NATO OTAN

Science & Technology Organization (STO)

2024 HIGHLIGHTS

SCIENCE & TECHNOLOGY ORGANIZATION

EMPOWERING NATO'S TECHNOLOGICAL EDGE

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FOREWORD

Dr Bryan WELLS, NATO Chief Scientist, STB Chairman

2024 marked the 75th anniversary of the North Atlantic Treaty Organization and has welcomed a new Secretary General committed to continuing NATO's mission and vision. The Washington Summit reaffirmed NATO's credible deterrence and defence posture, enhanced support to Ukraine, and strengthened NATO's relations with our Indo-Pacific Partners.

Science and technology (S&T) is key to NATO's ability to navigate the political and military environments in an ever-changing world. The NATO Science & Technology Organization (STO) continues to provide vital orientation for scientific research, for technology development, and for the application of S&T results to meet the needs of Nations. This year's edition of the *STO Highlights* explores 12 themes that align with the Alliance's objectives and allow us to effectively prepare for the challenges of the future.

Throughout 2024, the STO addressed topics that range from emerging and disruptive technologies to strengthening strategic foresight, while enhancing the STO's effective support to Nations and NATO. The challenges in climate change and security, the adoption of autonomous and robotic systems, and the emerging opportunities and threats in synthetic biology have all been in the focus of our work.

The support the STO provides to the Alliance relies on a vibrant knowledge base. To reinforce its network of experts, and the expertise residing in it, the STO welcomes diversity in all its forms. From celebrating the newest ally through meetings in Sweden, to gathering world-class scientists, engineers and analysts for more than 400 research projects, the STO is committed to engaging the right people with the right skills.

The STO's Scientific and Technical Committees (STCs) are vital to delivering relevant evidence-based solutions to current and future security challenges. Similarly, the STO's own research centre, the Centre for Maritime Research and Experimentation (CMRE), provides field-tested innovative solutions focused on the maritime domain. The work done by these hubs covers a broad range of applications, such as supply chain resilience, capability development, and informing NATO's concepts.

In 2024, the STO also adopted a focus on multi-domain operations. This will position the STO to maintain and strengthen its advisory function that translates the excellence of its knowledge base into decisive advantage for the Alliance.

"...Over the past decade, we have made tremendous progress in ensuring we have the forces and capabilities to deter and defend against any threat, from any direction.

But we must go further and faster to meet the enormous challenge ahead."

NATO Secretary General Mark Rutte

"As we navigate this deeply challenging period for Euro-Atlantic security and arms control, it is paramount that we use all tools at our disposal to increase our security today and in the future..."

- NATO Acting Deputy Secretary General Ambassador Boris Ruge, while in the role of NATO Assistant Secretary General for Political Affairs & Security Policy

"We have accelerated NATO's transformation to meet current and future threats and to maintain our technological edge, including through experimentation and more rapid adoption of emerging technologies, and through digital transformation."

- Washington Summit Declaration issued by the NATO Heads of State and Government participating in the meeting of the North Atlantic Council in Washington, D.C. 10 July 2024

OBSERVATIONS BY DIRECTORS

CSO Director, Mr John-Mikal Størdal

The Collaborative Programme of Work (CPoW) – consisting of eight different programmes of work – provides NATO Nations with the Science & Technology (S&T) they need to develop interoperable, cutting-edge capabilities. As the core of the STO, the CPoW is built on a unique collaborative business model that brings together more than 5,000 scientists, engineers and researchers from across the Alliance, making it the world's largest network for collaborative defence S&T. These experts, representing academia, government labs, and industry, come together to conduct research in areas of critical importance to NATO militaries. This research is carried out through eight Scientific and Technical Committees (STCs), each with their own Programme of Work, which collectively comprise the CPoW.

2024 was a banner year for the CPoW, with more than 400 activities carried outacross the eight STCs. This work spanned a broad range of areas, including important research on space, sensors, weapons, command and control, human enhancement, resilience, and emerging and disruptive technologies, such as artificial intelligence (AI) and quantum computing. Of particular note are the ANTICIPE prototype, which explores how AI could enhance command and control decision-making; the Nordic Pine 2024 Exercise, which sought to build the resilience of renewable energy systems in the face of emerging hybrid threats; and work on a directed energy weapon concept of employment, which introduced a solution to the "valley of death" for technological transitions.

The CPoW has grown in both size and scope over the years, in response to changing national priorities and military needs. It will change even more profoundly in the years to come, as the STO implements the *CPoW Strategy 2024–2030*. This strategy, approved by the NATO Science & Technology Board (STB) in 2023, calls for specific organizational changes – within the STO, the Collaboration Support Office (CSO), and the broader collaborative network – to ensure that the CPoW remains the "forum of choice" for collaborative S&T research for years to come. We took the first steps toward implementing this strategy in 2024, most notably with the creation of a new STC on Technology and Science Incubation (TSI), which will begin work in 2025.

As technologies continue to advance and converge, and at a time of growing geopolitical instability, NATO Nations need expertise and cutting-edge research to stay ahead of their adversaries. The CPoW will continue to evolve in response to this changing environment, providing Nations with a robust and cost-effective mechanism to maintain their collective technological advantage.

OBSERVATIONS BY DIRECTORS

CMRE Director Dr Eric Pouliquen

In 2024, the Centre for Maritime Research and Experimentation (CMRE) saw a sharp increase in interest from organizations wanting to collaborate, reflecting our growing reputation within NATO and beyond. This rise highlights the CMRE's enhanced capabilities and appeal as a leader in maritime innovation, particularly in the context of global challenges, such as the war in Ukraine and the strategic race for control of the Arctic and High North.

Our work is closely aligned with NATO's key priorities, especially the NATO Warfighting Capstone Concept (NWCC), which focuses on preparing for future conflicts. The CMRE continues to lead in key areas like data management and Multi-Domain Operations (MDO), using emerging and disruptive technologies to develop advanced solutions that help NATO maintain its operational edge. In 2024, we expanded into new research areas, including data-centric warfare and the protection of Critical Undersea Infrastructure (CUI), reinforcing the relevance of our work as these threats evolve.

The CMRE's strength lies in the quality of our people and technical capabilities. Our world-class engineering, IT, and marine operations teams ensure that we consistently deliver high-impact results. This expertise has made us an increasingly attractive partner within NATO, resulting in a growing number of work requests from stakeholders, such as Supreme Headquarters Allied Powers Europe (SHAPE), NATO Maritime Command (MARCOM), and Allied Command Transformation (ACT).

Looking ahead, our mission is clear: to support NATO's operational forces, helping them become more effective, faster. Through continued collaboration with ACT and MARCOM, we are committed to providing innovative solutions that strengthen NATO's ability to face complex, multi-domain challenges. With new research initiatives and ongoing investment in critical projects, the CMRE is set to play an even more vital role in shaping NATO's future capabilities and keeping the Alliance ahead in a rapidly changing world.

TABLE OF CONTENTS

TABLE OF CONTENTS

TABLE OF CONTENTS CONTINUED

TABLE OF CONTENTS CONTINUED

FOCUSING ON EMERGING AND DISRUPTIVE TECHNOLOGIES (EDTS)

Leveraging cutting-edge innovations to sustain and enhance the Alliance's technological superiority.

"Quantum technologies are potentially the most disruptive of all emerging technologies and will have an enormous transformative effect on deterrence and defence, exposing NATO to new challenges and risks while also enhancing the Alliance's capabilities for multi-domain operations."

- Mr Joao Alves, CMRE Maritime Unmanned Systems Enablers Programme Manager

In a rapidly shifting security environment, NATO must be at the forefront of emerging and disruptive technologies (EDTs). By advancing quantum technologies, the space domain, and next-generation communications networks, the STO ensures that the Alliance maintains its technological advantage. From exploring the non-proliferation of nuclear weapons, to pioneering AI-federated sensor integration and adaptive edge computing, the STO continues to push the boundaries of the possible. Through this work, NATO fortifies its defences and secures its technological advantage against an evolving array of threats in the modern battlespace.

Quantum Technologies

Quantum Communications, Navigation, and Computing

Quantum technologies (QT) have the potential to significantly enhance the warfighting capabilities of Allies, while also presenting new threats to those capabilities. The CMRE's QT projects (OCS000F51 and SAC000F11) focus on quantum communications, navigation, and computing. In quantum communications, the CMRE is exploring underwater applications of quantum key distribution and quantum optics, while continuing to develop its Quantum Laboratory. Quantum navigation is a new initiative focused on designing, developing, and validating a proof-of-concept maritime/underwater position, navigation, and timing system based on quantum sensors. Quantum computing is recognised for its substantial long-term disruptive potential, and the CMRE is committed to strengthening its expertise in this emerging field. In 2024, the Centre launched exploratory activities aimed at building skills in quantum computing for maritime applications, including funding PhD students and establishing a network of partners and consultants. These projects are funded by the Office of the Chief Scientist (OCS) and Allied Command Transformation (ACT).

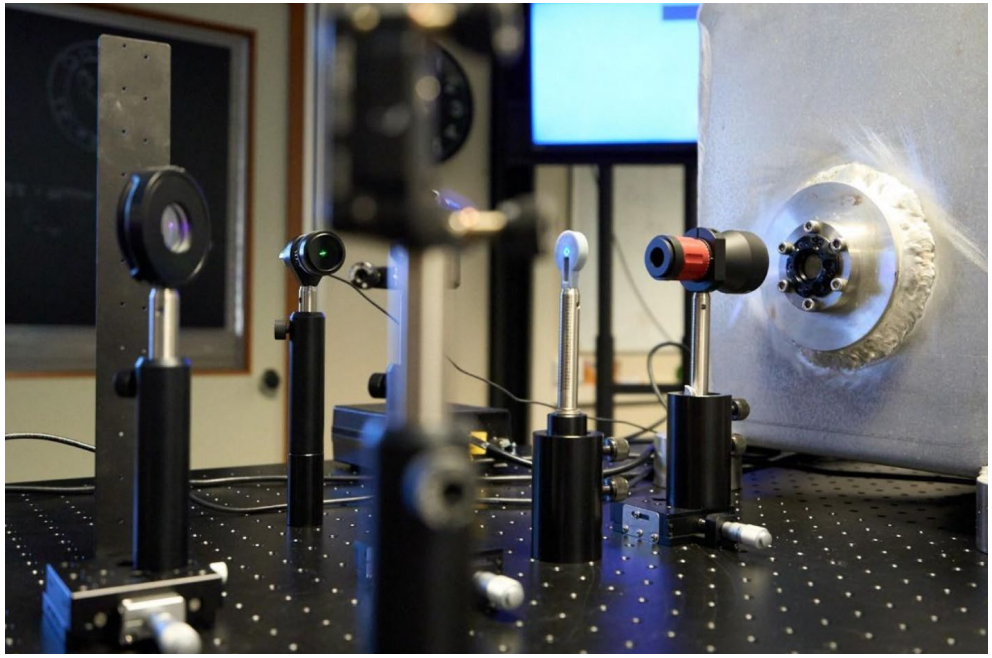


Figure 1: The optical bench setup at the CMRE's Quantum lab.

Technology and Science Incubation Panel

Within the CPoW, the new TSI Panel will focus on quantum technologies as one of two thematic areas for its research activities. The TSI Panel will leverage ongoing activities from the CPoW Quantum Challenge (now entitled TSI-001). The CPoW already has 31 quantum-related research activities, covering aspects such as quantum internet, sensors, quantum key distribution, and quantum-aided design for military applications. As part of the TSI-001 activity and the upcoming first TSI Panel Business Meeting, the TSI Panel will determine which activities need to be initiated to further ramp up quantum research within the CPoW.

Nuclear Non-proliferation

In July 2024, the NATO Chief Scientist launched a report titled "NATO S&T Work on the Verification of Nuclear Disarmament" at the 2nd Nuclear Non-Proliferation Treaty (NPT) Preparatory Committee meeting in Geneva, Switzerland. The report summarises the STO's work on Nuclear Disarmament Verification (NDV) since 2020, with a focus on the interplay between NDV and the sociological concept of trust. It argues that the breadth of science needed for modern defence and security extends well beyond the physical sciences traditionally associated with STO work, noting that the organization also draws on experts in social and psychological sciences. The report further demonstrates that there is a role for the STO to play in nuclear research, both on the topic of trust in NDV, as well as the implications of EDTs in the nuclear sphere.

Artificial Intelligence:

Employing AI to Federate Sensors in Joint Settings (SAS-158)

This Research Task Group was formed to design a system that enables optimal multi-sensor mission planning in a networked environment, based on simulated scenarios, multiple types of sensors, connectivity options and platforms. The research leveraged optimisation, sensor, and integration models that fused the resultant steps to determine whether mission objectives had been fulfilled with the predicted asset allocations. The study set forth a vision for improved sensor asset complexity management in future military scenarios, provided input for the standardisation of federated sensor planning, and offered insights into how to accomplish federated sensor allocation across NATO.

Further information is available in the SAS-158 Technical Report and video.

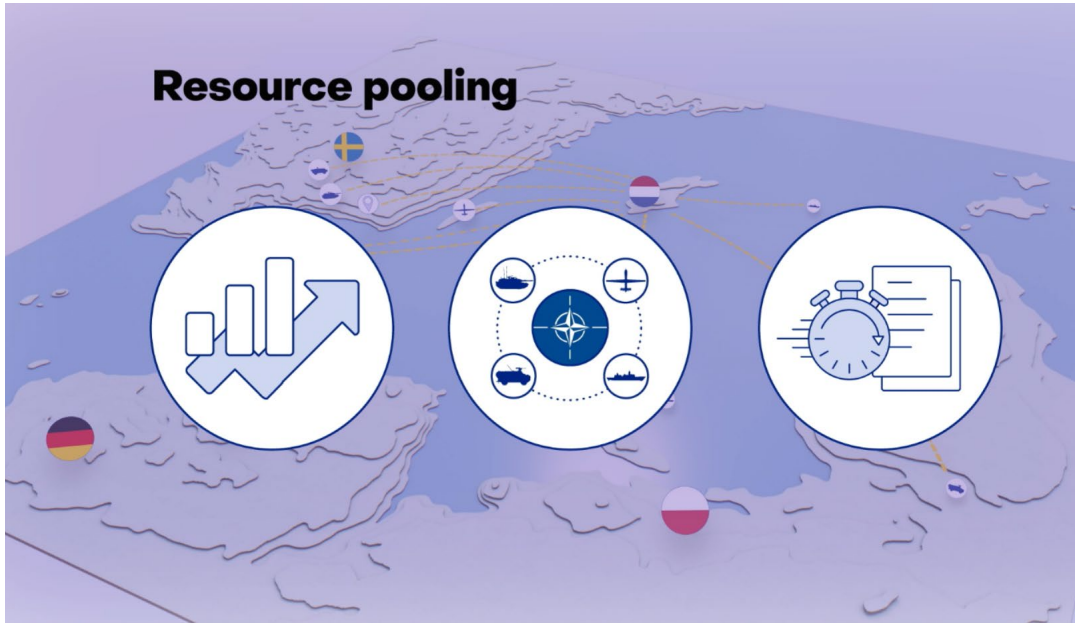


Figure 2: SAS-158: Accomplish federated sensor allocation across NATO through resource pooling.

AI/ML and Cognitive Radar (SET-318)

The SET-318 Research Specialists' Meeting promoted the exchange of state-of-the-art knowledge on the important topic of artificial intelligence (AI)/machine learning (ML) and cognitive radar. Understanding in this area is crucial to meeting the requirements of future NATO systems in different operational domains: land, sea and space. Findings from the meeting have applications in both civilian and military contexts, particularly with regard to improving performance through new processing paradigms, as well as identifying guidelines to define, design and experimentally validate next-generation radar systems. The proceedings from the meeting provide a detailed analysis of methodologies, applications and findings.

Figure 3: SET-318 Research Specialists' Meeting.

Next-Generation Communications Networks

Federated Interoperability of Military C2 and IoT Systems (IST-176)

The Internet of Things (IoT) is a disruptive technology that can be exploited for both military and civilian purposes. The IoT is an important data source in humanitarian assistance and disaster relief, logistics, and surveillance, for example, contributing to information superiority. This Research Task Group considered IoT standards, as well as existing standardisation agreements (STANAGs), architectures, and best practices, to better understand how to integrate commercial and civilian IoT technologies with military command and control (C2) systems, thereby exploiting IoT for improved detail in the common operational picture. The team also carried out successful federated interoperability experiments using the Message Queueing Telemetry Transport (MQTT) protocol for message exchange. The team's technical report provides further details on these experiments and sets forth recommendations to pursue edge intelligence/artificial intelligence. A video is being finalised and these efforts will continue in a follow-on activity (IST-223).

Edge Computing at the Tactical Edge (IST-193)

This Research Task Group aimed to explore innovative architectures and technologies for processing data generated by ubiquitous sensing devices, in order for data to be seamlessly accessible in tactical missions regardless of operational theatre. As military operations increasingly depend on data, troops in complex environments are vulnerable to congested communication networks, which can critically impair situational awareness. As a result, this activity focused on designing adaptive information processing and dissemination architectures that account for limited network connectivity in disadvantaged battlefield environments. The team explored advanced, autonomous orchestration mechanisms for real-time data exchange and service execution. Published technical papers provide a detailed analysis of the designed architecture, and a forthcoming technical report will provide further information and recommendations for federated and adaptive tactical clouds.

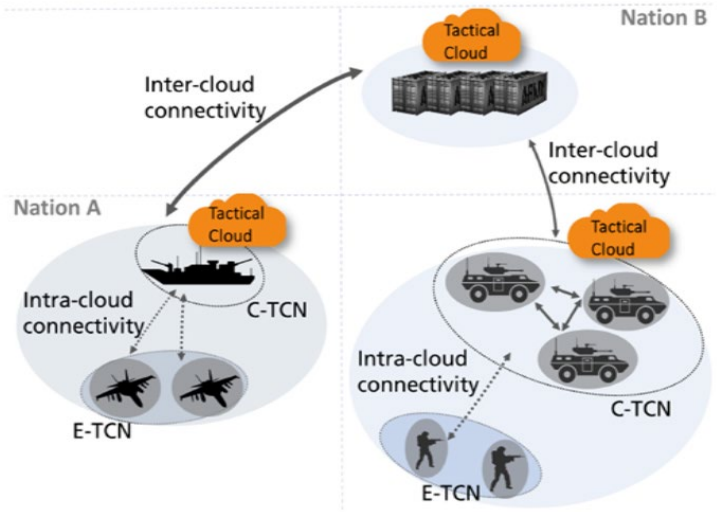


Figure 4: IST-193-RTG – Core and Edge Nodes in Tactical Clouds

Using Artificial Intelligence to Support Command and Control Decision-Making (IST-192)

This Research Task Group explored how an AI-enabled prototype would affect decision-making in an operational setting. ANTICIPE – Augmented Near real-Time Instrument for Critical Information Processing and Evaluation – was the first AI-based tool for assisted decision-making to be tested in an Article 5 NATO exercise. ANTICIPE supports commanders in their decision-making process by automating the extraction and treatment of critical information from all domains. The experimentation enabled the analysis of trust in autonomy, situational awareness, human-machine teaming, and cognitive workload of operators. Based on a wargaming tool using risk mitigation algorithms and critical factors criteria, the prototype showed how an AI-enabled tool can enhance the commander's critical information requirements process, thereby accelerating decision-making. More information is available in a forthcoming IST-192 Technical Report, and in a video on the NATO STO YouTube channel.

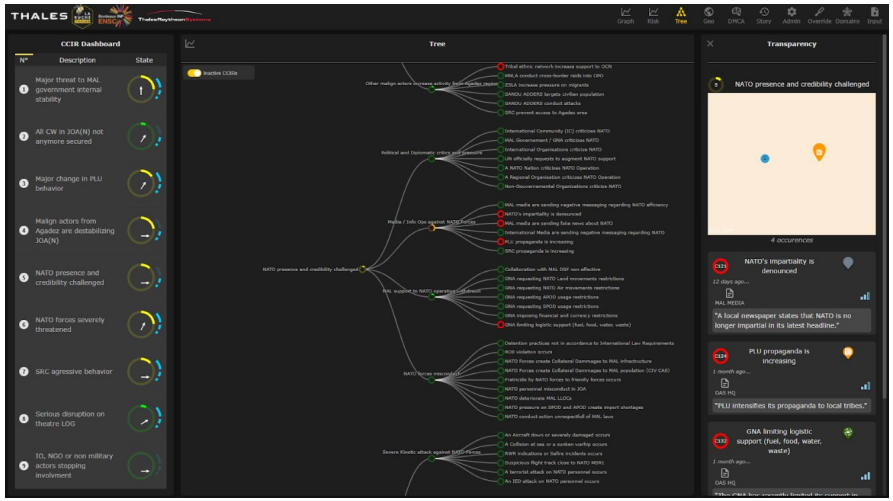


Figure 5: Desktop view of ANTICIPE.

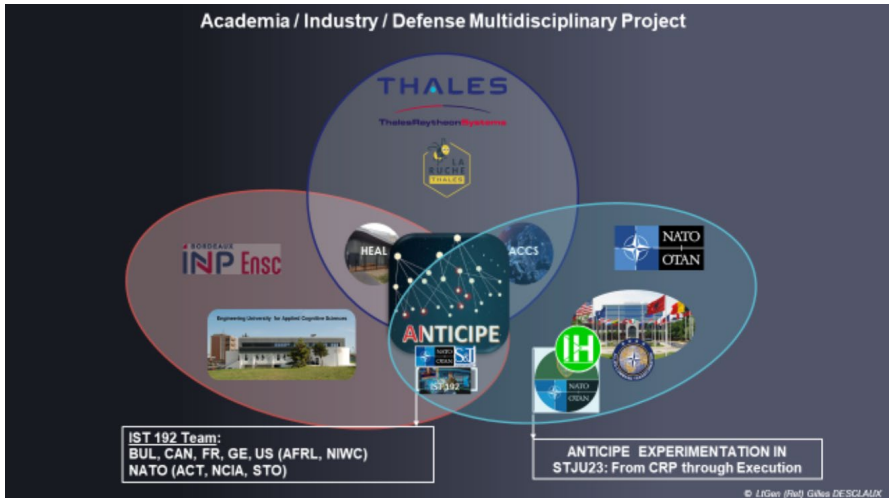


Figure 6: ANTICIPE – A true multidisciplinary cross-sector project.

Towards the Convergence of Edge Computing, Adaptive Networking, and Information Management at the Tactical Edge (IST-208)

This research symposium identified the need for new operational approaches to exploit new technologies, in order to increase both the survivability and information superiority of coalition forces. On the technology side, Kubernetes was proposed for service orchestration, and AI was proposed for a range of applications (e.g., networks, predictive maintenance, electronic warfare, and decision support). New technologies lead to more complex systems, demanding new approaches to cybersecurity. Information provenance and data-centric security were identified as enablers in edge computing. Follow-on activities need to further address the convergence of the technologies discussed in this symposium. More details about the symposium are available in a forthcoming Technical Evaluation Report.

GROWING THE RIGHT PEOPLE AND THE RIGHT SKILLS

People Inclusivity, Recognition and Resilience Promoting diversity of thought, acknowledging all scientific contributions and exercising inclusivity as a reflection of our values.

"Proud that our NATO Women & Girls in Science challenge has been recognised with the WomenInTech Europe Award for Most Impactful Initiative. Above all, this achievement reflects the dedication of our team, driving meaningful change in STEM and advancing gender diversity across NATO and beyond."

- Lola Villaro Yuste, Communications Specialist

People are at the heart of NATO's strength. The STO is committed to fostering diversity of thought, recognising all scientific contributions, and promoting inclusivity across its operations. The Women and Girls in Science Challenge exemplifies these values, encouraging greater participation in Science & Technology from under-represented groups. Equally important is the upskilling of current personnel and preparing the next generation through initiatives like the Chief Scientist's Grants Programme and the STEM Forward community. By championing inclusivity and constant learning, NATO strengthens its scientific community and ensures its resilience in an ever-evolving security landscape.

Shaping the Future of Security: Women & Girls in Science 2024 Challenge

This award-winning initiative aims to empower young women in STEM to address critical global challenges through innovative research proposals, while highlighting NATO's commitment to fostering diverse perspectives in defence and security. This approach is crucial in addressing evolving threats like energy security, climate change, human security, and societal resilience, which require fresh, multidisciplinary approaches. The three winners were invited to attend the July 2024 NATO Summit, where their research proposals were celebrated by Marie-Doha Besancenot, Assistant Secretary General for Public Diplomacy. They visited the CMRE later in the summer, where they explored the Centre's cutting-edge research and engaged with leading experts in maritime research. The STO's commitment to gender equality and scientific advancement was recognised at the Women In Tech Europe Awards, where it won the award for "Most Impactful Initiative".

Dr rer nat Karin Stein Receives 2024 Von Kármán Medal

In March 2024, the NATO Science & Technology Board (STB) awarded the 2024 von Kármán Medal to Dr rer nat Karin Stein, in recognition of her exceptional scientific contributions to S&T for more than 30 years. The annual von Kármán Medal is NATO's most prestigious award for scientific achievement, and underlines the crucial role that scientific collaboration plays for NATO. The first woman to receive the award, Dr Stein has been instrumental in fostering international collaboration and bridging the gap between military end-users and technical experts. She has provided valuable contributions to various STO activities since 1992, having served as Chair and Member-at-Large of the Systems Concepts and Integration (SCI) Panel. Over the course of her career with NATO, Dr Stein has played a leading role in driving collaboration between panels and advancing key initiatives in defence research.

STO STEM Forward Community

STEM Forward is a dedicated community of STEM professionals, whose main goal is to inform STO's efforts and widen the NATO scientific knowledge base. Launched as a pilot in fall 2024, the initiative builds on the STB's explicit commitment to enrich the professional and intellectual diversity of the experts supporting the STO's mission. STEM Forward reinforces STO efforts with talent from under-represented areas of the STEM ecosystem, to deliver cutting-edge S&T empowered by the right people with the right skills. STEM Forward focuses on delivering impactful, innovative solutions and advice for leadership, facilitating advancements, promoting equity, and enacting change. Mr Steen Søndergaard, the Danish Principal Member of the STB, has agreed to be the ambassador of this initiative.

Launch of the Chief Scientist's Grants Programme

In October 2024, the STO launched the NATO Chief Scientist Grants Programme, a new initiative to empower diverse minds to shape the future of global security. The programme funds S&T studies on emerging topics, as well as S&T awareness initiatives on the themes of deterrence and defence; diversity in science, technology, engineering, and mathematics; emerging and disruptive technologies; resilience from an S&T perspective; and S&T foresight. This initiative will help the NATO Chief Scientist in exercising their role as NATO's senior scientific advisor, by enabling research initiatives in areas of interest to NATO's agenda.

Understanding of Military Culture to Support Organizational Change: Systems Approaches, Critical Analyses, and Innovative Research Methods (HFM-363)

This Research Workshop critically assessed current scientific knowledge and frameworks for understanding military culture, proposing innovative research approaches and priority areas to enhance military culture change strategies in NATO Nations and partners. Workshop presentations, papers and discussions demonstrated the need for a comprehensive understanding of military cultures. The event also underscored the need to provide leaders with actionable and prioritised recommendations to meaningfully address persistent misconduct and inequities; foster a safe, inclusive, and respectful workplace for military and defence civilian employees; and support women, peace and security objectives, and human rights. An associated Technical Report integrates research papers, group discussions, and current scientific literature, and recommends priority areas for military culture research.

Modelling and Simulation as a Service (MSG-195)

This Research Task Group focused on building a cloud-based simulation ecosystem that allows NATO Nations to use simulations (via the as-a-service model of cloud computing) to enable more composable simulation environments that can be deployed and executed on demand. Given that simulation is a critical capability for the Alliance and its Nations, simulation environments have become highly valuable resources. It is therefore essential that simulation systems, data and processes are conveniently accessible to a large number of users as often as possible. This project matured relevant standards and demonstrated the use and benefits of such a simulation ecosystem in operationally relevant environments. The project's results have been adopted by various international acquisition programs.

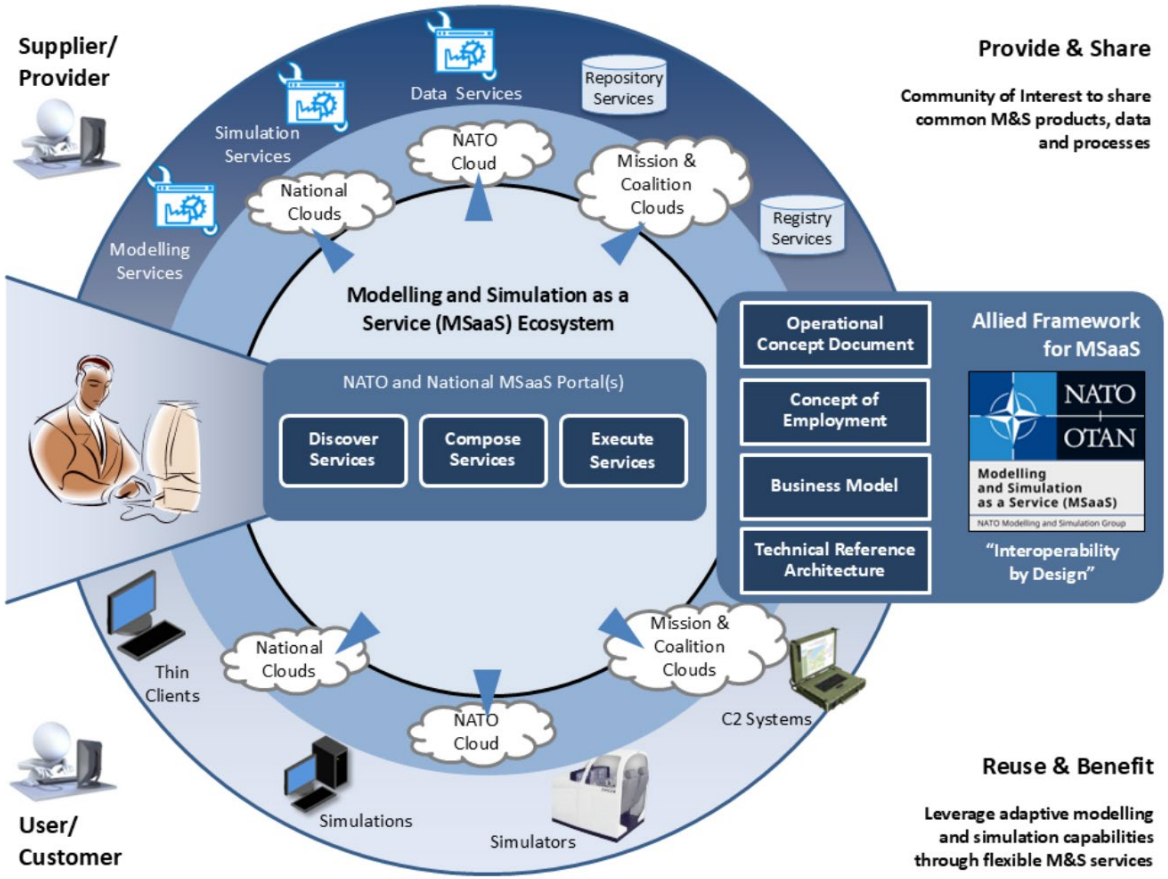


Figure 7: The Modelling and Simulation (MSaaS) Ecosystem.

Extended Reality (XR) in Medical Training: Current Applications and Future Directions (MSG-HFM-220)

This Specialist Team project analysed the current use and future potential of extended reality (XR) systems in military medical training. It provided recommendations for establishing an XR strategy within the medical military domain, and investigated the use of XR for training objectives such as skill acquisition, situational awareness, and psychological preparedness. The team developed first scenarios and training goals that are particularly suited for XR applications. They also identified key trends and carried out a comprehensive analysis of the state-of-the-art for XR technologies in the medical training domain, supplemented by an end-user survey on usage patterns and preferences. Their findings carry significant implications for future military and civilian decision-makers regarding the adoption and integration of XR technologies into future training curricula.

Figure 8: User interacting with extended reality (XR).

Research Workshop on Leader Development for NATO Multi-national Military (HFM-369)

This Research Workshop aimed to promote the exchange of innovative knowledge and ideas among leader development specialists, in order to enhance the community's ability to effectively respond to NATO requirements. The event also sought to validate the findings of the HFM-286 Technical Report. This was achieved through networking, presentations and discussion groups on current capabilities, as well as suggested additional components and ideas. Recommendations included: the establishment of a community of interest and practice for leadership across NATO; the production of a more digestible version of the Technical Report; a standard set of leadership-related definitions to remove ambiguity; and a review of NATO Defense Colleges to ascertain what is being taught and where.

ADDRESSING CLIMATE CHANGE AND SECURITY

Assessing and mitigating the security implications of climate change on global stability.

> ***"In consequence, understanding how warships and their sensors can characterise and withstand that novel operating environment is key to enabling safe navigation and effective maritime operations in Polar regions."***
>
> **Dr. John MacKay, Program Manager / Arctic Mobility, Defence Research and Development Canada, Co-Chair AVT-367**

Climate change is an increasingly critical issue for global security, presenting both direct and indirect challenges to military operations and political stability. The STO is at the forefront of assessing these implications, providing NATO with critical insights into the environmental shifts that threaten global peace. The CMRE Programme of Work, together with related initiatives, help to improve NATO's preparedness and response to future operations. These efforts support the Alliance's goal of mitigating climate-related risks, while ensuring that NATO forces are operationally effective in changing environmental conditions.

Climate Change and Security Initiatives

In 2024 the STO continued to support NATO in enhancing its understanding on how Climate Change impacts defence & security. The STO contributed directly to the Secretary General's Climate Change Impact Assessment Report, expanded NATO's underwater Arctic Climate Observatory, and established NATO's first Climate Change and Security Course in collaboration with the Naval Postgraduate School and NATO's Science for Peace and Security Programme. In addition, the STO and NATO's International Military Staff conducted a joint workshop on "Climate Change: Combining science and military expertise to enhance armed forces resilience", which produced several reports on how climate change affects NATO's missions and operations. Further information can be found here.

Figure 9: ACO24 sea trial, July 2024: recovery by NRV Alliance of the top float of an underwater mooring deployed for the NATO Arctic Climate Observatory in July 2023.

Climate Change and Security (CC&S) Analysis Project (OCS0000F50)

The Cooperative Security core task of the NATO 2022 Strategic Concept calls for the Alliance's leadership in understanding and adapting to the impact of climate change on security. The research conducted in the CMRE CC&S Analysis project contributes to this objective across three key strands. The first strand involves monitoring changes in the High North maritime domain, including the maintenance and expansion of the long-term NATO Arctic Climate Observatory, performed in summer 2024, and analysis of the collected data. The second involves introducing scalable capacity and tailored analysis tools to expand the computing framework for effectively exploiting massive cloud-based climate data. The third involves assessing how climate change affects naval sensor and platform performance in the maritime domain. The CMRE CC&S research initiative was funded by the OCS.

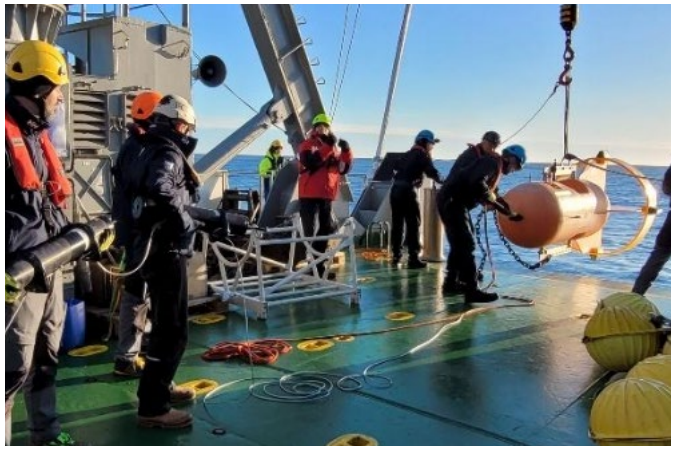


Figure 10: ACO24 sea trial, July 2024: recovery by NRV Alliance of the top float of an underwater mooring deployed for the NATO Arctic Climate Observatory in July 2023.

ENHANCING ALLIANCE MARITIME POWER

Directly contributing to maritime situational and environment awareness, and forging the next generation of naval capabilities

"By developing, testing and fielding adaptive and cooperative systems of autonomous, heterogeneous systems, CMRE contributes to enabling future NATO forces to present adversaries with operational dilemmas, for example, by holding submarines at risk in operationally relevant areas."

Mr Robert Been, CMRE Autonomous Anti-Submarine Warfare Programme Manager

To secure superiority in the maritime domain, the STO advances technologies and operational practices across various fields, including anti-submarine warfare and secure underwater communications. Maritime security is further reinforced through innovations in data knowledge management and the prediction of sea-ice collision risks, ensuring that NATO forces are not only technologically equipped, but also strategically prepared to face the challenges posed by complex maritime environments. These advancements will allow the Alliance to maintain a competitive advantage in safeguarding critical underwater infrastructure and ensuring freedom of navigation in contested waters.

Anti-Submarine Warfare Programme (SAC000F01 and SAC000F02)

The CMRE Anti-Submarine Warfare (ASW) programme aims to improve NATO's capabilities for submarine detection, classification, localisation, and tracking. CMRE researchers have developed innovative active and passive sonar prototypes, including highly advanced acoustic and quantum magnetic sensors. These prototypes were successfully tested at sea in the Golfo di Taranto in the fall of 2024, mounted on a variety of static and mobile maritime autonomous systems. Networked ASW capabilities with advanced signal and data processing were demonstrated near Elba in November 2024. These capabilities adapt to prevailing environmental conditions and target behaviour to optimise detection probability and maintain tracking once in contact, thereby holding the target at risk. The team also conducts operations research studies in order to characterise system performance and potential benefits of sensorised maritime autonomous systems in augmenting conventional ASW capabilities for NATO. This project is funded by NATO ACT.

Figure 11: NRV Alliance and Italian Navy frigate during 2024 sea trials.

Figure 12: NRV Alliance during fall 2024 experiments.

Data Knowledge and Operational Effectiveness Project (SACF0008)

As outlined in the NATO Warfighting Capstone Concept (NWCC), one of the five warfighting development imperatives is to achieve cognitive superiority through enhanced situational awareness and understanding. The CMRE Data Knowledge and Operational Effectiveness (DKOE) project supports NATO's Seabed-to-Space Situational Awareness (S3A) initiative by developing a variety of advanced AI and information fusion (AI2F) algorithms. These algorithms are based on statistical signal processing and machine learning, with a focus on multi-sensor multi-target tracking/localisation; underwater signal detection; vessel behaviour classification and anomaly detection; long-term vessel prediction and detection; and Global Navigation Satellite System (GNSS) spoofing detection. These sophisticated techniques are applied to heterogeneous data from monitoring systems, including different physical phenomena such as optical/multi-spectral imagery. The objective is to achieve cognitive superiority to anticipate potential changes in the operating environment. This project is funded by NATO ACT.

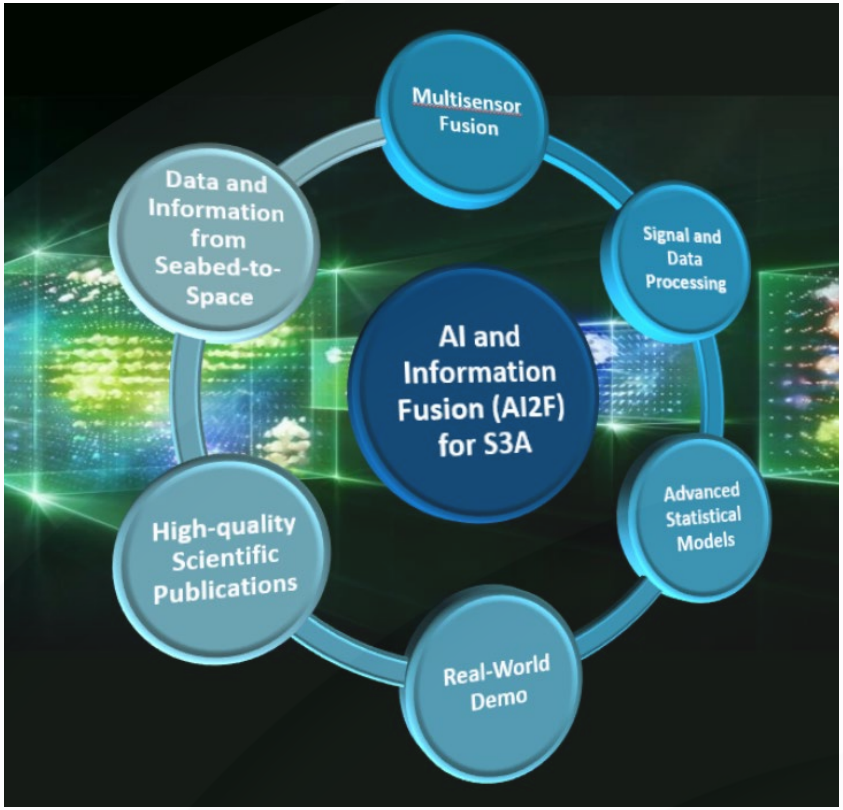


Figure 13: The main components of the DKOE project, which is focused on artificial intelligence and information fusion (AI2F) for Seabed-to-Space Situational Awareness (S3A).

Environmental Knowledge and Operational Effectiveness Programme (SAC000F06, SAC000F07)

The CMRE Environmental Knowledge and Operational Effectiveness (EKOE) programme provides critical knowledge of oceanographic conditions to inform NATO's anti-submarine warfare planning and operations execution. The CMRE has intensified efforts to update NATO's environmental knowledge and databases for ASW by gathering data from Arctic and Atlantic regions most affected by climate change. During the Nordic Recognized Environmental Picture (NREP) 24 sea trial in the central Barents Sea in June 2024, the CMRE performed extensive oceanographic measurements while transmitting sound waves to acoustic moorings. The principal objective was to measure the effect of Atlantification and variability of the Arctic Ocean on SONAR performance. To support rapid environmental assessment (REA), a sub-bottom profiling capability was integrated in an autonomous underwater glider. This project is funded by NATO ACT.

Figure 14: NRV Alliance in the Barents Sea during NREP24.

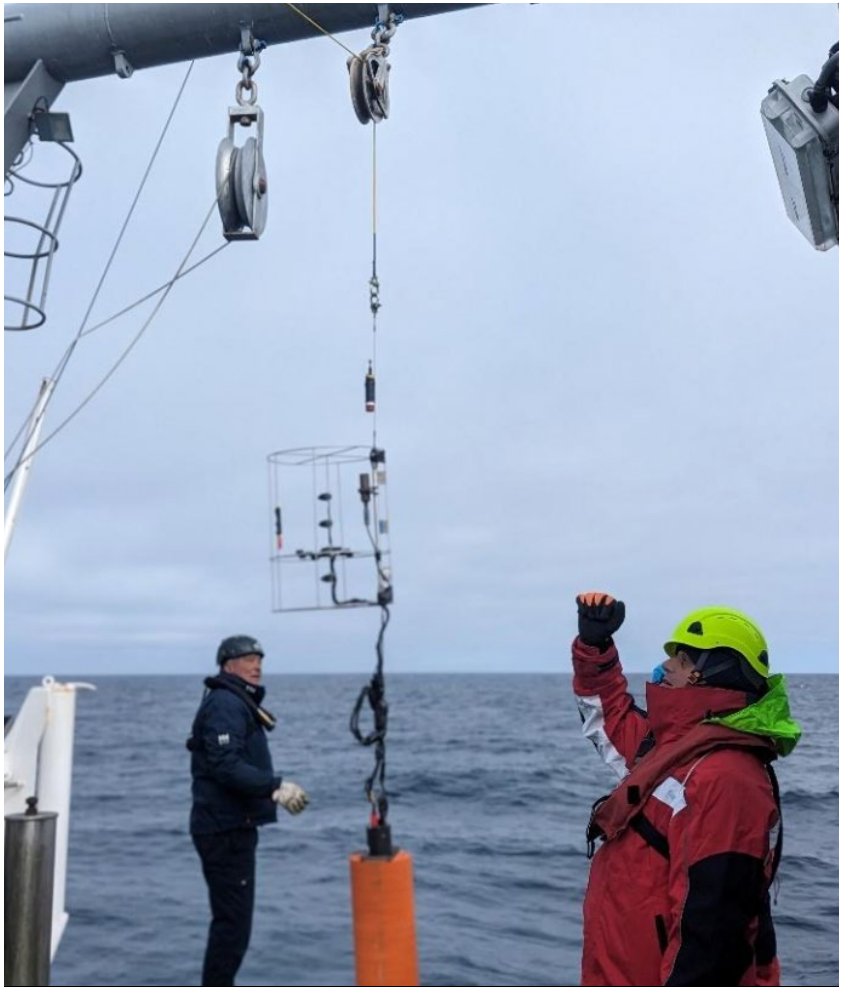


Figure 15: CMRE and ITA Navy Crew deploying an acoustic mooring from NRV Alliance during NREP24.

Maritime Systems: Sea-Ice Collision Risk Prediction and Mitigation for Naval Ships Operations (AVT-367)

This Research Task Group aims to enhance the capability of non-ice strengthened NATO naval vessels to operate in ice-infested waters. The team carried out an experimental study of the physics involved when warships, such as frigates and destroyers, push through floating ice, developed best practices for assessing warship operational limits in ice, and explored the use of sensors to navigate through ice fields. This work is especially important as NATO seeks to bolster its northern flank in the Arctic – a region that is disproportionately impacted by climate change and the associated challenges to Nations' sovereignty, security, and defence. A video with more information about this activity can be found on the STO YouTube channel.

Figure 16: Cone-shaped ice specimen grown in the laboratory for ship-ice impact experiments [Photo credit: Prof. Bruce Quinton, Memorial University of Newfoundland, used with permission].

Figure 17: Actual steel hull plating that was removed from the decommissioned Canadian warship, ex-HMCS Iroquois, and bolted into a testing frame for ship-ice impact experiments [Photo credit: Prof. Bruce Quinton, Memorial University of Newfoundland, used with permission].

Figure 18: Lab-grown, one-metre diameter ice cone (right) and steel warship hull specimen (left) fixed into an ice impact apparatus before testing [Photo credit: Prof. Bruce Quinton, Memorial University of Newfoundland, used with permission].

Secure Underwater Communications for Heterogeneous Network-enabled Operations (IST-174)

This Research Task Group focused on developing secure underwater communication standards to enhance Alliance maritime power. Underwater acoustic communications are crucial for various maritime applications, but there is a lack of standardised approaches to security. This, together with low adoption of existing standards and architecture across the Alliance, has hindered the adoption of underwater acoustic communications within NATO operations. The team addressed the growing need for reliable and secure underwater connectivity in a diverse range of maritime environments. They defined new communications and security protocols, which are now included in NATO STANAGs, and successfully demonstrated them in NATO multi-national exercises. The team's efforts to define secure waveforms, network protocols, and architectures have contributed significantly to the development of interoperable and resilient underwater communication systems, thereby enhancing NATO's maritime capabilities.

ADOPTING AUTONOMOUS AND ROBOTIC SYSTEMS

Integrating autonomous systems into new capabilities to bolster deterrence and defence in a safe and predictable manner

"At the STO CMRE, we are designing, developing and testing at-sea autonomous systems and novel sensors to improve the performance of NATO mine countermeasure capabilities in challenging environmental conditions, while removing the human from the minefield."

Dr. Yan Pailhas, CMRE Autonomous Naval Mine Warfare Programme

Autonomous and robotic systems are key to the future of warfare, providing unprecedented operational flexibility and efficiency. The STO drives advancements in the development of uncrewed maritime systems, autonomous mine countermeasures, and robotic experimentation. By harnessing these technologies, NATO aims to strengthen its deterrence posture, ensuring that these systems are deployed safely and effectively in a variety of military scenarios. From swarm system evaluations to autonomous naval systems, NATO's efforts to adopt autonomous technologies enhance its ability to respond to emerging threats with precision and speed, while reducing risks to human personnel.

Participation in Robotic Experimentation and Prototyping with Maritime Unmanned Systems 24 Exercise

The Robotic Experimentation and Prototyping with Maritime Unmanned Systems (REPMUS) 24 exercise aimed to test autonomous systems across maritime, land, and air domains, and assessing their ability to operate together. Led by Portugal, the host nation, REPMUS 24 was held from 9–27 September 2024 in the littoral waters of Sesimbra and Tróia Peninsula, Portugal. During the exercise, the CMRE deployed the Command, Control and Communications Maritime Robotic Exploitation (C3MRE) architecture. This helped to develop and test the crucial STANAG 4817 for command and control of unmanned systems, and facilitated their integration into the exercise's recognised common operating picture at the shore-based Maritime Operations Centre. Additionally, a CMRE unmanned underwater vehicle, designed for object identification, participated in REPMUS 24's exercises on naval mine warfare and the protection of critical undersea infrastructure. Collaborating assets, conducting search-only missions, issued taskings to the CMRE vehicle for autonomous reacquisition and identification of detected objects. This project was funded by ACT.

Figure 19: CMRE's BIONDo AUV ready for deployment in the Coastal waters of Sesimbra, Portugal during REPMUS24.

Autonomous Naval Mine Warfare Programme (SAC000F03, SAC000F04, SAC000F05)

The CMRE Autonomous Naval Mine Warfare (ANMW) programme has three principal work strands. The first strand is mine-like object sensing, by designing, developing, sea testing and validating novel sensors for enhanced target recognition. The second is uncrewed platform autonomy and interoperability, including perception of the underwater environment and potential targets by using AI and deep learning, which are essential enablers of platform adaptive and cooperative behaviour. The third is operations research into the optimal tactical exploitation of autonomous platforms in NATO naval mine countermeasure operations to minimize risks posed by naval mines to both naval and commercial shipping. Both the second and third strands were tested and validated during REPMUS 24 in September 2024. ANMW programme technologies are largely applicable to the remediation of underwater unexploded ordnance. This project is funded by ACT.

Figure 20: CMRE Unmanned Aerial System (with Infrared and Visible Light Payload

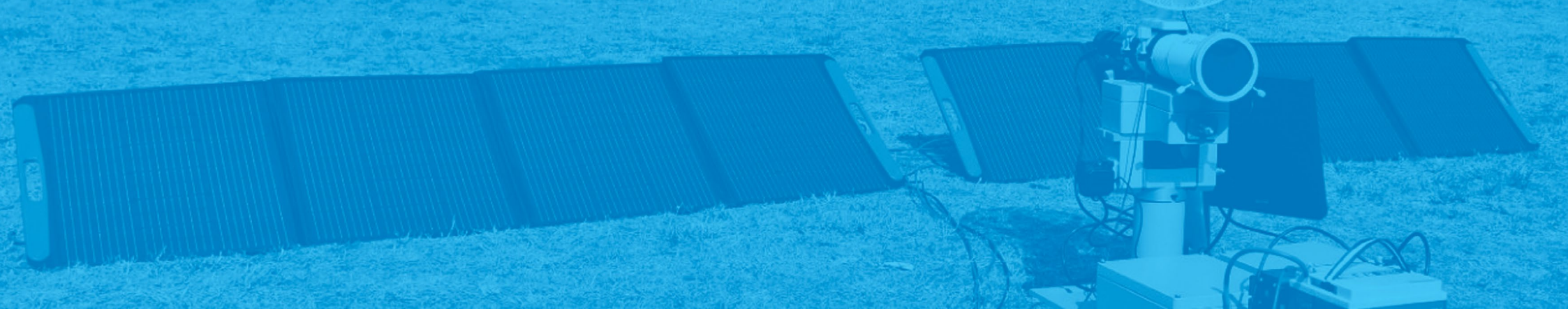
Figure 21: CMRE Test-Bed Unmanned Aerial Vehicle (UAV) Flying on CMRE BASIN during Drifting-Mines-24-Engineering-Trials experimentation.

Maritime Unmanned Systems Enablers Programme (SAC000F09, SAC000F10, SAC000F11)

The CMRE Maritime Unmanned Systems Enablers (MUSE) programme consists of three work strands on technologies to enable the effective employment of autonomous systems. The first strand is contributing to the development of NATO Standardization Agreement (STANAG 4817) on Interoperable Command and Control (C2) of Multi-Domain Unmanned Platform Control Systems, via validation and verification activities in virtual and real experiments. The second involves using modelling and simulation (M&S) to develop digital twins for maritime unmanned systems and command, control and communications (C3) capabilities to support experimentation and engagement with the NATO operational community. The third builds and expands on the CMRE's experience with STANAG 4748 on digital underwater signalling – the JANUS physical standard – using smart adaptive techniques to exploit the acoustic channels. The CMRE also hosted the seventh Underwater Communications and Networking Conference (UComms 24) in September 2024. This work is funded by ACT.

Figure 22: A fleet of Autonomous Underwater Gliders are ready to be deployed at sea.

Figure 23: Modelling and simulation capabilities being demonstrated to operational users at the CMRE Modelling and Simulation lab.



STRENGTHENING NATO'S SPACE PRIMACY

Securing NATO's final frontier in a safe, ethical and capable manner.

"As the revolution in space continues with changing business models and increasing opportunities to bring military and civil capabilities, it is imperative to further exploit the space domain. CPoW efforts include work on space policy, strategies, vulnerabilities, and data sharing...and the community is looking to expand research to leverage critical opportunities to meet the challenges in this competitive environment."

Colonel Andrew Hoffman. (United States Air Force), Head NATO STO CSO Operations and Coordination Office

Space is an increasingly contested domain, and NATO is committed to maintaining its superiority in this field. The STO leads innovative projects ranging from space weather environmental modelling to radio frequency sensing for space situational awareness. These efforts ensure that NATO Allies can operate effectively in space while safeguarding their assets from both natural and adversarial threats. Additionally, the STO's work on hybrid military and commercial satellite communications networks reflects the Allies' emphasis on resilient and secure space-based capabilities, ensuring that NATO remains at the forefront of space technology development while upholding ethical standards in its operations.

Report on the Relationship Between Space and Other Emerging and Disruptive Technologies

This report provided an overview of the scientific and technological advances behind the increasing reliance of NATO's operations on space. The report concludes that technology will continue to provide opportunities for the space domain both to enable, and be enabled by, other EDTs. This document served as the STO contribution to the Progress Report and Further Guidance on the Implementation of NATO's Overarching Space Policy, which was endorsed by NATO Defence Ministers at the June 2024 Defence Ministerial meetings.

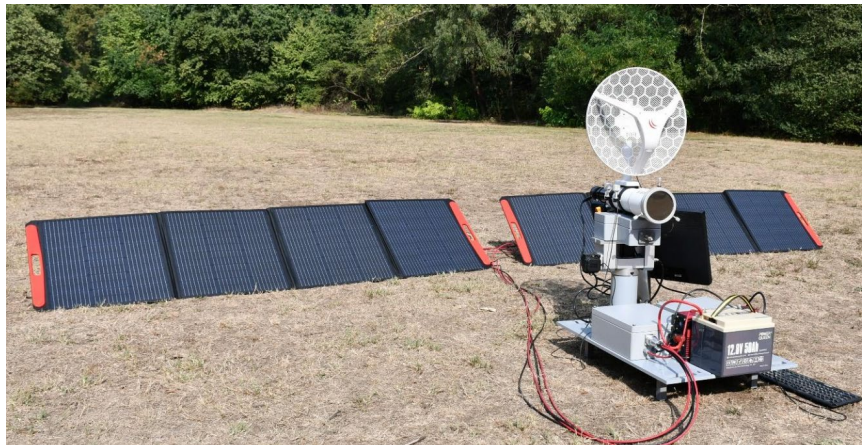


Figure 24: Ground-based Remote Outer Space Observation Terminal (GROOT).

Space Weather Environmental Modelling (MSG-187)

This Research Task Group focused on improving predictive capabilities in space weather modelling, which is critical for NATO's operational effectiveness. The project covered two key research areas: identifying correlations between space weather phenomena and Earth processes, and developing a ground-based remote outer space observation terminal (GROOT). GROOT was designed to acquire satellite data by providing ground-based solar activity monitoring, enhancing the accuracy of artificial intelligence models used to analyse the effects of space events on Earth. This will contribute to efforts to improve operational readiness and infrastructure resilience. The findings carry implications for both military and civilian sectors, particularly with regard to safeguarding critical infrastructure, communications, and navigation systems, while reinforcing NATO's technological superiority.

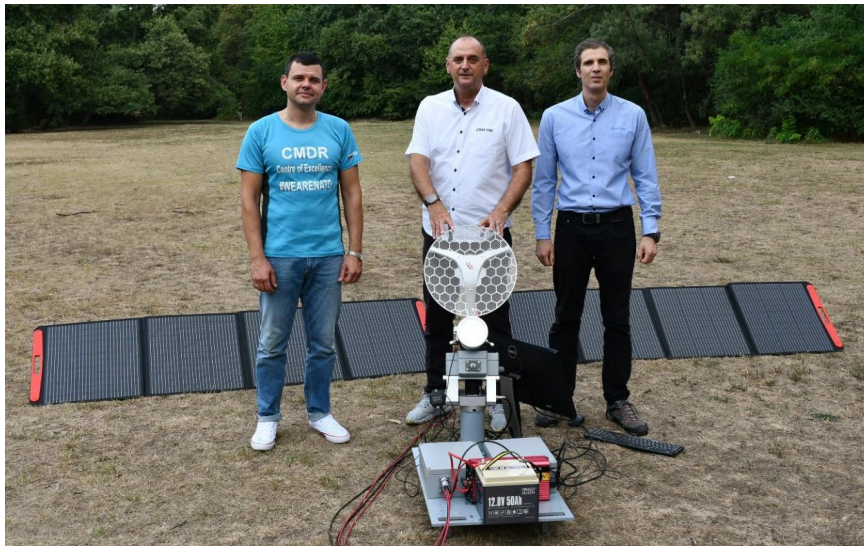


Figure 25: Ground-based Remote Outer Space Observation Terminal (GROOT) and team.

RF Sensing for Space Situational Awareness (SET-293)

This Research Task Group combined very powerful radar systems together in new ways to detect, track and characterise objects in deep space. The systems used included the Millstone Hill Radar (MHR) and the Ultra-wideband Satellite Imaging Radar (HUSIR) in Westford, Massachusetts, USA, as well as the Tracking and Imaging Radar (TIRA) in Wachtberg, Germany. These systems were combined with extremely sensitive radio telescopes, such as the e-Merlin array and the Goonhilly Earth Station in the UK, the Westerbork Synthesis Radio Telescope (WSRT) in the Netherlands, and the Sardinia Radio Telescope (SRT) in Italy. Multiple pairs of radar and radio telescopes were employed in long baseline bistatic configurations to collect unique data of Resident Space Objects at and beyond geosynchronous equatorial orbit, and to test and validate detection, tracking and imaging algorithms that were developed within SET-293. This work enriched existing capabilities among NATO Nations for space domain awareness.

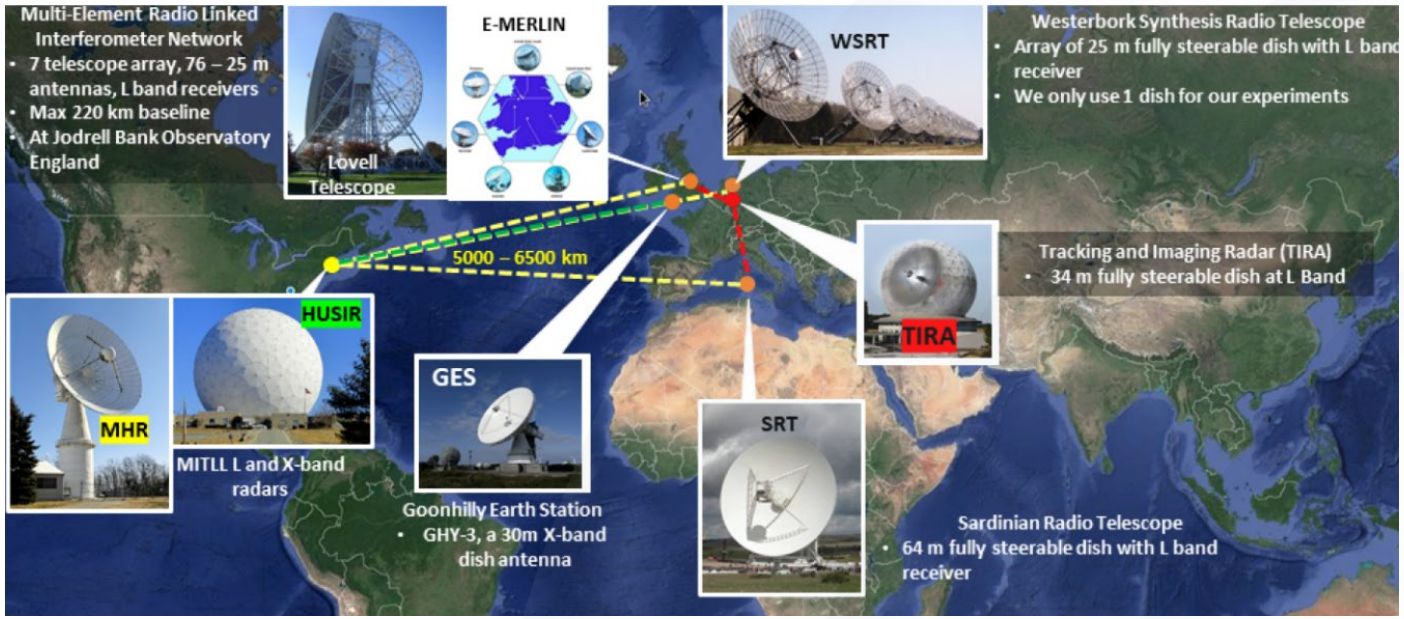


Figure 26: Long Baseline Bistatic Radar (LBBR) Network

Space Risk Assessment Matrix (S-RAM) (SCI-346)

This Research Task Group aimed to provide a comprehensive overview of potential threats to space assets and services, and assess the effectiveness and efficiency of countermeasure technologies. The team first identified all terrestrial, human-caused, and environmental impacts on satellite systems, determining the probability of occurrence and associated risk levels for each. This involved quantifying the potential loss of operational capability for NATO users. Possible countermeasures for each threat were then analysed and correlated. The group then developed a matrix that illustrates the relationship between threats and countermeasures (with or without cost considerations), providing insights into the effectiveness of each countermeasure.

Comparison of Allied Nations Space Strategies (SCI-357)

Many Allied Nations have developed their own space strategies, which must be “harmonized” for military use within NATO. This Research Task Group aims to identify and align key aspects of both national and NATO space strategies, contributing to a unified approach in space operations within NATO’s framework. The team will include participants from various Nations and NATO bodies, and will work to highlight differences, gaps, matches, and overlaps between national and NATO space strategies. The team is expected to provide recommendations on how to better integrate national strategies into NATO’s overall space strategy.

Figure 27: SCI-346 Space Risks rendition of an anti-satellite (ASAT) weapon targeting a space asset.

Hybrid Military and Commercial SATCOM Networks (IST-189)

This Research Task Group focused on the capabilities of satellite communications (SATCOM), current and emerging threats, and future technology trends that Nations will need to consider as they adopt blended military/commercial SATCOM systems. It also highlighted the challenges and benefits of integrating commercial SATCOM capabilities within NATO military infrastructures and operations. Leveraging on-demand commercial products and services will be crucial to expanding global coverage and achieving improved resilience, agility and flexibility. The findings address applications in both military and civil sectors, including the Federated Mission Networking (FMN) effort and many other military/commercial SATCOM systems. Findings and conclusions are documented in a Technical Report, due to be published in early 2025.

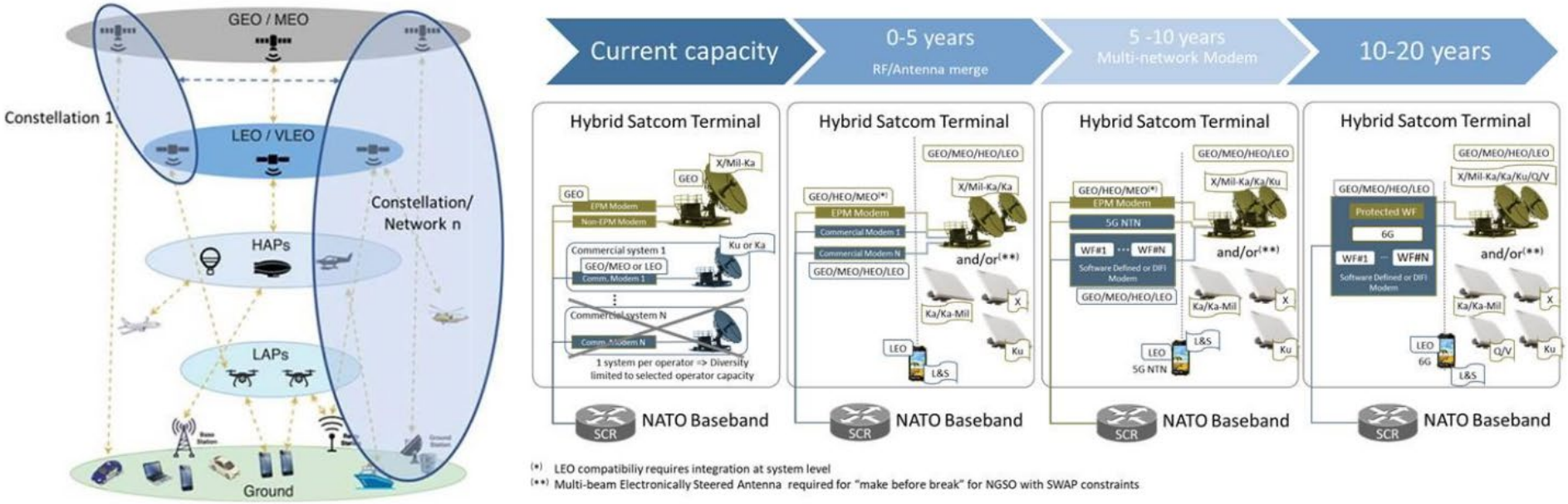


Figure 28: IST-189-Evolution of multi-band, multi-constellation architectures (left) and NATO Hybrid User Terminal Road Map (right).

BUILDING SUPPLY CHAIN RESILIENCE

Giving the Alliance resource depth to deter any adversary

The NATO Chief Scientist Grants Programme is a tool to expand the STO knowledge base. In 2025, the programme will award 400,000 Euros in total welcoming applications on six topics. These topics will include aspects not yet considered in the S&T programmes of work, and will fuel the development of further work strands."

Captain Salvatore Calabro (Italian Navy), Head, NATO STO Office of the Chief Scientist S&T Advice Section

Resilient supply chains are critical to NATO's ability to maintain operational readiness in the face of adversarial disruptions or global crises. The STO addresses these challenges by advancing technologies in additive manufacturing and exploring solutions to ensure energy security resilience. The interoperability of supply chains, from munition health management to energy security capabilities, is essential for NATO to sustain Allied forces in the field. Through developing a robust supply chain framework, NATO enhances its ability to rapidly adapt to any logistical disruptions and ensures that its forces are prepared for sustained operations across a wide range of environments.

STO Lecture Series: Munition Health Management (AVT-375)

This activity encompassed three editions of a Research Lecture Series (RLS) on the implementation of munition health management (MHM), based on Atlantic Treaty Organization Allied Ordnance Publication 4844. A total of 179 attendees participated in the three events, which were held throughout 2024. The implementation of MHM reduces costs, improves munitions stockpile management, and increases the reliability of munitions and the operational readiness of armed forces. The activity underlined the importance of cooperation among defence ministries, industry and research institutes in this field, and enhanced the development and implementation of MHM. It also confirmed that many NATO Nations have a strong interest in moving toward the implementation of MHM. Information from all of the lecture series is collated in a final report, alongside a complementary training video that captures the lecture series.

Interoperability of Additive Manufacturing in NATO Operations (AVT-342)

This Research Task Group focused on ways to implement additive manufacturing (AM) in NATO operations for improved interoperability and logistics support. It addressed the boundary conditions for AM (or 3D printing) in forward locations and home stations from legal, technical and quality assurance standpoints, as well as the secure transfer of information. The team provided examples for four domains of operation (land, sea, air and space), identifying specific requirements for each, and highlighted cross-domain military application areas. The examples underscore the importance of AM for improving platform availability and reducing downtime. The team also showed that interoperability, including the involvement of civil parties, is required to maximise the potential of AM. For more information, please see the AVT-342 report.

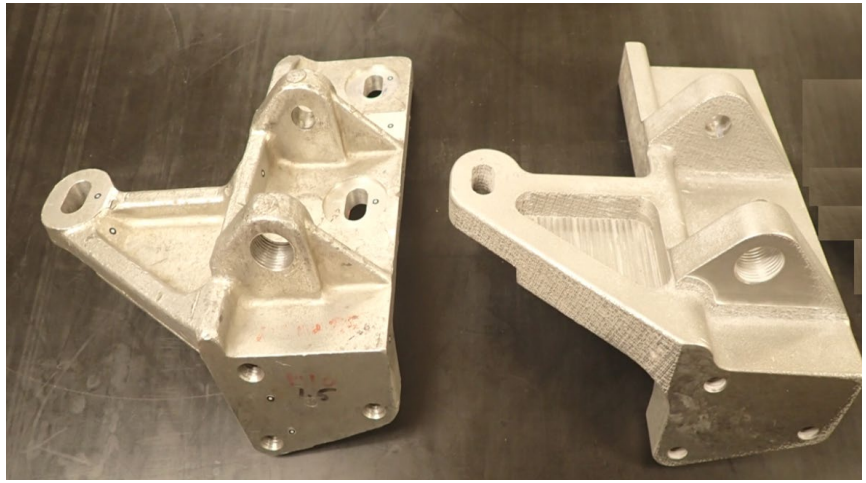


Figure 29: Example of an original and printed MT-LB (multipurpose towing vehicle, light armoured), alternator bracket.

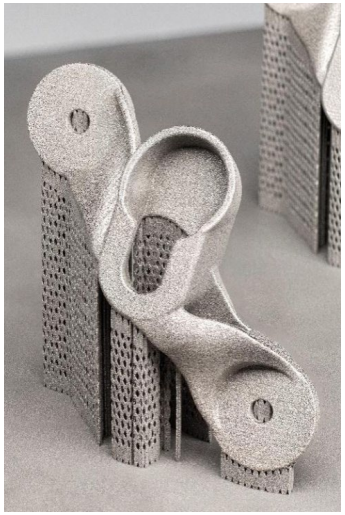


Figure 30: NH90 redesigned ladder bracket.

Figure 31: Engine speed governor. Original part (left) and additively manufactured part (right).

Figure 32: OEM filter (left) versus the polylactic acid printed filter (right). Photo: Jonas Leander.

Nordic Pine 2024 Exercise (SAS-191)

Nordic Pine is a yearly NATO exercise on hybrid threats to renewable energy systems. The Nordic Pine 2024 Exercise addressed emerging hybrid threats, including cyber threats, malignant influence, and the weaponization of supply chains. The exercise is of significant importance to NATO and the STO because it aimed to enhance the resilience of renewable energy infrastructure against hybrid threats through collaborative research and innovative technological solutions. For the first time ever, the Global Education Community Collaboration Online simulation system (from the US Naval Postgraduate School) was tested outside a military context, marking a significant step forward in integrating advanced simulation technologies into civilian energy security strategies. Additional information can be found in a video on the NATO STO YouTube channel.

Figure 33: Nordic Pine 2024 Exercise.

Figure 34: SAS-191 – Participants in the Nordic Pine 2024 Exercise.

ACCELERATING CAPABILITY DEVELOPMENT

Putting the latest technology in the hands of users

"One of our main S&T efforts is to develop integrated capabilities and be ready for the combined and joint fight of tomorrow. Integrating capability development signals the Alliance's modernization efforts at the pace the joint force demands, ensuring our warfighters can operate effectively."

Lieutenant Colonel Tuan Tran (United States Air Force), Executive Officer, NATO STO SCI Panel

In an era of rapid technological evolution, NATO's ability to quickly integrate and operationalise new capabilities is paramount. The STO plays a pivotal role in ensuring that the Alliance can transition cutting-edge innovations from research to deployment. By focusing on advancements like modelling and simulation for acquisition and directed energy weapons, the STO provides Allied forces with access to the latest capabilities. The rapid development and deployment of technologies, such as federated battle labs and non-lethal weapons, provides NATO with a competitive edge, ensuring that the Alliance remains agile and responsive to emerging threats.

Modelling and Simulation for Acquisition (MSG-179)

This Research Task Group focused on identifying critical acquisition activities where modelling and simulation (M&S) bring added value. The research team proposed a framework linking the acquisition process with M&S approaches and methods to identify the best opportunities to apply M&S. This framework is based on an analysis of acquisition processes and an M&S taxonomy, and can facilitate the application of M&S in both military and civilian acquisition processes. The framework consists of acquisition "activity" and "object" dimensions, as well as M&S "motivation" and "approach" dimensions. Its application is demonstrated in use cases. The comprehensive Technical Report provides a more detailed analysis of methodologies and recommendations, including a set of acquisition metadata used to tag models and simulations, and the use cases.

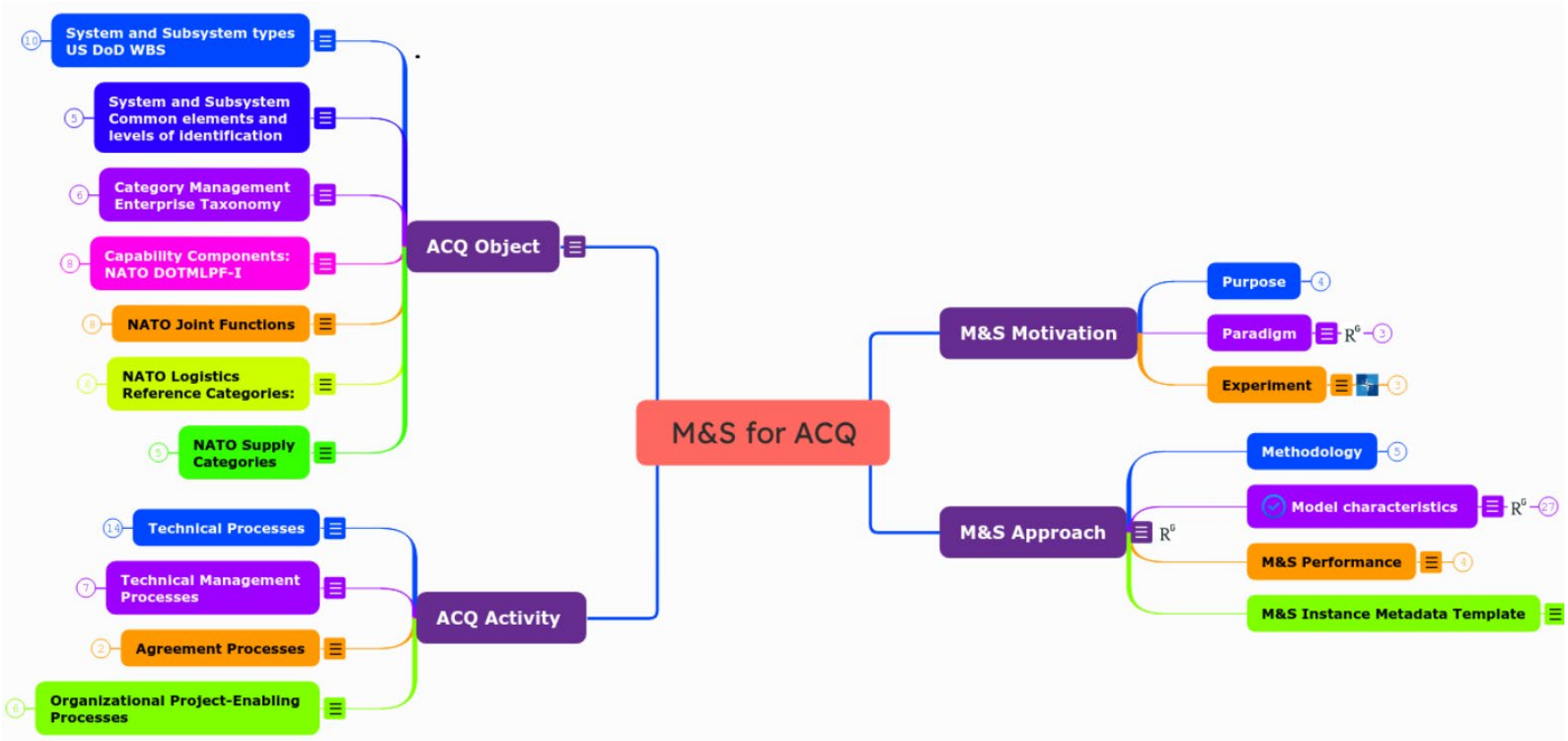


Figure 35: M&S for Acquisition Framework.

Radio-Frequency Directed Energy Weapons (SCI-356)

Radio-frequency directed energy weapons (RFDEW) can cause disturbance or damage to electronic systems, much like the effects caused by electromagnetic pulses from nuclear detonations at high altitudes. After decades of development, RFDEW technologies have matured to the point where manufactured solutions are ready for the field. At the same time, there are threats for which available countermeasures may be outperformed by RFDEW. This Research Symposium, held in Copenhagen, Denmark in May 2024, covered: high-power radio frequency (HPRF) effects and testing; test facilities and procedures; HPRF sources and systems; protection and hardening; HPRF against IEDs and UAVs; and bio effects, standards and legislation. Presentations and papers from the symposium are available on the STO website.

Figure 36: Demonstration of scenario for boat engine stopping using non-lethal RFDEW technologies; test campaign on Crete, GRC, October 2019, organized by the STO SCI-294 Task Group.

Framework for Avionics MissiOn Systems (FAMOS) (SCI-326)

Emerging radars and radios can change their transmitted waveforms by modifying their modulation, bandwidth, centre frequency, medium access protocols, and timing. This ability challenges traditional signal detection and identification techniques, which depend on comparisons of detected signal characteristics with known signal parameters in a pre-defined database. To address these challenges, this Research Task Group had two core objectives. One objective was to generate both NATO-relevant engagement scenarios and associated electromagnetic surveillance data, in the absence of existing data. The other was to develop AI-enabled agents that can identify the threat level of emitters from this surveillance data, in cases where traditional look-up table approaches fail. The team generated two synthetic datasets representing adaptive transmitters in NATO-relevant scenarios. It also developed a diverse set of AI-enabled electromagnetic surveillance algorithms that processed this data, with promising performance.

INFORMING NATO'S CONCEPTS

Informing the Alliance's latest ideas and concepts, based on sound technical and scientific expertise

"In September 2024, we hosted the STB as the first Senior Committee to convene in Sweden after we became full members of the Alliance. It was a pleasure and honour to provide the venue for three days of forward-looking discussions on the governance of S&T in NATO."

Dr Jens Mattsson, Director General of FOI and STB Swedish Principal Member

In a rapidly evolving security environment, NATO must continuously adapt its strategic concepts to stay ahead of potential adversaries. The STO provides the necessary scientific and technical expertise to inform and shape these strategies, from supporting the work on resilience to addressing the human factors of AI. Research into emerging fields, such as hypersonic weapons and directed energy systems, helps to ensure that NATO remains informed and capable of responding to new and emerging challenges. This commitment to evidence-based strategic development strengthens NATO's ability to defend its member Nations and protect global security.

Human Factors Needed in Artificial Intelligence

In March, the Chief Scientist provided a Food for Thought (FFT) paper on human-centred design approaches that enable ”responsible-by-design” AI-assisted technologies to the NATO Innovation Board. Technologies that focus on human-machine interactions present many potential benefits, as well as a number of performance challenges when used in complex, real-world military environments. The digital transformation demands new approaches to working with intelligent machines, which makes the user interface and user experience particularly important. Understanding how to optimise trusted human-machine collaborations has never been more essential. This paper contributed to the evidence base for NATO’s revised AI Strategy, and continues to inform NATO’s ongoing digital transformation work.

Supporting NATO’s Work on Resilience: CPoW Baselining Report

The 2024 NATO Summit Declaration highlights the need to enhance national and collective resilience for credible deterrence and defence to support and safeguard the societies of NATO Allies. This requires a whole-of-government approach, public-private cooperation, and societal resilience considerations. The OCS supported these efforts in 2024 by strengthening the STO’s CPoW activities against NATO’s seven baseline requirements for national resilience. Almost 50 STO activities currently address and align to the baseline requirements, especially within the areas of energy, health, and communication. The STB Chair and the Chair of the Resilience Committee (RC) have led efforts to strengthen collaboration and coordination between the S&T and resilience communities. Together, they have agreed to provide insights and guidance on how S&T can support national and collective resilience among Allies. Further information can be found on the NATO website.

Directed Energy Weapons Concepts and Employment (SAS-140)

This Research Task Group provided analytical and operational insights for a future directed energy weapon (DEW) concept of employment, highlighting a solution to the "valley of death" – the transition from Science & Technology to acquisition and concept implementation. The team analysed the benefits of DEW concepts, from tactical to strategic levels, and linked them to the military planning principles of NATO Allied Joint Publication-01. They developed a framework to support the introduction of a new capability into operational service, introducing the concept of a capability maturity scale that is defined by a series of Capability Readiness Levels (CRLs). More information is available from the SAS-140 Technical Report and the SAS-140 video on the NATO STO YouTube channel.

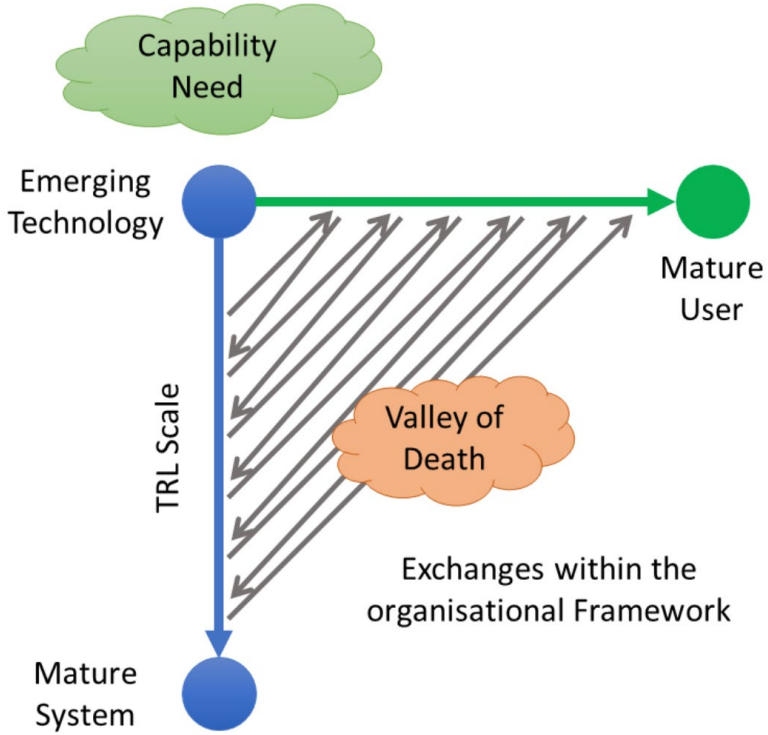


Figure 37: The Valley of Death challenge manifests earlier and more profoundly for emerging technologies considered to be disruptive (Diagram: SAS-140).

Technological and Operational Challenges Due to Hypersonic Flight and the Related Weapons Threat (AVT-SET- 396)

This Research Symposium focused on issues related to hypersonic flight vehicles, appraising the feasibility and capabilities of hypersonic weapons, while helping to demystify the potential threat. The threat of hypersonic weapons has emerged in recent years, with Russia using operational capabilities in the war against Ukraine (e.g., Kinzhal missile).

Better information in this area is key to building up operational capabilities for hypersonic strike weapons in NATO, and to designing effective defence systems for detection, tracking, and interception. More information is available in the AVT-SET-396 Meeting Proceedings, as well as the related AVT-ST-008 and AVT-359 reports.

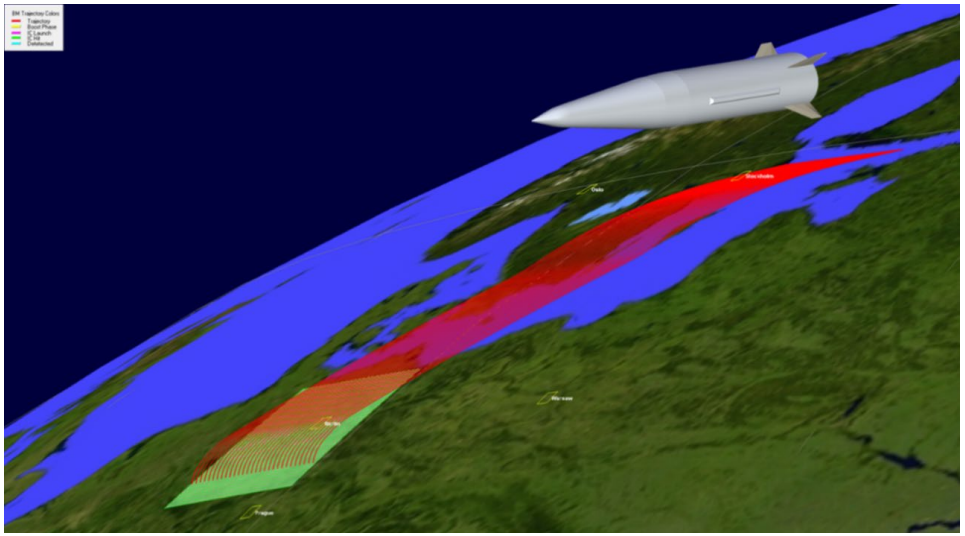


Figure 38: Simulated trajectories of hypersonic missile attack and target footprint (Ref. AMDC).

Figure 39: Russian Kinzhal hypersonic missile under MIG 31 (Ref. Stern).

MAINTAINING STRATEGIC FORESIGHT

Using predictive insights to guide long-term STO strategic planning and decision-making

"Environmental knowledge is a critical enabler to optimise the planning and execution of NATO maritime operations: NATO builds such knowledge through continuous multi-source data collection and analysis, and by rapid environmental assessment before and during operations, and STO CMRE research supports both approaches."

Dr Alberto Alvarez, CMRE Environmental Knowledge and Operational Effectiveness

Strategic foresight is essential to NATO's long-term success in an unpredictable world. Through the STO's workshops and conferences, such as the Young Voices Workshop on S&T Macro Trends and the Wilton Park Conference Series, NATO ensures that its decision-making processes are informed by predictive insights and emerging trends. By anticipating future challenges, the STO helps NATO to minimize strategic surprises, and prepares the Alliance for both immediate and long-term threats. These efforts guide the STO's approach to planning, ensuring that the Alliance remains future-ready in the face of evolving global security dynamics.

STO Plans and Programmes Workshop 2024

This workshop focused on a topical review of STO programmes through the lens of the NATO Warfare Capstone Concept (NWCC), highlighting the common ground between the political focus and military vision. Such strategic reflection is crucial to addressing the goals and problem statements brought forward by the NWCC, as well as its supporting Warfare Development Imperatives (WDI) of Cognitive Superiority, Layered Resilience, Influence and Power Projection, Integrated Multi-Domain Defence, and Cross-Domain Command. Supreme Allied Commander Transformation (SACT) General Philippe Lavigne delivered a keynote speech, emphasising the importance of S&T in supporting the NWCC. Following the workshop, the STB accepted Portugal's offer to lead a CPoW Challenge on "A System of Systems Approach to Multi-Domain Operations." This Challenge will identify and promote opportunities for interdisciplinary collaborative research work for the next three to four years.

Minimizing Strategic Surprise: Young Voices Workshop on Science & Technology Macro Trends

This workshop brought together experts under the age of 35 from across a range of disciplines to discuss S&T macro trends. Participants from both inside and outside NATO engaged in a scenario-based discussion, as well as surveys and foresight exercises, to identify long-term drivers of change in the international security landscape over the next 20 years and assess implications for NATO leadership. This event, held in May 2024, represented the inaugural workshop for NATO's work on Science & Technology Futures, and directly supported the STO's data collection and analysis in preparation for the *Science & Technology Trends Report (2025–2045)*.

Understanding Future Defence, Deterrence and Resilience

This event, co-funded by the OCS in partnership with Wilton Park and The Alphen Group, was the third in a series of "Future War" conferences. The conference brought together 70 leading practitioners and experts on deterrence, resilience and technology to consider a range of futures, policy and planning options to support the Alliance in delivering national and collective deterrence and resilience. Further information can be found here.

EMPOWERING MULTI-DOMAIN OPERATIONS:

Empowering the Alliance to strategically influence events, synchronise efforts with external stakeholders, and present formidable challenges to adversaries

"The STO Collaborative Programme of Work is at the forefront of research efforts helping the NATO Alliance achieve proficiency in multi-domain operations; such efforts will define the future strategic landscape. Enabling seamless integration of efforts across air, land, sea, space, and cyber will give the Alliance a strategic advantage in safeguarding peace and security in an increasingly complex threat environment."

Lieutenant Colonel Matt Mogensen (United States Army), PhD, Executive Officer, NATO STO SAS Panel

In today's complex security environment, NATO's ability to operate seamlessly across land, sea, air, space and cyber domains is crucial. The STO is at the forefront of empowering the Alliance's multi-domain operations (MDO) by developing new systems, concepts and strategies. Research efforts, such as the DATA-MARE programme and the investigation of agile C2 systems, ensure that NATO can coordinate across multiple domains and present adversaries with formidable challenges. This synchronisation enhances the Alliance's ability to strategically influence events, respond to threats and protect its interests across all operational domains.

Maritime Resources Enablers Project (SACF00012)

The effective sharing and exploitation of data and information are critical enablers for MDO, synchronising all of the Alliance's instruments of power to deliver deterrence and defence. The goal of the CMRE Maritime Resources Enables (MARE) project is to facilitate the sharing, exploitation, and repurposing of CMRE research data across the Centre's programmes, within the Alliance, and across multiple domains. The project is structured around three key strands. The first focuses on data governance, supporting the coordination and prioritisation of data management activities, guided by key performance indicators. The second involves the continued development and refinement of the CMRE Data Catalogue. The third focuses on creating data management and engineering tools to enhance data access, retrieval, transformation, sharing, and metadata lifecycle management. This project is funded by ACT.

Critical Undersea Infrastructure (SAC000F08, SAC000F34)

The importance of protecting critical undersea infrastructure (CUI) from physical attacks has gained greater attention recently, after incidents like the Nord Stream leakage. The CMRE has developed advanced technologies using machine learning and uncrewed maritime systems to address CUI protection. One key development is the Mainsail Operational Prototype, a data-centric platform co-designed with ACT and MARCOM to meet the needs of the NATO Maritime Centre for the Security of CUI at MARCOM. During ACT's Innovation Continuum SHINE event at the CMRE in October 2024, the CMRE also showcased a CUI Toolkit, featuring an AI-based anomalous behaviour classifier, a multi-domain command and control system for uncrewed maritime systems, an autonomous underwater inspection system, and virtual reality tools for mission planning. This work is funded by ACT.

Systems and Concept Challenges in Enabling Multi-Domain Operations (SCI-361)

This Research Specialists' Meeting marked an important milestone in ensuring that NATO MDO developments, and associated perspectives from policy makers, were brought forward to the System Concepts Integration (SCI) Panel and invited guests. Over the course of two days in October 2024, attendees developed a better understanding of future wartime strategies that impact human and system constructs. Discussions covered implications and challenges, as well as future Science & Technology activities, spanning educational thought to MDO interoperability and digital transformation research. The event also supported the CPoW Challenge Scoping Workshop on a systems-of-systems approach to MDO warfare. Outputs from the discussions and presentation material are available in the Meeting Proceedings Notes, and further details are available in a forthcoming Technical Evaluation Report (TER).

Agile, Multi-Domain C2 of Socio-Technical Organizations in Complex Endeavours (SAS-143)

This Research Task Group explored the nature of agile multi-domain command and control (C2). Given the increased reliance on robotics and artificial intelligence in MDO, there is a need to harmonize operations in the physical, virtual and social domains. This research classified MDO challenges in a structured way to assess potential harmonization efforts. The findings are of particular interest to NATO, as case studies and experiments show that MDO are likely to fail in the absence of harmonization. More information is available in the SAS-143 Technical Report.

HARNESSING SYNTHETIC BIOLOGY

Exploring the potential and risks of synthetic biology to safeguard against bio-engineered threats

"Synthetic biology will provide NATO Nations with the ability to create new materials and/or manufacturing processes to produce medicines, equipment, and supplies, as well as counter supply chain concerns and reduce operational costs. Working together, NATO Nations will demonstrate the capabilities of bio-products in military operations."

Dr Patrick Mason, Director, Human Performance, Training and BioSystems Directorate, United States Department of Defence and HFM Panel Chair

As the field of synthetic biology rapidly advances, NATO is taking proactive steps to understand and mitigate its associated risks. The STO spearheads efforts to explore the potential of synthetic biology to address bio-engineered threats, ensuring that NATO remains prepared for emerging biological challenges. Through collaboration with thought leaders and scientific institutions, the STO investigates cutting-edge solutions to safeguard against bio-threats, while also exploring the positive applications of this technology. NATO's engagement in synthetic biology research highlights the Alliance's commitment to staying at the forefront of biotechnology and ensuring security against biological risks.

Institute on Science for Global Policy (ISGP) Workshop on Emerging and Persistent Infectious Diseases

In October 2024, the OCS co-funded and hosted a workshop on “Global Emerging and Persistent Infectious Diseases,” and their impact on armed forces. Organized by the Institute on Science for Global Policy (ISGP), a US think tank, the conference brought together more than 50 experts from more than 15 countries, representing governments, the private sector, militaries, academia, and public advocacy. The conference agenda was structured to reflect scientific and technological options that directly affect NATO decisions on troop safety and disease transmission. Special attention was given to practical, real-world decisions informing NATO and Defence Communities on current actions concerning troop deployment and protection. The conference was held under Chatham House rules at NATO HQ. A non-attributed summary is publicly available in an ISGP publication.

STO AT GLANCE

The NATO Science & Technology Organization (STO) is NATO's hub for collaborative research for defence purposes. We are chartered by the North Atlantic Council to deliver innovation, evidence-based advice and scientific solutions that meet the Alliance's needs in an everchanging security environment. Our work ensures that Allied forces maintain their military edge over potential adversaries by drawing decisive advantages from current and evolving technologies. We strive to stay at the forefront of Science & Technology (S&T), forge and nurture partnerships, enhance Alliance decision-making, focus on Alliance needs to boost impact and promote technology demonstrations.

Who We Are

Our organization is governed by the NATO Science & Technology Board (STB), a senior NATO committee that reports to the North Atlantic Council. The STB is composed of members from the Allied Nations, typically responsible for the national defence research budget and programmes, who hold the decision-making authority in the committee. The STB also includes representatives from the wider NATO S&T community, and is chaired by the NATO Chief Scientist. The STB oversees and directs the work of the STO's eight Scientific and Technical Committees (STCs) as well as the three Executive Bodies: the Collaboration Support Office (CSO), the Centre for Maritime Research and Experimentation (CMRE), and the Office of the Chief Scientist (OCS).

Collectively, the STB, the STCs, and the Executive Bodies form the STO to deliver three main products: The Collaborative Programme of Work, the CMRE Programme of Work, and evidence-based advice to political and military leadership.

The Collaborative Programme of Work

The Collaborative Programme of Work (CPoW) addresses S&T issues and challenges of common interest to NATO Nations, through more than 400 activities at any given time. The CPoW brings together a network of 5,000 national scientists, researchers, analysists and engineers that covers all aspects of defence- and security-relevant Science & Technology. Collectively, these subject matter experts form the world's largest defence research network and embody the knowledge base of the Alliance. At the same time, they are directly funded by their national employers to work on national defence priorities.

These experts are organized into the eight STCs, commonly known as the Panels and Group, each of them with its own topical scope, planning and conducting its own research activities within the CPoW:

- Applied Vehicle Technology (AVT) Panel
- Human Factors and Medicine (HFM) Panel
- Information Systems Technology (IST) Panel
- System Analysis and Studies (SAS) Panel
- Systems Concepts and Integration (SCI) Panel
- Sensing Technology (SET) Panel
- Technology and Science Incubation (TSI) Panel
- NATO Modelling and Simulation Group (NMSG)

The CPoW serves as a mechanism for broadening the knowledge base (through international collaboration under a NATO umbrella) and sharing the results (through written reports, conferences, courses and technology demonstrations). The individual researchers and experts benefit from expanding their knowledge, the participating Nations benefit from leveraging their resources and de-risking their investments, and NATO benefits from the enhanced collective knowledge base for the technological advantages of the Alliance.

The CPoW is supported by the CSO, under its Director, Mr John-Mikal Størdal. The CSO facilitates all CPoW activities, maintains a vibrant network of scientists, and manages the publication of activity reports. The CSO also conducts outreach to ensure that S&T findings from the CPoW reach key audiences.

The CMRE Programme of Work

The CMRE Programme of Work is an entirely customer-funded programme. It is executed by the CMRE, which organises and conducts scientific research and technology development to deliver research-driven, innovative, and field-tested solutions to address the defence and security needs of the Alliance. The CMRE plans the Programme together with its paying customers, such as Allied Command Transformation.

CMRE's scientific activities are designed to address future defence requirements of the Alliance in the maritime domain:

- Autonomy for Anti-Submarine Warfare (ASW)
- Autonomous Naval Mine Warfare (ANMW)
- Environmental Knowledge and Operational Effectiveness (EKOE)
- Data-Environmental Knowledge and Operational Effectiveness (DKOE)
- Maritime Unmanned Systems Enablers (MUSE)
- Maritime Resources Enablers (MARE)

The CMRE, under its Director, Dr Eric Pouliquen, provides an outstanding at-sea and ashore research environment, enabling internationally recognised scientists and engineers from all NATO Nations to deliver results more effectively than would be possible by individual Nations.

Evidence-Based Advice

The STO delivers evidence-based advice on significant S&T issues, while leading the delivery of S&T and promoting its exploitation throughout the NATO enterprise. This advice is generated from the STO's Programmes of Work and other sources to inform planners and decision-makers in the Nations and NATO.

The NATO Chief Scientist, Dr. Bryan Wells, plays a vital role in advising on the S&T that underpins the next generations of military capability. The OCS supports him in two essential functions: as Chairman of the STB and as senior scientific advisor to the NATO leadership. In particular, the OCS provides analyses of significant S&T trends and developments, and conducts in-depth assessments of the impact of emerging and potentially disruptive technologies on Alliance objectives.

List of Acronyms and Abbreviations

3D	Three Dimensional
ACO24	Arctic Climate Observatory 2024
ACT	Allied Command Transformation
AI	Artificial intelligence
AI2F	AI and information fusion
AM	Additive manufacturing
ANMW	Autonomous Naval Mine Warfare
ANTICIPE	Augmented Near real-Time Instrument for Critical Information Processing and Evaluation
ASW	Anti-submarine warfare
AUV	Autonomous Unmanned Vehicle
AVT	Applied Vehicle Technology
C2	Command and Control
C3	Command, Control and Communications
C3MRE	Command, Control and Communications Maritime Robotic Exploitation
CC&S	Climate Change and Security
CMRE	Centre for Maritime Research and Experimentation
CPoW	Collaborative Programme of Work
CRL	Capability Readiness Level
CSO	Collaborative Support Office
CUI	Critical underwater infrastructure
DEW	Directed energy weapon
DKOE	Data Knowledge and Operational Effectiveness
EDT	Emerging and Disruptive Technologies
EKOE	Environmental Knowledge and Operational Effectiveness
FAMOS	Framework for Avionics MissiOn Systems
FFT	Food for Thought
FMN	Federated Mission Networking
FOI	Swedish Defence Research Agency
GNSS	Global Navigation Satellite System
GROOT	Ground-based remote outer space observation terminal
HFM	Human Factors and Medicine
HPRF	High-power radio frequency
HQ	Headquarters
HUSIR	Millstone Hill Radar and the Ultra-wideband Satellite Imaging Radar
IED	Improvised explosive device
ISGP	Institute on Science for Global Policy
IST	Information Systems Technology
IT	Information Technology
MARCOM	Maritime Command
MARE	Maritime Resources Enables
MDO	Multi-Domain Operations
MHM	Munition health management
MHR	Millstone Hill Radar
ML	Machine Learning

List of Acronyms and Abbreviations (Continued)

MQ	Message Queueing
MQTT	MQ Telemetry Transport
M&S	Modelling and simulation
MSaaS	Modelling and simulation as a service
MUSE	Maritime Unmanned Systems Enablers
NATO	North Atlantic Treaty Organization
NDV	Nuclear Disarmament Verification
NMSG	NATO Modelling and Simulation Group
NPT	(Nuclear) Non-Proliferation Treaty
NREP	Nordic Recognized Environmental Picture
NRV	NATO Research Vessel
NWCC	NATO Warfare Capstone Concept
OCS	Office of the Chief Scientist
PLA	Polylactic acid
QT	Quantum technologies
REA	aRapid environmental assessment
REPMUS	Recognised Environmental Picture augmented by Maritime Unmanned Systems
RF	Radio Frequency
RFDEW	Radio-frequency directed energy weapons
RLS	Research Lecture Series
RTG	Research Task Group
S&T	Science and Technology
S3A	Seabed-to-Space Situational Awareness
SACT	Supreme Allied Command Transformation
SAS	System Analysis and Studies
SATCOM	Satellite communications
SCI	Systems Concepts and Integration
SET	Sensors and Electronics Technology
SHAPE	Supreme Headquarters Allied Powers Europe
SONAR	Sonic navigation and ranging
S-RAM	Space Risk Assessment Matrix
SRT	Sardinia Radio Telescope
STANAG	Standardization Agreements
STB	Science & Technology Board
STC	Science and technical committees
STEM	Science, Technology, Engineering, and Mathematics
STO	Science & Technology Organization
TER	Technical Evaluation Report
TIRA	Tracking and Imaging Radar
TSI	Technology and Science Incubation
UAV	Unmanned aerial vehicle
Ucomms	Underwater Communications and Networking Conference
WDI	Warfare Development Imperatives
WSRT	Westerbork Synthesis Radio Telescope
XR	Extended Reality

List of Links/Contact Details

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