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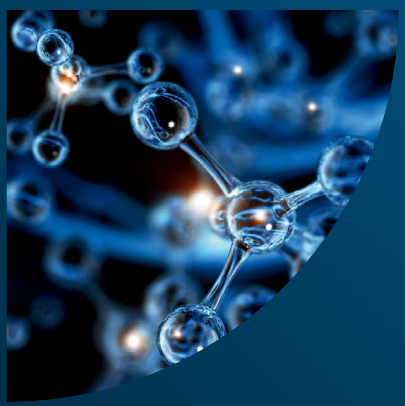
COLLABORATIVE PROGRAMME OF WORK 2025



BOOK OF ABSTRACTS

AVT . HFM . IST . NMSG . SAS . SCI . SET . TSI

This document gathers a selection of abstracts from scientific publications released in 2025 as part of the NATO STO Collaborative Programme of Work. It provides a well-structured overview, arranged in numerical order by activity and grouped by the names of the Scientific and Technical Committees.

In the digital version of the document, each title includes an active hyperlink directing users to the corresponding full reports available in the STO publications database. This user-friendly feature enhances accessibility, enabling stakeholders, academics, and other interested parties to efficiently locate and access specific documents.

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AVT Applied Vehicle Technology

STO-MP-AVT-384

Novel Materials and Manufacturing in Military Vehicle Design

The AVT-384 Research Specialists' Meeting on Novel Materials and Manufacturing in Military Vehicle Design, held in conjunction with the 54th AVT Panel Business Meeting (PBM) in Koblenz, Germany, from 16 – 18 October 2024, aimed to explore cutting-edge advancements in novel materials and manufacturing techniques for military vehicle design. The primary objectives were to identify existing technology gaps, facilitate collaboration, and enhance NATO's technological advantage by integrating innovative materials and agile manufacturing into modern design practices. Key discussion topics included the integration of novel materials such as smart, multiscale, and metamaterials; the adoption of advanced manufacturing capabilities like additive manufacturing and reconfigurable processes; and the development of novel design methods, including AI/ML-based generative design and multidisciplinary optimization. As new materials and manufacturing techniques evolved, NATO needed to bridge the gap in design tools and models to fully exploit these innovations, enabling rapid responses to changing battlefields. By implementing just-in-time design strategies, NATO could maintain technological superiority by adapting to new materials and processes, ensuring rapid updates to military systems and optimizing capabilities throughout future conflict.

STO-MP-AVT-391

Advanced Wind (Water) Tunnel Boundary Simulation III

The AVT-391 Research Specialists' Meeting on Advanced Wind (Water) Tunnel Boundary Simulation III, held in Washington, DC (19–21 May 2025), convened international experts to advance the integration of high-fidelity computational fluid dynamics (CFD) with experimental wind and water tunnel testing. Building on successful predecessors in 2018 and 2021, this meeting focused on assessing state-of-the-art CFD simulations for tunnel flow and boundary conditions—including inflow, outflow, walls, and model support hardware—while fostering collaboration between computational and experimental specialists.

Key objectives included characterizing tunnel environments and measurement processes for CFD validation, presenting high-fidelity CFD simulations (e.g., RANS, SRS, Lattice Boltzmann), and discussing results from coordinated activities such as AVT-387 and NASA's Common Research Model ecosystem. Participants aimed to develop recommendations for CFD simulation best practices and experimental characterization, as well as to link findings to the upcoming AVT-416 course on predicting wind tunnel interference effects.

The meeting also sought to identify critical research gaps, support long-term simulation and testing strategies, and cultivate a sustained Community of Interest (COI) across research, academia, and industry. By addressing these challenges, AVT-391 aimed to enhance predictive capabilities and physical understanding in aerodynamic and hydrodynamic testing.

STO-MP-AVT-393

Environmental and Thermal Barrier Coatings for Military Aircraft Engines

The AVT-393 Research Workshop convened leading experts from NATO nations and partner countries to examine the current landscape and future prospects of Environmental Barrier Coatings (EBCs) and Thermal Barrier Coatings (TBCs) for military aircraft engines. The event was held at NRC Canada from 15 – 17 May 2024. The workshop aimed to define military requirements, identify technical limitations, assess data availability, and highlight key development initiatives in the field of advanced protective coatings. The event addressed a wide range of technical and strategic topics, including harmonization of terminology and definitions; review of the state-of-the-art in coating technologies; analysis of ongoing R&D and investment efforts; evaluation of emerging solutions across the engineering lifecycle; advancements in modeling of particle- and aerosol-laden turbomachinery flows; and assessment of existing test and qualification standards. Structured around three targeted work streams, the workshop explored: Capability Requirements – Defining operational needs for TBCs and EBCs, mapping national capabilities, and identifying science and technology gaps. Materials and Application Methods – Characterizing coating materials, properties, and manufacturing processes. Testing, Modeling, and Cost-Benefit Analysis – Investigating durability, validation methods, and economic impact of coating solutions. AVT-393 provided a vital platform for international collaboration and knowledge-sharing, supporting the advancement of durable, high-performance coatings critical to the future of military aviation propulsion systems.

STO-MP-AVT-409

Life Cycle Analysis of Sustainable Technology for Military Platforms

The AVT-RSM-409 meeting convened experts from defence and industry to advance the understanding and application of Life Cycle Assessment (LCA) in defence procurement. LCA is inherently complex, and its integration into defence poses additional challenges due to sensitive data, diverse supply chains, and global operational requirements. The event gathered nearly 40 participants from 18 countries, featuring 16 presentations, two keynote addresses, and three posters across four sessions: policies and strategies for minimizing greenhouse gas emissions, LCA methodologies, case studies, and industry perspectives.

Key findings highlighted the necessity of regulation to ensure fair competition, as voluntary implementation of LCA may disadvantage proactive suppliers. Standardization emerged as critical for comparability, given the reliance on diverse data sources and assumptions. The development of shared databases was identified as essential for efficiency and cost reduction, while ensuring accuracy and transparency of data requires government oversight to address supplier concerns over proprietary information.

The meeting was well received, fostering collaboration and knowledge exchange. Recommended future activities include demonstration case studies through a Research Task Group (RTG), a lecture series to broaden awareness, publication of the presented papers, and advocacy for standardized LCA practices within NATO procurement frameworks.

STO-MP-AVT-SET-SCI-396

Technological and Operational Challenges Due to Hypersonic Flight and the Related Weapons Threat

The AVT-SET-SCI-396 Research Symposium, held from 14 to 17 October 2024 in Koblenz, Germany, addressed the technological and operational challenges posed by hypersonic flight and the emerging threat of hypersonic weapons. Recognized by NATO as an Emerging Disruptive Technology (EDT), hypersonic systems—capable of sustained flight at speeds above Mach 5 with high maneuverability—present both opportunities and strategic challenges for defence and deterrence. The symposium aimed to disseminate knowledge, assess the feasibility of hypersonic systems, and clarify the associated threats. Key areas of discussion included aerothermodynamics, high-temperature materials, and propulsion technologies such as ramjets, scramjets, and detonation engines. Design considerations for hypersonic platforms, which include Hypersonic Glide Vehicles (HGVs), Hypersonic Cruise Missiles (HCMs), and High-Speed Reconnaissance (HR) systems, were also covered. Participants explored system architecture, launch platform options, guidance and control, onboard sensing, and communication systems. Detection and tracking technologies, including radar and infrared, were examined alongside defence strategies such as area and point defence, synthetic environments, and C3I (Command, Control, Communication, and Intelligence). The symposium further addressed non-kinetic countermeasures, including lasers, directed energy, jamming, and blinding. Conceptual designs for both offensive and defensive systems were presented to illustrate technical feasibility and operational concepts. Through technical sessions and expert discussions, the symposium promoted cross-disciplinary collaboration, enhanced strategic awareness, and advanced NATO's understanding of hypersonic technologies and their implications for future defence planning.

STO-TM-AVT-ST-009

Future Rotorcraft Technologies

The importance of rotorcraft in past and current military operations is widely recognised. Currently there is considerable effort being expended in the development of uncrewed systems that will increasingly be introduced into service in the next decade. These are likely to be employed in multiple roles that are typically defined as "Dull, Dirty and Dangerous," nevertheless, it is expected that crewed systems will continue to be required for at least the next 50 years. The NATO Next Generation Rotorcraft Capability (NGRC) High Visibility Project is exploring options for a medium sized multi-role rotorcraft for entry into service around 2040.

STO-TR-AVT-309

Implication of Synthetic Fuels on Land Systems and on NATO Single Fuel Policy

The increasing availability of alternative fuels, and their blending with conventional petroleum distillate fuels, has created a need for closer coordination among NATO member nations to assess the implications of synthetic diesel fuels (Section 3.1), and synthetic jet fuels (Section 3.2). This includes evaluating their impact on land-based military vehicles, systems, and Tactical Fuel Handling Equipment (TFHE), particularly in the context of diesel synthetic applications. Synthetic fuels present significant opportunities, as well as potential challenges, from a military perspective, particularly with regard to interoperability and their impact on the NATO Single Fuel Policy (SFP). Through outreach with the extended "fuels" community, including vehicle and engine OEMs, fuel producers, tactical petroleum handling equipment (TPHE) suppliers, and elastomeric seal manufacturers, a number of key fuel property risks associated with the introduction of synthetic components in diesel and jet (kerosene) fuels for land systems are identified and studied in greater detail in this report. Namely, variability of cetane numbers from different feedstocks used to produce the synthetic fuels (Chapter 4); impact of the use of cetane and lubricity improving additives in relation to the SFP (Chapter 5); impact of synthetic components on elastomers seal swell (Chapter 6); and impact on storage stability (Chapter 7).

STO-TR-AVT-311

Availability and Quality Issues with Raw Materials for Rocket Propulsion Systems and Potential Consequences for NATO

In the last decade, all manufacturers of solid rocket motors and related subsystems have experienced issues with availability, continuous supply, and quality of raw materials for solid propellants, insulations, charge igniters, etc. A shrinking market and severely tightened regulations with regards to manufacture/processing and use of raw materials (e.g., REACh) are drivers for the chemical industry to question the business case for chemicals needed for solid rocket propulsion. Consequences include cancellations in the product portfolio of chemical companies, downsized and/or discontinuous production processes and increased lead times and price for orders. Occasionally, raw materials are available only from nations outside NATO. It is very important for NATO to be aware of the situation regarding propulsion subsystems of a major type of weapon systems.

STO-TR-AVT-314

Assessment and Reduction of Installed Propeller and Rotor Noise from Unmanned Aircraft

This document is the final report of the AVT-314 activity (Jan 2019 – December 2022) on the Assessment and reduction of propeller and rotor noise from Unmanned Aircraft Systems (UAS) for military and civil operations. The objective of this RTG was to assess the state-of-the-art in UAS noise prediction and reduction and provide technical assessment of the noise from UAS operations. The focus was on propeller and rotor noise in relation to improved effectiveness of UAS operations. The RTG members reported on the state-of-the-art in theoretical background, installed propeller noise, community noise and human response, experimental data and measurement techniques, operations and manoeuvres, sound propagation in general and in urban environments, methods for UAS rotor and propeller noise reduction with a focus on the effectiveness of UAS operations, community noise reduction, the role of new materials and computational tools in the design and development of quiet and efficient propellers and rotors. The RTG members presented their work during the years the RTG group met and contributed their respective inputs to this report. Based on the group's findings, the report concludes with recommendations for future activities.

STO-TR-AVT-331

Goal-Driven, Multi-Fidelity Approaches for Military Vehicle System-Level Design

The AVT-331 Research Task Group studied the potential benefits of Multi-Fidelity (MF) methods in vehicle design and documented the relative strengths and weaknesses of different MF methods using a common benchmark suite developed by the team. Benchmarks were established at three levels of complexity for air and sea vehicles and two levels of complexity for a space vehicle configuration. The use of benchmarks at different levels of complexity enabled broad collaboration and knowledge exchange while critically testing method practicality. MF methods were generally found to provide cost benefit for tasks related to the exploration of vehicle parameter spaces or in the optimization of vehicle designs. Cost decrease of one order of magnitude was observed for the sea benchmarks and the intermediate-complexity air benchmark. Numerous opportunities exist for larger and more reliable cost savings through further method development, e.g., improved dimensionality reduction and gradient-based methods. Studies were conducted by 21 appointed team members from nine countries, along with several additional collaborators. The strong collaboration within AVT-331 and the research relevance of the task group's activities are reflected by over 50 peer-reviewed articles, conference papers, and theses, many of which involve partnerships between AVT-331 members.

STO-TR-AVT-333

Integration of Propulsion, Power, and Thermal Subsystem Models into Air Vehicle Conceptual Design

Future tactical air vehicle platforms have competing requirements for increased mission power, flight speeds, performance, and engine efficiency. Components that drive these requirements are higher-capability sensors/avionics, directed energy systems, flight controls, increased aerodynamic heating loads, fewer ram air cooling openings, reduced fuel burn that absorbs less heat, and higher internal engine temperatures. The consequence of these competing objectives in the various subsystems results in propulsion integration and power and thermal management issues. Traditional design processes develop these disciplinary subsystems in silos after the air vehicle outer mold line has been frozen. Integration depends on static interface control documents made without a complete knowledge of both individual subsystem performance and system performance. This work develops a how-to guide on including these disciplines during the conceptual design process using multidisciplinary design analysis and optimization technology. The resulting Integrated Propulsion, Power, and Thermal Management Systems (IPPTMS) approach offers increased capability to close on designs with demanding and competing constraints leading to innovative design options only obtainable when the subsystems are developed in this integrated manner. IPPTMS should reduce development time and cost. The how-to guide was written to be applicable to fighter aircraft, high value airborne asset protection, small/medium UAS, and rotorcraft.

STO-TR-AVT-334

Cooperative Demonstration of Technology for Augmented Reality for Improved Situational Awareness and Survivability of Combat Vehicles

The AVT-334 Cooperative Demonstration of Technology (CDT) delivered against its two primary aims, first, to de-risk and prove the feasibility of technology integration of augmented reality systems into land vehicles; and secondly, to quantify the benefit of the system for increasing situational awareness. The CDT leveraged research conducted by partner nations to improve the human machine interaction and test different symbology options ahead of the main demonstration activity. The demonstration was conducted in Meppen, Germany on two Boxer vehicles provided by the German MOD, with German military end users testing and sharing feedback on the system. A range of data was collected during the demonstration which has hinted that SA can be enhanced by the use of Augmented Reality. Further follow-on research will be targeted at the standardization and integration of the solution showcased as part of the CDT.

STO-TR-AVT-346

Predicting Hypersonic Boundary-Layer Transition on Complex Geometries

Laminar-turbulent transition strongly affects drag, aerothermal heat load, and the effectiveness of aerodynamic control surfaces for hypersonic vehicles. Reliable transition prediction and control is therefore a key technology for improved design of reusable launch and re-entry vehicles, missile interceptors and missiles for time-critical strike. AVT-346 organized cooperative hypersonic-transition research to improve our understanding of the following phenomena:

1. Mechanisms of boundary-layer transition as affected by separation bubbles near control surfaces or compression corners;
2. Mechanisms of transition on complex surfaces with multiple interacting instabilities;
3. Ability to predict the effect of high enthalpy on transition induced by the second-mode instability; and
4. Ability to predict the effect of ablation. Improvements in physical understanding resulted, along with improved experimental and numerical simulation capabilities.

STO-TR-AVT-348

Assessment of Experiments and Prediction Methods for Naval Ships Manoeuvring in Waves

The AVT-348 Research Task Group studied the assessment of experiments and prediction methods for naval ships manoeuvring in waves. Two test cases were selected, and multiple facilities conducted experiments, enabling the quantification of facility bias vs. scale effects and experimental accuracy for self-propulsion and turning circles in calm water and waves. For each test case, predictions were performed using computational fluid dynamics (CFD) and System-Based (SB) methods. Averaged prediction errors were within the comparison uncertainties however programmatic requirements were not met such that the scatter in both experiments and predictions needs to be reduced. CFD shows reasonable capability for manoeuvring both in calm water and waves and is sufficiently validated for the analysis of flow physics. SB methods can show satisfactory capability for global variables at low computer costs such that they are useful at the early design stage. Future research should focus on physics-based improvements of SB methods using experiments and CFD, combined with data science and machine learning methods. The next step and future research will continue under the auspices of AVT-399 "Assessment of Experiments and Prediction Methods for Naval Ship Transient Manoeuvres in Calm Water and Waves."

STO-TR-AVT-349

Non-Equilibrium Turbulent Boundary Layers at High Reynolds Number

The AVT-349 research task group was formed to advance the accuracy and range of prediction models for high Reynolds number non-equilibrium boundary layers at incompressible conditions, with particular relevance to naval vehicles. The activity brought together a large group of researchers, comprising experimentalists, computers and modelers whose activities were focused on a series of experimental test cases. These included studies of two-dimensional smooth wall boundary layers in pressure gradient, rough wall boundary layers, and three-dimensional boundary layers with curvature, pressure gradient and separation. Most predictions were attempted using Reynolds Averaged Navier Stokes (RANS) calculations, though some Direct Navier Stokes calculations and low order methods were also used. The results of this effort included a systematic evaluation of RANS methods and models under a variety of non-equilibrium conditions, and findings concerning when these models work well, and when they do not. Furthermore, findings and recommendations were developed concerning the future needs for CFD mesh generation and refinement and the use of verification and validation metrics, as well as for both turbulence modelling and wall modelling and the applicability and/or extension of equilibrium models and predictions to non-equilibrium conditions.

STO-TR-AVT-359-Part-II

Impact of Hypersonic Operational Threats on Military Operations and Technical High Level Requirements Phase 2

Hypersonic weapons continue to evolve: the first employment of hypersonic hybrid capabilities was observed in the Russia-Ukraine war. Furthermore, research and development to enable other hypersonic capabilities continue globally. After releasing Phase 1 of the AVT-359 study in mid-2022, the research team started working on Phase 2 of the overall effort. The study analyzes the “Impact of Hypersonic Operational Threats on Military Operations and Technical High-Level Requirements.” As analytical lenses, the team took the four steps of the OODA (Observe, Orient, Decide and Act) Loop, where OOD was mainly looked at in Phase 1. Phase 2 of AVT-359 focuses on “Act,” looking into requirements for offensive and defensive capabilities, legal frameworks, and related topics like the role of space in hypersonic flight or hypersonic aircraft.

HFM Human Factors and Medicine

STO-MP-HFM-377

Meaningful Human Control in Information Warfare

The HFM-RSY-377 symposium, "Meaningful Human Control in Information Warfare," addressed the crucial issue of maintaining human oversight in the face of increasing integration of Artificial Intelligence (AI) in military operations. The event highlighted the distinction between common misconceptions, such as concerns over "killer robots," and the real challenges of modern warfare, emphasizing that Meaningful Human Control (MHC) is essential for interpreting data and coordinating military strategy. With contributions from 180 participants across 28 countries, the symposium focused on the integration of AI into both physical and cognitive warfare. Key discussions included the need for iterative testing of AI systems and interdisciplinary collaboration from the outset. A proactive approach to cognitive warfare was recommended, where influence operations take precedence over the truthfulness of information, and data access, particularly from social media, was identified as critical for national security. The challenges posed by multi-domain operations were also addressed, stressing the importance of establishing common operational pictures across various commands. In conclusion, the symposium emphasized the urgency of maintaining MHC amid technological advancements and called for continued research on human-AI interaction, the development of robust evaluation metrics, and the need for interdisciplinary collaboration to ensure human judgment remains central in military operations.

STO-MP-HFM-390

Reserve Forces: Challenges and Relevance to NATO and National Security

The NATO HFM Research Workshop on Reserve Forces (HFM-RWS-390), held from 27 – 29 January 2025 at NATO Headquarters in Brussels, convened experts to examine the evolving role of Reserve Forces within NATO and national defense structures. Co-hosted by the NATO Human Factors and Medicine (HFM) Panel with support from the NATO Reserve Forces Committee, the workshop addressed critical issues including integration with Regular Forces, recruitment and retention strategies, and the unique challenges of balancing military and civilian responsibilities. Through three days of presentations and discussions, participants exchanged research findings and best practices, fostering cross-national collaboration. The insights generated aim to inform future training, readiness initiatives, and policy development, reinforcing the essential contribution of Reserve Forces to NATO's security architecture.

STO-TR-HFM-281

Personalized Medicine in Mental Health and Performance

Personalized or precision medicine is emerging as a critical approach to enhance military health and performance. By tailoring medical care and treatments to individual service members, it can optimize physical and mental readiness, reduce health risks, and enhance the overall effectiveness of military forces. The adoption of personalized medicine can also foster collaboration and knowledge sharing among NATO allied countries, leading to improved healthcare practices, reduced medical costs, and a stronger and more resilient joint defence force. This innovative approach has the potential to revolutionize military healthcare, making it a valuable asset for NATO allied nations in safeguarding their security interests.

STO-TR-HFM-310

Human Performance and Medical Treatment Support During Cold Weather Operations

In the Arctic and high north regions, nearly every military task and mission is made more difficult by the inescapable cold. This RTG focused on the topic of sustaining soldier health and performance in the cold and translating research knowledge to soldier training applications. Previous academically oriented panels wondered why military leaders and users were not utilizing their laboratory findings. To better disseminate useful knowledge, the deliberations of this RTG and results of new field research obtained in the actual environment were published in open peer reviewed journals. Methods of institutionalizing these findings into modern training were discussed at a NATO symposium themed "training is more important than technology" (NATO RSY 349). RTG findings were reported in sessions at the International Congress on Soldier Physical Performance (ICSPP 2020; ICSPP 2023). Key RTG accomplishments included development of a graphical physiological scheme for individual action in the cold (yellow warning zones); a NATO definition of cold injury classifications; a draft epidemiological strategy for cold injury surveillance within NATO countries; improved predictive modelling for cold-wet conditions; characterization of operational performance in extreme cold field training exercises; and identification of research gaps for medical treatment in the cold.

STO-TR-HFM-316

Expert Panel for State-of-the-art Cardiovascular Risk Assessment in Aircrew

Heart disease, which includes coronary artery disease, cardiac rhythm and conduction disease, and structural heart disease, represents a threat to aviation safety and mission completion. It comprises a significant cause of loss of medical certification in both military and civilian aircrew. However, screening and disposition of heart disease for aircrew varies widely among different governing bodies. A six-nation occupational cardiology working group was established to provide a consensus approach to the assessment of cardiovascular disease in aircrew. The collaborative research and analysis of this working group culminated in a case-based approach to aircrew with cardiovascular disease. The first series of cases presents the current benchmark for assessing aircrew for occult coronary disease, and for assessment and disposition of aircrew with known coronary disease, with data derived from current aeromedical and clinical literature. The second series of cases provides recommendations for a stepwise screening approach and enhanced investigation of rhythm and conduction abnormalities for aircrew. The final series of cases provides insights into the appropriate investigation of aircrew with suspected or proven heart muscle disease, to include myocarditis, hypertrophic cardiomyopathy and the athletic heart.

STO-TR-HFM-319

Measuring the Cognitive Load on the Soldier

The capacity to manage cognitive load will become a rate-limiting factor in a soldier's ability to operate effectively in the future battlespace. The purpose of this report is to provide a comprehensive overview and analysis of available tools and techniques for assessment of cognitive load in soldier-relevant settings. The key drivers to assess cognitive load are assessed across member nations, and essential terms and concepts are reviewed. A literature review and accompanying analysis is described with assessment of seventeen cognitive load measures. An identification and analysis of cognitively demanding moments within operational scenarios are described, leading to the delineation of four test environments. Reasons for using multiple measures are also discussed. Examining the application of cognitive load measures across a set of distinct measurement scenarios revealed that large-scale exercises with high mobility requirements present significant challenges for measuring cognitive load. However, many physiological, subjective, and performance-based measures are feasible and effective for cognitive load measurement when mobility is limited. Similarly, when operating indoors with moderate-to-low mobility requirements, most cognitive load measures can be used. Rapid technological development is expected to enable more reliable measurement of cognitive load in mobile domains.

STO-TR-HFM-329

A Psychological Guide for Leaders Across the Deployment Cycle

Effective military leadership is essential for operational readiness and maintaining morale. Managing the effects of operational stress is one of the command tools of modern military leaders. This guide helps military leaders with relevant information and practical strategies for managing psychological stress and providing psychological support to enhance unit effectiveness. In reviewing the current literature base and best practice in the alliance, as relevant to contemporary society and recent deployments, this guide addresses the following:

1. What does the leader need to know? (Awareness)
2. How can the leader support mental health readiness and resilience? (Prevention)
3. What can the leader do when the things go wrong? (Care)

Psychological injury remains a significant burden that affects the effectiveness of military organisations, despite advances in the recognition and clinical management of mental health problems across the alliance. In modern military operations (direct conflict or peace keeping, or support or humanitarian activities) factors such as neutrality and non-intervention, witnessing atrocities, culture shock, separation from family, and existential or ethical questions can affect psychological functioning, the family, social and work reintegration and attitudes towards the organisation. Experiences during operations and leaders' expectations about psychological readiness are captured in a survey.

STO-TR-HFM-330

Human Systems Integration for Meaningful Human Control over AI-based Systems

The NATO STO HFM-330 RTG report examines Meaningful Human Control (MHC) in military AI systems, emphasizing the balance between AI autonomy and human judgment. While AI offers rapid decision-making, enhanced accuracy, and broader operational coverage, increasing autonomy raises concerns about ethical, legal, and accountability issues. NATO agrees human judgment will remain essential, but definitions of MHC vary, making it difficult to create precise design guidelines. MHC is presented as a property of a complex socio-technical system, requiring iterative oversight across political, legal, regulatory, ethical, organizational, cultural, and technological domains. Ensuring MHC demands layered control measures throughout the AI lifecycle (design, testing, deployment, and governance) rather than treating it as a single attribute. Safety research principles could guide these processes. The group identified 17 candidate methods for assuring MHC, ranging from design guidelines and situational awareness metrics to organizational training. A human-centered design process involving multiple stakeholders early in development is deemed critical. To conceptualize MHC's multi-layered nature, the holistic bowtie model maps influences from individual systems to global scales. The report calls for further research into MHC in the information domain (e.g., cognitive warfare), multi-domain operations, participatory design, and large-scale system-of-systems impacts.

STO-TR-HFM-ET-212

Evaluation Criteria and Use Cases for Information Operation/Social Media Simulators

The current security environment is replete with complexity, ambiguity, rapid technological developments, strategic shifts, and globalised processes. In this environment, NATO's adversaries have introduced methods and techniques targeting the way humans think, [re]act, and make decisions, giving rise to new ways to wage war on cognition, or Cognitive Warfare. The NATO Science and Technology Board (STB) has adopted cognitive warfare as one of its four priorities for advancement by the NATO Science and Technology Organization (STO) Collaborative Programme of Work. The objective of the study is to define evaluation criteria based on valuable use cases for the existing available Social Media Simulators to assess the level of effectiveness in reaching the objective to mitigate vulnerability to disinformation and deception. The study identifies measurable criteria to evaluate information operation and Social Media Simulators; defines military significant use cases to be employed during the evaluation exercise; provides the Training Audience with opportunities to practice with their training objectives; and assesses the Training Audience's performance, assisting the exercise to adapt the flow accordingly. The study defines the evaluation criteria for the available Information Operation and Social Media Simulators to be used during a related evaluation exercise, in order to demonstrate how using simulation within the Information Environment can enhance the capability of decision makers to successfully cope with the information threats spanning over the social media and allow effective offensive cognitive warfare effects to be realised.

STO-TR-HFM-MSG-354

Study, Design, Building and Deployment of a CBRN XR Training Platform

The findings of NATO STO-TR-HFM-273, "Long-Term Scientific Study on CBRN Defence," highlight an evolving and increasingly complex CBRN threat landscape. Within this context, expanding access to critical capability training, including through Extended Reality (XR) simulations, can add significant value by enhancing military readiness and preparedness, while supporting effective leadership execution. Among the significant benefits they offer, realistic XR simulations in support of CBRN exercises can reduce environmental burden and health risks associated with real-life exercises, decrease training costs, broaden access to rapid training across all operational levels, and ultimately extend training opportunities to NATO Allies that lack adequate testing facilities. RTG HFM-MSG-354 aimed to fill research gaps in this domain, as well as design and eventually deploy a demonstrator of functional CBRN defence mission operator training scenarios using advancing elements of XR. This report provides an overview of the results in relation to four key scientific objectives: assessing most suitable CBRN Defence Training Scenarios that can be simulated in an XR context, leveraging NATO CBRN Education and Training (E&T) Doctrine as a starting point; conducting user experience studies with a view to assessing the integration/creation of new technology (e.g., an integrated CBRN XR mask); investigating the potential of Artificial Intelligence (AI) applications for enhanced realism and evaluation features in XR simulations; and completing the design of a demonstrator CBRN XR training module.

IST Information Systems Technology

STO-MP-IST-203

Wireless Communications Standardisation for NATO

NATO relies on wireless communications standards, primarily through STANAGs, to attain interoperability. This RSM aimed to explore the development of these standards and the evolving telecommunications industry. Its objective is to offer recommendations to pertinent NATO bodies for potential enhancements to these processes.

STO-MP-IST-208

Towards the Convergence of Edge Computing, Adaptive Networking, and Information Management at the Tactical Edge

The IST-208 Research Symposium, held on 15–16 October 2024 in Lillehammer, aimed to explore the convergence of edge computing, adaptive networking, and information management at the tactical edge. The event provided a forum for scientists, industry practitioners, and military users to present novel ideas and research on the foundation, implementation, and application of edge computing in this critical context. The symposium's scope was intentionally broad, encompassing a wide array of topics beyond specific technologies like Kubernetes or mobile edge computing (MEC), focusing on distributed computing solutions deployed where information is generated or consumed, particularly in military and coalition operations. Topics ranged from service orchestration and resource discovery to the role of AI in edge computing and tactical cloud infrastructure. The symposium also addressed critical issues like trust and security, interoperability, and AI-driven network management. It provided an opportunity for sharing lessons learned from real-world exercises and operations, fostering innovation in edge computing's role in improving survivability and information superiority at the tactical edge. Ultimately, the symposium sought to stimulate ongoing collaboration, identify promising research directions, and promote the potential exploitation of existing, new, and disruptive technologies, leading to future research activities and potentially establishing a Community of Interest. The discussions aimed to enhance interoperability, resilience, and adaptability in future coalition operations.

STO-MP-IST-209

International Conference on Military Communication and Information Systems (ICMCIS) 2025

The 2025 International Conference on Military Communication and Information Systems (ICMCIS) took place on 13–14 May in Oeiras, Portugal, jointly with the 55th NATO Science & Technology Organization (STO) Information Systems Technology (IST) Scientific and Technical Committee (STC) Business Meeting. Organized by the NATO Communications and Information Agency (NCIA) Academy and supported by the Portuguese Ministry of Defence, the event gathered experts from academia, industry, and military organizations to address emerging challenges in defense-related information and communication technologies. Peer-reviewed submissions were evaluated on scientific rigor and relevance to NATO C3 objectives, covering topics such as resilient tactical networks, artificial intelligence, human-machine teaming, cyber security, and quantum-safe encryption. The conference served as a platform for exchanging state-of-the-art research and operational insights, with all sessions cleared for public release. As in previous years, IEEE technical sponsorship was anticipated, enabling accepted papers to be published in IEEE Xplore. Selected authors were required to submit revised manuscripts and presentations per the conference's detailed guidelines. ICMCIS 2025 continued its tradition of fostering collaboration and innovation across the NATO community, advancing the development and deployment of secure, interoperable, and resilient ICT solutions for modern defense environments.

STO-MP-IST-HFM-225

Military Applications of Generative AI

Generative AI makes it possible to recognize patterns and structures in training data and to generate new data with similar characteristics. It differs from discriminative AI, which classifies input into predefined categories. Generative AI has received enormous attention with the availability of ChatGPT. The technology enables, among other things, the generation and completion of natural language texts, the creation of program code and images, the translation, summary and sentiment analysis of texts as well as question/answer systems. Generative AI has the potential to change wide areas of social life, both professionally and privately.

STO-TR-IST-174

Secure Underwater Communications for Heterogeneous Networks

Although the area of underwater acoustic networking is maturing and becoming critical for a wide variety of commercial applications, the lack of secure underwater communication standards presents a major impediment for adopting these networking technologies within NATO operations. The NATO Research Task Group IST-174 "Secure Underwater Communications for Heterogeneous Network-enabled Operations" aimed to study and to demonstrate secure underwater communications in a holistic approach. In particular, this group's ambition was to define waveforms, network protocols, and architectures that will enable underwater connectivity in a secure and interoperable way and are amenable for standardisation. This report presents the secure communication concepts and methods progressed through the group that could be included in those standardisation efforts.

STO-TR-IST-176

Federated Interoperability of Military C2 and IoT Systems

This report presents the findings of Task Group IST-176, which investigated the federation and interoperability of Internet of Things (IoT) systems with Military Command and Control (C2) systems. The study addresses the need for seamless communication and coordination between diverse IoT devices and military systems to enhance situational awareness, decision-making, and operational efficiency. Key areas explored include the integration of commercial IoT technologies into military applications, the development of a federated model for IoT systems, and the use of MQTT for data exchange. The report also details experimental setups, including the use of Unity for simulation, the deployment of various sensors and drones, and the implementation of a TAK server for data visualization. The findings underscore the potential of IoT to transform military operations by providing real-time data and improving interoperability across multinational forces.

STO-TR-IST-187

5th Generation International Mobile Telecommunications (5G) Technologies Application to NATO Operations Vol. I-III

5G technology has the potential to radically transform wireless communications by enabling a significant leap in performance and introducing new service capabilities. Its development focuses on three primary domains: enhanced Mobile Broadband (eMBB), Ultra-Reliable Low-Latency Communication (URLLC), and massive Machine-Type Communication (mMTC), as well as support for vertical sectors such as public safety and vehicular communications. The 5G standard enables data rates of 10–20 Gbps, high spectral efficiency, support for large-scale IoT deployments, sub-millisecond latency, high reliability, and near-universal coverage through satellite communication integration. Core technologies include 5G New Radio, millimetre-wave frequency bands, massive MIMO, edge computing, spectrum aggregation, and separation of control and data planes.

At the same time, the architecture of 5G introduces new security challenges resulting from increasing levels of virtualisation, extensive use of open-source software, and a broadened attack surface. This is particularly relevant to edge security, virtualisation, SDN, hypervisors, and network slicing. Zero-trust security models can strengthen resilience, though at the cost of additional complexity.

This report evaluates the relevance of 5G to military applications in the fields of tactical communications, overlaid commercial systems, and strategic and BLOS communication. It highlights key areas for 5G Release 16 and beyond, including extreme IoT coverage, SatCom/HAP integration, mission-critical services, massive IoT support, multi-national access network sharing, and the ability to provide network slices for different branches of the armed forces.

STO-TR-IST-192

ANTICIPE @ STJU-23

IST-192 is the successor of the award-winning IST-157 “Human Considerations in Artificial Intelligence for Command and Control (HCinAI4C2),” an RTG project that stemmed from the work conducted by the Multinational Capability Development Campaign (MCDC, 2013–2014), a visionary work looking at the importance, in the military context, that systems that employ AI should remain under appropriate human control. IST-157’s principal deliverable was a tool, known as ANTICIPE, designed to be tested under live conditions during STJUJA20, a major NATO exercise. This proved impossible because of the COVID-19 pandemic. An updated version of the ANTICIPE tool was developed by a team of representatives from six nations (Bulgaria, Canada, France, Germany, United Kingdom and United States) and two NATO bodies (ACT, NCIA), all previously part of IST-157. it was tested during STJU23, a NATO Article 5 exercise. Four specific objectives of the experimentation were analyzed: i) Trust in autonomy; ii) Situation Awareness (SA); iii) Human and Machine Teaming (HMT); and iv) Cognitive Workload (CW) of operators over the course of the two-week exercise. IST-192’s main deliverables include a final report and its annexes and a six minute film “Using Artificial Intelligence to Enhance Military Decision-Making,” giving IST-192 the highest-level possible contextual presentation.

NMSG NATO Modelling and Simulation Group

STO-MP-MSG-229

Force Readiness for Multi Domain Operations through Modelling and Simulation

The NATO Modelling and Simulation Group (NMSG) Conference (MSG-229), "Force Readiness for Multi-Domain Operations Through Modelling and Simulation," was held in Warsaw, Poland, on 23–24 October 2025. The unclassified event gathered participants from NATO nations, Partner-for-Peace countries, and invited partners. Over the two days, 24 papers were presented across eight thematic sessions. The programme featured a keynote address on the opening day, an invited lecture delivered by the recipient of the 2025 NMSG Young Scientist Award, and an overview of the NATO Journal of Science and Technology.

The conference focused on NATO's evolving concept of Multi-Domain Operations (MDO), which emphasizes the coordinated employment of military capabilities across all operational domains, synchronized with non-military activities. This approach aims to provide the Alliance with agile, coherent, and creative options for shaping, contesting, and fighting, while influencing adversary behaviour through integrated military and non-military effects. Within this paradigm, Modelling and Simulation (M&S) was highlighted as a critical enabler of MDO implementation, supporting agility, interconnectivity, and decision superiority in increasingly complex and ambiguous environments.

Contributions addressed advances in M&S for decision support, operational planning, concept development, experimentation, acquisition, training, and education. Topics included AI and machine learning, autonomous and human–machine systems, cloud-based simulation, digital twins, XR technologies, computer-assisted exercises, and wargaming—demonstrating the broad applicability of M&S across physical, virtual, and cognitive dimensions of the operational environment.

STO-MP-MSG-238

Commercial Technologies and Games for Use in NATO and Nations

The 19th NATO MSG-238 Workshop on Commercial Technologies and Games for Use in NATO and Nations, held in Rome on 25 September 2025, explored the evolving role of civilian commercial and academic innovations in defence modelling and simulation (M&S). Increasingly, low-cost commercial technologies, digital game engines, AI frameworks, and immersive tools (e.g., xR) offer cost-effective opportunities for defence planning, training, operations, and capability development. The workshop aimed to foster a shared understanding among participants regarding the challenges and opportunities of adapting commercial solutions for military contexts. Key topics included interoperability and integration of commercial simulations, strategies for enhancing learning and decision support, and transferring these technologies into operational use cases, including warfighter preparation and support roles such as medical, logistics, and law enforcement training. Discussions also addressed the adoption of COTS solutions in cloud-based IT environments, associated business models, and concepts of employment. Looking forward, the workshop examined emerging initiatives including M&S as a Service (MSaaS), Distributed Synthetic Training (DST), AI-enabled simulations, and immersive technologies, highlighting their potential to create a dynamic ecosystem of suppliers and users. The outcomes of the workshop provide actionable insights on leveraging commercial innovations to enhance NATO's training, operational readiness, and capability development in a cost-efficient and sustainable manner.

STO-TR-MSG-181

Physics-Based Electro-Optic/Infrared Simulations – Best Practice Recommendations for Decision Support

Electro-optic/infrared sensing plays a critical role in many NATO military operations. Modelling and Simulation can be quite valuable for exploiting electro-optic/infrared sensors and imagery in these applications. However, the physical and operational environment has a strong impact on sensor performance and simulation accuracy. To better understand this impact, a two-week field trial was conducted in a humid, sub-tropical environment using CUBI targets of various size and composition. A virtual trial performed in conjunction with the field trial identified key meteorological and environmental parameters affecting model performance. Simulation results provide useful strategies for accurate prediction of thermal contrast and synthetic infrared imagery.

STO-TR-MSG-187

Space Weather Environmental Modelling

The increasing reliance of military and civilian infrastructure on satellite systems exposes NATO operations to significant vulnerabilities due to space weather phenomena. This report, STO-TRMSG-187, produced by the NATO Science & Technology Organization, focuses on the critical evaluation of existing space weather environmental models and aims to enhance predictive capabilities to mitigate risks associated with solar and geomagnetic disturbances. The complexities inherent in the Sun-Earth interaction system, such as solar flares, geomagnetic storms, and coronal mass ejections, necessitate a robust understanding and advancement in space weather modelling to ensure the reliability and operational readiness of satellite-based navigation, communication, and surveillance systems. This document outlines the objectives of comprehensively assessing the current status of space weather modelling technologies, identifying gaps in existing models, and proposing advancements to enhance these models. The report further aims to establish a strategic roadmap for the integration of improved space weather modelling into NATO's operational framework. By detailing the process of reviewing current models, forecasting potential impacts, and suggesting a series of model enhancements, the report sets the stage for future developments that will bolster NATO's resilience against space-weather-induced disruptions. Moreover, the report emphasizes the need for continuous research and collaboration among international partners to develop more accurate and reliable space weather forecasts that can effectively support the strategic and operational needs of NATO. The final sections of the report will propose actionable strategies and recommendations to advance the state of space weather modelling, thereby enhancing the preparedness and response capabilities of NATO forces in the face of space weather challenges.

STO-TR-MSG-191

NATO Standards for Federated Simulation and Services for Integration, Verification and Certification

NATO nations and partner nations have successfully applied SISO and NATO standards when developing Federated Simulations to support Education, Training, Exercise and Evaluation. Interoperability standards are needed, even mandatory, to build reliable federations of simulations. Improvements to standards contribute to enhancing the efficiency of simulation interoperability. To meet new and evolving simulation interoperability requirements, there is a continued need for NATO to experiment with, update, and further evolve standards for federated simulation and to harmonize with new and evolving SISO standards. The overall objective of this Technical Activity is to further evolve the NATO-standards for Federated Simulation and Services for Integration, Verification and Certification, including: maturing NETN-FOM modules, and developing interoperability requirements and capability badges; maturing IVCT-framework and developing test suites; maturing NATO HLA Certification Service; and increasing the awareness and the adoption of NATO-standards for federated simulation, and associated tools. In summary, this group increases the effectiveness of training by improving the quality of synthetic environments for operational readiness, in order to save lives, time, and money.

SAS System Analysis and Studies

STO-MP-SAS-190

Enhancing Energy Security Resilience, Capabilities and Interoperability

The NATO SAS-190 Research Symposium, titled "Enhancing Energy Security Resilience, Capabilities, and Interoperability," took place virtually on November 12–13, 2024. The event offered a comprehensive exploration of strategies to strengthen energy security resilience in the face of hybrid threats. Key areas of focus included the implementation of cyber early warning systems, adopting a total value systems approach to energy resilience, expanding the role of hydrogen energy, and integrating small and micro nuclear reactors into energy planning. The symposium also emphasized the importance of conducting more frequent and complex training exercises to identify vulnerabilities in critical infrastructure and bolster operational readiness. Several presentations addressed a broader framework for energy sector cyber resilience among NATO and partner nations, taking into account the evolving impact of Emerging and Disruptive Technologies (EDTs) and the rapidly shifting geopolitical landscape. The discussions highlighted the urgent need for adaptive strategies to safeguard critical infrastructure, particularly in light of ongoing developments in Ukraine, which served as a case study for future threats and their potential mitigation. A recurring theme throughout the symposium was the essential role of the private sector in advancing energy security through innovative solutions, enhanced interoperability, and resilient capabilities. As global security environments become increasingly unpredictable and complex, the need to fortify critical energy infrastructure remains a top priority. The symposium reaffirmed the importance of collaborative efforts between NATO members, partners, and industry stakeholders to address emerging challenges and build a more secure and resilient energy future.

STO-MP-SAS-192

18th NATO Operations Research and Analysis (OR&A) Conference

The Headquarters Supreme Allied Commander Transformation and the Science and Technology Organization co-hosted the 18th NATO Operations Research and Analysis (OR&A) Conference from 4–6 November 2024. The conference, held at the Residencia Militar Castañón De Mena in Málaga, Spain, had a high level of attendance with 140 attending in person out of the conference total of 150.

Held under the theme of the 'Collaboration to enable military advantage in an unstable world' this year's conference featured a mix of presentations, training sessions and a wargame demonstration. The presentations focused on new analytical methods and best practice in analysis for tackling the ever-evolving challenges facing NATO.

The annual NATO OR&A conference serves as an integral component to the continuous development of the NATO OR&A Community of Interest. It builds upon previous conferences and workshops and assembles esteemed members of the profession from across numerous organizations that include NATO commands and agencies, national defense analysis and research organizations, centers of excellence, academia, and industry.

STO-TR-SAS-154-H

Future Strategic Environment Assessment: Framework for Analysis. Handbook

Addressing complexity and rapid rate of change requires an in-depth understanding of the future strategic environment. However, NATO, as well as individual nations and institutions, often approach this issue in very different ways, with some lacking the necessary know-how and experience. The objective of the SAS-154 research task group was to identify a code of best practice on how to undertake future strategic environment assessments to help with this issue. The work is especially aimed at those states seeking to incorporate foresight into their defence planning and strategic thinking for the very first time. This report is in the form of a handbook that provides a generic framework of how to plan and conduct foresight. It is built on identified best practices and is adaptable to each user's needs and resources. The handbook contains practical advice on how to build a foresight project from the initial project management issues through selecting the appropriate combination of foresight methods towards delivering the results to decision-makers. It also provides recommendations on how to prevent or address some of the most common challenges that may hinder the quality or relevance of a foresight project; especially highlighting the role of diversity and the need to engage stakeholders throughout the entire process.

STO-TR-SAS-159

How Could Technology Development Transform the Future Operating Environment?

There is an increasing interest in understanding the features and potential impact of so called Emerging and Disruptive Technologies (EDTs). From a defence perspective we want to know if and how they make it possible to achieve critical capability needs in better or new ways than what is possible today. To reach that understanding, we need to develop ways to assess these technologies (i.e., a framework is needed that enables the assessment of the potential of a technology (what it could possibly do) as early as possible, and before it is included in systems/capabilities). In SAS-159 a framework is described that helps us to understand how technology development may transform the future operating environment. Using this framework, it is possible to describe how technologies may influence the elements of change—space, time, perception, cognition, choice, and effect—across the physical, virtual, and cognitive domains. Consideration is also given to the influence these technologies may have on military functions and operations, as well as to how they support the 'six outs' within the NWCC framework. All of this is then collected into an output showing the military potential of a technology.

STO-TR-SAS-168

Coalition Sustainment Interoperability Study

The NATO STO Research Task Group titled "Coalition Sustainment Interoperability Study" (reference SAS-168) explores the potential operational impact of implementing Artificial Intelligence (AI) and Machine Learning (ML) to enhance small unit sustainment operations within NATO members and NATO allied countries. The primary objective was to define the desired future capabilities and end state, in order to identify the interfaces, standards, and technologies that must be developed collectively. This study effort focused principally on the operational concepts, concepts of employment, generally applicable AI/ML technologies, critical areas of interface and consideration that must be adjudicated, and a potential near-term path forward to further develop these concepts.

STO-TR-SAS-178

Defence Investment Portfolio Decision-Making and Analysis Support

National and alliance investments in defence systems necessitated by advancing technologies are increasingly costly and difficult to select due to uncertain future need and delivery, economic pressures, and the intense resource competition with what other government mandates and agendas require. This report documents the presentations, deliberations, and conclusions with post-event reflection and follow-on recommendations from a research workshop to validate previous work by SAS-134 on Defence Capital Investment Prioritization (DCIP). Brief comparison of DCIP decision processes across 8 participating nations highlighted both the need for and difficulty of process integration. Key but often challenging features of sound DCIP include clearly identified investment portfolio outcomes linked to national interests and policy with explicit portfolio constraints. Common concept terminology across stakeholders, costed investment implications across DOTMLPFI, and a curated single data repository with uncertainty metrics and metadata enhance coherence and objectivity. A clear engagement process under defined governance to collect and disseminate stakeholder priorities and independent analysis clearly reporting alternative portfolio benefits, costs and risks including robustness to changed requirements and priorities engender decision confidence and prepare deliberations and decision documentation enabling portfolio execution best realizing prioritized benefits. Participants assigned highest follow-on work priority on the development of robust DCIP guidance.

SCI Systems Concepts and Integration

STO-TR-SCI-302

Directed Infrared Countermeasures (DIRCM) Concepts and Performance

Infrared-guided missiles and particularly MANPADS (Man Portable Air Defence Systems) represent a significant threat to NATO aircraft. Infrared missile threats are using more sophisticated infrared counter-countermeasures requiring the self-protection systems to be improved or replaced by new technologies. Directed Infrared Countermeasures (DIRCM) systems are introduced as a viable option to supplement the current flare dispensers. Many questions have risen regarding the effectiveness of this type of system on NATO aircraft against current and future generations of infrared missile threats. Investigating a wider variety of possible effective/novice codes as well as using standardised code validation methods could improve the DIRCM performance and efficiency of code development. As some methods require additional threat information the concept of Closed Loop DIRCM is explored. This report contains: a standardised data analysis tool and results database structure, an overview of alternative jam code techniques against a variety of threats, a description of a method intended to simply jam code validation and the outcome of the CL-DIRCM exploration which could help decision makers and DIRCM manufacturers to gain knowledge on requirements and specifications.

STO-TR-SCI-304

Optimised Antennas for Future Vehicle Electronic Countermeasures

Electronic countermeasures (ECM) systems provide a mission critical capability to lower risks from Improvised Explosive Devices (IEDs). To date, omnidirectional antennas have been almost exclusively used to implement system requirements but fulfilling ever increasing (frequency) coverage from conventional antennas and their subsequent means of integration is becoming more challenging. This research study objectively assessed whether the introduction of directional antennas and integration to less cluttered areas on military platforms offers a more sustainable and better performing path into the future. The study found that the use of directional antennas integrated around the circumference of complex military platforms provides system performance improvements from increasing system radiated power, decluttering infrastructure installed on the roof of platforms and by extension, and lowering mutual coupling phenomena, which improves interoperability between systems. Furthermore, directional antennas offer design freedom and flexibility to solve the challenges of today as well as tomorrow, particularly in terms of fulfilling bandwidth growth coverage towards higher frequencies. The findings and developments in this work provide many improvements to help designers and installers of ECM systems increase the effectiveness of their systems that translates into enhanced protection for personnel when applied operationally.

STO-TR-SCI-326

Electronic Support (ES) Techniques Enabling Cognitive Electronic Warfare

Modern adaptive radar and radio systems possess unprecedented flexibility, continuously modifying transmission characteristics including their modulation, bandwidth, center frequency, access protocols, and timing parameters. This dynamic capability presents formidable obstacles for conventional signal intelligence methods, which historically rely on matching intercepted emissions against static reference libraries of known signal parameters. This challenge is magnified when considering cooperative distributed systems that share information, creating networked threat environments with enhanced situational awareness capabilities beyond individual platforms. This Research Task Group (RTG) established dual primary objectives. Initially, recognizing the absence of relevant datasets, the team generated NATO-relevant engagement scenarios and corresponding electronic surveillance data that simulated monitoring advanced frequency-agile and environmentally-responsive communication systems. Subsequently, the group developed several Artificial Intelligence and Machine Learning (AI/ML) frameworks capable of evaluating threat levels from these dynamic emitters without depending on traditional database comparisons. Additional research thrusts explored within this collaborative effort included characterization methodologies for communication system physical layer parameters, alongside investigations into Counter Unmanned Aerial Systems (C-UAS) detection techniques and Inverse Synthetic Aperture Radar (ISAR) technologies, both critical domains requiring advanced signal processing capabilities to counter increasingly sophisticated electromagnetic threats.

SET Sensing Technology

STO-EN-SET-336

Artificially Intelligent Military Situational Awareness: A How to Deal with AI in Military Planning, Procedures, and Operations?

The Lecture Series "How to Deal with AI in Military Planning, Procedures, and Operations?" was held in Tallinn, Estonia (9–10 June 2025), Liptovský Mikuláš, Slovakia (12–13 June 2025), and Oeiras, Portugal (16–17 June 2025). The event, organized by NATO's Systems and Electronics Technology (SET) Panel, brought together defence planners, military end-users, programme managers, and systems engineers to discuss the evolving role of Artificial Intelligence in modern military operations. Building on the findings of the von Kármán Horizon Scan on AI commissioned by the NATO Chief Scientist, the series provided an overview of anticipated AI-enabled capabilities and their relevance to multi-domain, human-centric, software-defined operations.

Participants explored how model-based and data-driven algorithms had been applied to complete the full data-processing cycle—from real-time heterogeneous sensor inputs to mission-relevant situational pictures supporting decision-making and Manned–Unmanned Teaming. Special attention was given to multifunctional sensors, data integrity challenges in networked systems, and selected unclassified aspects of Electronic Warfare, Counter-AI, and Navigation Warfare. Lecturers presented advanced examples of probabilistic reasoning, statistical decision-making, tracking and classification, anomaly detection, Bayesian and machine-learning methods, Explainable AI, multiple-hypothesis logic, and sensor-resource management.

The series strengthened the community's understanding of AI's opportunities and risks, and encouraged further R&D efforts targeting NATO's operational needs.

STO-EN-SET-337

Advances on Array Calibration for Improved ESM Sensor Performance

ESM sensors have numerous applications, including, but not limited to transmit-receive beamforming for radar or communication systems, interference rejection using controlled reception pattern antennas, radio direction finding, and passive emitter localization. Sensors are the foundation of modern cognitive ESM systems, and signal processing methods require an accurate model of the array response to interpret and fuse sensor data. In practice, the antenna array can be subject to sensor position errors, electrical cable length differences, mutual coupling, cross-polarization effects, and effects of the sensor platform. There is an inherent trade-off between the performance and complexity of a model. While simple models are easy to calibrate (i.e., all unknown model parameters can be easily determined by a reference measurement) they often cannot fully capture the actual (complex) sensor response. On the other hand, the discrepancy between the actual and modeled sensor response can be reduced by an increasingly complex sensor model, but at the expense of costly calibration procedures. The upfront cost of calibrating a sensor can be enormous, so self-calibration procedures that reduce model deviations during sensor operation are highly desirable. A calibration during operation of the array sensor can mitigate model errors and improve the "installed performance" of the sensor.

STO-MP-SET-267

Advanced Mid-Infrared Laser Technology

Mid-infrared laser sources are needed for countermeasure systems against the next generation of heat seeking missiles, as well as for active imaging and remote sensing of targets and threats. These sources must be resistant to environmental variations, and sufficiently compact and conformable to fit on a variety of platforms, from ships and large transports to helicopters and ground vehicles. SET-170 and SET-224 have explored fiber lasers as an especially suitable technology for these applications, as they offer optical confinement for robust alignment and reduced environmental sensitivity, and a geometry that simplifies thermal management. Bulk crystal lasers and quantum cascade lasers, however, continue to provide robust competition and offer their own advantages—the former in higher pulse energies, the latter in compact size and efficiency.

Presentations and discussion addressed the applicability and the technical readiness level of various infrared laser technologies. They also aided in identifying the most critical technology gaps in the area of infrared lasers, to help prioritize future laser development efforts. The scope included both direct lasers and frequency conversion based approaches, in guided wave architectures or bulk materials, as well as semiconductor-based sources like QCLs.

The SET-267 workshop brought together experts in both infrared laser component development and in the integration of lasers into systems for countermeasures and other military applications. The knowledge shared was used to inform the recommendation of SET-ET-113 to initiate a new Task Group on Advanced Mid-IR Laser Technology, now SET-294.

STO-MP-SET-331

Photonic Integrated Circuits

The SET-331 Research Specialists' Meeting (RSM) on Photonic Integrated Circuits (PIC) was held in Dresden, Germany, on 21–22 October 2024. Organized by the Sensors and Electronics Technology (SET) Panel, the meeting aimed to provide a comprehensive understanding of the current state-of-the-art in PIC technology, focusing on manufacturing and engineering challenges affecting commercial viability. Key topics included thermal management, mechanical and material properties, device packaging, and the integration of semiconductor, optical, and photonic components. The central role of silicon photonics was highlighted alongside advances in indium phosphide, gallium arsenide, lithium niobate, and silicon nitride, which enhance device diversity and functionality. The RSM reviewed recent technological achievements and explored a wide range of military-relevant applications such as microwave photonics, multi/hyperspectral imaging, lidar, on-chip spectroscopy, communications, biosensing, free-space laser communication, positioning/navigation/timing, high-powered lasers, AR/VR, and optical neuromorphic computing. Discussions emphasized leveraging civilian PIC developments, especially in fiber communications and vehicular lidar, for military electro-optic systems. Advances in materials, manufacturing, foundry fabrication, packaging, and system assembly across NATO member states were benchmarked against non-NATO activities. The meeting identified immediate and short-term military uses of PIC technology and provided recommendations to guide NATO's future technology strategy and collaborative R&D efforts, fostering enhanced defense capabilities through integrated photonics innovations.

STO-TM-SET-269

EO/IR Ship Signature Dynamics

The SET-269 final report defines the activities completed during the lifetime of the organization and includes the draft NATO Standard Recommendation (STANREC) completed by the Group. The primary product of TG SET-269 was the preparation of a draft STANREC that provides recommended practices for defining and designing IR ship signature requirements during the acquisition of new surface vessels. The Group delivered drafts of the report to the Sensors and Electronics Technology (SET) Panel in Summer 2023 and to the NATO Standardization Organization (NSO) shortly afterward. The standardization proposal has been provided to the NSO for evaluation. The remainder of the final report documents the efforts of the Group and additional topics investigated during the lifetime of SET-269.

STO-TR-SET-220

Geospatial Information Extraction from Space-Borne SAR-Images for NATO-Operations

Geoinformation is essential to the decision making of military leaders concerning situation assessment in crises, conflicts, peace keeping missions, or war. Space-borne synthetic aperture radar (SAR) systems, which operate at microwave frequencies, are very useful for obtaining geospatial information, since they collect data independent of day- and night-time, and independent of adverse weather conditions. Since 2007, three space borne SAR-missions (Radarsat 2, COSMO-SkyMed, and TerraSAR-X) available, as well as Sentinel 1A and 1B since 2016. The research work of the SET-220 task group between 2015 and 2017 focused on the extraction of geospatial intelligence from this kind of SAR imagery. Its relevance for NATO operations was shown through the production of information layers, which are indispensable for the intelligence preparation of the operational environment. For this purpose, the group participated in the data collection during the NATO exercise Unified Vision 2014.

STO-TR-SET-283

Advanced Machine Learning ATR using SAR/ISAR Data

The Task Group executed a multifaceted approach to enhance Synthetic Aperture Radar (SAR) and Inverse Synthetic Aperture Radar (ISAR) Automatic Target Recognition (ATR). Initial efforts involved distributing diverse data for analysis and employing machine learning algorithms to assess proposed strategies. Focus areas included dedicated development of (Deep) Convolutional Neural Networks to improve ATR performance. The group explored advanced generative AI techniques like Generative Adversarial Networks and Latent Diffusion models to boost ATR system capabilities. Some workflows were investigated to clarify Machine Learning solutions' interaction with end-users, offering insights into performance impacts and effective utilization for military decision making. The group co-organized the SET-273/RSM Specialists' Meeting on Multidimensional Radar Imaging and ATR and collaborated with SET-288 by holding three joint meetings.

STO-TR-SET-288

Integrating Compressive Sensing and Machine Learning for Radar Applications

This report summarizes the findings of STO-SET-288, where members from 11 countries investigated the integration of Compressive Sensing (CS) and Machine Learning (ML), in particular Neural Networks (NN), for radar applications for the purpose of improving the speed and applicability of CS techniques using deep net architectures with learned signal priors, while supporting learning in data starved regimes with CS based models. Throughout this report several enabling technologies are identified, such as complex-data representations withing neural networks, algorithm unrolling and dictionary learning. The development of these CS and ML techniques to the applications of Synthetic Aperture Radar (SAR) image classification, detection of targets in non-Gaussian clutter, and Radio Frequency (RF) sensor design was studied. Three datasets were made available to NATO countries to enhance the repeatability and comparability of techniques:

i) UAV micro-Doppler signature measurements;

ii) the Synthetic and Measured Paired and Labelled Experimental (SAMPLE) dataset for SAR ground vehicle classification; and

iii) simulated targets within non-Gaussian clutter and Gaussian thermal noise in the form of radar range / Doppler maps.

STO-TR-SET-303

Military Applications of Extreme Laser Fields

This report summarizes the work of the RTG SET-303, providing insights on military utility and threat assessment for USPL technology. The RTG studied three areas: state of laser source technology; military relevant application of the technology; and benchmarking of codes to further interoperability. The team believed that the several scientific unknowns needing to be answered are considerable and that results are only achievable by effective collaboration, synergistic activities, and sharing of resources.

STO-TR-SET-304

Graphene Technologies and Applications for Defence

Optical turbulence reduces the performance of electro-optical systems operating within the envelope of the Earth's atmosphere. This includes passive and active imaging, free-space optical communications and directed energy laser systems. SET-304 aimed to predict and enhance turbulence-degraded performance of electro-optical systems when used in operational environments by making use of turbulence modelling and weather forecasting and by applying mitigation techniques (adaptive optics, image processing, beam shaping).

In order to validate these modelling and mitigation efforts, a field trial took place on the premises of ONERA in Toulouse, France, in October 2022. The trial has been attended by twenty participants from eight nations. Several joint experiments have been carried out during varying, sometimes very adverse weather conditions, which has produced a rich set of measured data (laser intensity, video sequences, measurements of standard meteorological parameters as well as turbulence properties). This dataset in turn has led to successful validation of the theory of optical turbulence, of software-based turbulence mitigation methods, and of the various measurement methods.

STO-TR-SET-305

Improved Field of View for Night Vision Goggles – Technical Challenges, Concepts, Performance Assessment

SET-RTG-305, "Improved Field of View for Night Vision Goggles – Technical Challenges, Concepts, Performance Assessment" focused on exploring possibilities and limitations of available technologies for panoramic Night Vision Goggles (NVG). The group first explored range and field-of-view requirement of NVGs in military context using vignettes as use cases. This allowed selections of sensors and optics for range performance simulation. After in-depth discussion, however, instead of examining range performance, the group proposed and elaborated concepts (Horizon 1, 2, 3) of large Field Of-View (FOV) night vision devices. As a result, nine concepts of large FOV night vision devices and their detailed aspects (technical specification, realisation, technical consideration and military relevance) were populated in the form of a Task Table. Special designs such as foveal and canted configurations were also elaborated for their advantages and compromises. Four concepts were selected for further investigation in future technical groups. Finally, technical work results, analysis, test plans, and recommendations, relevant to the selected four concepts were presented.

STO-TR-SET-306

Improved Panoramic Situational Awareness for Vehicle Platforms

Situational Awareness (SA) is essential for vehicle crews. Electro-optical panoramic Local Situational Awareness Systems (LSAS) offer comprehensive 360-degree surveillance with closed hatches. LSAS aid the crew with Detection, Recognition, and Identification (DRI) of objects of interest both in the vicinity of the vehicle and possibly longer ranges. Such systems often consist of multi-spectral cameras offering extensive SA in day, night and poor visibility conditions. For ease of use and DRI, such systems should have a simple and intuitive interface. This is also to ensure that the system does not add additional cognitive burden on the crew. As a part of this investigation, field trials were conducted where LSAS and multi-spectral camera systems were tested on different objects of interest at various distances from the system and scenarios with live gunfire. This report entails a comprehensive overview of LSAS systems with multispectral cameras, the findings from the field trials, and predictive analytical models for DRI. Based on the results obtained, it is possible to design a LSAS regarding choosing spectral region and number of cameras. Our results show the importance of IFoV on the DRI and that at longer ranges an additional system is required to obtain Identification.

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