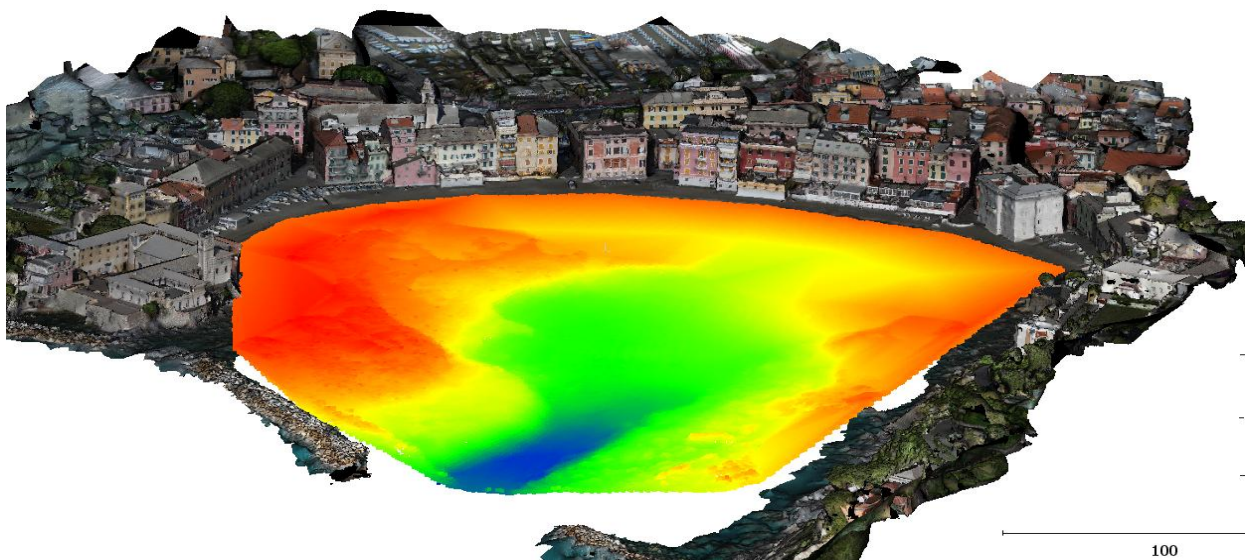


Ph.D. Program in Civil, Chemical and Environmental Engineering
Curriculum in Engineering for Marine and Coastal Environments



Department of Civil, Chemical and Environmental Engineering
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**INTEGRATING TOPOGRAPHIC AND UNDERWATER
MEASUREMENTS FOR COMPREHENSIVE COASTAL AREA
INSPECTION: AN INTERDISCIPLINARY APPROACH**

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FOR COMPREHENSIVE COASTAL AREA INSPECTION:
AN INTERDISCIPLINARY APPROACH

BY

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Cover

Integrating Topographic and Underwater Measurements for Comprehensive Coastal Area Inspection: An Interdisciplinary Approach

ABSTRACT

The Ph.D. research project focuses on the definition, implementation and validation of a methodology to execute integrated aerial and underwater surveys of coastal areas and harbor infrastructures to develop new services for marinas, public authorities, and blue economic operators. The present thesis work is carried out with an interdisciplinary approach mainly involving geomatics, robotics, ecology and other disciplines to suggest a methodology that may be realistically adopted by scientists. The integration of robotic technologies, including Unmanned Aerial and Surface Vehicles (UAVs and ASVs), with various remote sensing techniques, such as underwater acoustic sensors (single and/or multibeam echosounders), aerial and underwater photogrammetry, enables the acquisition of reliable and high-resolution data. This facilitates a holistic understanding of coastal environments by generating 3D models that seamlessly integrate the seabed and landscape into a unique reference frame. A common strategy is applied across the three survey scenarios, each employing different techniques, to produce a unified 3D model that merges both submerged and emerged survey data. A key challenge addressed in working with these different environments is underwater positioning, solved through an innovative image-based techniques. The methodology involves synchronized surveys, where UAVs capture images of a snorkeler or ASV performing underwater measurements. These images are used to estimate the position of the snorkeler or ASV, enabling the georeferencing of underwater features. The approach relies on accurately determining the underwater camera's position by synchronizing its data with UAV imagery in both time and space. The resulting georeferenced 3D model provides a comprehensive spatial representation from seabed to land. In contrast, for harbor environment, where safety rules, navigation protocols, and airspace restrictions make things trickier. Here, the approach to merging datasets has to work within these limits, to obtain a complete and accurate 3D model. This cost-effective and robust solution enhances the understanding of underwater habitats and their spatial relationships, supporting coastal management and resilience efforts. The methodology has been developed and validated across various scenarios, demonstrating its practicality and effectiveness.

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1. INTRODUCTION

This Ph.D. thesis work has a formal research collaboration with the Institute of Marine Engineering of the National Research Council (CNR- INM), under the scientific supervision of Dr. Massimo Caccia and his research team, particularly the researcher Dr. Angelo Odetti. The work addresses the need for integrated coastal monitoring by developing and evaluating methods for the combined acquisition and processing of terrestrial and underwater data. The thesis builds on technical foundation laid with Odetti's Ph.D. research, particularly the development and implementation of the Shallow Water Autonomous Multipurpose Platform (SWAMP), a prototype of an Autonomous Surface Vehicle (ASV) designed for hydrographic and environmental applications in shallow and transitional water zones. SWAMP was designed and constructed in collaboration with the Department of Naval, Electrical, Electronic and Telecommunications Engineering (DITEN) at the University of Genova, for measuring high-resolution underwater data in shallow water bodies.

The main aim of this thesis is to define a robust and flexible methodology for performing integrated terrestrial and underwater survey that balance the environmental complexities with the need for accurate and executable results. This methodology is designed not only to overcome technical constraints, such as sensor limitations and positioning errors, but also to support a wider interdisciplinary framework. By enabling the generation of continuous 3D models that seamlessly merge terrestrial and underwater environments, the proposed workflow offers a foundation for coastal analysis that can serve a variety of disciplines. The intention is to develop a smart, scalable approach that ensures data continuity and usability across sectors, while also remaining adaptable to specific site conditions and technological constraints. Within this context, this work focuses on the integration of multiple sensing systems, specifically single-beam and multi-beam echo sounders, mounted on SWAMP, for the acquisition of high-resolution underwater data. Simultaneously, an airborne photogrammetric survey was conducted using Uncrewed Aerial Vehicles (UAV) over the same coastal area. The adoption of this integrated survey methodology, ASV and UAV aimed to embrace methodological innovation in coastal mapping, with a particular emphasis on spatial continuity and data accuracy. The research covers the full lifecycle of geospatial data handling: pre-survey planning phase, field data acquisition, to the post-processing and integration phase. The outcome is a unified DSM (Digital Surface Model) that bridges terrestrial and underwater environments, enabling a comprehensive representation of coastal environments.

A key technical challenge addressed in this thesis work involves the accurate combination of data from different systems, particularly in environments where GNSS (Global Navigation Satellite System) support is challenging. Such limitations are common in coastal and harbor settings, where electromagnetic interference and obstructed satellite visibility can compromise positioning accuracy. This raises critical research questions: how can accurate geospatial models be generated in GNSS limited environments? And more broadly, how can accurate results be achieved to provide guidelines for a successful integrated survey of emerged and submerged environments?

To answer the research questions, the methodological development for this Ph.D. research was structured around a three-phase progression, each aligned with specific goals, technologies, and interdisciplinary

outcomes. The project began with the definition of application scenarios, aimed at identifying suitable coastal and harbor contexts in which integrated survey techniques could be applied. During this initial phase, the focus was placed on exploring potential use cases such as ecosystem monitoring, coastal morphodynamics analysis, and underwater surveys for infrastructure management. The goal was to assess the feasibility and relevance of combined terrestrial-sea surveying across a range of real-world settings, while also identifying the operational challenges specific to each environment. Simultaneously, this first phase involved the selection and evaluation of appropriate sensing technologies and robotic platforms, including UAVs, ASVs, and various types of acoustic and optical sensors. These included single-beam and multi-beam echosounders, 360° panoramic cameras, cameras for photogrammetry, each chosen for their ability to contribute to a continuous and accurate 3D spatial representation of the coastal zone.

The second year of the research was dedicated to system design, development, and implementation. This phase focused on building the technical architecture of the proposed workflow, integrating hardware and software components, and adapting the methodology to respect environmental, legal, and social constraints. Emphasis was placed on ensuring that the workflow could be practically deployed in various settings and remain compliant with relevant safety and regulatory standards. Prototypes were tested and refined to ensure technical coherence between platforms, and efforts were made to develop custom processing pipelines using tools such as Agisoft Metashape© (V 1.8.2), and Python[1].

The final year of the project concentrated on experimental validation and impact assessment. The developed methodology was applied to selected case studies to evaluate its technical performance, accuracy, operational feasibility, and cost-effectiveness. These tests aimed not only to confirm the functionality of the proposed system but also to assess its adaptability to different site conditions and constraints. Additionally, this phase included an exploratory component focusing on the inspection of man-made structures, in both dry and submerged conditions. Advanced 3D photogrammetry and multibeam echo sounding were applied to assess the condition and geometry of these features. The robotic platforms UAVs and ASVs were also evaluated for their guidance and navigation capabilities in complex nearshore environments.

Through this structured development process, the research ultimately aimed to establish a comprehensive, interdisciplinary framework that supports the integration of aerial, terrestrial, and underwater surveys. The final goal was to ensure not only the completeness and continuity of spatial data collection but also the generation of accessible, high-quality geospatial products such as digital maps, 3D models, and Digital Twins capable of supporting decision-making across scientific, environmental, and technical domains.

The primary objective of this research is to develop and validate a comprehensive and adaptable methodology for integrating terrestrial and underwater survey data to enable a continuous, high-resolution representation of coastal environments. This methodology is intended to support interdisciplinary applications in areas such as environmental monitoring, marine habitat mapping, infrastructure inspection, and coastal zone management.

To achieve this overall aim, the research pursues the following specific objectives:

1. define technologies and methods to execute integrated surveys;
2. propose planning and preparing phase guide for integrated surveying techniques, considering the time management;

3. implement integrated survey technology including robotic and remote sensing techniques;
4. develop the methodology/workflow to provide continuous 3D combined DSM of emerged and submerged areas;
5. develop new services and methodologies that contribute to economic growth and improve the efficiency of marine services;
6. develop new methodology for marine habitats mapping;
7. perform critical analysis to investigate the quality of survey for different methods in terms of accuracy;
8. validate technology performance and effectiveness with respect to associated accuracies;
9. assess social and environmental impact and legal issues for the employed technologies;
10. obtain multiple technical experience by working with several techniques such as Single and Multi Beam echo sounders, Side Scan Sonar, UAV photogrammetry, LiDAR and Laser scanner;
11. monitor and analyze the evolution of seabed and marine ecological characteristics.

In this context, the following research questions arise:

1. how to effectively integrate the existing methodologies for terrestrial and underwater surveys to enhance data accuracy and coherence?
2. what role do emerging technologies (e.g., remote sensing, optical sensors and robotics) play in facilitating the integration of terrestrial and underwater survey data?
3. what methodology can be used to integrate underwater and terrestrial data with minimal use of GNSS, while ensuring accuracy and consistency?
4. what are the challenges and limitations associated with integrating terrestrial and underwater survey data, and how can these be addressed through methodological advancements?
5. how to use integrated terrestrial and underwater survey methodologies to accurately assess the spatial distribution, presence, and health of marine and coastal habitats, such as coral reefs and seagrass beds?

In response to the objectives outlined above, this research proposes a flexible and adaptive methodology for combining terrestrial and underwater spatial data in coastal and transitional environments. Rather than offering a one-size-fits-all solution, the proposed methodology emphasizes context-driven adaptability. In real-world coastal settings, survey operations frequently encounter logistical, legal, and environmental constraints. For example, in busy harbor environments, the deployment of ASVs may be restricted due to navigation safety protocols or port authority regulations [2]. Similarly, UAV flights may be prohibited or limited in certain urban or industrial zones due to airspace restrictions and safety standards. These practical limitations necessitate a modular and versatile approach that can integrate different sensing platforms and positioning strategies depending on the specific characteristics of the site.

Despite the variability in tools and deployment strategies, the core objective remains consistent: to accurately merge data from terrestrial and submerged environments into a unified spatial model. Whether using ASVs, manned boats, snorkelers, or fixed underwater cameras and whether relying on GNSS-based georeferencing or alternative solutions, the methodology is designed to generate continuous DSMs that meet both scientific and operational requirements. Within this adaptable framework, one of the thesis's key methodological innovations addresses situations where GNSS positioning is unavailable or compromised. In such cases, the workflow replaces traditional georeferencing techniques with a novel use of high-resolution orthophotos as a spatial reference. The core idea lies in synchronizing aerial and underwater photogrammetry through the orthophoto, which is generated from UAV-acquired imagery and used as a stable and consistent geospatial tool for aligning submerged models. Rather than depending on ground control points or costly underwater positioning systems, this method is based on positioning the underwater camera in the terrestrial reference frame. This makes it possible to accurately position the underwater model within the same spatial frame as the terrestrial environment, creating a seamless transition between the two domains [3], [4]. The integrated workflow involves coordinated data collection: UAVs carry out detailed aerial mapping of the emerged terrain, while underwater imagery is acquired either by a snorkeler or by an ASV equipped with submerged cameras. The combination of these platforms ensures comprehensive spatial coverage and supports the generation of continuous 3D reconstructions that capture the full complexity of the coastal interface. While orthophotos have long been used for cartographic and analytical purposes, their application as a georeferencing tool for underwater datasets remains largely unexplored [4]. This thesis work redefines their role not simply as visualization products, but as functional spatial frameworks that enable consistent and accurate alignment between terrestrial and underwater photogrammetry. This approach is especially valuable in GNSS-degraded locations such as narrow inlets, urban waterfronts, or industrial harbor areas. Compared to existing methods that depend on total stations, real-time GNSS corrections, or the physical placement of control targets, the orthophoto-based technique offers a cost-effective, low-intrusion alternative. To implement this orthophoto-based georeferencing, the methodology introduces the concept of dynamic ground control points (dynamic GCPs). These are defined as the positions of the snorkeler or ASV at specific times, captured simultaneously within the UAV derived orthophotos. By recording these dynamic GCPs, it becomes possible to reconstruct the position of the underwater camera in relation to the terrestrial reference system [3], [4], [5]. In practical terms, each time the snorkeler or ASV appears in the aerial imagery, its location is treated as a dynamic GCP, which serves as a temporal and spatial reference point connecting the submerged survey to the emerged one. These dynamic GCPs are not physical targets underwater; they are the estimated positions of the snorkeler or ASV visible at the water surface in the orthophotos, computed in the terrestrial reference frame using the orthophoto and terrestrial GCPs and time-matched to the underwater image sequence. They therefore do not need to coincide with the exact seafloor observation points; rather, they act as kinematic tie points that allow the underwater camera trajectory and the submerged dataset to be linked consistently to the terrestrial-based survey. This concept is elaborated in detail in the Methodology chapter of the thesis, where its implementation and applicability were tested. Two experimental cases were designed to evaluate the reliability and accuracy of the dynamic GCP approach. In the first case, a snorkeler equipped only with an underwater camera (and without GNSS support) was employed to assess the feasibility of positioning underwater imagery through synchronization with UAV-derived orthophotos. In the second case, the methodology was tested using an ASV equipped

with GNSS, enabling a direct comparison between positions estimated via dynamic GCPs and positions recorded by GNSS. This comparative evaluation provided a clear basis for assessing the accuracy of the workflow, highlighting both its potential and its limitations. In contrast to the two cases described above, which focused on solving underwater positioning through dynamic GCPs and orthophoto, a third scenario addressed survey operations in a harbor environment. Harbors are subject to strict regulations and safety standards, meaning that UAV flights are often restricted and snorkeler-based surveys are impractical due to navigation safety concerns. These constraints required a different approach for merging terrestrial and underwater datasets. In this case, each survey simultaneously combined an emerged 360° camera with a multibeam sonar system, ensuring a coverage of both domains. The surveys were repeated at different tidal stages, one during high tide and another during low tide. The tidal variation created natural overlap zones that served as tie points, enabling the two datasets to be connected across survey times. By exploiting these natural GCPs, it was possible to merge the terrestrial and submerged data into a single 3D model, showing that even under strict operational restrictions, reliable and flexible integration of coastal datasets can be achieved.

Performing tests in harbor environments made evident that specific operational constraints required further adaptation of the proposed methodology. Due to safety regulations, privacy concerns, and airspace restrictions, the use of UAVs was not permitted in these areas. To comply with these constraints while maintaining the goal of integrated coastal surveying, the methodology was modified to exclude aerial photogrammetry and instead rely on a combination of surface-based and underwater systems.

In place of UAVs, traditional boats and ASVs were employed to perform the above-water survey. These platforms were equipped with 360° panoramic cameras, which provided comprehensive visual coverage of the harbor emerged features. For the underwater component, the survey continued to rely on underwater sensors including single-beam and multi-beam echo sounders mounted on the same ASV or additional vessels. The use of wide-angle imagery, combined with precise underwater data, enabled the construction of detailed 3D models of both the waterline and the submerged harbor infrastructure. Although this setup deviated from the original UAV-ASV configuration, it maintained the methodological integrity of the integrated workflow: generating continuous 3D spatial models that represent both emerged and submerged features within a coherent spatial frame. This case study demonstrated that the workflow can be dynamically adjusted to site-specific constraints without compromising data quality or the broader objectives of interdisciplinary coastal monitoring. By successfully applying the workflow in a regulated and operationally complex harbor environment, the research highlights the scalability and resilience of the proposed methodology. It confirms that high-resolution and integrated spatial models can be produced even when access to conventional survey technologies is restricted.

Finally, the third scenario in Hamburg harbor demonstrates the extension of the methodology to a highly dynamic tidal environment. Although a dynamic marker was not employed as in the previous cases, the tidal variation itself provided natural overlapping tie points that acted as ground control references. The integration of MBES bathymetry with 360° camera imagery under both high and low tide conditions enabled validation of infrastructure mapping and continuity between submerged and emerged datasets in a harbor environment

By introducing these methods, the present research offers a scalable and adaptable solution for integrated coastal mapping. The resulting georeferenced 3D models are not only geometrically accurate but also situated within a unified spatial context, thereby enhancing their value for ecological monitoring, infrastructure assessment, spatial planning, and communication with stakeholders.

Overall, this introduction establishes the motivation, challenges, and innovations of the proposed research, setting the stage for the detailed state of art and methodological developments presented in the following chapters. The thesis is organized into five chapters, each contributing to a different aspect of the investigation and collectively forming a coherent pathway from background analysis to practical validation:

- **Chapter 2 – Literature Review:** provides an in-depth review of current methodologies and technologies employed in terrestrial and underwater surveys, identifying trends, limitations, and research gaps.
- **Chapter 3 – Methodology:** describes the design of the integrated survey system, including platform selection, data acquisition strategies, georeferencing techniques, and data processing workflows. The chapter also introduces the case studies used for validation.
- **Chapter 4 – Results and Discussion:** presents the outcomes of field experiments, evaluates the system performance, and analyzes the implications of integrated surveys for coastal monitoring and interdisciplinary applications.
- **Chapter 5 – Conclusions and Future Work:** summarizes the main findings, outlines the contributions to the field, and offers recommendations for further research and practical implementation.

This thesis makes several contributions to the field of integrated coastal surveying.

- **Methodological:** Development of a novel workflow that integrates UAV-based photogrammetry, underwater photogrammetry (by snorkeler/ASV), and acoustic surveys (SBES/MBES) into a seamless georeferenced 3D model, adaptable to both clear-water lakes and complex harbor environments.
- **Experimental:** Validation of the methodology across three case studies (Laghi del Gorzente, Silent Bay of Sestri Levante, Elbe Harbor in Hamburg), each demonstrating adaptability to different operational challenges such as GNSS-denied environments, tidal cycles, and turbidity.
- **Practical:** Introduction of the dynamic Ground Control Point (GCP) concept, where a snorkeler or ASV serves as a positioning reference, enabling accurate underwater georeferencing without reliance on expensive underwater positioning systems.
- **Technological innovation:** Implementation of orthophoto-based positioning from UAV imagery to replace or complement GNSS measurements, achieving centimeter-level accuracy and validating this approach against synchronized GNSS datasets.

- Visualization: Creation of immersive Virtual Reality (VR) models from integrated 3D meshes, enabling novel ways to communicate, explore, and apply coastal survey data for environmental management and education.

The originality and impact of this work are reflected in its scientific output: a peer-reviewed article in the *Journal of Marine Science and Engineering* (2022), a second paper in the same journal, and a conference paper at MetroSea 2024, which was awarded Best Outstanding Paper and Presentation. A key element of this research is the author's active role in the entire process: from survey planning to execution, including the acquisition of a UAV pilot license (A1/A3 and A2) to independently collect aerial data, as well as conducting bathymetric and topographic surveys, processing, and analysis.

The following scientific publications are directly related to the work presented in this thesis:

1. A. A. Karaki, M. Bibuli, M. Caccia, I. Ferrando, S. Gagliolo, A. Odetti, and D. Sguerso, "Multi-Platforms and Multi-Sensors Integrated Survey for the Submerged and Emerged Areas," *JMSE*, vol. 10, no. 6, p. 753, May 2022, doi: 10.3390/jmse10060753.
2. A. A. Karaki, I. Ferrando, B. Federici, and D. Sguerso, "Bridging Disciplines with Photogrammetry: A Coastal Exploration Approach for 3D Mapping and Underwater Positioning," *Remote Sensing*, vol. 17, no. 1, p. 73, Dec. 2024, doi: 10.3390/rs17010073.
3. A. A. Karaki, I. Ferrando, R. Nardini, B. Federici, M. Guideri, N. Langellotto, and D. Sguerso, "Integrating Topographic and Underwater Measurements for Comprehensive Coastal Area Inspection: An Interdisciplinary Approach," in 2024 IEEE International Workshop on Metrology for the Sea; Learning to Measure Sea Health Parameters (MetroSea), Portorose, Slovenia: IEEE, Oct. 2024, pp. 197–201. doi: 10.1109/MetroSea62823.2024.10765652.

In addition, this last contribution was awarded Best Outstanding Paper and Presentation at the MetroSea 2024 conference, further recognizing the scientific and practical impact of the proposed methodology.

2. STATE OF ART

The management of coastal areas presents a unique challenge for several disciplines [6], [7], [8], [9] such as socio-ecology, morphodynamics, infrastructure management, and environmental studies, due to the dynamic interaction between two distinct environments: the terrestrial and the sea [6], [10], [11], [12]. This complexity is further intensified by anthropogenic activities such as coastal urbanization, industrial pollution, and marine traffic, as well as by climate change and its effects (e.g., storms, floods, rising sea level and coastal erosion) [13], [14], [15]. Traditional surveying techniques and methodologies often struggle to capture the multiple relationships between the terrestrial and submerged elements of these environments [5], [11]. Only through the collaboration of various disciplines is it possible to comprehensively understand and address the coastal environment to assess its resilience [4], [16], [17], [18], [19], [20], [21]. The concept of coastal resilience in the scientific literature refers to both a system's response to patterns of change and a goal to be achieved through managed decision-making [13], [22], [23], [24]. Because the term is applied across environmental, ecological, physical, and social sciences, [13], [25], [26]. This highlights the need for an interdisciplinary approach [6], [27], [28], [29], [30], and the development of a common language that integrates knowledge from diverse fields and ensures a comprehensive understanding of coastal systems in all their dimensions [31], [32], [33], [34]. In practice, that common language relies on the collection and analysis of reliable datasets, particularly geospatial and hydro-spatial data [35], [36], [37], [38], [39], [40] [41]. These data sets serve as a bridge between terrestrial and marine studies, enabling researchers to explore the interconnection of coastal processes, to identify drivers and responses. Furthermore, these datasets address both aspects of coastal resilience, documenting the response of a system to a changing pattern, and providing a comprehensive understanding of the environment to improve decision-making. Therefore, the need arises for a common reference frame capable of seamlessly integrating terrestrial and marine datasets. This integration is essential to generate a unique 3D model or a Digital Twin (DT) for the effective representation of virtual information in the emerged and submerged coastal areas [18], [42], [43], [44]. Beyond geometric and scientific analysis, 3D models and DTs can effectively represent the environment [42], [45], [46], merging inputs from several disciplines for stakeholders. This approach is also fruitful in social assessments, providing a better understanding of how people behaviors affect the environment [47], [48], [49], [50], [51], especially when assessing the underwater environment that is beyond our sight.

A fundamental question arises from this interdisciplinary context: how to build a robust methodology that integrates the wide range of existing survey techniques to capture both terrestrial and underwater attributes [11], [35], [52], [53], [54], [55], [56]? Data collected from terrestrial and underwater environments domains rely on distinct equipment and techniques [2], [24], [25], [35], [57], [58], [59], each with specific accuracy and spatial resolution [32], [48], [60], [61], [62], [63], [64], [65] as well as their own type of output data. For instance, an accurate underwater survey can be achieved using echosounders, resulting in a precise underwater mapping of the seabed [10], [33], [55]. However, such data alone, although essential, may not be sufficient to provide a comprehensive assessment of ecological habitats [26], [32], [58], [66], [67]. This is where a photogrammetric model emerges as a promising solution for

ecological assessment, offering the potential to overcome these interdisciplinary challenges and to provide a more holistic understanding of coastal ecosystems [11], [35], [68], [69], [70], [71]. This methodology finds extensive applications ranging from geomatics and cartography to archaeology and environmental monitoring [4], [6], [25]. Its ability to reconstruct accurate three-dimensional models from two-dimensional imagery has positioned it as a primary tool in modern geospatial analysis. Within the domain of photogrammetry, two distinct yet interconnected domains stand out: terrestrial and underwater photogrammetry [23], [49], [72]. Terrestrial photogrammetry, with terrestrial or aerial acquisition, often facilitated by UAVs, employs imagery to map the Earth surface, offering high-resolution data [31], [34], [56], [58]. In contrast, underwater photogrammetry explores hidden depths, leveraging imagery captured by individuals equipped with underwater cameras to expand knowledge of submerged environments [6], [73]. In this framework, the integration of terrestrial and underwater photogrammetry presents a promising solution for bridging terrestrial and underwater environments. It offers the potential to create a unified framework for geospatial and hydro-spatial analysis in coastal areas [37]. At the same time, this integration introduces critical technical challenges related to differences in scale, accuracy, and especially georeferencing. This represents a core technical challenge, particularly in underwater environments where GNSS positioning is not directly available.

Photogrammetry has gained widespread recognition as a cost-effective method for spatial data acquisition, particularly for ecological and habitat assessments, archaeological documentation, and coastal infrastructure inspection, where visual detail and spatial continuity are critical. As with any other discipline, underwater photogrammetry has advanced significantly through the development of various innovative techniques. The advancement of computer vision algorithms, especially Structure-from-Motion (SfM) and Simultaneous Localization and Mapping (SLAM), has significantly enhanced the capabilities of underwater photogrammetry [74], [75], [76], [77], [78]. These algorithms allow for the reconstruction of dense point clouds from sequences of overlapping images, even when collected in challenging underwater conditions with variable lighting, turbidity, or scene complexity. As a result, underwater photogrammetry has become an increasingly viable complement to acoustic-based systems for a range of scientific and engineering applications. However, the main challenge in underwater photogrammetry remains the accurate georeferencing of the generated models. Unlike terrestrial or aerial surveys, which can easily integrate GNSS data for spatial positioning, underwater environments inherently lack direct satellite visibility. The dominant technique in underwater photogrammetry involves scaling the model based on camera calibration [3], [49], [58], [62], [79], [80], [81], [82], [83], [84], [85], facilitating the monitoring of changes over time [26], [32], [34], [35], [56], [59], [61], [63]. Although the substantial value of this scaling approach is recognized, a significant challenge arises due to the lack of standardized georeferencing in the collected underwater data. The data is often recorded in local coordinates system, as underwater positioning systems tend to be expensive. One adopted approach for underwater positioning to obtain a georeferenced model is using underwater targets [3], [32], [54], measured by GNSS elongated from seabed up above the water surface. This technique has its difficulties and limitations depending on the depth and the sea current situation. This lack of georeferencing causes the well-known spatial disconnection between terrestrial and aquatic environments and interrupts the connectivity necessary for effective coastal management and resilience planning between emerged and submerged areas [10], [11], [60].

Research in this field increasingly explores alternatives to GNSS dependent alignment for sustainable coastal mapping [4]. Previous studies have primarily focused on using GNSS and total station measurements to align above-water and underwater datasets [86]. Some works have investigated the use of aerial or satellite imagery for coastal monitoring, but they have not directly applied orthophotos as a reference framework for dynamic positioning and merging terrestrial and underwater environments. To address these georeferencing challenges, recent research including the approach developed in this thesis has investigated the use of orthophotos as a stable alternative to GNSS-based positioning. The idea of using orthophotos emerged from the need to overcome GNSS limitations in some areas. This method offers a novel and practical solution for integrated mapping in coastal and nearshore environments, while significantly reducing reliance on GNSS-based positioning systems. By leveraging orthophotos as georeferencing tools, the approach avoids many of the logistical and technical limitations. In addition, it reduces complexity of field operations, making it especially advantageous in environments where access is limited, conditions are hazardous, or time is constrained. This enables more frequent environmental monitoring, which is critical in the context of climate change, coastal erosion, and habitat degradation. Furthermore, the integration of terrestrial and underwater photogrammetry within a unified spatial reference frame enhances the quality of environmental models used for decision making. The visual and spatial continuity of the models also facilitates clearer communication with stakeholders, enabling more inclusive and transparent coastal management processes. Terrestrial and underwater survey methods depend on several factors, primarily the survey objectives and standards. A deep understanding of surveying techniques is essential, particularly regarding accuracy, precision, coverage limitations, cost-effectiveness, and time efficiency[87]. Terrestrial and underwater surveys are commonly used to investigate and monitor the changes in geomorphological processes over time, such as coastal erosion, sediment transport, and submarine landslides, which shape and transform the landscape [88], [89]. Despite the existence of multiple available methods and techniques, the quality of data collected from terrestrial and underwater environments rely on the usage of different equipment at different times and is obtained with assorted accuracy and spatial resolution [90], [91]. Subsequently, several methods have been proposed to combine the datasets deriving from terrestrial and underwater areas to achieve a holistic knowledge of these environments [92], [93]. The goal is to achieve a continuous model as an output between the two environments.

Existing approaches, ranging from traditional techniques such as underwater vessels, total stations, and GNSS, to the latest innovations in remote sensing like photogrammetry, laser scanning, LiDAR, and acoustic sensors, provide the opportunity to collect huge amounts of data. The availability of several sensors and techniques leads to various methods of combining datasets. Generally, acquiring data from different environments terrestrial and underwater leads to better quality by using a dedicated sensor for each environment. This is due to the different specifications for each sensor that influence the spatial resolution of measurements. In light of this, investing available resources and combining data from various sensors [94] offers the potential to create a precise, seamless DSM between terrestrial and underwater environments [95].

To apply a methodology for survey execution in a shallow water area, underwater environments are surveyed collecting underwater measurements, which are conducted using acoustic methods, such as SBES

and a MBES. SBES are typically used for less detailed surveys or when covering smaller areas, while MBES are used for high-resolution mapping and larger or more complex survey areas. [96], [97]. Conversely, the terrestrial environments are generally surveyed using photogrammetry, which is becoming one of the most cost-effective techniques for terrestrial surveys in terms of time and effort [15] as well as in terms of accuracy and coverage. The common nature of the product from these different sensors is presented as a point cloud that eases the merging process of the two datasets. In addition to acoustic methods, other surveying techniques and sensors are used to enhance data collection and improve accuracy. MLS (Mobile Laser Scanner) can be mounted on ASV which is considered an efficient solution to combine terrestrial and underwater datasets in shallow water areas, since it ensures the continuity of data [15], [97]. From a different perspective, LiDAR offers a conceptual methodology for creating a seamless model integrating both terrestrial and underwater zones, providing a continuous and comprehensive representation of the terrestrial environment. Terrestrial and underwater LiDAR sensors have different specifications, which lead to different accuracy, vertical datum, resolution and data processing [93]. Among photogrammetric techniques, there is a substantial new photogrammetric technique called Structure from Motion (SfM), which permits the generation of a 3D model in coastal areas integrating terrestrial and underwater zones through algorithms including camera motion [98]. Hence, unlike conventional photogrammetry, SfM benefits from highly calibrated cameras and stable imaging geometry. SfM relies on the overlapping between consecutive images to reconstruct a 3D model starting from 2D images [98]. The output product of this technique is a point cloud with spatial resolution that is generally comparable to LiDAR, which is the achieved accuracy underwater are related to several environmental issues such as seafloor texture, water clarity and effective depth [96]. The difficulties in creating a single coherent DSM for terrestrial and underwater zones are related to the vertical datum variation between underwater and terrestrial measurements. Moreover, the occurrence of horizontal gaps due to the merging of two datasets impacts the reliability of the obtained DSM. The use of ASV, capable of working and collecting SBES data in less than 15 cm of water, obtaining data at the boundary layer between terrestrial and water, thus providing the possibility of integrating the data into a better way.

Beyond the technological overview, it is important to examine the methodologies that have been developed in recent years to enable seamless 3D reconstructions across the terrestrial–sea interface. Several studies have proposed integrated workflows combining terrestrial and underwater survey techniques to address the spatial discontinuity between datasets. For instance, a previous study demonstrated a methodology that merges UAV-based SfM photogrammetry with MBES data for mapping intertidal rocky shores, using ground control points and underwater correction to ensure continuity [99]. Similarly, a combined aerial laser scanning and underwater LiDAR, applying water refraction correction to align elevation models across submerged and emerged zones [100]. Another example was the combination of sonar, LiDAR, and photogrammetric data to reconstruct coastal defense structures, highlighting the potential of multi-sensor data fusion in coastal engineering [101]. While these approaches illustrate the potential of unified coastal mapping, they also face notable limitations. Many rely on ideal acquisition conditions, require expensive positioning systems or extensive infrastructure for ground control, and often assume unimpeded GNSS availability conditions that are not always feasible in operational environments such as harbors, narrow inlets, or protected coastal zones. In addition, despite advancements in SfM, some

workflows omit crucial corrections for water refraction, which can introduce significant vertical errors in shallow water reconstructions if not properly addressed. These issues raise concerns about the repeatability and accuracy of such methods in real-world applications.

In addition to acoustic methods such as SBES and MBES, other technologies are increasingly used to survey shallow sea bottoms, particularly in areas where boat access is restricted or water clarity is high. Among these, Satellite-Derived Bathymetry (SDB), LiDAR bathymetry, and photogrammetry are gaining traction for their ability to capture extensive areas efficiently. SDB techniques rely on multispectral satellite imagery (e.g., Sentinel-2, WorldView) and radiative transfer models to estimate bathymetry based on watercolor and seabed reflectance. Studies have demonstrated the utility of SDB for mapping coral reef zones and lagoon environments with depths typically ranging from 0.5 to 20 meters, depending on water clarity [102]. Despite lower vertical accuracy compared to active sensors, SDB provides a cost-effective and scalable option for preliminary or large-area assessments [102], [103]. However, airborne underwater LiDAR systems, particularly green-wavelength ones, enable direct depth measurements in clear, shallow waters by differentiating the return times of infrared and green laser pulses. Applications include coastal erosion monitoring, habitat mapping, and shoreline delineation [104], [105]. While these systems are more accurate than SDB, their performance is still limited by factors like water turbidity and sea surface conditions. Photogrammetric methods, especially those using UAVs, have also been adapted for shallow water bathymetry through two-media SfM workflows. When refraction corrections are applied, these workflows can deliver accurate reconstructions of submerged features, especially in calm and clear conditions. Notable examples, used UAV-SfM photogrammetry to map tidal flats [106], and others applied refraction correction algorithms for improved underwater accuracy in UAV-derived models of submerged sandbanks. These approaches are particularly attractive due to their low cost, accessibility, and ease of deployment. However, such optical and photogrammetric methodologies are limited to very shallow waters, typically within the few meters of depth, depending on water clarity and light attenuation[107], [108], [109]. Beyond this range, the penetration of visible light decreases exponentially, making reliable reconstruction impossible without active sensors[110]. Furthermore, their performance is restricted to calm water conditions, where wave motion, surface ripples, or turbidity do not distort light propagation or image matching[107]. In summary, these alternative technologies SDB, LiDAR, and photogrammetry offer promising solutions for mapping shallow seabeds. Their integration into broader survey workflows is essential for improving spatial continuity across terrestrial and underwater datasets, especially in areas where traditional acoustic methods are either impractical or insufficient. Nonetheless, their applicability remains constrained by environmental conditions and water transparency, making them complementary rather than substitutive to acoustic methods such as SBES or MBES in deeper or more dynamic waters[109]. SDB, while cost-effective and scalable, is highly sensitive to water clarity, seabed reflectance which can introduce substantial uncertainty in depth estimation [102], [103]. Studies report that SDB accuracy is unsuitable for applications requiring fine-scale underwater detail or modeling of subtle seafloor changes. Airborne underwater LiDAR systems offer high resolution and accuracy but are limited by operational costs, environmental constraints, like turbidity and wave motion, and the need for open and unrestricted airspace. These factors make them impractical in many nearshore and urbanized coastal zones. UAV-based photogrammetry, though highly effective for terrestrial surveys, faces significant challenges

in coastal contexts. Airspace regulations can restrict UAV flights in harbor areas or near infrastructure [99], and the accuracy of underwater photogrammetry is strongly affected by image clarity, and camera calibration. Moreover, if refraction correction is omitted, vertical errors may exceed 50% of the true depth [111], undermining the reliability of photogrammetric reconstructions in shallow waters. Taken together, these constraints motivate the search for flexible integration strategies that remain reliable across diverse operational contexts. Further technical details concerning terrestrial-based and underwater survey methods and instrumentation are discussed in the upcoming sections. The methodology proposed in this Ph.D. Thesis builds upon these foundations but introduces several key advancements: (1) a modular, context-sensitive workflow that substitutes GNSS with orthophoto-based georeferencing when necessary; (2) flexible use of different acquisition platforms depending on site constraints (e.g., ASVs, snorkelers, handheld systems); and (3) an emphasis on accessibility and repeatability. This approach not only reduces dependency on high-cost equipment but also enhances adaptability to diverse coastal settings, supporting more frequent and interdisciplinary use of coastal survey data.

1.1 LAND SURVEY

Traditional terrestrial surveying methods are time consuming and expensive, yet they guarantee high accuracy. The historical records for beach surveys are limited both spatially and temporally [112]. However, survey data can be an accurate source for coastal information although their collection typically requires costly field campaigns and specialized personnel. The goal of data collection in coastal areas is to measure the beach profile of the targeted area, the rise and the position of the coastline and to represent them as a map which may incorporate elevations, contours and 3D models. This information would then be used for an assortment of purposes, e.g., the representation of shoreline volumes and evolution of shoreline material. A shoreline can be graphically represented by interpolating between a series of separate shore-normal beach profiles [113] (Figure 1). These terrestrial profiles are a set of measurements of distance recorded perpendicularly to the shoreline alongside predetermined lines. Accurate beach-profile measurements are important in the study of shoreline variability and tracking beach recovery [114]. If suitable beach profiling data are available for a specific site, tidal datum-based shorelines can be easily and accurately determined because beach profiles provide detailed cross-sectional measurements of coastal topography, allowing for precise elevation referencing. Tidal datums, such as mean high water (MHW) or mean lower low water (MLLW), serve as standardized elevation benchmarks, that help define the shoreline position. By aligning beach profile data with these datums, researchers can accurately track shoreline changes, assess coastal erosion, and monitor the impacts of sea-level rise.

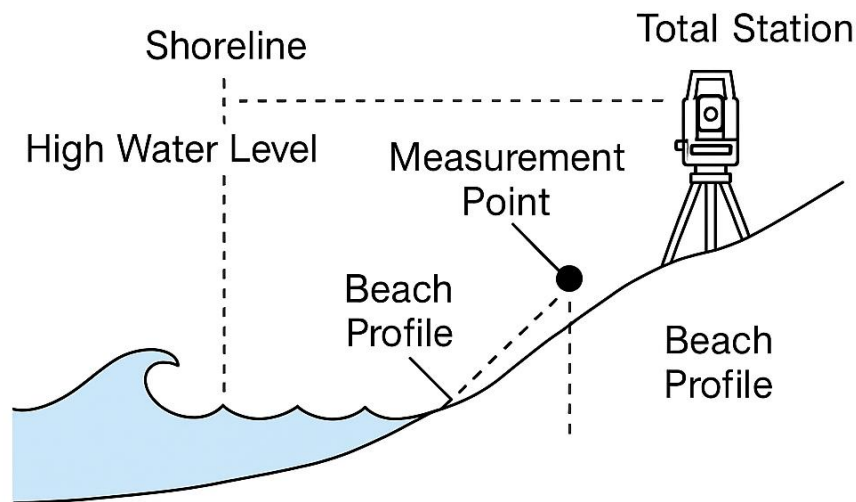


Figure 1. Schematic diagram of a beach profile and shoreline detection during a terrestrial surveying on a beach environment. Source adapted from [115].

1.1.1 Photogrammetry

Photogrammetry is measuring technique that uses images as an essential factor for 3D object reconstruction. The substantial principle used in photogrammetry is triangulation [116]. By collecting images from at least two different locations, the line of sight can be developed from each camera to the object. These lines of sight are intersected to obtain three-dimensional coordinates of the interest point. The images are generally taken with at least 60% overlap on longitudinal direction, i.e., along the direction of flight, between two consecutive images in the observed area. Thus, objects existing in the overlapping area between images could be then seen in three dimensions. To construct the geometry of overlapping images, the principle of stereoscopic vision is used in interpreting and studying overlapping images. [117]. The procedure for aerial surveying includes reconnaissance of the area, establishing ground control points, flight planning, acquisition of images, and data processing, including computation and plotting. Exploration of the area is undertaken to identify the important features of the ground, which serve as ground control points (GCPs). The GCPs are essential for establishing a set of known reference positions, allowing for accurate positioning and mapping within the survey area. The number of GCPs depends upon the extent of area covered, scale of the map, flight plan and the process of preparing the map. A minimum of three GCPs must exist in each block and control points must be established for both horizontal and vertical references. Flight planning includes the decision of UAV speed, altitude, covered area, longitudinal and traverse overlaps and flights number. Overlaps ensure to provide less central part distortion than the outer edges and overlapping is required also to ensure entire coverage of the target area. An image unlike a map (based on orthographic projection) does not have uniform scale, since it's a central projection. The scale of photographs harshly related to the representation of any object in the photograph depends upon the distance of the object from the camera [4]. As all the ground features do not have the same elevation, it is obvious the scale representation will be different for features lying at different elevations. The scale variation is related to flying height and to reduce this variation an average elevation and average scale can be considered [5].

The 2D and 3D models generated from arial photogrammetry represent physical features in true dimensions on terrestrial. Aerial images can't be used directly since they are distorted so they must be corrected before usage; the images distortions include the distortion in radial, relief, tilt and pitch of the aircraft, while the scale variation is due to the changing in the altitude along the flight line. Digital aerial photos are used as input to build a digital surface model using photogrammetric software that could be georeferenced with respect to a real reference frame. To achieve the three-dimensional coordinates of any object, it is necessary firstly to identify the same point on at least two images. By projecting collinearity rays from each image their intersection defines the point's position in space. The relationship between image coordinates and ground coordinates is established through collinearity equations [118].

$$x = x_0 + f \frac{(r_{11}(X - X_s) + r_{12}(Y - Y_s) + r_{13}(Z - Z_s))}{r_{31}(X - X_s) + r_{32}(Y - Y_s) + r_{33}(Z - Z_s)}$$

$$y = y_0 + f \frac{(r_{21}(X - X_s) + r_{22}(Y - Y_s) + r_{23}(Z - Z_s))}{r_{31}(X - X_s) + r_{32}(Y - Y_s) + r_{33}(Z - Z_s)}$$

Equation 1. Collinearity equations[119]. These equations relate object space coordinates (X, Y, Z) to image space coordinates (x, y) using a rotation matrix (rij) and focal length (f), fundamental for georeferencing in photogrammetry.

Where x and y are the image coordinates (in pixels); x_0 and y_0 are the principal point coordinates of the camera; f is the focal length; X, Y, Z are the ground coordinates of the object point; X_s, Y_s, Z_s are the camera projection center coordinates in the external reference frame; rij are the elements of a 3×3 rotation matrix (computed from roll, pitch, and yaw angles). The collinearity condition is expressed by non-linear equations, used for estimating points coordinate (x and y). Thus, the object coordinates are computed depending on the intersection of lines of each frame referring to a non-linear least squares estimation called Bundle Block Adjustment [119]. Some parameters should be taken into consideration: (1) the external orientation, which allows defining the position and the attitude angles of each frame in the object system during acquisition; (2) the internal orientation, which parameters are assessed by calibrating the camera and include image distortions; (3) the image coordinates of the single analyzed pixel. This operation needs to know the geometry of the camera, tie points and GCPs [118]. The result is achieved by determining the three-dimension space of object from the dimension of the image, in other words, switching from image coordinates of a point that is 2D to the object coordinates in space that is 3D (Figure 2). It is also possible to obtain the final product in an external reference frame by assigning GCPs coordinates measured through the survey by using GNSS or total station. This technique has become commonly employed due to its easy usage, simple field procedure, and cost-effective high accuracy positioning [120].

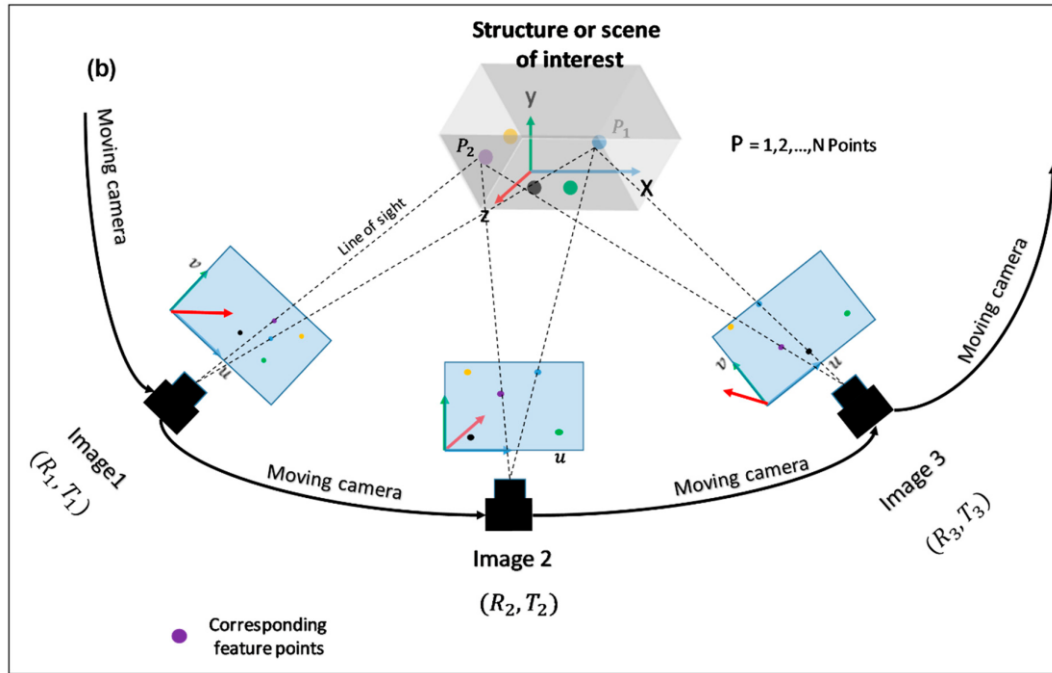


Figure 2. Photogrammetric 3D reconstruction using multiple images. The camera captures overlapping images from different viewpoints, identifying identical feature points across images. These feature points are then used to reconstruct the 3D structure of the object by triangulating their positions along the lines of sight. Source adapted from [121].

1.1.2 Global Navigation Satellite System

Global Navigation Satellite System refers to constellations of satellites transmitting time and positioning signals to receivers on ground to determine location. In GNSS positioning, the obtained accuracy is strongly dependent on the visibility satellites in terms of the number and geometry of visible satellites. GNSS consists of three segments, the spatial segment, control segment and the user segment. The space segment is related to satellites in orbit. GNSS satellites consist of several active satellites that are arranged in a known and specific orbit around the earth. This arrangement ensures the visibility of four satellites 15° above the horizon at any time and from any position on the Earth [122]. Each satellite contains highly accurate atomic clocks, and they constantly transmit two carrier waves L1 and L2 (in the standard double frequencies version) with different frequencies. The carrier waves are important because they transmit information from satellite to Earth that allows the receiver to determine the location. The control segment refers to several ground stations distributed around the equator to track, check and send information to each satellite. The user segment is meant by the GNSS receivers on the ground that acquire the signals transmitted from the satellite that will provide it position and time. This positioning method is based on a process called reverse intersection in terrestrial surveying [122]. To obtain a position requires at least 4 measurements due to solve the 3 geometric unknowns of the position and 1 more to acquire perfect synchronization between satellites and receiver clocks (Figure 3). This concept is essential especially when the measurements are conducted where satellite signals could be disturbed like in narrow channels, harbors, coastal areas with noises presence, or any place that are surrounded by obstructions or by presence of electromagnetic radiation. To overcome this problem, GNSS includes all satellite global navigational

systems, such as GPS (Global Positioning System), GLONASS (Russian satellite navigation system), Compass or Beidou (Chinese satellite navigation system) and Galileo (European satellite navigation system) measurements, especially to achieve more accurate results by increasing the number of visible satellites in sky with better geometry. More observations like GLONASS, are used to enhance the positioning accuracy especially in case there are not enough numbers of GPS satellites are visible. The provided precise information of orbits and clock for all the satellite navigation system leads to the ease usage for the multi-systems receivers.

One of the uses of GNSS is for mapping the shoreline using the kinematic differential satellites that the operator will locate the positioning system (antenna connected to the receiver or embedded in the receiver itself) along the line of interest and take consecutive measurements along the coastal line to define its position by real coordinates. This allows us to collect data with vertical and horizontal accuracies of centimeters [123] using phase measurements.

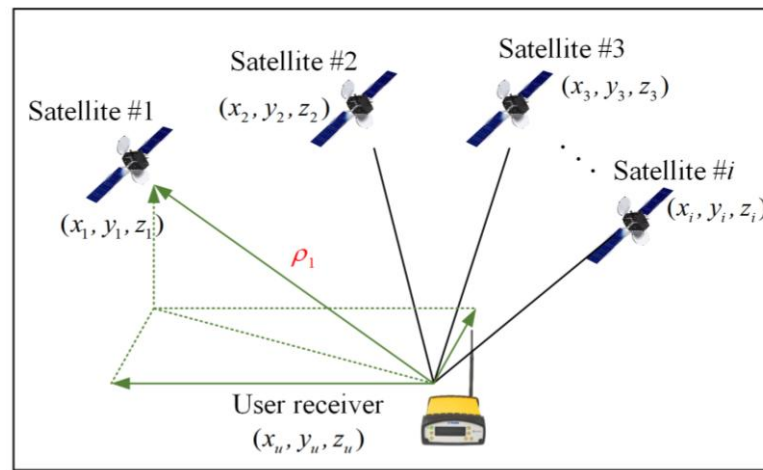


Figure 3. GNSS positioning process. At least four satellites with known positions (X, Y, Z) and time (T) transmit signals to a receiver, which measures the signal travel times (ranges). These measurements are used to estimate the receiver's position in three dimensions (X, Y, Z) and correct the GNSS time (T) for accurate positioning. Source adapted from [124].

As known, post-processing GNSS surveying allows for the highest level of accuracy and, above all, reliability, while real-time surveying allows us to achieve the highest level of productivity in the survey, with a good accuracy level. Real-Time Kinematic (RTK) is a technique that uses two receivers: one stationary (the base station) and the other mobile (the rover). The basic concept is to estimate the main effect on the signal in the base station, to apply with differential correction to the rover station, strongly reducing the positioning errors common to both the base station and rover. The base station stays in a fixed location and sends correction data to the rover, that uses this data to calculate its position (Figure 4-a).

The decimeter positioning accuracy in the stand-alone receiver positioning is strongly improved with RTK technique to a sub-meter level in the code-based positioning and to a centimeter level, using carrier-based ranging.

Network Real-Time Kinematic (NRTK) is based on the same principle but the base is represented by a network of several permanent stations that regularly communicate positioning data to a central processing

station. The approximate location of the operator is sent to the central station, where it will be calculated and then it transmits correction information or corrected position to the RTK user terminal. The advantage of this method is the elimination of base station required. Data may be transmitted over cellular radio links or any wireless medium (Figure 4-b).

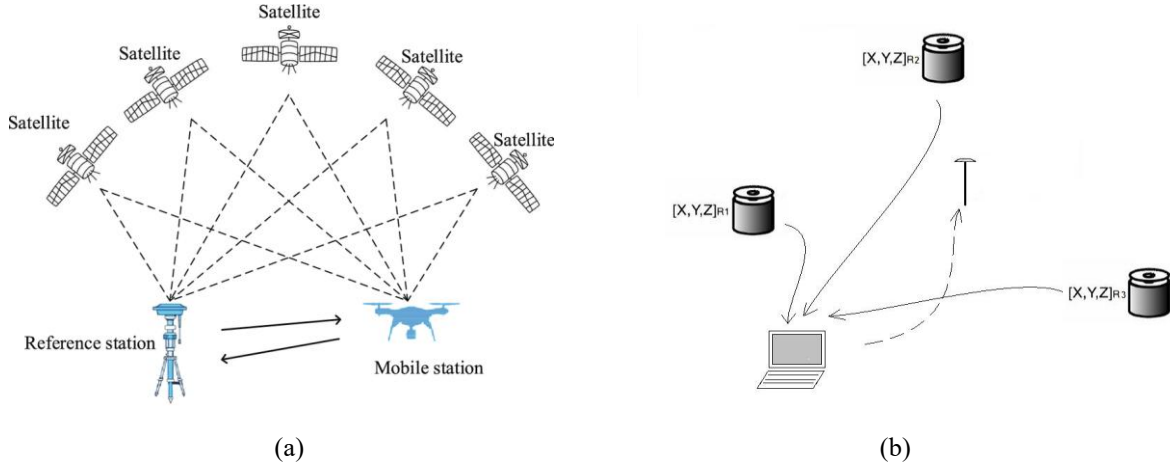


Figure 4. RTK positioning system (a) where corrections are transmitted from a base station to a rover to improve accuracy, and NRTK positioning system (b) where corrections from a network of reference stations are combined and transmitted to the rover to provide accurate 3D positioning Source adapted from [125].

In coastal environments, GNSS technology plays a fundamental role in establishing accurate spatial reference frameworks for both terrestrial and marine surveys. High-precision GNSS, particularly in its Real-Time Kinematic (RTK) and Post-Processed Kinematic (PPK) modes, is routinely employed for shoreline mapping, intertidal monitoring, and ground control point (GCP) establishment for UAV and LiDAR surveys. In shoreline surveys, RTK-GNSS systems mounted on backpacks, ATVs, or small vessels record continuous position data along the instantaneous waterline, enabling the derivation of precise coastal topography and shoreline change rates with horizontal and vertical accuracies typically better than ± 3 cm under optimal satellite geometry[126]. The technology is particularly valuable in dynamic intertidal zones, where rapid morphological changes from tides, waves, and sediment transport demand high-frequency and repeatable measurements. Furthermore, GNSS positioning provides the geodetic control necessary to integrate multi-sensor coastal datasets such as UAV photogrammetry, terrestrial laser scanning, topobathymetric LiDAR, and satellite-derived bathymetry into a unified vertical datum, ensuring the seamless continuity of coastal elevation models[127]. In hydrographic applications, GNSS is coupled with echosounders on small boats or autonomous surface vehicles (ASVs) to obtain georeferenced depth profiles referenced to ellipsoidal or tidal datums, supporting bathymetric charting and sediment budget studies[106]. Recent developments also include the integration of GNSS with inertial measurement units (IMUs) to enhance trajectory stability under signal degradation, which is common near cliffs, harbor structures, or dense vegetation along the shoreline. Overall, GNSS remains the backbone of coastal surveying infrastructure, providing the positional accuracy and temporal stability required for change detection, coastal vulnerability assessments, and validation of remote-sensing products such as LiDAR- or photogrammetry-derived digital elevation models.

1.1.3 LiDAR and Laser Scanner

LiDAR (Light Detection and Ranging) is a remote sensing method that uses light in form of laser to measure variable distances. It has the ability to cover vast areas quickly, with some systems capable of surveying up to several hundred square kilometers in a single flight, depending on the altitude and scan rate [128]. The method is based on measuring the time taken by the laser beam from leaving the instrument until it returns after reflection from the surface (i.e., terrestrial or water, only in shallow and calm water). LiDAR can accurately determine the water depths only in specific depth and specific conditions, by measuring the time of flight of two lasers that are sending by the airborne at different wavelengths: the first laser is send is an infrared one that backscattered by the sea surface, while the second laser that is green light travels through the air-water interface to the bottom of the sea, as shown in (Figure 5). A receiver on the aircraft detects the difference in time for the reflections from both the seabed and the sea surface. The water depth is determined by differentiation of the time between the two lasers, after taking into consideration the several factors such as the system operating geometry, propagation-induced biases, tides effects and wave heights.

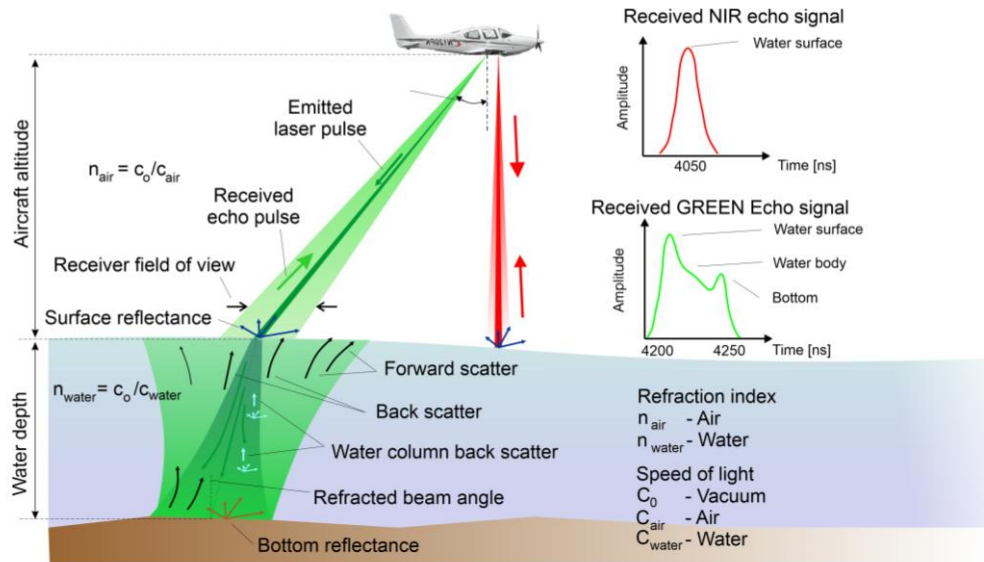


Figure 5. Schematic of airborne topo-bathymetric LiDAR. The near-infrared (NIR) beam reflects off the water surface (land/topography), while the green laser beam penetrates the water to capture bottom echo enabling simultaneous mapping of land and submerged terrain. Source adapted from [129]

Similarly as LiDAR, Laser Scanner (LS) has been successfully implemented for a wide variety of applications ranging from 3D modeling of small objects to large-scale terrain mapping [130]. LS uses laser technology to capture shape, size and details of an object, and it performs at high speed, in particular, phase-based scanners compare phase shifts between a modulated laser beam to determine distance to a target at close ranges. The measure of the laser pulse travel time and the angle of return is required to determine the coordinates of the reflective objects relative to the scanner origin. Various laser scanners are currently available with varying speeds, scanning resolutions and point measurement accuracies. Most scanners concurrently acquire the scene to provide photorealistic RGB values to each scan point. Moreover, an intensity value is returned, which is the strength of the signal degradation and provides information

about the type of material the laser pulse was reflected from. The output will be based on a point cloud indicating the coordinates (x, y and z) and the intensity (reflected energy) for every point.

In coastal environments, airborne and terrestrial LiDAR have become indispensable for producing seamless topographic–bathymetric digital elevation models that integrate the land–sea interface with high vertical accuracy. The most common coastal application is topo-bathymetric LiDAR (TBL), which uses green laser pulses (≈ 532 nm) capable of penetrating the water column to depths of up to two to three times the local Secchi depth, depending on turbidity and bottom reflectance. This capability allows simultaneous acquisition of terrestrial topography and shallow-water bathymetry within a single flight, facilitating continuous coastal terrain models essential for flood modelling, sediment-budget analysis, and habitat mapping. In addition to traditional discrete-return processing, recent research has focused on full-waveform (FWF) LiDAR approaches that analyse the entire backscattered signal rather than isolated peaks, thereby improving discrimination between water surface, water column, and seabed returns. Advanced waveform-stacking and deconvolution techniques, such as volumetric nonlinear ortho full-waveform stacking, significantly enhance bottom-return detection in optically complex waters, extending the measurable depth range and reducing uncertainty due to surface roughness and turbidity [131], [132].

Furthermore, hybrid coastal LiDAR strategies increasingly combine airborne and terrestrial (or mobile) laser scanning to capture intertidal zones that are partially submerged or obscured by breaking waves, where bathymetric returns are degraded. In addition, machine-learning classification methods are being introduced to automate the discrimination of bottom types and removal of water-column noise from LiDAR point clouds, thereby enhancing seabed characterization [133]. Despite its advantages, LiDAR bathymetry remains constrained by optical water quality, wave-induced noise, and laser-beam refraction at the air–water interface. Nevertheless, when properly calibrated and integrated with GNSS/IMU navigation data, topo-bathymetric LiDAR offers an unparalleled means of mapping coastal morphology with high accuracy and spatial continuity, making it one of the most mature and operationally reliable technologies in modern coastal geodesy.

1.2 UNDERWATER SURVEYS

Hydrography is the branch of applied science that focuses on the measurement and description of the physical features of oceans, seas, coastal areas, lakes and rivers, as well as with the prediction of their change over time, for the primary purpose of safety of navigation and in support of all other marine activities, including economic development, security and defense, scientific research, and environmental protection [134]. Hydrography often employs tools like echo sounder and sonar and even remote sensing technologies (such as LiDAR). The planning of the underwater survey must provide accurate and reliable output derived from appropriate data coverage. The creation of underwater contours is closely related to spatial resolution. In this context, resolution refers to the ability to distinguish two objects from each other; higher resolution allows for more detailed contours, helping to represent underwater features accurately. In bathymetry, higher resolution allows for more detailed contours, helping to accurately represent underwater features. Hydrographic surveying involves mainly three major surveying units including the

marine vessel used, positioning techniques and depth measurements. The size of the marine vessel depends on the depth of the area that is going to be surveyed. The geodetic positioning system and the methodology are selected based on the specific requirements, including site conditions and the nature of the survey. GNSS, primarily used for navigational purposes, plays a crucial role in hydrographic surveys by providing accurate positioning of survey vessels or uncrewed platforms. For marine environments, GNSS is used in modes able to achieve centimeter-level accuracy, which is essential for mapping underwater features and conducting precise depth measurements, e.g., GNSS RTK or NRTK. This ensures accurate georeferencing of the underwater data collected during the survey. Depth measurement is performed using transducers that transmit sound pulses into the water. The return signal is analyzed to determine depth.

A common technique of depth measurement is using echosounder sensors [135]. An echo sounder performs the following operations: transmits sounds, measures round trip travel time and uses sound speed to compute the distance. Two important components of sounding sensors include frequency and beam divergence. Many sonar units operate in the ranges of 38, 125, 200, 455, and 770 kHz [136]. A high frequency (192 or 200 kHz) sonar provides the highest resolution while 50 kHz that is considered as low frequency units have much greater depth penetration, but less resolution [137]. Besides frequency, characteristics of echo sounders are determined by transducer directivity and beam width. Knowledge of seawater physical properties and of acoustic wave characteristics is important, due to the presence of several factors in the sea that could affect the efficiency of the survey (e.g., speed of the acoustic signal can be modified in different water bodies). As factors affecting wave propagation that include temperature, salinity and pressure that is a function of depth. The variation in these factors that occur with depth affect the rate of change in the sound wave velocity that will lead to inaccurate depth measurements. Hence, several sound velocity calibrations measurements must be performed before, through and after any survey using a CTD (Conductivity-Temperature-Depth), providing vertical profiles of salinity and temperature throughout the water column, in different locations and at different times. Generally, vertical accuracy is uncontrolled due to dynamic physical properties of the water column and the morphology of the bottom. This requires an accurate link with reliable vertical Datum that can be based on geodetic vertical Datum, tidal datum and sea surface levels. The instantaneous water surface elevation is derived by various factors including tides, wind and currents. This concept is essential because hydrographic surveys will occur and provide depths from the instantaneous surface water level and then relate underwater measurements to vertical datum.

Other factors influencing underwater accuracy include:

- underwater acoustics
- calibration measurements
- vessel attitude and heave measurements, referring to vessel orientation, pitch, roll and yaw, and to vertical “up-and-down” motion of the vessel, respectively
- sound velocity profiler to check variation versus depth
- CTD instrument to measure conductivity, temperature, and depth.

Real-time data collection requires accurate synchronization of acoustic sensors and the three-dimensional positioning systems [138]. In addition, the necessary synchronization with Motion Unit (MU) sensor mounted on the vessel. Then depth measurement systems involve the link between several sensors,

positioning data from a GNSS, depth data from an electronic echosounder, and motion data from the internal motion sensor into a computer to be recorded. Generally, to conduct the underwater survey a minimum of two operators is needed. However, a robotic setup can reduce this survey to one operation. The advantage of using a robotic system is that it provides direct measurements of the seafloor, while also being more cost-effective and easier to calibrate compared to traditional methods. Ultimately, project specifications typically dictate the survey methodology to be used, ensuring that the most suitable approach is selected for the given environment and objectives.

1.2.1 Single Beam echo sounder (SBES)

A single beam is a type of sonar device that uses acoustic signals under water to compute the depth of the sea floor. The same transducer is installed to transmit and receive signal under the ship hull or it can be mounted on the side, its active face smoothly following the hull shape, in a place chosen to avoid propeller noise as well as hydrodynamic perturbations and bubble clouds from the bow. SBES transmits vertically a signal below its carrier platform in a beam of moderate angular aperture (typically 5° - 15°) [139]. The SBES could operate on several frequencies depending on the required application, that generally range between 12 kHz up to 400 and even 700 kHz for shallow-water [140]. Then chosen frequency depends on different factors. Higher frequencies are typically chosen for shallower environments because they optimize the maximum operational depth and provide better resolution. This results in less uncertainty of measurements. Additionally, higher frequencies require a smaller transducer. On the other hand, low frequencies are ideal for deeper environments, as they can penetrate further into the water. However, they come with greater uncertainty in measurements and require a larger transducer due to the longer wavelengths. The beam (the angular spread of the acoustic signal) is linked to transducer size and the required survey accuracy. Narrower beams provide higher resolution but smaller coverage, and usually require larger transducers (at fixed frequencies). Wider beams increase coverage but reduce accuracy.[140]. The power of the signal and the pulse width both contribute to increasing the signal range, allowing it to travel farther. However, as the range increases, the ability to detect objects with high precision decreases, leading to higher uncertainty. SBES signals are generally not modulated; their duration is sufficiently short for an acceptable resolution, the pulse duration is less in shallow water to increase resolution, and higher in deep water to increase the instantaneous acoustic power available at reception. Typically, SBES transmit a new signal only after receiving the full echo from the previous signal. However, in some cases, multiple echoes, which have traveled several times through the water column, may still produce noticeable amplitudes. These overlapping echoes can occur, particularly in shallow water, where the signal bounces back more quickly and can result in interference or multiple returns. To avoid ambiguities caused by overlapping, the repetition rate can be reduced. The depth is computed by the concept of two-way travel time that is converted into depth range. The fundamental measurement principle is the two-way travel time of the acoustic pulse[141]:

$$H = ct/2,$$

Equation 2. Two-way travel time equation for SBES depth measurement, where H is the vertical distance from the transducer to the seafloor, c is the speed of sound in water, and t is the round-trip travel time of the acoustic pulse[141]

where H is vertical distance from the sensor to sea floor, c is the speed of sound in water and t is the two travel time for the wave. It can be easily observed that neglecting the actual Sound Velocity Profile (SVP) and instead using a constant sound speed (c) averaged over the water column results in a negligible error in the depth measurements. The data acquired by sounders are time-stamped and referenced with the location at which they are acquired by using GNSS system.

Additional information from a SBES can include the type of seabed, which is inferred from the analysis of the backscattered signal. This analysis depends not only on the detected area but also on the strength of the backscatter and the beam directivity pattern. The seafloor backscattering strength (BS) is approximated by its vertical value, and the signal footprint area is represented by its maximum value. The measured sounding depth ($H = ct/2$) can be affected by inaccuracies in the average sound speed. Since H and c are proportional, the relative errors in both values are the same, meaning that the relative error in depth ($\delta H/H$) is equal to the relative error in sound speed ($\delta c/c$). Hence a 1% depth error should imply a 15 m/s error on the sound speed c averaged over the water column which is very unlikely to occur [140]. To reduce these errors, sound velocity profiles (SVPs) are often measured and applied during data processing. The resolution of a sounding measurement is defined as its ability to distinguish two close distinct targets. The resolution for the vertical direction is given by the pulse duration:

$$\delta z = cT/2$$

equation 3. Depth resolution of an SBES (or any pulse-echo sonar), where δz is the vertical resolution, c is the speed of sound in water, and T is the pulse duration. This formula follows the standard expression for sonar range resolution based on pulse length

while for the horizontal resolution is related to the beam angular width. So, to be distinguishable, two targets need to be spaced a part by at least the beam width at the depth considered (Figure 6).

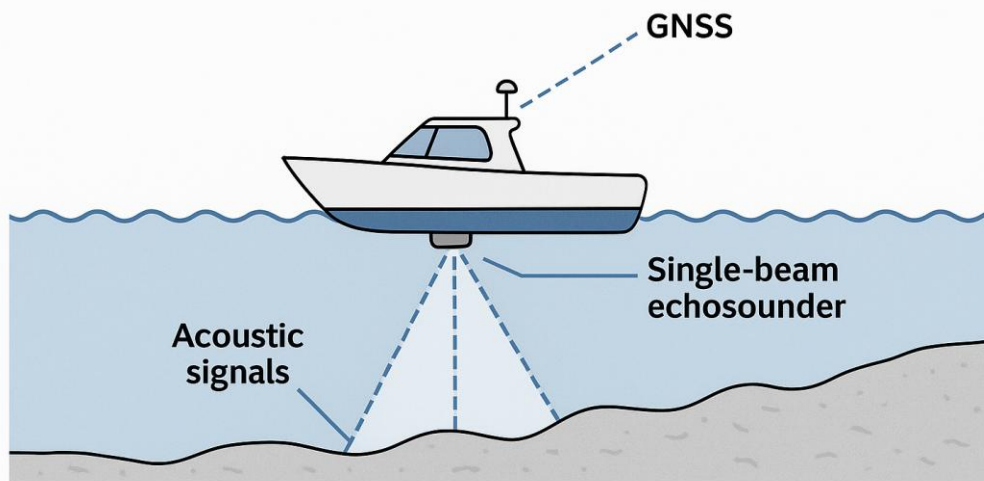


Figure 6. Underwater survey using a single beam echosounder mounted on a survey boat. The system relies on GNSS for positioning accuracy and uses acoustic signals to measure water depth and map the seabed.

1.2.2 Multi Beam echo sounder (MBES)

Differently from SBES, a MBES is a sonar system that emits multiple acoustic signals across a wide swath. It uses an array of transducers, to measure simultaneously the water depth and the seabed reflectivity [142]. Each beam travels vertically through the water and will reflect off the seafloor or underwater object. MBES has two approaches for depth computing, the first is called Beamforming that relies on fixing the angle of arrival and measuring the time of arrival (Beamforming measure time), while the second system is called Interferometry that measures the time series of the angle of arrival of the signal (Interferometry measures angle) [143]. The fundamental principle of bathymetry measurement for MBES is the estimation of times and angles. In the simplified case where the sound velocity profile is constant across the water column, depth can be computed directly (Figure 7). However, in the more realistic case where sound velocity varies with depth, a Sound Velocity Profile (SVP) must be used. This requires geometric ray-tracing software to reconstruct the acoustic path and provide accurate depth estimation. For each beam, a ray is launched at the given angle and followed through the water column until the echo is received. The resulting depth measurement is corrected for all relevant parameters (time of reflection and reception, sound speed, and beam angle).. Three main system categories mainly could be distinguished for the use of MBES:

- deep-water systems (typically 12 kHz for the deep ocean), designed for regional mapping. The large dimensions of their arrays limit their installation to large deep-sea vessels;
- shallow-water systems (typically 70-200 kHz), designed for mapping continental shelves. These systems are best suited to hydrography;
- high-resolution systems (typically 300-500 kHz). They are used for local surveys: hydrography, shipwreck location, inspection of underwater structures. Their small size makes them suitable for installation on small ships, tow fishes or underwater vehicles.
 - To achieve accurate positioning, MBES systems must integrate multiple data sources: The positioning system for the accurate geographical position of the ship; typically, it is GNSS, preferably DGPS (Differential Global Positioning System) or even high-accuracy RTK (Real Time Kinematic).
 - The Motion sensor unit, giving the angular and linear component values of the ship instantaneous movements: orientation of the navigation line, effective orientation of the beam, pitch and roll, vertical movements heave.
 - Sound velocity profiles are used to correct acoustic paths between the sonar and the seafloor, while sound velocity measurements, acquired near the array using a thermometer or velocimeter, help improve beamforming accuracy.

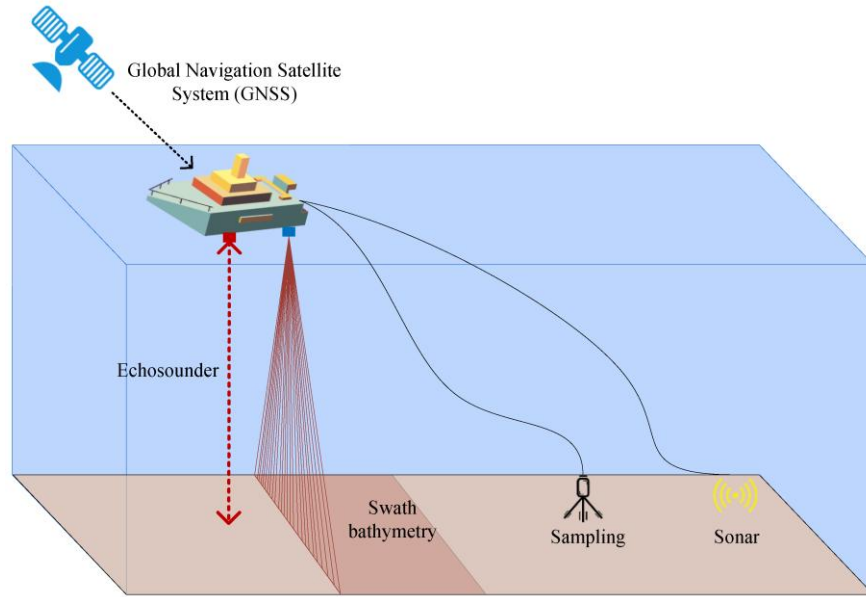


Figure 7. Underwater survey using a MBES mounted on a survey boat. The system relies on GNSS for precise positioning and emits multiple acoustic beams in a swath pattern to measure water depth and create a detailed map of the seabed. Source adapted from [144].

1.3 CURRENT TRENDS AND TECHNOLOGIES IN SURVEY INTEGRATION

Satellite-Derived Bathymetry (SDB) represents a remote-sensing methodology that estimates shallow water depths by exploiting the relationship between spectral reflectance and light attenuation within the water column. The principle relies on the exponential decay of downwelling solar irradiance with increasing depth, where shorter wavelengths in the blue-green region ($\approx 450\text{--}560\text{ nm}$) penetrate deeper, while red and near-infrared wavelengths are almost completely absorbed near the surface. After radiometric and atmospheric correction, depth is inferred from multispectral or hyperspectral satellite imagery acquired by platforms such as Sentinel-2, Landsat-8/9, or WorldView-2. SDB approaches can be broadly divided into two main categories: empirical models, which establish a statistical relationship between reflectance and known depth using acoustic or LiDAR references, and physics-based or semi-analytical models, which invert simplified radiative-transfer equations to decouple the effects of water attenuation, bottom albedo, and depth [145], [146]. A third, increasingly dominant class involves machine-learning algorithms including Random Forest, Support Vector Regression, and Convolutional Neural Networks that learn non-linear relationships between spectral bands and measured depth, achieving greater adaptability across heterogeneous water types [147]. Methodologically, empirical algorithms such as the logarithmic band-ratio model compute depth as a function of the reflectance ratio between blue and green bands, partially compensating for bottom-albedo variability [148]. Under optimal optical conditions, these methods have demonstrated depth accuracies of $\pm 0.5\text{--}1\text{ m}$ to depths of approximately 25 m, with coefficients of determination (R^2) often exceeding 0.9 when validated against LiDAR soundings [149]. Semi-analytical models, although more computationally demanding, have shown comparable performance while offering improved transferability between sites by explicitly accounting for water-column properties and substrate reflectance [150]. The latest generation of ML-based SDB achieves similar or better precision, with

reported RMSE values of 0.6–0.9 m in clear tropical waters and stable performance in optically diverse conditions due to model generalization capabilities [147]. Pre-processing remains critical for accuracy, involving sunlight removal, adjacency correction, and masking of turbid zones, as these factors can introduce systematic depth biases exceeding ± 2 m if uncorrected [148].

Recent advances focus on multi-sensor data fusion, in which SDB products are calibrated using sparse in-situ or airborne LiDAR control points, significantly reducing bias and extending coverage across optically shallow coasts [151]. Cloud-computing infrastructures now enable global, near-real-time SDB production by automating atmospheric correction, glint filtering, and depth inversion, allowing temporal monitoring of bathymetric change and coastal morphology over large spatial domains [152]. Although SDB is inherently limited by optical water quality, bottom type, and spatial resolution (typically 5–30 m depending on the sensor), it remains an efficient and cost-effective approach for large-scale coastal reconnaissance, change detection, and management when integrated with higher-resolution LiDAR or acoustic surveys.

UAVs and marine robotics are increasingly being integrated into survey methodologies, providing innovative solutions for capturing high-resolution spatial data in both terrestrial and underwater environments [153]. These technologies enable researchers to conduct surveys more efficiently and accurately, overcoming many of the limitations associated with traditional surveying methods. UAVs, commonly known as drones, have revolutionized terrestrial surveying through their ability to capture aerial imagery and collect geospatial data at unprecedented scales. Some of the UAVs applications include:

- **Terrestrial Mapping:** drones equipped with LiDAR or photogrammetric tools can create highly detailed 3D terrain models, significantly reducing the time and labor required for ground surveys;
- **Vegetation Analysis:** UAVs enable the monitoring of vegetation health and density by using specialized sensors such as multispectral, hyperspectral, and thermal cameras. These sensors capture various wavelengths of light, allowing to assess factors like plant stress, nutrient deficiencies, and overall vegetation health, facilitating ecological assessments and terrestrial use planning;
- **Environmental Monitoring:** drones can rapidly survey large areas for environmental changes, such as deforestation, terrestrial degradation, or impacts from natural disasters;
- **AUVs:** the self-propelled robots can collect data on underwater habitats, seabed topography, and water quality parameters over extended periods of time, with a navigation planned pre-survey. Their capabilities make them ideal for mapping and monitoring marine environments;
- **Remotely Operated Vehicles (ROVs):** provide real-time video and data collection capabilities, allowing to explore underwater environments and assess the health of habitats, such as coral reefs and seagrass beds, in greater detail.

The integration of UAVs and marine robotics into surveying methodologies provides several benefits:

- **increased efficiency:** UAVs can cover large areas more quickly than traditional methods, significantly reducing the time required for data collection;
- **Enhanced data quality:** high-resolution imagery and precise positioning data improve the accuracy of surveys, enabling more detailed analyses of environmental conditions;
- **Safety and accessibility:** these technologies can operate in hazardous or difficult-to-access environments, such as deep water or remote terrains, reducing risks to human surveyors.

Despite their advantages, the use of UAVs and marine robotics in surveying is not without challenges:

- Regulatory issues: the operation of UAVs is subject to strict regulations, which can vary by region and may limit their use in certain areas;
- Data processing complexity: the large volumes of data require advanced processing techniques and software, which can pose challenges for effective analysis and integration;
- Cost considerations: while the costs of UAVs and marine robots have decreased, initial investments in equipment and training are still being significant, particularly for smaller organizations.

The future of UAVs and marine robotics in surveying is promising, with ongoing advancements in sensor technologies, AI-driven data analysis, and improved interoperability between terrestrial and underwater platforms. These innovations will further enhance the capabilities of integrated survey methodologies, enabling comprehensive environmental assessments that account for the complex interactions between terrestrial and marine ecosystems.

1.4 DATA INTEGRATION

One of the most serious challenge in implementing coastal zone management is to obtain accurate data and spatial information so that objects and features can be easily distinguished across the water-terrestrial interface [154]. This difficulty mainly arises from the differences between terrestrial and offshore (underwater) survey techniques, combined with the dynamic nature of coastal zones where waves and tides continually modify water levels underwater [155]. The difference of vertical reference frames will be one of the most challenging points to deal with. factors combined lead to produce fundamental problems in combining emerged and submerged data. The horizontal datum discrepancies can usually be resolved with existing transformation tools; vertical datum inconsistencies remain one of the most critical issues. Seasonal changes, tidal cycles, river discharge, and wind-driven water movement all affect water levels and thus complicate the use of a common vertical reference. So, guarantee a reliable merge for both offshore and onshore data, vertical datum must be accurately detected. These depend on the fixation and maintenance of real-time tidal measuring, to obtain the hydrodynamic models around the detected area, and the development of methods and tools for merging underwater and terrestrial datasets.

Fortunately, GNSS measurements provide the opportunity to use common datum that is the ellipsoid. The GNSS measurements are made by a three-dimensional coordinate system that depends on ellipsoidal reference system. The ellipsoid is defined as a geometric model that approximates the shape of the Earth surface. Therefore, both elevation and underwater data collected with GNSS can be referenced to this common continuous, mathematically defined, ellipsoidal surface. While depth measurements and elevations are both referenced to the ellipsoid datum, there is always a need to refer the data with respect to the water level. This is because of the variation of the water level due to several factors, especially the change of water level due to tidal and waves effect in case of coastal area and weather condition in case of small lake. Nautical charts, for example, must always be referenced to a tidal datum to provide data related to a common standard and to ensure that mariners will have the ability to recognize the depth of water with respect to the real water level. In this context, another datum should be defined to be aware of the real position of water level. This datum is mainly defined by physical meaning related to gravity field that is

called geoid that provide elevations compatible with what is called orthometric heights approximating the MSL (Mean Sea Level). In this case, following the common datum necessity, also terrestrial data will typically be referenced to orthometric datum. The key to producing an accurate and continuous dataset across the onshore and offshore zone, however, is to be aware of the differences between different reference surfaces used to obtain correct measurements (i.e., the difference between the ellipsoid and the geoid, between the ellipsoid and real terrain, also between the MSL and the ellipsoid). With the detailed knowledge of these differences, conversions can be done among the various reference frames to produce a continuous dataset referred to the same datum. On other hand, underwater data collection has more difficulties because of the highly dynamic environment, with the sea surface, where the data is collected from, is continuously changing due to waves and tides. Precise vertical reference frames for underwater data exist where water-level gauges have precisely defined a datum, or by accurate GNSS measurements for the water level. Since the depths are computed based on the water level, then GNSS surveys are required to transform the water level to the orthometric datum. Once a continuous digital model is available, then a hydrodynamic model can be used to produce water surface. The benefits of generating hydrodynamic model applied on a real integrated terrestrial-underwater model is to display several scenarios for the shoreline position (Figure 8).

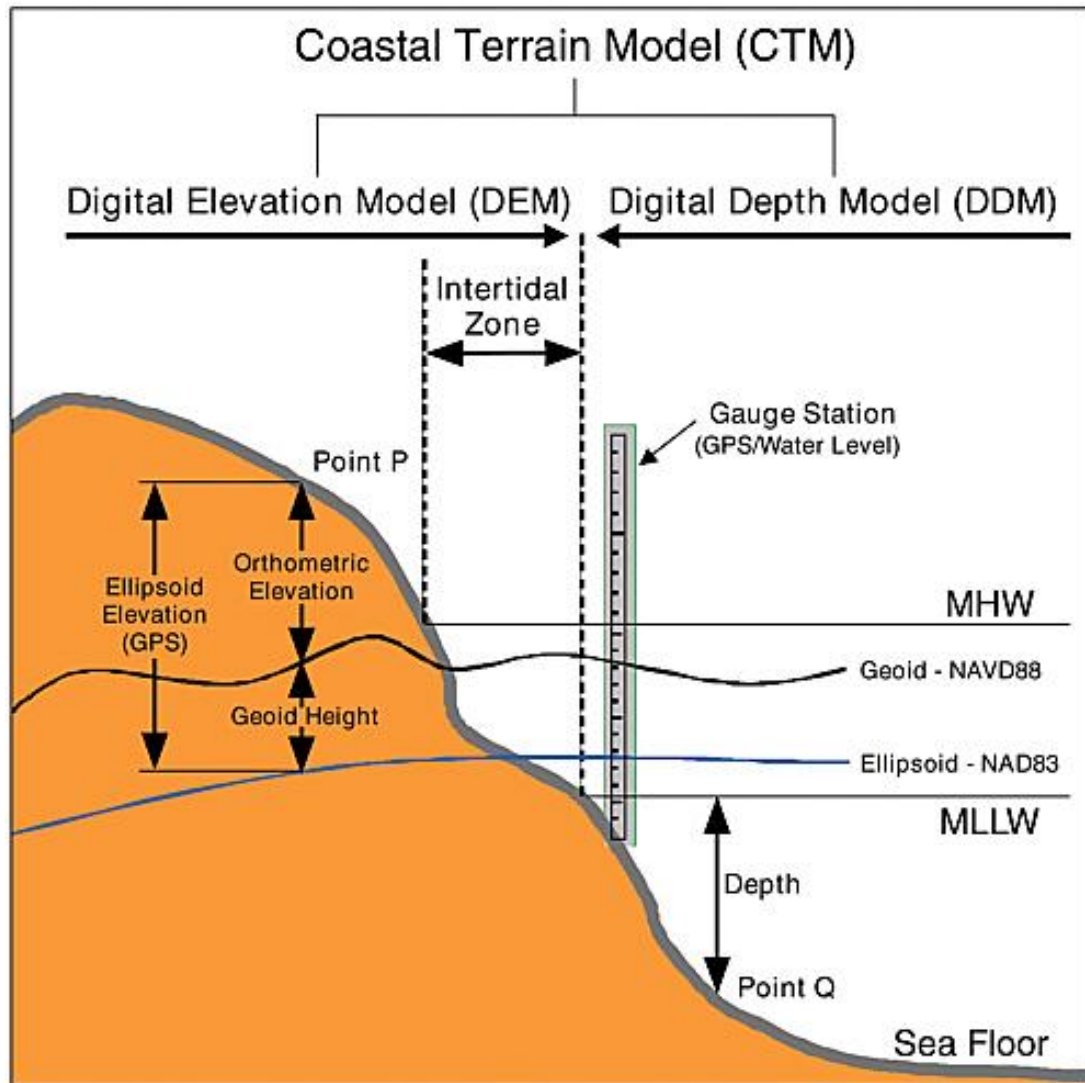


Figure 8. Coastal Terrain Model (CTM) integrating Digital Elevation Model (DEM) and Digital Depth Model (DDM). The model highlights key features such as the intertidal zone, gauge station for GNSS water level monitoring, and point P with ellipsoid elevation. It also includes geoid height references and sea floor details within the NAD83 ellipsoid framework, with MLLW (Mean Lower Low Water) as a datum. Source adapted from [156].

In the context of geospatial data processing for coastal zone applications, it is essential to differentiate between the commonly used terms integration, fusion, and merging, as they represent distinct conceptual and technical approaches to combining data from multiple sources. This research adopts a consistent use of the term data integration, and it is important to define it in contrast with the others to avoid ambiguity and to situate the work within the broader literature. Throughout this thesis work, data integration is used to describe the core methodological process: aligning terrestrial and underwater datasets often captured with distinct technologies into a shared spatial reference frame. This usage reflects a practical, modular approach that emphasizes interoperability, spatial coherence, and adaptability to diverse environmental and logistical constraints. By clarifying these terms, the present work contributes to the standardization of terminology in interdisciplinary coastal mapping and ensures methodological transparency for researchers applying similar workflows.

Data Integration refers to the process of aligning and combining heterogeneous datasets often collected with different sensors, at different times, and across different spatial domains into a coherent and unified spatial framework without necessarily altering the original data. In coastal applications, integration might involve aligning underwater sonar data with terrestrial photogrammetric models to generate a seamless DSM [99], [100].

Data Fusion is a more sophisticated and often computationally intensive process that combines data from multiple sources to create a new, enhanced dataset. Fusion typically operates at various levels (sensor, pixel, feature, or decision levels) and is used to enhance spatial resolution, detect features, or improve classification [102]. For example, previous study employed data fusion techniques to combine multispectral satellite imagery with LiDAR for enhanced shallow seabed classification, and explored fusion of hyperspectral data with underwater LiDAR for improved habitat mapping [157].

Data Merging is generally used to describe the process of joining datasets of the same type such as overlapping point clouds or adjacent sonar swaths into a larger, continuous dataset. Unlike integration or fusion, merging assumes relatively similar data characteristics (e.g., format, resolution, acquisition method). An example would be combining multiple UAV-acquired photogrammetric models of neighboring coastal sectors into a single orthophoto mosaic.

1.5 WATER REFRACTION EFFECTS IN PHOTOGRAMMETRY AND LiDAR-BASED BATHYMETRY

1.5.1 The Optical Refraction Challenge in Coastal Mapping

Water refraction is one of the most critical yet often overlooked sources of error in photogrammetric and LiDAR-based surveys of shallow coastal waters [158], [159]. When light passes from air into water, it changes direction due to the difference in refractive index. This bending of light results in an optical illusion: submerged objects appear closer to the surface than they are. If uncorrected, this effect introduces systematic underestimation of depth in 3D models derived from aerial or above-water imaging platforms. This includes UAVs, manned aircraft, satellite sensors, and static terrestrial-based cameras.

The degree of error introduced by refraction depends on several factors:

- the angle of image acquisition (nadir vs. oblique);
- the depth of the object;
- water clarity (since turbidity affects light penetration);
- surface conditions (ripples distort light paths);
- sensor characteristics (e.g., focal length, resolution).

In photogrammetric models, especially those generated via Structure-from-Motion Multi-View Stereo (SfM-MVS), the effect manifests as a vertical compression of submerged features. Studies have shown that depth errors can be significant when using uncorrected imagery over shallow water [158]. For instance, studies observed vertical discrepancies exceeding 2 meters in 4-meter-deep test sites [100], [158]

confirmed similar findings, reporting that underwater features appeared at significantly reduced depths unless ray-based or empirical refraction correction methods were applied [158]. The problem is compounded by the popularity and accessibility of SfM software like Agisoft Metashape© (V 1.8.2), which by default does not account for refractive index changes unless manually corrected. As a result, researchers or practitioners may unknowingly generate underwater models that are visually plausible but quantitatively inaccurate, potentially misleading if used in habitat analysis, coastal modeling, or infrastructure planning. In contrast, underwater LiDAR systems (e.g., green laser systems) are specifically designed to handle refraction by emitting both infrared (IR) and green-wavelength (532 nm) pulses[160], [161]. The IR pulse reflects off the water surface, while the green pulse penetrates the water and reflects off the seabed. By calculating the difference in time-of-flight between these two signals, the system estimates water depth. However, even LiDAR systems must apply correction models for varying water column properties (e.g., salinity, turbidity) and angular refraction based on beam entry angles. Studies have shown that failure to apply these corrections can result in errors exceeding 20% in sloped or variable-depth areas[104], [162]. However, in coastal mapping applications where the goal is not to derive bathymetry from aerial images, but rather to integrate separately acquired terrestrial and underwater datasets, refraction correction is generally not necessary[163]. For example, if submerged areas are mapped using acoustic sensors or underwater cameras and are not reconstructed from aerial imagery, the images above water serve only for orthophoto production or for terrestrial modeling, thus bypassing the need for refraction adjustments. This distinction is critical to avoid over-engineering correction procedures where they are not relevant. Consequently, the literature emphasizes that refraction correction should be applied only when the optical path crosses the air-water interface and is used to infer underwater geometry. Whereas this is not the case as in workflows combining UAV photogrammetry for terrestrial and acoustic/underwater imaging for submerged areas the issue of refraction may be acknowledged, but it does not significantly impact modeling accuracy.

1.5.2 Methods for Water Refraction Correction in Coastal Surveying

Correcting the effects of water refraction in coastal photogrammetry and LiDAR is essential for ensuring the geometric accuracy of reconstructed 3D models, particularly when submerged features are visible in aerial imagery. A range of correction strategies has been developed, typically falling into three broad categories: empirical correction, geometric (ray-tracing) models, and photogrammetric bundle adjustment extensions[158], [163], [164].

- Empirical Depth Scaling

The simplest and most widely applied method is empirical scaling, which uses known water depth measurements (e.g., from sonar) to develop a correction curve or scaling factor that adjusts the apparent depths captured in image-based reconstructions[165]. This approach assumes a constant refractive index and vertical imaging geometry, allowing for a linear or polynomial relationship between observed and actual depths.

For example, some studies used regression-based scaling to adjust SfM-generated 3D models of shallow seabeds captured by UAVs[158]. The method was validated against ground-truth depth soundings, and the authors reported reductions in vertical RMSE from over 1.2 m to less than 0.3 m

after correction[158]. However, this method is site-specific and dependent on having reference data across the full depth range of interest, which limits its generalizability.

- Ray Tracing and Two-Media Geometry Models

A more physically accurate technique is ray-tracing correction[163], which models the path of light through two media (air and water) using Snell's Law. In this approach, the bending of light at the air–water interface is computed based on the angle of incidence and the difference in refractive. This method adjusts both the image ray directions and the apparent object positions, allowing the 3D model to represent the true underwater geometry. Such models was implemented in LiDAR processing to correct for angular displacement of return signals[111], [166]. Raytracing has also been integrated into SfM workflows by incorporating two-media camera models, where the air–water interface is treated as a refractive surface that modifies the projection geometry. While accurate, this approach requires precise knowledge of camera parameters, platform height, water surface orientation, and calibration procedures, which are often difficult to maintain in field settings.

- Refractive Bundle Adjustment

A more advanced but less commonly applied method involves extending bundle adjustment the optimization process at the core of photogrammetric reconstruction to account for refractive media[167], [168]. In a traditional SfM workflow, bundle adjustment aligns multiple overlapping images by minimizing reprojection error assuming a single refractive medium (air). In refractive bundle adjustment, this is replaced with a two-medium projection model, which accounts for the light path bending at the water surface. This technique showed that integrating the refractive interface into the camera model allows for simultaneous recovery of accurate camera poses and true 3D point locations, with reported accuracy improvements of 30–50% compared to uncorrected models. However, implementation is complex, and only a few open-source toolkits (e.g., HydRo3D) currently support this approach[169], [170] .

- Correction in LiDAR Systems

Underwater LiDAR systems often integrate correction modules directly in their waveform processing pipelines. After identifying the surface and bottom returns using dual-wavelength measurements, corrections are applied based on the angle of incidence, depth-dependent light attenuation, and local water properties (e.g., turbidity, chlorophyll)[171]. These systems often employ look-up tables or modeled corrections derived from prior field calibration and Monte Carlo simulations of light transmission. Even so, inaccuracies may persist, particularly in shallow sloped areas where light paths are complex, or when bottom reflectivity introduces noise into the waveform return[172]. As a result, modern systems like coastal mapping and imaging Lidar allow for post-processing refinement using raytracing and waveform analysis tools, improving depth accuracy and reducing the need for extensive ground truthing. In the context of this thesis, UAV-derived orthophotos were employed primarily for terrestrial reconstruction and for positioning dynamic markers (snorkeler or ASV) at the water surface. Crucially, they were not used to reconstruct submerged geometries from aerial imagery. For this reason, no refraction correction was applied to UAV images, since the underwater bathymetry was acquired independently through sonar and underwater cameras. Consequently, the potential distortions caused by water refraction did not influence the integrated models presented in this work.

1.6 GAPS IN EXISTING RESEARCH

Despite advancements in both terrestrial and underwater surveying techniques, there is a notable lack of standardized methodologies that effectively integrate data from these two domains. Current research tends to focus on either terrestrial or aquatic environments separately, which can lead to fragmented datasets and hinder comprehensive environmental assessments [173]. This gap underscores the need for interdisciplinary frameworks that can bridge the methodologies of terrestrial and underwater surveys. Existing research often lacks interdisciplinary collaboration, limiting the potential for innovative solutions to address complex environmental challenges. Strengthening collaboration among researchers from various fields is crucial for developing comprehensive approaches to environmental monitoring and resource management. Although technologies such as machine learning offer significant potential for data analysis and interpretation, their application in the integration of terrestrial and underwater survey data remains limited. Current research often fails to leverage these technologies to improve data processing, enhance accuracy, and facilitate real-time monitoring of environmental conditions. There is a critical gap in understanding the interactions between terrestrial and aquatic ecosystems, particularly how changes in one environment affect the other [174]. For example, terrestrial-based activities such as agriculture and urban development can impact coastal water quality and habitat health. Research that explicitly investigates these interconnections is necessary to inform sustainable management practices. While theoretical frameworks for integrating terrestrial and underwater surveys have been proposed, there is a lack of empirical case studies that showcase successful applications. More research is needed to document and analyze real-world examples, which can provide valuable insights into best practices and lessons learned. The integration of terrestrial and underwater survey data is often complicated by issues of data standardization and sharing. Different disciplines may use varying protocols and formats for data collection, making it challenging to integrate datasets. Research is needed to develop common standards and protocols that facilitate data sharing among researchers and organizations. As the field of integrated surveying evolves, there is a growing need for comprehensive training programs that address the interdisciplinary nature of the work. Current educational curricula often lack a focus on integrated approaches, which may limit the capacity of future researchers and practitioners to engage in effective data integration.

Beyond these broad challenges, specific technical gaps also affect the accuracy of integrated coastal mapping workflows. One critical example relates to photogrammetric workflows relying on Structure-from-Motion and Multi-View Stereo (SfM-MVS). In such workflows, the accuracy of the final 3D reconstruction is strongly dependent on the camera calibration parameters, particularly the focal length (camera constant) and lens distortion coefficients [175]. Typically, SfM software such as Agisoft Metashape© (V 1.8.2) applies self-calibration during bundle block adjustment, estimating intrinsic camera parameters directly from the image dataset itself. While self-calibration is generally robust for terrestrial surveys with consistent imaging geometry, complications arise when aerial imagery includes both terrestrial and submerged areas, particularly in coastal photogrammetry. As noted, self-calibration applied to such datasets yields inaccurate and unstable focal lengths due to the varying optical conditions between air and water [176]. Specifically, water refraction alters the apparent geometry of underwater features, which results in a systematic distortion of image-space distances [176]. Since the SfM process treats all

light paths as if they were in a single medium (air), the estimated focal length becomes an average of multiple inconsistent viewing conditions, varying across pixels depending on the depth and extent of submerged area in each image.

This has two key consequences:

1. The reconstructed 3D model may show vertical compression or expansion of the underwater terrain;
2. The estimated camera positions may be slightly incorrect, leading to horizontal displacement of features, especially at the interface between terrestrial and submerged zones.

In the context of this research, where orthophotos are used as the georeferencing framework to position underwater photogrammetric models, this calibration inconsistency can lead to a positional bias between the overwater and underwater datasets. The degree of this bias depends on several factors, including:

- the proportion in each image covered by submerged area;
- the depth and clarity of water (i.e., how far underwater features shift);
- the total number of control points available on terrestrial for anchoring the orthophoto.

Studies report that uncorrected focal length variations due to mixed-media calibration can introduce positional discrepancies of up to 1–2% of flight altitude [177]. For example, in a UAV survey conducted at 50 m altitude, this could correspond to a horizontal shift of 0.5 to 1 meter, particularly in the alignment between the terrestrial and underwater portions of the model.

In the present work, such effects were mitigated by:

- using imagery acquired at low tide or in highly visible conditions, to limit the percentage of submerged area in each image;
- anchoring the photogrammetric model with dense terrestrial GCPs and evaluating calibration stability across image subsets;
- applying empirical adjustments where necessary, based on ground-truth validation using acoustic underwater data or known structural features.

While minor positional deviations may still exist (estimated to be within 0.3–0.5 m), this level of inaccuracy is acceptable for the intended applications of the present work, such as morphological analysis, habitat visualization, and preliminary ecological assessment [178], [179]. Nevertheless, this calibration-related uncertainty is explicitly acknowledged and will be considered in future extensions of the workflow, particularly those requiring sub decametric spatial alignment across domains.

2. METHODOLOGY AND TECHNIQUES

One of the most important and essential factors that must be taken into consideration before implementing any survey campaign is the legal/social constraints. Public concern in relation to safety and security is one of the main issues. This demonstrates the necessity to be aware of the regulations that are related to the use of survey technologies within the survey area. As the case of using a drone, regulations specify some standards about flight height depending on the surveyed area classification and drone specification. safety regulations often impose restrictions on UAV flights in specific periods or locations, making prior authorization mandatory. Other challenges related to cybersecurity and electromagnetic interference in some zones may affect the mission survey campaign. This is a challenging issue, since it will affect and limit the use of some technologies, mainly GNSS, as this technique could be susceptible to some performance limitations due to the eventual presence of electromagnetic interference, or to the lack of satellite visibility. Furthermore, these motivations support the necessity of proper initialization, planning and thinking for alternative methods. Given these operational constraints, the methodology must carefully balance legal compliance with technical feasibility, making the choice of platforms and sensors a critical step in the workflow

Choosing the appropriate method to achieve the primary objective, which in this research is to obtain a continuous 3D model combining emerged and submerged surveys, is a key focus of ongoing research, especially with the rapid advancements in technology. Success depends on selecting the right tools and techniques, balancing the instruments used, and meeting accuracy standards within a reasonable timeframe. Shallow water areas pose significant challenges for conventional survey methods. These regions are often difficult and dangerous to access with traditional vehicles, and data for such areas may be unavailable. When data is available, it is often collected using manned boats, which can be costly and inefficient for survey campaigns. Robotics offers a practical alternative to traditional methods, improving the efficiency and accuracy of underwater data collection in shallow waters. This technology enhances the quality, speed, and accessibility of surveys in challenging environments [180]. ASVs are widely used for creating reliable and detailed underwater maps in shallow environments. The use of robotics also supports the development and integration of innovative survey techniques, allowing for smarter, cost-effective, and safer operations. Robotic systems, such as UAVs and ASVs, are flexible in design and size, enabling them to meet specific survey requirements. They also improve spatial resolution and overall data quality. By combining robotic technologies with advanced remote sensing techniques such as underwater acoustic sensors (SBES and MBES) and aerial optical sensors (photogrammetry), it becomes possible to acquire detailed and reliable data. This integration addresses the challenges of shallow water surveys while paving the way for more efficient and accurate methodologies (Figure 9).

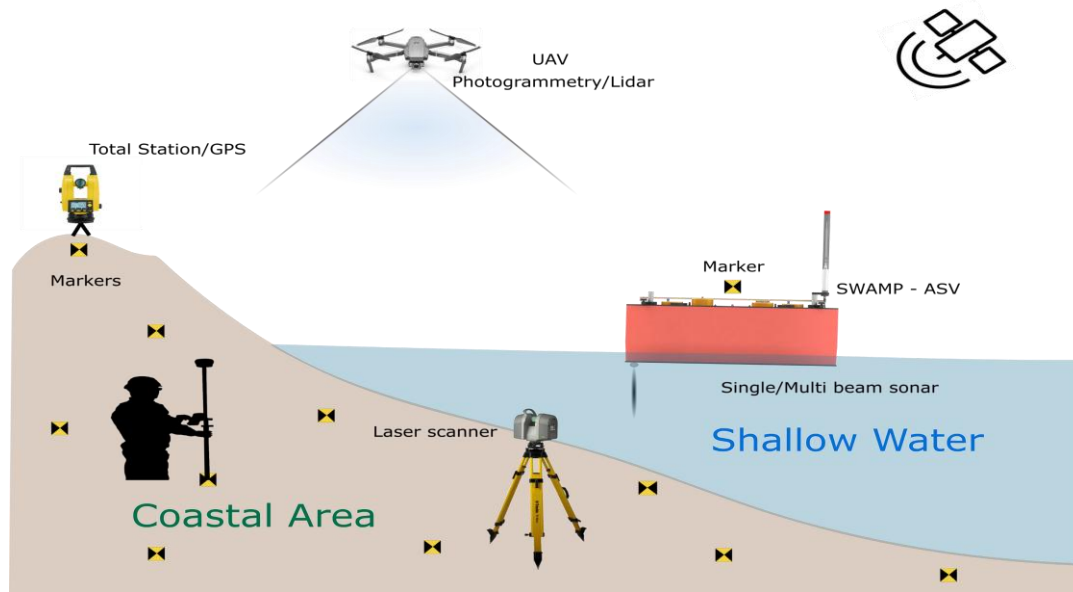


Figure 9. Integrated coastal survey setup: combined use of terrestrial and underwater measurement techniques. On terrestrial, terrestrial laser scanners, GNSS rovers, total stations, and ground control markers are employed for high-resolution terrestrial mapping. Aerial photogrammetry using UAVs captures the coastal terrain, while in shallow water areas, an Unmanned Surface Vehicle (ASV) equipped with single- or multi-beam echosounders collects underwater data. Satellite positioning supports accurate georeferencing across domains. Source adapted from [5]

In this context, this thesis work develops a methodology that integrates several techniques and sensors to survey and combines terrestrial and underwater environments into a single model. For underwater surveys, the methodology relies on ASVs, specifically the SWAMP (Shallow Water Autonomous Multipurpose Platform)[180]. SWAMP was developed to acquire underwater data in shallow water areas. SWAMP offers versatility through its multifunctional design, which can be reconfigured to meet the needs of various tasks. Its compact size and lightweight design make it easy to transport and deploy. The vehicle is equipped with an IMU and GNSS sensors, providing precise orientation (yaw, pitch, and roll), angular velocity, and real-world positioning. For this research, a single beam echosounder was mounted on SWAMP for underwater surveys (Figure 10).

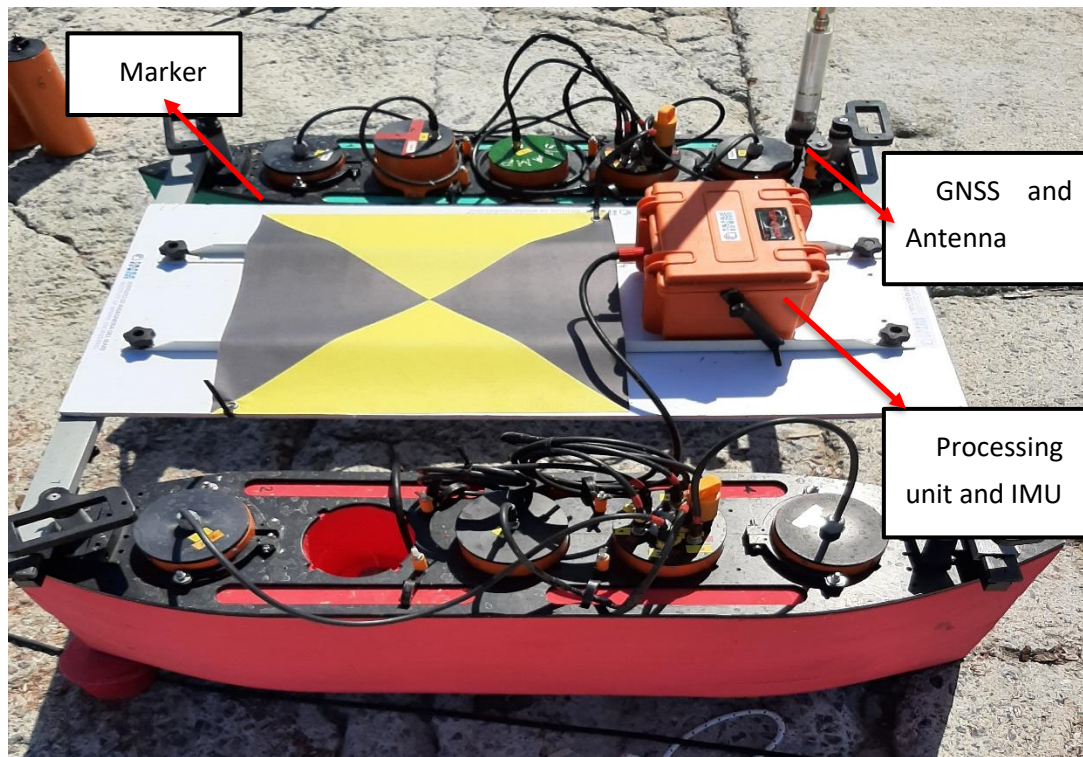


Figure 10. SWAMP is equipped with an Inertial Measurement Unit (IMU), Global Navigation Satellite System (GNSS) sensor and a target.

Additionally, an ASV provided by the Hydrographic Institute of the Italian Navy was also used, equipped with different sensors, including a MBES and LiDAR, to capture both submerged and emerged data. This system was tested in Sestri Levante, Italy (Scenario 2). While in harbor environments, where using ASVs can be challenging due to ship traffic, traditional boats were used to carry out surveys effectively; these tests were performed in the Elbe River harbor in Hamburg, Germany (Scenario 3).

In another experiment, the SWAMP was substituted with single- or multi-beam echosounders, tested in the Laghi del Gorzente lakes in Italy (Scenario 1), combined with a snorkeler performing surface photogrammetric surveys. This snorkeler-based approach was also validated in Sestri Levante, Italy (Scenario 2). For the terrestrial survey, aerial optical sensors were used, mounted on a DJI Mavic 2 PRO drone equipped with a Hasselblad L1D-20c camera. The optical sensor captured images for photogrammetric processing, enabling the creation of a 3D model.

To ensure accurate georeferencing, the 3D model was supported by measurements from a total station or GNSS depending on the surveyed area. The focus of this methodology is to establish a workflow that allows underwater and terrestrial surveys to be performed in parallel, resulting in a unified model that represents both environments. A key challenge to address is determining a method to georeference both models within the same reference system. When GNSS is available for both terrestrial and underwater surveys, georeferencing both environments in the same reference frame is straightforward. However, when GNSS is unavailable either due to interference or because it cannot be used underwater, a new approach is needed to match the underwater and terrestrial reference frames.

The proposed methodology addresses the challenge of georeferencing underwater environments without relying on GNSS. It utilizes advanced image processing techniques to achieve accurate spatial positioning. The approach focuses on determining the position of the ASV or snorkeler conducting underwater measurements by analyzing images captured by the UAV. The new positioning system relies on the intersection paths between the UAV and the ASV/snorkeler. By detecting and locating the ASV/snorkeler in the UAV images, their position can be accurately determined and integrated into the survey.

To implement this methodology and achieve intersecting paths between the two techniques, proper planning is essential. This involves balancing the photogrammetric planning required to create an accurate 3D model with the need to position the ASV/snorkeler by ensuring they are detectable by the UAV. In photogrammetric projects, flight planning is a critical first step. To obtain accurate results, it is necessary to design an efficient flight mission. Since GNSS technology plays a vital role in photogrammetry, it must be carefully considered during planning, especially to mitigate factors that could limit its performance. Such limitations can directly impact the efficiency of aerial image acquisition during photogrammetric surveys. The initial step involves preparing flight plans digitally and importing them into systems that display and manage the mission. The primary goal of flight planning is to determine the optimal flight trajectory, altitude, and desired resolution, which will vary depending on the drone specifications. Careful planning ensures the targeted area is covered with the minimum number of flight lines, reducing flight time, enhancing safety, and minimizing the size of collected data. Additionally, the planning phase must align with the specific requirements of the project to ensure overall success of the mission. Considering the requirements of the project, survey area dimension, images scale, longitudinal and transversal overlap, stripes direction, coordinate system or reference frame and camera specifications must be determined. According to these factors, the distance between two adjacent images along flight line and the distance between two adjacent strips are determined. Also, the flight height through the mission is calculated from the terrain level. In photogrammetric applications, to obtain stereo model, it is essential to have longitudinal overlap minimum 60% between images. The flight line directions are generally planned with respect to the study area and the objectives. Therefore, terrestrial limitations must be considered through planning the project such as in mountain area, lake, and coastal zones may affect the flight line directions. Calculating the flight height is also important and related to the survey area and affects the results, i.e., a lower flight height causes a greater image scale than desired scale and it has an influence on the overlaps between strips. In this case the overlaps will be higher and may cause a need for additional flights lines to avoid gaps in the study area. All these processes have influence also on the time of flight, so it must be planned carefully. Any mistakes might cause many errors and negatively affect the process. To determine the effect of different flight heights, two flight plans were calculated. The first plan was based on a flight height of 80 meters, designed to cover the entire area with images from the drone. The second plan used a lower flight height of 50 meters to achieve a more detailed view, enabling precise detection of the ASV/snorkeler and ensuring the overlap between the two techniques. From the calculations below, it becomes evident how flight height impacts key parameters such as image coverage, shooting intervals, and image dimensions.

Camera parameters for the aerial photogrammetry using UAVs:

- Sensor dimensions = 13.2×8.8mm
- Resolution = 20 MP
- Image dimensions (I) = 5472×3648 pixel; 13.9×8.8 mm
- Pixel dimensions (d) = 0.002 mm
- Focal length (c) = 10.26 mm
- Overlap = 70%

Table 1. Comparison of UAV flight planning parameters at two flight heights (80 m and 50 m), showing how flight altitude influences Ground Sample Distance (GSD), image footprint dimensions, shot base, and distance between strips (calculated with 70% overlap in both longitudinal and transversal directions).

Parameter	80 m flight height	50 m flight height
GSD (Ground Sample Distance)	16 mm	10 mm
Real dimensions (L × W)	87.2 × 58.4 m	54.5 × 36.5 m
Shot base (B)	26.16 m	16.35 m
Distance between strips	26.16 m	16.35 m

After understanding the UAV photogrammetric planning, it was necessary to consider the methodologies to obtain overlapping trajectories between different instruments. Achieving accurately this scope is challenging and needs a well definition of the technologies uses with the aware of specification of each. The main complexity refers to obtaining overlapping between data and to represent the terrestrial and seafloor features with the concern of common representation scale, good accuracy, and full coverage to build a reliable DSM. In the initial planning stage, the process was separated for each instrument based on their specifications and the characteristics of the target area. After determining the dimensions of the study area, photogrammetric planning is carried out to define the flight trajectory and strip directions.

For planning the ASV/snorkeler trajectory, two key aspects must be considered:

1. Intersection with the UAV path to ensure proper positioning.
2. Underwater measurements, which depend on the sensor used.

If the acoustic sensor is a SBES, the planning becomes simpler. Since SBES performs point-based measurements rather than fan-shaped scans, the marine vehicle does not need to follow a uniform path or specific strips. Instead, it is essential to cover the entire target area and ensure a high density of measurement points to create a reliable underwater model. On the other hand, if a MBES or an underwater camera is used, the vehicle must follow a consistent trajectory based on a specific plan. This ensures complete coverage of the seabed while maintaining the required intersection with the UAV path. After the planning for each instrument is completed, the surveys execution takes place in parallel. The UAV collects terrestrial images while simultaneously detecting the ASV/snorkeler, and underwater measurements are acquired. A

deeper understanding of this process will be provided in the following sections, where the methodology is applied to different scenarios.

The experiences presented in this thesis highlight the different possibilities for applying the proposed methodology to achieve a unified submerged and emerged model. In the following sections, three scenarios are introduced to demonstrate its adaptability in diverse contexts. The first scenario, conducted in the Laghi del Gorzente lakes in Italy, tested the integration of UAV photogrammetry with the SWAMP ASV equipped with a single-beam echosounder, assessing the feasibility of linking emerged and submerged datasets in a controlled lake environment. The second scenario, carried out in Sestri Levante, Italy, applied the methodology using both a snorkeler without GNSS and an ASV equipped with GNSS, enabling evaluation of the orthophoto-based positioning approach by comparison with GNSS referenced results. The third scenario, developed in the Elbe River harbor in Hamburg, Germany, addressed the additional challenges posed by complex harbor environments. Here, surveys were performed using boats equipped with a 360° panoramic camera for the emerged domain and a multi-beam echosounder for the submerged domain, while the natural tide-induced variations between high and low water provided tie-points for connecting datasets acquired at different times. Together, these applications provide a comprehensive overview of the methodology's potential and set the stage for the detailed analysis presented in the next sections.

2.1 FIRST SCENARIO: LAGHI DEL GORZENTE

The study was carried out on a small portion (20,550 m²) of Laghi del Gorzente, located in the provinces of Genoa (Liguria) and Alessandria (Piedmont). The Laghi del Gorzente are three artificial reservoirs created by dams. They help store water and support the ecosystem by improving an area that would otherwise be dry. Based on my monitoring of the study area, it is characterized by a funnel-shape that lies embedded in a steep valley. The terrestrial cover surrounding the lake with a steep bare slope is characterized by mixed sedimentation, composed of a combination of rocky coast, gravels, sand and silt with tall trees on the outer boundaries which sets a natural limit to the lake. The study area is shown in (Figure 11).



Figure 11. Study area overview of Laghi del Gorzente, located in northwestern Italy. The red boundary delineates the surveyed region within the lake. The inset map shows the lake geographical location within Italy.

Background imagery sourced from Google Earth. Source adapted from [5].

The water level depends on the water flows to the lake; periods of null-discharge flows are frequent, mostly during summer, as well as floods in winter or spring. Since no database in terms of underwater measurements and accurate merging with terrestrial surface is available, integrated survey measurements have been carried out in this area to analyze the bathymetry of this watercourse. Moreover, obtaining three-dimensional information corresponding to this area is a significant contribution to extending the existing national databases. Furthermore, as the coastal areas survey is affected by the water surface and wave action, then the survey performance in a steady environment like the study area in Laghi del Gorzente represents the ideal conditions to examine and evaluate new survey methodologies. These factors, aside from the legal and social constraints regarding the possibility of conducting a survey campaign in the targeted area, made it an ideal location for safety reasons, as there were no people around to interfere. This made the area convenient for examining the efficiency of the proposed measurement methodology.

The primary obstacle to working in different environments using distinct instruments consists of the occurrence of gaps between the resulting datasets. Mostly, the scarcity of acquiring hydrographic data from shallow water (below 1 m) is inextricably linked to the lack of hydrographic vessels capable of carrying out measurements in similar environments. In this context, the robotic platform SWAMP was used to acquire data through terrestrial/water interface zones. SWAMP is an ASV the characteristics of which can be modified and correlated to the mission specifications. It is a catamaran 1.23 m long and 1.1 m wide. The hull height is 0.4 m; including the structure and communication antennas; which is 1.1 m high. SWAMP is

considered a small and lightweight (38 kg) vehicle adequate to be transportable by hand; this is particularly useful in areas where access is limited. SWAMP flexible design is adequate for hosting different tools, e.g., thrusters, control systems, samplers and sensors. SWAMP is based on the use of four pump-jet thrusters, the configuration of which allows for efficient control that is especially required in shallow water zones for high quality survey and performance. The underwater survey measurements were performed by using an ultra-compact precision SBES Echologger ECS400 with 200 kHz frequency mounted inside the SWAMP hull. The vertical measurements were performed by the SBES with an altimetric resolution better than 1 mm, with real time backscatter data collection along the water column up to a depth rate equivalent to 1000 m. SBES measurements were synchronized with an IMU sensor provided by a Microstrain 3DM-GX3-35, a high-performance, miniature AHRS (Attitude Heading Reference System). The GNSS receiver present on board provided absolute orientation (yaw, pitch and roll), and a Drotek DP0106 absolute position sensor provided GNSS positions during data collection. The SBES sensor performs underwater measurements directly beneath the sensor itself, providing only depth information along the track line of the vehicle. The SBES depth measurements were based on measuring the acoustic pulse travel time from the transducer to the waterway bottom and back to the receiver. Hence, auxiliary information about sound speed in water is essential. Generally, sound velocity ranges between 1400 and 1600 m/s, depending on water characteristics. When a sound velocity profile is not available through the water column, the echosounder system uses average sound velocity as 1500 m/s. SBES is the most common survey technique used in lake and river environments, because of its efficiency, low cost and accessibility. Considering the SBES resolution, the acquired data are considered precise and cost effective. Instead, for big data coverage, it is more efficient to use MBES to have more precise DSM generation with the highlight that this system is more expensive. According the IHO standards, the survey could be considered order 1b since the survey was performed in a lake environment, so not related to safety of navigation [181]. Like underwater data collection, terrestrial data collection relies on robotic vehicles. UAV photogrammetry was performed through a 20 MP camera mounted on a DJI Mavic 2 Pro. The proper overlapping between images was obtained by extracting them from a video with a frame rate of one image per second, leading to a percentage of 70% overlapping for both forward and side directions. Further images were taken with terrestrial close-range photogrammetry by the embedded camera of a smartphone with a 24.8 MP sensor size. The resulting 649 images, coming from both UAV and terrestrial photogrammetry, were processed by means of the photogrammetric software Agisoft Metashape© (V 1.8.2), producing a 3D point cloud by merging four different image datasets based on the single shooting geometries, i.e., nadiral or facing the object. Each image dataset covers a portion of the study area, such that they are mutually complementary. To survey the distributed GCPs coordinates, Total Station Leica TC703 was used with a display resolution equivalent to 1 mm. The employed instruments are shown in (Figure 12).

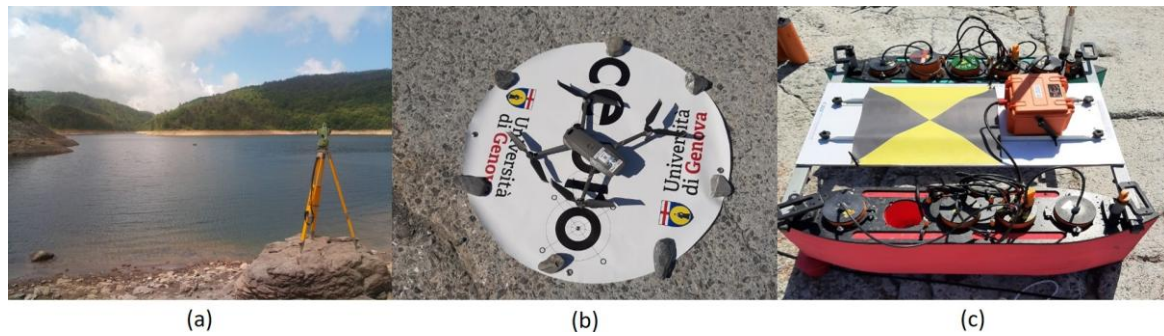


Figure 11. Instrumentation used through the survey campaign execution; (a) the Total station, (b) the UAV to perform terrestrial photogrammetric survey, (c) the SWAMP that carried out the underwater survey (refer to figure 10 for description of the different parts).

To pursue the goal of at present, the main task is precise data merging acquired from submerged and emerged environments of the lake, considering cost-effectiveness and timing. Consequently, SBES was nominated as an efficient and cost-effective technology to perform the underwater survey in steady environments such as lakes. However, if the goal is to achieve a reliable combination of data from both environments, SWAMP was presented as a surface vehicle capable of acquiring underwater information in areas less than 1 m depth.

SWAMP thus enhances the ability to survey less accessible shallow zones and extends standards of accuracy for integrated surveys.

Auxiliary information is necessary to obtain and georeference the collected measurements. These are provided by the on-board IMU sensor (absolute orientation: yaw, pitch, roll) and the GNSS sensor (absolute position). Precise synchronization of all sensors on board is essential to ensure a common reference frame. In this case, due to the absence of direct sound velocity profile measurements, a standard sound speed of 1500 m/s in water was assumed. The acquisition is automatic, and the outputs are metrically reliable and provided in a short time. However, expert operators are still required for system setup, calibration, and data processing. Moving forward to the photogrammetric technique, the effectiveness of the mentioned technology is represented mainly in the huge coverage of data provided and the semi-automatic processing of data which reduces operator dependency and benefits from the low cost of instrumentation. Typically, UAV photogrammetry relies on nadiral images of the area of interest, with sufficient overlap between consecutive images to ensure 3D reconstruction. Locating a sufficient number of well-distributed GCPs was needed to scale and georeference the 3D model with adequate accuracy and precision. Once the images and the coordinates of GCPs have been acquired, it is possible to reconstruct a digital 3D model of the surveyed environment by processing the data.

The performed flight was constrained by interference issues that obliged the pilot to stay at 30 m AGL (Above Ground Level). To achieve full coverage at this altitude, two video strips were collected, resulting in high-resolution images with a GSD of ~ 7 mm. The study area was divided into four portions, surveyed separately with different shooting geometries: two portions with UAV video frames, and two with lateral-view smartphone imagery, ensuring sufficient overlap. However, obtaining images with

several techniques and orientations implies more processing effort to achieve a final photogrammetric 3D model comparable with the expected accuracy.

Aside from what is stated, the correlation between a well-structured GCPs' distribution over the study area and the obtained accuracy is evident. Hence, considering the study area's morphology and dimension, 19 markers were distributed with 20 m separation between two consecutive markers building a grid of markers a net-like shape. GCPs were measured by means of the total station. On this occasion, the total station was an alternative opportunity to determine the positions and heights of points, instead of GNSS, with consequently more effort needed to survey the GCP. Moreover, the choice of the location of the total station in the field was properly managed considering the visibility between the total station and the prism put on all the GCPs markers in the field. Image relative orientation was performed on a medium accuracy relying on the GCPs measurements for the four subsets of images using Agisoft Metashape© software. The choice of the accuracy rate in the image alignment process must tie in with the expected accuracy and the duration of data processing, e.g., the highest accuracy setting is recommended only for very sharp image data and corresponding processing being quite time consuming. Based on the aligned images, a dense point cloud for the targeted area is generated. Generally, a dense point cloud is created by the software based on the exterior and interior image orientation parameters by calculating the depth maps for overlapping images estimated by bundle block adjustment. Hence, the software generates a depth map for each camera position and combines them to create a merged dense point cloud. A dense cloud was built at a medium quality for each image dataset knowing that the quality specifies the depth map generation of the obtained point cloud. Subsequently, several dense point clouds were merged into one representing the basis of GCPs coordinates. The digital images were orthorectified and combined into a mosaic with 2 cm/pixel resolution, for ground display. However, photogrammetry is not the best solution to identify the interface boundary between emerged and submerged zones, since the achieved point clouds may not be reliable in terms of accuracy in that area, due to refraction and reflection phenomena in the zones along the border and the lack of GCPs in such areas.

1. Therefore, the following question is raised: how can underwater data collected with an ASV using GNSS be integrated with terrestrial data gathered with a total station? In this case, electromagnetic interference made GNSS unreliable, so accurate georeferencing was required to ensure that both datasets could be combined into a unified coastal model. To address this challenge, several aspects were considered before the survey execution in order to identify the key issues that obstruct data integration: underwater the lake surface level as vertical datum reference;
2. the occurrence of expected gaps between the terrestrial surrounding the lake and the bathymetry;
3. differences between the planimetric datum and the complexity due to the no-collocation of the sensors on the SWAMP.

Indeed, in underwater measurements, depths are related to sensor position. This is done by measuring the distance between the sensor and the underwater ground. After that, the measurements will be transformed to the water level as a reference surface. On the contrary, the approach to establish vertical datum for terrestrial measurements is quite different because terrestrial measurements could be related to

the geoid model or to the ellipsoidal reference, as with the ones derived from GNSS. However, conceptually, these two approaches should produce comparable results. Hence, datum differences must be considered and treated during the survey data integration processes. The altimetric process uses the water level as a reference surface. For the planimetric datum shift, SWAMP was removed from the water after performing underwater measurements and was located on the ground in two different positions called SWAMP 1 and SWAMP 2, shown as red dots in (Figure 13).

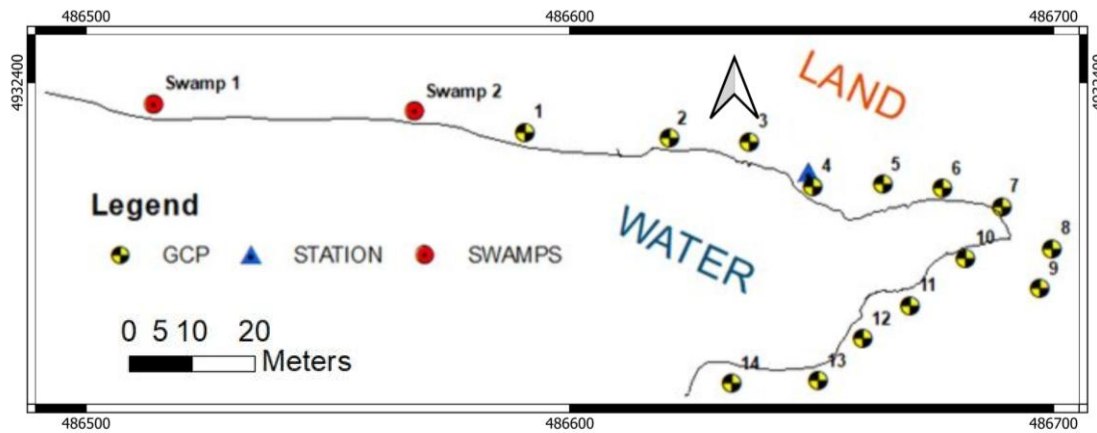


Figure 12. Total station location (blue triangle), GCPs (black and yellow dots) distribution and the two locations of SWAMP on Point 1 and Point 2 (red dots). Source adapted from [5].

A target was attached to the SWAMP hull and measurements were performed by using the total station and prism to compute the local coordinates of the two different locations of SWAMP on the ground, i.e., SWAMP 1 and SWAMP 2. In parallel, the GNSS mounted on SWAMP was recording measurements for the same two locations. Thus, two points, SWAMP 1 and SWAMP 2, are measured in two different reference systems, one related to the terrestrial reference system (local system) by total station, while the other related to the underwater reference system (WGS84) by the GNSS receiver mounted on SWAMP. A second step was represented by the transformation of the local coordinate points measured by total station to the WGS84, depending on the common control points SWAMP 1 and SWAMP 2. To perform this, the Autocad Civil 3D [182] software was employed. A common reference frame must be computed, because the GNSS and the marker mounted on the SWAMP have different positions, so measurements from the total station and from GNSSASV have been adequately attributed by referring them to the same point represented by the center of the target. Furthermore, to obtain a common vertical reference frame between both environments, all measurements were referred to the real water surface level, identified by several points on the shoreline measured by the total station during the survey campaign. The position of the shoreline terrestrial was considered as the zero level surface. Then, all the measurements were shifted with respect to the water surface level. It is necessary to note that, to integrate the two datasets, a distribution of the locations of SWAMP on several terrestrial points (red points in Figure 14) permits a better evaluation of the planimetric roto-translation transformation [5]. Unfortunately, different technical problems occurred during the survey and it was not possible to survey other targets with SWAMP (for example the markers

number 7 and number 14 in Figure 14) to connect the terrestrial and underwater datum, with a redundancy and well distributed set of common points. Hence, the adopted approach was to manage the existing gaps in order to maintain the quality and continuity of the generated DSM. The lower is the extension of gaps, the higher is the probability of obtaining a realistic, smooth and seamless integrated solution. In this context, aside from merging data in correspondence to the measured GCPs and shoreline points, the digitalization of the shoreline on the georeferenced orthophoto was carried out through the GIS (Geographic Information System) [183] environment for obtaining a reliable integration of the two datasets. Subsequently, Natural Neighbor Interpolation was carried out after merging both to obtain one model.

2.2 SECOND SCENARIO: SILENT BAY OF SESTRI LEVANTE

To further develop and validate the proposed methodology, a second practical case study was applied and tested. The goal was to incorporate underwater photogrammetry and georeference the underwater model using image processing tools from the UAV. The Silent Bay in Sestri Levante (Liguria, Italy) was selected because of several relevant considerations:

1. the possibility of flying to acquire a photogrammetric survey considering the legal/social constraints; include airspace regulations, flight permissions, privacy laws, environmental protections, public safety concerns, and noise pollution.
2. water transparency and seabed depth allow the snorkeler to obtain optimal images, making it possible to apply underwater photogrammetry;
3. notable underwater features, including rocky formations, sandy areas, and sea grass, which is of ecological significance by providing habitat and sustenance for diverse marine species.

All these factors make the Bay an ideal spot to apply the interdisciplinary approach case study (Figure 14).

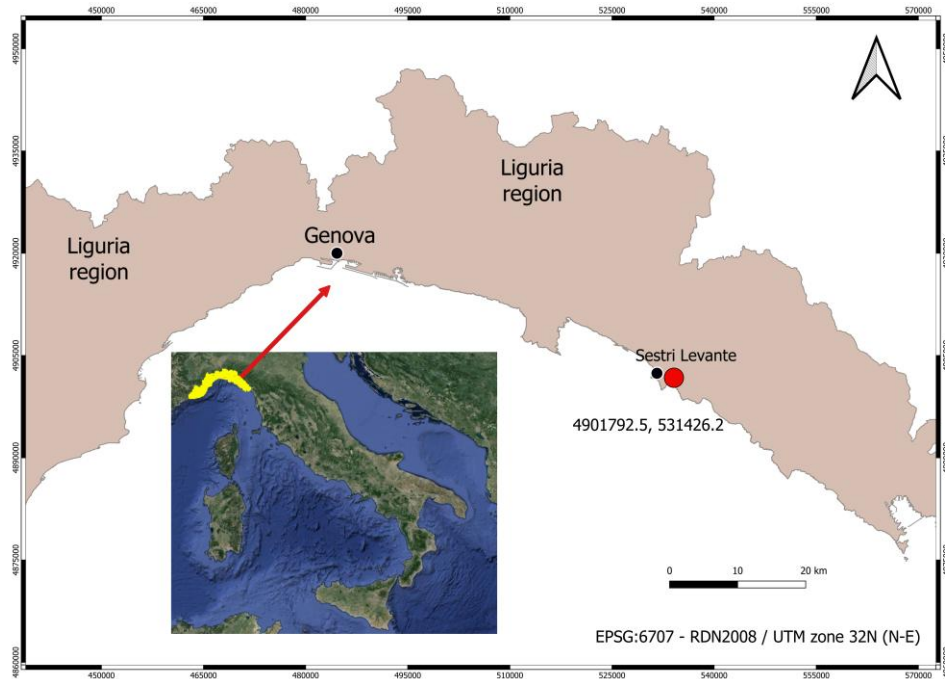


Figure 13. Study area location: the red dot indicates the study area, Sestri Levante, located in the east coast of Liguria region (Italy). The coordinates 4901792.5, 531426.2 are provided in the ERTF2000-2008.0/UTM 32 N (EPSG:6707) system.

Due to the large dimension of the bay (approximately 400 m wide and 300 m long), the snorkeler recorded videos in two distinct locations while the UAV collected frames across the emerged area of the bay and captured the snorkeler in various locations. The data acquisition started for both UAV and the snorkeler simultaneously, with a known starting time for both techniques. The UAV, operating along a defined plan, systematically acquired 128 nadiral images. The GoPro attached to the snorkeler, collected two separate videos at 60 frame per second (fps). The terrestrial survey was conducted utilizing the DJI Mini 2 drone, known for its compact design and agility: it weighs under 250 grams, making it compliant with regulations in many areas. Equipped with a high-resolution camera, 12 MP sensor, F2.8 equivalent to 24 mm focal length, and a sensor size of 6.17×4.65 mm, the drone facilitated detailed imaging of the emerged areas, providing a crucial component for the data collection. UAV frames were captured automatically, following a pre-drawn path for the UAV. The chosen flight height was 80 m with front overlap of 80% and side overlap of 70%. The STONEX S850+ GNSS receiver was used to measure natural points, supporting the photogrammetric workflow. Since the study area includes several artificial structures, the use of natural points as GCPs rather than target placement provides greater flexibility. Moreover, these natural points can serve as benchmarks for future surveys. The STONEX S850+ GNSS device, able to receive signals from GPS (Global Positioning System), GLONASS and Galileo satellites constellations, was used in NRTK (Network Real Time Kinematic) mode, getting differential correction from the network of Liguria Region GNSS positioning service [184]. A total of 18 natural terrestrial points are measured using GNSS to serve as GCPs for the terrestrial survey (Figure 15), with a spatial accuracy of a few cm for the terrestrial integrated survey.



Figure 14. Orthophoto with the distribution of GCPs (yellow dots with numbers along the coast) in the study. Water refraction not taken into account.

For the underwater survey, the GoPro Hero 10 Black, a rugged action camera designed for underwater exploration, was used. The camera capabilities include 4K resolution at a rate of 120 fps video, a 24.4 mm lens, and a sensor size of 6.40×5.60 mm, allowing for the capture of detailed imagery in water environments. The camera robustness and advanced features made it an ideal and cost-effective tool for the underwater photogrammetry process. Videos were recorded during the underwater survey, then frames were extracted ensuring sufficient overlapping between consecutive images. This approach allowed to obtain comprehensive coverage of the underwater environment.

To precisely determine the locations and movements of the snorkeler carrying the underwater camera, a target was incorporated on his back. This target was designed to be detected by the UAV during the snorkeler underwater survey. The UAV images captured the target, enabling precise alignment and spatial reference between the underwater photogrammetric data and the terrestrial survey conducted by the UAV. The target appears in 41 images; this means it is possible to compute a 41 position for the snorkeler. After knowing the coordinates of the 41 positions of the snorkeler, underwater video was processed. The videos were converted for 2 frames per second, then depending on the starting time of the video and the number of frames, the timing was assigned for every frame. By matching the timing of each of the 41 frames

detecting the snorkeler, it was possible to understand which UAV frame corresponds to which underwater frame.

The innovative methodology seamlessly integrates emerged and underwater photogrammetry, with the objective of unifying their respective workflows. The initial step in achieving this integration involves establishing a common reference system for both surveys. It is widely recognized that terrestrial photogrammetric surveys can be easily georeferenced. The method of georeferencing depends on the required precision and the type of employed UAV. For instance, when utilizing a UAV, the collected images are inherently georeferenced thanks to the GNSS measurements (in stand-alone or RTK mode) performed by the drone itself. In this case, the generated model relies on the camera position. However, if a camera lacking GNSS is used, GCPs become necessary on terrestrial. These GCPs are identified in the collected images and serve as reference points for georeferencing the model within a specific coordinate system, as well as for performing the Bundle block Adjustment (BBA). Notably, underwater environments present unique challenges in obtaining a georeferenced model due to the limitations of using GNSS underwater and the high cost of alternative underwater positioning systems. An option is using targets on the seabed and measuring them by extended GNSS rover out of water. This method is considered cost-effective and generates a georeferenced underwater model, however it has its limitations and difficulties. Fixing markers on the seabed and measuring them is not simple and becomes even more complicated with greater depth and stronger currents. The proposed methodology is based on georeferencing underwater habitats without using an underwater positioning system nor underwater targets and treating both emerged and underwater environments as a unified system. This involves establishing a fixed reference system for both, allowing for the correlation of emerged and underwater features. In this unified system, sea level serves as the zero level for altitude. Consequently, features above sea level are expressed with positive values of altitude, while those below sea level are expressed with negative values. This approach simplifies the merging of aerial and underwater surveys, providing a unified model while overcoming the complexities associated with underwater georeferencing. The methodology implementation relies on estimating the underwater camera position while conducting the survey within the external reference frame. Consistent with common scientific practice, where researchers collect underwater photogrammetry by snorkeling or diving, we selected an affordable method adoptable by multiple disciplines. A snorkeler equipped with an underwater camera conducts the underwater photogrammetric survey. Since the snorkeler has no GNSS equipment, the challenge is how to align the underwater reference system with the terrestrial reference system during the underwater survey. This requires careful consideration and innovative solutions to estimate both the snorkeler and camera positions. The integration of UAV with the snorkeler offers a comprehensive solution to acquire terrestrial and underwater photogrammetry data. The integration opens the possibility of estimating the snorkeler position using image processing tools applied to images captured by the UAV. The methodology revolves around estimating the snorkeler position during underwater photogrammetry with respect to the terrestrial model. To achieve this, it is essential to attach a target to the back of the snorkeler, aligning its centre with a fixed camera kept by the snorkeler or allowing for a known shift. Additionally, ensuring a consistent intersection between the snorkeler and the UAV is essential. This guarantees that the snorkeler is detected in multiple images captured from various locations during the UAV flight. By incorporating these measures, the snorkeler effectively serves as a dynamic control point with respect to the UAV (Figure 16). Indeed, both the UAV and the snorkeler assume essential roles in the methodology,

each contributing significantly to the seamless integration of emerged and submerged data. The UAV plays a dual role, acquiring the photogrammetric data and detecting the snorkeler in multiple locations. Meanwhile, the snorkeler responsibilities encompass capturing underwater photogrammetry and acting as a dynamic GCP. This dual engagement of the UAV and the snorkeler serve as the foundation for establishing connectivity between emerged and submerged data.

Basically, the UAV flight path is planned to ensure both adequate coverage of the area and overlapping of the images for precise 3D reconstruction. In our scenario, working within a coastal region with the presence of a water body, introduces a challenge. This shows complexities for photogrammetric methods, as matching tie points between images becomes intricate. Since one of the primary objectives is to generate an orthophoto covering the bay, including its water surface, a specific approach to UAV path design and image acquisition is needed. Each image must encompass a sufficient terrestrial-water composition to facilitate seamless relative orientation of images, thus, a balance between covered area and image dimensions is required, which can vary with flight altitude.

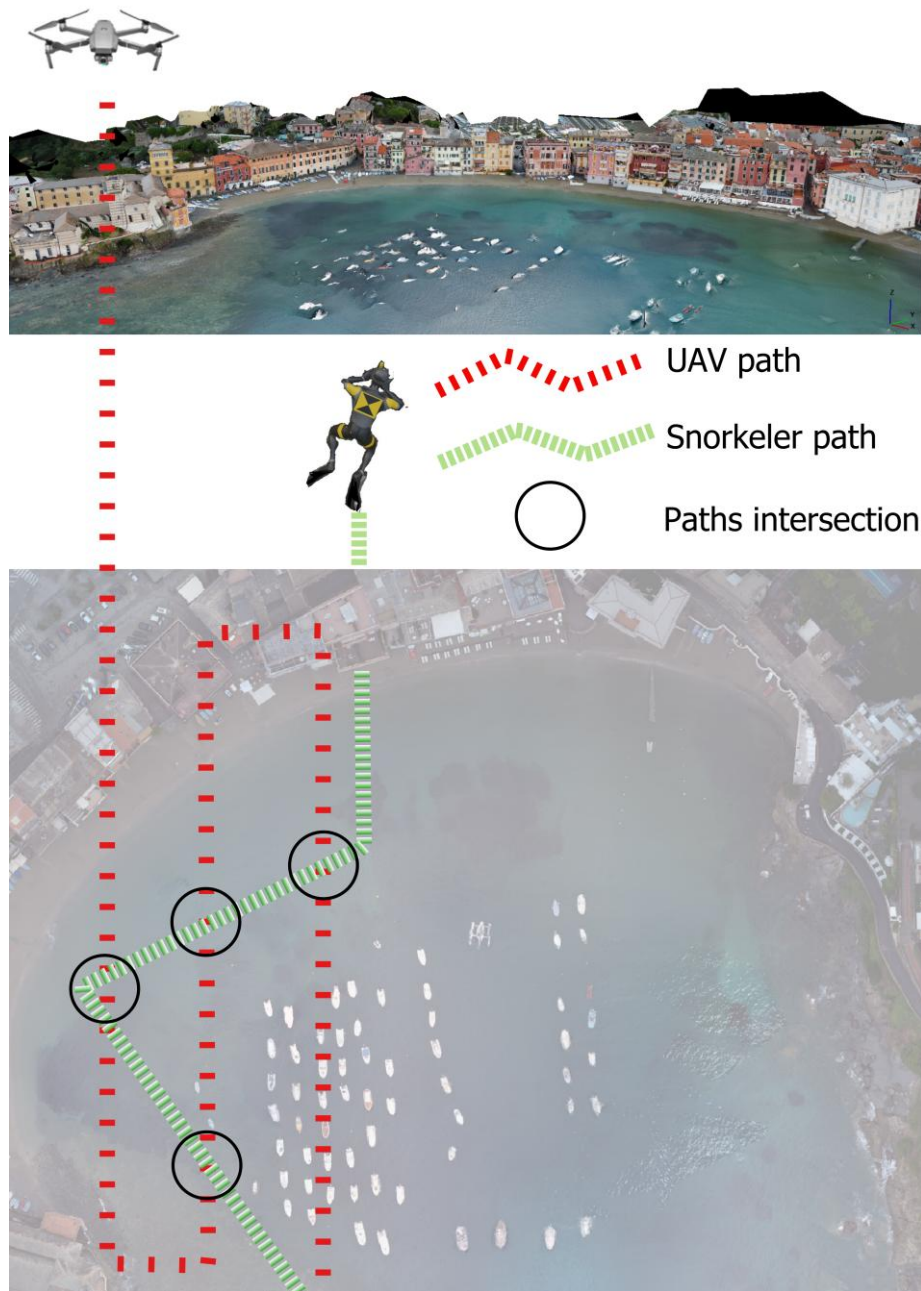


Figure 15 The UAV (in red) and snorkeler (in green) paths and their intersections (in the black circles) over the study area which is around $400\text{m} \times 300\text{m}$.

The precise synchronization of start timing and frames count between the underwater camera and the UAV is essential because the positioning accuracy harshly depends on it. However, it was expected that when snorkeler is detected in the UAV frames, the snorkeler would appear in consecutive frames, leading to the snorkeler position being calculated in several positions. The terrestrial GCPs play a pivotal role in the photogrammetric workflow, because they provide precise reference coordinates that anchor the photogrammetric model to the real-world reference system. By identifying these points in multiple overlapping UAV images, the software can optimize the Bundle Block Adjustment (BBA), correct scale and orientation errors, and ensure that the resulting orthophoto is metrically accurate and georeferenced

Once the data is gathered, a standard photogrammetric processing workflow for UAV-derived data is executed relying on the measured natural points to generate a point cloud, DSM, and orthophoto. During the aerial photogrammetry data processing, certain images also capture the snorkeler on the water surface. Hence, for each image featuring the snorkeler, his new position within that specific image is computed referred to the terrestrial system. This task presents challenges, primarily because the snorkeler lacks GNSS equipment, and his role as a dynamic control point adds complexity to the process. Orthophotos were used to tackle this complexity, coupled with an image processing tool to compute the snorkeler coordinates from images. As known the orthophoto permit to obtain metric information of the points, thus permit to measure the snorkeler coordinates position.

The accuracy depends on the Ground Sample Distance (GSD), and so depend on the shooting captured altitudes other than the focal length of the camera.

A Python script was developed to create an interactive application (reported in Appendix) to sequentially display each corrected image (orthorectified image), georeferenced and ready for analysis. The user can pan, zoom, and interact with the image, clicking on it; when the snorkeler is identified, a click at the target centre triggers automatic storage of the coordinates, labelled with the frame name, in a text file. This process continues for successive corrected frames until completion, generating a text file with three columns: frame name, x-coordinate, and y-coordinate. This application expedites the computation of target coordinates in each image.

Once the target position on the snorkeler's back is obtained, the task shifts to aligning this position with the camera centre. Measurements were conducted to determine the distance between the target centre and the camera centre, facilitating this adjustment. This means that for the specified underwater frames, time-matching with the UAV frames, the camera coordinates are known. Conversely to UAV photogrammetric workflow, that relied on measured GCPs for bundle block adjustment, the underwater photogrammetric data elaboration relied on the computed camera coordinates. For every frame, camera positions (easting and northing coordinates) were involved from the beginning in the relative orientation process. An essential step for underwater elaboration was the camera calibration by using a chess board, this was done contextual to the relative orientation in Metashape. A proper camera calibration parameter (focal length f ; principal point coordinates c_x , c_y ; radial distortion coefficients k_1 , k_2 , k_3 , k_4 ; affinity and non-orthogonality (skew) coefficients b_1 , b_2 ; tangential distortion coefficients p_1 , p_2) must be set as pre-calibration parameters. Otherwise, the relative orientation process will not be realistic. The camera calibration, using a chess board, is obtained in an underwater dedicated survey, contextually to the underwater survey to have the same optical water conditions.

The method workflow of the underwater data processing is a georeferenced model based on the camera position (Figure 17).

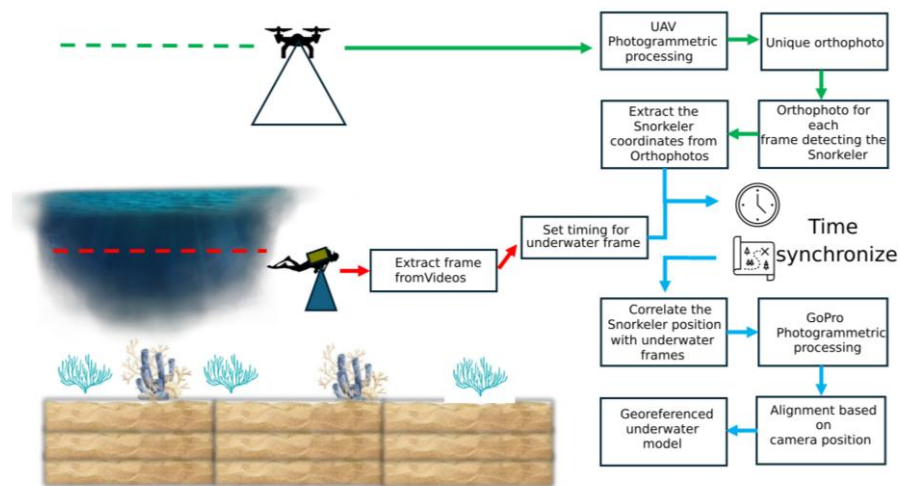


Figure 16. Methodology steps: (1) UAV and underwater image acquisition; (2) generation of orthophoto over the study area; (3) snorkeler position extraction; (4) UAV and underwater frames time synchronization; (5) underwater photogrammetry processing; (6) seamless 3D georeferenced model. The arrows indicate the sequence of steps and data flow between aerial (green) and underwater processes (red) and time synchronization (blue).

Both sets of data, coming from the UAV and underwater camera, were processed using Agisoft Metashape® (V 1.8.2) to generate accurate and georeferenced 3D models. The evaluation of the accuracy of this model is related to the least square method, which minimizes the sum of the squared differences between observed and predicted values, provided that at least 4 frames with known positions are oriented during the same data collection. The obtained emerged and submerged models can be integrated into interactive platforms, such as gaming software, to create a realistic virtual model of the environment. This allows for better public engagement with the research, providing an accessible way to visualize and explore the coastal and underwater data, which is valuable for environmental education and awareness.

One key aspect that remains unaddressed in the previous methodology is the evaluation of positioning errors and the development of an accurate underwater model of the seabed. Building on the previous snorkeler-based methodology, where underwater positioning relied entirely on orthophotos, a new approach was designed to validate and improve this workflow. In this second phase, the snorkeler was replaced by an Autonomous Surface Vehicle (ASV) equipped with a GNSS receiver. Unlike the snorkeler, the ASV provides precise positional data in real time, allowing for direct comparison between the camera positions derived from orthophotos and those measured through GNSS. This parallel acquisition enables a rigorous assessment of how accurate the orthophoto-based positioning method is, offering a benchmark against ground-truth GNSS readings. Introducing the ASV also allows the integration of additional sensors and ensures better synchronization with UAV data, ultimately providing a more reliable framework for constructing accurate and seamless 3D models of the coastal environment. The equipment sensors and techniques represented in (Figure 18) were utilized. The ASV was equipped with a underwater system consisting of NORBIT Wideband MBES with a resolution standard of $0.9^\circ \times 1.9^\circ$ at 400 kHz synchronized with GNSS receivers and IMU for precise positioning and navigation of ASV, and a NORBIT LiDAR, a compact terrestrial mapping sensor fully integrated with a high resolution underwater multibeam system.

Moreover, GoPro Hero 10 Black was used for underwater imaged collection. The GoPro Hero 10 Black capabilities include 4K video, a 24.4 mm lens, and a sensor size of 6.40×5.60 mm, allowing for the capture of detailed imagery in aquatic environments (Figure 18). As the camera is separated system and not synchronized with underwater system, it does not provide positioning information. In this context, a target was fixed on the top of the ASV, oriented to be easily detected by the UAV to support the positioning of the underwater camera, as explained in the following. The survey campaign lasted approximately for half a day and acquired data from terrestrial and underwater environments. The ASV started to acquire underwater and underwater images data; at the same time, the UAV started the flight mission to acquire the images for the terrestrial reconstruction and for the marker detection on the ASV. The UAV was following an automatic pre-planned mission while the ASV was manually navigated for the data collection. The flight height chosen for nadiral image acquisition was approximately 80 m, as planned with mission planning tool. The chosen flight height balances the need for good resolution to detect the target on the ASV and the need for images containing an adequate proportion between terrestrial and sea to enable and facilitate the images relative orientation.



Figure 17. Photographs of the different devices used in this study. A) GoPro camera, and MBES, B) Autonomous Surface Vehicle (ASV), C) Marker, and LiDAR system, D) UAV. E) Set up of the integration of all the instruments for comprehensive data collection and analysis.

This sensor integration enables an interdisciplinary approach by combining various survey techniques, i.e., photogrammetry from the UAV, the MBES, LiDAR and underwater camera mounted on the ASV. The choice was to work with an ASV rather than a traditional vessel, both because it was considered a more cost-effective technique and because of the ASV ability to acquire data from less accessible areas than a traditional vessel; furthermore, this technology was tested to extend new standards in terms of data coverage and accuracy. The absolute orientation (yaw, pitch and roll) and absolute position, needed to obtain a georeferenced point cloud, were provided by the on-board IMU and the GNSS sensor, respectively. To achieve better understanding of the seabed and better monitoring of underwater habitats, the GoPro was fixed under the ASV, enabling nadiral videos acquisition. While the underwater system on the ASV was synchronized with GNSS measurements, so the depth measurements produce a georeferenced output.

A new methodology was developed in this study to georeference underwater models using aerial photogrammetry. The workflow is conceptually similar to the snorkeler-based approach: a target fixed on the ASV acts as a dynamic GCP, whose positions are determined from UAV images and refined through orthophotos. This ensures geometrically correct measurements despite image distortions. What distinguishes this scenario is that the ASV is equipped with GNSS, which provides ground-truth positioning data. This allows a direct comparison between the coordinates derived from orthophotos and those recorded by the GNSS, enabling a quantitative evaluation of the method's accuracy. To support this, an interactive Python application was used to extract target coordinates from orthophotos efficiently, generating a file with frame name and position for subsequent integration. These positions were then compared with the GNSS data to assess the accuracy of orthophoto-based camera localization and to validate the overall workflow. To evaluate the accuracy of the method, the positions of the ASV derived from orthophotos were compared directly with the GNSS measurements recorded on board. The comparison was performed frame by frame, matching the UAV capture time with the corresponding GNSS timestamp. Both datasets were transformed into the same reference system to ensure consistency. For each matched pair, the horizontal and vertical positional differences were calculated, and statistical indicators such as mean error, root mean square error (RMSE), and maximum deviation were computed. This procedure provided a quantitative assessment of how closely the orthophoto-based estimates align with the GNSS ground truth, thereby validating the robustness of the proposed workflow.

2.3 THIRD SCENARIO: ELBE HARBOR HAMBURG

An additional study case, where the methodology was applied to obtain a submerged and emerged unique model, is presented in a new scenario in the harbor environment. This scenario extends the workflow tested in lakes and coastal areas to a more complex and constrained context, where safety regulations, infrastructure, and tidal variability play a critical role. It is necessary to specify that what was obtained before integrating UAV photogrammetric surveys with dynamic markers placed on the snorkeler or on the marine drone is here applied to 360° camera imagery, combined with natural GCPs identified on the harbor structures. As this thesis work deals with coastal and harbor environments, an additional case study was applied in the harbor environment. Maintaining critical harbor infrastructure, quay walls, buildings with waterfronts, or urban infrastructure in areas which are predominantly marked by waterways and channels is an ongoing challenge for any urban environment built at rivers or estuaries. The key issues to support critical infrastructure studies in harbor areas start with collecting reliable geospatial and hydrospatial data. In this context, a case study is located in the Elbe River within the harbor of Hamburg, a major port in northern Germany (Figure 19).

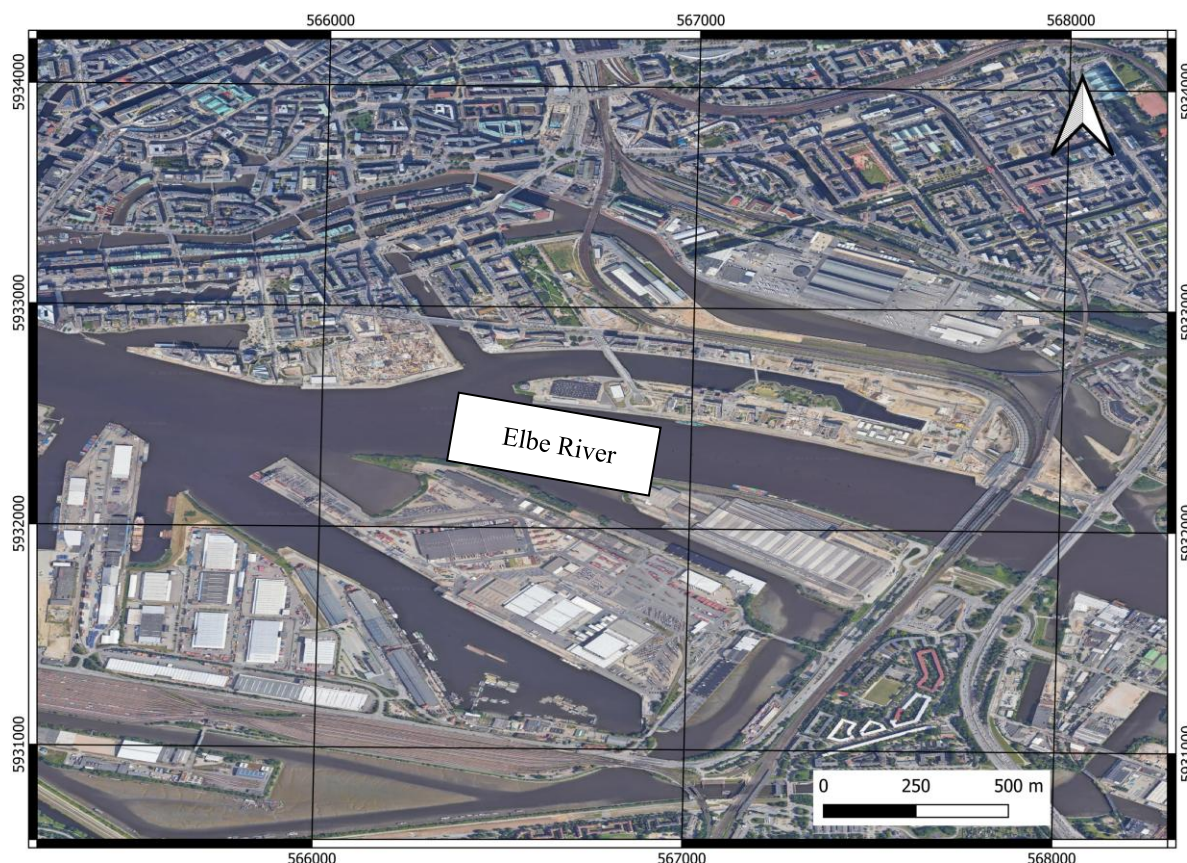


Figure 19. Satellite imagery of the study area, section of the Elbe River, within the Hamburg harbor.

The Elbe River, plays a significant role in European trade, and the Hamburg harbor serves as one of the largest and most important ports in the region [185]. The harbor area features a complex infrastructure, including docks, piers, shipping channels (Figure 20), and industrial facilities, which are essential for the city's economy.

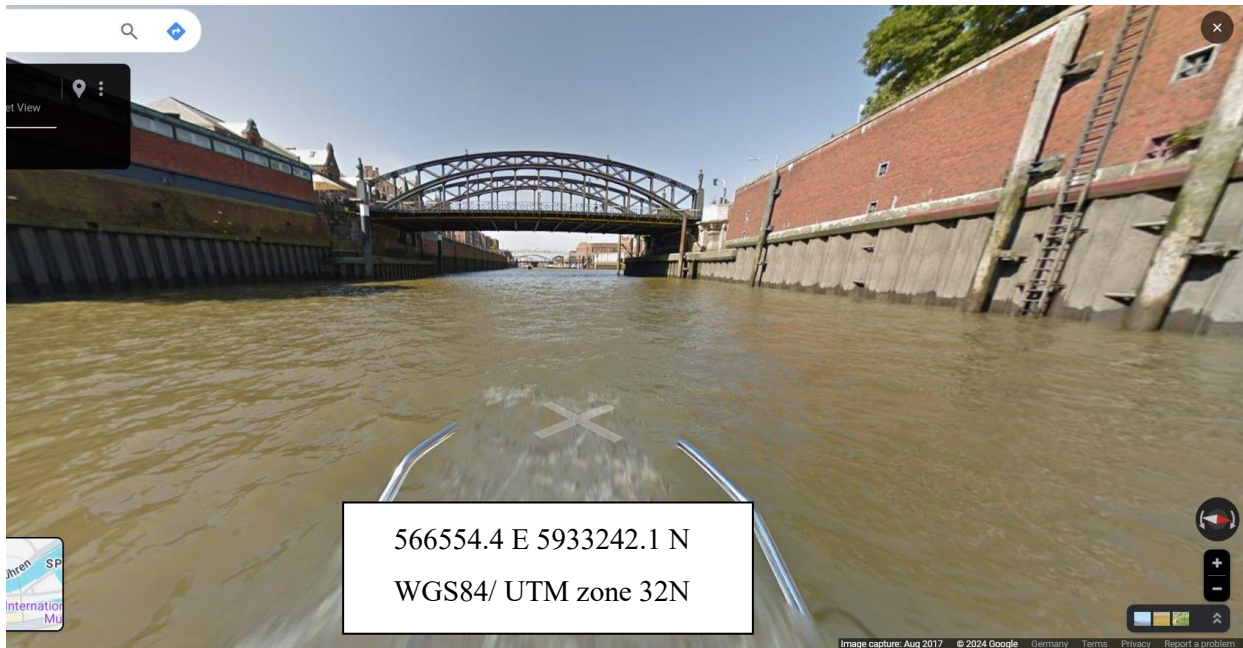


Figure 18. A screenshot from Google Maps street view to show an example of the harbor channels.

The river course in this area is highly modified by human-made infrastructure, with the width and depth completely influenced by the infrastructure (channels, dams, ...), and the presence of tidal currents significantly affect navigation and environmental conditions. Then monitoring of harbor infrastructure and riverbed morphodynamics is essential to provide insights into the harbor situation and the impact of maritime activity. Tidal and current patterns within the harbor area further influence sedimentation and water quality, making it a challenging environment to study. The area also supports diverse ecosystems, though it faces environmental pressures from shipping traffic and industrial activities. This location was chosen for its unique combination of hydrodynamic complexity, environmental significance, and its relevance to maritime research, presenting both challenges and opportunities for further investigation. This scenario is included not only to test the integration of MBES and 360° camera photogrammetry but also to evaluate the applicability of the methodology in a complex tidal environment. Unlike the previous scenarios, no dynamic target was mounted on the acquisition platform. Instead, the natural overlap created by tidal variation between high- and low-water surveys served as control references, ensuring the continuity of both underwater and above-water models. In this way, the tidal cycle acted as a ‘dynamic georeferencing condition,’ providing tie points to merge the two environments into a unified model. An integrated optical and acoustic survey can help to develop new services for marinas and blue economic operators in the harbour. The methodology integrates terrestrial and underwater survey, using a 360° Camera and MBES mounted on a small research vessel, also on ASV and/or ASV (Figure 21).



Figure 19. Equipment used for surveying in Elbe River: 360° camera ladybug (on the left) and MBES Kongsberg EM2040 (on the right).

While the MBES provides the most efficient method to chart bathymetry and infrastructure below the water surface, the 360° camera captures the surroundings in high-quality and immersive imagery and video. The high-resolution imagery resolves in a SfM 3D model for all areas above the waterline. RGB values are recorded by the camera enhancing the natural representation of the environment of interest. Both camera and MBES are instances of one multi sensor platform and therefore synchronized in time and aligned regarding their on-board location. In this configuration, accurate GNSS measurements from the platform itself provide the necessary external reference, making the deployment of additional Ground Control Points (GCPs) unnecessary, since both sensors already share the same spatial reference system. Below the water surface, the 3D model's quality depends primarily on the MBES. For the Kongsberg EM2040 used in this study, the nominal performance specifications indicate a resolution better than 10 cm and an accuracy of approximately 5 cm, both vertically and horizontally, consistent with shallow-water hydrographic survey standards.

Above the water surface, the 3D model depends on the performance of the 360° camera. The 360° cameras offer flexibility for capturing images in any direction, and the large field of view benefits in reducing the number of images. However, it remains essential to ensure proper overlapping between images to enable accurate reconstruction of photogrammetric processes. A 3D model solution derived from photogrammetric workflow can vary depending on several factors including camera specifications and georeferencing method, reaching down to the centimetric scale. Since this approach relies on the GNSS solution for camera positioning, the ultimate precision corresponds to the GNSS accuracy itself.

The main problematic aspect is to obtain the overlapping and continuity between the camera model and MBES model. Since both instruments are fixed on the boat, in the data collection there was no overlapping between the camera coverage and the MBES which led to have a non-covered area of the quay wall during the survey (Figure 22). Two different surveys were performed: the first was carried out on high tides level, whereas the second on a low tide level (Figure 23). To respect the safety standards, on low tides it is not possible to use traditional boat due to the shallow depth in some areas. In this context, an ASV was

employed to perform the survey so to acquire the quay wall area that remained non-covered during the high tide survey. A GoPro was mounted on the ASV to collect images for the walls and extend the covered area.

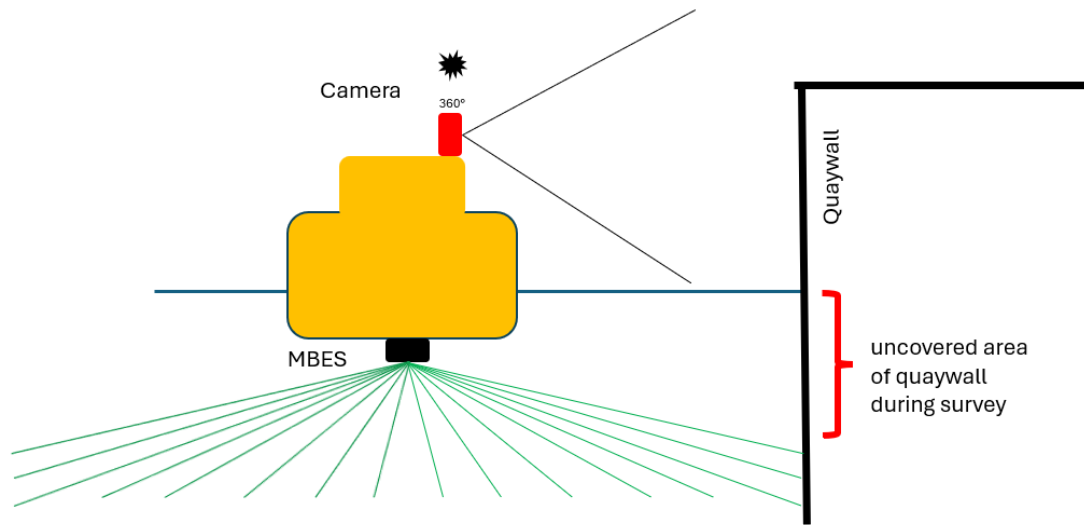


Figure 20. Survey setup with MBES and a 360° camera with a high tide. The MBES captures the underwater bathymetry, while the camera records the surroundings. The uncovered area of the quay wall during the survey is highlighted. From here we took advantage of the environmental factors in the harbour. Since we have extreme tides effects in this area which approximately is around 3 m of variation in the water surface every 6 hours.

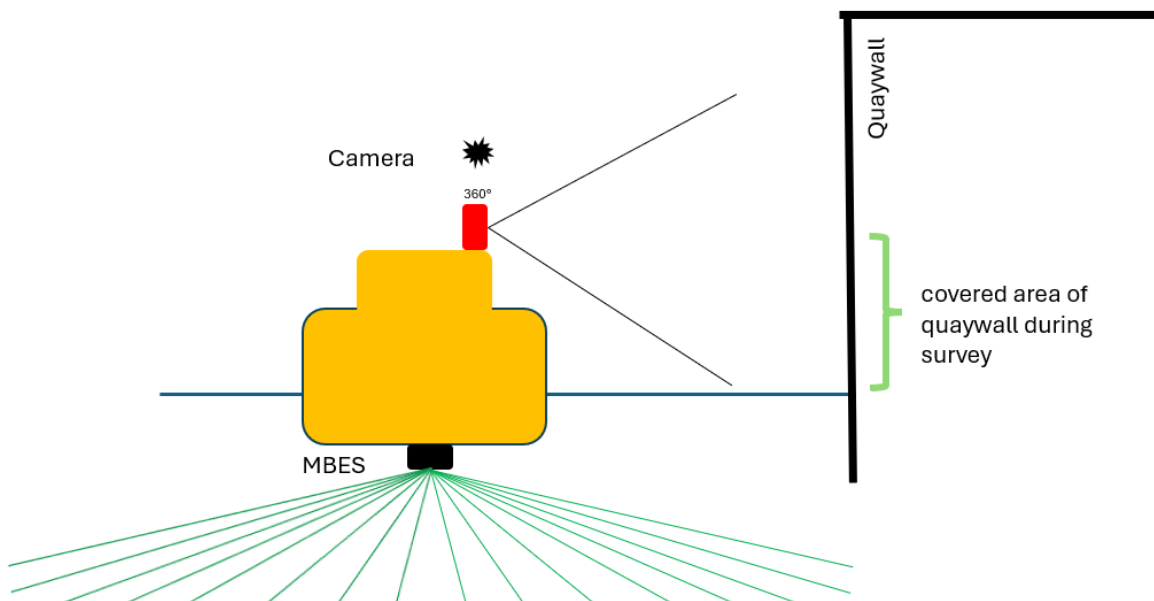


Figure 21. Diagram illustrating the survey setup with an MBES and a 360-degree camera on a low tide. The MBES captures the underwater bathymetry, while the camera records the surroundings. The covered area by the quay wall during the survey is highlighted.

For underwater mapping, prior to data collection, a patch test was performed to ensure accurate calibration of the MBES system. This test involved determining and correcting sensor misalignments, latency, and roll, pitch, and yaw offsets by surveying a series of predefined lines over known features such as a flat seabed or prominent underwater objects. Once calibrated, the MBES was used to acquire high-resolution underwater data, which provided a detailed representation of the underwater topography. Simultaneously, a 360° camera was mounted on the boat to capture panoramic images of the harbor channel walls and adjacent terrestrial features. These images were processed to create seamless panoramic views, but unwanted objects, such as the boat structure, reflections, or other obstructions, were manually masked during post-processing to ensure clean and usable visuals. While this method provided extensive coverage, certain areas of the channel walls were not fully captured due to limitations at high tide.

To address gaps in the first survey, a second survey was conducted at low tide using an ASV equipped with a GoPro camera. The ASV smaller size and maneuverability allowed it to navigate closer to the channel walls, capturing the previously missed sections. The combination of the high-tide MBES data and low-tide panoramic images ensured complete spatial coverage of the study area, enabling detailed analysis of both underwater and terrestrial features.

The accuracies of both surveys are further analysed by quantitatively comparing both measurements on the same location. By using predefined survey spots on significant structures during high and low tide, the same quay wall structures were surveyed by both acoustic and optical measurement systems.

Combining the photogrammetric imagery of the camera with the point cloud acquired underwater by sonar measurements lead to a surface model providing a georeferenced 3D representation of any waterway surroundings. Possible further applications include a collective network of publicly accessible imagery data spatially connected, for instance a “street-view” for waterways and water channels in lagoon cities. This will enhance hydrographic measurements contributing to smart e-navigation solutions.

3. RESULTS

This chapter presents the outcomes of the surveys carried out in the three different scenarios described in the previous section. The results are organized as follows: first, the findings from the Laghi del Gorzente lake survey are presented, focusing on the integration of SBES bathymetry with UAV photogrammetry in a controlled environment. Next, the outcomes from the Silent Bay of Sestri Levante survey are reported, where the methodology was tested with a snorkeler and later extended using an ASV to compare GNSS-based positioning with orthophoto-derived positions. Subsequently, the Elbe Harbor case study in Hamburg is analyzed, emphasizing the integration of 360° imagery and MBES data in a complex harbor environment. Finally, a synthesis of results is provided, comparing the three scenarios, highlighting the strengths and limitations of each approach, and discussing the broader applicability of the proposed methodology.

3.1 FIRST SCENARIO: LAGHI DEL GORZENTE

This section is dedicated to present the final outputs, by providing the computed coordinates, validating the obtained merged model from the emerged and submerged environments, and finally displaying the resulting data as a 3D model. The computation of the local coordinate system is based on the azimuthal and zenithal angles coming from the total station to compute X, Y and Z for every point. Local coordinates are provided in Table 1, where SWAMP 1 and SWAMP 2 relate to SWAMP locations, points 1A–14A represent GCPs and point SH is measured on the shoreline as a zero-level surface. h_w represents the points elevation with respect to the real surface water level measured through the survey campaign. The local coordinates were determined by the software Sierrasoft Topko [186] respectively for X, Y and Z components, by assigning the coordinate for the total station position as (1000, 1000, 1000) m. The computed values are shown in Table 2.

Table 2. The coordinate of the GCPs, the common points SWAMP 1 and SWAMP 2 and point SH is measured on the shoreline as a zero-level surface. h_w represents the elevation with respect to the real surface water level measured through the survey campaign.

	X [m]	Y [m]	Z [m]	h_w [m]
Total station	1000.000	1000.000	1000.000	2.755
Point 1	1193.370	1000.231	998.907	1.662
Point 2	1117.080	1005.870	998.476	1.231
1A	1084.254	1002.970	998.820	1.575
2A	1041.931	1005.447	999.254	2.009
3A	1018.379	1006.942	999.840	2.595
4A	998.526	995.534	998.041	0.796
5A	978.128	998.304	1000.341	3.096

6A	960.436	998.991	999.742	2.497
7A	942.682	995.473	998.138	0.893
8A	926.621	984.640	998.572	1.327
9A	928.973	972.711	1002.569	5.324
10A	951.608	979.439	998.248	1.003
11A	966.553	963.835	1002.158	4.913
12A	979.328	952.617	1002.793	5.548
13A	991.116	938.973	1003.621	6.376
14A	1016.537	935.708	999.748	2.503
SH	1023.948	938.685	997.245	0.000

The study area was divided into four portions; two of them were surveyed by aerial photogrammetry (Chunk 2 and 4, Figure 24), while the rest by terrestrial photogrammetry (Chunk 1 and 3, Figure 24). After collecting the photogrammetric images, the processing workflow of the model was performed mainly by considering the four different datasets separately (Figure 24).

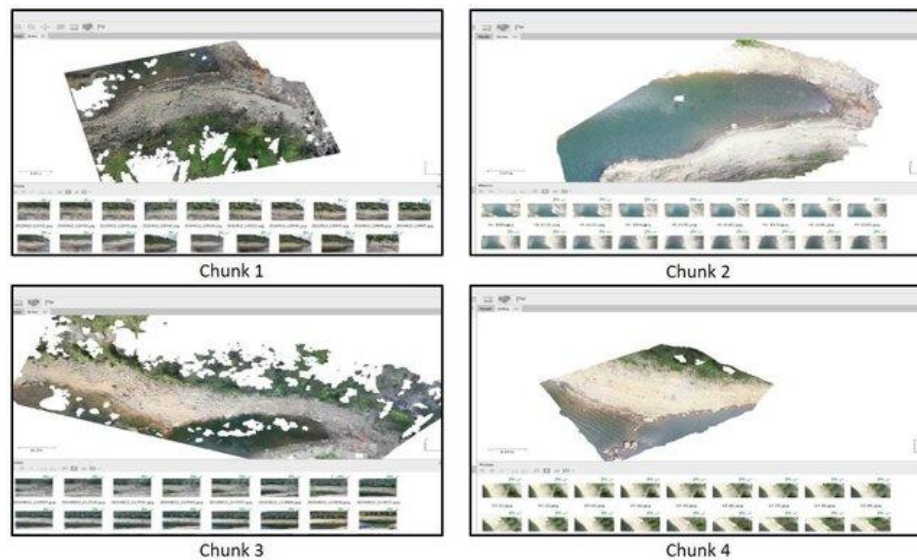


Figure 22. Images of the different area covered by each of the four datasets through the processing of data using Agisoft Metashape© software. Chunk 1 and 3 represent a portion of the area that was surveyed by terrestrial photogrammetry while Chunk 2 and 4 by aerial photogrammetry.

To achieve a single model by merging the four datasets, a validation assessment was performed for each dataset separately (Table 3). Dataset processing was carried out using Agisoft Metashape©, following the standard workflow: alignment, aero-triangulation, and reconstruction of the dense point cloud. In the first dataset, three GCPs (points 8, 9, 11) and one check point (CP 10) were available. The CP error from bundle block adjustment (BBA) was 1 cm. In the second dataset, three GCPs (points 6, 7,

11) and CP 10 were accessible. The CP error was ~ 5 mm, which represents the smallest residual among all datasets. In the third dataset, four GCPs (points 5, 7, 8, 9) and CP 6 led to an error of 1 cm, similar to dataset 1. In the fourth dataset, three GCPs (points 2, 3, 5) and CP 4 gave an error of ~ 2 mm. These results highlight the role of redundancy and GCP distribution in controlling accuracy. Although all datasets had a limited number of GCPs (3–4) and only one CP each, the achieved errors were in the millimeter-to-centimeter range, which is acceptable for this type of survey. The smallest error (~ 5 mm) was obtained in dataset 2, likely due to the favorable positioning of its three GCPs, showing that well-distributed GCPs can compensate for limited redundancy. Conversely, datasets with more GCPs (such as dataset 3 with four points) did not necessarily achieve a lower residual (1 cm), indicating that the quality and distribution of GCPs is more critical than their absolute number. Overall, the residuals confirm that the BBA performed reliably even with minimal redundancy, although additional GCPs and CPs would have provided greater robustness and reduced the risk of local deformations.

Table 3. GCPs and CPs errors over each dataset. Tables are ordered consecutively (datasets 1–4) from top to bottom. The coordinates are provided in WGS84/UTM32N. The residuals are computed by Agisoft Metashape© (V 1.8.2) based on BBA. All the values are in meters.

Targets	East	North	Z	Residuals	Type
8	486,670.100	4,932,363.000	1.326	0.041	GCP
9	486,666.500	4,932,351.000	5.32	0.044	GCP
10	486,644.800	4,932,360.000	1.002	0.010	CP
11	486,628.300	4,932,346.000	4.906	0.013	GCP
Control Points				0.036	
Check Points				0.010	
Targets	East	North	Z	Residuals	Type
6	486,638	4,932,380	2.497	0.004	GCP
7	486,655.3	4,932,375	0.893	0.001	GCP
10	486,644.8	4,932,360	1.003	0.005	CP
11	486,628.3	4,932,346	4.913	0.003	GCP
Control Points				0.003	
Check Points				0.005	
Targets	East	North	Z	Residuals	Type
5	486,620.3	493,238,1	3.094	0.008	GCP
6	486,638	4,932,380	2.496	0.017	CP
7	486,655.3	4,932,375	0.892	0.013	GCP

8	486,670.1	4,932,363	1.326	0.007	GCP
9	486,666.5	4,932,351	5.32	0.004	GCP
Control Points				0.009	
Check Points				0.017	
Targets	East	North	Z	Residuals	Type
2	486,557.5	4,932,395	2.008	0.001	GCP
3	486,581.1	4,932,394	2.593	0.002	GCP
4	486,599.7	4,932,381	0.829	0.003	CP
5	486,620.3	4,932,381	3.094	0.001	GCP
Control Points				0.002	
Check Points				0.003	

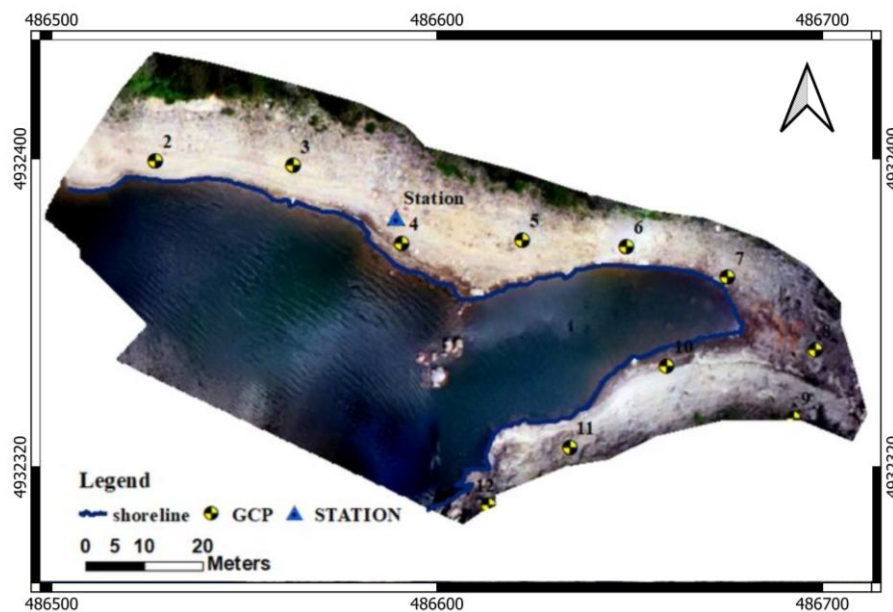


Figure 23. Orthophoto representing the merged point, showing the location of the total station (blue triangle) from where GCPs (black and yellow symbols) were measured. The shoreline is outlined in blue. The study area dimension is around 20,550 m². Water refraction not taken into account.

After the results were obtained for each dataset separately, they were merged based on the GCPs positions. Using this method, the software calculated the estimated residual error on the selected CP, providing an accuracy estimation, conditionally on the GCPs coordinates. The merged four datasets turned into a single dataset, thus in a single point cloud. Ten markers (GCPs 2–11) were allocated as eight GCPs (2–5, 7, 8,

10 and 11) and two CPs (6 and 9) to validate the result in terms of the final merged point cloud. Highlighting that in dataset 4, only one GCP (point 5) is common with the other datasets, natural common points were considered in this case in the merging process. Overall, the obtained result of the merged point cloud had a representative error in terms of CPs equivalent to 4 cm, as shown in Table 3.

Table 4. GCPs in the merged point cloud and final residuals in correspondence of the CPs. The coordinates are expressed in WGS84/UTM32N. All the values are in meters.

Markers	Easting	Northing	Z	Error	Description
	[m]	[m]	[m]	[m]	
2	486,557.547	4,932,394.944	2.008	0.055	GCP
3	486,581.138	4,932,394.035	2.593	0.048	GCP
4	486,599.691	4,932,380.808	0.829	0.084	GCP
5	486,620.266	4,932,381.365	3.094	0.058	GCP
6	486,637.965	4,932,380.246	2.497	0.037	CP
7	486,655.269	4,932,374.944	0.893	0.018	GCP
8	486,670.145	4,932,362.537	1.326	0.041	GCP
9	486,666.530	4,932,350.942	5.320	0.037	CP
10	486,644.754	4,932,359.903	1.002	0.044	GCP
11	486,628.256	4,932,345.965	4.906	0.031	GCP
Control Points				0.051	
Check Points				0.037	

From the merged dataset, an orthophoto with 2 cm/pixel resolution was generated (Figure 25). GCPs and shoreline zero-level markers matched well with the orthophoto, ensuring proper georeferencing (Figure 26). Forty-one shoreline points representing the zero-level surface were digitized and imported into GIS as the reference for interpolation.

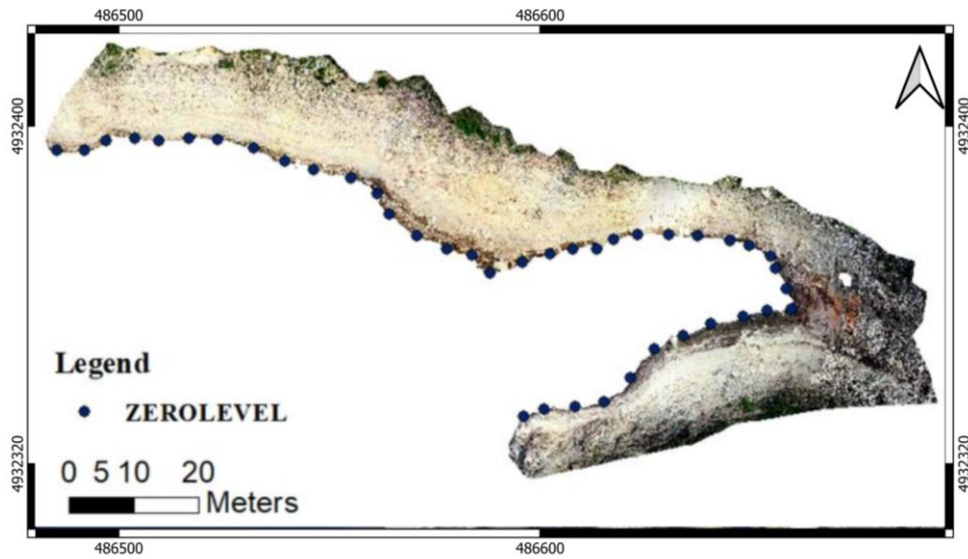


Figure 26. Orthophoto obtained from digital photogrammetric images elaboration. The black dots represent the points along the shoreline, i.e., zero-level.

After importing the orthophoto and the dense cloud previously obtained into GIS software, a DSM was built. The results are shown in Figure 26a. As shown, the terrestrial area is divided into several colors representing a range of elevation values, from blue (as lower elevation) to red (as the highest elevation). Obviously, these ranges contain many outliers and noise that must be filtered out. Knowing that this DSM is related to the terrestrial area that is above both the real water level and the reference zero levels, all the points measurements having an elevation value less than zero must be eliminated. Moreover, as shown in the legend of the DSM, there are also height ranges between 8 and 30 m, and this is because of the presence of high trees in the outer boundary of the study area that influence the obtained DSM. Hence, after eliminating these points, for the emerged zone, the overall result is a DSM ranging from the water surface level (0 m) to 8.7 m as shown in Figure 26b.

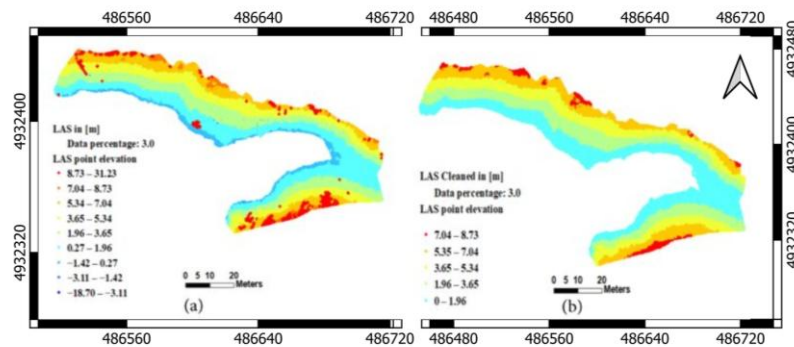


Figure 24. DSM of the emerged zone. In (a), outliers are represented in red color close to the outer boundary of the study area, while (b) represents the emerged zone after filtering and cleaning noises to obtain a more reliable elevation range.

The acquired underwater data are represented by colors ranging from light blue to dark blue, according to the increasing energy of the refracted acoustics signal. A lighter blue represents deep water, whereas a darker blue is used to display shallower areas, where the intensity of the refracted acoustic signal is higher. From this acquired underwater data, initial information on the variations of depth over the study area is obtained (Figure 28).

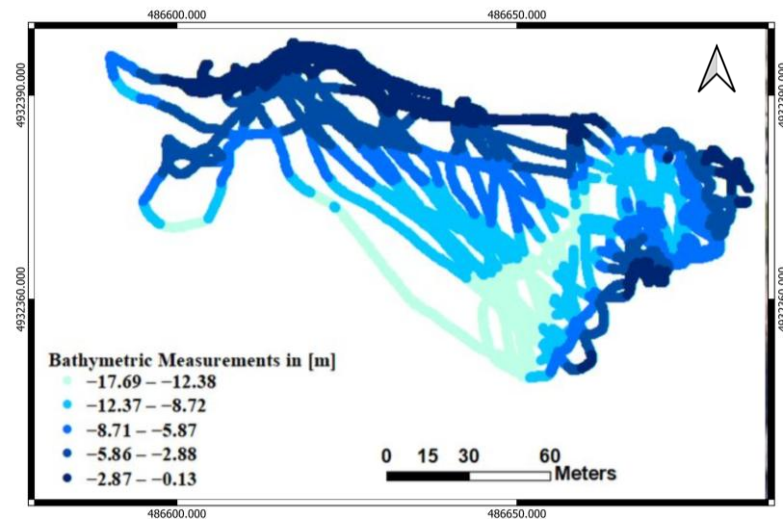


Figure 28. Underwater points measurements with color intensity representing the distance with respect to the sensor: lighter color stands for higher depth (lower intensity of refracted acoustic signal) and darker color represent shallow water.

After showing the results for terrestrial and underwater data separately, the data are merged based on the calculated control points and the digitized shoreline between the two data sets. Data merging is performed by using a dedicated tool in GIS (LAS Dataset to Point Cloud) that provides a single continuous model. As previously described, the merging operation is carried out with respect to the same horizontal and vertical reference frame and considering the water level as the zero level for the elevation (Figure 29). The used dense cloud has been filtered by deleting those outer limits defined as noise. The shoreline overlaps perfectly between the emerged and submerged area. The results are displayed in (Figure 29) and show the merged datasets and the terrestrial and underwater measurements. This is the first step to obtaining a common continuous model of both environments.

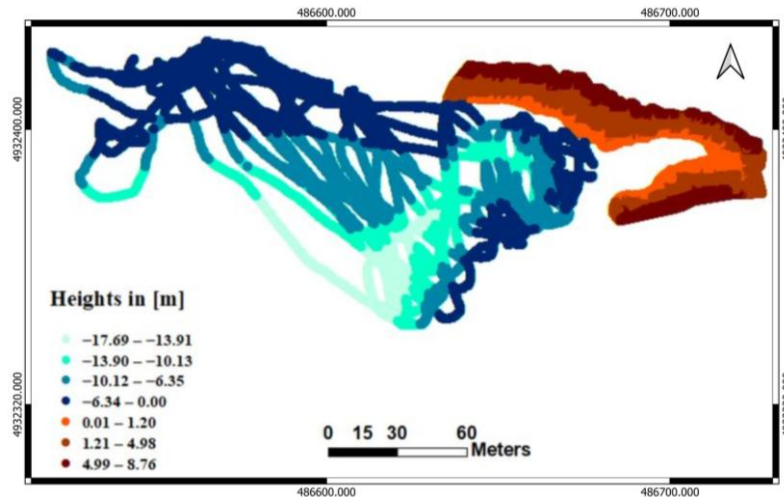


Figure 29. Merged measurements including terrestrial and underwater data. The dense point cloud has been used to represent the terrestrial area highlighted in brown.

After merging the data, the last step to obtain the DSM is to interpolate the data depending on the elevation measurements. Among several interpolation methods, the Natural Neighbor (NN) interpolation has been considered one of the most suitable methods for this scattered data. Since SBES is used, it is important to ensure that the interpolation stays within the range of the samples, meaning the values are estimated only based on data points that are within the area covered by the measurements. Hence, NN interpolation was used knowing that it does not infer trends nor produce peaks or valleys that are not already represented by the input samples. NN seeks to find the closest sample point to a query point and assigns weights to each based on polygon proportionate areas around each point. The DSM from the NN interpolation with a resolution of 5×5 cm (Figure 30) shows a range of water between -17.68 m for maximum depth and 8.76 m as the maximum height from the water level.

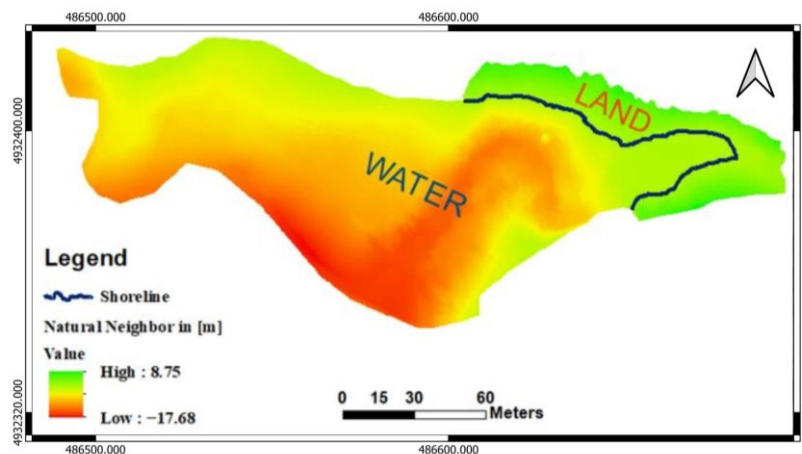


Figure 30. Resulting DSM based on Natural Neighbor interpolation for the entire environment.

Finally, a 3D model was built in ArcScene by overlaying several data layers (Figure 30a). Underwater terrain is shown from white to green to yellow, while terrestrial elevations range from yellow to red to brown. An animation was created to visualize water levels relative to the model (Figure 31b). Additionally, the total water volume was

computed relative to the measured surface level, providing a baseline for future monitoring of morphological and hydrological changes.

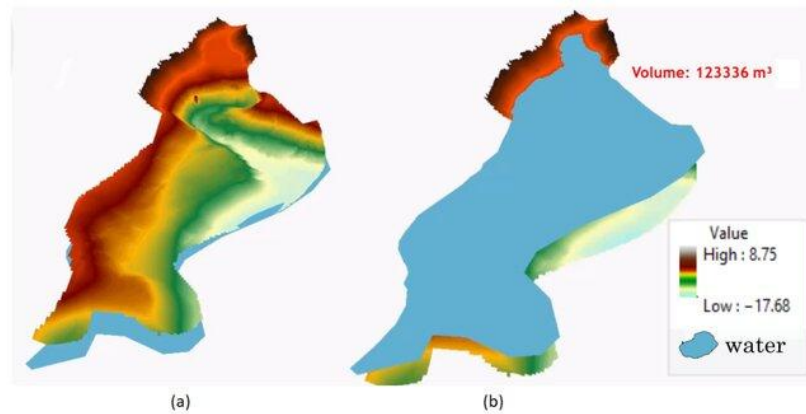


Figure 31. 3D model for rendering visualization analysis; (a) shows the morphology of the entire merged area, while (b) shows the results of surface and water volume determination. The study area dimension is around 20,550 m².

3.2 SECOND SCENARIO: SESTRI LEVANTE

In this section, the results provided by obtaining a unique orthophoto are presented. Moreover, the user-friendly Python application to support computing the coordinates of the snorkeler while performing the underwater survey is described.

The implementation of the proposed methodology provided noteworthy outcomes, highlighting the adaptability of the approach in seamlessly merging data from disparate environments. Through the systematic deployment of UAV-based terrestrial photogrammetry and simultaneous underwater photogrammetry by snorkeler, a coherent and georeferenced 3D model for both terrestrial and underwater was successfully generated.

As outlined in the methodology workflow, the starting point regarded the generation of an orthophoto for the entire study area, representing the terrestrial and the water surfaces where the snorkeler is moving and performing the underwater photogrammetry. The orthophoto was produced after following the photogrammetric workflow of Agisoft Metashape© (V 1.8.2) starting by computing the relative orientation of the 128 acquired frames covering an area of 0.151 km². The coordinates of 18 GCPs expressed in ETRF2000-2008.0 reference system with UTM zone 32N projection (EPSG: 6707) were inserted, achieving an average error of 3 cm. The outputs included a colored point cloud, a 3D model, and a DSM with 10.4 cm/pix. The DSM was processed by Python code (Appendix, code 5) to obtain a flat surface water representing the zero level reference (Figure 32).

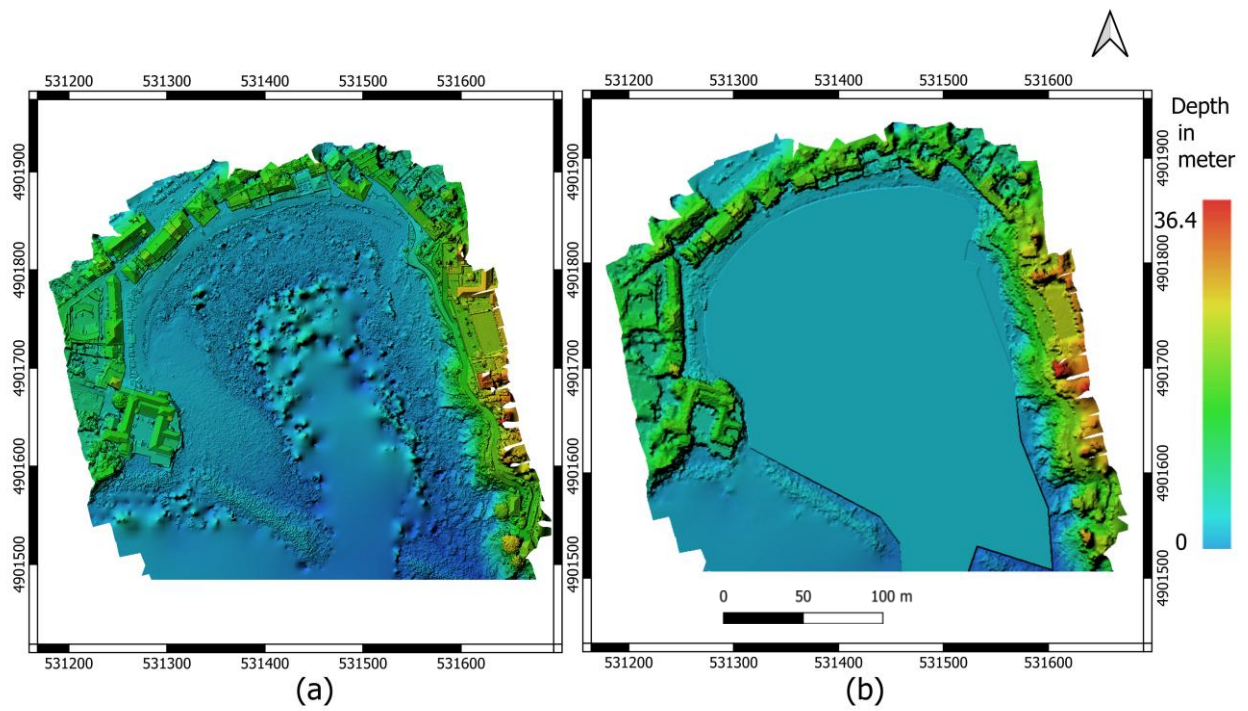


Figure 32. Original DSM, with surface water distortion (a) and modified DSM with flat water surface by Python (b).

Using the processed DSM, an orthophoto with 2.6 cm/pix (Figure 33) was the final product of the photogrammetric processing.

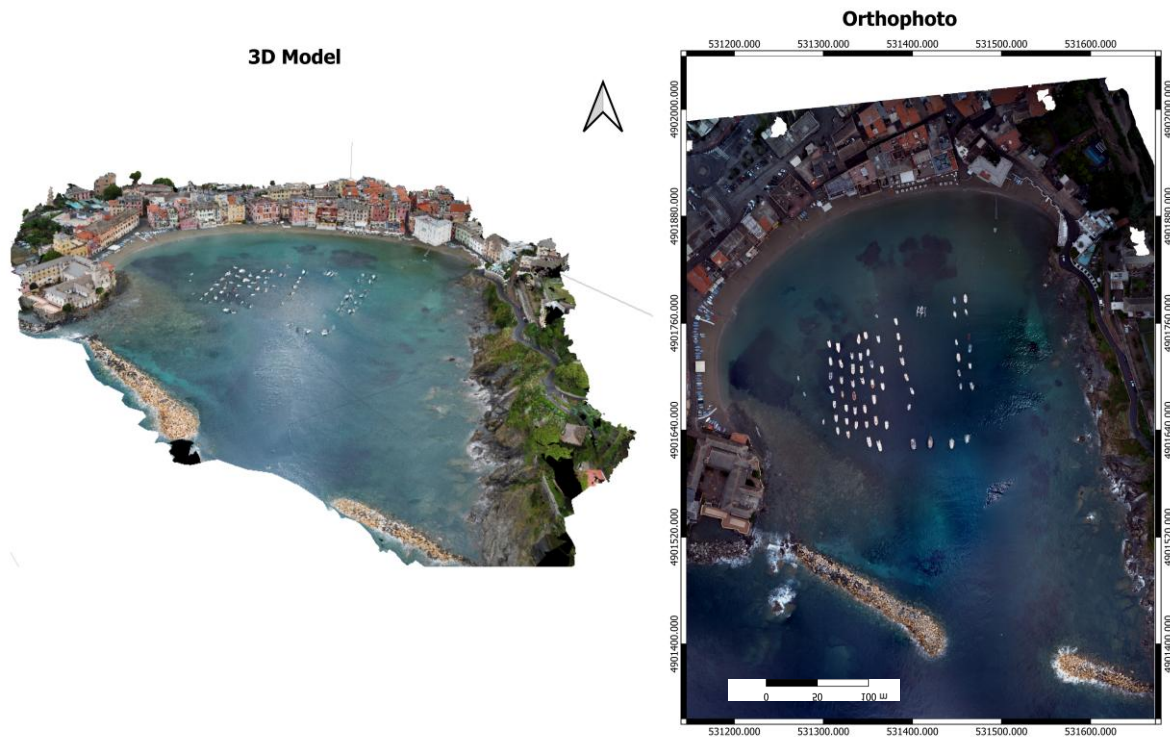


Figure 33. 3D model and orthophoto of the study area. Water refraction not taken into account.

The orthophoto generated from all the UAV frames serves multiple purposes: some frames contribute to realize the comprehensive model, while others facilitate the detection of the snorkeler and the estimation of his position. In this context, the unified orthophoto covering the entire study area was segmented into individual orthorectified images, resulting in a corrected and georeferenced image for each UAV frame (Figure 34). The orthorectified images capturing the snorkeler can be used to estimate his position within the same terrestrial reference system, i.e., ETRF2000-2008.0 with UTM zone 32N projection.

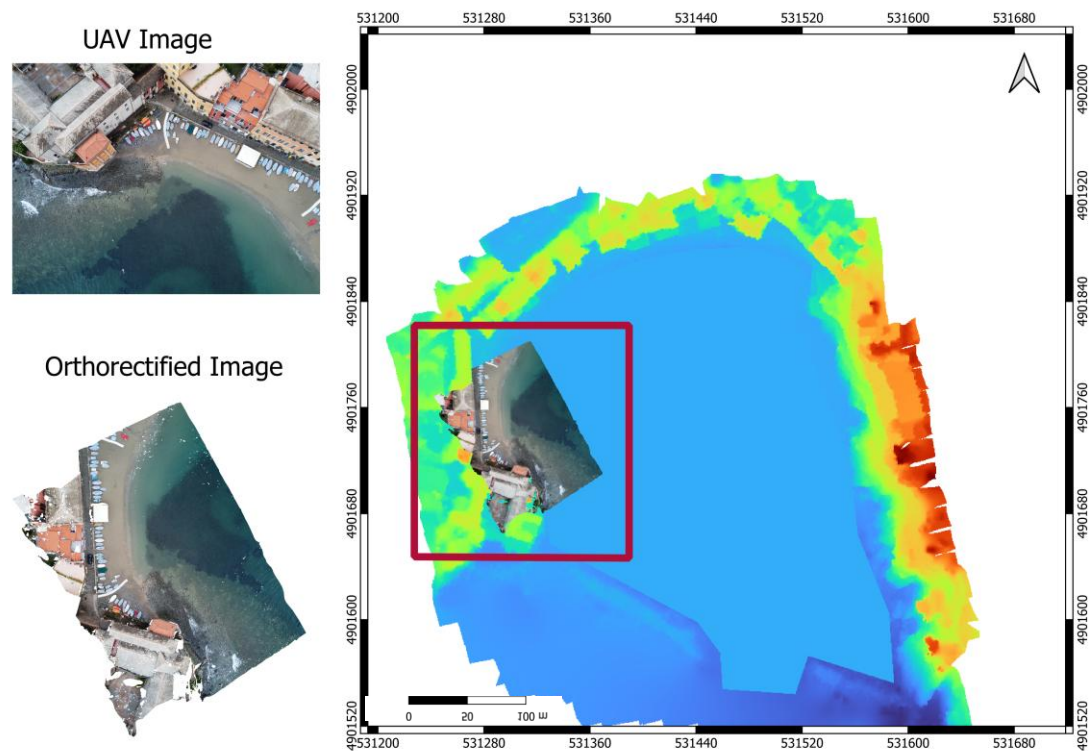


Figure 34. Original UAV image, orthorectified image, and orthorectified image overlaid on the DSM. The DSM is color-coded based on elevation, starting from blue at the lowest elevations (zero) and transitioning to red at the highest elevations.

Having obtained several orthorectified images detecting the snorkeler in various locations, a tool was required to extract the coordinates of the snorkeler. To address this need, a user-friendly Python application was developed to extract the target coordinates from images (Appendix, code 2 and 3). The user can sequentially recall the orthorectified images providing the appropriate file path, zoom in on the snorkeler, and click on the target on his back. The application then automatically extracts the target coordinates and saves them to a separate text file along with the corresponding frame name (Figure 35).

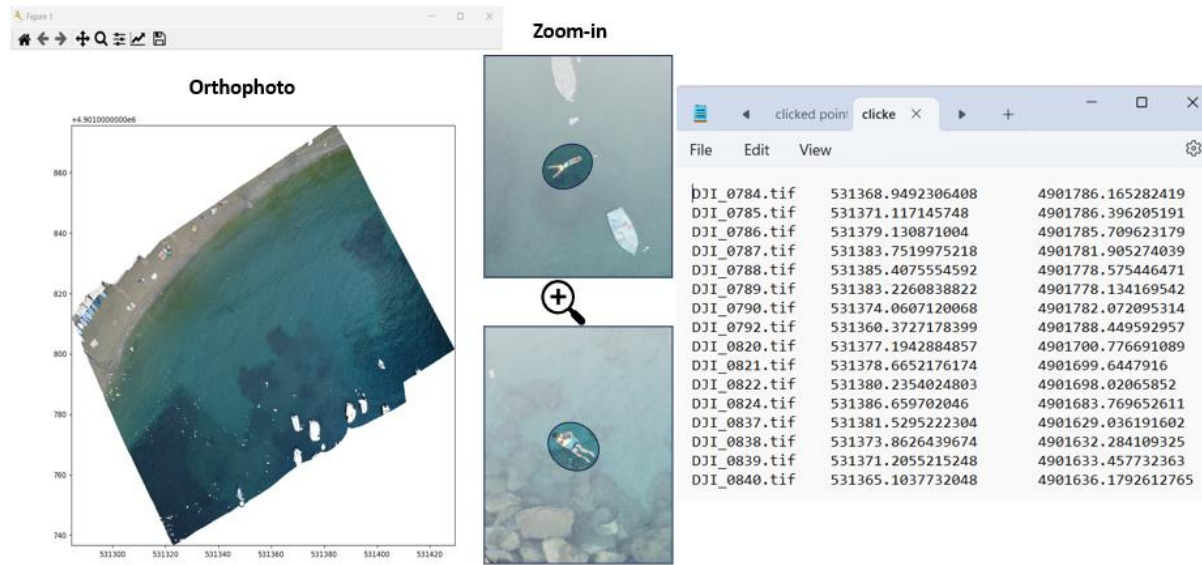


Figure 35. The interactive Python application for snorkeler coordinates extraction from orthorectified images.

An essential step in underwater photogrammetry is camera calibration. In this section, the results obtained with automatic camera calibration done by Agisoft Metashape© (V 1.8.2) are compared with the ones coming from a pre-calibrated model.

What emerges is that Agisoft Metashape© (V 1.8.2) for automatic calibration in underwater context results in significant issues, specifically the inability to reconstruct a realistic underwater model. The relative orientation process for the underwater model showed a spiral behavior, due to inaccurate camera calibration parameters, which compromised the accuracy of the models (Figure 36).



Figure 36. Image from Agisoft Metashape© (V 1.8.2) showing the tie points obtained with automatically computed camera calibration parameters (side view for both panels).

To overcome this problem, a pre-calibrated model was applied by inserting the calibration parameters manually and fixing them during the processing (Figure 37). The parameters were obtained from the camera calibration performed underwater using a chess board. This approach effectively eliminates refraction and distortion effects in the images, leading to a more realistic and accurate underwater model.

Initial	Adjusted	Bands	GPS/INS Offset
Type:	Precalibrated		
		cx:	5.52271
f:	1169.67733	cy:	4.24585
k1:	-0.118253	p1:	0.000526855
k2:	0.14846	p2:	0.00121922
k3:	-0.0462529	b1:	0
k4:	0	b2:	0
Fixed parameters:	All	Select...	
Image-variant parameters:	None	Select...	

Figure 37. Manual camera calibration parameters settings.

The proper calibration parameters ensured the accuracy of the underwater photogrammetric reconstruction, providing reliable results that are essential for accurate modeling and analysis (Figure 38).

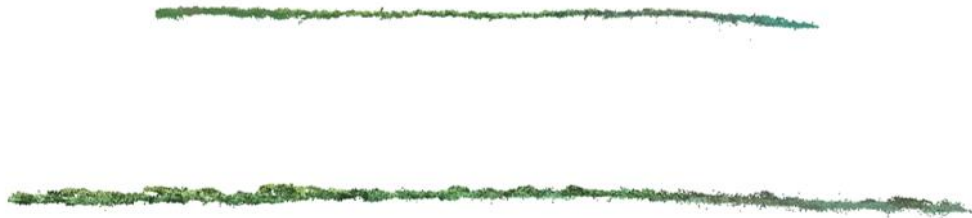


Figure 38. Image from Agisoft Metashape© (V 1.8.2) showing the tie points obtained with manually computed camera calibration parameters (side view for both panels).

The difference between the spiral shape obtained from the first calibration and the realistic surface from the second calibration likely arises from incorrect or extreme parameter values in the first set, leading to distorted projection (Table 5).

Table 5. Automatic and manual camera parameters calibration in micron.

Parameter	Automatic Calibration	Manual Calibration
Width	1920	1920
Height	1080	1080

Focal Length (f)	1368.77	1169.68
Principal Point (c_x)	31.38	5.52
Principal Point (c_y)	-32.48	4.25
Radial Distortion k_1	-0.01597	-0.11825
Radial Distortion k_2	0.27339	0.14846
Radial Distortion k_3	-0.00831	-0.04625
Tangential Distortion p_1	0.00191	0.00053
Tangential Distortion p_2	-0.01254	0.00122

Considering camera calibration parameters, in particular the principal point (c_x , c_y) and distortion coefficients (k_1 , k_2 , k_3), as these parameters significantly influence image projection characteristics. According to the automatically computed calibration, the principal point notably far from the center compared to the expected optical center of the image. Combined with the radial distortion coefficients, particularly the high value of $k_2 = 0.27339$, it leads to asymmetric distortion corrections, that demonstrate a spiral effect in the projected images. The manual calibration set is therefore more realistic in configuration, where the principal point are closer to the optical center. Moreover, distortion coefficients are more balanced. This comparison underlines the essential role that calibration parameters play in the definition of optical behavior.

As previously mentioned, 41 positions of the snorkeler were computed. However, not all these positions were useful, as in some cases, the snorkeler was in turbid water, making it impossible to align the underwater images with the model. After filtering these positions based on water clarity, 21 useful positions were obtained and used to evaluate the residuals by bundle block adjustment (Table 6).

Table 6. Error analysis over x, y coordinates and the total error in meters.

	x	y	Total
Count	21	21	21

Mean	0.068	0.093	0.08
Standard deviation	0.05	0.09	0.05
Minimum	0.01	0.01	0.02
Maximum	0.16	0.34	0.19

The average error for the x coordinate is 0.068 m, while for the y coordinate, it is slightly higher at 0.093 m, resulting in a total mean error of 0.080 m. The standard deviation indicates that the errors are more variable in the y direction 0.09 m compared to the x direction 0.05 m, suggesting a greater variation in the y-axis measurements. The range of errors also shows a wider spread for y with a maximum error of 0.34 m, whereas the x axis only reaches a maximum error of 0.16 m. The minimum error across both axes remains low, starting at 0.01 m for both x and y, indicating that some measurements are highly accurate. This suggests greater variability along the y-axis. A histogram (Figure 39) shows most errors fall within 0.025–0.050 m, with fewer cases above 0.1 m.

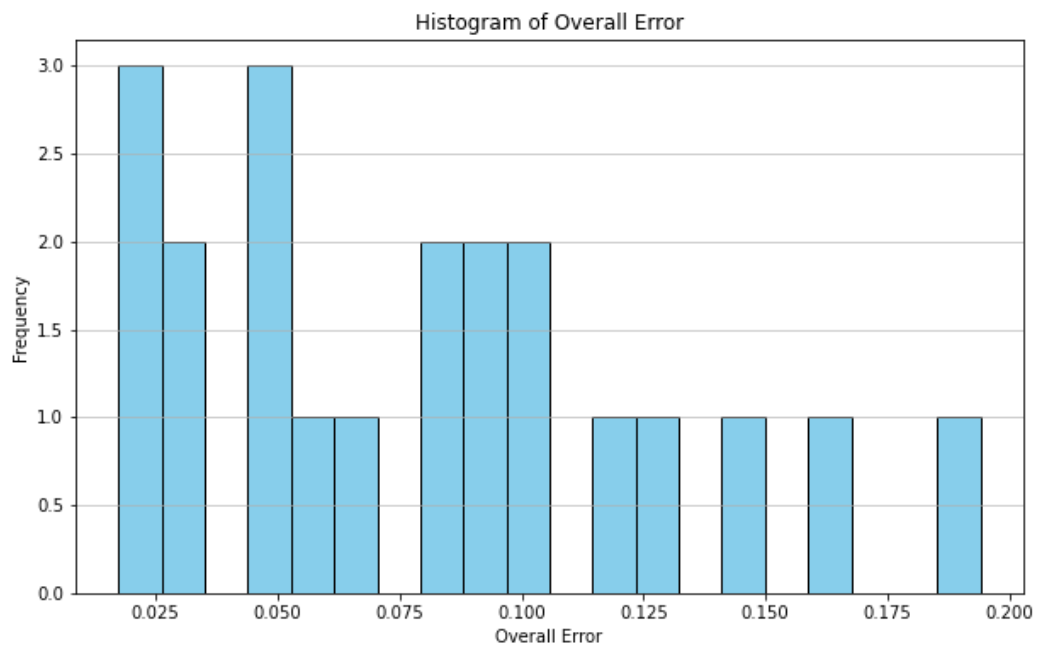


Figure 39. Histogram showing the frequencies of the overall error of the coordinates for positioning the snorkeler in meters.

The histogram of overall error presents a frequency distribution of error values ranging from approximately 0.025 m to 0.200 m. The highest frequency of errors falls within the 0.025 m to 0.050 m range, indicating that most of the data points have relatively low error values. There is a notable drop in frequency as the error increases, with moderate frequencies around the 0.075 m to 0.100 m range, and further decline as the error exceeds 0.100 m. This distribution shows that while most of the data points have small errors, there are some outliers with higher errors. To further explore the source of this variability, the data was

categorized into two groups based on the snorkeler position relative to the orthophoto: “M” for when the snorkeler is in the middle area, and “B” for when the snorkeler is in the boundary area of the relative orthophoto.

Table 7. Error analysis over 2 categories expressing the relative location in meters of the snorkeler: “M” for when the snorkeler is in the middle area and “B” for when the snorkeler is in the boundary area of the relative orthophoto.

	M	B
Count	21	21
Mean	0.04 m	0.11 m
Standard deviation	0.03 m	0.04 m
Minimum	0.02 m	0.05 m
Maximum	0.1 m	0.19 m

Statistical analysis shows that frames in category “M” tend to have lower and more consistent errors, with a narrower range of values. In contrast, category “B” exhibits both higher mean error and greater variability, indicating more pronounced inaccuracies and potential outliers. A scatter plot of the x and y errors by category further supports these findings, with category “B” displaying a wider spread of errors compared to the more tightly clustered errors in category “M” (Figure 40).

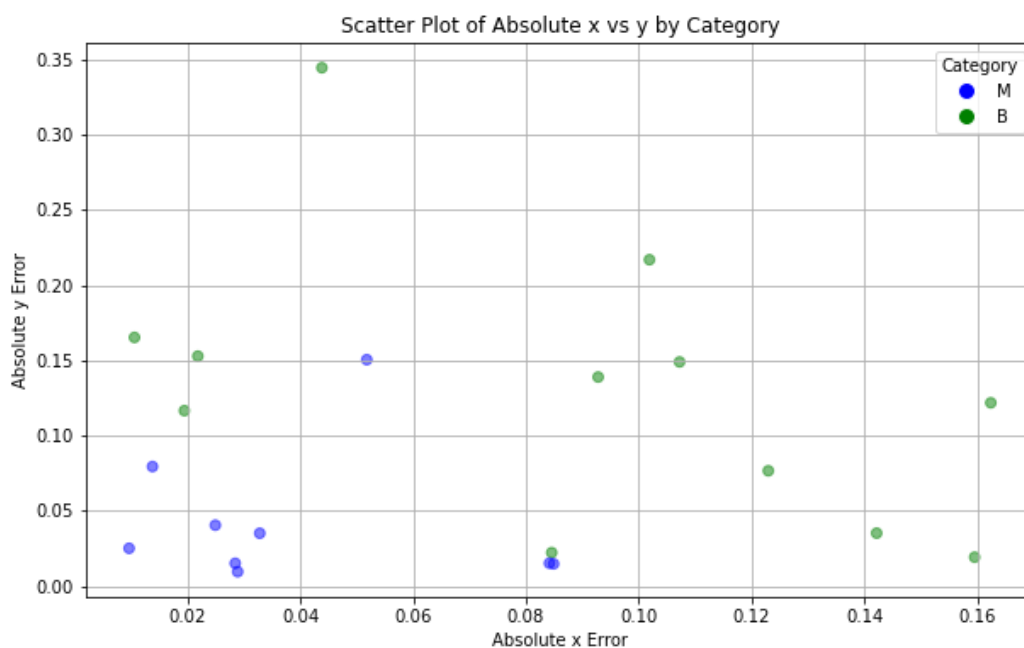


Figure 40. Scatter plot showing the x and y error over two categories. Value in meters.

This suggests that frames categorized as “B” are less accurate, potentially due to differences in the frame distortions between the middle and boundaries of the orthophotos. After error evaluation, colored point clouds and 3D models were generated. These 3D models for the different blocks represented various features on the seabed, including rocky regions, sandy areas, and the presence of both healthy and dead seagrass. This detailed representation of the underwater environment highlights the method capability to accurately capture and model diverse seabed characteristics, contributing valuable insights for coastal management and conservation efforts.

Terrestrial and underwater models were merged into a unified entity, aligning both datasets in the same frame. This allowed integrated interpretation of sandy zones, infrastructures, and vegetation (Figure 41)

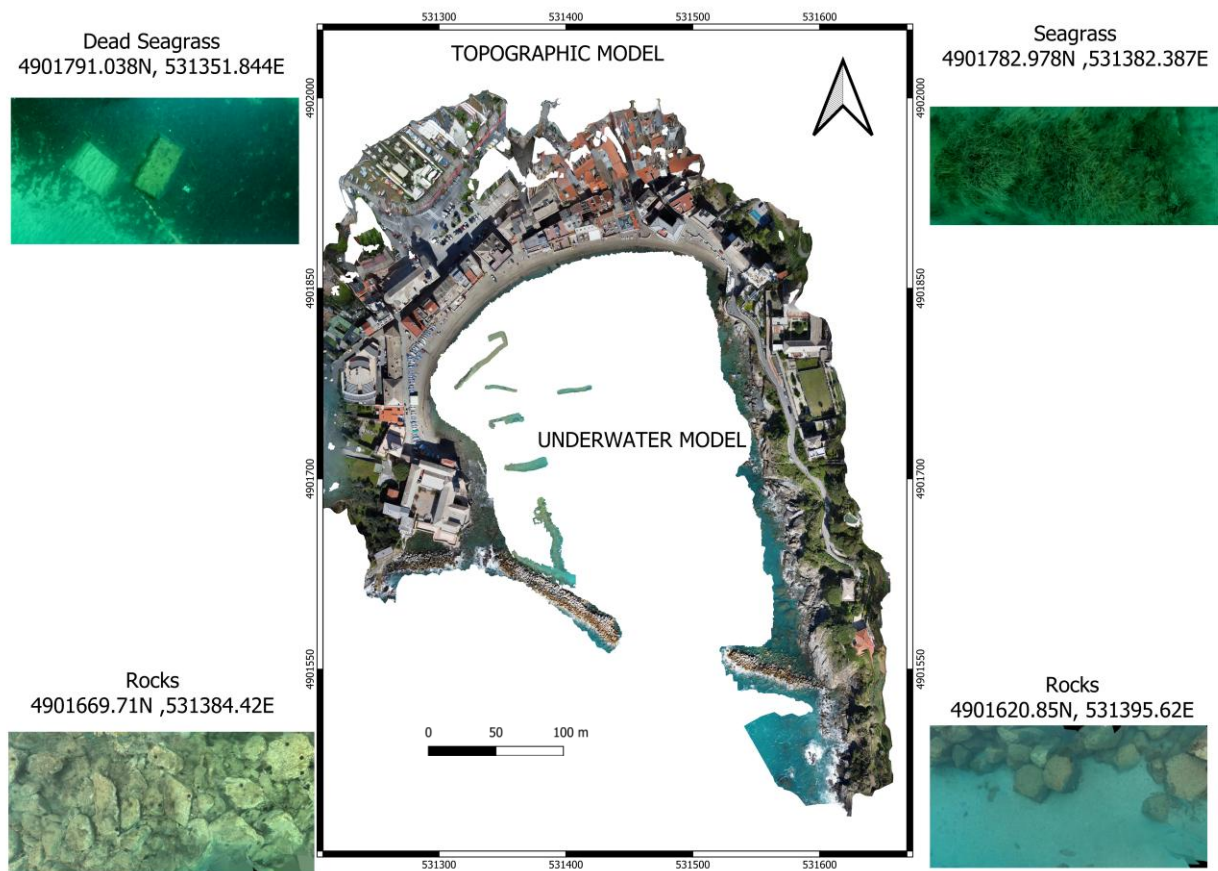


Figure 41. Merged model (emerged and submerged) with georeferenced underwater features, rocky and seagrass patches.

As is it clear, such model is missing the bathymetry and there is no real evaluation for the computed positioning of the snorkeler. Here we get the benefit from applying the survey on the same area using the ASV with GNSS, MBES and GoPro as underwater camera. Following the same workflow for the terrestrial photogrammetry we obtained the new orthophoto for the full area as shown in Figure 42.

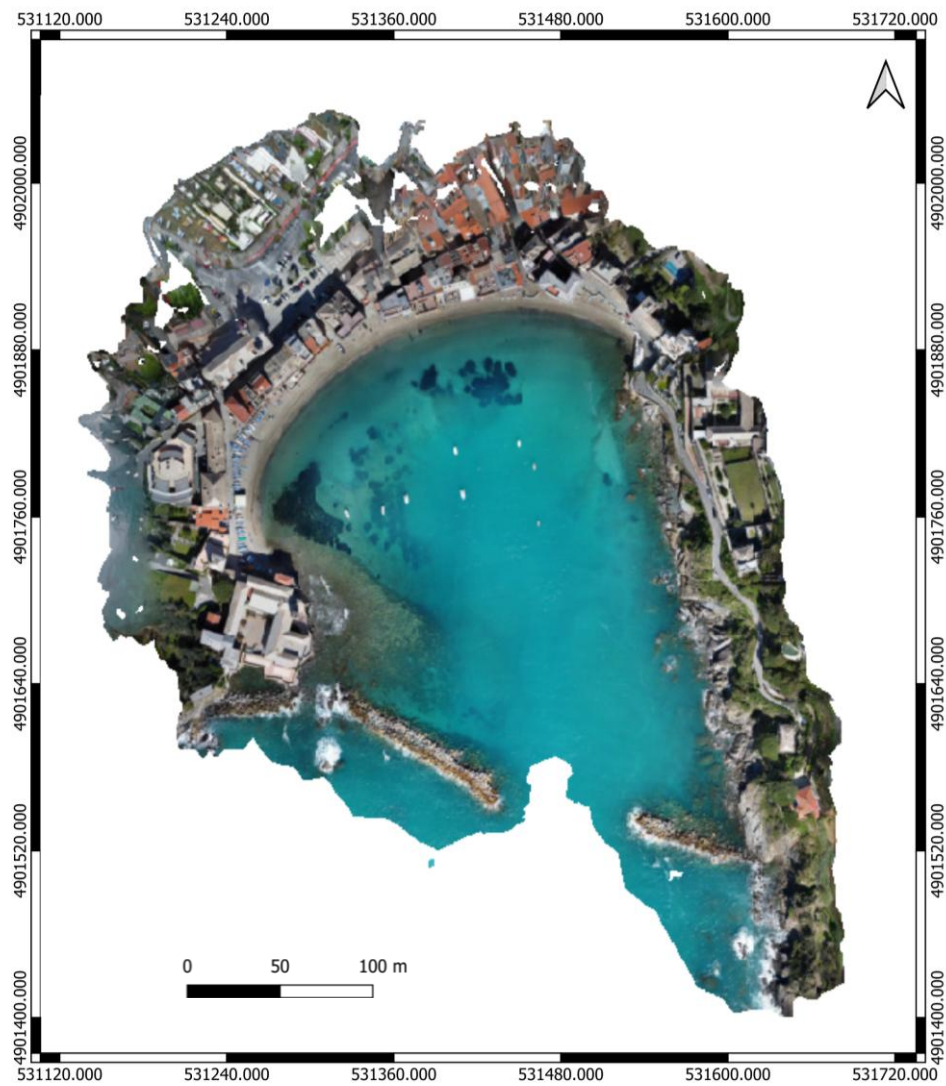


Figure 42. Orthophoto of the study area, generated using Agisoft Metashape© (V 1.8.2). Water refraction not taken into account.

This model was built using the same GNSS natural points for georeferencing the model to evaluate its precision. Figure 43 shows that the accuracy achieved for the model was around 6 cm.

Markers		Easting (m)	Northing (m)	Altitude	Accura	Error (n
☒	1	531317.951...	4901706.647...	46.264...	0.005...	0.0103...
☐	3	531486.757...	4901885.099...	45.849...	0.005...	0.0470...
☒	4	531511.941...	4901884.833...	47.019...	0.005...	0.0215...
☒	5	531518.523...	4901878.371...	46.750...	0.005...	0.0299...
☐	6	531405.493...	4901881.921...	45.929...	0.005...	0.0613...
☒	7	531344.161...	4901861.798...	45.871...	0.005...	0.0141...
☒	8	531321.288...	4901840.954...	46.286...	0.005...	0.0138...
☐	9	531300.831...	4901822.675...	46.484...	0.005...	0.0816...
☒	11	531278.296...	4901727.294...	46.649...	0.005...	0.0073...
☒	12	531313.006...	4901647.607...	51.583...	0.005...	0.0038...
☐	13	531276.050...	4901766.420...	46.815...	0.005...	0.0350...
☒	14	531274.020...	4901797.149...	47.385...	0.005...	0.0236...
☒	16	531567.345...	4901776.179...	59.198...	0.005...	0.0148...
☒	17	531575.664...	4901735.526...	62.736...	0.005...	0.0122...
Total Error						
Control points					0.0169...	
Check points					0.0588...	

Figure 43. GCPs and CPs accuracy assessment from Agisoft Metashape© (V 1.8.2). The table presents easting, northing, altitude, and associated errors for each target. The total residual values differentiate control points from check points, providing an evaluation of georeferencing accuracy of the terrestrial model.

After obtaining the terrestrial model, the underwater data from the MBES was processed and filtered. This provided an output for underwater surface showing a depth starting from approximately zero, representing the shoreline, to a deepest point in the bay around 14 m.

UnderwaterBy merging both the underwater and terrestrial models in the same reference with an overlapping between the two models, one continuous unique model expressing both environments was obtained (Figure 44).

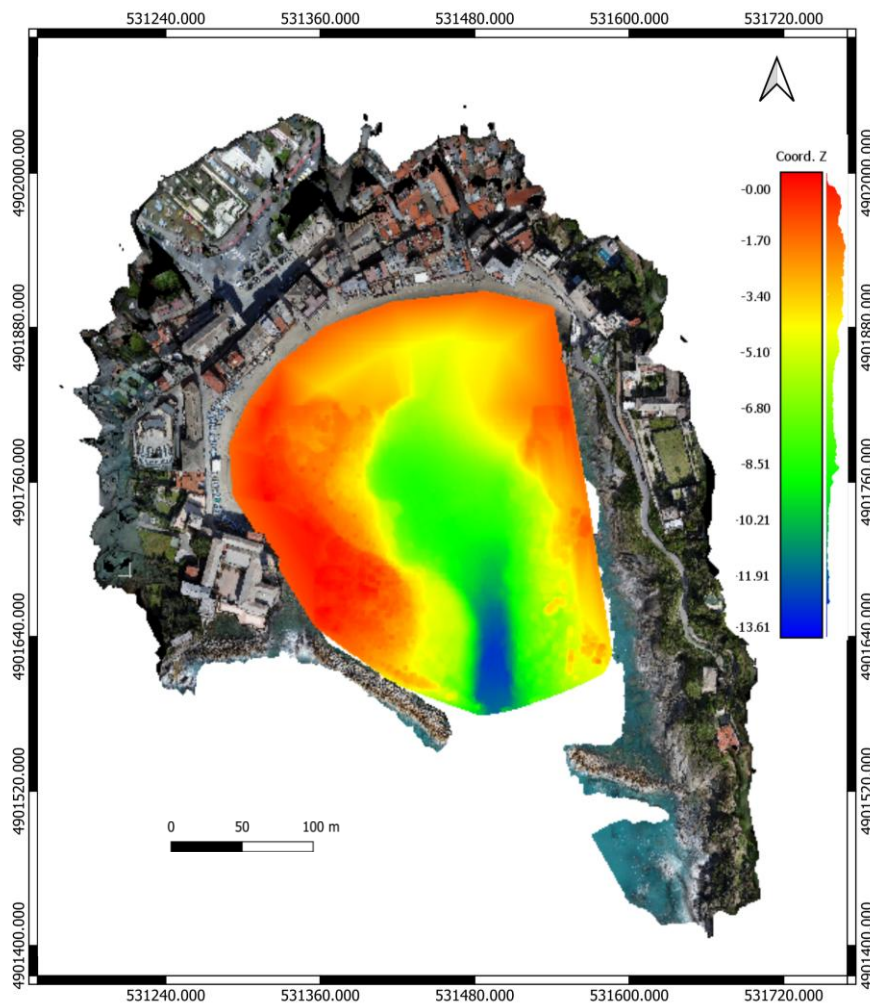


Figure 44. Merged terrestrial and underwater model. The terrestrial model is generated from UAV data, while the underwater model is derived from MBES data and color-coded based on depth range.

Integrating the data captured from the GoPro will give an overview about underwater environmental characteristics including georeferenced underwater habitats. One additional advantage in this methodology was the possibility to compare the GNSS measurements and positioning method based on orthophoto, thanks to time synchronization, to assess their concordance. The results show an overall mean error for around 14 cm, distributed as 11 cm on X and 16 cm on Y. This error evaluation was carried out using 43 measurements (figure 45).

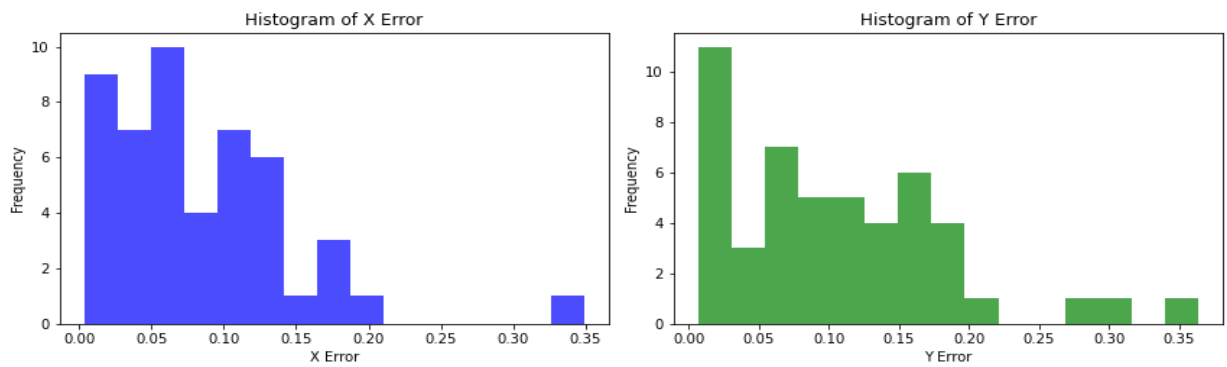


Figure 45. Orthophoto positioning error with respect to the GNSS measurements. The error is expressed in meters on X and Y axis.

To further refine the evaluation, a Bundle Block Adjustment (BBA) was applied to 22 of these measurements, redistributing the residuals within the adjustment process. This yielded a slightly lower total error of ~11 cm (10 cm in x, 11 cm in y). Thus, the direct comparison shows the baseline accuracy of the orthophoto-based method, while the BBA demonstrates its potential improvement when integrated into a photogrammetric adjustment framework. After evaluating and validating the underwater positioning accuracy, the 3D model was built by merging all the data from the UAV, MBES and underwater camera. The result of such integration is shown in Figure 46, where the terrestrial and underwater features are georeferenced in the same reference frame.

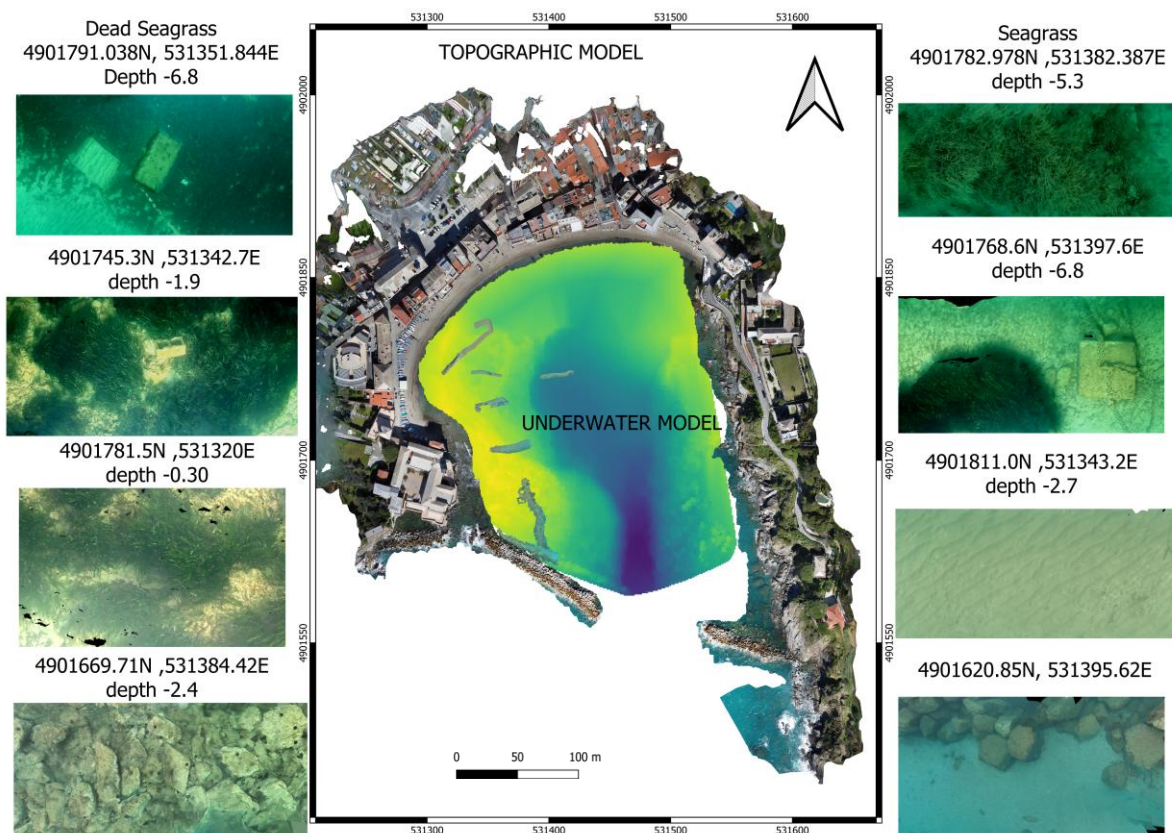


Figure 46. Combined terrestrial and underwater model of the study area. The central image displays the seamless integration of both environments, with the underwater model color-coded by depth. The surrounding images highlight different seabed conditions, with coordinates and depth values provided for each observation.

Following the creation of 3D models, a Virtual Reality (VR) model was generated by exporting the obtained point clouds and importing them into Unreal Engine[187]. In Unreal Engine, virtual environment was created that accurately represents real-world geometry, integrating both terrestrial and underwater (Figure 47).



Figure 47. Virtual model of Silence Bay in Sestri Levante (Italy) (note: screenshot taken from Unreal Engine software). The study area dimension is around $400\text{ m} \times 300\text{ m}$.

The integration process involved placing the models in their correct geographical positions within the virtual space. This approach not only visualizes the terrestrial and underwater environments but also includes features such as seagrass positioned accurately according to their real-world locations. By Unreal Engine capabilities, the static 3D models were transformed into dynamic virtual representations, offering an immersive platform for visualizing and exploring the coastal environments. This advancement enhances the ability to analyze and communicate complex spatial data effectively, supporting applications in coastal management, environmental monitoring, and educational outreach.

3.3 THIRD SCENARIO: ELBE HARBOR HAMBURG

The surveys provided a comprehensive dataset covering both terrestrial and underwater features of the harbor channel in the Elbe River. The MBES data from the high-tide survey successfully captured the underwater bathymetry with high resolution, revealing key morphological features such as the channel bed depth variations, sediment deposits, and any submerged structures. The patch test calibration ensured the accuracy of the depth data, which aligned well with known reference points in the study area. Data collected

from the MBES by using QINSY software and were processed and cleaned Qimera software [188]. The data shows the seabed and the boundary of the walls. Figure 47 presents the MBES bathymetry overlain with the quay wall data, color-coded relative to depth. The targeted depth below the mean sea level was starting from -3 m to 21 m as deepest point in the study area. The top panel displays the underwater map, where depth variations are represented by a color gradient ranging from shallow areas (red and yellow) to deeper regions (blue). The quay walls on either side of the channel are distinctly visible as steep boundaries. Flow patterns or navigation tracks are overlaid on the bathymetry, illustrating movement of the boat during the survey within the channel.

The bottom panel shows a cross-section of the channel, extracted from the MBES data. It highlights the depth profile across the channel, with sharp changes in elevation corresponding to the quay walls and relatively consistent depth within the channel central area.

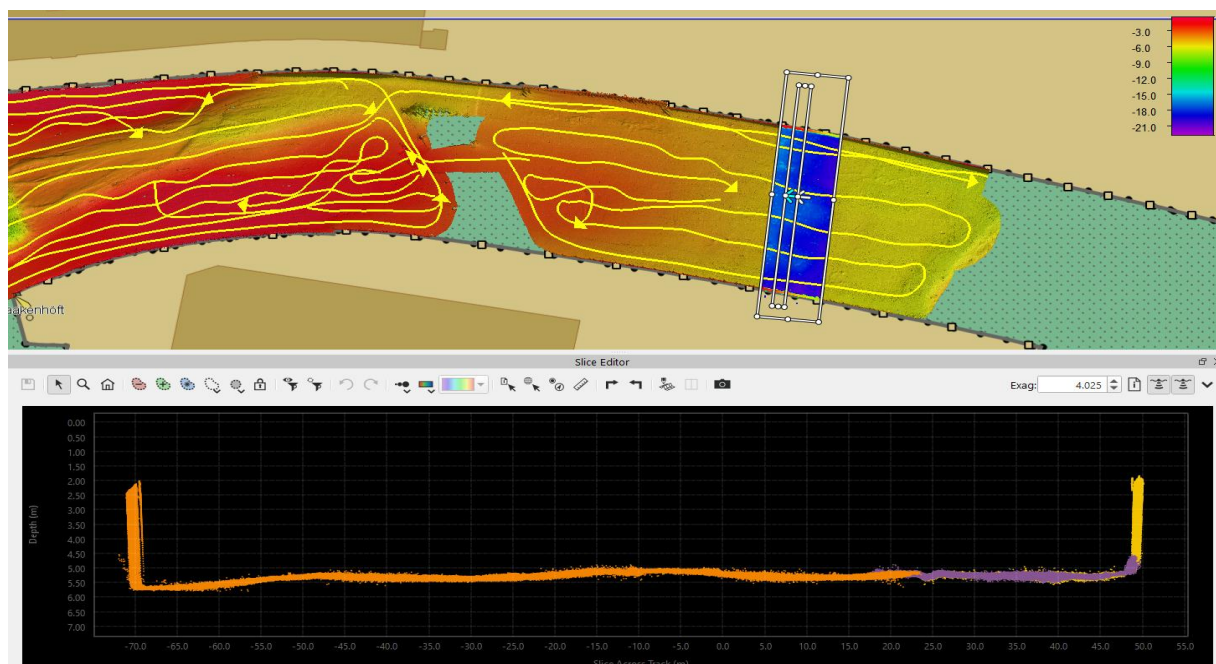


Figure 48. MBES data processing. Screenshot from Qimera displaying the riverbed with depth color coding in the upper image. The lower image shows a cross-section, illustrating the seabed and the boundary wall.

Values in the legend are in meters.

For the terrestrial survey, the panoramic images captured using the 360° camera during the high-tide survey provided detailed visual documentation of the harbor channel walls and surrounding areas. However, a significant portion of the images included irrelevant elements such as the sky and parts of the boat structure, as shown in Figure 49.



Figure 49. Panoramic image from the 360° camera taken from the boat. The boat appears in white and must be masked for proper photogrammetric processing.

These elements posed challenges to the photogrammetric process, as their presence could introduce noise and inaccuracies, potentially compromising the quality of the 3D model. To address this issue, a masking process was performed by Python code (Appendix code 4) to remove the unwanted areas from the images. The masking process combined geometric masking for the boat and color-based masking for the sky Figure 50. This step was critical to ensure that only relevant sections of the captured environment such as the quay walls and adjacent structures were used for photogrammetric elaboration. By isolating the areas of interest, the data processing was streamlined, reducing confusion during image alignment and improving the accuracy of the final 3D reconstruction. This pre-processing step played a vital role in achieving a clean, reliable, and georeferenced model of the harbor infrastructure.

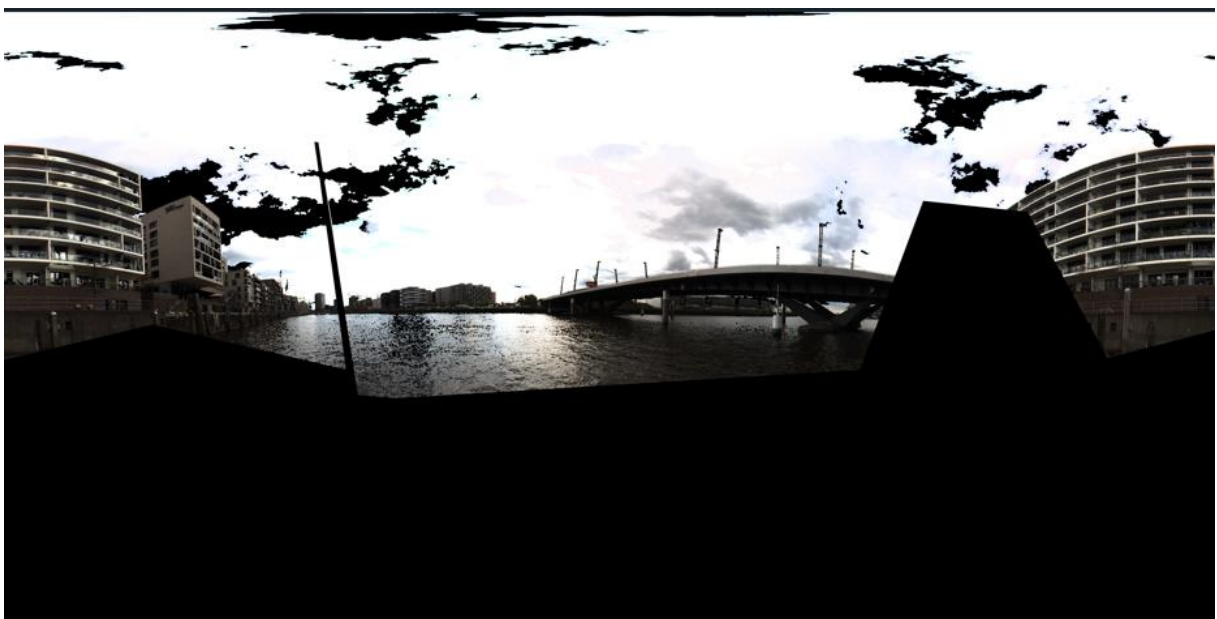


Figure 50. Mask applied on the panoramic image.

The masked images were then used for photogrammetric processing in Metashape to generate a detailed 3D model of the harbor's terrestrial features. The process of generating a 3D model began with organizing and importing the high-resolution panoramic images into the software, ensuring they were georeferenced with precise GNSS data recorded during the survey. These images were then aligned through Agisoft Metashape© (V 1.8.2) SfM algorithm, which identifies matching points (tie points) across overlapping images to construct a "sparse" point cloud representing the surveyed area. Once the sparse point cloud was generated, it was further refined into a dense point cloud creating a highly detailed representation of the quay walls and surrounding infrastructure. Texture mapping was then applied using the RGB values from the images, enhancing the natural appearance and providing realistic visual details. The final output was a georeferenced 3D model that accurately represented the above-water environment of the harbor. The quality of the model depended significantly on the overlap and continuity of the images, which were carefully managed during data collection and processing to ensure sufficient coverage. This photogrammetric approach not only provided a high-resolution visualization of the harbor infrastructure but also laid the foundation for integrating the above-water data with underwater datasets from the MBES to achieve a comprehensive digital representation of the study area (Figure 51).



Figure 51. A sample of the 3D model of the quay wall. The screenshot was taken from Agisoft Metashape© (V 1.8.2).

The outcome of this survey was an integrated point cloud. But not continuous model due to the gap coverage between the two data (Figure 52).

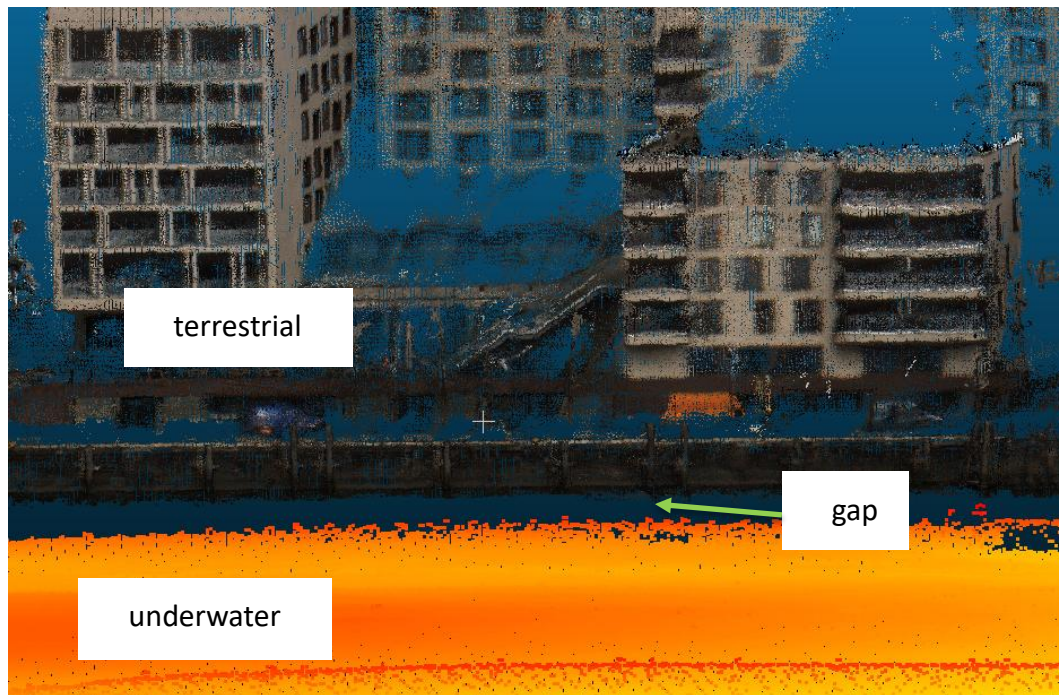


Figure 52 Merged 3D model generated from the 360° camera, showing the monitored walls in the harbor and the existing gap in the 3D model between terrestrial and underwater.

To address the coverage gaps identified during the high-tide survey, a supplementary survey was conducted at low tide using an ASV equipped with a GoPro camera. This approach was specifically designed to extend the coverage and achieve a seamless and continuous model bridging the terrestrial and underwater environments. The ASV smaller size and enhanced maneuverability allowed it to navigate closer to the channel walls, successfully capturing high-resolution images of previously inaccessible or obscured areas. These images provided critical data to fill the spatial voids left by the initial survey, particularly along the quay walls where high-tide conditions had limited visibility. The integration of these detailed visuals from the ASV survey with the existing underwater and panoramic datasets significantly improved the continuity and completeness of the final georeferenced model, ensuring a comprehensive representation of the harbor complex topography and morphology Figure 53.

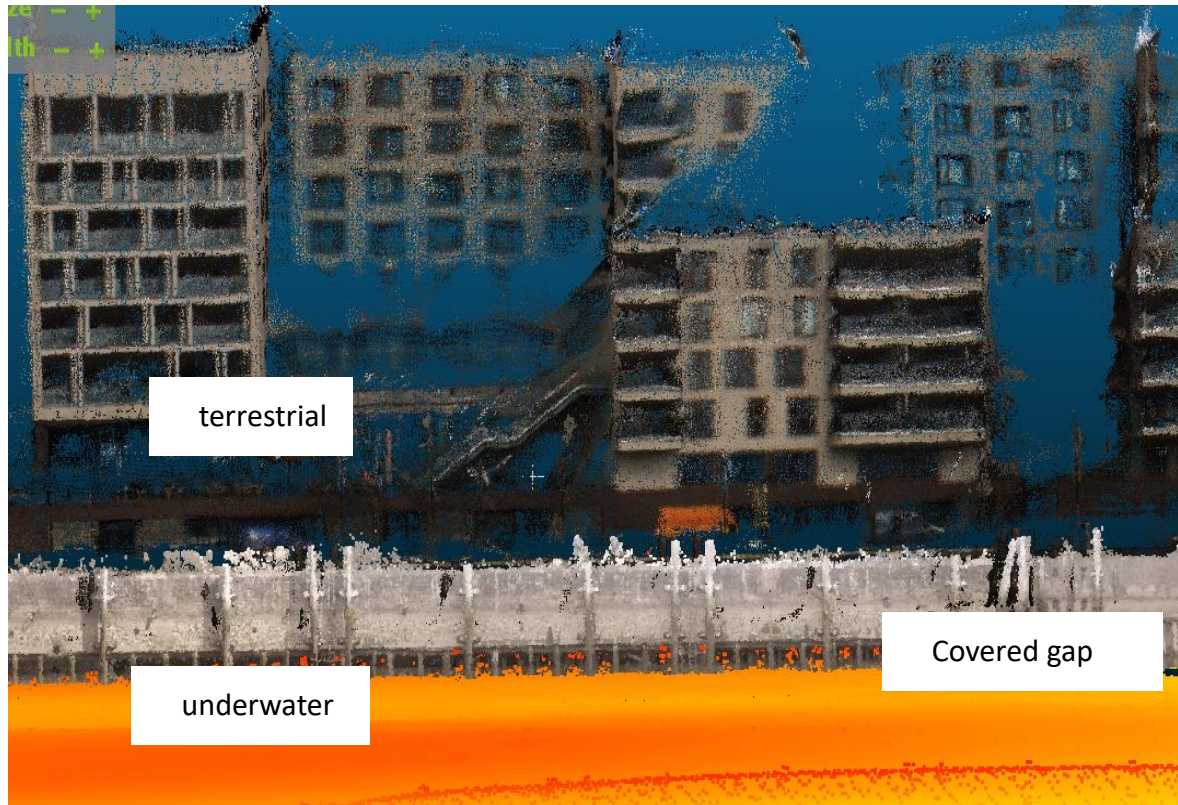


Figure 53. The merged 3D model generated from the GoPro images, showing the monitored walls in the harbor and the continuity of the 3D model between terrestrial and underwater (orange color).

This comprehensive model accurately represented the study area intricate terrestrial and morphological features, capturing both underwater and terrestrial component. By combining these complementary datasets, the model provided enhanced insights into the spatial relationships between submerged and terrestrial structures, facilitating a refined understanding of the harbor environmental and infrastructural dynamics. The successful merging of data from multiple survey techniques highlighted their effectiveness in addressing challenges related to spatial continuity and coverage, paving the way for improved monitoring and management of complex waterway systems. The final output was a continuous DSM spanning from the riverbed to harbor infrastructure starting from around -16 m till 82 m above the mean water level (Figure 54).

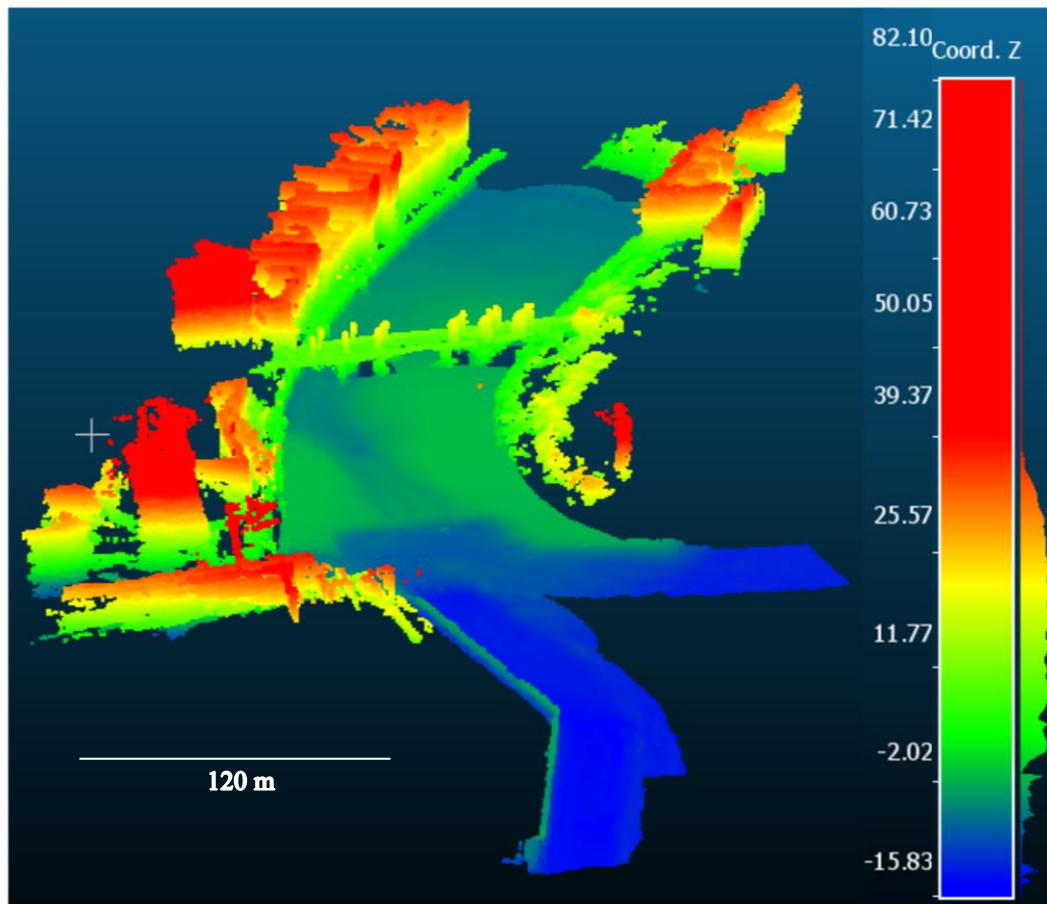


Figure 54 The combined 3D model shows the integration of underwater data (underwater terrain) with terrestrial elevation data. The color gradient represents the elevation, transitioning from deep underwater regions (blue) to higher terrestrial area (red). Values in the legend are in meters. The study area dimension is around $900\text{ m} \times 250\text{ m}$.

A comparative analysis was conducted between the 3D models generated using the 360° camera and the GoPro camera to assess their accuracy and performance. Both models were evaluated using the BBA method in Agisoft Metashape© (V 1.8.2), relying on GNSS measurements and seven markers placed strategically along the quay wall for reference. The results revealed that the 360° camera achieved an accuracy of approximately 4 cm (a residual well within the expected range for close-range photogrammetry in complex environments, confirming the suitability of the method for infrastructure monitoring) (Figure 55), while the GoPro model demonstrated a slightly higher error margin of around 5 cm (Figure 56). These differences reflect the impact of camera specifications, field of view, and image resolution on the photogrammetric reconstruction process, with the 360° camera providing a marginally more precise model under the same processing conditions.

Markers		Easting (m)	Northing (m)	Altitude (m)	Accuracy (n)	Error (m)
	 7	567077.292000	5932749.457000	4.995000	0.005000	0.005916
	 6	566996.873000	5932768.314000	4.886000	0.005000	0.004604
	 5	566924.470000	5932783.325000	4.778000	0.005000	0.046520
	 4	566926.576000	5932781.673000	4.882000	0.005000	0.027597
	 3	566832.027000	5932795.715000	4.941000	0.005000	0.019417
	 2	566727.889000	5932806.789000	4.856000	0.005000	0.006757
	 1	566679.260000	5932806.651000	4.851000	0.005000	0.002096
Total Error						
Control points						0.013175
Check points						0.035645

Figure 55. 360° camera GCPs and CPs accuracy assessment from Agisoft Metashape© (V 1.8.2). The table presents easting, northing, altitude, in WGS84/UTM32N and associated errors for each target. The total error values differentiate between GCPs from CPs.

Markers		Easting (m)	Northing (m)	Altitude (m)	Accuracy (n)	Error (m)
	 7	567077.292000	5932749.457000	4.995000	0.005000	0.003619
	 6	566996.873000	5932768.314000	4.886000	0.005000	0.016619
	 5	566924.470000	5932783.325000	4.778000	0.005000	0.063183
	 4	566926.576000	5932781.673000	4.882000	0.005000	0.007052
	 3	566832.027000	5932795.715000	4.941000	0.005000	0.019152
	 2	566727.889000	5932806.789000	4.856000	0.005000	0.006992
	 1	566679.260000	5932806.651000	4.851000	0.005000	0.003145
Total Error						
Control points						0.008920
Check points						0.046685

Figure 56. GoPro camera Ground control and check point accuracy assessment from Agisoft Metashape© (V 1.8.2). The table presents easting, northing, altitude, and associated errors for each marker. The total error values differentiate control points from check points, providing an evaluation of georeferencing accuracy

3.4 GENERAL OUTCOMES

The results of this thesis work demonstrate the effectiveness of integrating advanced survey methodologies to overcome the challenges associated with creating continuous, georeferenced 3D models of both terrestrial and aquatic environments. The general research goal, presented in the methodology chapter, was to establish and test a flexible workflow able to merge emerged and submerged data into a single reference system, minimizing the reliance on GNSS and adapting to different operational constraints. Three distinct scenarios were presented, each offering unique insights and contributions:

1. Case study 1, Laghi del Gorzente: the integration of terrestrial and underwater data resulted in a seamless 3D model of the study area. This process involved merging data from multiple sources using shared GCPs and a digitized shoreline, followed by Natural Neighbor interpolation to ensure a reliable and

realistic representation. The final model successfully combined the geometrical information of both environments into a single, unified representation, in a unique reference frame.

2. Case study 2, Silent Bay in Sestri Levante: the implementation of UAV-based photogrammetry combined with underwater imaging by a snorkeler resulted in a georeferenced orthophoto and 3D model of the study area. This approach enabled the accurate positioning of the snorkeler and seamless integration of underwater features into the same reference frame as the terrestrial. Despite challenges like water clarity, it demonstrated reliability and adaptability across different environments. Ultimately, this process produced a continuous and unified model connecting bathymetry and terrestrial, not only achieving a geometrically accurate representation, but also correctly positioning underwater features. To validate the positioning method, the same workflow was later replicated using an ASV equipped with GNSS and an underwater camera. By synchronizing orthophoto-derived positions with GNSS measurements, the achieved precision was quantified, confirming the reliability of the orthophoto-based approach and strengthening the robustness of the methodology.
3. Case study 3, the Elbe Harbor in Hamburg, the methodology was extended to a harbor context where tidal variation created natural overlapping tie points. This enabled the integration of MBES bathymetry and 360° photogrammetry to validate infrastructure mapping and to connect submerged and emerged models without artificial targets. The conceptual contribution here lies in demonstrating how natural tidal cycles can substitute dynamic markers, making the approach adaptable to port environments where vessel-based surveys and tidal effects dominate. Elbe Harbor in Hamburg: the use of ASV-based on low-tide surveys was useful to fill the gap between high-tide surveys. By capturing additional imagery and underwater data, this approach successfully extended the spatial coverage and ensured a continuous model in a harbor channel. The integrated model from multiple datasets provided an enhanced understanding of the area terrestrial and morphological features.

In summary, the overall results demonstrate the successful development of a cost-effective and accurate methodology for creating a unified 3D model that integrates both topographic and underwater environments. By merging data from UAV-based photogrammetry, snorkeler-based underwater imaging, and ASV or vessel-based surveys, a seamless and continuous representation of different study areas was achieved. The approach enabled the precise positioning of underwater features through the integration of UAVs and dynamic GCPs, represented by a snorkeler or ASV moving on the sea surface. This innovative method minimizes reliance on GNSS while ensuring high positional accuracy, making it adaptable to diverse and challenging environments.

4. CONCLUSIONS

This research was conducted in collaboration with CNR-INM, focusing on using robotic platforms or surface surveyor to solve the challenge of combining terrestrial and underwater survey data considering an interdisciplinary approach for better coastal management. The need of this innovative method arises because traditional techniques often miss the connections between terrestrial and sea when surveying coastal areas. This thesis explored how new technologies like drones and underwater sensors can work together to create a complete 3D model of these environments. The outcome is that it's possible to combine data from different sensors, even when GNSS signals are weak or blocked, like in harbors. By using orthophotos instead of relying heavily on GNSS, accurate underwater models can be created and align them with terrestrial data. The methodology represents a comprehensive and innovative approach to integrating terrestrial and underwater photogrammetry with MBES data for accurate coastal mapping. By utilizing UAV-based photogrammetry, MBES, and underwater imaging performed first by a snorkeler and later validated with an ASV equipped with GNSS technology, this study has effectively exposed key challenges in positioning, georeferencing, and data integration. The use of MBES provided highly accurate underwater data, which, when combined with UAV imagery, resulted in a continuous model connecting underwater and terrestrial environments. The snorkeler-based underwater imaging allowed for the precise positioning of underwater features. This demonstrates the adaptability and reliability of the proposed methodology, even in challenging environmental conditions such as low water clarity (high turbid water) and water level changes (i.e., tidal cycles). By using existing technologies in cost-effective ways, this methodology reduces the reliance on expensive underwater positioning systems while providing accurate and georeferenced results. The combination of MBES and UAV-based photogrammetry allowed to merge datasets from both environments into a single unified model, highlighting the spatial relationships between underwater habitats and terrestrial features. The use of the ASV with GNSS not only replaced the snorkeler as a dynamic GCP but also provided a robust evaluation of positioning accuracy. By comparing orthophoto-based coordinates with GNSS measurements, the methodology was validated through multiple accuracy assessments, demonstrating a significant reduction in positional errors and achieving reliable georeferencing for both terrestrial and underwater data. This demonstrated the reliability and precision of the proposed positioning methodology in integrating terrestrial and underwater data. Beyond the creation of static models, an advancement towards Virtual Reality (VR) environments was carried out by exporting the integrated 3D meshes into Unreal Engine. This allowed for the transformation of real-world geometry into dynamic, interactive virtual representations. The VR models accurately visualize terrestrial and underwater environments, including features such as seagrass, positioned in their real-world locations. Such immersive environments enhance the ability to analyze, explore, and communicate spatial data, offering valuable tools for coastal management, environmental monitoring, and educational outreach.

Despite its success, the methodology presents challenges, including the dynamic movement of the snorkeler acting as a GCP, which can be challenging. Image distortions, synchronization of UAV and underwater cameras, and underwater lighting conditions also remain critical considerations for improving data quality. In summary, our methodology successfully merges terrestrial and underwater photogrammetry

with MBES data to create a comprehensive, georeferenced 3D model. This unified approach enables accurate mapping of coastal environments while addressing key technical challenges. The results evidence the robustness, cost-effectiveness, and potential of this methodology for advancing coastal surveying, offering a valuable tool for future geospatial analyses and interdisciplinary applications.

5. DISCUSSION

Through this thesis work several challenges were addressed regarding underwater photogrammetry (i.e., camera calibration, underwater 3D model reconstruction and georeferencing), underwater positioning, and generating a unique continuous model representing both underwater and terrestrial environments. Additionally, challenges related to the limitation in GNSS performance due to interference were considered. To overcome these challenges, the innovative proposed methodology represented a significant advancement in integrating terrestrial and underwater surveys, offering a comprehensive and unified approach to survey coastal environments, by combining terrestrial measurements (aerial photogrammetry) with underwater measurements (underwater photogrammetry and sonar) to generate a unique continuous 3D model spanning from the seabed to terrestrial.

Across the three case studies, a common strategy was applied: integrating different techniques (UAV photogrammetry, SBES/MBES sonar, and underwater imagery) into a flexible workflow capable of producing a georeferenced and continuous 3D model. While the survey platforms and environments varied ranging from a lake (Scenario 1), to a coastal bay (Scenario 2), and finally to a complex harbor (Scenario 3) the overall goal was consistent: to align submerged and emerged datasets into a common reference frame while minimizing dependence on GNSS.

The methodology relies on UAV-based photogrammetry for terrestrial measurements and either a snorkeler or an ASV for underwater data acquisition. A key aspect of the integration process was the positioning of underwater features relative to terrestrial data. In Scenario 1 (Laghi del Gorzente), the controlled lake environment allowed the methodology to be tested under stable conditions, validating the merging of SBES bathymetry with UAV-based terrestrial data and establishing the role of shoreline points and total station measurements as common reference elements. In Scenario 2 (Silent Bay, Sestri Levante), the use of a snorkeler as a dynamic GCP enabled underwater photogrammetry to be integrated into the same terrestrial reference frame, demonstrating the feasibility of orthophoto-based positioning but also revealing challenges such as the need for precise underwater camera calibration. In Scenario 3 (Elbe Harbor, Hamburg), the methodology was pushed into a more complex environment with tidal variations, dense infrastructure. Here, the use of MBES, 360° panoramic cameras, and ASV-based surveys provided complementary datasets, validating the approach under real-world operational conditions.

Rather than using GNSS for positioning, an orthophoto-based approach was used to dynamically position the snorkeler and ASV. The UAV ability to capture multiple images of the snorkeler/ASV, combined with a target system, allowed for precise georeferencing, achieving centimeter-level accuracy. This level of accuracy is a promising starting point, considering the challenging nature of positioning a dynamic GCP from orthophoto images. For instance, dynamic GCP, moving over the water surface, can lead to inaccuracies in the orthophoto reconstruction due to water movement and surface undulations. Additionally, the target attached to the snorkeler could have minor movements caused by waves. Despite these challenges, the methodology demonstrates significant potential for improving the integration of

terrestrial and underwater photogrammetric data. Furthermore, this approach effectively reconstructs both underwater and emerged environments within a single 3D model, accurately positioning underwater habitats and features in the same reference frame as terrestrial features. This holistic approach provides a comprehensive understanding of the coastal environment, highlighting the spatial relations between underwater and terrestrial features. Moreover, the methodology is cost-effective, as it avoids the need for expensive underwater positioning systems by leveraging existing technologies in innovative ways. However, the methodology presents challenges and limitations. The reliance on visual targets for positioning, coupled with the effect of water clarity, lighting conditions and depth, can influence the quality of underwater images. In deeper areas, artificial lighting would be required, which adds complexity and cost to the survey process. Additionally, the snorkeler-based approach is limited in scale, as it can only cover small areas efficiently. Large-scale surveys would require deploying an ASV equipped with an underwater imaging system, to improve efficiency and coverage. Furthermore, the accuracy of the unified model depends on precise synchronization between the UAV and the snorkeler/ASV, and on the correct calibration of the underwater camera. Additionally, image distortions correction and accurate georeferencing in the orthophoto stage are crucial elements to achieve appreciable results. Furthermore, the study explored the application of these 3D models in Virtual Reality environments, enabling interactive and immersive visualization of the surveyed areas. This aspect extends the practical implications of the methodology beyond scientific research, offering tools for public engagement, education, and coastal planning. Future improvements could focus on standardizing the VR models to facilitate their use in decision-making processes. Overall, this research contributes a novel, interdisciplinary approach to integrating terrestrial and underwater surveys, successfully addressing key challenges in positioning, georeferencing, and data fusion. While limitations exist, the methodology provides a strong foundation for future advancements in coastal and underwater mapping.

While Scenarios 1 and 2 relied on dynamic markers (ASV/snorkeler) for positioning, Scenario 3 introduced a different strategy: exploiting natural tie points created by tidal variation between high- and low-water surveys. This demonstrates that the methodology is adaptable, since continuity between datasets can be achieved either through artificial dynamic markers or through environmental conditions such as tides. The harbor application further emphasizes the method's practical value for infrastructure monitoring and management. In summary, the three scenarios together validate the methodology under increasingly complex conditions: from controlled in terrestrial to semi-open coastal bays, to highly dynamic harbor environments. The common thread is the integration of datasets into a unified georeferenced 3D model. While limitations remain such as synchronization, calibration, and scaling to larger environments, the results establish a robust foundation for future developments in coastal and underwater mapping.

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7. APPENDIX

Code 1: Coordinates computation

```

import os
import matplotlib
matplotlib.use("Qt5Agg") # Set the backend to Qt5
import matplotlib.pyplot as plt
from osgeo import gdal
import csv

# Variables to store clicked coordinates
clicked_points = []

# Flag to track if a right click occurred
right_click_occurred = False

def on_rightclick(event):
    global right_click_occurred
    if event.button == 3: # Right mouse button
        clicked_points.append((event.xdata, event.ydata))
        right_click_occurred = True

def open_next_image(image_files, folder_path, image_index):
    global right_click_occurred
    if image_index < len(image_files):
        # Load the georeferenced image using GDAL
        image_path = os.path.join(folder_path, image_files[image_index])
        dataset = gdal.Open(image_path)
        if dataset is None:
            print(f"Failed to open image: {image_path}")
            return

        # Reading and preparing the image data
        image_data = dataset.ReadAsArray()
        if image_data.ndim == 3:
            image_data = image_data.transpose(1, 2, 0).astype(float)
            image_data /= 255.0
        else:
            image_data = image_data.astype(float)
            image_data /= 255.0
            image_data = image_data[:, :, None] # Convert to 3D for consistency

```

```

geotransform = dataset.GetGeoTransform()

fig, ax = plt.subplots(figsize=(10, 10))
ax.imshow(image_data, extent=(geotransform[0], geotransform[0] + geotransform[1] *
image_data.shape[1],
                        geotransform[3] + geotransform[5] * image_data.shape[0], geotransform[3]),
        interpolation='nearest')
ax.set_aspect(abs(geotransform[1] / geotransform[5]))

cid = fig.canvas.mpl_connect('button_press_event', on_rightclick)

plt.show(block=False)

while not right_click_occurred:
    plt.pause(0.1)

fig.canvas.mpl_disconnect(cid)

print("Clicked Points for", image_files[image_index], ":", clicked_points)

save_points_as_text(clicked_points, image_files[image_index])

clicked_points.clear()
right_click_occurred = False

plt.close(fig)

open_next_image(image_files, folder_path, image_index + 1)

def save_points_as_text(clicked_points, image_file):
    # Path to save the text file
    save_path = "E:/Projects/IIM_Sestri Levante_project/results/exported orthophoto/clicked_points
mid.txt" # Replace with your desired path

    with open(save_path, 'a') as f:
        writer = csv.writer(f, delimiter='\t')
        for point in clicked_points:
            formatted_point = [format(coord, '.2f') for coord in point]
            writer.writerow([image_file] + formatted_point)

# Path to the folder containing the images

```

```
folder_path = "E:/Projects/IIM_Sestri_levante_project/results/exported orthophoto" # Replace with your  
folder path
```

```
# Get a list of image files in the folder
```

```
image_files = [f for f in os.listdir(folder_path) if f.endswith('.tif')]
```

```
# Start from the first image
```

```
image_index = 0
```

```
# Open the first image
```

```
open_next_image(image_files, folder_path, image_index)
```

Code 2: video and frame time synchronization

```
import cv2

def extract_frame(video_path, photo_path, video_timestamp, photo_timestamp, save_path):
    # Read the photo
    photo = cv2.imread(photo_path)

    # Read the video
    video = cv2.VideoCapture(video_path)

    # Get the frame rate of the video
    fps = video.get(cv2.CAP_PROP_FPS)

    # Calculate the frame number corresponding to the time the photo was taken
    photo_time = (photo_timestamp - video_timestamp).total_seconds()
    frame_number = int(photo_time * fps)

    # Set the video's current frame to the desired frame number
    video.set(cv2.CAP_PROP_POS_FRAMES, frame_number)

    # Read the frame at the desired time
    ret, frame = video.read()

    # Check if the frame was successfully read
    if ret:
        # Calculate the center coordinates of the frame
        height, width, _ = frame.shape
        center_x = int(width / 2)
        center_y = int(height / 2)

        # Define the marker properties
        marker_color = (0, 0, 255) # Red color (BGR format)
        marker_size = int(fps * 0.01) # Marker size in pixels (assuming 1 cm radius)
        marker_thickness = 2 # Marker thickness in pixels

        # Draw the marker at the center of the frame
        cv2.drawMarker(frame, (center_x, center_y), marker_color, marker_size, marker_thickness)

        # Save the modified frame
        cv2.imwrite(save_path, frame)
        print("Frame with marker saved successfully.")
    else:
        print("Failed to read frame from the video.")
```

```
# Release the video capture
video.release()

# Example usage
video_path = "C:/Users/karak/OneDrive - unige.it/Desktop/Sestri-bathymetry/Mattia/GX010055.MP4"
photo_path = "C:/Users/karak/OneDrive - unige.it/Desktop/Sestri-bathymetry/pics/Manual_searching_markers/2nd.video/DJI_0854.JPG"
save_path = "C:/Users/karak/OneDrive - unige.it/Desktop/Sestri-bathymetry/pics/Manual_searching_markers/2nd.video/water.frames/extracted.jpg"

from datetime import datetime

# Example timestamp representation in UNIX format
video_timestamp = datetime(2023, 7, 4, 9, 54, 1) # 1st July 2023, 08:35:59
photo_timestamp = datetime(2023, 7, 4, 10, 13, 54) # 1st July 2023, 08:40:30

extract_frame(video_path, photo_path, video_timestamp, photo_timestamp, save_path)
```

Code 3: masking images

```
import cv2
import numpy as np
import glob
import os

image_paths = glob.glob(r"E:\Projects\hamburg\ali\images_original\*.jpg") #path to the images
output_directory = r"E:\Projects\hamburg\ali\maskall"

os.makedirs(output_directory, exist_ok=True)

def create_sky_mask(hsv):
    # Define range for sky color (including clouds)
    lower_sky = np.array([50, 50, 50])
    upper_sky = np.array([180, 225, 255])
    sky_mask = cv2.inRange(hsv, lower_sky, upper_sky)
    return sky_mask

def create_boat_mask(image_shape, boat_coordinates):
    boat_mask = np.zeros(image_shape[:2], dtype=np.uint8)
    boat_polygon = np.array([boat_coordinates], dtype=np.int32)
    cv2.fillPoly(boat_mask, boat_polygon, 255)
    return boat_mask

def apply_masks(image_path, boat_coordinates):
    # Load the image
    img = cv2.imread(image_path)

    hsv = cv2.cvtColor(img, cv2.COLOR_BGR2HSV)

    sky_mask = create_sky_mask(hsv)

    boat_mask = create_boat_mask(img.shape, boat_coordinates)

    combined_mask = cv2.bitwise_or(sky_mask, boat_mask)
```

```
kernel = np.ones((5, 5), np.uint8)
refined_mask = cv2.morphologyEx(combined_mask, cv2.MORPH_CLOSE, kernel)
refined_mask = cv2.morphologyEx(refined_mask, cv2.MORPH_OPEN, kernel)

mask_inv = cv2.bitwise_not(refined_mask)

result = cv2.bitwise_and(img, img, mask=mask_inv)

base_name = os.path.basename(image_path)
result_path = os.path.join(output_directory, base_name)
cv2.imwrite(result_path, result)

print(f'Processed and saved: {result_path}')

boat_coordinates = [(0, 6144), (0, 3514), (1529, 3150), (3483, 3606), (3164, 1308), (3201, 1314),
                    (3600, 3858), (3950, 3895), (8675, 3606), (9314, 1904),
                    (10371, 2015), (11175, 3489), (12288, 3200), (12288, 6144)]

for image_path in image_paths:
    apply_masks(image_path, boat_coordinates)

cv2.destroyAllWindows()
```

Code 4: DSM modification

```
from osgeo import gdal, ogr
import numpy as np

# Paths to your DSM and shapefile
dsm_path = r'E:\Projects\IIM_Sestri levante_project\modified_DEM.tif'
shapefile_path = r'E:\Projects\IIM_Sestri levante_project\shapefile.shp'
modified_dsm_path = r'E:\Projects\IIM_Sestri levante_project\modified_DEM1.tif'

# Example flat elevation (adjust as needed)
flat_elevation = 45.6

def modify_dsm_with_shapefile(dsm_path, shapefile_path, modified_dsm_path, flat_elevation):
    # Open shapefile
    shape_ds = ogr.Open(shapefile_path)
    if shape_ds is None:
        print(f'Could not open shapefile at {shapefile_path}')
        return

    # Get the first layer (assume only one layer in shapefile)
    layer = shape_ds.GetLayer()

    # Open DSM dataset
    dsm_ds = gdal.Open(dsm_path, gdal.GA_Update)
    if dsm_ds is None:
        print(f'Could not open DSM at {dsm_path}')
        return

    # Get DSM geotransform info
    geotransform = dsm_ds.GetGeoTransform()

    # Get raster extent and pixel dimensions
    x_res = dsm_ds.RasterXSize
    y_res = dsm_ds.RasterYSize

    # Initialize a flag to check if any modification occurred
    modification_occurred = False

    # Iterate through features in shapefile
    for feature in layer:
        # Get geometry of the feature
        geom = feature.GetGeometryRef()
```

```

# Transform geometry to DSM spatial reference
geom.TransformTo(dsm_ds.GetSpatialRef())

# Iterate through DSM pixels and check if within geometry
for i in range(x_res):
    for j in range(y_res):
        # Transform pixel center coordinates to geographic coordinates
        x_coord = geotransform[0] + i * geotransform[1] + j * geotransform[2]
        y_coord = geotransform[3] + i * geotransform[4] + j * geotransform[5]

        # Create a point geometry for the pixel center
        pixel_point = ogr.Geometry(ogr.wkbPoint)
        pixel_point.AddPoint(x_coord, y_coord)

        # Check if pixel center is within the transformed geometry
        if geom.Contains(pixel_point):
            dsm_array = dsm_ds.GetRasterBand(1).ReadAsArray()
            dsm_array[j, i] = flat_elevation
            dsm_ds.GetRasterBand(1).WriteArray(dsm_array)
            modification_occurred = True

# Save the modified DSM to a new file if modification occurred
if modification_occurred:
    driver = gdal.GetDriverByName('GTiff')
    modified_ds = driver.Create(modified_dsm_path, x_res, y_res, 1, gdal.GDT_Float32)
    if modified_ds is None:
        print(f'Could not create output dataset at {modified_dsm_path}')
    else:
        modified_ds.GetRasterBand(1).WriteArray(dsm_array)
        modified_ds.SetProjection(dsm_ds.GetProjection())
        modified_ds.SetGeoTransform(geotransform)
        modified_ds = None
        print(f'Modified DSM saved to {modified_dsm_path}')
else:
    print("No modification made to DSM.")

# Close datasets
dsm_ds = None
shape_ds = None

# Call the function to modify DSM based on shapefile
modify_dsm_with_shapefile(dsm_path, shapefile_path, modified_dsm_path, flat_elevation)

```

Code 5: ping position

```
import os
from datetime import datetime, timedelta
import pandas as pd

# Define the directory where your text files are located
directory = r"E:\Projects\IIM_Sestri levante_project\results\exported position pings"

# Define the specific times and target coordinates
specific_times = [
    {"time": "12:04:05", "target_x": 531355.57, "target_y": 4901770.44},
    ...
]

def adjust_time_for_file(target_time_str):
    """Adjust target time to match the file's time reference (subtract one hour)."""
    target_time = datetime.strptime(target_time_str, "%H:%M:%S").time()
    target_datetime = datetime.combine(datetime.now().date(), target_time)
    adjusted_datetime = target_datetime - timedelta(hours=1)
    return adjusted_datetime.time() # Return only the time part

# Define the time window (±2 seconds)
time_window = timedelta(seconds=1.4)

# Path to the output file (open in append mode)
output_file_path = os.path.join(directory, "best_matches_output.modified1sec.txt")

# Get the list of files in the directory
files = [f for f in os.listdir(directory) if f.endswith(".txt")]
total_files = len(files)

# Loop through each specific time
for idx, specific_time in enumerate(specific_times, start=1):
    target_time_str = specific_time["time"]

    # Adjust target_time for the file's time reference
    adjusted_target_time = adjust_time_for_file(target_time_str)
    target_datetime = datetime.combine(datetime.now().date(), adjusted_target_time) # This should now work

    target_x = specific_time["target_x"]
    target_y = specific_time["target_y"]
```

```

# Print progress for each specific time
print(f"\nProcessing time {idx}/{len(specific_times)}: {target_time_str} (adjusted to
{target_datetime.time()}")

# Read all files at once with specified encoding and error handling
all_data = []
for f in files:
    try:
        df = pd.read_csv(
            os.path.join(directory, f),
            header=None,
            names=["time", "x", "y", "z"],
            sep="\t",
            encoding='ISO-8859-1' # Adjust encoding as needed
        )
        all_data.append(df)
    except Exception as e:
        print(f"Error reading {f}: {e}")

# Concatenate all DataFrames
all_data = pd.concat(all_data, ignore_index=True, sort=False)

# Convert times, allowing for fractional seconds
all_data['time'] = pd.to_datetime(all_data['time'], errors='coerce') # Allowing for automatic parsing

# Check if any times failed to convert
if all_data['time'].isnull().any():
    print("Some times could not be parsed. Check your data format.")

# Filter for time window
time_window_start = target_datetime - time_window
time_window_end = target_datetime + time_window
filtered_data = all_data[(all_data['time'] >= time_window_start) & (all_data['time'] <=
time_window_end)]

# Initialize variables to track the closest match
closest_match = None
min_combined_distance = float('inf')

# Check filtered data for closest match
for _, row in filtered_data.iterrows():
    file_time = row['time']
    x = row['x']

```

```
y = row['y']

# Calculate combined distance for x and y coordinates
combined_distance = abs(x - target_x) + abs(y - target_y)

# Check if this is the closest match within the time window
if combined_distance < min_combined_distance:
    min_combined_distance = combined_distance
    closest_match = (file_time, x, y)

# Store the best match for the specific time and write it immediately
if closest_match:
    with open(output_file_path, 'a') as output_file: # Open file in append mode
        file_time, closest_x, closest_y = closest_match
        output_file.write(f"At time {target_time_str}, closest match within ±2 seconds:
time={file_time.time()}, x={closest_x}, y={closest_y}\n")

# Print the result to the console
print(f"At time {target_time_str}, closest match: time={file_time.time()}, x={closest_x},
y={closest_y}")
else:
    print(f"No match found for time {target_time_str}.")

# Print final confirmation
print(f"Best matches written to {output_file_path}")
```