both. Aircraft like the HC-130 and the re-configured F/A-18 buddy tanker can only offer probe-and-drogue refuelling. Therefore, if the receiver requires boom tanking but the only available tanker is limited to probe-and-drogue, the aircraft cannot be made compatible in the air. For example, the USAF recently developed a modular refuelling probe for the Fairchild A-10 to support US Central Command operations. The device can be installed and removed by aircraft maintenance personnel, effectively converting a boom receiver into a probe-and-drogue receiver when required by the mission.[10] This pragmatic adaptation enables A-10s to receive fuel from low-flying tactical tanker fleets such as the HC-130s, and allows combat aircraft to refuel closer to the fight and reducing demand for heavy tankers.

Early ACP development has focused on Collaborative Combat Aircraft (CCA), and USAF leadership has

A US Marine Corps CH-53 and USAF HH-60 conduct aerial refuelling with an MC-130 assigned to Combined Joint Task Force – Horn of Africa, demonstrating that refuelling capability exists beyond the rear echelon.

indicated an interest in aerial refuelling capability for future increments.[11] The US Navy's Boeing MQ-25, an uncrewed refuelling platform, is now in low-rate production. It was developed to extend range for the carrier air wing and reduce the burden of buddy tanking on the F/A-18 fleet.[12] The aircraft also offers an early example of distributed, low-volume aerial refuelling. The MQ-25 meets Modular Open System Architecture (MOSA) design standards, allowing major components to be incrementally replaced without major system redesign.[13,14] This allows faster adaptation to meet future system requirements or to expand existing capability. For example, future integration of a refuelling receptacle could allow the MQ-25 to operate as an AAR 'worker bee', receiving fuel from traditional tankers at-range, and then delivering mission-critical fuel deep into contested airspace without increasing the risk to traditional HVAA tankers. If incorporated across NATO nations at scale, uncrewed platforms could help close the reach-survivability gap for Allied AAR.

While a distributed refuelling model in a resource-limited context seems counter-intuitive, these challenges must be weighed against operational realities. To be clear, non-traditional refuelling methods do not render traditional heavy tankers obsolete. Large HVAAs remain relevant by serving as high-volume foundational 'hubs' that move massive quantities of fuel within the theatre and the battlespace. The objective is simply to introduce flexibility through smaller, more survivable 'spokes' capable of pushing that fuel further inside the threat ring. Admittedly, utilising existing strike aircraft as buddy tankers assumes excess capacity within the current fleet. However, this trade-off is often necessary to stage fuel closer to the target, significantly increasing the time-on-station and overall effectiveness of the remaining strike package. Lastly, smaller platforms offer limited offload quantity compared to heavy tankers, extending the range of only a few combat aircraft.[15] But at the tactical edge, that marginal extension is often the determining factor between successfully servicing a critical target and accepting unacceptable mission risk. As ACPs enter the battlespace, pairing traditional crewed buddy tankers with small, low-volume uncrewed systems will allow commanders to project power deep into the Missile Engagement Zones of A2/AD environments while mitigating risk to crewed platforms. NATO's future investment decisions must weigh these trade-offs.

Conclusion

The luxury of operating heavy, vulnerable tanker fleets in permissive environments is rapidly becoming a relic of a bygone era. In an A2/AD environment, relying solely on vulnerable HVAAs to bridge the tyranny of distance is a strategic gamble that NATO and its Partners can no longer afford. Nations must pursue a two-pronged approach: procuring larger, more survivable heavy tankers to sustain bulk fuel requirements, while developing smaller, repurposed, and uncrewed platforms. These include the MQ-25, converted combat aircraft, and future ACP variants, to push fuel closer to the contested edge. This shifts the focus from sheer offload capacity to survivability, agility, and tactical innovation, ensuring the total strike package maintains its required range and lethality without assuming unacceptable operational risk. Ultimately, aerial refuelling is not merely a logistical support function that can be confined to the rear area. Acknowledging this reality requires a commensurate commitment in survivability, research, development, and procurement to keep refuelling capability effective, even in the most hostile environments. ●

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A laser-armed Stryker manoeuvres during US Army testing at Fort Sill, Oklahoma. For NATO, the challenge is no longer directed energy technology, but rather its integration.

Bringing Directed Energy Weapons into Focus

Integrating Emerging Capabilities into NATO Air Defence

By James Black, Deputy Director, RAND Europe,
& Stuart Dee, Research Leader, RAND Europe

For some, directed energy weapons (DEWs) represent the realisation of a 'Star Wars' vision of modern conflict, and a timely solution to proliferating air, missile, and drone threats.[1] For others, they represent the pinnacle of hype and an overstatement of the operational relevance of outdated technology.[2] The reality is that years of research and development (R&D) have unlocked a transformational capability, shifting the focus from technology maturation, testing, and experimentation towards operational deployment. Why, then, are DEWs generating such heated debate once again, and what can NATO do to maximise their utility?

The answer lies largely on the battlefields of Ukraine and the Middle East. Russia's war in Ukraine has catalysed rapid advances in uncrewed air systems (UAS), alongside industrial developments that enable them to be produced cheaply and at scale, overwhelming air defences and stretching stockpiles and production lines for kinetic interceptors.[3] Proponents therefore present DEWs as a low 'cost-per-effect'[4] solution to the challenges of saturation, cost asymmetry, and industrial sustainment in contemporary air defence, shifting the cost-exchange ratio of engagements against massed UAS in favour of the defender.[5] Whilst NATO efforts are primarily focused on DEWs' utility as counter-UAS (C-UAS) tools, the technology has much wider applications. These include not only short-range air defence (SHORAD) or counter-rocket, artillery, and mortars (C-RAM) missions closely aligned with C-UAS tasks, but also anti-satellite (ASAT) use cases, with threatening implications for strategic stability.[6]

Advances in Technology Readiness Levels (TRLs) confirm that DEW capabilities are maturing rapidly. Yet discussion too often focuses narrowly on the technology itself rather than the wider doctrine, organisation, training, materiel, leadership and education, personnel, facilities, and interoperability (DOTMLPFI) needed to field it effectively. This article addresses the role NATO can play in shaping DEW adoption through shared doctrine, standards, and integration.

Types of Directed Energy Weapons

Coherent adoption starts with clear definitions. 'Directed energy' is a contested term that different nations interpret to include a range of military applications. In its broadest sense, it captures many systems operating across the electromagnetic spectrum (EMS). Fundamentally, these systems rely on energy at specific wavelengths being directed to generate military effects, whether through deception, confusion, or kinetic intervention. This aligns with NATO and national-level policy and doctrine, which define effects more broadly than a simple 'hard kill'. 'Soft kill' effects, such as impairing sensors or reducing a target's capability, are often sufficient.[7] Australian doctrine, for example, frames Directed Energy as both an aspect and augmentation of electronic warfare (EW).[8] For NATO Allies, DEW technologies sit within this broader spectrum at the intersection of kinetic and EW capabilities. This sets the scene for the disaggregation of types of DEW, which focus largely, but not exclusively, on neutralisation of targets.

A 2025 RAND Europe study for the Ukrainian government classified and examined two principal categories of DEW from the perspective of C-UAS operations, offering a typology for NATO Allies.[9] High-energy lasers (HELs) emit a focused beam of photons (light, typically not in the visible spectrum). At low settings, these can 'dazzle' or blind a target's electro-optical sensors, including the human eye. At higher wattages,

The US Navy demonstrates the Laser Weapon System (LaWS) HEL during operations in the Arabian Gulf.

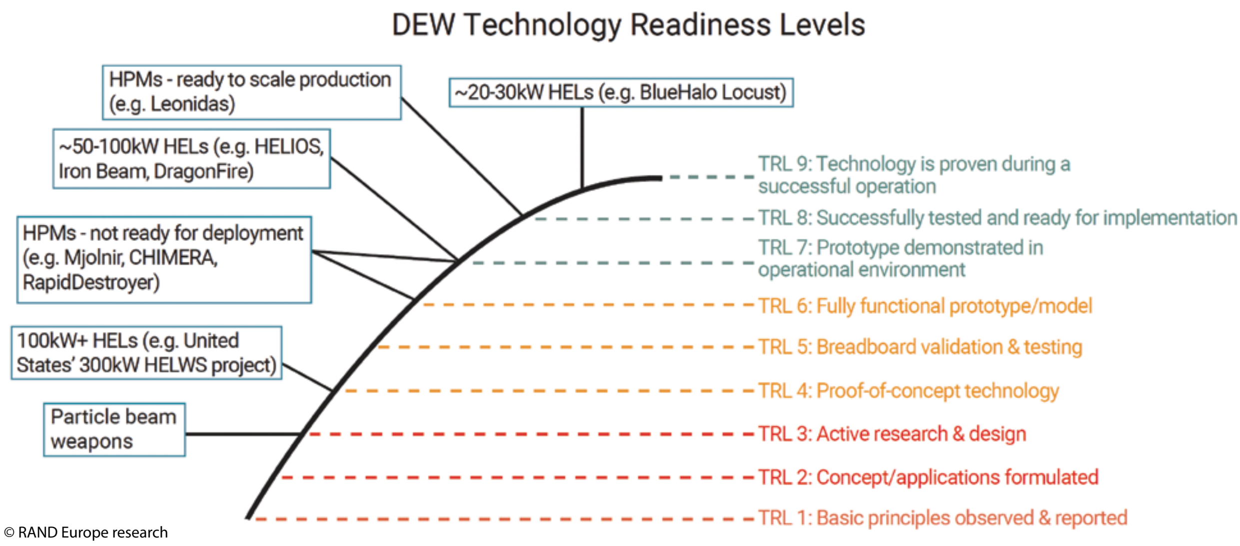

Figure 1: *Technology Readiness Levels of Selected DEWs.*

the laser burns through the targeted structure, for instance, the wing or body of a drone, causing it to crash. By contrast, high-power microwave (HPM) systems or radio frequency (RF) DEWs use concentrated pulses of energy to disrupt the electronics on board their target. Such systems can engage multiple targets simultaneously within a wider beamwidth, while lasers require greater accuracy to be effective.

While the current discourse on DEWs focuses largely on 'laser warfare', in practice DEWs have a more nuanced range of applications. As such, they are better considered by NATO Allies as emerging complementary elements of the EW toolkit rather than a new standalone effector option. Figure 1 provides an indicative assessment of TRLs across different types of DEWs based on open-source information. This reveals a patchwork of capability offerings, from the near-deployable through to those that remain largely conceptual.

Potential Applications and Benefits of DEWs

Development efforts commonly focus on DEWs' low cost-per-shot potential as C-UAS systems or as part of a wider layered approach to Integrated Air and Missile Defence (IAMD).[10] The Israeli Iron Beam concept will reportedly engage targets up to 10 km away using HEL technology, leveraging its high accuracy and rapid re-engagement against high-volume UAS threats.[11] Low-cost UAS such as the Iranian Shahed system are massed against exquisite, low-volume systems such as the PAC-3 interceptor, integral to the US Patriot missile system but reported to cost roughly $4M per interceptor.[12] The UK Ministry of Defence reports a cost-per-effect for its in-development DragonFire Laser DEW of only £10 per shot, or using a regular heater for just an hour.[13]

The Tactical High-power Operational Responder (THOR) at Kirtland Air Force Base ahead of its April 2023 counter-swarm demonstration. In contrast to a HEL's tightly focused beam, THOR's wide-beamwidth microwave pulses can disable multiple UAS near-simultaneously.

Proponents also emphasise the sustainment case for DEWs. Promotional materials often refer to unlimited magazine depths, in contrast to the interceptor replenishment bottleneck already noted.[14] Neither DEWs nor low-cost kinetic interceptors can fully replace exquisite systems such as PATRIOT, THAAD, or SAMP-T NG, but a high-low force mix may ease pressure on munitions production lines and keep NATO forces in the fight for longer.

Proponents typically cite other benefits, including high accuracy and the ability to deliver a range of scalable effects with a single system. This could include HELs fully disabling or simply blinding the sensors on a target, presenting a route for de-escalation in a crisis. This is a consideration that may cut across operational and strategic imperatives. Similarly, the US military has explored the potential of HPMs as scalable options for non-lethal crowd control, for instance during urban operations, or counter-insurgency missions.[15] In counterspace roles, DEWs offer a more controlled means of holding hostile space assets at risk than direct-ascent ASAT missiles, which generate clouds of debris that risk cascading collisions that render entire orbits unusable (the Kessler syndrome).[16]

Taken together, such attributes of DEWs could create a deterrent effect. Limiting the potency of attritable UAS or massed fires may shift that offence-defence balance further, reinforcing strategic stability.[17] Deterrence is in the eye of the beholder, and this potential is a key driver of investment, as with the $40B Drone Edge initiative announced at the 2026 Ankara Summit.[18]

Technical and Operational Limitations

DEWs have a potentially strong case as integral elements of the future IAMD toolkit, but they are not without limitations. These fall into two categories, mobility and employment, on top of which a plethora of policy and regulatory hurdles could hinder widespread adoption.[19]

First, the requirement for a suitable energy source constrains the mobility of future DEWs. Most large-scale HEL systems currently in development report requirements of between 20 and 100 kW, entailing substantial fixed energy support infrastructure.[20] Some of the newest programmes are even more power-hungry. In July 2026, the US Department of War awarded Lockheed Martin Aculight and nLIGHT Defense contracts to develop prototypes for a containerised Joint Laser Weapon System (JLWS) starting at 150 kW, with ambitions to scale to 500 kW.[21] This demand for increasingly large energy systems, potentially at MW rather than kW scales by the 2030s, drives system size, complexity, thermal management and reliability issues, and cost.[22] This demand therefore limits the operational flexibility and manoeuvrability of systems. The more powerful HELs are likely to remain static air defence nodes, vulnerable to attack and around which an enemy force may easily manoeuvre. That said, these systems could become smaller and more mobile over time. DEWs are also likely to generate signatures, making them easier for an adversary to find and fix, and limiting their use in fast-moving operational situations.

While the current discourse on DEWs focuses largely on 'laser warfare', in practice, DEWs have a more nuanced range of applications. As such, they are better considered by NATO Allies as emerging complementary elements of the EW toolkit rather than a new standalone effector option.

Employment considerations will also impact adoption. Reported engagement ranges are limited to 10 km (though rising with elevation), and atmospheric limitations add to this constraint. Moisture, turbulence, or obscurants in the air can absorb, scatter, and defocus lasers, generating restrictions in conditions such as fog, rain, smoke, heavy dust, and humidity. HELs must be held on target during engagement, adding complications when engaging a fast-moving, small object or doing so from an unstable platform (such as a ship in heavy seas). This requires advanced stabilisation and target tracking integration. As lasers grow more powerful, they also cause more 'thermal blooming': the laser heats the air it passes through,

The DragonFire HEL fires during a trial at the UK Ministry of Defence Hebrides Range, January 2024, marking the UK's first high-power laser firing against aerial targets.

which in turn defocuses the beam and could reduce the laser's effectiveness. This is most problematic if engaging a target heading directly at the HEL system on a constant bearing. As such, HELs are limited to line-of-sight employment. HPMs, on the other hand, can deliver effects in a range of climatic conditions, but present a higher risk of adverse collateral effects to friendly forces. Countermeasures could harden targets or shield electronics against these effects, but this comes with increased costs. Together, these size, weight, and power (SWaP), employment, and support demands sit in tension with NATO's Agile Combat Employment (ACE) concept, which will likely focus early DEW deployment on protecting key installations and high-value assets.

Barriers to Capability Fielding and Integration

Beyond technological maturity considerations, the wider DOTMLPFI implications of DEWs will demand considerable focus from NATO defence planners. This means resolving issues such as a lack of doctrine and Tactics, Techniques, and Procedures (TTPs);[23] immature training for DEW employment; and issues with spectrum management, battlespace management, and the avoidance of fratricide. For example, HELs could affect other air assets, even satellites, behind their targets, while HPMs could affect all unshielded electronics along their beamwidth. It similarly means addressing the lack of adequate infrastructure, energy generation, storage, or transmission capacity and ensuring robust field maintenance solutions for novel and unproven high-tech systems.

This uncertainty extends into the true cost of DEWs as well. Defence customers must absorb high R&D and related costs while DEWs remain deployed in small numbers, skewing efforts to ascertain their true cost-per-effect. Open-source reports suggest that initial tranches of Israel's Iron Beam laser system could cost tens of millions of dollars per unit.[24] In November 2025, the UK Ministry of Defence placed a £316 million contract with MBDA to equip two Royal Navy Type 45 air warfare destroyers with DragonFire HELs from 2027.[25]

Until DEWs are ordered and deployed in much larger numbers, batch production will constrain economies of scale in manufacturing. It is equally unclear how industry suppliers will adapt their through-life support solutions and commercial models for DEWs. Maintaining DEWs does not produce the enduring revenue that replenishing traditional munitions does. As such, the full-lifecycle costs and long-term financial appeal to industry for DEW programmes remain uncertain, despite investment currently seen in the sector.[26]

A further consideration is the potential sensitivities with norms and standards on the ethical use of weapons systems. HELs can cause physical harm to persons, including permanent blindness, and intentional use of this type is banned under international law.[27] There is also concern about other inhumane use, such as HPMs for non-lethal anti-personnel or crowd control tools. Relatedly, national legislation and regulations covering everything from management of unsegmented airspace to health and safety can restrict safe testing of DEWs, as well as domestic peacetime deployment. For example, use of a US military C-UAS laser system on loan to Customs and Border Protection forced US officials to close El Paso International Airport in February 2026, disrupting civil aviation across Texas.[28]

Notably, Russian and Chinese discourse on DEWs typically does not focus on tactical applications in C-UAS roles, as in the West. Rather, it considers potential ASAT roles and the resultant threats to critical space infrastructure, including the space segment of nuclear command, control, and communications (NC3) or early warning systems.[29] This highlights a strategic dimension to DEW development and requires careful intent signalling to avoid unintended escalatory outcomes.

Overcoming these policy, legal, regulatory, and DOTMLPFI barriers could unlock DEWs' potential capability-enhancing role in the NATO force mix. Their benefits and limitations mean DEWs are no silver bullet, but they remain a useful addition to the IAMD toolkit. DEWs could form a key part of a layered architecture, integrating active and passive sensors, artificial intelligence (AI)- and cloud-enabled command and control (C2). Current kinetic interceptors should be augmented by affordable mass solutions, such as missile, drone, or gun systems, to counter low, slow, and cheap threats.[30] Further, DEWs could sit alongside Suppression/Destruction of Enemy Air Defence (SEAD/DEAD) and deep strike capabilities, undertaking counterforce missions and supporting not just NATO deterrence by denial but also deterrence by punishment.

Priorities for NATO

Given the outstanding issues surrounding DEWs, NATO's Science and Technology Organisation (NATO STO) has recently developed a Military Utility Readiness Framework (MURF) for DEWs. This framework aims to guide NATO Allies on how to mature DEWs across all defence lines of development.[31] NATO STO designed the approach with industry to embed whole-of-capability thinking from the outset, ensuring Allied nations reach 'mature user' standards before receiving DEWs into service. This MURF approach provides a template for future capability rollouts beyond DEWs.

Still, more remains to be done. Crucially, many of the priority actions apply not only to those NATO Allies already deploying or planning to deploy DEWs (France, Germany, the UK, and the US, in particular). Nations lagging in DEW development or procurement must prepare to operate alongside Allies that field the technology, just as all Allies should prepare for adversaries fielding DEWs of their own. This means work at both NATO and national levels to:

- Refine plans, doctrine, standards, training, and exercises to reflect developments in DEWs and their integration into wider IAMD. Practical examples could include ensuring the NATO Defence Planning Process (NDPP) and associated capability codes continue to evolve to reflect new technologies such as DEWs; including emerging DEW-related considerations into Allied Joint Publications, such as AJP 3-3 Allied Joint Doctrine for Air and Space Operations, and subsidiary documents; and updating the air and air defence elements of joint exercises to stress-test new approaches to managing Joint Engagement Zones (JEZs) and avoiding fratricide when layering DEWs into IAMD.[32]

- Update legislation, policy, and regulation, and ensure access to suitable ranges, to accelerate testing and maturation of DEW technology. This includes modernising approaches to air traffic management via fora such as EUROCONTROL, to reflect testing or operational use of DEWs;[33] ensuring civil-military coordination to avoid unplanned airspace closures, as with the El Paso incident, or unintended danger to satellites and space services;[34] and updating defence safety regulations or broader national health and safety legislation to include DEWs, as early adopters such as the UK military have recently done for HELs and HPMs. At the international level, existing arms control treaties do not directly address DEWs, though they do come under wider International Humanitarian Law;[35] NATO Allies should continue to influence global norms on DEW usage and any future instruments governing their deployment or use, both terrestrially and on orbit (for example, via agreements with adversaries to avoid the targeting of space assets involved in nuclear C2).[36]
- Share lessons learned from operational use of DEWs in contemporary conflicts, such as via NATO's Joint Analysis and Lessons Learned Centre (JALLC). Conduct intelligence gathering on evolving adversary DEW capabilities, concepts of operations, and countermeasures. Commission wargaming and academic research into evolving Russian and Chinese views on DEWs, including the strategic stability implications and inadvertent escalation risks around possible future Ballistic Missile Defence (BMD) or ASAT applications of DEW technology.[37]
- Invest in joint procurements to share costs and promote economies of scale (e.g. via the NATO Support and Procurement Agency, EU, or other groupings), building on recent initiatives such as the new NATO Front Door for Industry, or the $40 billion Drone Edge effort.[38] Promote interoperability and common standards, both for DEW systems themselves and for the Application Programming Interfaces (APIs) and software components that connect them to AI- and cloud-enabled C2. Develop robust supply chains, including for the critical raw materials used in energy technologies, building on existing NATO and European efforts.

DEWs are no longer science fiction. But they remain a source of fierce debate as they are hyped by some and derided by others. The prime barriers to realising DEWs' full potential within the NATO force mix lie not in the technology itself but in the challenges of integration within legacy structures, processes, and policy environments. Though no silver bullet, the maturation of DEWs offers a real opportunity to swing the offence-defence balance and cost-exchange ratio in IAMD in the defender's favour. Seizing that advantage, however, will demand the same focus that NATO brings to the technology itself: implementing the wider reforms needed to turn this once-fictional capability into an operational reality. ●

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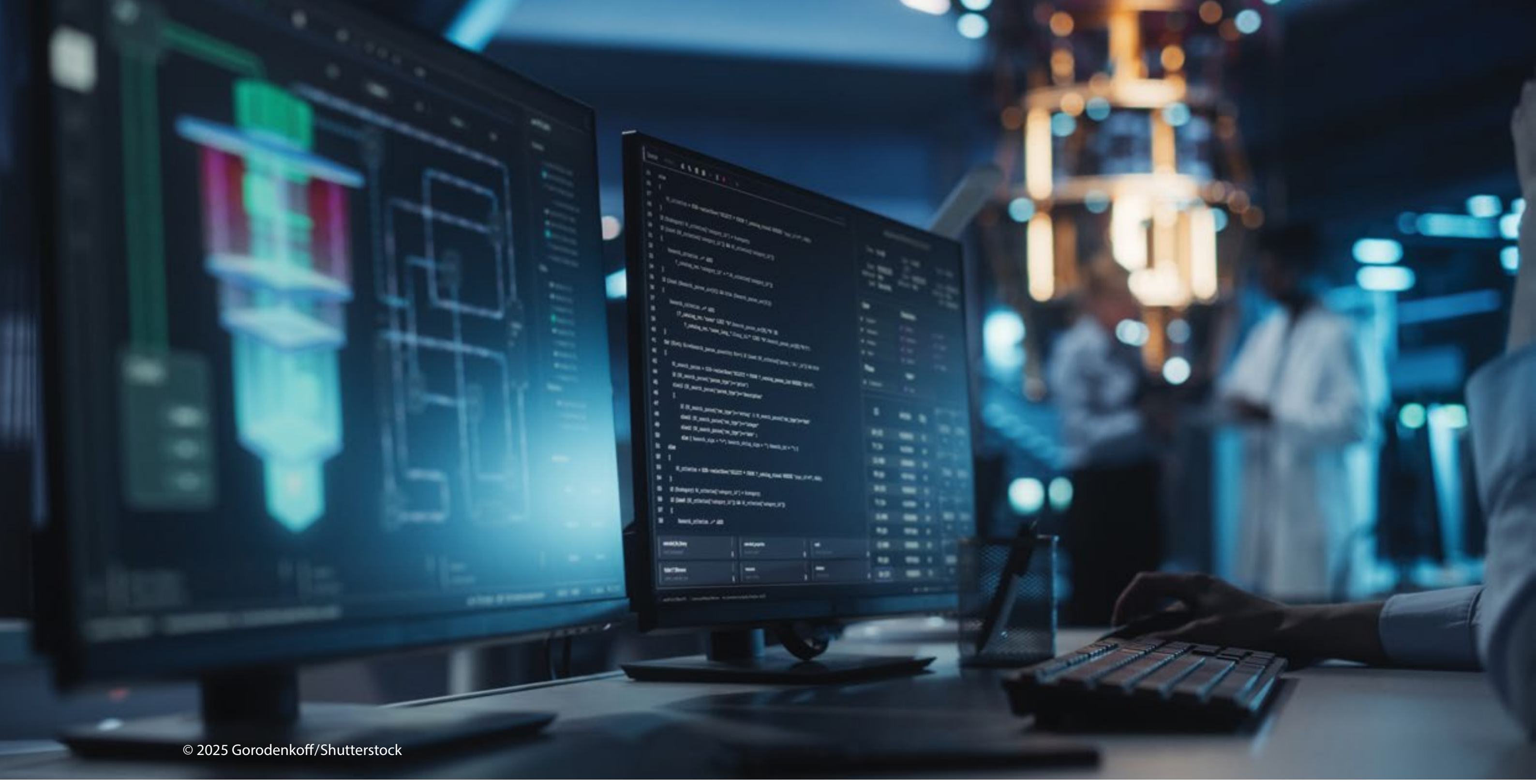

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Quantum Technologies for NATO Air and Space Power

Military Risks, Operational Implications, and the Imperative for Allied Action

By Lieutenant Colonel Nakul Nayyar, CAN AF, JAPCC
& 1st Lieutenant Dr. Matthias Rößler, DEU AF, JAPCC

Once confined to academic laboratories, recent advances in quantum technologies have the potential to affect key enablers of NATO Joint Air and Space Power. Among those key enablers are Air Command and Control (Air C2), intelligence-sharing, satellite communications, and cybersecurity.[1] Quantum computing, quantum communications, and quantum sensing are distinct fields within the universe of quantum technologies with differing levels of maturity, operational applications, and timelines for potential military relevance. Tracking this uneven technological evolution is essential for NATO to maintain its operational freedom of action and deliver joint air effects across the continuum of competition. This article focuses on quantum computing and secure Air C2, where centralised command, distributed control, and decentralised execution all depend on cryptographic integrity.

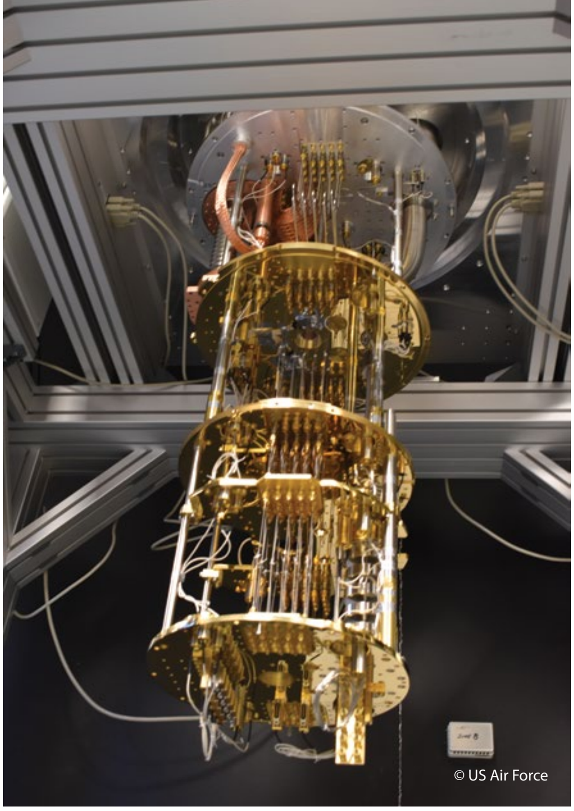
Unlike previous technological transitions, quantum computing does not merely introduce a new capability. It challenges the very assumptions underpinning NATO's digital Air C2 architecture, which relies on the premise that the encryption securing its communications is computationally infeasible to break. Consequently, preparing for the quantum era is not simply a technical modernisation effort, but an urgent operational imperative that requires synchronising post-quantum cryptography (PQC) standards, updating Allied joint doctrine, and establishing binding NATO procurement mandates.

Command and Control (C2) of allied air operations – the architecture this article argues is exposed to quantum-enabled cryptographic risk.

Secure Communications and Cryptographic Resilience in Air C2

Air C2 communications rely on cryptographic mechanisms to ensure confidentiality and integrity across NATO and coalition networks. In essence, a cipher scrambles a message according to a rule that only the intended recipient can reverse. Modern ciphers are trusted not because they are unbreakable, but because breaking them takes too long to be worth attempting. The dominant public-key cryptographic schemes in use, including Rivest-Shamir-Adleman (RSA) and elliptic-curve cryptography, derive their security from mathematical problems that classical computers cannot solve within operationally relevant timeframes.

Quantum computing represents a fundamentally different approach to computation, compared to the methods classical computers use today. Classical computers use binary bits for computation, which can only exist as either 0 or 1. Quantum computers, by contrast, use quantum bits, or qubits, which can exist in multiple states simultaneously through the principles of superposition[2] and entanglement.[3] This allows quantum computers to evaluate many possible solutions to a problem simultaneously and exploit quantum mechanical effects to identify the correct ones more efficiently than classical computers. As a result, quantum computers could potentially solve certain computational tasks in a timeframe that jeopardises the security of many current cryptographic systems. Two examples potentially affected are integer factorisation (breaking a large number down into the prime numbers that produce it) and discrete logarithm calculations (determining the exponent required to produce a known result within a mathematical group). Both would take classical computers impractically long periods to complete. Quantum computers move beyond classical computing by using Shor's algorithm, a specialised formula that solves these exact mathematical problems in minutes or hours.[4] This strips away the protection on which digital systems depend, undermining the security assumptions that form the basis of present-day encryption. For instance, researchers estimate that classical computers cannot factor a 2048-bit RSA key at all, but a large-scale, error-corrected quantum computer could in principle achieve this within days.[5] Although large-scale, fault-tolerant quantum computers remain under development, their projected capabilities have prompted growing concern regarding the long-term security of cryptographic systems that underpin modern military, governmental, and commercial communications.[6]



A cryogenic refrigerator at US Air Force Research Labs used to measure superconducting qubits – the first such demonstration at a US military service laboratory.

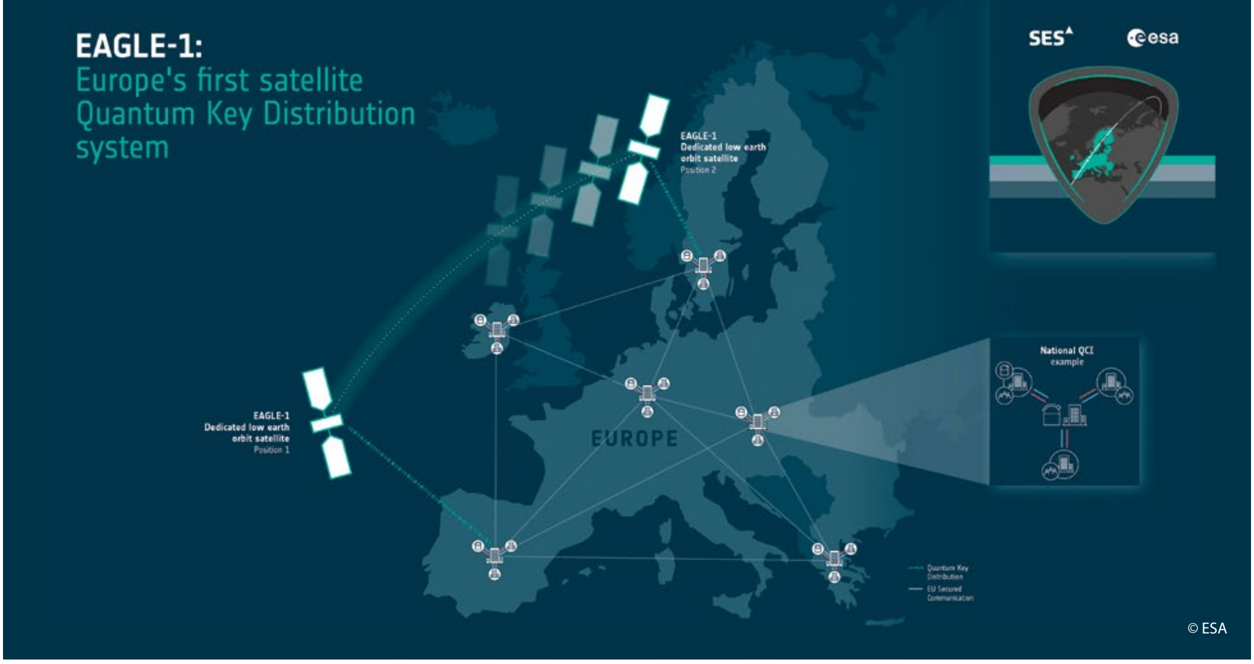
The risk posed by quantum computing to NATO communications does not depend on adversaries possessing a cryptographically relevant quantum computer today. Adversaries with mature signals intelligence programmes are already capable of intercepting and archiving encrypted NATO communications at scale; the barrier is not collection, but decryption. A more immediate concern is the 'store-now, decrypt-later' attack vector, in which they systematically harvest and archive encrypted Alliance communications, with the intention of decrypting them retrospectively once sufficient quantum capability becomes available.[7] For NATO Air C2, such cryptographic compromise could directly affect operations security (OPSEC) and Alliance interoperability. Exposure or manipulation of Air Tasking Order data, Air C2 messaging, or Tactical Data Link traffic could undermine trust in the Recognised Air Picture (RAP). It could also degrade the conditions necessary for centralised command, distributed control, and decentralised execution. In this context, quantum computing represents a systemic risk to Air C2, reinforcing the need for early transition to quantum-resilient cryptographic standards across the Alliance.

For NATO, this shift has two implications. First, the pace of quantum-enabled encryption and decryption capability development may accelerate, as commercial incentives will likely drive iterative improvements and deployment.[8] Second, access to quantum computing capabilities may progressively extend beyond a small number of state actors through commercial cloud-based services and international research partnerships. Major technology firms already provide limited access to quantum processors through cloud platforms, allowing universities, private companies, and smaller states to experiment with quantum applications without needing to build out their own quantum infrastructure. Adversary states and non-state actors that lack sovereign quantum programmes could nonetheless leverage cloud-based quantum resources to probe or attack cryptographic systems underpinning NATO communications. Continued advances in quantum computing and sustained state investments suggest that NATO defence planning must prepare for their eventual emergence. However, there are additional factors and challenges to take into consideration.

Quantum-Resistant Cryptographic Standards and the Migration Challenge

The most significant practical development in cryptographic resilience in recent years is the publication of finalised PQC standards by the National Institute of Standards and Technology (NIST). They comprise Federal Information Processing Standards 203, 204, and 205.[9] These standards rely on two mathematical safeguards to withstand quantum attacks: complex high-dimensional grids and irreversible one-way functions. Quantum algorithms cannot easily shortcut these mathematical problems, thus the encryption remains secure against both classical and quantum attacks. Consequently, NATO and its member nations now have standardised, implementable solutions available.

However, the challenge is not identifying the solution but executing the transition at Alliance scale. Migrating NATO Air C2 systems to quantum-resilient cryptographic standards is a complex, multi-year undertaking. The Air C2 architecture spans a wide range of national and multinational systems with different procurement timelines, certification requirements, and interoperability dependencies.



Eagle-1 will be the first European space-based quantum key distribution system, designed to launch by early 2027.

Another challenge lies in maintaining cryptographic interoperability across NATO and coalition networks during the transition to PQC. NIST standards provide a common technical foundation, and many NATO Air C2 systems rely on US-developed cryptographic equipment, key management infrastructures, and security architectures. Consequently, the modernisation of US military cryptographic capabilities and the availability of approved quantum-resistant solutions will shape NATO's migration timeline. During the transition period, legacy, hybrid, and PQC implementations will likely coexist across Allied networks, creating potential interoperability challenges that NCIA and national authorities must manage carefully. Ensuring smooth information exchange between NATO and national Air C2 systems will therefore be as important as the technical adoption of PQC itself. Additionally, a coordinated, NATO-wide migration plan is essential to avoid a fragmented transition in which some Allied systems achieve quantum resilience while others remain vulnerable, creating exploitable seams in the collective defence architecture.[10]

Overcoming these challenges to achieving successful migration of NATO Air C2 systems to PQC will require close coordination among three NATO bodies. These are the NATO Communications and Information Agency (NCIA), the NATO Consultation, Command, and Control Board (C3 Board), and Allied Command Transformation (ACT).[11] The C3 Board will play a central governance role by establishing Alliance-wide policy, interoperability requirements, and implementation priorities for quantum-resilient communications. ACT will incorporate PQC into future capability development, experimentation, and digital transformation initiatives, ensuring that emerging Air C2 concepts are designed with quantum resilience from the outset. Meanwhile, NCIA will serve as the principal technical implementation authority, translating policy and capability requirements into deployable solutions through system engineering, testing, certification, and integration across NATO networks and C2 systems. Together, these organisations will provide the governance, innovation, and technical expertise necessary to coordinate a coherent Alliance-wide transition while maintaining operational effectiveness and interoperability throughout the migration process.

Quantum Key Distribution: A Complementary, Not Alternative, Approach

Aside from quantum-proofing encryption algorithms by implementing PQC standards, another complementary approach to securing communications is through a technology called Quantum Key Distribution (QKD).[12] QKD offers a niche defensive option for securing especially sensitive Air C2 links. It enables the detection of interception attempts and provides security assurances that are independent of computational assumptions by exploiting the physical properties of quantum measurement. These characteristics fundamentally distinguish QKD from the PQC standards. Demonstrations of QKD over operational

NIST is an agency leading the charge on post-quantum cryptography for the government sphere.

fibre networks have shown increasing technical maturity over the past two years.[13] However, consistent with prior JAPCC analysis of quantum-enhanced technologies for the air and space domains, QKD should be considered as a complementary capability rather than a scalable solution for tactical airborne communications.[14] It is best suited to protecting high-value command links or critical nodes in both the air and space domains.

QKD payloads can operate within the size, weight, and power limits of small platforms, a key determinant of whether the technology scales. In 2019, the 2.6 kg satellite SpooQy-1 generated and detected entangled photon pairs in low Earth orbit, demonstrating that the entanglement sources underpinning QKD can operate on power- and compute-constrained platforms.[15] Moreover, the Eagle-1 satellite represents a major milestone in Europe's efforts to develop sovereign quantum-secure communications capabilities.[16] Developed through a partnership between the European Space Agency, the European Commission, and European space industry partners, Eagle-1 will demonstrate the feasibility of space-based QKD within the EU. It is due to launch in late 2026 or early 2027, followed by a three-year validation phase.[17] China, however, reached this milestone first. Its Micius satellite performed satellite-to-ground QKD over distances of up to 1,200 km and supported the first intercontinental quantum-secured video conference between Beijing and Vienna in 2017.[18] For now, the Alliance is not setting the pace with quantum for air and space power, but reacting to it.

Conclusion

The potential disruption of public-key cryptography by future adversary quantum computing presents a significant threat to NATO Air C2. NIST's PQC standards provide the technical blueprint, yet adversaries may already be harvesting encrypted communications against a decryption capability that does not yet exist. QKD complements that blueprint, offering assurance independent of computational assumptions for high-value command links and critical nodes in both the air and space domains. However, a quantum-resilient migration across NATO's federated Air C2 architecture is a complex undertaking, requiring close synchronisation with US cryptographic modernisation timelines.

As an Alliance structurally dependent on digital networks, shared situational awareness, and seamless multinational interoperability, NATO cannot afford a passive approach to quantum computing. By driving collaborative, Alliance-wide migration standards today, NATO will outpace adversary capabilities and safeguard its decisive operational edge for tomorrow.

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Optical Satellite Communications

Lasers in Space are No Longer Sci-Fi

By Major Luke Stensberg, US Space Force, JAPCC

High in the Arctic Circle, a formation of Autonomous Collaborative Platforms (ACPs) flies an intelligence, surveillance, and reconnaissance (ISR) mission to collect on enemy air defence systems. Beyond line-of-sight from any other airborne platform or ground infrastructure, the formation depends on satellite communications (SATCOM) to transmit real-time data to the operations floor. At this high latitude, however, satellites in geostationary Earth orbit (GEO) sit low on the horizon rather than overhead, so the radio frequency (RF) link is marginal.[1] The ACPs collect and process vast sensor data in volumes that exceed the RF link's ability to complete the transmission. Then the adversary begins uplink jamming the satellite. Together, suboptimal SATCOM geometry and jamming sever the connection, and the formation must return to base for maintainers to offload the ISR collection by hand. Terabytes of time-sensitive data arrive too late to act on, and the window of opportunity closes for prosecuting critical adversary targets.

This is not a speculative High North edge case in the distant future; the vulnerability exists today. Wherever modern forces operate, legacy RF links will struggle to keep pace, and adversaries who understand this vulnerability will exploit it. Recent conflicts in Ukraine and Iran have demonstrated that the electromagnetic spectrum (EMS) is contested terrain for which NATO's communications architecture was not designed. Even in a permissive environment, current radio communication throughput is insufficient for the high-tempo, data-intensive operations of large-scale conflict. Continued reliance solely on the RF spectrum for SATCOM creates three principal challenges:

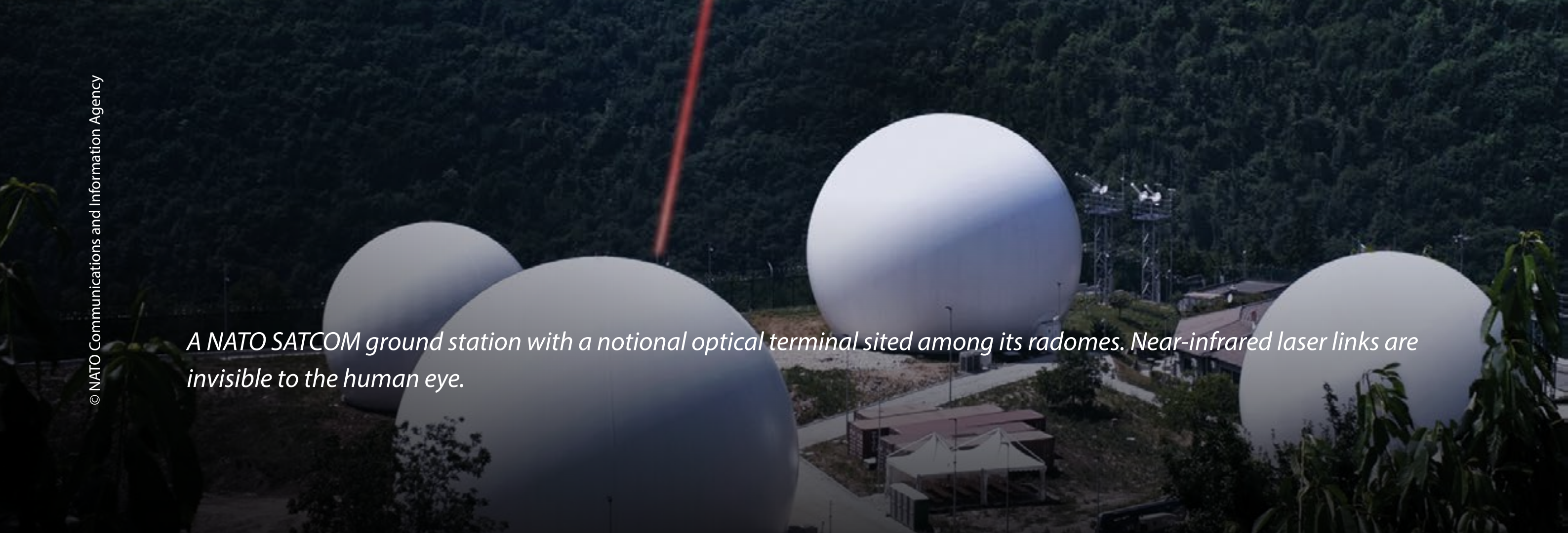
1. **Bandwidth Congestion:** The radio portion of the EMS is increasingly crowded, necessitating constant de-confliction to avoid link fratricide.[2]

2. **Vulnerability:** Traditional radio signals remain susceptible to geolocation, interception, and disruption by adversaries.

3. **Throughput Deficits:** The multi-Gbps data rates required for data-sharing at the edge exceed the capacity of many legacy RF links.[3]

Shifting Up the Spectrum

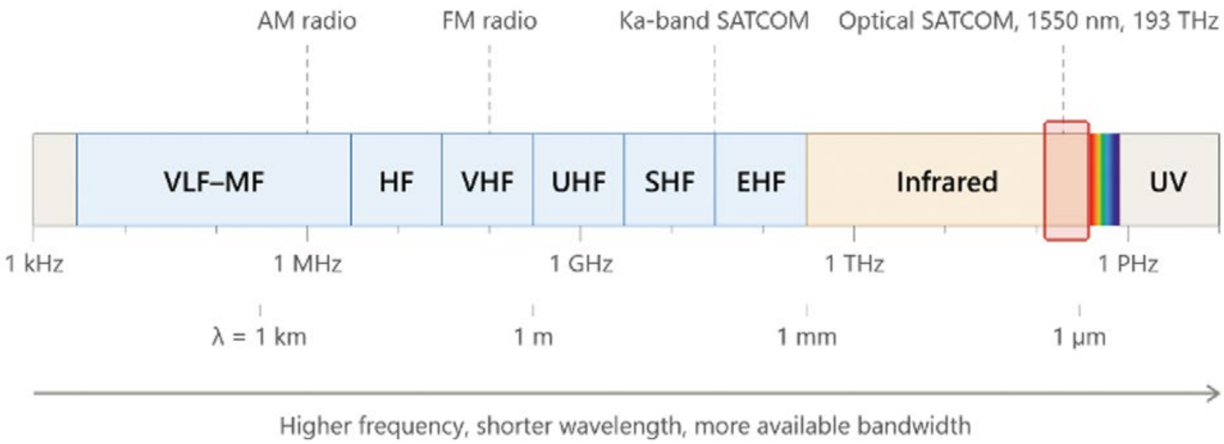
To overcome those three challenges, the Alliance requires additional pathways that reduce reliance on congested and contested RF SATCOM while increasing throughput, all



A NATO SATCOM ground station with a notional optical terminal sited among its radomes. Near-infrared laser links are invisible to the human eye.

© NATO Communications and Information Agency

Optical SATCOM in the EMS



The EMS plotted logarithmically, where each tick marks a tenfold increase in frequency. The entire RF spectrum fits below 300 GHz. Optical SATCOM operates in the near-infrared, more than two orders of magnitude higher, where correspondingly more bandwidth is available.

without creating a new generation of national or commercial solutions that complicate interoperability. Instead of radio waves, optical SATCOM (also known as laser SATCOM) transmits data as pulses of infrared light between terminals, similar to how fibre optic transmissions function terrestrially. It addresses the three challenges of sole reliance on RF SATCOM:

1. **Reduction of Bandwidth Congestion:** Unlike the RF spectrum, which the International Telecommunication Union (ITU) partitions and regulates, the optical spectrum is vast and currently free from regulatory licensing hurdles.[4] This allows Allies to bypass the years-long frequency coordination process and avoid the spectrum congestion when multiple users compete for limited frequency slots.

2. **Inherent Security:** The narrow beam of a laser, often compared to hitting a basketball hoop from hundreds of kilometres away, fundamentally changes the detectability dynamic.[5] These optical links provide inherent Low Probability of Intercept (LPI) and Low Probability of Detection (LPD), making them far less susceptible to the signals intelligence (SIGINT) and electronic warfare (EW) campaigns that challenge today's RF systems.

3. **Orders-of-Magnitude Throughput Increase:** Operating at frequencies far above the RF spectrum, optical links provide the capacity necessary for future network-centric warfare. Against narrowband systems such as Ultra High Frequency (UHF) SATCOM, optical terminals deliver improvements of more than four orders of magnitude.[6] Even compared to wideband systems in the Ku-band, optical links offer roughly two orders of magnitude more throughput today.

These benefits, however, depend on close Allied coordination.

Upgrades Across NATO's Space Segments

To prevent disparate national procurement efforts from creating an incoherent Alliance architecture, NATO should adopt a common Optical Communication Terminal (OCT) standard and use the NATO Defence Planning Process (NDPP) to synchronise growing Allied and commercial momentum into an interoperable network backbone.

NATO's space architecture comprises four segments: the orbital (or space) segment consisting of the satellites themselves; the terrestrial (or ground) segment used to manage the architecture; the user segment of warfighting platforms and devices; and the link segment that connects them to one another. While optical

Segments Linked	What is Connected	Proof of Concept	What it Demonstrates for NATO
Orbital ↔ Orbital	Satellite ↔ Satellite	Proliferated Low Earth Orbit (pLEO) architectures such as Starlink already employ laser crosslinks, or Optical Inter-Satellite Links.[7]	Demonstrates that an optically linked orbital network backbone is viable at scale.
Orbital ↔ Terrestrial	Satellite ↔ Fixed Ground Site	The Netherlands' SmallCAT mission demonstrated a 1 Gbps laser downlink to a station in The Hague, Netherlands in 2024.[8]	Allies are already fielding orbital-to-ground optical connectivity. The terrestrial interface is now procurable, rather than speculative.
Orbital ↔ User	Satellite ↔ Moving Platform	US Space Development Agency (SDA) in July 2025: Two-way air-to-space link between a General Atomics airborne terminal and a Kepler commercial satellite.[9]	Optical communications are reaching the tactical edge; interoperability across vendors is achievable when common interfaces and standards are enforced.

***Table 1:** Demonstrations of space segments linked by optical communications.* © JAPCC

communications represent a modernisation of the link segment, this upgrade is only effective when the nodes are optical-capable. If an orbital, terrestrial, or user segment lacks a compatible OCT, it cannot participate in the high-throughput and secure optical communications architecture. Fortunately, upgrades at each of these nodes are already underway. Allies and industry have achieved proof-of-concept milestones across all segment types, as seen in Table 1.

The US Space Force's SDA demonstration is particularly significant because different commercial vendors from different Allied nations provided each end of the SATCOM link via a common standard. This validates a coalition model in which nations procure hardware from their preferred domestic vendors while remaining part of a single interoperable Allied architecture.

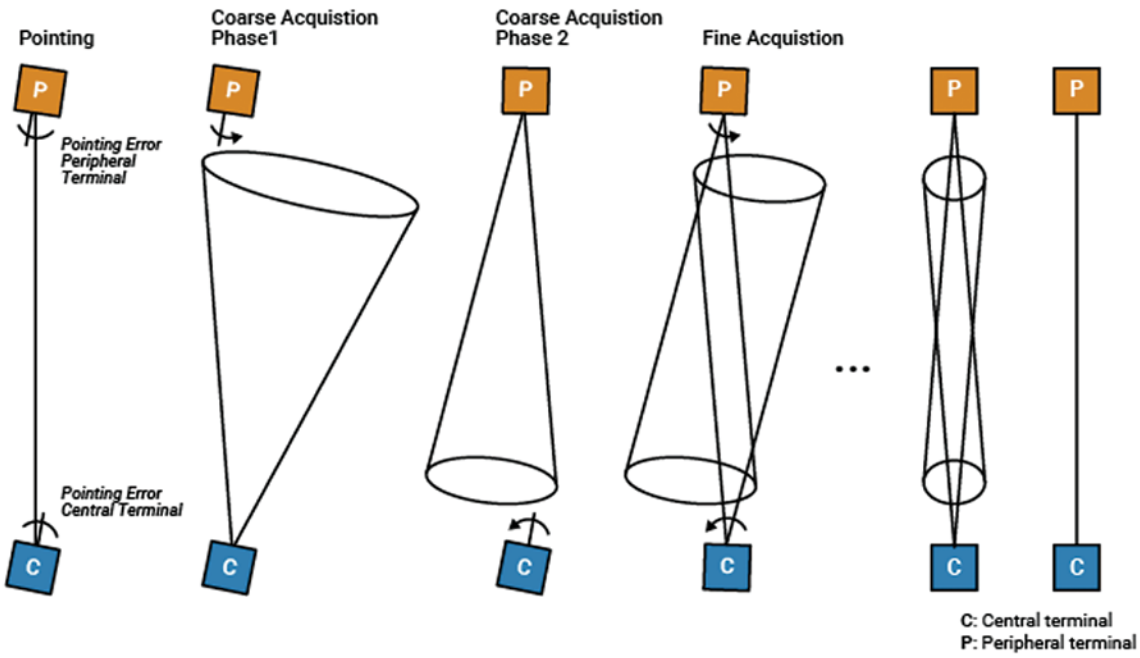
Reality Check

While optical communications offer a transformative leap in capability, they are not a singular replacement for RF SATCOM links due to the physics of the medium. Unlike many radio waves, which penetrate most atmospheric conditions, optical links to and from space suffer significant attenuation from clouds, fog, and precipitation. Orbital crosslinks between satellites are unaffected, but for the ground and user segments, a reliable backbone requires diverse pathways that integrate optical communications into a broader architecture rather than relying on them alone. Promising research suggests a rotating outer laser beam could shield a signal-carrying beam through cloud and rain, though the work remains at the laboratory stage.[10] In the meantime, this is not an unfamiliar problem. Atmospheric conditions already degrade the higher frequencies of today's SATCOM, such as Ka-band and Extremely High Frequency (EHF), so procedures to manage those challenges are already established.

Additionally, the precision that provides optical links with their security also introduces significant pointing, acquisition, and tracking (PAT) demands. Establishing a link between a satellite moving at approximately 8 km/s[11] and an airborne platform requires near-perfect alignment. This precision requires sophisticated hardware capable of maintaining consistent line of sight in a dynamic battlespace.

To weigh the operational advantages against their physical limitations, as shown in Table 2 on page 56 compares the trade-offs between traditional SATCOM and emerging optical systems.

The PAT Process



The diagram above illustrates the PAT process for establishing an optical communications link between two terminals. Beginning with coarse pointing, where both terminals scan a wide angular area, the beam progressively narrows through successive acquisition phases until a precise, stable link is achieved.

Finally, beyond the physical constraints, the political dimension presents its own challenges. NATO's consensus-based framework and national industrial interests make standardisation difficult to enforce. The same sovereign preferences that produced today's fragmented network architecture could repeat themselves with optical SATCOM if left uncoordinated. However, an early standard does not require the same amount of enforcement as one developed later. A public standard from the outset creates an adequate incentive, as vendors build to the specification that maximises their addressable market. This is why achieving optical standards before the technology's proliferation is essential.

Recommendations: Synchronise Momentum into an Interoperable Architecture

NATO does not own or operate satellites, relying instead on national and commercial space data, products, and services made available to the Alliance. Plus, few nations can build a complete optical backbone across all space segments alone. Therefore, NATO must ensure sovereign national and commercial optical space capabilities remain usable by the Alliance through interoperability standards, NDPP alignment, and OCT procurement that keeps pace with national and commercial innovation. Three concrete steps can translate this momentum into an interoperable Alliance architecture.

Step 1: Standardise OCT Interfaces

The first step is adopting a baseline OCT standard. The 2025 SDA demonstrations prove that when interface design has open standards, multi-vendor interoperability is achievable. By adopting OCT specifications under a NATO Standardization Recommendation (STANREC) first and then escalating to NATO Standardization Agreement (STANAG) as the technology matures, NATO can ensure national procurements are interoperable by design. An open standard could prevent vendor lock-in and ensure that a ground terminal from one nation can natively link to another nation's optical terminal in orbit.

Two such specifications already exist, and they are compatible. The SDA has an open OCT standard which

	Narrowband RF (UHF)	Wideband RF (e.g. Ku-Band)	Optical/Laser
Data Rate	kbps [12] (voice, telemetry)	Mbps to low Gbps[13] (imagery and full-motion video)	Multi-Gbps today, with Tbps targeted (bulk offload of full day's ISR collection in minutes)[14]
Susceptibility to Intercept / Detection	Very High (wide-area broadcast)	Moderate (regional beam)	Very Low (LPI/LPD)[15]
Susceptibility to Jamming	Very High[16]	High[17]	Very Low[18]
Antenna Pointing	Wide beamwidth permits less precise pointing and supports on-the-move operations with low-profile antennas	Requires more accurate pointing due to narrow, focused beams	Requires highly precise pointing due to very narrow, laser-based beams; can prove challenging for mobile platforms[19]
Spectrum Availability	Congested; requires licensing	Congested; requires licensing	Unlicensed; bandwidth measured in terahertz[20]
Standardisation	STANAG 4231[21]	STANAG 4484[22]	No STANAG; open standards available to adopt
Size, Weight, and Power (SWaP)	Large	Medium to Large	Compact terminal; overall SWaP favourable for the orbital segment; though varies for user segment[23]
Atmospheric Impact	Low (capable of penetrating clouds)	Low to Moderate (rain fade)	Very High (susceptible to cloud blockage)[24]

Table 2: *RF vs optical communications.*

derives largely from existing international and civil optical specifications rather than any design unique to the US military.[25] The European Space Agency's specification for optical links incorporates requirements in line with the SDA standard, along with commercial fibre standards for the highest data rates.[26] A common transatlantic baseline therefore already exists for the rates being fielded today. That window may not stay open indefinitely, so NATO should act now to codify the areas where the two specifications are already synchronised.

Step 2: Align National Investments Through the NDPP

The Alliance must translate these standards into specific capability targets via the NDPP. The NDPP can specify a defined percentage of national SATCOM investment to meet the NATO optical baseline. This allows NATO to steer national decisions towards interoperable technologies without requiring a central budget for satellite ownership. Because PAT technology for tactical platforms is still maturing, the NDPP

An orbital-to-terrestrial optical downlink connecting a satellite terminal to a ground station. Proof-of-concept demonstrations of this link type are already operational among NATO Allies.

should prioritise the orbital backbone first, specifically inter-satellite crosslinks and terrestrial segments. User segment investment can proceed in parallel as standards solidify. The result is a networked mesh of interoperable terminals in orbit and at ground stations, which tactical platforms can join as their own technology matures.

Step 3: Integrate a Trailblazer

NATO should designate a test case from among its organic missions or Allied multinational projects. This could be a NATO SATCOM ground station, the NATO ISR Force, NATO Airborne Early Warning and Control Force (NAEW&FC), Hybrid Alliance Layered Operations in Space (HALO),[27] or the NORTHLINK Arctic communications project.[28] NATO can then begin incremental integration into this architecture.

A test case serves a purpose beyond communications. It demonstrates Alliance commitment to emerging technology, identifies interoperability gaps early, and builds the institutional experience needed to scale. Because atmospheric factors like cloud cover will remain a persistent constraint on ground and user segments, this transition should follow a hybrid-by-design logic. Rather than fully replacing RF, NATO should build redundancy into the architecture, maintaining mission-critical data flows via RF while leveraging the full throughput of optical links when conditions permit.

Conclusion

NATO cannot control how aggressively an adversary contests the EMS, but it can determine whether its procurement strategy produces a resilient, interoperable Alliance architecture or a collection of isolated national endeavours. The standards must be set now, before national procurements lock in incompatible interfaces.

Consider again the opening vignette. Had the mission been equipped with optical SATCOM alongside its RF links, the jamming that severed the uplink would not have been the end of the story. Hours of time-sensitive intelligence could have found an alternative pathway, one that is narrow and invisible to the adversary. That redundancy is achievable. Whether it exists when needed depends upon the decisions NATO makes today. ●

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From Controller to Integrator

The Evolution of the TACP in Contested Airspace

By Major Harun Elbeyi, TUR Air Force, JAPCC

For decades, Allied ground forces have operated on the assumption that fixed-wing air support would be available, responsive, and decisive. However, the evolution of the modern threat environment challenges this premise. Particularly along the Eastern Flank, immediate and enduring air superiority cannot be assumed. Consequently, control of the air will likely be temporary, localised, and contested, particularly in Anti-Access/Area Denial (A2/AD) environments.[1] Ground units must be prepared to fight and survive without traditional air support while under continuous threat from precision fires and unmanned systems.

In such an environment, the ability to integrate and synchronise all available fires at the tactical edge becomes a condition for survival, not just an enabler. Achieving this objective necessitates convergent effects across all domains, particularly under degraded command and control conditions. These circumstances challenge the Tactical Air Control Party (TACP), NATO's primary air-ground integration capability at the tactical edge, whose traditional close air support (CAS) focus is no longer sufficient in contested, multi-domain environments.

This article argues that the TACP's role as communicator, coordinator, and controller must evolve into that of a Multi-Domain Fires Manager, integrating organic multi-domain fires, counter-UAS and unmanned systems, and electronic warfare (EW) effects while managing airspace in contested conditions.

Why the Current Paradigm is Insufficient

The new threat environment exposes a structural problem in how TACPs are trained and organised. Terminal attack control and support to land forces have evolved significantly over time, but the evolution has largely occurred under conditions of uncontested skies. TACP personnel are commonly qualified as Joint Terminal Attack Controllers (JTACs), who provide coordination and 'cleared hot' clearance for air-to-ground fires. Consequently, existing training pipelines are structured primarily around achieving and maintaining JTAC qualification, as defined by ATP-3.3.2.2 Joint Terminal Attack Controller Program. Along with ATP-3.3.2.1 Tactics, Techniques and Procedures for Close Air Support and Air Interdiction, these publications emphasise terminal attack control, including localised airspace coordination, targeting procedures, and collateral damage estimation, but largely omit broader multi-domain integration.

As a result, cross-domain fires integration, electromagnetic spectrum (EMS) coordination, unmanned aircraft systems (UAS) and counter-UAS (C-UAS) employment, and degraded-communications operations remain underrepresented in current training constructs. Unless Allies adapt training and force development to reflect new realities, TACP syllabi will become progressively less capable of preparing personnel to support land force commanders in contested and degraded multi-domain battlespaces.[2,3] Therefore, it is vital to identify what must be preserved, what must be added, and what must be enabled to address this gap.

Enduring Core Functions: Communications, Coordination, and Control

TACPs operate multiple radio and data link systems to maintain connectivity with aircraft, higher headquarters, and adjacent units. This includes voice communications, digital targeting systems, and emerging data link-based coordination tools, enabling real-time integration of fires. Under degraded or denied communications conditions, the TACP's ability to fulfil its core functions depends on pre-planned control measures, delegated authorities, and the commander's intent embedded at the lowest level prior to execution. This underscores the requirement for organic EMS awareness at the tactical edge.

Beyond terminal control, TACPs play a critical role in airspace deconfliction at the tactical level. This includes the procedural and positive separation of airspace users through coordination with entities such as the Air Support Operations Centre (ASOC) and the Joint Air-Ground Integration Centre (JAGIC), as well as adherence to the Airspace Control Order (ACO), Air Tasking Order (ATO), and Special Instructions (SPINS).[4]

'The TACP's role as communicator, coordinator, and controller must evolve into that of a Multi-Domain Fires Manager, integrating organic multi-domain fires, counter-UAS and unmanned systems, and EW effects while managing airspace in contested conditions.'

In contested environments, the TACP's airspace coordination function must expand beyond the traditional focus on fixed-wing CAS to encompass a broader range of airspace users and fires systems operating simultaneously within the same battlespace. This includes the synchronisation of rotary-wing assets, artillery and rocket fires, UAS, and loitering munitions, all of which may operate at overlapping altitudes, timelines, and engagement zones.

The TACP's defining authority is the control of air-delivered fires within the supported commander's battlespace. This includes executing terminal attack control in accordance with NATO doctrine, where the JTAC provides clearance and control instructions to aircraft, ensuring compliance with targeting procedures, rules of engagement, and collateral damage estimation. This authority is currently scoped to crewed air-delivered fires and Medium-Altitude, Long-Endurance (MALE) UAS; the employment of autonomous and semi-autonomous systems at the tactical level, including One-Way Attack (OWA) drones and First-Person View (FPV) UAS, falls outside this framework.

The growing proliferation of small UAS (sUAS) requires TACPs to combine procedural control measures with dynamic coordination to deconflict trajectories, frequencies, and effects across multiple domains. In such a construct, the TACP retains its doctrinal authority for terminal attack control of air-delivered fires while simultaneously coordinating additional fires systems that may not fall under traditional JTAC control frameworks. Realising this expanded integration function requires three new organic capabilities within the TACP: an sUAS operator, a C-UAS specialist, and an EMS specialist.

The Rise of sUAS and C-UAS

Since 2022, the war in Ukraine has been characterised by small FPV UAS on the battlefield and thousands of OWA drones supplementing conventional cruise and ballistic missiles for long-range strike campaigns. The tactical success of these weapons increasingly depends on persistent local Intelligence, Surveillance, and Reconnaissance (ISR) and rapid sensor-to-shooter integration at the lowest levels of command.

A TACP-organic sUAS operator provides an immediate, manoeuvre-integrated capability at the tactical edge. Operating primarily within NATO Class I and Class II UAS categories, the sUAS operator enables persistent observation, target detection, identification, and tracking in support of time-sensitive targeting and dynamic fires execution.

A critical function of the sUAS operator is the seamless interface with the JTAC during the execution phase of the kill chain. This includes target handoff, target location confirmation, and persistent sensor-based support to collateral damage estimation and battle damage assessment, enabling the JTAC to accelerate decision-making in time-sensitive scenarios while maintaining doctrinal compliance.

Beyond ISR, the sUAS operator contributes directly to fires integration through the employment and coordination of strike-enabled unmanned systems, including loitering munitions and emerging collaborative and swarm-enabled capabilities. The operator coordinates with the JTAC to sequence unmanned strike effects within the fires plan, deconflicting with crewed air-delivered fires to prevent competing engagement geometries.

A NATO TACP completing the landing phase under an autonomous or remotely controlled parachute system designed to deliver equipment loads of up to one tonne in 3rd Main Jet Base LTD-9 Shooting Range, Konya, Türkiye.

C-UAS specialists within the TACP are responsible for the detection, identification, classification, and coordination of responses to adversary unmanned aerial threats. To do this, they employ a layered capability set including radio frequency (RF), electro-optical/infrared (EO/IR), acoustic, and radar sensors. Defeat options may include electronic attack, directed-energy systems, dedicated

An Electronic Countermeasures Officer of the VAQ-130 Zappers, the US Navy's oldest active electronic attack squadron, at his station.

C-UAS effectors, or conventional air defence weapons. While engagement authority remains with the supported commander, air defence element, or EW authority, the C-UAS specialist provides threat assessment, recommends the most suitable defeat mechanism, and ensures airspace and spectrum deconfliction with friendly aircraft and UAS operations. This deconfliction responsibility requires continuous coordination with the organic sUAS operator to prevent fratricide during concurrent unmanned operations.

Finally, the increasing use of OWA drones and FPV UAS introduces a significant doctrinal gap within NATO's existing fires and targeting authority frameworks. OWA and FPV systems do not fit neatly within the authority framework. These systems are new and typically controlled directly by ground elements who operate with varying levels of autonomy, particularly in electronically contested environments. A practical resolution is a tiered advisory clearance model in which engagement authority remains with the supported commander. In this model, the TACP provides mandatory target validation, collateral damage assessment, and airspace deconfliction for OWA drones and FPV UAS employment, scaled according to target type, proximity to friendly forces, and the degree of system autonomy. Adding sUAS and C-UAS competencies brings the TACP role into the present, but a third organic capability is required to prepare TACPs for the multi-domain, integrated future: EMS management at the tactical edge.

Electromagnetic Spectrum Operations

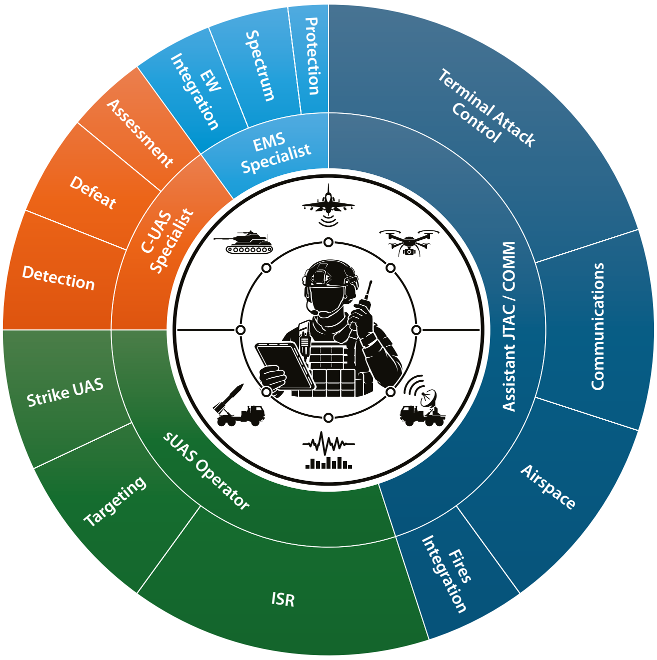
EMS coordination within TACP operations is currently conducted at higher echelons or by dedicated EW and communications units, with TACPs relying on pre-planned measures and higher headquarters coordination for spectrum management and the delivery of electronic effects. The inability to achieve even limited air superiority without synchronised electronic and cyber effects makes organic EMS expertise at the tactical edge essential.[5]

TACPs synchronise rotary-wing, fixed-wing, and artillery fires while maintaining local force protection in a simulated contested environment. Exercise Anatolian Phoenix 2024, Türkiye.

In degraded or denied environments where persistent jamming, spectrum congestion, and dynamic threat emissions are highly likely, the traditional model becomes increasingly ineffective. TACPs at the tactical edge often lack real-time visibility of the electromagnetic environment and have limited ability to request, coordinate, or adapt electronic effects in response to rapidly evolving conditions. EMS Operations (EMSO) are therefore integral to modern joint operations, encompassing the ability to detect, exploit, and protect the electromagnetic environment.[6]

Consequently, TACPs require an organic EMS specialist to sense, manage, and influence the electromagnetic environment at the tactical edge. The specialist is responsible for spectrum deconfliction, ensuring that friendly communications, data links, and sensor systems can operate effectively within a congested and contested electromagnetic environment. This includes managing frequency allocation, coordinating emission control measures, and mitigating interference between joint and coalition systems. This function is particularly critical in degraded communications conditions, where the EMS specialist provides the local spectrum visibility needed to sustain command and fires integration without dependence on higher-echelon coordination.

The EMS specialist coordinates the integration of EW effects in support of operations. This includes requesting, synchronising, and directly enabling electronic attack, electronic protection, and electronic support activities in alignment with the supported commander's intent and the TACP's fires integration function. The specialist should be equipped with portable spectrum-monitoring and direction-finding systems, spectrum analysis tools, and secure interfaces to higher-echelon EMSO assets. The specialist provides local electromagnetic situational awareness, recommends electronic effects, and coordinates their integration with fires and manoeuvre under delegated electromagnetic spectrum management authorities and established frequency assignment procedures. Electronic attack and active electronic effects require coordination with, and in most cases authorisation from, the appropriate EW authority at a higher echelon. The EMS specialist does not independently direct offensive electronic action but provides the targeting data, deconfliction analysis, and integration advice that enable faster and more precise authorisation. This distinction preserves the existing command authority framework while embedding the expertise needed to exploit it at the tactical edge. By embedding this capability within the TACP, electromagnetic effects can be integrated directly into the fires and manoeuvre



The Modular TACP Organisation © JAPCC

framework, enabling the TACP to coordinate and contribute to these effects within its area of operations.

Enabling Capabilities and Recommendations

Institutionalising the Multi-Domain Fires Manager concept requires enabling action across the five key areas. The following recommendations address doctrine, technology, logistics, training, and organisation in turn.

Doctrine: Codify a tiered, pre-delegated fires integration and local airspace management authority for TACPs, distinct from terminal attack control, enabling procedural deconfliction, fires synchronisation, and unmanned systems employment under degraded communications conditions in a contested environment. A practical solution would be a tiered advisory clearance model in which the TACP provides target validation, collateral damage assessment, airspace deconfliction, and fires integration advice for OWA/FPV employment, while engagement authority remains with the supported commander.

Technology: Technological enablers, such as Digitally Aided CAS (DACAS), Edge artificial intelligence (AI), and C-UAS systems, will be critical to achieving this transformation.[7,8] Decision support at the tactical level requires a distributed and resilient hardware architecture capable of operating under contested conditions, including deployable processing units at both the dismounted soldier and vehicle-mounted levels.[9,10] In such degraded communications conditions, TACPs and manoeuvre units require systems that can operate with limited connectivity, enabling local data processing, decision-making, and fires integration without reliance on centralised coordination nodes.

Logistics: Recent high-intensity conflicts confirm that small unmanned systems are effectively ammunition-class assets, with direct implications for logistics and force structure.[11] Rather than being managed as specialised or scarce assets, sUAS should be integrated into standard supply chains with clearly defined allocation scales and replenishment procedures. Ukraine's rapid expansion of drone factories and pilot schools highlights the need for continuous sUAS replenishment at scale.[12]

Resupply rates must account for high expenditure in contested environments, where losses due to adversary action, EW, and operational wear are frequent. Consumption rates for sUAS can mirror or exceed traditional munitions usage rates, requiring continuous replenishment cycles to sustain operational tempo and ISR coverage. Integration with existing ammunition supply point infrastructure is critical for efficiency and scalability. Classifying sUAS alongside conventional munitions enables their incorporation into established logistics processes, including transportation, accountability, and prioritisation within contested supply chains.

Training: Rebalance TACP qualification pipelines towards multi-domain fires integration, adopting a 40/25/15/10/10 training split across CAS, cross-domain fires, airspace management, EW/degraded command and control, and digital/AI competencies, complemented by modular specialisation tracks. Modular specialisation tracks should enable individual TACPs to qualify as sUAS operators, C-UAS specialists, or EMS specialists, without requiring all team members to hold all qualifications, preserving force structure efficiency while building the collective capability the team requires.

Organisation: The TACP construct should be expanded to include three new specialist roles: an sUAS operator, a C-UAS specialist, and an EMS specialist. This integration requires highly flexible and rapidly adaptable organisational structures capable of absorbing these specialist roles to maintain operational relevance and effectiveness in modern, multi-domain conflict environments.

To balance capability with force structure constraints, these specialists do not need to be organic to every TACP; instead, they should be modularly assigned based on mission requirements, threat assessment, and the operational environment. The TACP team leader retains overall responsibility for fires integration and airspace coordination, while each specialist operates within their domain under the supported ground commander's authority and in coordination with relevant higher-echelon functions: fires, airspace, EW, and UAS management. This structure preserves the TACP's existing command relationships while embedding the organic multi-domain capability the contested battlespace demands.

Conclusion

By evolving from a fixed-wing liaison role into a Multi-Domain Fires Manager, the TACP provides a practical and scalable solution to the challenges of contested airspace and degraded communications. The TACP achieves its evolution into a Multi-Domain Fires Manager through three new organic roles: the sUAS operator, the C-UAS specialist, and the EMS specialist, gaining the capacity to sense, contest, and integrate effects across domains where air superiority can no longer be taken for granted. This evolution is not an expansion of function for its own sake, but a necessary adaptation to ensure continuity of joint effects under conditions where traditional airpower advantages cannot be assumed. This adaptation enables distributed control while preserving established command relationships, ensuring that NATO can maintain tempo, resilience, and coherence in future contested operations across NATO airspace. ●

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Faster Than the Threat

AI-Enabled Decision Advantage for NATO Integrated Air and Missile Defence

By Lieutenant Colonel Sebastian Kurzepa, POL Air Force, JAPCC

It begins subtly, much like any other day on duty. Sensor networks deployed along NATO's Eastern Flank start registering small deviations from expected patterns. At the same time, satellite imagery reveals launchers for advanced missile systems relocating away from their permanent garrisons. Open-source intelligence reports unusual convoy activity towards less significant areas, accompanied by a rise in encrypted, command-level communications between key adversary nodes.

Considered in isolation, none of these indicators are necessarily decisive. Analysts and operators have encountered similar signals before, and over time they can grow desensitised to such minor deviations. Currently, Integrated Air and Missile Defence (IAMD) operators must manually classify the threat, estimate the manoeuvring trajectory, identify assets at risk and coordinate effectors. These steps can limit the pace at which the overall system can respond, particularly when the recognised air picture (RAP) is highly saturated by both friendly and threat tracks from high-volume assets such as unmanned aerial systems (UAS).

An AI-supported IAMD architecture changes this dynamic by fusing multi-domain sensor inputs at machine speed, identifying the weapon class, calculating

Large-scale UAS attacks compress decision timelines and challenge traditional air defence architectures.

the path a threat is likely to follow, and ranking the available defensive responses. Commanders must retain decision authority while AI compresses the Sense, Make Sense, Act cycle from minutes to seconds by automating multi-sensor correlation, pre-classifying threat types and generating ranked courses of action (COAs) prior to human decision.

This article argues that NATO must accelerate the responsible integration of artificial intelligence/machine learning (AI/ML) into IAMD, as traditional architectures are no longer sufficient for modern, multi-vector, high-speed attack environments.

Compressed Timelines: NATO IAMD Challenges

Isolated indicators only become significant in combination. On its own, a sensor anomaly, a vehicle movement or a rise in message traffic means little. Correlated at scale, the same indicators may reveal pre-launch preparations for hypersonic systems, low-observable missiles or UAS swarms. Such correlation, increasingly dependent on advanced data-processing methods, remains difficult to achieve when it relies entirely on human-centric processes. Multiple factors add to the difficulty of detecting, predicting and responding to complex threats quickly:

Advanced hypersonic threats: Hypersonic glide vehicles (HGVs) and hypersonic cruise missiles combine high speed with manoeuvrability, complicating prediction and cueing.

Outpaced traditional kill chains: The war in Ukraine demonstrates that the use of AI is compressing decision-making cycles and increasing both the speed and complexity of battlefield operations, posing a significant challenge to traditional, human-centric air and missile defence architectures.[1]

UAS saturation and low-observable cruise missiles: Ukraine has also demonstrated how large UAS swarms can overwhelm surveillance and classification systems, reducing to mere seconds the available time for an operator to react.[2]

Fragmented multinational sensor networks: NATO relies on national systems of varying age, capability, and interoperability levels. While the Alliance aims to build a unified, 360-degree operational picture, differing data formats, classification rules and system architectures slow cross-domain fusion. This reflects longstanding capability development challenges, documented in broader European IAMD assessments.[3]

Insufficient real-time decision agility: Traditional command and control (C2) architectures were not designed for ambiguous, rapidly evolving threat environments, which require near-instantaneous assessment. The increasing density and complexity of airspace further degrade the cognitive ability of humans to distinguish between decoys, hostile platforms, Allied assets and

AI-enabled sensor fusion can transform fragmented observations into a coherent operational picture, supporting faster decision-making.

civilian traffic. Compounding this, contested electromagnetic environments mean IAMD cannot assume continuous connectivity to a central node, forcing critical processing toward the tactical edge.

While NATO recognises these challenges and acknowledges the need for deeper technological integration and improved resilience, as the NATO IAMD Policy reflects, progress has not kept pace with the threat environment.[4] IAMD remains effective for now, but sustained investment in innovation is needed to ensure long-term credibility, particularly in emerging and disruptive technologies such as AI/ML.

Potential Applications of AI/ML

Each AI/ML application that follows reduces a different kind of uncertainty. Sensor and data fusion establishes what has been detected; trajectory prediction narrows where it is going. Historical trend analysis then widens the frame, indicating when particular threat types tend to appear, while intent modelling infers what a detected object is likely to do next.

Sensor and Data Fusion for Threat Detection and Classification

Threat detection relies on radar systems supported by infrared detectors, satellites, signals intelligence (SIGINT), airborne early warning (AEW) platforms, cyber intelligence data and open-source information. This has historically required manually processing, fusing and analysing large quantities of data. AI/ML algorithms can collate this data across varying formats from disparate sources in real time, integrating radar and other multi-sensor inputs into a single analytical process.[5] The resulting datasets can then be compared against historical baselines, providing operators with more holistic and probabilistic threat assessments. This is particularly useful for detecting targets with low radar cross sections (RCS), such as small drones or cruise missiles, as their radar signatures appear sporadically or are inconclusive without further corroboration and analysis.

A relevant example is Ukraine's capability to detect UAS using an extensive network of acoustic sensors.[6] AI/ML-enabled fusion could integrate this acoustic data with radar and SIGINT inputs at scale, particularly under overwhelming saturation where manual rule-based correlation becomes infeasible. In such settings, AI/ML can merge dispersed and inconsistent signals, difficult for human operators to correlate, into a coherent IAMD Common Operational Picture (COP) to generate warnings significantly faster than today's systems.

Trajectory Prediction

Prediction algorithms can be used to reduce uncertainty about an object's future position. This is critical in

USS Hopper launches a Standard Missile-3 during an exercise, intercepting a short-range ballistic missile target in the Pacific.

scenarios involving hypersonic weapons and cruise missiles. Stabilising engagement geometry earlier in the kill chain enables faster effector assignment and improves sensor-shooter alignment, converting warning time into usable engagement time. Those valuable seconds can be the difference between life and death in IAMD scenarios.

Classic estimation techniques such as Kalman filtering have long underpinned trajectory prediction. They have demonstrated their ability to enhance position and velocity estimations of ballistic missiles, which directly translates into a higher probability of a successful interception.[7] Practical research on ballistic trajectories provides the mathematical frameworks and algorithms used for rapidly determining the predicted interception point (PIP) and dynamically shaping trajectories in real time.[8] These techniques perform best against threats whose flight paths follow predictable physical models. Manoeuvring threats such as hypersonics and UAS do not follow ballistic trajectories, and the assumptions that make classic estimation fast and reliable hold less well against them.

AI/ML approaches the problem differently, learning flight behaviour rather than assuming it. Existing AI models can be trained on both simulation and flight-test data. These include deep learning systems that identify motion states and predict hypersonic glide vehicle trajectories,[9] and long short-term memory (LSTM) architectures whose attention mechanisms model complex manoeuvres.[10] Once trained, they generate predictions updated with each successive sensor input, enabling commanders to determine the threat vector far more precisely and quickly than with classic estimation techniques to allow for effective and timely defensive actions.

Historical Trend Analysis and Intent Modelling for Strategic Cueing

Historical trend analysis supports predictive cueing in IAMD, as AI/ML assists analysts in identifying long-term behavioural patterns across large, disparate datasets. ML-supported simulation can reveal recurring tendencies in beyond visual range (BVR) engagements and track how adversaries adjust their behaviour over time,[11] while multi-agent modelling highlights patterns in UAS swarm coordination, preferred attack timings and evolving multi-vector strike profiles.[12] Taken together, these studies suggest that adversary behaviour may be patterned,

AI-driven decision support has the potential to improve effector allocation under conditions of simultaneous multi-vector attack.

and that with sufficient data those patterns are learnable. Incorporating such patterns into predictive processes lets NATO ready sensors, effectors and rules of engagement (ROE) before a threat emerges rather than after.

While historical trend analysis helps indicate where and when threats are most likely to emerge, intent modelling addresses what a detected object will do next. AI/ML-enabled intent modelling draws on observed behaviours (e.g., flight profiles, sensor signals, and communications) to infer probable objectives and future adversary actions. In the air domain, deep learning methods and structural behaviour models can transform kinematic tracks into probabilistic assessments of intent, including attack, transit, reconnaissance or deception.[13,14]

By distinguishing between kinematically similar but behaviourally distinct flight profiles, intent modelling helps prioritise effector employment and may reduce false alarm rates. Drawing on multiple sensor types together, rather than any one in isolation, improves the accuracy of intent estimates.[15]

Data and Interoperability

While AI/ML models are evolving rapidly, the data required to train them remains the limitation. Models trained on fragmented or poorly governed inputs will produce assessments no commander should act on. The risks compound from there, across operational, technical and ethical dimensions.[16] Misclassification, predictive errors, operator overreliance and system-level vulnerabilities under degraded data conditions can all undermine the assessments these systems output. So can deliberate adversary manipulation, such as spoofed radar signals or injected malicious data.

AI/ML must rely on trustworthy data sources, secure supply chains, and robust cybersecurity processes to prevent the spread of corrupted inputs or compromised models across defence networks.[17] Another major challenge involves interoperability issues across the Alliance, including potentially inconsistent data standards, heterogeneous national architectures, and restrictions resulting from classification levels, all of which hinder effective information sharing and coordinated action.

Recommendations for NATO Decision-Makers

NATO's AI Strategy already recognises AI as a foundational capability that must enhance interoperability, resilience, and decision-making across all Alliance tasks. Realising that potential within the NATO Integrated Air and Missile Defence System (NATINAMDS), however, requires a systematic and institutionalised approach to adoption rather than opportunistic fielding. The preceding sections identified where current architectures fall short: fragmented data, slow cross-domain fusion, limited decision agility, and unresolved questions of trust and interoperability. The following recommendations address those shortfalls through four architectural requirements essential to an AI-ready IAMD.

Data readiness: The article establishes that data, not algorithms, is the binding constraint: models trained on fragmented or poorly governed inputs produce assessments no commander should act on, and differing national data formats already slow cross-domain fusion. NATO must therefore transition from data availability to data readiness. The Data Exploitation Framework Policy (DEFP) recognises data as a strategic resource and establishes the foundations for its secure, interoperable use.[18] Within IAMD this means operationalising the DEFP through harmonised data standards, structured metadata, disciplined data preparation and lifecycle management of AI models. This spans training; test, evaluation, verification and validation (TEV&V); and implementation.[19] NATO must also establish federated data pipelines, supported by secure sandbox environments, that allow controlled experimentation on operational data while preserving responsible-use safeguards.

Interoperability and security by design: The preceding sections both identify interoperability as a first-order obstacle: national systems of varying age and capability, inconsistent data standards, and heterogeneous architectures that impede shared action. AI integration must therefore be interoperable and secure from the outset, resting on standardised interfaces, shared data taxonomies and secure supply chains.[20] Doctrine, training, and exercises must evolve in parallel to enable effective human-AI teaming, mitigate automation bias, and preserve the primacy of human command authority. Standardised model documentation, certification, and recertification underpin the transparency on which multinational trust depends.

Institutionalised trust and responsible use: The preceding section identifies the ethical exposure directly: gaps in explainability and accountability, potential algorithmic bias, and the escalation risk of rapid AI-enabled responses. Responsible adoption requires human oversight, rigorous testing, resilient architectures, and adherence to NATO's Principles for Responsible Use of AI – legality, accountability, explainability and traceability, reliability, governability, and bias mitigation.[21] Engineering practice must give these principles effect through continuous monitoring of fielded models, resilience testing, red-teaming and validation under degraded data conditions.

'Data, not algorithms, is the binding constraint: models trained on fragmented or poorly governed inputs produce assessments no commander should act on...'

A distributed edge-core architecture: IAMD must function when connectivity is contested or lost. Accordingly, AI/ML capability should be distributed rather than centralised: edge systems providing real-time decision support at the tactical level, while a protected core retains model development, training, and governance. This division must be codified in a NATO reference architecture to guarantee coherence and interoperability across the two layers.

These four requirements cannot be pursued in isolation. Alignment with the NATO AI Strategy and integration into the NATO Defence Planning Process (NDPP) are essential to coherent capability development, sustained funding and lasting interoperability across the Euro-Atlantic area. Only through such a structured and consistent approach can the Alliance maintain its technological edge while ensuring that the adoption of AI remains controlled, responsible, and operationally effective.

Conclusion

Accelerated AI adoption across NATO's air and missile defences is not optional. Adversaries' use of proliferated UAS, HGVs and low-observable long-range fires compresses IAMD engagement timelines irrespective of Allied adoption choices. The decisive question is therefore not whether these threats exist, but whether NATO can adapt quickly enough to meet them. NATO must develop a comprehensive strategy that uses AI/ML to accelerate and sharpen decision-making in an increasingly complex and data-rich operating environment, while building the political consensus its broader use will require in the face of real ethical and legal challenges. Without timely adaptation, the strengths of today's IAMD architecture will erode; with it, AI offers a realistic means of preserving NATO's operational and strategic edge. ●

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Rebalancing Combat Aviation Training

Integrating Synthetic Environments for Multi-Domain Mission Readiness

By Lieutenant Colonel Antonio Gutierrez, ESP Air Force, JAPCC

Combat pilots have always preferred to fly, and that preference has shaped how militaries train. However, in recent decades, simulator training has increasingly supplemented live flight hours. As the synthetic training environment evolves in sophistication and scope, the question is no longer whether live flying matters. It is whether a training model built around it can produce the volume, variety, and readiness that modern combat demands. Many Allies reference a benchmark of 180 live flying hours per pilot per year, of which only 40 may be accomplished in a full-mission simulator.[1] Meanwhile, operational requirements are evolving: fighter aircraft inventories are decreasing, and sustainment costs for fifth-generation aircraft such as the F-35 are higher than anticipated.[2] Simultaneously, advances in simulated training through live, virtual, and constructive (LVC) environments create opportunities for NATO members to adopt a next-generation approach to mission readiness.

High-performance professions have long used simulation to compress learning cycles and supplement live training time. Formula 1 teams, for example, rehearse procedures and refine decision-making in high-fidelity simulators before the car ever reaches the circuit. The difference is the operating environment: a Formula 1 driver optimises performance on a known track with relatively stable parameters, whereas a combat pilot must prepare for changing theatres, adaptive threats, and unpredictable mission conditions. Networked, high-fidelity LVC environments can expose aircrews to scenarios and threat densities that live flying in peacetime cannot reliably replicate.

NATO air forces face compounding pressures: the battlespace has expanded into cyber and space domains, while the airspace available for training has become increasingly restricted.[3] Consequently, Allied air training must undergo a fundamental transformation to enable Multi-Domain Operations (MDO) and the integration of fifth- and sixth-generation platforms. Operators must integrate multi-domain effects with advanced threat replication to win in a future near-peer, large-scale conflict. NATO should develop and adopt LVC training as an essential and complementary training environment for preparing aircrews for MDO. It can improve mission-ready proficiency and integration at scale, delivering a repetition rate and variability that live flying alone cannot match.

The Requirement for Complexity

NATO's Joint Air Power Strategy, issued in 2018 and revised in 2025, identifies MDO as the linchpin of operational success, requiring the orchestration and convergence of effects across all five domains.[4] The ability of NATO combat air power to perform MDO depends on advanced sensors, weapons, and integration capabilities. Fifth- and sixth-generation aircraft and autonomous collaborative platforms (ACP) increasingly provide these capabilities, acting not only as shooters but also as sensor and data-fusion nodes within a broader system of systems. These systems are redefining the tactical training requirements for air power employment. Against this backdrop, two primary drivers are reshaping how NATO must train its aircrews.

Data Density and the Shift to Mission Management: Pilots must adapt to increasingly complex battle management interfaces. In fourth-generation aircraft, pilots processed fragmented sensor inputs and translated them into aircraft manoeuvre and weapons employment. In fifth-generation aircraft, advanced automation aids in basic flight control, data fusion, and system-driven effects, enabling the pilot to concentrate on battlespace awareness, effects management, and broader tactical decision-making.

Supporting this evolution, modern simulators can replicate multi-domain threats that the live-fly environment cannot as easily generate: cyber effects, electronic warfare, and a saturated information environment that increases cognitive load. Future air combat will depend on superior package-level situational awareness, battle management, multi-domain effects application, and prioritisation, rather than stick-and-rudder skill.

Preparing for Autonomy: ACPs are uncrewed platforms that use artificial intelligence (AI) to translate human intent, ranging from specific commands to broader objectives, into autonomous actions.[5] The Uncrewed Combat Air Vehicle (UCAV), **also known as Collaborative Combat Aircraft (CCA),** is one such type. Crewed aircraft will likely supply the human intent behind ACP employment, transforming a single platform into a human-machine team across missions ranging from offensive and defensive counter-air to airlift and aerial refuelling. This development demands that aviators shift from traditional cockpit skills toward the competencies required to manage distributed, multi-effector teams. These include task delegation, supervisory control, cognitive offloading, and the integration of autonomous agents into dynamic mission environments.

Aircrews will likely develop, rehearse, and validate human-machine teaming (HMT) competencies in synthetic environments before executing them safely in the physical domain. Within the virtual space, pilots and mission aircrew can explore, discuss, and test the boundaries of AI responsibility and the scope of human oversight.

The Operational Imperative: Advanced Training in a Constrained World

Realising full capability requires an advanced and realistic training environment. Three constraints prevent NATO from achieving this complexity through live-fly training alone.

Airspace Geometry: Modern beyond-visual-range air-to-air missile systems, such as the AIM 424 Long Range Air to Air Missile (LRAAM), are projected to reach up to 460 km (250 NM), while the AGM-158B Joint Air-to-Surface Standoff Munition-Extended Range (JASSM-ER) can strike land targets beyond 500 NM.[6]

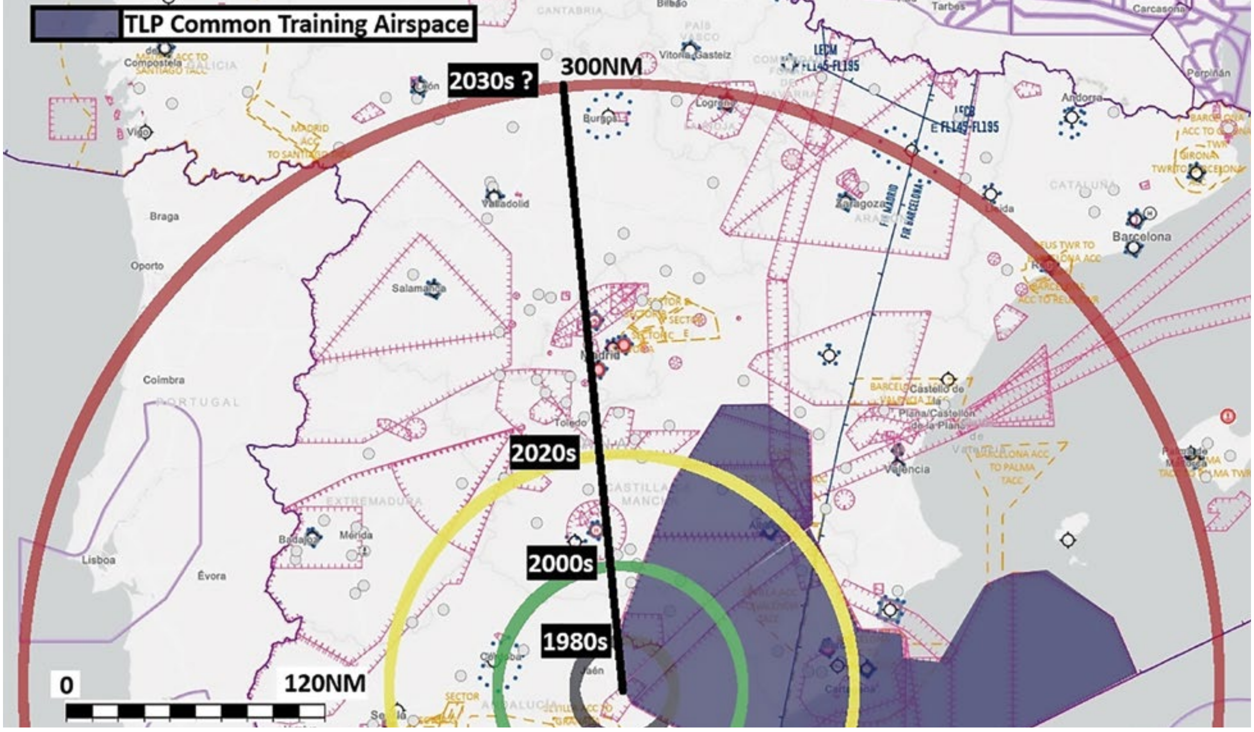

***Figure A:** Baseline Air-to-Air Weapons Ranges overlayed with Spanish Tactical Leadership Programme (TLP) training areas. The above graphic is derived from open-source, historical data to provide a perspective by which the baseline for air-to-air weaponry has shifted from the 1980s to the 2020s (2030s range is notional).*

Emerging capabilities such as hypersonic air-launched weapons promise even greater range. Similarly, the range and capabilities of adversary systems continue to increase. The Russian S-400 surface-to-air missile system can threaten targets at up to 400 km (216 NM).[7] Expanded engagement ranges require live-fly airspace that can replicate realistic engagement geometries.

This technological leap has expanded the airspace volume required for realistic training (Figure A), creating a direct conflict with civil aviation. European airspace is among the most saturated in the world, and nations remain reluctant to constrain economically beneficial air traffic.[8] Efforts such as the Single European Sky and Flexible Use of Airspace improve coordination but cannot increase the amount of available training airspace.[9]

Electromagnetic Spectrum (EMS) Replication: Replicating multi-domain convergence in live training is not feasible, even under optimal conditions. To prepare for high-end conflicts, NATO must familiarise operators with a broad range of multi-domain effects, EMS degradation, and the resulting impact on aircraft systems and weapons performance. However, containing these effects within training-airspace boundaries is impractical, particularly in the space and cyber domains, given the risk of spillover into civil navigation and communications signals.[10]

Force Design and Cost Requirements: To date, 13 NATO nations have committed to purchasing the F-35 Lightning II, adopting it as an advanced but costly capability upgrade over their ageing fourth-generation fighters. Approximately 650 European-owned F-35s are expected to be operational by 2030, comprising roughly 20 percent of the Alliance's fighter aircraft inventory of 3,300.[11] This increase in capability is predicated on proficient pilots who understand what fifth-generation aircraft can do and how to employ them. However, rising sustainment costs and finite airframe life render flying hours an increasingly constrained resource.[12] The Alliance must adopt an LVC model and establish the infrastructure to realise the promised benefits of this fifth-generation fleet.

Operationalising the Synthetic Roadmap

An LVC training model integrates live and synthetic technologies to create a scalable training environment.[13] The train-how-we-fight concept now depends heavily on the ability to replicate a multi-domain environment while overcoming spatial, EMS, and economic constraints. While traditional live-flight training and standalone simulators will remain indispensable, they cannot integrate multi-domain effects at the scale the modern combat environment demands. Therefore, NATO should develop and normalise LVC training while preserving the essential competencies that only live flight can provide, including critical airmanship and somatosensory training. LVC comprises three distinct elements.

Live (L): Involves real people operating real systems. This remains essential for the aerodynamic and physiological effects of flight, including g-loading and somatosensory feedback.

Virtual (V): Involves real people operating simulated systems. This supports mission-management training, allowing operators to master platform interfaces and HMT in a high-repetition environment without airframe wear.

Constructive (C): Involves simulated people and systems driven by computer models. 'Constructive' forces provide the necessary mass and complexity, generating large-scale, reactive, and AI-driven threats that cannot be replicated with live assets.

By blending these environments, a pilot in live flight can train alongside a wingman in a simulator, while engaging a system-generated and numerically superior force package of enemy air and land systems in a manner that is repeatable and scalable. Organisations and nations across the Alliance have pursued initiatives that address this requirement:

- In 2020, the US Air Force (USAF) launched the Rebuilding the Forge (REFORGE) concept, using advanced simulators to support basic pilot training.[14] Major exercises such as Red Flag (USAF integration exercise) and Valiant Shield 24 (US Pacific Command joint exercise) also use LVC components, integrating virtual and constructive assets.
- The Netherlands Aerospace Centre, in collaboration with the Royal Netherlands Air and Space Force, focuses on user-oriented LVC concepts in air-domain training.[15]
- The French Armed Forces have pursued the Massive Network Simulation project, *Simulation Massive en*

Airmen participate in the LVC portion of Red Flag (2015) at the Combined Air Operations Center at Nellis Air Force Base. Red Flag 15-2 was the first Red Flag exercise that included hundreds of virtual and constructive participants in simulators at their home stations or the Distributed Mission Operations Center at Kirtland Air Force Base, US.

Réseau, and the Jeannette system, making significant efforts to interconnect simulators.[16]

- Within the Tactical Leadership Programme (TLP) in Albacete, Spain, the Modern Air Combat Environment (MACE) provides a high-fidelity simulation system used to generate realistic air combat scenarios.[17]
- The International Flight Training School at Decimomannu Air Base in Sardinia, Italy, uses the Embedded Tactical Training System (ETTS) to enable pilots to interact in real time through LVC modes within its closed environment.[18]

While these efforts illustrate substantial progress, they also highlight the need for a unified, Alliance-wide framework capable of integrating and scaling such developments. The NATO Distributed Synthetic Training (DST) initiative provides a framework for such integration. As one of NATO's 31 high-visibility projects to boost operational effectiveness, economies of scale, and Allied connectivity, DST prepares forces for complex operational environments.[19] DST envisions a comprehensive federation of national synthetic training capabilities to support mission readiness and high-fidelity operational training.[20] Launched in October 2024, DST gained rapid momentum with 13 Allies signing a Memorandum of Understanding in October 2025, establishing the strategic framework upon which technical execution must now build.[21]

Recommendations for Implementation

Establish the Foundation: Transitioning to an LVC model requires clear doctrine and standardised architecture.[22] Before procuring hardware, NATO should enforce common standards, such as the High-Level Architecture (HLA) and Distributed Interactive Simulation (DIS) protocols. This will ensure that nations develop systems aligned with NATO reference architectures rather than in isolation. National procurement agencies should mandate compliance with these standards for all future simulation acquisitions. Nations should still maintain the ability to operate national-only simulators for sensitive national training purposes, while a standardised architecture permits integrated coalition training when required. NATO should treat any simulator that cannot connect to the coalition network as operationally limited.

Solve the Multi-Level Security Paradox: Classification and releasability constraints further impede coalition training. NATO should accelerate standardised cross-domain solutions to enable real-time, classification-aware data exchange and prioritise secure federation over default isolation. Acquisition requirements must define both operational and training modes, allowing systems to filter data by classification and connect to coalition simulation networks while preserving the option to isolate from network risks. In practice, some operators will access the system's full data picture while others receive data only authorised for their classification or national caveats. Embedding this dual-mode architecture as a core interoperability requirement will ensure future systems support both operational employment and coalition synthetic training from the outset.

Professionalise the Synthetic Workforce: Running complex LVC scenarios requires embedded simulation structures within Combat Wings and Air Operations Centres, supported by permanent, specialised staff to manage the technical and doctrinal requirements. Yet current manning structures treat simulation support as a secondary function across most Allied organisations. Allies should grow the training and support for personnel who facilitate the LVC environment, and foster either an organic military or a contract workforce to evolve and sustain synthetic training capabilities.

Rebalance the Investment Portfolio: High initial capital costs deter nations from committing to LVC infrastructure, but operations and maintenance costs for the synthetic environment are low in comparison to those of an aircraft fleet. NATO nations should shift the metric of value from 'unit cost' to 'training value', measured, for example, in repetitions or integration density (the total number of systems or platforms participating). LVC preserves airframe life and enables scenarios not feasible in peacetime live training, and this value should be weighed against the acquisition cost of LVC systems.

Conclusion

Addressing these challenges is not merely a technical undertaking but a strategic imperative requiring a fundamental transformation of NATO's internal processes and culture. Live flight remains indispensable for validating aerodynamic performance, physiological stress, and mission integration in the physical domain. However, LVC must carry the burden of scale, repetition, and multi-domain integration required for future combat readiness. Without this recalibration, the Alliance risks fielding fifth- and sixth-generation aircraft within a fourth-generation training construct. ●

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Learning from the Adversary: Insights from the Early Russian Rotary-Wing Campaign

By Lieutenant Colonel Emiliano Pellegrini, ITA Army, JAPCC

The rotary-wing attack platform differs from fixed-wing air power in both form and function – in many militaries it is not an air asset at all, but fire support with rotors, tasked and controlled by the ground scheme of manoeuvre it serves. Nowhere is this clearer than in Russia, which has no separate rotary-wing air doctrine: army aviation follows inherited Soviet combined-arms principles, planning helicopters centrally as an extension of the ground fight.[1] By Western standards, that arrangement was rigid and overly centralised. It prevented multi-domain integration –SEAD/DEAD, integrated early warning, and shared command and control (C2) – and became the thread running through the losses that followed.

Those losses were heavy. By the summer of 2023, 58 Russian military helicopters had been lost in combat since the invasion of Ukraine, roughly one-quarter of the ~234 active rotary-wing airframes in the pre-war fleet.[2,3] Early analysts cited several probable factors for the high initial loss rate: air-denial stalemate in the medium-altitude regime where fixed-wing assets operate, overestimation of Russia's ability to run an air campaign, or the inferiority of Russian technology.[4] Closer analysis shows the high attrition was not merely a product of air power's diminished relevance or technical inferiority, but of the doctrine, C2 mechanisms, and tactics, techniques, and procedures (TTPs) underlying their employment.

Viewed from 2026, the obvious objection to revisiting those figures is that they are old. The lessons, however, have aged well. Their value lies less in what they say about Russian helicopters than in what the following three years reveal: how fast a force in contact corrects itself. The operative issue is tempo. A military at war learns in days: it gets feedback the moment a tactic fails, and pays for it immediately, so it corrects fast. An alliance at peace learns in years, because change moves through requirement, procurement, and fielding cycles

Helicopter Category / Model	Pre-Invasion Active Fleet (IISS)	Visually Confirmed Losses (2022–2023)	Percentage Lost of Active Fleet
Ka-52 Alligator (Attack)	75	32	42 %
Mi-24 / Mi-35 Hind (Attack)	95	14	14 %
Mi-28 Havoc (Attack)	64	12	18 %
All Models Combined	~234 (Total Active)	58	25 %

A breakdown of helicopter fleet attrition from 2022 to mid-2023.

rather than through contact with the enemy. Russia's rotary-wing campaign is therefore most useful to NATO not as a catalogue of an adversary's failures, but as a measure of adaptation rate, and a benchmark NATO must exceed from a standing start.

This article assesses why so many Russian helicopters were destroyed in the opening weeks and asks what it means for the viability of NATO rotary-wing doctrine and TTPs in a future conflict. It analyses the technical specifications and operational tactics of a peer competitor to identify operational, doctrinal, and technical deficiencies that could exist within the Alliance.[5]

Operational Vulnerabilities, Threat Vectors, and Tactical Compression

The effect of sensor, weapon, or geographic and environmental limitations which force an aircraft into closer proximity to the front line is termed tactical compression. Russian forces faced exactly this, and it significantly accelerated their attrition. Each threat below narrowed the band in which a helicopter could survive.

During the initial phase, the Russian fleet sustained catastrophic damage, with Man-Portable Air-Defence Systems (MANPADS) posing the greatest threat.[6] Exploiting the low-altitude profiles of Russian sorties, they accounted for roughly 50 % of confirmed shootdowns.[7] Their lethality lies in passive infrared (IR) guidance, which often bypasses outdated Russian Aircraft Survivability Equipment (ASE).

Surface-to-Air Missiles (SAM) such as the SA-13 Gopher and SA-11 Gadfly caused fewer losses, owing to their minimum engagement altitudes.[8] To evade them, Russian units flew 'nap-of-the-earth' profiles, hugging the terrain and mitigating the SAM threat but forcing aircraft into the lethal envelope of short-range air defences and small-arms fire. The losses proved the trade-off ineffective.

Massing compounded the problem. Flying six to eight helicopters together to concentrate firepower produced large, low, loud formations over occupied areas. These formations were easy to see and hear, and exposed to concentrated small-arms fire. Such engagements accounted for 20 % of Ka-52 losses, in which armour and flares offered little protection against high-volume kinetic fire.[9] These losses forced the first significant adaptation. The Ka-52 withdrew behind the demarcation line, firing less accurate unguided rockets.[10]

Finally, an unexpected threat emerged in the Anti-Tank Guided Missile (ATGM). Systems such as the Stugna-P were used in direct-fire mode against hovering or low-flying helicopters, tracking with precision wherever line of sight could be maintained.[11] The lesson is that rotary-wing aircraft need laser warning receivers alongside electronic countermeasure suites, of the type fitted to the AH-64 Apache, to survive a direct kinetic engagement.[12]

Technical Vulnerabilities, System Failures, and De-Modernisation

This conflict has forced a re-evaluation of platforms once marketed as world-class, and a comprehensive reassessment of vertical-lift survivability in large-scale peer conflict. The attrition cannot be dismissed as a testament to Ukrainian tactical proficiency alone; it reveals a systemic misalignment between Russian doctrine, equipment, and battlefield reality.[13,14]

A decisive factor was the inadequacy of Russian ASE. Field evidence suggests flare-dispensing systems were frequently deployed ineffectively or failed to trigger automatically against modern IR threats.[15] Reliance on manual, pre-emptive deployment, rather than automated reactive countermeasures, exposes a significant lag in the Russian military-industrial complex's ability to update electronic threat libraries. Its failure to account for the multi-spectral seekers of Western-supplied MANPADS has effectively neutralised Russia's perceived technological edge.

Chronic structural vibrations in the Ka-52 compounded the problem, degrading gyroscopic stabilisation and high-resolution optical sensors.[16] By blunting long-range target acquisition, these flaws fed tactical compression, forcing crews to operate in lethal proximity to the forward edge of the battle area, and turning sophisticated assets into targets for low-cost, asymmetric weapons.

The deeper strategic revelation for NATO is the Russian defence sector's dependence on Western-sourced microelectronics.[17] Embargo and supply-chain disruption have created a critical scarcity of high-end semiconductors and thermal-imaging components, driving a de-modernisation of the fleet most visible in the decline of night operations.[18] As Russia cedes the night-time advantage it once claimed, Ukraine has secured a window for manoeuvre under darkness – enabled by its integration of superior Western electro-optical (EO) sensors and night-vision equipment.

Command, Control, and Doctrinal Rigidity: The Failure of Integration

Beyond technical malfunctions, the decimation of Russian rotary-wing assets stems from a systemic failure to adapt its inherited Soviet-era doctrine to a high-intensity, multi-domain battlefield. Battlefield reality forced Russian crews into decentralised decision-making their doctrine never prepared them for. Centralised control remains the doctrinal default, but a fractured communications and intelligence architecture left crews unable to exercise it.[19] Disconnected and improvising, they made isolated decisions that led to many of their losses.

Doctrine and TTPs compounded these failures. Russian practice uses helicopters in close support of ground manoeuvre, saturating targets to enable the main effort. Standard weapons-delivery profiles, such as the pop-up manoeuvre to release unguided rockets, turned aircraft

A Javelin anti-tank guided missile launches from its firing post. Weapons designed to defeat armoured vehicles have seen use against low-flying aircraft into high-visibility and static targets for MANPADS.[20] That large formations operated in daylight over open terrain suggests a significant gap in training on terrain masking and low-level flight.

Most damaging was the absence of multi-domain integration. There is little observed evidence of SEAD/DEAD missions in support of rotary-wing operations, and no manned-unmanned teaming (MUM-T) to push a sensor forward for reconnaissance or electronic warfare (EW). Crews were left with limited situational awareness and therefore vulnerable to ambush. Without a unified digital battlespace, ground units could not pass real-time fires and intelligence. Russian C2 remained anchored in localised, attrition-based paradigms that never evolved towards Multi-Domain Operations (MDO).[21]

Recommendations for NATO's Rotary-Wing Force

The evidence points to an urgent requirement: NATO should recalibrate rotary-wing doctrine and TTPs around the lessons of the Ukrainian theatre. Even the most formidable assets slide towards obsolescence without rapid-cycle technological and doctrinal adaptation, or within fractured C2. Three findings carry directly into Alliance capability development.

Survivability: Russian flare dispensers failed against multi-spectral seekers because the threat library behind them could not keep pace. To avoid tactical compression, rotary-wing platforms must find, fix, and target from a distance – which demands advanced target acquisition and ASE and EO/IR sensors kept current with the electromagnetic spectrum.

The Russian fleet's degradation shows how quickly the inability to secure microelectronics erodes operational capability. NATO must ensure resilient supply chains that support the rapid updating of self-protection sensors and countermeasures against increasingly sophisticated MANPADS and anti-tank systems.

Reach: Russia's gap was not a lack of drones. It used them as artillery spotters, enabling Russia's reconnaissance-strike complex.[22] But that complex was built around artillery rather than aviation. It corrected ground fires, while the rotary-wing force operated outside it. Russia implemented few measures to link the drones it already fielded with its rotary-wing force. Such coordination did not require full manned-unmanned teaming (MUM-T), a capability yet to be widely fielded, but even basic integration might have prevented the tactical compression that followed.

Autonomous Collaborative Platforms (ACP) and Air-Launched Effects (ALE) could meet that same requirement, but without the limits of cockpit-controlled teaming. An uncrewed system flown from the cockpit still consumes the crew's attention and remains bound by the datalink, but an autonomous system can extend the range of sensors and weapons when integrated with rotary-wing platforms.[23] When unmanned systems perform high-risk reconnaissance and EW tasks, the crewed platform can remain outside the lethal envelope and use them as a force multiplier. Industry is designing the concept already.[24]

Integration: The absence of a unified digital battlespace left Russian crews unable to draw on ground-unit fires and intelligence in real time. For NATO, the speed of its own doctrinal adaptation is decisive. The choice is to integrate or be isolated. Superior airspeed and lift can broaden Alliance reach, but the linchpin is a unified Joint All-Domain Command and Control (JADC2) framework.[25] Linking sensors and shooters across domains lets Alliance forces detect and neutralise threats from standoff distances. A synchronised C2 architecture also ensures airspace deconfliction and reduces fratricide in a saturated electromagnetic environment.

Conclusion

The observations in this article are not exhaustive. They are offered as a catalyst for a more urgent examination of NATO's vertical-lift capabilities, and for the institutional question behind it. That question is not whether the Alliance knows what to fix. The findings above are neither novel nor contested, and the capabilities that answer them are already the subject of Alliance programmes. It is whether NATO can translate a lesson identified into a fielded capability on a timeline set by the operational environment, not the procurement cycle. Nothing in the Ukrainian theatre suggests that timeline will lengthen to accommodate the Alliance. The work ahead is therefore institutional as much as technical. It should begin now.

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Training Against the Threat

How JAPCC Supports Allied Readiness Through Air, Space, and Cyber OPFOR

As strategic competition extends across the warfighting domains and the electromagnetic spectrum, NATO's collective training portfolio must prepare headquarters to operate in contested, complex, and rapidly changing environments. To ensure exercises provide value and realism in this context, the Joint Air Power Competence Centre (JAPCC) provides subject matter expertise in the design and execution of operational-level exercises for the NATO Joint Warfare Centre (JWC).

The JAPCC strengthens operational readiness through opposing forces (OPFOR) development, dynamic exercise execution, and effects integration across the air, space, and cyber domains. It translates contemporary operational experience into doctrinally consistent adversary behaviour, enabling NATO headquarters to train under contested multi-domain conditions.

Training for Multi-Domain Conflict

Competition and future conflict are not confined to a single domain. Modern adversaries integrate long-range fires, electronic warfare, cyber operations, space capabilities, and information activities to generate simultaneous effects across the battlespace. Therefore, the challenge for NATO is to break out of domain-centric threat replication and exercise execution. Consequently, NATO's Multi-Domain Operations (MDO) concept requires operational headquarters to synchronise military effects across all domains while maintaining decision advantage in increasingly compressed timelines.

To prepare for this environment, NATO conducts large-scale operational exercises through the JWC in Stavanger, Norway. Since signing a Letter of Agreement in 2012, the JAPCC has supported the JWC by providing expertise in air, space, and cyber operations.[1] That expertise is applied most directly through the development and execution of realistic OPFOR actions within exercises such as STEADFAST DUEL and STEADFAST DETERRENCE.

Developing a Credible OPFOR

A realistic OPFOR is fundamental to operational training. Rather than representing isolated tactical actions driven by domain-centric training objectives, the JAPCC develops adversary behaviour based on campaign-level objectives, doctrinal principles, and intelligence-based threat assessments. This approach reflects how potential adversaries integrate air power, cyber operations, space effects, and electromagnetic activities into coherent operational campaigns.

Modern OPFOR design has evolved from predetermined scripting towards behaviour-based modelling. Instead of following fixed sequences, adversary actions adapt continuously to Blue (friendly) Force, decisions, creating realistic operational fog and friction. This compels commanders to make decisions under unforeseen, contested conditions rather than simply executing planning procedures.

Throughout the exercise lifecycle, the JAPCC contributes to scenario development and execution support, ensuring that adversary behaviour remains operationally credible and aligned with NATO doctrine.

Harmonising Air, Space, and Cyber Effects

Air operations remain central to the JAPCC's contribution. Red (adversary) Force campaigns represent enemy integrated air and missile defence systems, long-range precision strikes, and unmanned systems. OPFOR planners incorporate these capabilities into coherent schemes of manoeuvre that challenge NATO air planning, targeting processes, and airspace management while requiring headquarters to adapt to changing operational conditions.

Space has become equally important. Modern military operations depend heavily on satellite communications, positioning, navigation, and timing (PNT), and space-based intelligence, surveillance, and reconnaissance (ISR). The JAPCC incorporates Red space effects into exercises by denying Blue communications, degrading PNT, and disrupting ISR capabilities, forcing headquarters staffs to operate with degraded command and control (C2), imprecise navigation, and reduced situational awareness.

Cyber operations are also integrated as operational effects rather than isolated technical incidents. Exercise scenarios include compromising C2 systems, degrading logistics networks, manipulating operational data, and interfering with information flows.

> *The JAPCC adjusts air, space, and cyber effects as each scenario unfolds – creating a living operational environment that outpaces static exercise scripting.*

The synchronisation of these cross-domain actions creates realistic dilemmas in which effects in one domain generate cascading operational consequences across the others. Demonstrating an adversary's ability to conduct MDO is one of the surest ways to operationalise the concept for NATO.

Supporting NATO's Major Operational Exercises

The JAPCC's expertise is employed across NATO's principal operational-level exercises; however, exercise support is always tailored to the scenario and warfighting development objectives at hand.

STEADFAST DUEL trains joint headquarters to plan and conduct joint operations under high-intensity, Article 5 conditions. The JAPCC develops and controls OPFOR activities that challenge commanders through integrated air, space, cyber, and electromagnetic effects, often through the enemy's most dangerous course of action (COA).

STEADFAST DETERRENCE focuses on crisis response, escalation management, and deterrence below the threshold of armed conflict. By integrating hybrid activities, grey-zone competition, and rapid escalation into adversary behaviour, the JAPCC helps ensure that training reflects the complexity of contemporary strategic competition in response to most likely enemy COAs.

No matter the type of exercise, the JAPCC supports the JWC by dynamically adapting OPFOR actions to both influence and respond to Blue Force decisions. These contributions enable exercises not only to validate operational concepts but also to inform future doctrine and capability development.

As NATO implements MDO, operational realism has become essential to collective training. The JAPCC contributes significantly to this objective by delivering doctrinally consistent adversary effects across the air, space, and cyber domains. Through its support to exercise design, dynamic OPFOR execution and lessons integration, the JAPCC enables operational and strategic headquarters to train against adaptive adversaries capable of contesting every domain simultaneously.

More than a provider of specialist expertise, the JAPCC serves as a bridge between contemporary operational experience, NATO doctrine, and collective training. By continuously translating evolving threats into realistic exercise scenarios, it strengthens NATO's operational readiness and enhances the Alliance's ability to prepare headquarters for the complexity of future conflict. ●

1. Joint Air Power Competence Centre and NATO Joint Warfare Centre, Letter of Agreement Between the Joint Air Power Competence Centre and the NATO Joint Warfare Centre, 12 December 2012.

Connecting Excellence and Leadership

JAPCC Strengthens Connections at the 2026 NATO COE Marketplace

The JAPCC contributed to NATO's transformation efforts at the NATO Centres of Excellence (COE) Marketplace, hosted by NATO Headquarters in Brussels from 12–13 May 2026. The JAPCC used the event to present its latest products, engage with NATO Headquarters personnel, and strengthen connections across the wider COE community.

Colonel Patrick Parrish, Chief of Staff; Lieutenant Colonel Kim Vogt, Assistant Chief of Staff; Lieutenant Colonel Andreas Lütz, Section Head Planning and Control Section (PCS); and members of the administrative team represented the JAPCC, highlighting its current work and ongoing support to NATO and the Nations while reinforcing the Centre's role as NATO's advocate for Joint Air and Space Power transformation.

The biennial Marketplace brought together NATO-accredited COEs, NATO Headquarters staff, Allied Command Transformation personnel, national representatives, and senior leaders from across the Alliance to promote interaction and mutual understanding between COEs and NATO staff, bringing COE expertise directly into NATO's political and military environment.

The JAPCC exhibit offered visitors opportunity for engagement and insight into Air and Space Power challenges, recent publications, and areas of future cooperation. The exhibit attracted strong interest throughout the two-day programme, showcasing JAPCC's research, analysis, concept development, and support to NATO and the Nations, while highlighting how JAPCC expertise can contribute to ongoing Alliance priorities and future transformation efforts. The team also held discussions with representatives from other COEs, NATO Headquarters personnel, and the broader NATO community, promoting JAPCC products, clarifying current priorities, and identifying potential counterparts across the network.

Participation in an event of this scale requires considerable preparation, but the benefits were evident: face-to-face engagement with COE peers strengthened professional relationships, catalysed collaboration among experts, and clarified how other COEs address their areas of expertise, thereby strengthening the foundation for future collaboration and highlighting the work conducted across the NATO COE community.

JAPCC's participation in the 2026 NATO COE Marketplace reaffirmed its commitment to supporting NATO through independent thought, specialist expertise, and practical products, and its readiness to contribute – through continued engagement with NATO Headquarters and fellow COEs – to the Alliance's ongoing adaptation and the future development of Joint Air and Space Power. ●


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Air Power Excellence, Validated

JAPCC Successfully Completes ACT Periodic Re-Assessment

The JAPCC earned reaffirmation of its Allied Command Transformation (ACT)-accredited Centre of Excellence (CoE) status this past spring, underscoring NATO's first and largest CoE as a key catalyst for improvement and transformation of Joint Air and Space Power within the Alliance. The process was a critical accountability mechanism to assess JAPCC's outputs against the needs of ACT, Allied Command Operations (ACO), and the entire NATO community. Feedback from the ACT team validated the efforts of JAPCC members and the contributions of its 14 Sponsoring Nations, but also allowed the Centre to reflect on NATO's needs for the future.

Preparation began in February, with JAPCC staff compiling a comprehensive submission documenting the Centre's activities, governance, and support to NATO and the Nations. The ACT assessment team visited the JAPCC for the on-site phase of the periodic re-assessment from 19–21 May. Through a detailed review of the JAPCC Programme of Work and processes, the JAPCC showcased the full scope of its contribution to NATO. During the visit, the team engaged with JAPCC leadership and staff, reviewed the submitted documentation, and examined how the Centre delivers value to NATO's priority initiatives. The review also identified areas for improvement over the next three years, encouraging continued development and adaptation to help the Alliance confront the rapidly changing strategic environment. It also provided an opportunity to demonstrate both formal outputs and the professional expertise that underpins JAPCC's contribution to Joint Air and Space Power.

This event served as an opportunity to showcase JAPCC's programmes, projects, and published works that provide key decision-makers with effective solutions on Joint Air and Space Power and help to safeguard NATO Nations' interests. The re-assessment confirmed JAPCC's ACT accreditation for another three-year period. This milestone highlighted the Centre's continued value to NATO and the Nations, while supporting further improvement in the years ahead. Through its proven expertise, committed personnel, and willingness to adapt, the JAPCC remains well-positioned to support NATO's transformation and strengthen Joint Air and Space Power.

Following 21 years of supporting NATO's transformation and capability development, the JAPCC continues to benefit from the expertise, perspectives, and commitment of its Sponsoring Nations. As NATO has grown to 32 Nations, the Centre remains open to strengthening cooperation with Allies that are not yet participants in the JAPCC Memorandum of Understanding, offering further opportunities to contribute to NATO's transformation and capability development efforts.

For further information on the JAPCC and opportunities for participation, please contact us at contact@japcc.org. ●

JAPCC Sponsoring Nations Set Strategic Direction for the Year Ahead

Representatives from all 14 JAPCC Sponsoring Nations gathered at the Joint Air Power Competence Centre in Kalkar, Germany, on 1–2 July 2026 for the annual Steering Committee (SC) and Senior Resource Committee (SRC) meetings. Together, the meetings provided the Centre's principal governance forum, enabling Sponsoring Nations to review achievements, address emerging challenges, and set strategic direction and resource priorities that will shape the JAPCC's activities over the coming year.

SC/SRC 2026 Key Outcomes

14 Sponsoring Nations

2027 Budget Approved

51 % Posts Filled

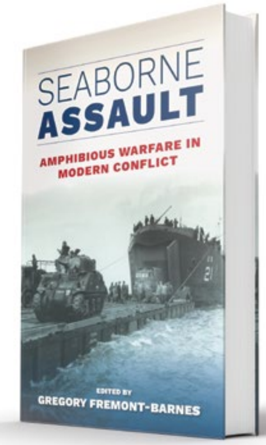
41 % SME Positions Filled

Opening the Steering Committee, JAPCC Executive Director Lieutenant General Thorsten Poschwatta highlighted the increasingly complex security environment and underscored the Centre's enduring role in bridging today's operational demands with the future development of NATO's Air and Space Power. Discussions focused on JAPCC's core activities, including doctrine custodianship, concept development, analysis, education, training, exercises, and engagement across the Alliance. Delegates also reviewed a year of notable achievements, including significant contributions to NATO doctrine, the continued success of the Counter-Unmanned Aircraft Systems (C-UAS) Fundamentals Course, and an ambitious publication programme supporting NATO transformation.

A central theme throughout both meetings was the challenge of personnel shortages across the NATO Centre of Excellence community. With only 51% of all posts and 41% of subject-matter expert positions currently filled, Sponsoring Nations exchanged views on practical measures to sustain delivery, including voluntary national contributions, innovative working arrangements, and opportunities for future growth. Despite these challenges, nations reaffirmed the JAPCC's enduring value to the Alliance, and their shared commitment to maintaining its operational relevance and output.

The Senior Resource Committee reviewed the Centre's financial position and approved all decision points, including the 2027 budget, adjustments to national position contributions, and the conduct of a future financial audit. The approvals provide the financial foundation necessary for the JAPCC to continue delivering its programme of work while adapting to ongoing personnel constraints.

The meetings concluded with a shared commitment from Sponsoring Nations to ensure the JAPCC remains NATO's leading catalyst for the improvement and transformation of Joint Air and Space Power. As the Centre prepares for a leadership transition later this year, delegates expressed confidence that the JAPCC will continue to deliver timely, relevant, and innovative solutions for the Alliance's evolving security challenges.



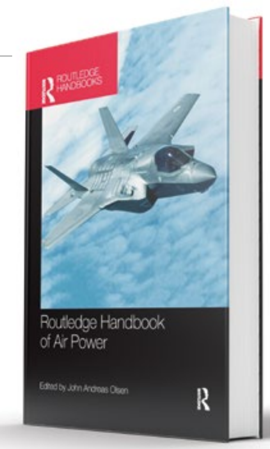
Seaborne Assault – Amphibious Warfare in Modern Conflict

Gregory Fremont-Barnes provides a comprehensive historical analysis of amphibious operations, examining twelve case studies from Operation Albion in 1917 to the Falklands campaign in 1982. Drawing on detailed operational narratives, the editor argues that seaborne assault remains the most complex form of warfare, demanding seamless integration of surface, subsurface, land, and air capabilities at the ship-to-shore interface.

Central to the book is the synthesis of enduring operational lessons that transcend specific historical contexts. The narrative highlights the complex interplay of logistics, command structures, intelligence, and environmental friction. What sets *Seaborne Assault* apart is its focus on the fragility of the amphibious objective area and the necessity of mission command in an opposed littoral environment.

Of particular interest to the MDO community is the analysis of prerequisite conditions for amphibious success. Fremont-Barnes contends that without local air superiority, robust airborne early warning, and combat air patrols, the amphibious force remains critically exposed. For air power practitioners, this serves as a critical reminder: naval manoeuvre and land combat power are fundamentally reliant on the joint air component. Its relevance extends beyond history: contemporary forces face similar challenges in integrating multi-domain capabilities against contested littorals. A must-read for those involved in joint planning. ●

By Gregory Fremont-Barnes (Ed.); Naval Institute Press, 2026
Reviewed by: Lieutenant Colonel Kim Vogt, DEU AF, JAPCC



Routledge Handbook of Air Power

Air power is easy to admire for its technology. Understanding how all the pieces fit together, and what air power can realistically deliver, is much harder. That is what makes John Andreas Olsen's Routledge Handbook of Air Power such a worthwhile read.

The book is at its strongest here. It looks past systems and tactics to the questions that shape how air power is planned and employed: what is air power for, what can it deliver, and where are its limits? Bringing together practitioners and academics, the handbook takes the reader from the foundations of air power through its roles and functions to cross-domain integration and the wider political, social and economic environment in which air power must operate. This is not a book you need to tackle from cover to cover. Its value lies just as much in dipping into a particular subject, following an argument and coming away with a broader perspective.

For anyone working in NATO air power today, that makes it particularly relevant. Technology, threats and terminology will continue to change, but the fundamental questions surrounding how air power should be understood and employed remain.

Olsen's handbook does not offer a single answer. It offers something more useful: the perspectives needed to ask better questions. ●

Edited by John Andreas Olsen; Routledge, 2018
Reviewed by Major Tamás Oszlár, HUN AF, JAPCC

CONNECTING AND
PROTECTING OUR
WORLD
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