Under and Through Water Datasets for Geospatial Studies: the 2023 ISPRS Scientific Initiative “NAUTILUS”

Under and Through Water Datasets for Geospatial Studies: the 2023 ISPRS Scientific Initiative “NAUTILUS”

Alessio Calantropio [1], Fabio Menna [2], Dimitrios Skarlatos [3], Caterina Balletti [4], Gottfried Mandlburger [5], Panagiotis Agrafiotis [6], Filiberto Chiabrando [7], Andrea Maria Lingua [8], Alessia Giaquinto [9], Erica Nocerino [1]*

[1] Department of Humanities and Social Sciences, University of Sassari, Sassari, Italy – (acalantropio; enocerino)@uniss.it
[2] Department of Chemical, Physical, Mathematical and Natural Sciences, University of Sassari, Sassari, Italy – fmenna@uniss.it
[3] Photogrammetric Vision Lab, Cyprus University of Technology, Limassol, Cyprus - dimitrios.skarlatos@cut.ac.cy
[4] Laboratorio di fotogrammetria CIRCE, Università Iuav di Venezia, Venezia, Italy - balletti@iuav.it
[5] Department of Geodesy and Geoinformation, TU Wien, Wien, Austria - gottfried.mandlburger@geo.tuwien.ac.at
[6] Faculty of Electrical Engineering and Computer Science, Technische Universität Berlin, Germany - agrafiotis@tu-berlin.de
[7] Department of Architecture and Design, Politecnico di Torino, Torino, Italy – filiberto.chiabrando@polito.it
[8] Department of Environment, Land and Infrastructure Engineering, Politecnico di Torino, Torino, Italy – andrea.lingua@polito.it
[9] Department of Sciences and Technologies, University Parthenope of Naples, Italy – alessia.giaquinto001@studenti.uniparthenope.it

Commission II/WG7

Key Words: ISPRS Scientific Initiative, Underwater data collection and processing, Benchmark dataset, WebGIS, Data sharing, Dataset accessibility.

Abstract:

Benchmark datasets have become increasingly widespread in the scientific community as a method of comparison, validation, and improvement of theories and techniques thanks to more affordable means for sharing. While this especially holds for test sites and data collected above the water, publicly accessible benchmark activities for geospatial analyses in the underwater environment are not very common. Applying geomatic techniques underwater is challenging and expensive, especially when dealing with deep water and offshore operations. Moreover, benchmarking requires ground truth data for which, in water, several open issues exist concerning geometry and radiometry. Recognizing this scientific and technological challenge, the NAUTILUS (uNder And throUgh waTer datasets for geospatIaL stUdieS) project aims to create guidelines for new multi-sensor/cross-modality benchmark datasets. The project focuses on (i) surveying the actual needs and gaps in through and under-the-water geospatial applications through a questionnaire and interviews, (ii) launching a unique publicly available database collecting already existing datasets scattered across the web and literature, (iii) designing and identifying proper test site(s) and methodologies to deliver to the extended underwater community a brand-new multi-sensor/cross-modality benchmark dataset. The project outputs are available to researchers and practitioners in underwater measurements-related domains, as they can now access a comprehensive tool providing a synthesis of open questions and data already available. In doing so, past research efforts to collect and publish datasets have received additional credit and visibility.

1. Introduction

Benchmark datasets are essential tools in scientific research, providing a reliable testing ground for researchers and practitioners who may not have access to real-world data collection opportunities. They enable fair comparisons of existing techniques, fostering progress towards more sophisticated and performant solutions. However, creating and maintaining benchmark datasets is a demanding task that requires significant human and financial resources. Depending on the dataset's scope and complexity, it may necessitate extensive planning, data acquisition, processing, organization, and dissemination efforts. To date, several research initiatives have produced benchmark datasets addressing a wide range of topics in remote sensing and geospatial data acquisition, including LiDAR (Bakula et al., 2019), photogrammetry (Knapitsch et al., 2017), oblique photography (Schops et al., 2017), uncrewed aerial vehicles (UAVs) (Nex et al., 2015), visual odometry (Özdemir et al., 2019), and combinations thereof. These datasets have been spearheaded by organizations such as the International Society for Photogrammetry and Remote Sensing (ISPRS) and its sister societies (EuroSDR) and within related communities. Mapping, navigation, and monitoring of underwater environments present unique challenges regarding data collection, processing, and accuracy assessment. While some datasets have been gathered (Ballarin et al., 2020; Berman et al., 2020; Ferrera et al., 2019), reliable reference measurements remain a major limitation. Excluding examples where ground truth data is artificially created (Agrafiotis et al., 2021), high-accuracy ground truth remains scarce, particularly in real-world underwater environments. An example is the COMEX dedicated pool test site (Menna et al., 2019). However, it still represents a controlled environment with very clear water that may not represent all underwater scenarios and is only suitable for certain studies, e.g., for analyzing the accuracy potential under ideal conditions. Acquiring accurate reference measurements underwater poses significant challenges due to the inherent characteristics of underwater environments. For instance, it is often difficult, if not unfeasible, to guarantee the standards expected in aerial photogrammetry (Nocerino et al., 2020; Skarlatos et al., 2019), such as the requirement that ground control points (GCPs) be *n* times more accurate than the expected theoretical accuracy of the photogrammetric survey. Furthermore, there are no metric

* Corresponding author

standards for underwater surveys like those established by organizations such as ASPRS for aerial photogrammetry surveys and products.

The ISPRS Working Group (WG) II/7 on Underwater Data Acquisition and Processing has recognized the lack of shared underwater datasets as a critical issue. In June 2021, an online meeting was organized to address this gap, bringing together 83 researchers and practitioners from 21 countries with expertise in underwater topics. Most participants (70%) were affiliated with the photogrammetry community, while 48% were involved in computer vision and 30% in robotics. Participants were asked about the need for shared underwater datasets and unanimously expressed their support for such initiatives. They expressed a strong interest in benchmark datasets that align with their specific research areas. The lack of standardized and widely available benchmark datasets for underwater data acquisition and processing hinders progress in the field. Creating and disseminating such datasets would provide researchers and practitioners with valuable resources for evaluating and comparing techniques, fostering innovation, and accelerating advancements in underwater mapping, navigation, and monitoring applications.

2. The NAUTILUS Project

The NAUTILUS project has been initiated to address this crucial need in response to the growing demand for benchmark datasets for underwater geospatial applications. To achieve this objective, the project's framework is structured into three work packages (WPs) (Figure 1). The NAUTILUS work packages are designed to be interconnected and mutually reinforcing, ensuring that the project's activities are aligned with the evolving needs of the underwater geospatial community: WP1 focuses on identifying user needs and gaps, WP2 establishes a publicly available dataset repository, and WP3 designs and provides guidelines for benchmark datasets. The insights gained from WP1 inform the selection and preparation of datasets for WP2, while the data collected and analyzed in WP2 and WP3 will provide valuable feedback for WP1. The NAUTILUS project's approach, encompassing user needs assessment, dataset curation, and benchmark dataset development, aims to provide valuable tools for researchers, practitioners, and anyone involved in underwater geospatial applications.

Work Package 1: Identifying User Needs and Gaps - The first WP focuses on gathering insights into specific requirements and challenges raised by users of underwater geospatial data. To this end, a questionnaire was distributed, and face-to-face interviews were conducted involving interested persons from diverse fields, including photogrammetry, remote sensing, and robotics. This data collection effort aimed to identify the current state of underwater geospatial technology, the open needs of users, and the areas for potential improvement.

Work Package 2: Establishing a Publicly Available Dataset Repository - Building upon the knowledge gained from WP1, the second WP focuses on creating a centralized repository of existing underwater geospatial datasets. This repository is a resource for researchers, practitioners, and anyone involved in underwater imaging applications. The repository facilitates easy access to diverse datasets, enabling comparative analyses and identifying potential gaps in the existing data.

Work Package 3: Designing and Implementing a Benchmark Dataset - Building on the insights and resources developed in the previous WPs, WP3 focuses on designing and implementing a benchmark dataset specifically tailored to the needs of the underwater geospatial community. The benchmark dataset should be designed to provide standardized sets of data and methodologies that can be used to evaluate and compare the performance of different underwater imaging systems, algorithms, and techniques. The development of this dataset should represent a key opportunity in the field of underwater geospatial technology by providing a common test ground for researchers and practitioners. It would represent a critical step towards advancing this field and enabling more reliable and efficient underwater data acquisition, processing, and analysis.

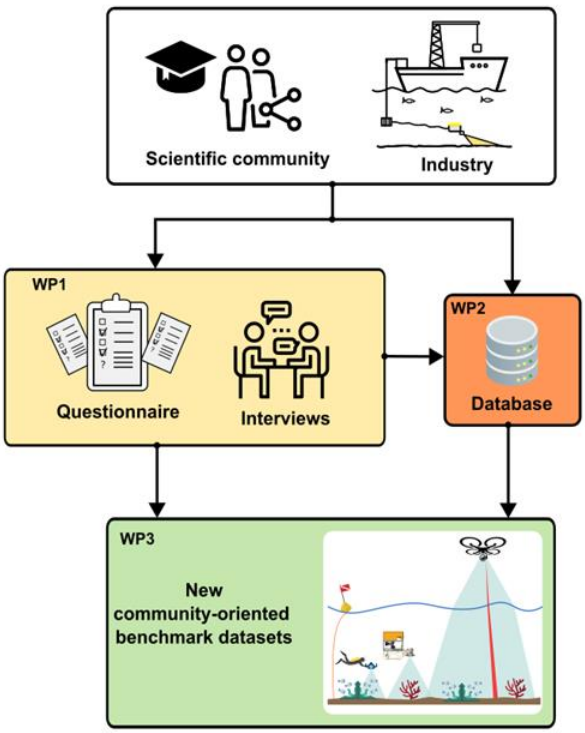

Figure 1. NAUTILUS Project Work Packages.

2.1 WP1: Questionnaire and interviews

The NAUTILUS project began by designing and sharing a questionnaire to gather insights into the needs and requirements of the underwater geospatial community, encompassing researchers and professionals from diverse fields, including biology, ecology, archaeology, industry, and others. The target respondents were primarily identified among the ISPRS WGII/7 members, consisting of over 120 individuals with various backgrounds and national origins. Additionally, the network of potential interviewees was extended by contacting colleagues in related disciplines and seeking their recommendations. The initiative was also publicized through the organizers' social media channels to reach a wider audience. The questionnaire was crafted to be simple and quick to fill in but still informative for the project’s aims of collecting qualitative and quantitative data. The survey addressed various aspects, including the participants' interest in a benchmark dataset for underwater geospatial applications, their background, application domains, operational depth range, data requirements, geomatic techniques employed, preferred data acquisition platforms, and preferred NAUTILUS project activities. A specific section addressed the possibility of participants sharing their existing datasets for inclusion in the NAUTILUS database. It comprised ten questions, presented in Appendix A.

This contribution has been peer-reviewed. The double-blind peer-review was conducted on the basis of the full paper.
https://doi.org/10.5194/isprs-annals-X-2-2024-33-2024 | © Author(s) 2024. CC BY 4.0 License.

The questionnaire was circulated in June-July 2023 and received responses from 48 individuals, representing approximately 25% of the total number of individuals contacted. A resounding positive response emerged, with all participants expressing interest in a benchmark dataset for underwater geospatial applications. Most respondents (83%) held academic backgrounds, indicating a strong presence of researchers and academics among the target audience.

Based on the participants' application domains, three macro-areas were identified: Cultural Heritage (37 participants), Marine Ecology, Biology, and Environmental Monitoring (33 participants), and Seafloor Mapping and Industrial Applications (40 participants). This shows a balanced distribution of interests across various application fields. Regarding operational depth ranges, 41 out of 48 respondents indicated activities within 10 meters of depth, while 37 out of 48 indicated activities within 10 to 40 meters of depth. This suggests that a considerable portion of the target audience focuses on shallower underwater environments. Regarding data requirements, most applications (42 out of 48) have areas between 1 and 100 square meters, while the required spatial resolution is predominantly between 1 and 5 centimeters. These findings indicate that the target audience's primary concern is high-resolution data for underwater surveys of small areas. A near-unanimous preference for three-dimensional data emerged, with 97% of the respondents expressing interest in this type of data. Underwater photogrammetry emerged as the preferred acquisition technique employed by 93% of the participants. Scuba diving operators were the most common data acquisition method utilized by approximately one-third of the respondents. This figure is not surprising, as it reflects the composition of the members of the ISPRS WGII/7, whose field of research is predominantly image-based techniques.

Overall, the questionnaire’s findings provide valuable insights into the interests, backgrounds, and needs of the NAUTILUS project's target audience. The results highlight a strong demand for benchmark datasets, a preference for three-dimensional data, and the widespread use of underwater photogrammetry for data acquisition. These findings guided the development of the NAUTILUS project's activities and resources to better cater to the needs and interests of the target audience.

This WP's second activity consisted of a series of face-to-face interviews to delve deeper into topics of particular interest that emerged during the surveys. The interviews were carried out online and recorded with the consent of the interviewees to review, analyze, and create dissemination material. Each interview followed a basic format to extrapolate meaningful data for the project.

The interview was structured in three sections:
(i) an introduction with a short presentation of NAUTILUS and the aims of the interview;
(ii) a second part following a guided interview with questions related to the field of the expertise or activities of the interviewees, the data usually collected or used, procedures followed or developed to check and validate the achieved results or products, highlight the innovative aspect of the conducted research/business and what is still missing, and which are the open challenges;
(iii) a free part to elaborate on topics that emerged in the discussion.

Additional topics covered were the importance of color-correcting underwater images, the need for fully 3D data compared to 2.5D data, and training and safety for underwater operations. In addition, participants were presented with the NAUTILUS portal developed within WP2 and were asked to consider sharing any datasets or benchmark datasets. In total, 15 interviews were conducted, including two double interviews, with interviewees from seven countries. Fourteen participants were from academia, two from companies, and one from a Marine Protected Area (government organization), working in the following application domains: robotics, computer vision, archaeology, marine ecology, subsea metrology, and industry. On average, an interview was about ¾ of an hour long.

The interviews provided invaluable insights into various facets of underwater research, spanning a broad spectrum of disciplines such as photogrammetry, computer vision, artificial intelligence, data processing, safety protocols, collaboration endeavors, and the intricate challenges surrounding data sharing. Throughout these discussions, experts outlined the intricate web of interconnections within these fields, dedicating considerable effort to developing simulation toolkits tailored specifically for underwater environments. These toolkits served as foundational steppingstones, allowing researchers to emulate the complexities of underwater ecosystems and phenomena while simultaneously advancing techniques in reproducibility and calibration methodologies. One interviewee passionately emphasized the importance of validation methodologies, particularly in coral reef research, and underscored the critical need for expanding research into emerging domains like land-water interface mapping. Another interviewee delved deep into the realm of autonomy, underwater IoT, and human-robot interaction, grappling with the formidable challenges of underwater communication and harnessing the power of deep learning algorithms in this context. A representative of a company specialized in pioneering 3D modeling solutions for underwater asset inspection emphasized the importance of precision, efficiency, and the development of innovative surveying solutions to advance the frontier of underwater research. The discussion also focused on open challenges in data processing, dynamics of collaboration with academia, the criticality of safety considerations in underwater operation, and the challenges inherent in data sharing within the underwater imaging domain. Throughout these conversations, another interviewee highlighted the importance of validation methodologies, particularly within underwater archaeological surveys.

The need to foster collaborative partnerships between experts was recognized as the driving force for the underwater research community. Most interviewed people depicted NAUTILUS as an important initiative to establish a public database catalog of underwater cultural and natural heritage datasets, addressing glaring deficiencies such as the absence of centralized repositories. It emerged that many researchers are currently investigating the process of crafting realistic simulated images for photogrammetry studies and, in one case, also simulating sonar using photogrammetry data. Discussions drew attention to the challenges surrounding color restoration and the scarcity of datasets conducive to accurate simulation. Concurrently, conversations revolved around the challenges and benefits inherent in utilizing photogrammetry for documenting submerged archaeological sites, advocating for establishing international benchmarks, and the systematic testing of various underwater camera technologies. Further exchanges on data collection, precise georeferencing, and the ongoing evolution of underwater mapping technologies highlighted the pressing need for rigorous simulation environments and real datasets supported by reliable ground truth. Finally, discussions delved

This contribution has been peer-reviewed. The double-blind peer-review was conducted on the basis of the full paper.
https://doi.org/10.5194/isprs-annals-X-2-2024-33-2024 | © Author(s) 2024. CC BY 4.0 License.

into the complexities surrounding data processing protocols, the importance of securing permissions for data disclosure, and the necessity of establishing a centralized database aggregating underwater research activities to enhance visibility and optimize resource allocation.

The following key elements emerged from the interviews:

Research Directions:
- Seamless integration of photogrammetry, computer vision, and pattern recognition.
- Validation, collaboration, and expanding research into new areas like land-water interface mapping.
- Developing technologies for divers' navigational localization and monitoring underwater infrastructure.
- Integration of optical and acoustic methods for improved bathymetry data collection.
- Discussing projects involving citizen science and marine drone data collection.
- Working on underwater mapping technologies, highlighting challenges in image enhancement, underwater localization, and automatic species/target recognition.

Challenges:
- Stressing the importance of reproducibility, scalability, calibration methods, and real datasets for evaluating underwater mapping algorithms.
- Overcoming the unexploited potentialities of 3D products compared to standard legacy 2D data, which is still used by many final users.
- Improving underwater communication and applying new deep-learning techniques.
- Implementing color correction algorithms in high-depth and low-visibility environments
- Work towards sharing training datasets for AI algorithms.
- Lack of a centralized repository of underwater research activities
- Precise georeferencing of data at medium and high depths
- Permission for data disclosure in compliance with property rights

Needs:
- Discussing data processing, collaborating with academia, governmental institutions, and companies, considering safety, and sharing data in the underwater imaging domain.
- Synthetic underwater images for AI algorithms training
- Emphasizing the need for standardized data formats and a centralized repository for underwater imaging data.
- Aiming to create a public repository for underwater cultural and natural heritage datasets.
- Emphasizing the need for international benchmarks and testing different underwater cameras.
- Emphasizing the need for robust simulation environments and datasets with reliable ground truth.

2.2 WP2: A publicly available database of already existing datasets

In parallel to the survey and interviews conducted in WP1, a systematic effort was initiated to gather, organize, and integrate existing datasets and benchmark datasets relevant to underwater survey applications. This extensive collection is thought to be further enriched by incorporating data contributions from participants engaged in the questionnaire, interviews, and user meetings. These efforts culminated in an online self-maintained repository — the NAUTILUS portal[1] —a centralized hub for housing and managing datasets about diverse underwater case studies. In the context of this work, clarifying the concepts and understanding the difference between “dataset” and “benchmark dataset” is important. A dataset is a collection of data, typically organized in a way that is consistent, efficient, and easy to understand (based on schemas, definitions, and relationships), representing a particular domain or problem. It is a fundamental resource for training, evaluating, and comparing algorithms, models, or systems. Depending on the specific application, datasets can vary significantly in size, format, and complexity.

A benchmark dataset goes beyond a mere collection of data. It is specifically designed to serve as a standard reference for evaluating the performance of different techniques or algorithms on a particular task. Benchmark datasets typically include reference data, such as ground truth labels or checkpoints, against which the performance of evaluated methods can be compared. They often have published results for a specific task, such as classification accuracy or regression metrics, providing a benchmark against which new methods can be compared. In addition, benchmark datasets should have a well-documented data acquisition process, clearly explaining the methods and procedures used to collect the data. This documentation helps ensure the reliability and consistency of the dataset, making it more valuable for comparative evaluations. Finally, benchmark datasets should be freely accessible to the research community, typically through a dedicated website or repository.

The main output of WP2 is a web application that serves as a centralized platform for collecting, managing, and disseminating available datasets and benchmark datasets related to underwater data acquisition and processing. The NAUTILUS portal (Figure 2) underwent continuous updates throughout the project’s duration, with additional data being incorporated as it became available from WG affiliates and the broader ISPRS community. The portal is based on the ESRI web app, which utilizes ArcGIS technology to visualize and analyze geographic data. It combines mapping capabilities with interactive features and widgets to provide users with a comprehensive and engaging platform for exploring geospatial information. ESRI web apps are built using a variety of frameworks and tools, including HTML, JavaScript, and CSS, and are designed to run on any device, including desktops, tablets, and smartphones. Initially developed utilizing ESRI technology, the web app’s functionality remains intact while exploring alternative open-source solutions. This openness to exploration aligns with the project's philosophy of embracing technological advancements and identifying cost-effective, flexible solutions. If a suitable open-source alternative emerges, it will be evaluated thoroughly to ensure its compatibility with the web app's existing architecture and adherence to data integrity standards. To feed the data into the NAUTILUS portal, a user-friendly interface based on Google form[2] was set up to facilitate the submission of metadata describing the injected datasets. While Google Forms is not specifically designed as a data table management tool, it can be effectively utilized to create and manage attribute tables for ESRI web apps and related hosted feature layers, providing a seamless solution for updating the dataset lists and metadata whenever new entries are available. Upon submission, the data is seamlessly integrated into the web app's database, and an

[1] https://nautilus-isprs.fbk.eu/dataset/dataset-collection
[2] https://forms.gle/LFKNPuKmdVMi98oy8

authorized admin performs a thorough review before publicly displaying the information. This streamlined process ensures data integrity and consistency, while the automated data entry reduces manual effort and potential errors.

The Google Forms entries match the NAUTILUS portal’s database structure, comprising a set of attributes for qualitative and quantitative descriptions of each dataset package. The attributes table has been structured by following and adjusting the schema of the BeMeDa Benchmark Metadata Database (Budde et al., 2022). The data collection form is divided into sections covering the metadata depicted in Table 1. The web app's structure fosters community engagement and long-term sustainability. While the NAUTILUS team manages it, its modular design enables a seamless transition to community ownership and maintenance. This approach promotes shared responsibility, fosters collective knowledge, and empowers the NAUTILUS community to actively contribute to the project's success. This meticulous categorization facilitated efficient data identification and retrieval by users seeking specific datasets based on their requirements.

To ensure the utmost flexibility for the original data owners, the NAUTILUS portal exclusively stores metadata rather than the actual data files themselves. This strategic approach mitigates copyright conflicts and external hosting issues. The portal preserves intellectual property's integrity by preserving metadata while empowering data owners to manage their assets independently. The decision regarding archiving datasets unavailable online was made during the project lifecycle, ensuring informed and timely decisions aligned with the project objectives. By carefully evaluating the availability and accessibility of these datasets, the project team ensured that only relevant and accessible data was incorporated into the repository. This approach prioritized the quality and usability of the dataset collection, catering to the needs of researchers and practitioners seeking reliable and relevant underwater data for their applications. The NAUTILUS portal represents a valuable resource for the underwater data acquisition and processing community, providing a centralized repository for accessing and utilizing diverse datasets. Its comprehensive structure, flexible metadata-based approach, and ongoing updates make it an indispensable tool for researchers, practitioners, and anyone involved in underwater imaging applications. The portal's commitment to data integrity and accessibility ensures that the community can access the high-quality data necessary for advancing research and innovation in this field.

2.3 WP3: A brand-new through and underwater benchmark

To address the data gaps identified in the previous section, the NAUTILUS project will propose a new data collection strategy that focuses on collecting high-quality multisensory data in three distinct environmental conditions: running (rivers), still (lakes, ponds), and coastal (sea) water. It will provide researchers with a valuable resource for developing and evaluating underwater geospatial techniques for various applications. Representative sites for diverse underwater environments will be suggested, including rivers, lakes, ponds, and coastal waters. Guiding criteria will be environmental diversity, geographic diversity, accessibility, and scientific value. Ideally, identified sites should be located in different geographic regions to ensure that the data represents a global range of underwater environments. They should also be easily accessible for data collection to facilitate the project's ability to collect the necessary data promptly and efficiently.

Attribute	Description
Name	name of the dataset or benchmark dataset
Description	Short description of the dataset
Keywords	List of keywords, separated by a semicolon
URL	Link to the dataset landing page
Download	Link to the dataset download page. If no download link is available, the dataset will be marked as downloadable "Upon request"
UID	Unique dataset identifier of the dataset, e.g. DOI, if available.
Task	The tasks for which the dataset is designed, such as cultural heritage, marine ecology, or environmental monitoring.
Sensors	The types of sensors used for data acquisition, such as cameras, structured light scanners, and LiDARs.
Techniques	The data acquisition techniques employed, such as underwater photogrammetry, laser scanning, and sonar.
Acquisition Configuration	The configuration in which the data were acquired, such as multi-temporal, multi-spectral, or multi-view.
Acquisition Platform	The configuration in which the data were acquired, such as multi-temporal, multi-spectral, or multi-view.
Date	The date on which the dataset was recorded.
Latitude	Expressed in decimal degrees (DD)
Longitude	Expressed in decimal degrees (DD)
Minimum depth	The minimum depth reached by the data contained in the dataset
Maximum depth	The maximum depth reached by the data contained in the dataset
Covered area	The estimated area covered by the survey conducted to gather the data contained in the dataset [e.g. 100] expressed in squared meters.
Spatial resolution	The estimated spatial resolution of the data contained in the dataset [e.g. 10] expressed in cm
Data included	The types of data included in the dataset, such as 3D models, 2D maps, RGB images, multispectral images, and acoustic data.
Benchmark	Whether the dataset is considered a benchmark dataset, which implies that it meets certain criteria for evaluation and documentation.
Contact	The contact information for the person responsible for the dataset.
Paper	If there is any additional paper, which introduces the dataset or the benchmark dataset and, in particular, evaluation results
Title	Title of the paper
ID	Unique identifier of the paper, e.g. DOI
PubDate	Year of publication of the paper
Authors	Authors, separated by semicolon
Image	A link to a sample image from the dataset.

Table 1. Attribute tables employed for the dataset’s metadata collection.

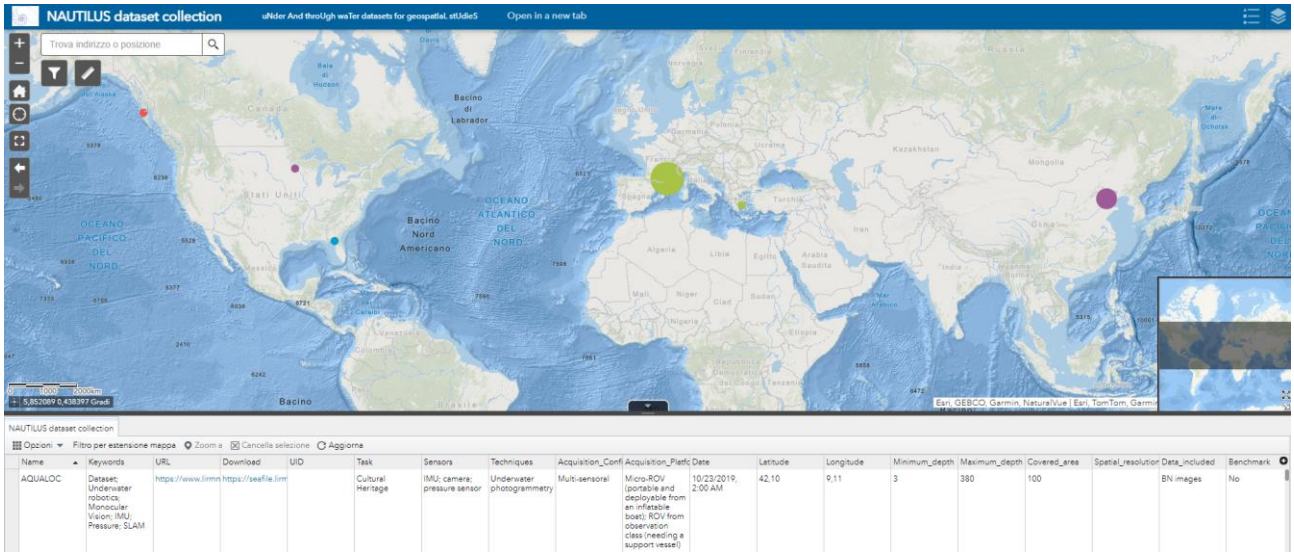

Figure 2. The landing page of the NAUTILUS portal (https://nautilus-isprs.fbk.eu/dataset/dataset-collection).

Additionally, the sites should have significant scientific value to research on underwater geospatial applications. The multisensory data collection will focus on collecting high-quality data from various sensors, including imagery, positioning, and other sensors, to capture different aspects of the underwater environment. This will allow researchers to generate detailed 3D models of the underwater environment, assess the positional accuracy of the collected data, and evaluate the radiometric accuracy of the data for applications such as benthic species recognition.

The collected data will address various research questions and applications, including multi-temporal monitoring of changes in the underwater environment over time, positional accuracy assessment, radiometric accuracy assessment, and automatic benthic species recognition. The project will provide a comprehensive report outlining the selected test site(s), the multi-sensor/cross-modality data acquisition planning, and the expected results and analyses derived from the collected data. This report will provide a valuable resource for the underwater geospatial community and contribute to advancing this field. WP3 is currently under development, and the results will be available by the end of the project.

2.4 NAUTILUS Online User Meeting

On January 15th, 2024, the NAUTILUS project convened an online user meeting to engage diverse experts in underwater geospatial data acquisition and processing. This virtual gathering was a great opportunity for open dialogue, collaborative exchange, and a collective endeavor to chart future advancements in this rapidly evolving field. The meeting was organized in two sessions to allow participants from around the world with different time zones to attend. More than 90 researchers and practitioners from about 20 countries registered, with a final attendance of approximately 50 participants per session.

The meeting started with an overview of the NAUTILUS project's aims and contributions to the underwater geospatial domain. Participants were presented with a detailed account of the project's objectives, methodologies, and outcomes, highlighting the significant advancements in underwater data acquisition, processing, and application. 23 five-minute presentations were given by the participants, covering a broad range of topics: 3D reconstruction; color restoration; virtual and augmented reality; multimedia and through water photogrammetry; photo-bathymetry; photogrammetry in low visibility; underwater archaeology, marine ecology, and industrial applications; multi-techniques and muti-sensor underwater acquisition and integration, including geophysical prospection, acoustic measurements, multispectral and fluorescence data; marine robotics and remotely operated and autonomous underwater vehicles; underwater, navigation, localization and mapping; simulation environment. The presenters discussed their current research projects, funded by different agencies both at international and national levels. Two companies developing solutions for underwater positioning and industrial inspections presented their latest developments.

Throughout the meeting, participants actively engaged in a spirit of collaboration, sharing their expertise, insights, and experiences. This exchange of knowledge fostered a deeper understanding of the current state of underwater geospatial technology and identified key areas for future research and development. The meeting concluded with a consensus on the importance of continued collaboration and sharing of knowledge to accelerate advancements in underwater geospatial data acquisition and processing, enabling more comprehensive and accurate representations of underwater environments for a wide range of applications.

3. Discussions and Conclusions

The NAUTILUS project was implemented to address the critical need for a comprehensive and accessible database of underwater geospatial data. NAUTILUS recognized the amount of underwater data scattered across various sources, including scientific publications and online repositories. The project embarked on a systematic approach to gathering, organizing, and presenting this existing data in a centralized repository. This effort streamlined access to existing resources and highlighted gaps and areas for further development within the underwater geospatial domain. User-centered data collection can be extremely beneficial in the community when addressing domain-specific problems; these aspects could be related, for

This contribution has been peer-reviewed. The double-blind peer-review was conducted on the basis of the full paper.
https://doi.org/10.5194/isprs-annals-X-2-2024-33-2024 | © Author(s) 2024. CC BY 4.0 License.

example, to general issues that can be of interest to different scientists, such as color correction, synthetic data generation, flora and fauna monitoring, caustic removal (to name a few) or specifically related to professional and researcher that are working a certain specific subject (archaeological remains, environmental assets, or the employment of specific sensors).

NAUTILUS undertook an extensive data and opinion-gathering campaign to address these gaps and fulfill the community's growing demand for underwater data resources. The team engaged with researchers, practitioners, and industry experts from diverse fields through a questionnaire and in-depth interviews. This collaborative effort yielded a wealth of insights into the current state of underwater data collection, processing, and application.

The persons who agreed to fill in the questionnaire and be interviewed spanned different communities, although they focused more on image-based techniques. In the feature, the NAUTILUS team aims to reach a broader audience by addressing better topics such as LiDAR bathymetry and remote and acoustic sensing. The collected data and the findings from the questionnaire and interviews were integrated into an open-access website and repository, making this valuable information readily available to the global underwater data acquisition community.

Additionally, NAUTILUS is currently focusing on designing and planning a brand-new multi-sensor/cross-modality benchmark dataset. This initiative would contribute to creating a standardized dataset for benchmarking and evaluating underwater data acquisition algorithms and techniques. NAUTILUS has supported ISPRS's scientific mission to foster interdisciplinary collaboration by engaging with researchers and practitioners from diverse disciplines. The project aimed at bringing together experts from fields such as computer vision, image processing, and underwater robotics to expand the horizons of underwater data acquisition towards innovative research approaches. The web app serves as a centralized hub for underwater data resources. Its user-friendly interface allows users to easily browse and access existing datasets, while its automated data entry and admin review process ensures data quality and accessibility. The modular design of the web app promotes community ownership and encourages ongoing maintenance, ensuring its long-term viability as a valuable resource for the underwater data acquisition community. The moment of discussion represented by the online event was met with great enthusiasm and participation by the community. The authors know that different discussions and interactions followed the event between the participants, confirming the importance of interaction between the communities involved in the NAUTILUS initiative.

The efforts undertaken by NAUTILUS will be pursued in follow-up projects, such as the ISPRS Education and Capacity building initiative POSER - an oPen sOurce Simulation platform for tEaching and tRaining underwater photogrammetry (Menna et al., 2024), which aims to create an underwater simulation environment for teaching and systematic testing. Still in the context of education and dissemination among young researchers and students, NAUTILUS will support the second edition of the SUNRISE (Seashore and UNderwater documentation of aRchaeological herItage palimpSests and Environment) summer school (Balletti et al., 2023), also funded as part of the ISPRS Education and Capacity building initiative 2024.

Acknowledgements

NAUTILUS is funded by the ISPRS Scientific Initiatives 2023 program. The authors would like to thank the participants of the NAUTILUS project, the people who answered the questionnaire and were interviewed, and those who attended the NAUTILUS Online User Meeting (January 15th, 2024).

References

Agrafiotis, P., Karantzalos, K., Georgopoulos, A. and Skarlatos, D., 2021. Learning from synthetic data: Enhancing refraction correction accuracy for airborne image-based bathymetric mapping of shallow coastal waters. *PFG–Journal of Photogrammetry, Remote Sensing and Geoinformation Science*, *89*(2), pp.91-109.

Bakula, K., Mills, J.P. and Remondino, F., 2019. A review of benchmarking in photogrammetry and remote sensing. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*.

Ballarin, M., Costa, E., Piemonte, A., Piras, M. and Losè, L.T., 2020. Underwater Photogrammetry: Potentialities and Problems Results of the Benchmark Session of the 2019 Sifet Congress. *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, *43*, pp.925-931.

Balletti, C., Capra, A., Calantropio, A., Chiabrando, F., Colucci, E. et al., 2023. the SUNRISE summer school: an innovative learning-by-doing experience for the documentation of archaeological heritage. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 48, pp.147-154.

Berman, D., Levy, D., Avidan, S. and Treibitz, T., 2020. Underwater single image color restoration using haze-lines and a new quantitative dataset. *IEEE transactions on pattern analysis and machine intelligence*, *43*(8), pp.2822-2837.

Budde, L. E., Schmidt, J., Javanmard-Ghareshiran, A., Hunger, S., and Iwaszczuk, D., 2022. Development Of A Database For Benchmark Datasets In Photogrammetry And Remote Sensing, *ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci*., V-1-2022, 187–193, https://doi.org/10.5194/isprs-annals-V-1-2022-187-2022.

Ferrera, M., Creuze, V., Moras, J. and Trouvé-Peloux, P., 2019. AQUALOC: An underwater dataset for visual–inertial–pressure localization. *The International Journal of Robotics Research*, *38*(14), pp.1549-1559.

Menna, F., Torresani, A., Nocerino, E., Nawaf, M.M., Seinturier, J., Remondino, F., Drap, P. and Chemisky, B., 2019. Evaluation of vision-based localization and mapping techniques in a subsea metrology scenario. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *42*(2/W10), pp.127-134.

Knapitsch, A., Park, J., Zhou, Q.Y. and Koltun, V., 2017. Tanks and temples: Benchmarking large-scale scene reconstruction. *ACM Transactions on Graphics (ToG)*, *36*(4), pp.1-13.

Nex, F., Gerke, M., Remondino, F., Przybilla, H.J., Bäumker, M. and Zurhorst, A., 2015. ISPRS benchmark for multi-platform photogrammetry. *ISPRS Annals of the*

Photogrammetry, Remote Sensing and Spatial Information Sciences, *2*(3), p.135.

Menna et al., 2024. POSER - an oPen sOurce Simulation platform for tEaching and tRaining underwater photogrammetry. Submitted to the ISPRS TCII Sympsium 2024.

Nocerino, E., Menna, F., Gruen, A., Troyer, M., Capra, A., Castagnetti, C., Rossi, P., Brooks, A.J., Schmitt, R.J. and Holbrook, S.J., 2020. Coral reef monitoring by scuba divers using underwater photogrammetry and geodetic surveying. *Remote Sensing*, *12*(18), p.3036.

Özdemir, E., Toschi, I. and Remondino, F., 2019. A multi-purpose benchmark for photogrammetric urban 3D reconstruction in a controlled environment. In *Evaluation and Benchmarking Sensors, Systems and Geospatial Data in Photogrammetry and Remote Sensing* (Vol. 42, pp. 53-60).

Schops, T., Schonberger, J.L., Galliani, S., Sattler, T., Schindler, K., Pollefeys, M. and Geiger, A., 2017. A multi-view stereo benchmark with high-resolution images and multi-camera videos. In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition* (pp. 3260-3269).

Skarlatos, D., Menna, F., Nocerino, E. and Agrafiotis, P., 2019. Precision potential of underwater networks for archaeological excavation through trilateration and photogrammetry. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *42*(2/W10), pp.175-180.

Appendix A

List of the questions from the NAUTILUS questionnaire

1) Are you interested in a benchmark dataset for underwater geospatial applications?
   - Yes
   - No

2) What is your background? (Tick all that apply)
   - Academia
   - Hardware manufacturer
   - Software developer/vendor
   - Data and service provider
   - Public authority (mapping agency, environmental agency, etc.)
   - Non-governmental organization

3) Which applications are you interested in? (Tick all that apply)
   - Marine ecology
   - Environmental monitoring
   - Sea floor exploration and mapping
   - Oil & gas industry
   - Coastal engineering
   - Offshore engineering
   - Fishery/Aquaculture

4) What is the depth range at which your activities take place: (Tick all that apply)
   - < 10 m
   - 10-40 m
   - 40-100 m
   - 100-300 m
   - 300-1000 m
   - >1000 m

5) How large is the area in your typical applications? (Tick all that apply)
   - < 1 sqm
   - 1-100 sqm
   - 100 - 250 sqm
   - 250 sqm - 1 sqkm
   - > 1 sqkm

6) What is the spatial resolution required in your typical applications? (Tick all that apply)
   - < 1 cm
   - 1 - 5 cm
   - 5 - 25 cm
   - 25 cm - 100 cm
   - 1- 5 m

7) What kind of data are you interested in? (Tick all that apply)
   - 3D
   - 2.5D
   - 2D
   - RGB images
   - multispectral images acoustic

8) Which geomatic techniques do you use for your project or are you interested in? (Tick all that apply)
   - Underwater photogrammetry
   - Multimedia photogrammetry
   - Underwater laser scanning
   - Acoustic positioning
   - Sonar based mapping
   - Airborne laser bathymetry

9) Which data acquisition platform would better fit your project? (Tick all that apply)
   - Scuba-diving
   - Micro-ROV (portable and deployable from an inflatable boat)
   - ROV from observation class (needing a support vessel)
   - AUV
   - ASV
   - UAV fixed wing
   - UAV multirotor
   - Helicopter
   - Airplane
   - Satellite

10) Which of the following activities within the NAUTILUS project would you be interested in? (Tick all that apply)
   - Sharing needs and requirements of your application domain
   - Sharing an underwater dataset
   - Using benchmark datasets for your research/application
   - Designing and setting up an underwater dataset
   - Contributing to a white paper on underwater geospatial data collection needs
   - Having access to the results of a benchmark dataset or comparative evaluation of different methods
   - Being interviewed on the topics of this questionnaire not interested