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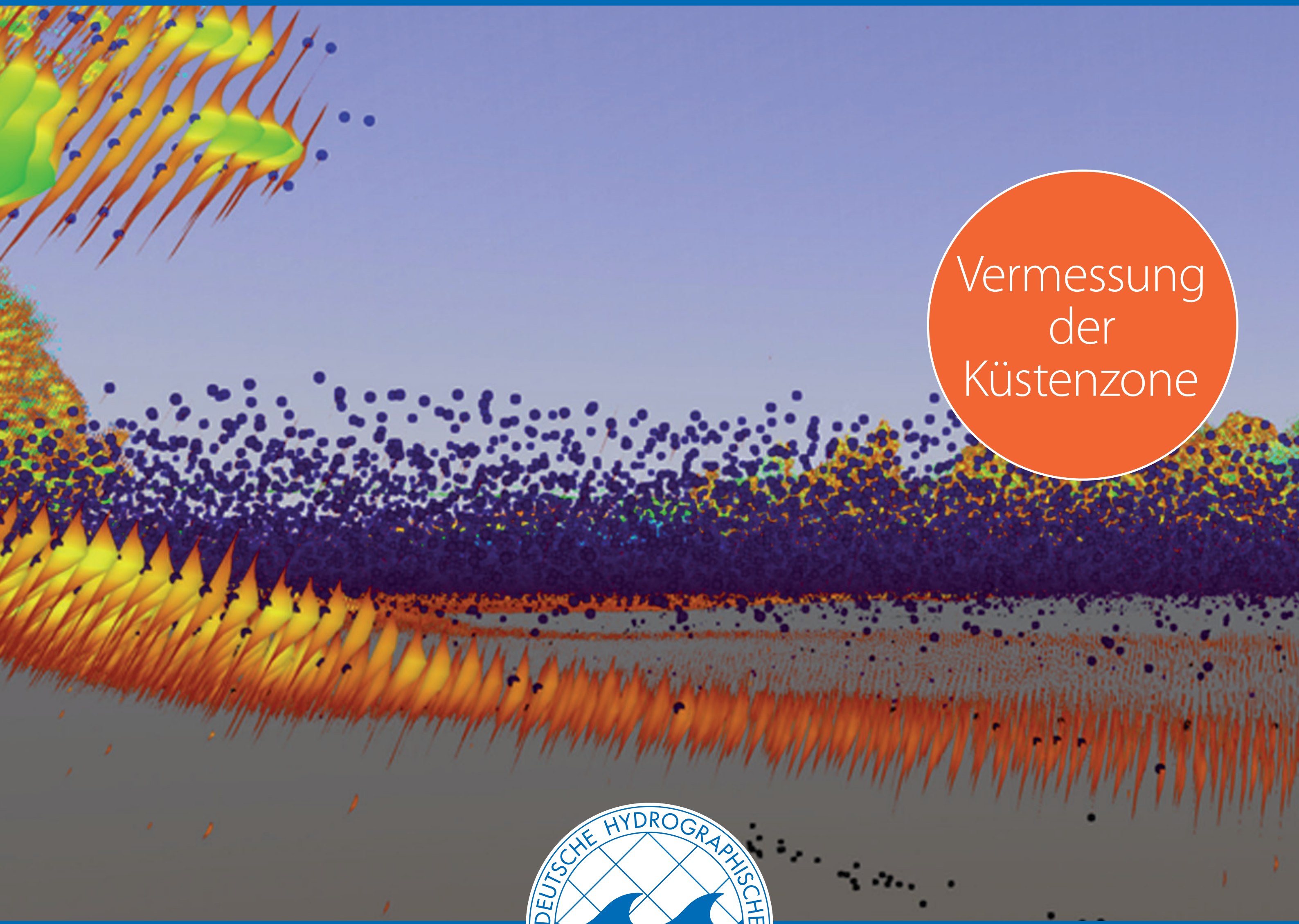

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REPMUS: A catalyst for innovation in uncrewed hydrography

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REPMUS (Robotic Experimentation and Prototyping with Maritime Unmanned Systems) is an annual multinational exercise led by the Portuguese Navy with NATO, EU, academia and industry partners. Unlike traditional military drills, it focuses on technological development, prototyping and integration of uncrewed systems across maritime, aerial and subsurface domains. REPMUS24 gathered over 2,000 participants from 30+ nations to test capabilities in realistic scenarios, such as hydrography, rapid environmental assessment (REA), amphibious surveys, glider-based oceanographic monitoring and critical underwater infrastructure protection. The exercise accelerates innovation by transitioning prototypes into operational tools, fostering interoperability and knowledge exchange.

REPMUS | maritime unmanned systems (MUS) | rapid environmental assessment (REA) | critical underwater infrastructure (CUI) protection | multi-domain operations (MDO)
REPMUS | maritime unbemannte Systeme (MUS) | schnelle Umweltbewertung (REA) | Schutz kritischer Unterwasserinfrastruktur (CUI) | Multi-Domain-Operationen (MDO)

REPMUS (Robotic Experimentation and Prototyping with Maritime Unmanned Systems) ist eine jährliche multinationale Übung unter der Leitung der portugiesischen Marine mit Partnern aus der NATO, der EU, der Wissenschaft und der Industrie. Im Gegensatz zu traditionellen Militärübungen konzentriert sie sich auf die technologische Entwicklung, das Prototyping und die Integration unbemannter Systeme in den Bereichen See, Luft sowie unter Wasser. REPMUS24 versammelte über 2000 Teilnehmer aus mehr als 30 Nationen, um Fähigkeiten in realistischen Szenarien zu testen, darunter Hydrographie, schnelle Umweltbewertung (REA), amphibische Vermessungen, ozeanografische Überwachung mit Glidern und Schutz kritischer Unterwasserinfrastruktur. Die Übung beschleunigt Innovationen, indem sie Prototypen in einsatzfähige Werkzeuge überführt und Interoperabilität und Wissensaustausch fördert.

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Introduction

REPMUS (Robotic Experimentation and Prototyping with Maritime Unmanned Systems) is an exercise series spearheaded by the Portuguese Navy and co-organised by the Faculty of Engineering of the University of Porto (FEUP), the Northern Atlantic Treaty Organization (NATO) Centre for Maritime Research and Experimentation, the NATO Joint Capability Group for Maritime Unmanned Systems and the European Defence Agency. REPMUS is designed to foster large scale experimentation with uncrewed systems, while promoting collaborative efforts among military, academia and industry stakeholders. Its ultimate goal is to develop, assess and validate state-of-the-art technology applicable to both maritime security and naval operations.

The latest edition, REPMUS24, convened a large-scale international participation, gathering over 2,000 participants, including civilian and military personnel from more than 30 nations. Contributions spanned over 130 official entities from Portugal, NATO and the European Union (EU), alongside with industry and universities.

Herein, the hydrography-related activities conducted during the exercise are addressed, with a particular emphasis on the deployment of uncrewed assets to perform environmental characterisation under an operational context.

REPMUS

Unlike traditional military exercises that focus primarily on tactical manoeuvres or combat readiness, REPMUS is centred on technological development and operational prototyping. Bringing together military forces, academia, and industry it tests and validates cutting-edge systems in realistic maritime environments.

The exercise is held annually in Portugal's Infante D. Henrique Technological Free Zone (TFZ), a vast area encompassing oceanic, estuarine and terrestrial domains. This diverse and challenging setting provides an ideal sandbox for experimentation with surface, subsurface and aerial systems, with a primary focus on security and defence applications (Fig. 1). Covering over 2,500 square kilometres, it includes the municipalities of Sesimbra and Setúbal, historic maritime hubs with enduring significance in shipping and fishing. The TFZ Infante D. Henrique is managed by the Portuguese Navy's Operational Experimentation Centre (Centro de Experimentação Operacional da Marinha – CEOM). Its facilities, including an artificial island, host a significant portion of REPMUS activities.

One of REPMUS' defining features is its multi-domain scope. While maritime unmanned systems (MUS) are the core focus, the exercise also explores their integration into broader operational contexts, including cyber defence, communications and intelligence, surveillance and reconnaissance (ISR). This holistic approach is in line with NATO's strategic emphasis on Multi-Domain Operations (MDO), where capabilities across air, sea, land, space and cyber must be synchronised to achieve mission success.

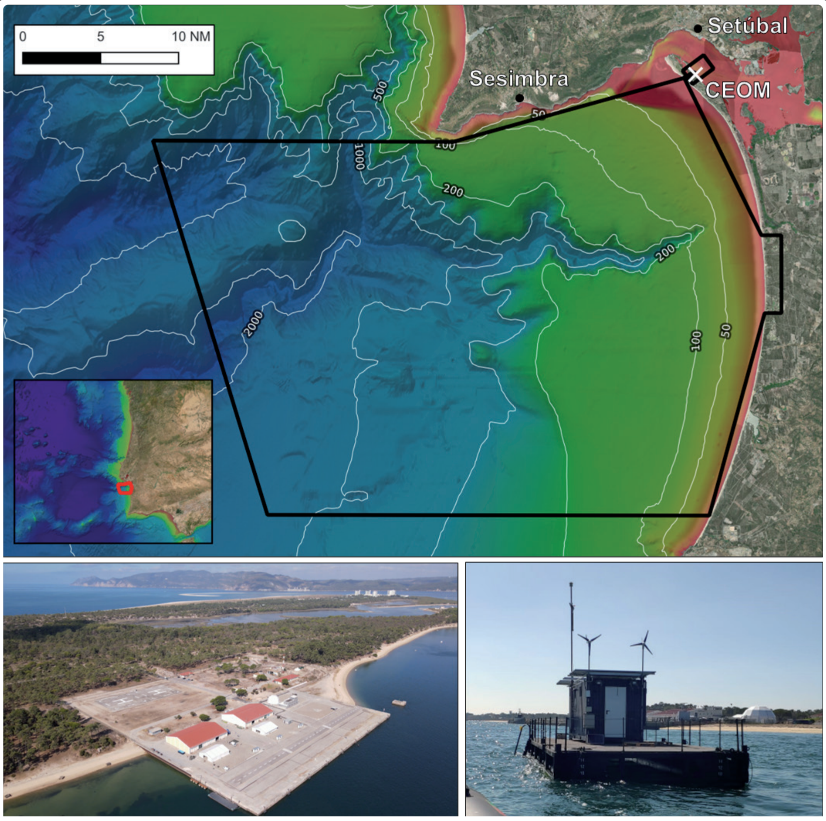
REPMUS is structured to simulate real-world operational scenarios, allowing participants to test systems under conditions that mirror those encountered in crisis response, humanitarian missions and conventional warfare. These scenarios often involve complex coordination between crewed and uncrewed platforms, data fusion from multiple sensors and rapid decision-making based on real-time information. For example, unmanned aerial vehicles (UAV) may be tasked with ISR missions, while unmanned underwater vehicles (UUV) conduct seabed mapping or mine detection, and unmanned surface vehicles (USV) perform hydrographic surveys or logistics.

A key objective of REPMUS is to accelerate the transition from concept to capability. By enabling live experimentation with prototypes and pre-commercial technologies, the exercise helps identify operational strengths, limitations and integration challenges early in the development cycle. This feedback loop is invaluable for refining system design, improving interoperability and aligning technological innovation with national and international organisation's doctrinal and strategic requirements.

Moreover, REPMUS fosters a culture of collaboration and knowledge exchange. It provides a venue for NATO, EU and partner nations to share best practices, harmonise standards and build trust through joint experimentation. The inclusion of academic institutions and private sector innovators ensures that the exercise remains at the forefront of technological advancement, while also promoting dual-use applications that benefit both defence and civilian sectors.

Participating in REPMUS

Participation in REPMUS is highly structured and requires coordination through official channels. The exercise is open to a range of stakeholders, including NATO nations and partners, industry and academic institutions, under specific conditions:



Bottom left: courtesy of the Portuguese Navy

Fig. 1: REPMUS whereabouts. Top: TFZ Infante D. Henrique. Bottom left: CEOM facilities (courtesy of the Portuguese Navy). Bottom right: CEOM's artificial island

- NATO nations and partners: Military forces from NATO nations and invited partners participate through their respective national chains of command and NATO planning teams, ensuring alignment with operational objectives and security protocols.
- Industry participation is divided into two categories:
  - Directly contracted companies – participate under formal agreements with a navy or the Ministry of Defence of a participating nation;
  - Sponsored companies – supported by a participating nation, which may demonstrate or integrate systems during the exercise.
- Academia and research institutions: typically involved through partnerships with NATO, EU or national sponsors, contributing to experimentation and knowledge exchange.

The experimentation goals of each participant are integrated into thematic Working Groups (WG). The so-called Operations WGs, which foster a considerable slice of the experimentation activities, are the following:
- Underwater Warfare (UWW),
- Above Water Warfare (AWW),
- Naval Mine Warfare (NMW),
- Maritime Safety and Security (MSS),
- Rapid Environmental Assessment (REA).

Each WG is mandated to identify the main problems and challenges within its community and to coordinate the activities to address them.

REA and the MGEOMETOC COE

The evolving nature of NATO's operational landscape – ranging from crisis response and humanitarian missions to traditional warfare – demands rapid, accurate and comprehensive environmental intelligence. REA has emerged as a critical capability to meet this demand, enabling the collection, processing and dissemination of environmental data to support decision-making and enhance operational effectiveness.

During the REPMUS24 exercise, REA was exercised as a warfare capability under the coordination of the NATO Maritime Geospatial, Meteorological, and Oceanographic Centre of Excellence (MGEOMETOC COE), headquartered in Lisbon, Portugal.

The MGEOMETOC COE played a central role in orchestrating REA activities, acting as the doctrinal and operational hub for environmental support. Its mandate includes developing and standardising NATO's geospatial and METOC capabilities. REPMUS24 provided a unique opportunity to test and refine REA procedures in a realistic, multi-domain operational scenario. The MGEOMETOC COE coordinated the integration of MUS across underwater, surface and aerial domains to collect in-situ environmental data, which was then processed and transformed into actionable products.

REA activities were conducted in the TFZ Infante D. Henrique. This region offers a diverse and complex bathymetric landscape – featuring submarine canyons, sandbanks and narrow channels – ideal for testing REA capabilities and presenting realistic challenges for environmental data collection and analysis.

The planning of REA activities followed a structured approach aligned with the four stages of the REA process: direction, data collection, processing and dissemination. The REA WG, composed of NATO member states, industry partners and academic institutions, collaboratively defined four key challenges to guide the exercise:

- Improving expeditionary shallow-water and littoral REA,
- contributing to the Seabed Warfare concept,
- optimising REA information exchange,
- conducting REA operations from the sea.

To address these challenges, specific objectives were established, including bathymetric surveys of Setúbal Harbour, topographic and bathymetric mapping of amphibious landing beaches, hydrographic and oceanographic monitoring and support for underwater contact detection. These objectives simulated real-world operational needs and tested the effectiveness of MUS in delivering timely and accurate environmental data.

The execution of REA activities involved a wide array of MUS platforms, including gliders, UUVs, USVs and UAVs, provided by multiple participants. These systems were equipped with advanced sensors such as multibeam echo sounders (MBES), side-scan sonars, Light Detection and Ranging (LiDAR) sensors, multispectral and hyperspectral cameras and physical sampling probes. The integration of these technologies enabled comprehensive data collection across all environmental domains.

A notable innovation during REPMUS23 was the deployment of a multinational REA Processing Team, composed of subject matter experts from NATO COEs, partner nations' navies, research institutions and industry. This team was responsible for processing, analysing and validating the data collected by MUS, and for generating REA products to support operational decision-making. The collaborative structure ensured interoperability and leveraged diverse expertise, significantly enhancing the quality and speed of product development.

The REA Command and Control structure was also tested and refined during the exercise. Led by the REA Commander, the structure included three support cells: underwater/surface operations, air operations and data handling. Each cell was tasked with specific responsibilities, from MUS deployment and data acquisition to processing and dissemination. This model, developed in accordance with NATO's doctrine, proved effective in manag-

Images courtesy of Schiebel, Maritime Robotics, Naval Research Lab, Instituto Hidrográfico, Xer and Yellowscan

Fig. 2: Platforms and payloads used for the topographic and bathymetric surveys conducted during REPMUS24

Platform	Payload	Designation
Maritime Robotics Mariner (USV)	Kongsberg Discovery EM2040 (MBES)	Mariner-EM2040
Schibel Camcopter S-100 (UAV)	Riegl VQ-860-G (Topo-bathy LiDAR)	S100-Riegl
Xer X8 (UAV)	Yellowscan Navigator (Topo-bathy LiDAR)	X8-Yellowscan
Naval Research Laboratory (NRL) helicopter (UAV)	Headwall HyperSpectral camera	NRL-HSI
DJI Matrice 300 RTK (UAV)	DJI Zenmuse L1 (Topo LiDAR)	M300-L1

Table 1: Platforms and payloads used for topographic and bathymetric surveys in REPMUS24

ing complex REA operations and coordinating efforts across multiple domains.

One of the key achievements of REPMUS24 was the development and demonstration of a cloud-based REA dissemination tool, created in partnership with Kongsberg Geospatial. This tool allowed exercise participants to access, visualise, and download REA products immediately after they had been created and validated by the data handling team, greatly enhancing information exchange and operational responsiveness. Although bandwidth limitations affected accessibility from certain locations, this tool marked a major advancement in REA product dissemination and is slated for further development and integration into future exercises.

Hydrography related experimentation highlights

Topo-bathymetric surveys

One of the central responsibilities of the REA WG at REPMUS is to deliver actionable environmental information to operational clients in a specific area of operations. This includes coordinating multi-platform data acquisition, ensuring its timely processing and the rapid dissemination of products tailored the mission's needs.

Since REPMUS23, the Malha da Costa beach has been designated as the primary amphibious operations area, serving as a natural laboratory for testing uncrewed systems in hydrographic applications. Its comprehensive survey requires both bathymetric and topographic data to produce a continuous model of the area. To achieve this, several uncrewed surface and aerial systems, equipped with MBES, LiDAR and hyperspectral optical payloads were deployed, as listed in Table 1 and illustrated in Fig. 2.

In the context of REA, timeliness outweighs formal accuracy, resulting in products not being expected to comply with hydrographic or cartographic standards (e.g. International Hydrography Organization (IHO) S-44). Nonetheless, assessing data quality remains crucial to understand how processes can be improved. To this end, prior to the start of REPMUS, a traditional crewed vessel equipped with a 1° × 1° Kongsberg Discovery (KD) EM2040C MBES and Real-Time Kinematic (RTK) positioning, partially surveyed Malha da Costa. This dataset outputted a reference bathymetric model, fully compliant with IHO S-44 Special Order standard, which served as a benchmark for the following uncrewed surveys. The survey coverage of each platform-payload pair is illustrated in Fig. 3. These were more often constrained by logistical and scheduling issues than actual technological limitations of either the platform or the payload.

From an operational perspective, UAVs fitted

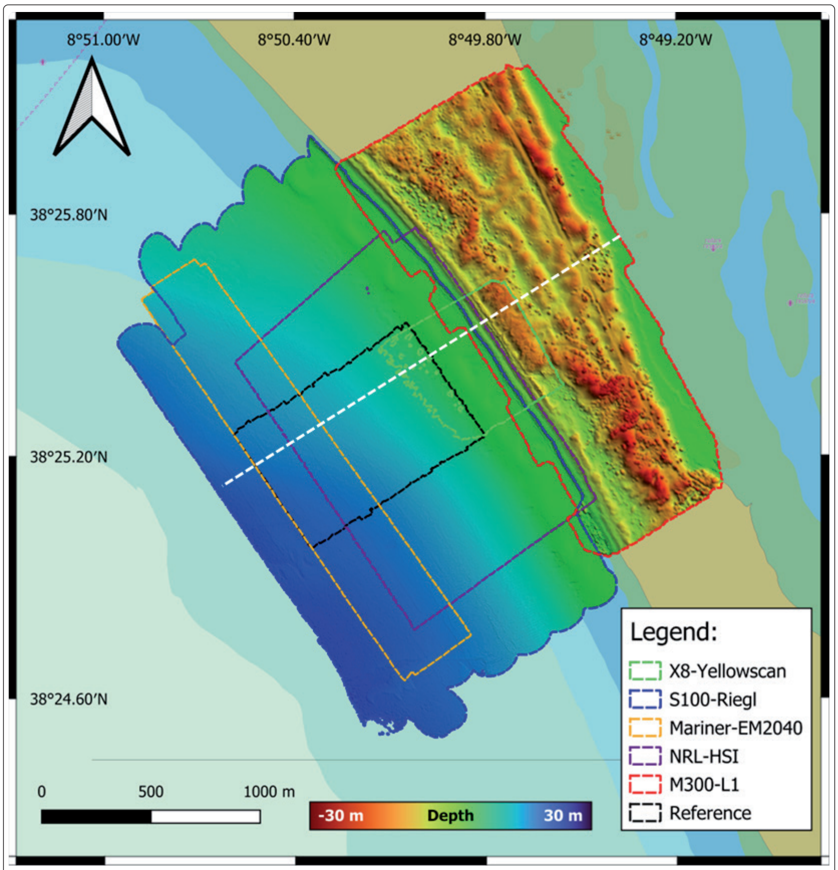


Fig. 3: Contribution of each system to the Malha da Costa bathymetric model. Depth profiles along the white dotted line are represented in Fig. 4

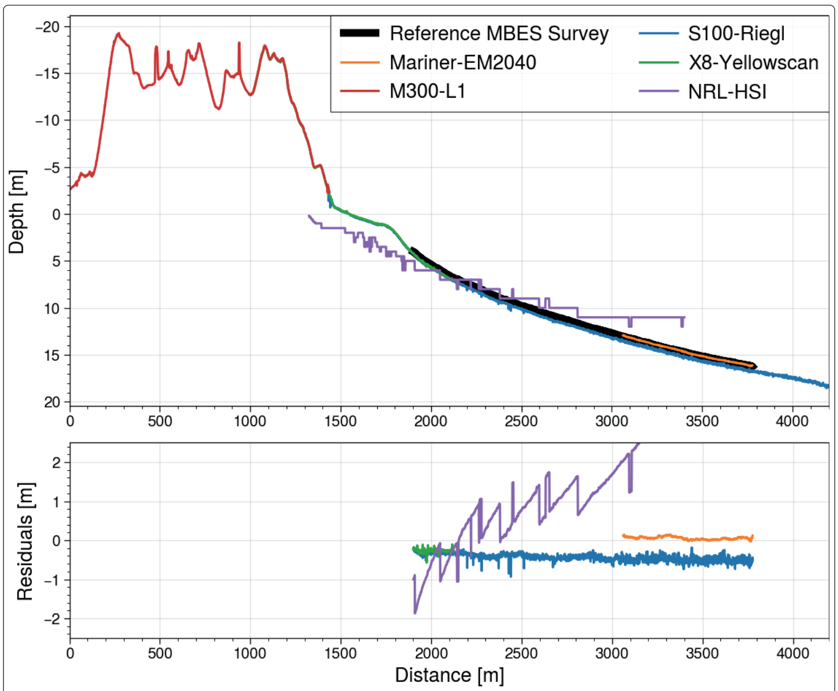


Fig. 4: Residuals between the reference model and the UxV bathymetric models, along the white dotted line represented in Fig. 3

with topo-bathymetric LiDARs delivered particularly valuable coverage, completing in a few hours what would take days with a sonar-equipped ves-

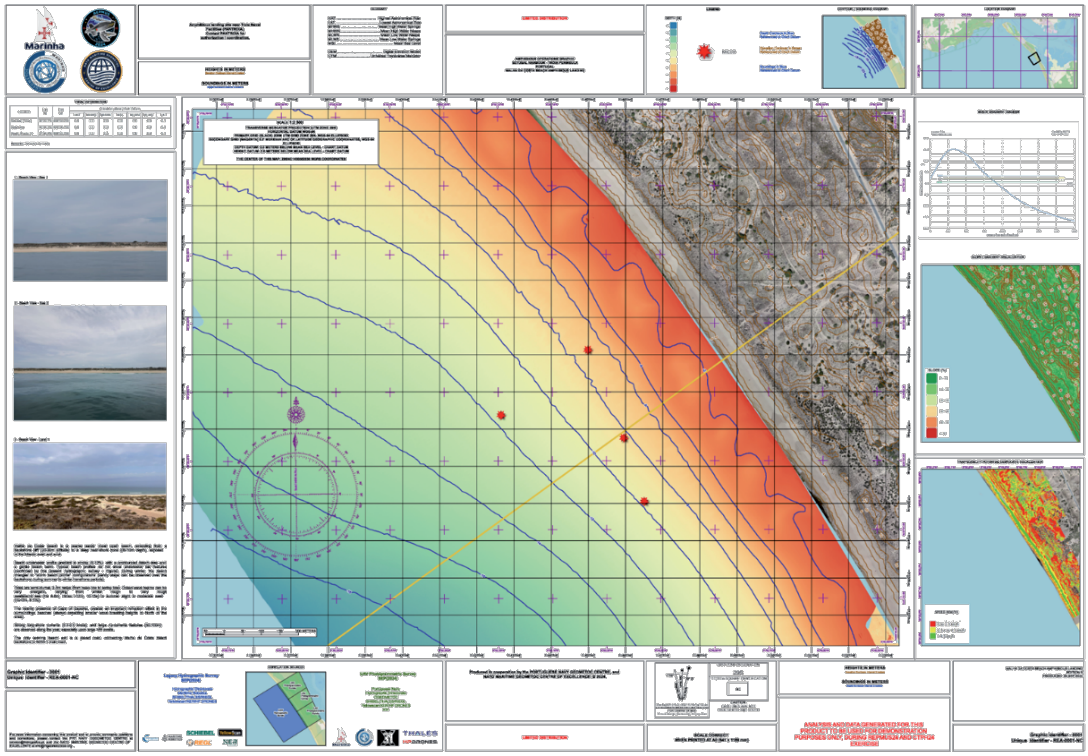


Fig. 5: Amphibious Operations Graphic produced for Malha da Costa

sel. Of the tested LiDAR systems, only the S100-Riegl pair successfully reached the deeper zone (to a maximum depth of ~20 m), while the others were limited to shallower waters.

To assess vertical accuracy, the residuals between the digital terrain models obtained from UxV surveys and the reference model were computed (Fig. 4), showing that the MBES data yielded the lowest residuals. As a prototyping exercise, REPMUS platforms and payloads may not have been operating at full capacity, thus no system performance ranking is implied.

An in-depth assessment of the surveys performed throughout REPMUS23 is available in Constantinoiu et al. (2024).

The digital terrain models generated by the uncrewed surveys were fused into an Amphibious Operations Graphic (AOG) (Fig. 5), integrating both bathymetry and topography, and annotations such as hazards (e.g. wrecks, mines) and aids to navigation. The AOG aimed to provide operational commanders a mission-oriented chart depicting beach gradients, approach corridors and terrain trafficability (i.e. the speed at which a soldier on foot or in a vehicle can traverse the terrain). Although not IHO compliant, the AOG exemplifies REA products: fast, tailored and operationally relevant.

Top: retrieved from Alseamar (2024). Bottom: retrieved from Marinha (2024)

Fig. 6: Examples of gliders deployed during REPMUS24. Top: Alseamar SeaExplorer. Bottom: Teledyne Slocum

Glider deployment

Throughout REPMUS24, eleven gliders (some depicted in Fig. 6) – long-endurance autonomous UUVs capable of adjusting their buoyancy to move through the water column – continuously roamed the area of operations. Their task was to characterise its oceanographic environment and provide a persistent environmental dataset which, directly or indirectly, supported the activities of the other WGs.

Gliders profiled the water column from the surface to depths of up to 1,000 m, sampling, among other parameters, temperature, salinity, oxygen, and chlorophyll. These were interpolated into the so-called Oceanographic Cube, allowing the comprehensive modelling of the water column (Fig. 7). For the UW WG, the Cube enabled the generation of sound speed profiles (SSPs), essential for sonar processing and for feeding acoustic propagation models to predict sonar detection ranges.

From a hydrographic standpoint, gliders also proved valuable. Some USVs used for bathymetry acquisition lacked onboard sound speed profilers, and interrupting surveys to perform a SSP cast is both inefficient and potentially risky. By supplying sound speed data, the gliders enabled uninterrupted surveying and reduced dependence on winch-deployed profilers – devices often prone to tangles that ultimately still require human intervention.

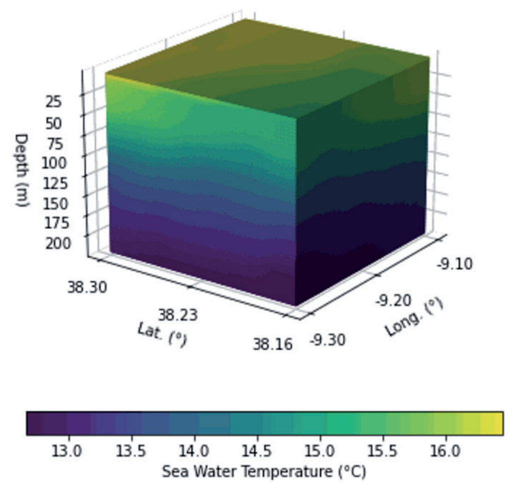


Fig. 7: The Oceanographic Cube, herein used to model sea water temperature

Critical underwater infrastructure monitoring

Submarine cables are the backbone of the global information infrastructure, carrying an estimated 99 % of international internet traffic (International Telecommunication Union, 2024). By 2025, more than 570 active cables span over 1.48 million kilometres of seabed (Telegeography, n.d.). Every year, approximately 100 cables suffer considerable damage with 70 % of incidents stemming from human activity – from accidental anchor strikes to deliberate sabotage (Carvalho, 2023).

Given this vulnerability, REPMUS has incorporated Critical Underwater Infrastructures (CUI) monitoring and protection scenarios since 2023. These typically involve laying a mock fibre-optic cable on the seabed and tasking uncrewed systems to locate, inspect and monitor it, while simulated threats are introduced. In REPMUS23, a cable was deployed at 60 m depth near Sesimbra, rigged with decoy »explosives« to evaluate MUS monitoring and detection capabilities. In REPMUS24, the scenario escalated considerably: an 18 mm diameter cable was laid at 800 m depth, with a lander simulating the threat. Fig. 8 depicts the locations of the 2023 and 2024 CUI scenarios.

From a hydrographic perspective, these scenarios required high-resolution seabed mapping and imaging. Only two UUVs were capable of tackling the 800 m CUI scenario (Fig. 9): the KD HUGIN 3000, fitted with a KD EM2040 and a KD HISAS 1032, and the INESC TEC (Instituto de Engenharia de Sistemas e Computadores, Tecnologia e Ciência) EVA UUV/Remotely Operated Vehicle (ROV), equipped with a Norbit iWBMS and custom optical scanners. Both successfully located the asset threatening the fiber-optics cable (Fig. 10).

Closing remarks

REPMUS is more than a military exercise – it is a strategic innovation engine for uncrewed maritime operations. It has demonstrated how MUS can deliver rapid, actionable environmental intelligence that directly supports operational decision-making in complex maritime environments. By bridging research, prototyping and field experimentation, the exercise accelerates the transition from concept to capability, offering tangible lessons for future operations.

REPMUS has been providing hydrographic-ena-

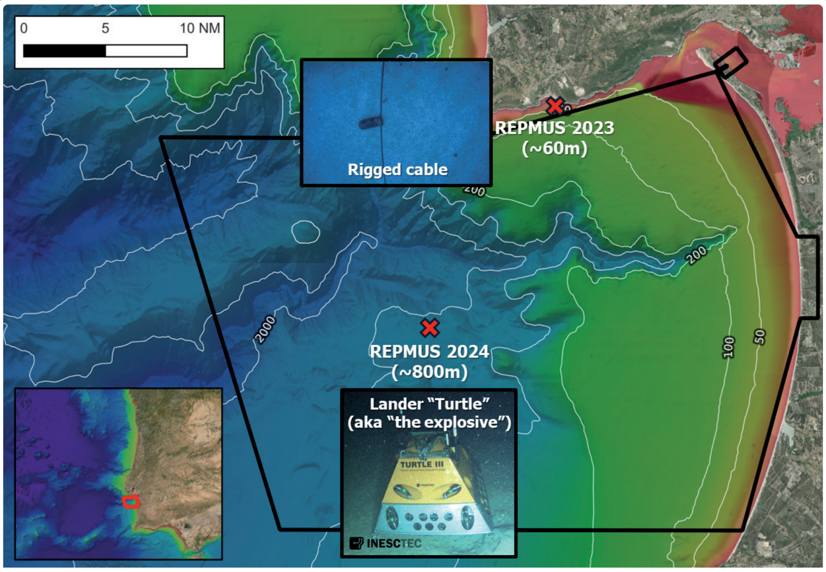


Fig. 8: CUI scenarios: 60 m (REPMUS23) and 800 m (REPMUS24)

Fig. 9: Assets employed in REPMUS24 CUI scenarios: KD HUGGIN 3000 (left) and INESC TEC EVA (right)

Top: courtesy of the Norwegian Defence Research Establishment (FFI), the Norwegian Navy and Kongsberg Discovery. Bottom: courtesy of INESC TEC

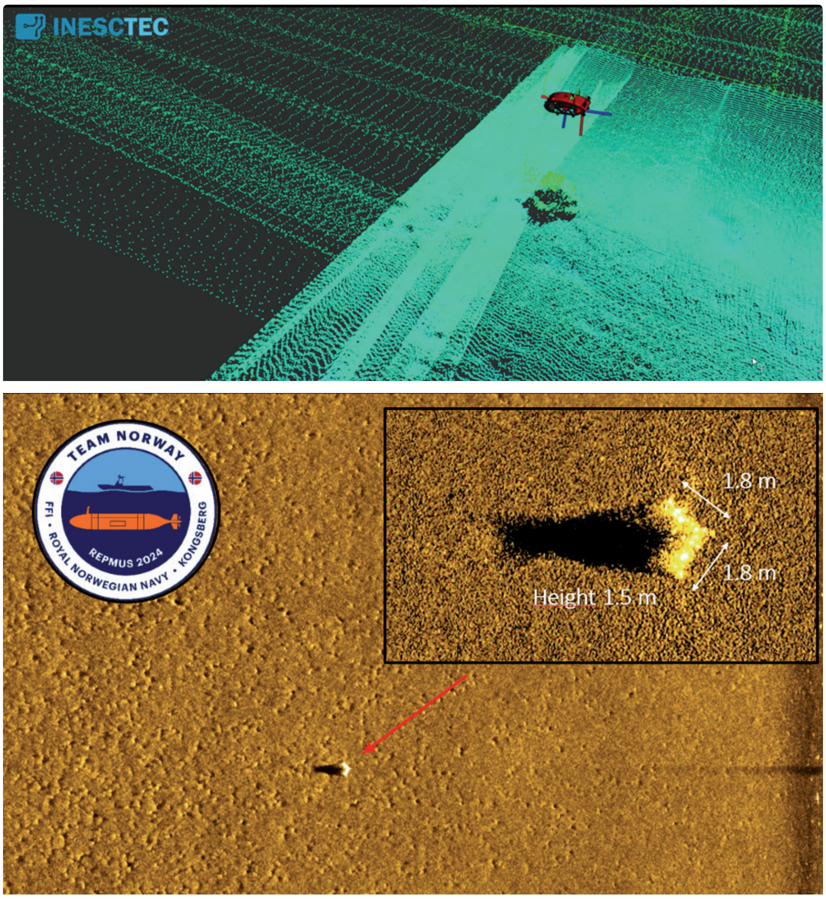


Fig. 10: Detection of the lander threatening the cable. Top: KD HUGGIN 3000 results. Bottom: INESC TEC EVA

bled assets with opportunities to prove their mettle across diverse scenarios:

- Amphibious operations areas have been thoroughly and swiftly surveyed using both UAVs and USVs.
- Oceanographic modelling of a large area of operations was made possible by the deployment of multiple gliders, which persistently and comprehensively sample the water column properties.
- Deep CUIs have been successfully monitored and protected.
- A cloud-based infrastructure was deployed, demonstrating its ability to rapidly disseminate environmentally relevant products to operational clients.

Looking ahead, REPMUS25 will build on these achievements. Planned activities include more complex CUI monitoring scenarios and conducting REA operations exclusively from naval vessels – raising the bar for MUS command and control, data processing and fusion, and the subsequent dissemination of data and products.

In conclusion, REPMUS exemplifies how rapid experimentation, multi-platform integration and multinational cooperation address maritime capability gaps, ensuring that participating nations, NATO and EU remain agile, technologically advanced and prepared to operate in increasingly complex maritime domains. //

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