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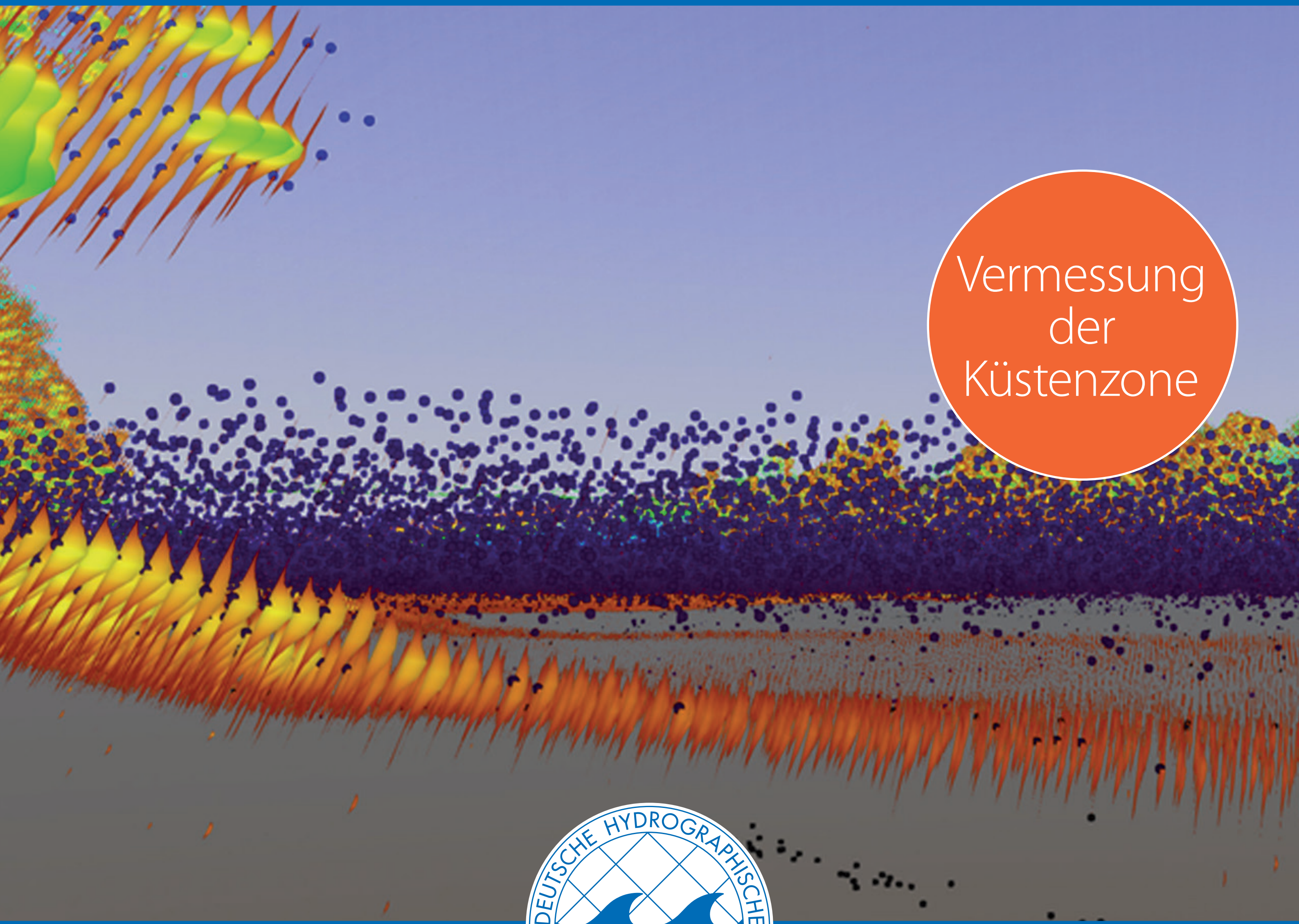

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Large-scale seafloor mapping of the Italian coasts using multi-sensor surveying to characterise Posidonia oceanica and seafloor morphology in shallow waters

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The Italian Institute for Environmental Protection and Research (ISPRA) is leading a nationwide initiative to map and restore seagrass meadows under the Marine Ecosystem Restoration (MER) project. This effort addresses the alarming decline of Posidonia oceanica and Cymodocea nodosa habitats, which are critical for carbon sequestration, biodiversity and coastal resilience. The MER project's mapping component, executed by Fugro and Compagnia Generale Ripreseaeree (CGR), in partnership with EOMAP and PlanBlue, employed a multi-sensor approach, combining satellite, airborne, vessel-based (high-resolution multibeam echo sounder, MBES) and autonomous underwater vehicle (AUV) technologies. The integration of bathymetric LiDAR, MBES, optical and multispectral data allowed continuous bathymetric coverage from the coastline to a depth of 50 metres. The Virgeo platform, specifically developed by Fugro, facilitated real-time monitoring of acquisitions and data collected by ships and aircraft engaged in the surveys. This integrated approach provides a robust baseline for restoration planning and long-term monitoring, offering a scalable, cost-effective solution for national marine habitat assessments.

marine ecosystem restoration | habitat and seafloor mapping | multi-sensor surveying | seagrass monitoring | machine learning classification
Wiederherstellung mariner Ökosysteme | Kartierung von Lebensräumen und Meeresböden | Multisensor-Vermessung | Seegrasüberwachung | Klassifizierung mittels maschinellen Lernens

Das italienische Institut für Umweltschutz und -forschung (ISPRA) leitet eine landesweite Initiative zur Kartierung und Wiederherstellung von Seegraswiesen im Rahmen des Projekts »Marine Ecosystem Restoration« (MER). Diese Initiative befasst sich mit dem alarmierenden Rückgang der Lebensräume von Posidonia oceanica und Cymodocea nodosa, die für die Kohlenstoffbindung, die Artenvielfalt und die Widerstandsfähigkeit der Küsten von entscheidender Bedeutung sind. Die Kartierungskomponente des MER-Projekts, die von Fugro und Compagnia Generale Ripreseaeree (CGR) in Zusammenarbeit mit EOMAP und PlanBlue durchgeführt wurde, basierte auf einem Multisensor-Ansatz, bei dem Satellitentechnologien, luft- und schiffsgestützte Technologien (mit hochauflösendem Fächerecholot) und autonome Unterwasserfahrzeugtechnologien (AUV) kombiniert wurden. Die Integration von bathymetrischen LiDAR-, Fächerecholot-, optischen und multispektralen Daten ermöglichte eine kontinuierliche bathymetrische Abdeckung von der Küstenlinie bis zu einer Tiefe von 50 Metern. Die speziell von Fugro entwickelte Virgeo-Plattform ermöglichte die Echtzeitüberwachung der Erfassungen und der Daten, die von den an den Vermessungen beteiligten Schiffen und Flugzeugen gesammelt wurden. Dieser integrierte Ansatz bietet eine solide Grundlage für die Planung von Wiederherstellungsmaßnahmen und die langfristige Überwachung und stellte eine skalierbare, kostengünstige Lösung für nationale Bewertungen von Meereslebensräumen dar.

Introduction

Seagrass meadows are among the most valuable coastal ecosystems on the planet. They provide a wide range of ecosystem services, with carbon storage standing out as one of the most important. Beyond their remarkable capacity to capture and retain carbon, seagrass meadows enhance marine biodiversity, stabilise sediments and reduce wave energy, offering natural protection for coastlines against storms.

In the Mediterranean Sea, meadows of Posidonia oceanica – an endemic species – have been recognised as a priority habitat under the European Union's Habitats Directive (Habitat Type 1120: Posidonion oceanicae). It is estimated that Posidonia oceanica alone has sequestered between 11 % and 42 % of the region's carbon dioxide emissions since the onset of the Industrial Revolution (Pergent et al. 2014).

Despite their ecological importance, Posidonia oceanica and other seagrass meadows are increasingly under threat from human activities such as coastal development, bottom trawling, anchoring, pollution and declining water quality. Climate change further accelerates their decline through rising sea-surface temperatures and sea-level rise (Boudouresque et al. 2009). Alarmingly, research suggests that Posidonia oceanica meadows in the Mediterranean have shrunk by about 34 % over the past 50 years (Telesca et al. 2015).

To counteract this degradation, the Italian government has established the Piano Nazionale di Ripresa e Resilienza (PNRR) Marine Ecosystem Restoration (MER) project, implemented by the Italian Institute for Environmental Protection and Research (ISPRA). The activities are carried out within the framework of the NextGenerationEU investment projects – Mission 2: Green Revolution and Ecological Transition; Component 4: Protection of Land and Water Resources; Measure 3: Safeguard air quality and biodiversity through the protection of green areas, soil and marine areas; Investment 3.5 has been planned: Restoration and Protection of Seabeds and Marine Habitats.

The MER project aims to restore the marine habitats and fortify the national system for observing marine and coastal ecosystems. The first crucial component of the MER project involves the mapping of Posidonia oceanica and Cymodocea nodosa seagrass meadows across Italian waters. Secondly, it aims to provide high-resolution bathymetric coverage and morphological mapping with continuity from the subaerial to the submerged portions down to a depth of 50 metres, in order to provide high-resolution digital elevation models (DEMs) useful for: maritime navigation; coastal risk indicators to which people and infrastructure are exposed; monitoring coastal infrastructure and assets in relation to climate change; geomorphological analysis of the seabed in relation to coastal geohazards; support for the management of coastal areas by the State Property Agency; support for the management of archaeological assets, scenarios of relative sea level rise and more.

Only by fully understanding the status of seagrass meadows along the Italian coast, appropriate steps can be taken to protect and restore this vital marine ecosystem. An integrated approach using multiple data acquisition methods ensures the accurate and high-resolution mapping of the abundance and distribution of seagrass meadows with different spatial configurations (Rende et al. 2020).

The seagrass mapping initiative under the MER project is performed by Fugro and Compagnia Generale Ripreseaeree (CGR), in partnership with EOMAP – a Fugro company, and PlanBlue. The project started in March 2024 and will last until June 2026. The project includes mapping the entire Italian coastline, covering 12,600 km² using topographic and bathymetric LiDAR, aerial RGB-NIR imagery, aerial gravimetry and satellite sensors, 3,798.2 km² using high-resolution MBES technology from vessels and 4,000 km² using autonomous underwater vehicles (AUVs).

The unique feature of this project is the extensive spatial coverage combined with the high number of sensor platforms, instrument types and data derivatives employed. Data is collected from space, air, water surface and below water – each of these datasets with its own characteristics and advantages. The strength lies in the integration of these different datasets and types, which enables the creation of a comprehensive data basis for a thorough and complete analysis of the seafloor morphologies.

Table 1 provides an overview of the equipment and data used in the MER project. Typically, a specific data type is acquired through multiple sensors. For instance, bathymetric and

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Sensor/platform	Type	Data derivatives	Resolution
Satellite EO	WorldView-2, WorldView-3	RGB, Satellite-derived bathymetry (SDB), Subsurface reflectance (SSR)	2 m
Topographic LiDAR (ALT)	Leica TerrainMapper CityMapper 2/3	Orthophotos, DSM, DTM	10 cm
Bathymetric LiDAR (ALB)	Fugro RAMMS 2.0	Bathy DTM, Topo DTM, Bathy Intensity, RGB-NIR	1 m
MBES	Kongsberg EM2040, EM 710-712	DEM, Backscatter	0.2 m to 0.5 m
AUV SeaCat	Camera PlanBlue, MBES, SSS	RGB imagery, Orthophoto, Point Clouds, DEM	Sub-centimetre
Gravimetry	Strapdown Airborne Gravimeter, Land Relative Gravimeter	Free-Air Gravity Anomalies along track, Complete Spherical Bouguer Anomalies along track, Gridded Free-Air and Complete Spherical Bouguer Anomalies	Variable, ranging from 1.5 to 3.0 km

Table 1: Overview of employed sensors and their data derivatives

intensity data are collected via satellites (satellite-derived bathymetry, or SDB), by airborne LiDAR bathymetry (ALB), as well as by ship-borne high-resolution MBES. Whereas SDB and ALB are limited in terms of penetration depth, MBES completes these datasets by covering deeper water areas. In contrast, space- and airborne systems are particularly effective in capturing data in very shallow and onshore areas, enabling a seamless and comprehensive data compilation across the entire survey domain ranging from the land to a water depth of approximately 50 metres.

Fig. 1 shows examples of the different data (LiDAR bathymetry and intensity, MBES bathymetry and backscatter and RGB-NIR satellite imagery), covering a large seagrass meadow.

Challenges in the large-scale multi-sensor mapping MER project

The MER project, which aims to conduct large-scale mapping of the Italian coastline using a wide variety of sensors and datasets, presents significant technological and methodological challenges. These include the integration of geophysical, optical and multispectral data; the generation of high-resolution digital land-sea models; and their homogenisation within a national reference system and official datum. Some of the key considerations are outlined below.

Planning data acquisition

When multiple sensors complement each other in terms of spatial coverage and depth ranging, such as ALB and MBES for bathymetry and intensity/backscatter data, careful acquisition planning is essential to ensure sufficient data overlap.

ALB covers shallow water areas. It can penetrate up to three Secchi depths, which is about 20 metre depth (depending on the environmental characteristics). MBES, on the other hand, is used in deeper waters beyond ALB's range, extending to about 50 metre depth. This depth marks the natural limit for seagrass growth due to its reliance on photosynthesis.

An effective acquisition planning must account for various factors:

- Seafloor morphology: MBES is typically acquired parallel to the slope (i.e., parallel to the isobaths and shoreline), while ALB acquisition patterns may differ as subaerial terrain features such as mountains and coastal infrastructure must be considered when planning flight lines and the turns in between.
- Environmental conditions: weather plays a significant role, particular for ALB. Water turbidity, which negatively affects ALB measurement range, varies not only by location but is also influenced by recent weather events. Rainfall, for instance, can increase the water turbidity (i.e., flash flood), sea condition, etc.
- Operational constraints: local restrictions on flight times or airspace usage may also impact the scheduling and execution of airborne data acquisition. As for vessel- and AUV-based operations, they can be affected by local survey permit regulations as well as tourism during the summer period. Furthermore, emergencies such as summer fires and volcanic activity (Stromboli and Etna) may also have an impact.

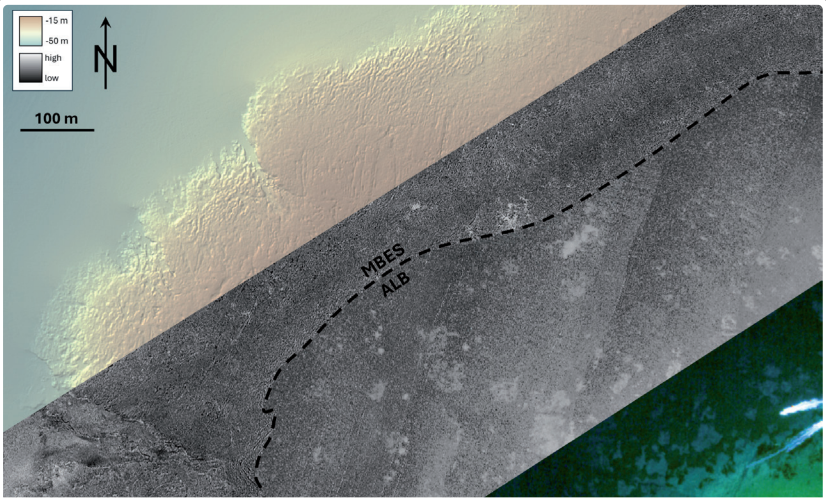


Fig. 1: Different data collected by sensors for high-resolution seafloor mapping. From bottom right to top left: RGB satellite imagery, combined ALB and MBES bathymetry and backscatter. Seagrass meadows are visible in the RGB imagery as darker-toned areas, indicating denser vegetation. In the intensity data seagrass appears as regions of generally lower values with greater inhomogeneity due to stronger variation in reflectance and backscatter intensity. Posidonia oceanica meadows in bathymetric data (DEM) are associated with morphologically detected features with a specific roughness. The dotted black line separates the MBES backscatter from LiDAR intensity data

Positioning, datum and reference system

All MBES bathymetric data, bathymetric and topographic LiDAR datasets, ortho-mosaics and derived cartographic products are integrated within a standard Reference System and Datum (ETRF2000 RDN2008). National GNSS CORS geodetic networks (Leica SmartNet, Trimble Spectra and Topcon) are employed for all kinematic positioning systems.

The maximum baseline distances used for post-processing kinematic (PPK) positioning between aircraft/ship platforms (rovers) and the CORS reference stations does not exceed 20 km. This ensures a plano-altimetric accuracy of only a few centimetres, and in any case less than one decimetre.

Data acquisition is carried out using latest-generation, multi-frequency and multi-constellation GNSS receivers in combination with IMUs. Post-processing is performed using precise ephemerides, allowing the generation of DEMs in both orthometric height (H – ITALGEO2005) and ellipsoidal height. Finally, the data are also referenced to the local mean sea level.

Monitoring project progress and data status

Managing large and heterogeneous datasets requires a robust system to ensure effective oversight of project progress and data processing status. For the MER project, Fugro adopted Virgeo – a cloud-hosted platform specifically designed to streamline data management.

Field, vessel and office teams can upload datasets into Virgeo, making them accessible in real-time to all project stakeholders. This centralised access not only enhances decision-making but also significantly improves operational efficiency.

As illustrated in Fig. 2, the Virgeo interface allows users to visualise the real-time positions of vessels and aircraft, alongside all datasets collected. In addition to displaying spatial data layers, the platform provides live asset tracking and colour-coded indicators that reflect the temporal status of the MER project.

Merging MBES and ALB data

The integration of MBES and ALB datasets is essential for generating unified information layers, which can subsequently be used for advanced analyses such as automated seafloor classification. When applying machine learning and other AI techniques, it is particularly important to ensure that the datasets are free of artefacts and that differences in data properties, such as resolution, are properly addressed.

One of the main challenges in this process is the integration of MBES and ALB intensity data. MBES backscatter values are typically expressed in decibels, whereas ALB intensity values are derived from laser reflectance and depend on both post-processing steps and the specific data format of the derivative product.

To obtain consistent and artefact-free results, inter-sensor normalisation is required. For MBES backscatter data, normalisation is carried out using the Kongsberg system (the equipment employed in this project) for each sector and acquisition mode, ensuring internal consistency within datasets collected by the same system. The subsequent step involves the normalisation of datasets acquired from different vessels and flight missions, thereby homogenising the data and ensuring high-quality, comparable outputs across all sources.

Automated seagrass classification

Once all datasets have been processed, automated classification techniques using machine learning are applied to identify and assess seagrass coverage and other morphologies such as rock and mobile sediment. The success of this classification is strongly influenced by the diversity and quality of input data. Especially data derivatives such as slope, aspect, backscatter and intensity can improve the classification results.

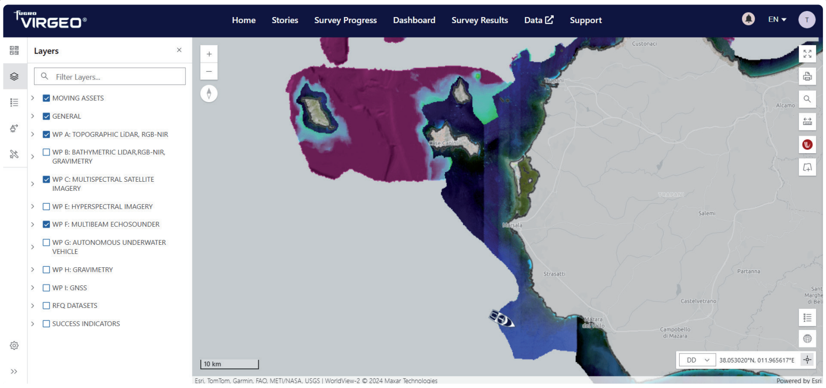


Fig. 2: Virgeo user interface of western Sicily (Egadi Islands – Italy)

The classification process in this project is carried out using Trimble eCognition software (Rende et al. 2020; Rende et al. 2022; Tomasello et al. 2022). The process starts with a segmentation, where the data is divided into regions based on shared properties across different datasets. These segments are then grouped and assigned to thematic classes such as rock, sediment or seagrass, using high-resolution orthophotos as ground truth, to validate information retrieved from other sensors and training machine learning classification. Fig. 3 shows a preliminary result of the automated seafloor classification (part D, bottom right), alongside some of the data layers used in the process.

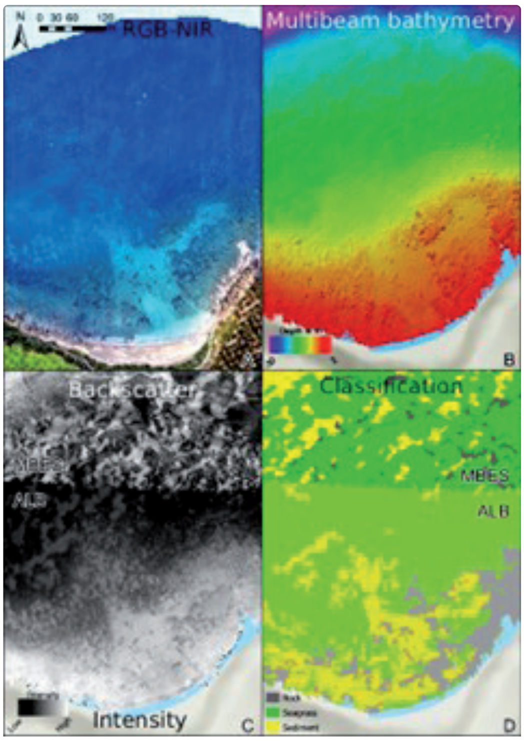


Fig. 3: Mapping process for seafloor classification.
A: Aerial RGB photo. B: High-resolution MBES and LiDAR bathymetry. C: LiDAR intensity (preliminary, not processed) and MBES backscatter. D: Preliminary seafloor classification results derived from their integrated analysis

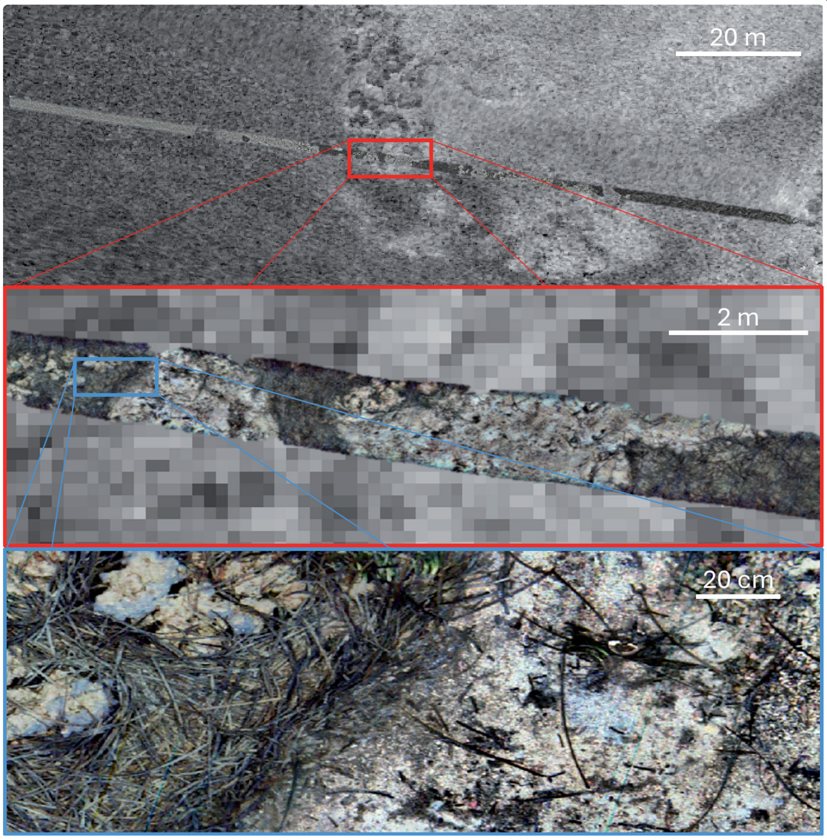


Fig. 4: MBES backscatter mosaic (0.2 metre) with seagrass area overlaid by an high-resolution AUV orthophoto. The different inset maps show the high detail of the visual information

The orthophotos used for ground-truthing are captured by an AUV, operating two to three metres above the seafloor at speeds of up to three knots. These images provide detailed visual information that not only confirms seagrass presence but also enables assessments of its health.

Fig. 4 and Fig. 5 illustrate the high amount of detail provided from the AUV imagery (orthophoto, resolution 0.2 cm, PlanBlue). This AUV survey was carried out during seagrass winter dormancy in Secche di Vada (Tuscany). Fig. 4 shows AUV imagery overlaid on MBES backscatter data (resolution of 0.2 metres) in an area of seagrass coverage at a water depth of approximately 35 metres.

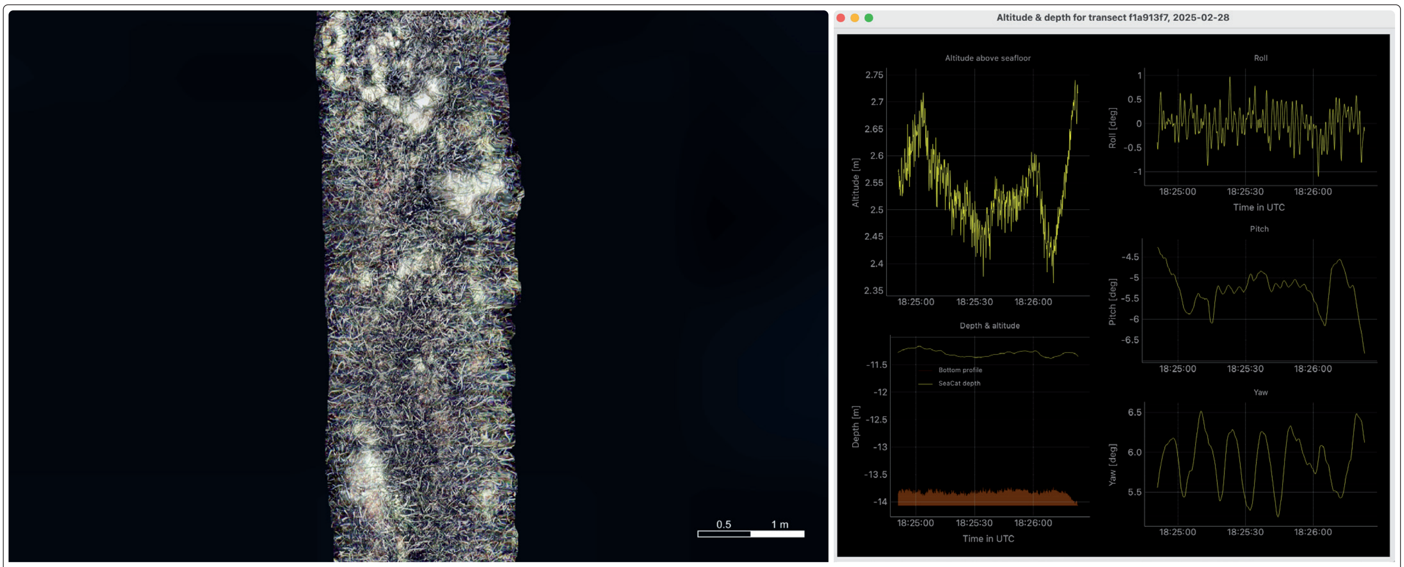
Conclusion and remarks

The MER project represents the first national-scale, high-resolution mapping initiative dedicated to the study of Posidonia oceanica meadows and seabed morphology. It addresses significant technological and methodological challenges, with the capacity to generate DEMs and accurate maps through the integration of ground, marine (surface and deep), aerial and satellite sensors, all referenced within a unified official system.

This multi-sensor approach ensures full coverage of Posidonia oceanica habitats, from the coastline down to depths of about 50 metres. By combining different acquisition methods, it provides reliable mapping of seagrass meadows and seabed classification, supporting both restoration planning and long-term monitoring. Moreover, it offers the most cost-effective solution for establishing ecological baselines and conducting large-scale, repeatable assessments. The integration of multiple high-resolution data sources reduces the uncertainties of single-sensor analyses and enables investigation down to the lower limits of meadow distribution.

Within this framework, the project directly contributes to the implementation of major European policies and regulations:

- The Habitats Directive (92/43/EEC), which recognises Posidonia oceanica meadows as a priority habitat requiring protection.



Credit: PlanBlue

Fig. 5: Left: High-resolution orthophoto collected during night test (low environmental visibility) in east Pianosa Island, Tuscan Archipelago, Italy. Right: Windows showing altitude, depth and motion parameters for quality checks

- The Marine Strategy Framework Directive (2008/56/EC), which requires Member States to achieve good environmental status of marine ecosystems.
- The recent Nature Restoration Law, which sets legally binding targets for the restoration of degraded habitats, including seagrass meadows.

The knowledge generated will support policy-makers in developing targeted strategies to mitigate pressures, preserve existing meadows and guide effective restoration actions, in line with European regulatory commitments. In this way, the MER project makes a significant contribution to the long-term protection of one of the Mediterranean's most valuable marine ecosystems. //

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