BULLETIN
OF "CAROL I" NATIONAL DEFENCE UNIVERSITY

https://buletinul.unap.ro/index.php/en/

GEOMETOC Assessment of the Littoral Environment Using Maritime Unmanned Systems

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Abstract

In naval operations, a detailed understanding of the operational environment is essential for mission success. At present, environmental assessments within the geospatial, meteorological, and oceanographic (GEOMETOC) domains are significantly improved through the employment of maritime unmanned systems (MUS). These systems are advancing rapidly, delivering information faster while maintaining, or even improving the data quality. However, effective use of these technologies requires not only proficiency in their operation, but also a comprehensive understanding of the characteristic limitations of these systems. This article examines the main systems employed for environmental surveys and outlines the advantages and constraints associated with these platforms and their sensors.

This study is derived from observations regarding the utilisation of MUS during a series of experimental activities conducted within the framework of the operational experimentation exercise known as the Robotic Experimentation and Prototyping using Maritime Unmanned Systems (REPMUS) series, covering the period from 2021 to 2025. This exercise, recognised as the largest multinational experimentation initiative, is organised by the Portuguese Navy in collaboration with NATO Center for Marine research and Experimentation (CMRE), Faculty of Porto (FEUP), and European Defence Agency.

Keywords:

Geospatial; Meteorology; Oceanography; Hydrography; Maritime Unmanned Systems; Environmental Assessment; Naval Operations.

Article info
Received: 5 November 2025; Revised: 27 November 2025; Accepted: 3 December 2025; Available online: 15 January 2026

Citation: Constantinoiu, L.F., L. Dumitrache, and E. Rusu 2025. „GEOMETOC Assessment of the Littoral Environment Using Maritime Unmanned Systems." 2025. "Security Communities. Theoretical Perspectives." *Bulletin of "Carol I" National Defence University*, 14(4): 154-168. https://doi.org/10.53477/2284-9378-25-64

1. Introduction

Armed forces conduct operations across multiple environments and geographical regions, relying on an in-depth understanding of both current and forecasted physical conditions to enhance the effectiveness of sensors, weapons and multi-domain operations (Zakiev and Kozhakhmetov 2020).

Serving as a vital element in the decision-making process, GEOMETOC information (data, products, and services) provide commanders and planning staffs with critical situational awareness of the physical environment, enabling them to anticipate and exploit optimal windows for the planning, execution, and sustainment of operations and missions. Furthermore, accurate, timely, relevant, consistent, and reliable GEOMETOC support is essential to achieving decision superiority, ensuring the optimal employment of military capabilities in pursuit of safe, effective, and successful operations (NATO 2018).

Moreover, the ability to maintain an advantage in rapid decision-making is increasingly dependent on the availability of accurate, detailed, and timely environmental information. A foundational element of any operational picture, regardless of the military operation or Allied mission, is the comprehensive understanding of the environmental information of the Theater of Operations (TO), delivered in the correct format at the appropriate time.

GEOMETOC information encompasses geospatial, meteorological, hydrographic and oceanographic data, products, and services, which are vital for anticipating or identifying optimal windows of opportunity for planning, executing, and sustaining operations. This information also plays a critical role in optimizing the deployment of sensors, weapons, logistics, equipment, and personnel in a manner that maximizes efficiency, safety, and mission success. Both current and forecasted GEOMETOC information significantly contribute to the creation of an enhanced Common Operational Picture (COP) and provide real-time situational awareness. This is essential for improving decision-making processes for commanders, as well as for enabling planners and operators to effectively exploit, plan, and execute military operations or tasks.

These operational environments have compelled NATO and nations to enhance its capabilities, including in non-permissive theaters, and to develop new capabilities to complement conventional military assets, such as the employment of unmanned systems.

From a military perspective, the main objective for assessing GEOMETOC parameters is to gain tactical advantage over an adversary by exploiting environmental and ocean conditions. To do so, it is important to have detailed knowledge of what these conditions are and how they are likely to vary in space and time. It is also essential to know how such conditions are likely to affect sensors and weapons, and those likely to be used by the adversary.

Evaluating and leveraging the effects of GEOMETOC conditions on both friendly and adversary military capabilities across all operational domains—including air, land, maritime, space, cyberspace, and the electromagnetic spectrum—enables military forces to secure and sustain informational superiority over the enemy. This asymmetric advantage provided by METOC should be systematically integrated and utilized across all joint operational functions (Joint Staff 2024).

Rapid Environmental Assessment (REA) delivers environmental information to forces operating in littoral waters within tactically relevant timeframes. REA data collection can be performed using a diverse array of platforms and sensors, including those not specifically designed for REA, such as magnetometers and thermal infrared cameras. This process can range from a basic hydrographic sweep using a dinghy, to the deployment of advanced drones equipped with innovative sensors that simultaneously gather environmental and monitoring information.

Unmanned systems have become very popular in environmental surveys, both in military and civilian applications, due to their ability to be used in various fields of activity, such as: data acquisition operations in remote areas, transporting objects in critical zones, search and rescue, video recording and aerial photography, journalism, scientific research, agriculture and crops monitoring, national parks and wildlife surveillance, hydrography, oceanography, topography, critical underwater infrastructure monitoring (Tănase(Măxineanu) and Scipanov 2025, 36-39), border control, industry and construction for monitoring aqueducts and dams, or for inspecting high-voltage power lines, among others.

Environmental monitoring has become a key function of MUS, enabling routine and continuous coverage in a cost-effective and real-time manner. Therefore, the practical steps for employing MUS in environmental monitoring, encompassing technical considerations, scientific foundations, and valuable recommendations, are of critical importance.

This research is based upon experimental results from the annual Portuguese multinational REPMUS exercise, which facilitates collaboration among operational communities, academia, and industry to advance and assess innovative concepts, interoperability, and technological developments in maritime unmanned systems. The REA Working Group, one of the main groups in the organization of the REPMUS exercise, has been under the leadership of the NATO Maritime Geometoc Centre of Excellence for the past five years. This experimentation has been exercised in close collaboration with international industry, and Portuguese Academia with the objective to assess the use of MUS for environmental monitoring within a military operational scenario.

2. Challenges of traditional REA survey missions

Traditional methods of conducting Rapid Environmental Assessment surveys rely on manned assets such as submarines, vessels, aircraft, and helicopters, as well as the deployment of personnel within the operational theatre. Special forces continue to be assigned reconnaissance missions in challenging or contested areas. However, the conventional approach to REA involves a significant logistic and financial burden, in addition to exposing personnel to risks in conflict zones (Leder and Leder 2018). Furthermore, conventional vessels present high hydrodynamic resistance, which limits their range and autonomy, and generate elevated noise levels that can significantly interfere with onboard monitoring equipment (Zaghi, et.al. 2016).

Regarding the utilisation of legacy aerial platforms for environmental surveys, this approach has become significantly more costly compared to drone-based surveys and is increasingly falling out of use, except in cases involving large areas or regions with adverse weather conditions where aerial drones are unable to operate.

3. Advancements in Maritime Unmanned Systems for Environmental survey

MUS have increasingly become integral to modern conflicts, demonstrating significant potential across a wide spectrum of operational functions. The development of autonomous capabilities represents a natural progression of innovation, with NATO, its partners, and civilian society collaborating to integrate these systems into military operations. As a result, the technologies and operational concepts surrounding the employment of MUS in support of Alliance operations continue to present challenges, through which NATO is enhancing combat systems and platforms, increasing operational effectiveness, while simultaneously reducing human risks in theater and associated costs.

The utilisation of MUS for environmental surveys has experienced a significant increase in recent years. This growth is attributable to their numerous advantages, including high accuracy, cost-effectiveness, ease of operation, adaptability to various sensors, seamless integration with different software tools, and the facilitation of data processing through Artificial Intelligence (AI) and Machine Learning (ML) techniques (Slingsby, et.al. 2023).

The methodology used for assessing the unmanned systems relied upon multiple criteria, concerning the characteristics of the platform itself, the sensors utilised and the data gathered by these systems. Regarding the assessment of the platform, the assessment was directed upon factors such as endurance, autonomy, stability, precision and accuracy of the positioning system, payload capacity, ease of use and the time required for minimal operator training. Concerning the sensors, the evaluation focused on the quality of the data collected, accuracy and precision, speed of data collection and processing, capability for real time processing, the format of the delivered data, and the assessment of the final products. The systems were evaluated under various scenarios according to their capabilities—including shallow and deep waters, long-endurance surveys vs. short and rapid surveys—and the resulting products were compared with data obtained from traditional, manned assets. Furthermore, to evaluate the interoperability of the MUS, the various platforms were assigned to conduct surveys within the same operational scenario. This approach enabled the systems to complement one another and facilitated the creation of a comprehensive environmental picture, utilising data collected from different platforms and sensors.

MUS can be categorised in 3 main categories for naval missions, based on the operating environment: underwater, surface and aerial. Underwater MUS can be generally split into 3 categories: Remotely Operated Vehicles (ROVs), Autonomous Underwater Vehicles (AUVs) and gliders. Regarding the surface vehicles, they are generally called Unmanned Surface Vehicles (USVs), and the aerial ones Unmanned Aerial Vehicles (UAV – referring to the platform only) or Unmanned Aerial Systems (UAS – referring to the system composed of platform and sensors).

3.1. Underwater MUS

Underwater conditions significantly influence the anti-submarine warfare (ASW) battlefield, where the functionality of most weapons and sensors depends on sound propagation. A thorough understanding of oceanographic parameters within the underwater domain is crucial to the support provided by a REA survey. However, there is an increasing need for a deeper comprehension of oceanographic factors, as military operations involving advanced platforms, weapons, and sensors are progressively impacted by environmental conditions in ways that were not previously foreseen.

Over the past several years, the autonomous underwater vehicles have been regarded as the preferred tool for specific underwater applications. However, with increasing acceptance, the use of AUVs has now become a well-established solution within the subsea survey community (Tena 2013).

AUVs have become indispensable tools for inspecting offshore structures, owing to their capacity to carry extensive equipment while maintaining relatively low operational costs (Palomer, Ridao and Romagos 2019).

During the operation of Unmanned Underwater Vehicles (UUVs), the positioning system serves as a critical component, ensuring both operational efficiency and safety. Recently, with the growing emphasis on enhancing UUV automation and optimizing operational efficiency, positioning systems are required to deliver higher levels of accuracy, with an expected error margin of less than 0.1 meters (Yang, Zhizun and Jia 2022).

There are a multitude of typical sensors that underwater vehicles hold for seabed survey or environmental survey, like:

- multibeam echosounders (typically used to provide bathymetric information of the seafloor and object detection);
- sidescan sonars and synthetic aperture sonars (used to provide a high-fidelity image of the seafloor, primarily used in object detection, such as Unexploded Ordnance and geology) (Frey, Wehner and Keller 2021);
- magnetometers (used to detect anomalies in the magnetic field of the seabed, meaning ferrous object detection on or below the seabed);
- photographic, stereographic and video cameras for identification of objects and possible sea mines;
- oceanographic sensors such as conductivity, temperature, depth (CTD) and sound velocity probes.

Nevertheless, underwater systems continue to face limitations regarding their ability to accurately determine their position while submerged, as they primarily rely on inertial navigation (Miller, Miller and Miller 2021).

Although contemporary solutions exist for underwater positioning using underwater buoys or relay systems, these platforms must still surface to obtain precise coordinates via their Global Navigation Satellite System (GNSS) receivers. This requirement increases their visibility and vulnerability during covert operations.

Currently, underwater gliders are routinely deployed by several nations primarily for scientific or governmental activities related to the study of marine life and the underwater environment, as well as for everyday societal activities such as fisheries monitoring and control. Navies have begun experimenting with the use of gliders equipped with hydrophones in passive mode to support ASW operations and wide-area surveillance, considering them as potential solutions and force multipliers (Constantinoiu, Quaresma and Rusu 2022). These systems are generally regarded as capable of reliable performance over extended periods, sometimes achieving continuous operation for two to three months, thereby providing a dependable solution to existing operational challenges with the integration of passive sensors and associated equipment.

a b

Figure 1 Underwater gliders used in REPMUS exercise series
Sources: a: https://www.jasco.com/news/2024/repmus-24,
b: https://www.alseamar-alcen.com

Glider launch and recovery can be conducted by small Rigid Hull Inflatable Boats (RHIBs) organic to surface units. Tests have also been conducted for air launch and sur-face recovery. These systems can be equipped with hemi-directional or omnidirectional hydrophones. Typically, the array of a glider consists of four hydrophones (placed at the front, wings, and tail of the glider) at small distances. This array configuration results in greater sensitivity and increased directionality of detections (Marine 2025).

While the routine employment of gliders in ASW operations is not yet established, Nations and research institutes continue to evaluate their potential, and industry is developing new technical capabilities. Advancements in autonomy, energy efficiency, data storage, computing capacity, and the miniaturization of sensors and systems are expected to impact the functionality of gliders. These platforms could potentially support existing manned platforms or conduct surveillance missions independently.

Nonetheless, gliders demonstrate certain operational constraints that must be thoroughly understood to enable effective mission planning. The operating speed of gliders does not exceed 1-1.5 knots. Some models are equipped with a small electric motor to increase speed up to 3 knots for short periods. Consequently, gliders may not operate effectively in areas with strong currents, and a glider barrier would function more as a semi-static passive barrier than a moving one. The estimated endurance of gliders can reach two to three months of continuous operation, with reduced endurance when additional speed is required.

The information obtained from the gliders and underwater unmanned systems was compared with data sourced from fixed oceanographic buoys within the exercise area, as well as with data collected by survey ships operating in the same region. The results were noteworthy, as the data provided by the gliders demonstrated equivalent accuracy and precision to that of traditional systems.

3.2. Surface maritime unmanned systems for REA

In the maritime battlespace, the ocean surface serves as the interface between the underwater and above-water domains. This boundary is utilized by various manned and unmanned systems to remotely monitor and observe the respective domains.
The utilisation of USVs for environmental surveys has significantly advanced in recent years, due to their numerous advantages. USVs have emerged as the preferred method for conducting surveys in lakes, ports, and enclosed waters due to their compact size, capability to integrate sensors equivalent to those used on manned vessels, and superior navigational accuracy, which ensures the collection of precise and reliable data.

Furthermore, several surface unmanned systems are now available that can autonomously deploy and recover underwater unmanned systems, enabling the execution of diverse missions such as Anti-Submarine Warfare (ASW), Mine

TABLE no. 1. Typical underwater MUS for REA

Model	Sensors	REA Products	Common applications
ROV	Optical camera	Images	Port assessment Objects identification Wreck surveys
	Oceanographic sensors (CTD, etc.)	Oceanographic Information of the water column	Environmental monitoring Water column information Antisubmarine Warfare forecasts
	Bathymetric sonar	Digital model of the seabed Objects on the seafloor or in the water column	Environmental monitoring Digital charting of the seabed
	Magnetic sensors	Chart of Magnetic anomalies	Wrecks and metallic objects detection
AUV	Sidescan sonar/ synthetic aperture sonar	Image of the seafloor	Object detection Seafloor
	Oceanographic sensors (CTD, ADCP, fluorescence, etc.)	Sound velocity measurements, Underwater currents, biological information	Characterization of the water column Environmental monitoring
	Bathymetric sonar	Digital model of the seabed Objects on the seafloor or in the water column	Environmental monitoring Digital charting of the seabed
	Optical camera	Optical Images	Port assessment Underwater objects identification Wreck surveys
	Hydrophones	Underwater noise maps Underwater sound detections	ASW Mammal monitoring Environmental survey
Glider	Hydrophones	Underwater noise maps Underwater sound detections	ASW Mammal monitoring Environmental survey
	Oceanographic sensors (CTD, ADCP, fluorescence, dissolved oxygen, etc.)	Sound velocity measurements, Underwater currents, biological information	Characterization of the water column, Environmental monitoring

Countermeasures (MCM), and environmental monitoring. A key advantage of USVs is their ability to operate in shallow waters and confined areas where conventional vessels are unable to move, reducing the risk to personnel.

The main scenarios for the utilisation of USVs included conducting hydrographic surveys in both shallow and deep waters, evaluating the autonomy and endurance of the systems, as well as assessing the accuracy and precision of the data collected. The data obtained from the unmanned surveys was compared with reference data from the Portuguese Hydrographic Office, collected prior to the exercise. The results were predominantly positive, attributable to the state-of-the-art sensors installed on the unmanned platforms. However, in some smaller USVs, data corruption occurred, mainly in offshore areas affected by swell and waves, due to the movement of the platform itself. Conversely, larger USVs were assigned to long-endurance surveys, the longest lasting 72 hours, with real-time data monitoring conducted from the shore.

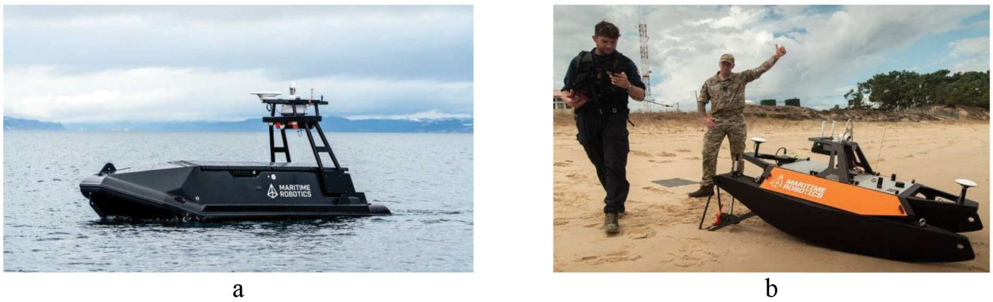
a
b

Figure 2 Unmanned surface vehicles used in REPMUS exercise series
Sources: a: https://www.maritimerobotics.com/news/maritime-robotics-showcases-sea-drone-capabilities-nato-repmus-2025,
b: https://www.joint-forces.com/exercise-news/47080-repmus-21-nato-tests-unmanned-vehicles

TABLE no. 2. Typical surface MUS for REA

Model	Sensors	REA Products	Common applications
USVs	Bathymetric sonar	Digital model of the seabed Objects on the seafloor or in the water column	Environmental monitoring Digital charting of the seabed
	Oceanographic sensors (CTD, ADCP, fluorescence, etc.)	Sound velocity measurements, Underwater currents, biological information	Characterization of the water column, Environmental monitoring
	Hydrophones -towed	Underwater noise maps Underwater sound detections	Mammal monitoring Environmental survey
	Sidescan sonar/ synthetic aperture sonar	Image of the seafloor	Object detection Seafloor - for shallow water survey

3.3. Aerial maritime unmanned systems for REA

In the maritime battlespace, the above-water domain is utilized for various observations of shallow water regions, the intertidal zone, and adjacent land areas. These tasks are primarily accomplished through remote sensing via sensors operated by Unmanned Aerial Systems (UASs). These systems are commonly employed for Intelligence, Surveillance, and Reconnaissance (ISR) missions and serve as communication relays in support of Command, Control, and Communications (C3).

In the maritime domain, the integration of UAS into naval forces offers significant advantages, enhancing the range of military capabilities across both the above-water and land domains.

UAS can be equipped with a wide array of sensors and payloads. For ISR operations, the typical payload includes high-resolution video and thermal infrared cameras, though additional sensors are being used to produce Geospatial Intelligence (GEOINT) products, such as georeferenced orthorectified images, Digital Elevation Models (DEM), bathymetric models, and seabed sediment classification maps. These systems are equipped with photogrammetric cameras, multispectral cameras, and miniaturized Light Detection and Ranging (LiDAR) systems, enabling comprehensive environmental and geospatial analysis.

Figure 3 Unmanned aerial vehicles used in REPMUS exercise series
Sources: a: https://www.navalnews.com/naval-news/2024/10/schiebel-camcopter-s-100-uas-demonstrates-multi-mission-capabilities-at-repmus-2024/,
b: https://www.joint-forces.com/exercise-news/47080-repmus-21-nato-tests-unmanned-vehicles

Unmanned Aerial Systems (UAS) share several limitations with manned aircraft, including dependence on datalinks and susceptibility to adverse atmospheric conditions such as wind, turbulence, and icing.

Additional factors such as fog, smoke, heavy precipitation, low ceilings, thermal cross-over, extreme heat, high altitude, high humidity, and sea state may also impact various UAS components.
All UAS components are, to varying degrees, affected by METOC conditions. The aircraft itself, along with its payload/sensors and data link, are particularly vulnerable, while other systems can typically be safeguarded on the ground or aboard ships.

During the REPMUS exercise series, multiple UASs were evaluated to determine their operational performance, their integration with naval vessels and units, the time required for data processing, and the extent of their year-on-year improvements.
The systems were evaluated in both bathymetric and topographic surveys. For the bathymetric assessments, the UAS equipped with advanced LiDAR sensors, were tested in different scenarios upon several parameters, including penetration depth, accuracy, and precision of the data, in comparison with traditional multibeam

sonar surveys. The results were comparable, with the notable advantage that the UAS survey required less than half the time of a conventional multibeam survey. However, some experimental LiDAR sensors exhibited misalignments, which were subsequently corrected during post-processing. For instance, in highly transparent waters such as those of the Atlantic Ocean, a topo-bathymetric LiDAR system can achieve penetration depths of up to 30 meters (Constantinoiu, et all. 2024), whereas in the Black Sea the same sensor is typically limited to approximately 7–8 meters.

TABLE no. 3. Typical aerial MUS for REA

Model	Sensors	REA Products	Common applications
UAS	Topographic camera	Digital terrain models Digital surface models	Environmental survey Topographic measurements
	LiDAR	Digital surface models Digital model of the seabed Objects on the seafloor or in the water column	Topographic and bathymetric measurements
	Optical and I/R camera	Optical and infrared Images	ISR, environmental monitoring Surface objects identification
	Hyperspectral camera	Digital terrain models Topographic models Terrain roughness	Environmental survey Topographic measurements

4. Environmental information for operational use

A substantial range of environmental products may be generated through the utilisation of maritime unmanned systems. Within the underwater domain, oceanographic information is essential for the antisubmarine community, as it enables the determination of sonar propagation conditions and facilitates the monitoring of critical underwater infrastructure.

Regarding the surface domain, bathymetric maps constitute the principal output of USVs, while in the aerial domain, the topographic characterization of the terrain is of strategic importance.

Using aerial unmanned systems, the hydrographic and topographic information can be collected much faster than the traditional methods, with the same quality of the data, and in non-permissive environments.

A significant challenge over the past five years has been achieving interoperability among the systems, particularly regarding their integration into naval Command and Control (C2) systems and the diversity of their output data formats. Important progress has been made in integrating these systems onboard naval vessels and in familiarizing military personnel with their operational use. With respect to data interoperability, the NATO Maritime Geometoc Centre of Excellence has played a leading role in promoting the adoption of standardized data formats for GEOMETOC information—such as the netCDF format, which is now utilized within NATO for environmental data exchange.

The true value emerges when a product, such as the Amphibious Operations Graphic (AOG), integrates data from all categories of maritime unmanned systems—underwater, surface, and aerial—resulting in a comprehensive resource. This complete product is employed by the Amphibious Operational Commander to plan the landing exercise, providing precise information on beach terrain, water depths, obstacles, meteorological and oceanographic conditions.

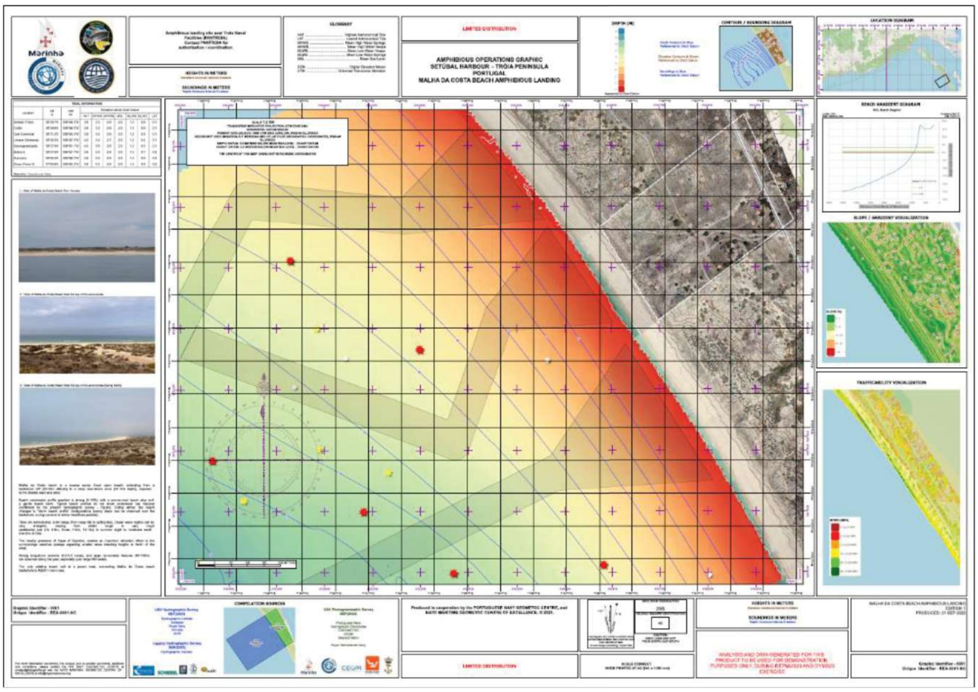

Figure 4 AOG from REPMUS 2023 exercise
Source: NATO Maritime GEOMETOC Centre of Excellence)

Conclusions

As a Naval Operation approaches the coast, the bottom topography and shallow water, waves and currents become critical to support the Commander's decisions. MUS are of great value to be employed in these areas to remotely survey littoral bathymetry and ocean currents. Wave buoys and drifters can complement the environmental assessment to support Amphibious Operations and Mine Countermeasures missions.

Emerging technology offers us the opportunity to address the challenges posed by new methods of high-resolution information. However, we cannot overlook or ignore the inherent limitations of the unmanned systems and the uncertainties in our survey data. These techniques allow us to estimate and exploit data uncertainty, creating new GEOMETOC products and services while fulfilling critical missions of maintaining navigation safety.

When employing sensors based on acoustic transmission principles (singlebeam and multibeam echosounders, sidescan and synthetic aperture sonars), it is essential to determine the approximate depth of the area and clearly define the survey objectives — whether it involves a large-area assessment or a detailed examination of a specific location. This information is critical for selecting the appropriate frequencies and configuring optimal altitude and depth settings for the vehicle to ensure the highest quality results.

Surface survey systems are commonly employed in confined environments, such as ports and coastal areas, due to their shallow draft and greater efficiency compared to manned platforms. However, they are susceptible to adverse weather conditions and communication challenges.

To support the force projection planning, from sea to shore, UAS may be used by Naval Forces to extend their environmental observation range into very shallow water and shore domains. For aerial vehicles, sensor selection is determined by the platform's capabilities — such as payload capacity, endurance, and level of autonomy — as well as by the pilot's expertise and the specifics of the flight plan.

It is crucial, during every environmental assessment operation, that the commander should rely on technical specialists to provide guidance on the appropriate sensors and platforms to meet the survey objectives.

The use of unmanned systems in naval operations is no longer a concept of the future. It is imperative to develop proficiency in employing these systems efficiently to complement traditional methods of environmental monitoring. A thorough understanding of both the advantages and limitations of this emerging technology is essential, as is its application across diverse scenarios to mitigate human risk and conduct rapid environmental assessment. Recent conflicts, such as the War in Ukraine, have demonstrated that these systems can exert a significant impact on adversaries and enable smaller armed forces to counter global powers. Looking ahead, it is crucial to integrate advanced artificial intelligence capabilities into unmanned systems to facilitate real-time operational environmental products. Nevertheless, it remains vital to preserve the human element, ensuring that final decisions regarding product assessment and courses of action rest with human operators.

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ACKNOWLEDGEMENTS

We express our gratitude to the ***NATO Maritime Geospatial, Meteorological and Oceanographic Centre of Excellence*** for the information provided.

FUNDING INFORMATION

N/A

CONFLICT OF INTEREST STATEMENT

The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available on the Internet.

DECLARATION on AI use (if applicable)

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