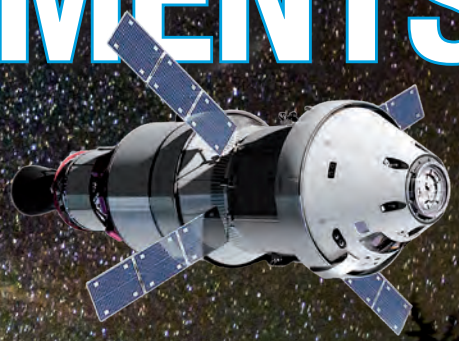
"With more than half of active satellites orbiting the Earth belonging to NATO Allies or companies based in Allied territory, NATO countries increasingly rely on space in key functional areas."

TECHNOLOGICAL ADVANCEMENTS IN SPACE



An NCIA Perspective

by **Elena Morando**
and **Flavio Giudice**
NCIA Chief Technology Office
Digital, Innovation and Technology Section
Space Technology Adoption and Resilience Team

Photo by NASA

NCIA manages six satellite ground stations and one satellite centre.

OVER THE PAST two decades, demand has surged in the space sector due to reduced launch costs, new commercial launch services and the miniaturization of satellite technology. This has provided wider commercial access to space, confirmed by increased involvement from industry and academia.

Commercial capabilities have gained significance in terms of innovation pace and service availability. The ability to integrate these technologies into the military architecture faster than adversaries is a way for NATO to maintain its strategic advantage in this domain. The NATO Communications and Information Agency (NCIA) supports NATO by identifying and integrating these technologies. With more than half of active satellites orbiting the Earth belonging to NATO Allies or companies based in Allied territory, NATO countries increasingly rely on space in several key NATO functional areas.

Space is critical, for example, to secure communications (satellite communications), navigate and track forces (positioning, navigation and timing), maintain situational awareness (intelligence, surveillance and reconnaissance and space situational awareness), forecast the weather (meteorology and oceanography) and detect missile launches (shared early warning).

New technologies offer new opportunities but also new risks. NATO must be aware of and understand these risks and vulnerabilities to maintain reliable access to space data, services and products critical to the success of its operations, missions and activities. As these capabilities evolve, NATO also adapts the ways in which it utilizes space.

1 Satellite Communications (SATCOM)

As the demand in satellite services increases, traditional SATCOM radio frequency bands are experiencing bottlenecks, especially in lower-frequency bands. Optical (or laser) communication systems enable the relay of larger volumes of data, over greater distances and at a much faster rate than radio frequency systems. This communication interconnects satellites, generating inter-satellite links, and connects them with ground stations, aircraft, ships and vehicles. Laser SATCOM is more secure and more robust than radio SATCOM as laser beams are harder to intercept and jam.

Another innovation in SATCOM is the development of constellations of smaller low Earth orbit (LEO) satellites, moving away from traditional large geostationary orbit (GEO) satellites. As satellites in LEO are closer to the Earth, LEO SATCOM experience lower latency, enabling faster transmissions of data. Moreover, GEO satellites orbit the Earth above the equator and, due to geometrical constraints, cannot offer coverage over the poles. This can be supplemented by large constellations of satellites in highly inclined LEO, capable of offering global coverage, including over previously underserved regions. The under-coverage of the poles is also being addressed by missions flying on highly inclined and highly elliptical orbits (HEOs). These offer excellent coverage of the poles and the surrounding area. A constellation with even a few of these satellites can offer seamless services.

"Reliable access to space data, services and products is critical to NATO."

NCIA operates the SATCOM capabilities and infrastructure necessary for the connectivity of NATO forces. The Agency manages six satellite ground stations and one satellite centre. Four ground stations were upgraded recently to improve satellite anchoring capabilities, nearly doubling the previous SATCOM ground coverage. In early 2025, Luxembourg and Spain joined four already participating Allies in the NCIA-led multinational SATCOM consortium, NATO SATCOM Services 6th Generation (NSS6G), which supplies military SATCOM services to NATO. The NSS6G project started in 2020 between NCIA, France, Italy, the United Kingdom and the United States. Through NSS6G, Allies provide NATO with a greater, more resilient and more flexible space capability to conduct its operations and exercises. The addition of capabilities from Luxembourg and Spain expands these services, increasing the overall resilience and availability of SATCOM to NATO.

Above from left
The NCIA operates six satellite ground stations and one satellite centre. Pictured here are the ground stations SGS-S01 in Kester, Belgium, and SGS-S02 in Lughezzano, Italy. Photos by NCIA

2 Positioning, Navigation and Timing (PNT)

With respect to PNT, the ability to exploit simultaneously different global navigation satellite systems (GNSS) can guarantee high signal accuracy and availability. The accuracy of PNT services relies on the number of satellites in view of the receiver. With every addition to a GNSS constellation, the precision, availability and robustness of the PNT service is improved. GNSS satellites are being modernized to increase signal integrity and reliability in contested environments characterized by signal jamming and denial. Modernization efforts include deploying satellites with enhanced cybersecurity and encryption features to expand current GNSS constellations, making them more resistant to jamming and spoofing.

In line with efforts to mitigate jamming effects, NCIA has developed a software tool to understand the impact on operations. This Radar Electromagnetic and Communication Coverage Tool (REACT) can estimate the area where an interfering signal would degrade or deny GNSS. REACT is employed in the exercise environment to provide estimation of GNSS jammers' impact for operational planning purposes.

To achieve better coverage with fewer satellites, GNSS constellations are typically in medium Earth orbits (MEO). Another augmentation layer for enhanced GNSS coverage under consideration is the addition of LEO satellite constellations. As LEO satellites are closer to the Earth than GEO, GNSS signals received on the ground from LEO would be stronger and less prone to jamming. In the context of operations, a more robust network of multi-orbital satellites would provide greater GNSS accuracy, enabling the employment of less destructive, more precise targeting. Stronger signals would also provide better support to urban operations.

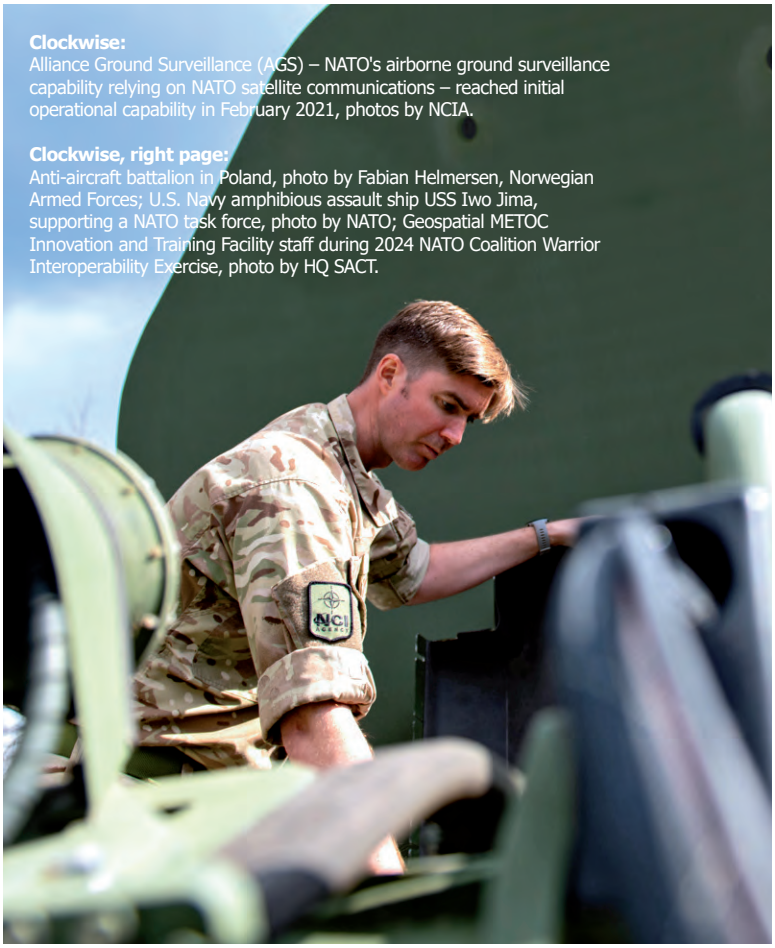
In urban environments positioning accuracy is degraded by the obstruction of the direct line of sight between GNSS satellites and receivers caused by buildings. In this context receivers rely on weaker and delayed reflected signals, leading to decreased PNT services accuracy. To provide services to the High North, a region characterized by GNSS signal degradation, new HEO constellations are better suited for the coverage of polar regions.

3 Intelligence, Surveillance and Reconnaissance (ISR)

New ISR constellations are also populating the orbits, especially LEO satellites. As the number of Earth observation satellites grows, the revisit time decreases, turning persistent and quasi-real time high-resolution global monitoring into a reality. The high-resolution aspect is important for these applications. Continuous monitoring can already be achieved with GEO satellites, but given their altitude, the resolution of the systems, while allowing environmental monitoring, cannot provide below-the-metre applications such as target recognition. With technological advancements, LEO satellites are being equipped with very high-resolution sensors, providing a better solution.

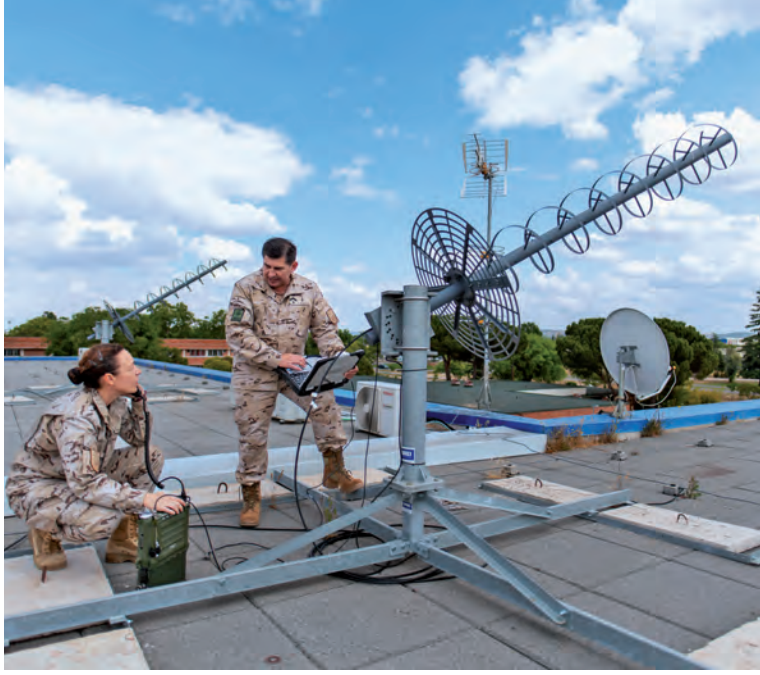
The resolution of commercially available space imagery has enhanced to below half a metre, for both electro-optical (EO) and synthetic-aperture radar (SAR) systems, enabling to capture finer details on the Earth's surface from distances of hundreds of kilometres.

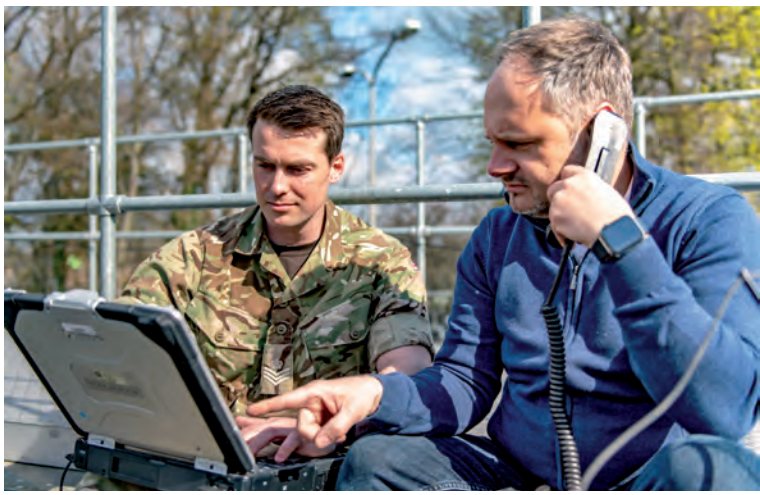
Beyond EO and SAR, infrared (IR) sensors collect valuable information that helps measure surface and water temperatures. Recently launched commercial multispectral (MS) and hyperspectral (HS) satellite missions



Clockwise:
Alliance Ground Surveillance (AGS) – NATO's airborne ground surveillance capability relying on NATO satellite communications – reached initial operational capability in February 2021, photos by NCIA.

Clockwise, right page:
Anti-aircraft battalion in Poland, photo by Fabian Helmersen, Norwegian Armed Forces; U.S. Navy amphibious assault ship USS Iwo Jima, supporting a NATO task force, photo by NATO; Geospatial METOC Innovation and Training Facility staff during 2024 NATO Coalition Warrior Interoperability Exercise, photo by HQ SACT.





collect data that enable the identification of material compositions. Applications include large-scale environmental mapping of, for example, soil composition, vegetation biodiversity, and water and air quality.

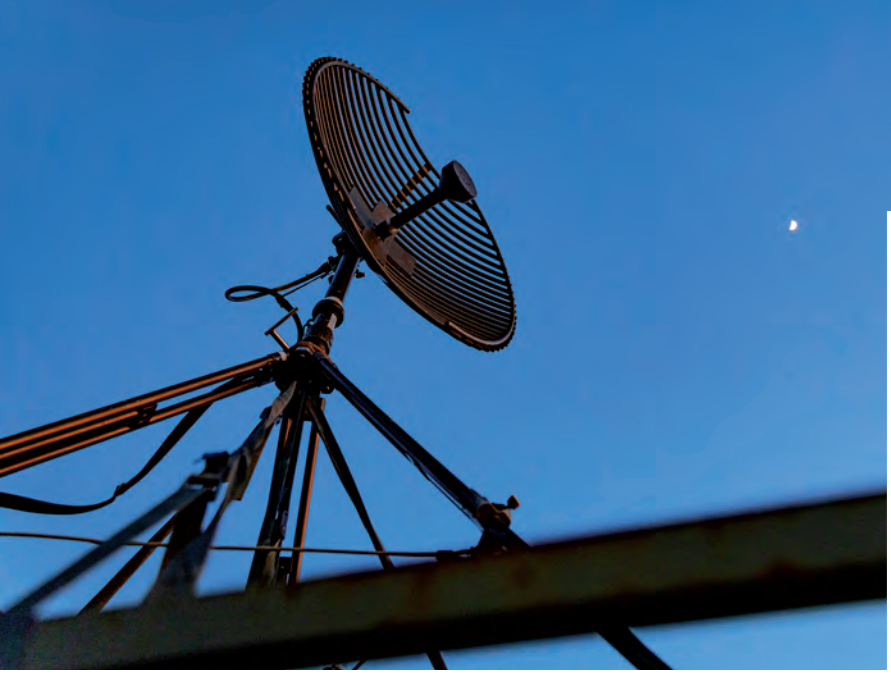
Commercial systems able to collect electromagnetic (EM) signatures emitted by devices such as radars and satellite telephones are also supporting the understanding of activities at sea and over land. In the maritime domain, automatic identification system (AIS) messages, which are mandatorily transmitted by ships of certain classes for identification and positioning, have long been collected from space to assess vessel activity. When vessels go "dark," either by turning off or manipulating their AIS transponders, SAR and EO satellite imagery can help track them.

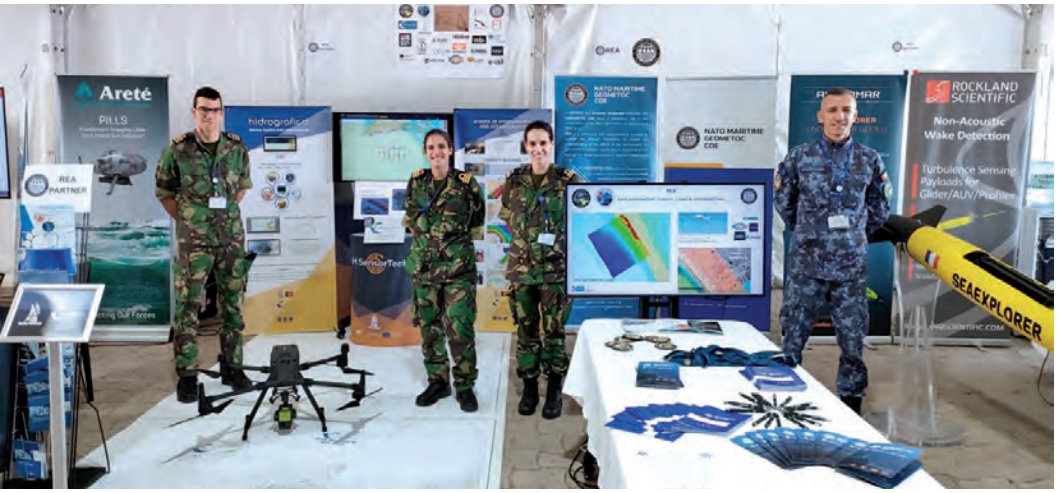
In recent years tracking of these vessels has benefitted from radio frequency (RF) data collected from space. Different providers can collect EM signatures in different bands, geolocating different types of equipment that can lead to finding vessels (e.g. maritime navigation radars). Industry is also working on profiling particular types of equipment from collected RF signatures to recognize them in different instances, and also when no other information (e.g. ship detections from imagery) is available.

To transform the way NATO gathers and uses data from space, NCIA has set up a multinational programme, the Alliance Persistent Surveillance from Space (APSS). This initiative establishes a virtual constellation of national and commercial space assets, such as satellites, leveraging the latest advances in commercial space technology. Seventeen Allies are currently part of the initiative, which will enhance NATO's space-based capabilities for operational support, intelligence sharing and situational awareness.

The growing number of satellites and their greater information collection capabilities generate large amounts of data collection. The data generated by modern satellite instruments can exceed the limit of what can be transmitted to the ground. Refinements in artificial intelligence (AI) algorithms and reductions in mass and size of the required AI hardware could provide a solution when integrated into satellites, an effort that is ongoing. Furthermore, AI-powered techniques could facilitate satellites to autonomously process imagery in-orbit, discard unusable imagery (e.g. cloud-covered EO imagery) and transmit only exploitable imagery.

In the past, the lack of satellites and the slow data collection and processing times could not fulfil ISR demands. Nowadays, the volume of data available to imagery analysts for ISR exploitation is greater than the processing capacity. AI-based techniques, such as automatic target detection and classification and change detection, will be leveraged further to support with prioritization and data exploitation, reducing the workload of analysts and operators.





Within the APSS programme, NCIA is assessing the technical exploitation of advanced analytics required by the NATO Command Structure and identifying technologies to provide imagery analysts with assisting tools. NCIA is exploring the potential for industry to provide advanced analytics, primarily on EO commercial satellite imagery. NCIA will select, procure and test technologies alongside NATO imagery analysts to understand which can best support the processing of vast amounts of imagery.

4 Space Situational Awareness (SSA)

As the number of satellites and our dependence on space-based technologies grow, so do the threats posed by an overcrowded environment. Both natural and human-made space debris threaten space operations, particularly in LEO orbits. SSA helps track, monitor and mitigate risks by predicting conjunctions between objects to enable collision avoidance manoeuvres. Currently, some objects remain untraceable due to small dimensions, but they could be tracked with the development of more sensitive instruments. Efforts in enhancing SSA consist of enlarging the ground network of radars and telescopes, increasing their interconnectedness and improving the ability to catalogue space objects with the aid of AI. Satellites capable of non-Earth imaging (NEI), capturing images of other space objects, can also assist in detecting and cataloguing. Recognizing and attributing actions in space could discourage malicious actors from compromising space assets, for example through close-proximity operations. More commercial entities are tracking the skies, leveraging technology including AI and detection of RF signals transmitted by satellites, collecting more information for faster, more precise and independent activity monitoring and attribution.

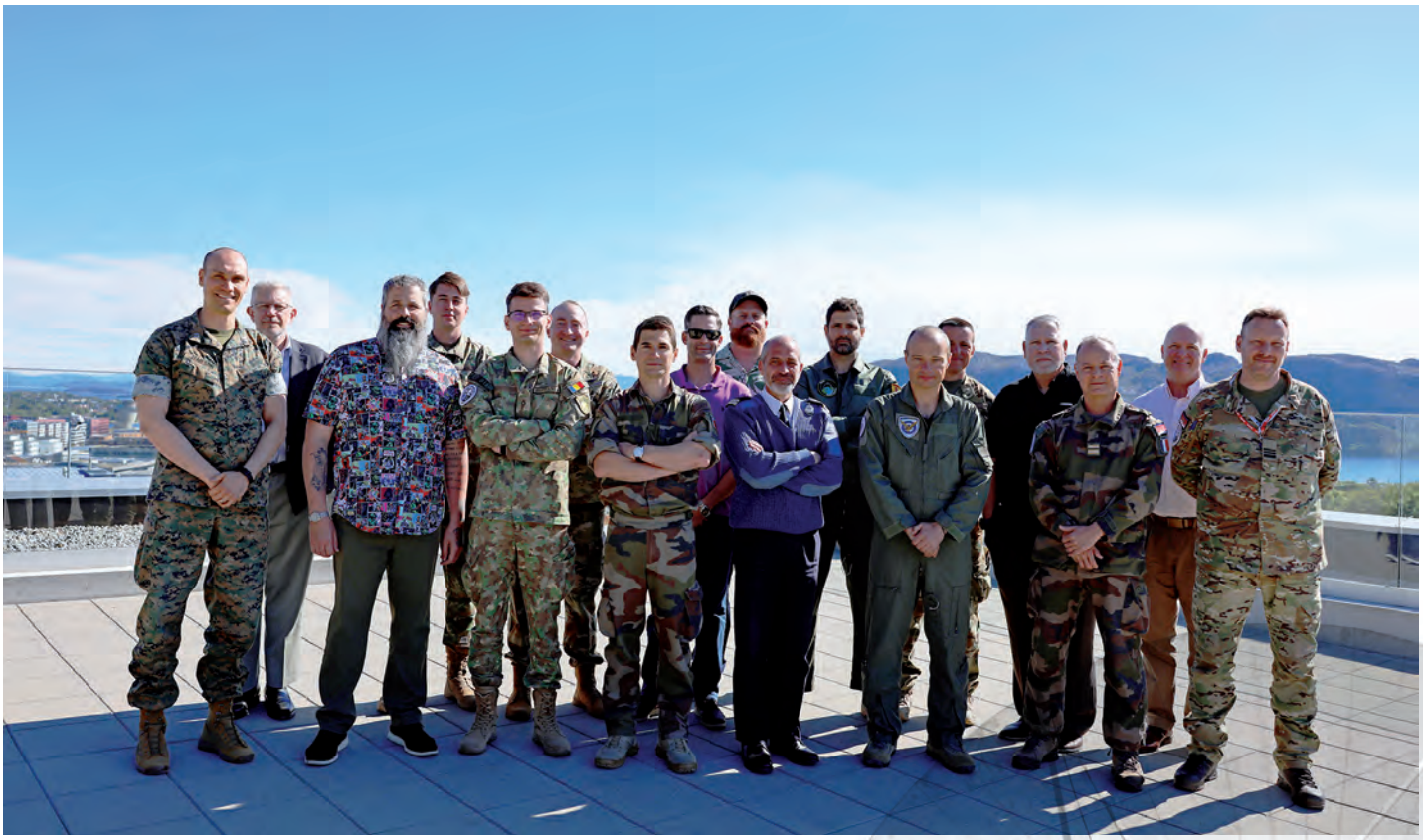
5 Meteorology and Oceanography (METOC)

Science missions are building understanding of meteorological phenomena, for example by analysing cloud compositions, measuring wind speeds and studying atmospheric dynamics. Imagers onboard new METOC satellites have increased imagery resolution, enabling finer and more accurate meteorological assessments. New missions include launching satellites in polar LEO to decrease current revisit times to provide short-range weather forecasting across the globe and increased coverage over the polar regions.

METOC products are fundamental for the planning, execution and support of military operations on land and at sea by strengthening understanding of, for example, soil conditions and wave height. Climate change is increasing the need to predict extreme weather events and understand more complex phenomena. More precise forecasting and finer detail information from current and upcoming METOC satellites can optimize logistics, equipment and targeting to ensure the effectiveness of military operations in more complex and demanding environmental conditions.

In September 2023, the NATO Communications and Information Academy inaugurated its Geospatial METOC Innovation and Training Facility in Oeiras, Portugal, to support agile innovation and training across the full spectrum of future environmental services required by NATO.

This new facility is the first of its kind and allows the geospatial, meteorological and



Above
The Space Response Cell during NATO Exercise STEADFAST DETERRENCE 2025 at the Joint Warfare Centre (JWC). Photo by JWC PAO

oceanographic communities of interest to work collectively on joint environmental information challenges. It enables the advancement of the NATO recognized environmental picture, thus providing military operations with relevant information of the impact of their physical environment.

6 Shared Early Warning (SEW)

SEW is a capability that involves the use of space-based assets, such as satellites able to detect infrared signatures, to detect missile launches and provide early warnings to Allies and military units. Upgrades for the current SEW system include expanding the network of ground stations and the existing constellation, which includes satellites in GEO and HEO. New constellations from other Allies are also under development. These advancements will contribute to increased situational threat awareness against ballistic and hypersonic threats.

NCIA delivers the SEW tool, which is crucial to the Alliance for the dissemination of information to protect NATO populations, territories and forces against a ballistic missile threat or attack.

Conclusion

In today's global security environment, the Alliance's use of sophisticated capabilities in space is a cornerstone of deterrence and defence. Through collaboration with Allies, partners and international organizations, combined with innovation and integration of commercial capabilities, NATO continues to hone its strategic edge in this vital domain, which will only continue to become more important in the future. ✧