3D Acoustic Remote Sensing mapping of the Underwater Cultural Heritage in the Marine Protected Area of Baia submerged Park (Bay of Pozzuoli, Southern Italy)

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Abstract

Underwater archaeology has historically depended on geophysical and remote sensing technology to identify and document submerged archaeological sites and shipwrecks. Acoustic remote sensing for seabed archaeology developed from sonar systems originally designed for military use and geological exploration. These systems assess the physical characteristics of the seafloor, particularly backscatter and water depth, by emitting acoustic energy towards the bottom and capturing the arrival times and directions of the returning acoustic signals. These methods are efficient in data acquisition and yield results that are both repeatable and quantifiable.
In recent decades, significant advancements in marine geophysical techniques have afforded the maritime archaeological community remarkable opportunities to redefine site mapping, evaluation, and monitoring procedures. The introduction of very-high resolution sonar systems has made it possible to determine the three-dimensional shapes of submerged objects, providing an invaluable resource for identifying and characterizing archaeological assets on the seabed.
In this work we present the preliminary results of an acoustic remote sensing survey conducted with the latest generation of ultra-high resolution (UHR) multibeam echo-sounders (MBES) in the Baia submerged park (southern Italy). These systems integrates advanced acoustic array geometry, high-precision inertial navigation and positioning systems that can rapidly generate massive point clouds of millions of individual bathymetric measurements with unprecedented resolution and accuracy. The exceptionally high density of these measurements lead to the development of multiresolution models, which can be effectively utilized for interactive 3D visualization on digital platforms.

1. Introduction

In the underwater environment, sound waves are the most efficient methods of measurement due to their ability to travel long distances (up to several kilometers) without significant attenuation. Modern echo sounders, or marine Sonars, use acoustic energy to measure water depth and backscatter of the seafloor by transmitting sound pulses toward the bottom and detecting the arrival times and directions of the reflected signal that returns from the bottom. These information can be used to map seabed morphology and composition.

Acoustic remote sensing techniques encompass various types of Sonar, which can deliver a continuous view of both seafloor and subseafloor features. Sonar systems are designed to produce electrical signals that are converted into acoustic energy by a transducer. This pulse of acoustic energy is then transmitted into the water column at a specified frequency. The reflected acoustic signal from the seabed is then converted back into electrical energy via a receiving transducer.

In recent decades, marine acoustic remote sensing techniques have provided the maritime archaeological community remarkable opportunities to redefine site mapping, evaluation, and monitoring procedures (Violante, 2020). The techniques with the greatest potential for high-resolution 3D seabed surveys include side-scan sonar and multibeam echo sounders (MBES). Side-scan sonar systems differ from MBES systems in that their primary function is to produce acoustic images from the backscatter of the seafloor, rather than measuring depth.

These techniques produce results of high spatial resolution, repeatability and quantifiability, and can be seamlessly integrated with other scientific and terrestrial data. They have been used at specific sites, such as shipwrecks (Plets et al., 2011; Ferentinos et al., 2020) as well as over large areas of seabed to map ancient submerged landscapes of archaeological interest (Westley et al., 2011; Violante, 2018; Violante et al., 2023). Multibeam systems are currently key instruments for deep-water archaeologists (Warren et al., 2011), enabling the study of submerged archaeological sites that were previously inaccessible.

Acoustic remote sensing techniques for seabed survey aids the preservation of artefacts and landscapes in their original settings, with significant implications for archaeological conservation. Multibeam bathymetry and backscatter data have proven invaluable in studies of site formation, enabling analysis of the physical, biological and chemical processes influencing archaeological sites over time (Quinn, 2006). Their interpretation provide significant insights into the quantitative assessment of submerged cultural resource degradation and risk analysis.

As technology continues to evolve, marine sonar systems are increasingly refined, enabling detailed spatial investigations and interpretations of submerged archaeological features. Among the bathymetric systems, the latest generation of Ultra-High Resolution (UHR) multibeam echo-sounders (MBES) represent a major step forward for the documentation and monitoring of the Underwater Cultural Heritage (UCH). These systems integrates advanced acoustic array geometry, high-precision inertial navigation and positioning systems that can rapidly generate massive point clouds of millions of individual bathymetric measurements with unprecedented resolution and accuracy. These data can be effectively processed with 3D modelling techniques for implementation in advanced spatial data visualization platforms.

In this work we present the results of an ultra-high resolution (UHR) acoustic remote sensing survey based on multibeam bathymetry in the Baia submerged park (Southern Italy). This

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area is located within the Campi Flegrei caldera, a large active volcanic complex north of Naples characterized by vertical ground movements known as bradyseism. Due to this phenomena the ancient settlement of Baiae has been gradually flooded and many Roman artefacts, including thermal complexes, villas and harbour structures, are now submerged off the coast of the modern town of Baia. The main results include very detailed 3D reconstructions of underwater artifacts and the development of multiresolution models for interactive visualization of spatial bathymetric data.

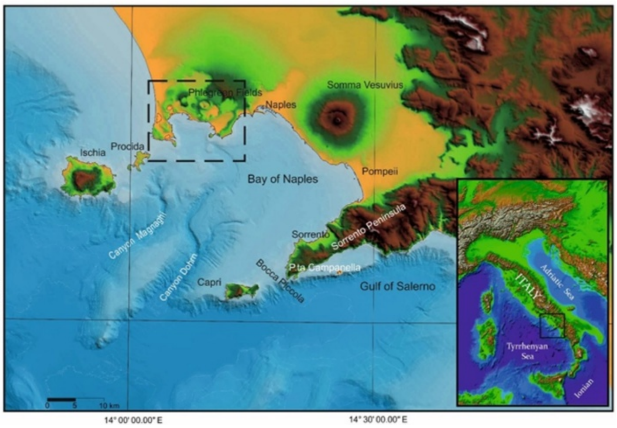

Figure 1. Location of the study area (dashed box).

2. Methods

2.1 Study area

The study area (Fig.1) is part of a large active volcanic complex, the Campi Flegrei caldera (De Natale et al, 2006), located north of Naples (southern Italy). The volcanic activity in this area leads to frequent earthquakes, hydrothermal manifestations, and vertical ground movements known as bradyseism. Evidence of volcanic activity in this region dates back 60,000 years BP (e.g., Rosi et al., 1983) with two catastrophic eruptions of the Campanian Ignimbrite (Fedele et al., 2003) and the Neapolitan Yellow Tuff (Deino et al., 2004) occurred 39 ka and BP15 ka respectively. Currently, the remnants of several small-scale volcanic edifices are present within the caldera perimeter. The most recent eruption occurred in 1538, following a quiescent period of approximately 3000 years, with the formation of a new volcanic structure, the Mt. Nuovo (D' Antonio et al., 1999). During this event, a seaward shift of the coastline by 200 m was documented.

Over millennia, bradyseism caused the submergence of extensive coastal sectors and has significantly altered the coastal landscape. Long-term ground movements with alternating phases of subsidence and uplift have led to both inland and seaward migrations of the coastline by several tens of meters. Bradyseism was first identified in the first half of the 18th century following the excavation of the so-called "Temple of Serapis," the remnants of a Roman market in Pozzuoli. Lyell (1850) interpreted the borings made by marine molluscs on its columns as indicative of the ground's submersion and subsequent emergence. These biological boreholes, now situated 7 m above sea level, serve as significant evidence of rapid sea-level fluctuations due to bradyseismic events at this location.

This study area is also characterized by seabed gas discharges. Approximately 1500 meters south of Pozzuoli, a hot vent (the Secca delle Fumose) is present, exhibiting thermal emissions (up to 93°C) that contain methane, sulphur dioxide, arsenic, and carbon dioxide (Vaselli et al., 2011).

The archaeological finds in the Campi Flegrei trace back to 770 BC, marking the establishment of the first Greek colony, Kime (Cuma). The city of Dicearchia, known today as Pozzuoli, was founded in 531 BC. Since that time, the presence of numerous thermal springs, a result of volcanic activity, along with its proximity to Rome, have drawn the Roman aristocracy during the late Republican period, leading to the rapid occupation of the entire coastal region.

The Roman city of Baiae was built on the shores of a volcanic coastal lake, known as the Baianus Lacus, which was linked to the sea by an artificial channel (Fig. 2). Several structures were constructed around the Baianus Lacus during the latter half of the 1st century BC, with their remains now partially visible along the coast, while most are submerged to a depth of approximately 15 meters off the modern settlement of Baia. Among the submerged structures are the Nymphaeum of Claudius, a thermal complex consisting of two buildings adjacent to the Nymphaeum, a large villa attributed to the Pisoni family, and the so-called Villa a Protiro (Scognamiglio, 1993). The Pisoni villa featured several rooms arranged in a rectangular layout, with the majority of the internal space dedicated to gardens and bordered by apses and columns. Sedimentary evidence indicates that the city of Baiae remained active until at least the end of the 4th century AD, when it began to decline due to the onset of bradyseism and the resulting flooding of large portions of the city (Pappalardo and Russo, 2001).

The Roman city of Baia was connected to the Portus Julius, the ancient port of Puteoli, by the Via Herculanea, a pathway approximately 1,300 m in length, which is currently submerged at depths between -8 and -5 m. Portus Julius was primarily situated within a larger coastal lagoon than the Baianus Lacus, the ancient Lucrinus Lacus, with some activities also taking place inland. Twenty-five years after its establishment, the port was relocated to the natural harbour of Miseno, south of Baiae, due to the gradual filling of the ancient Lucrino. Nevertheless, commercial operations at the harbour continued until the 4th century AD, when it began to become submerged due to a gradual increase in seafloor depth.

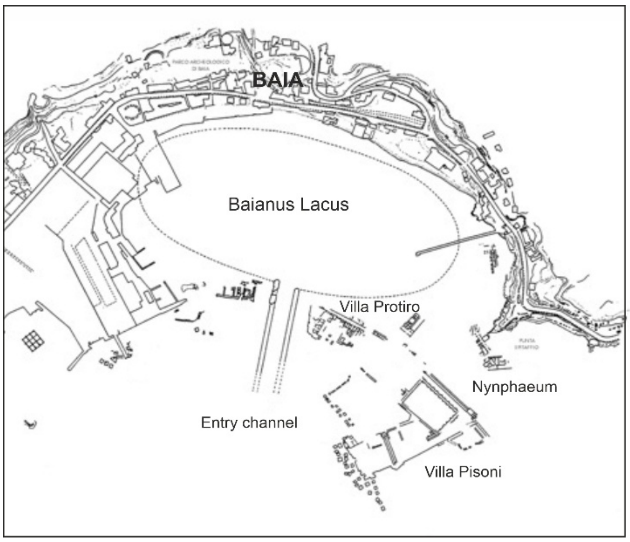

Figure 2. Archaeological map of the study area (modified from Scognamillo, 1993).

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2.2 Multibeam sonar

Multibeam Echo Sounder (MBES) systems utilize multiple narrow, adjacent acoustic beams arranged in a fan-like configuration to scan extensive areas of the seabed in a full-coverage survey mode. The system calculates the time of flight for each returning acoustic pulse as it travels between the vessel and the seafloor, thereby generating a digital elevation model (DEM) of the seafloor bathymetry.

MBES comprises a pair of linear acoustic arrays mounted orthogonally, consisting of transmitter and receiver elements (hydrophone) arranged in the shape of a cross, known as the Mill's cross (Hughes Clark, 2018). The transmitter (Tx) is usually aligned with the fore-aft axis of the vessel's bottom, while the receiver (Rx) is positioned athwartship.

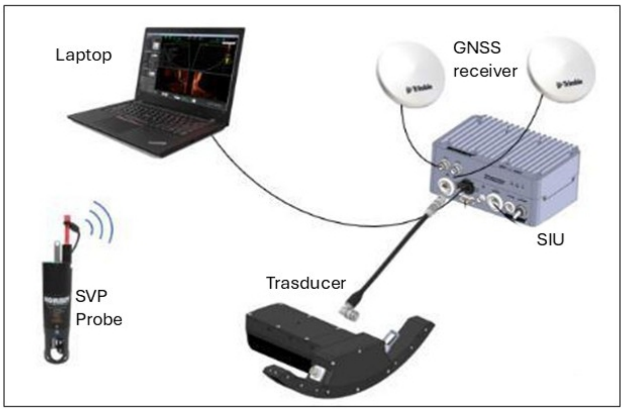

Figure 3. Components of the NORBIT i77h MBES

The dimensions of the transmitter are designed to emit a consistent acoustic pulse across the track (swath), illuminating a corridor with a narrow fore-aft beam (horizontal plane) and a broad cross-track beam (vertical plane). A composite electrical signal is generated using a beam steering technique by applying time or phase delays to hydrophone readings and summing them. This process enables multiple channels to be formed simultaneously on the receive transducer, each of which has its own relatively broad main lobe in the along-track direction (horizontal plane) and a relatively narrow main lobe in the cross-track direction (vertical plane). When the illumination pattern on the seafloor aligns with the reception pattern a series of small beam footprints are created. Depth measurements can be obtained within each footprint by utilising the imaging geometry (azimuth and incident angle of the beam) and correcting for the refracted ray path (i.e. the sound velocity profile, SVP). This configuration enables the detection of an echo, providing both range and bearing to the point in space where the echo originated.

2.3 Bathymetric data collection and processing

In the study area, a bathymetric survey was carried out with the NORBIT i77h multi-beam echosounder (MBES) that operates at frequencies of 400 kHz and 700 kHz (Violante et al. 2024). This system can measure depths from 0.5 m to about 300 m. With 1024 individual beams, each with a spatial resolution of 0.9° x 0.5°, this advanced MBES features ultra-high resolution sonar capabilities. It features electronic beam steering to facilitate mapping of vertical structures and shallow coastal areas, and is designed to cover an exceptionally wide swath of up to 210°. To ensure a high level of vertical accuracy, the data was acquired at a frequency of 400 kHz with the swath primarily limited to 150°. The system comprises three primary components: a curved transducer, a compact Sonar Interface Unit (SIU), and two GNSS receivers (Fig. 3). The integration of the navigation system with water depth measurements occurs within the sonar head, which houses a high-performance Inertial Measurement Unit (IMU) as part of the sonar motion unit, specifically the Applanix OceanMaster navigation system. This configuration facilitates precise georeferencing providing information regarding location, elevation, movement, and time synchronization. Additionally, the system is equipped to support RTK (Real Time Kinematic) corrections, ensuring centimeter-level accuracy in horizontal positioning. RTK corrections were sourced from online services in Italy, achieving positioning accuracy of approximately 2-4 cm in both horizontal and vertical dimensions. The GNSS antennas are spaced 2 meters apart, which guarantees a heading accuracy of 0.02°, while the IMU demonstrates an impressive accuracy of 0.01° for pitch and roll movements. Depth measurements are dynamically adjusted to account for boat movements and variations in water sound speed, enabling bathymetric measurements with an accuracy of 2 cm and a resolution of about 1 cm.

The sonar weighs 4kg underwater, allowing the sonar to be mounted on a small pole with a draft of 60 cm. Data acquisition was carried out using this side-mounted T-shaped pole attached to a rubber boat (Fig. 4). Adjustments were made to the survey lines to account for water depth conditions and to ensure overlap of bathymetric measurements between adjacent survey lines, given the relatively shallow nature of the survey area and the rocky coastline.

The QINSy (Quality Integrated Navigation System) software, developed by QPS (Quality Positioning Services), was utilized for the acquisition and processing of bathymetric data. The processing module of this software allows a comprehensive evaluation of the data through three basic steps: position correction, depth correction and statistical control. The processed and filtered bathymetric data were subsequently gridded to produce a highly detailed Digital Bathymetric Model (DBM) with a cell size of 0.1 meters.

Figure 4. MBES mounted on T-shaped pole attached to a rubber boat.

The UHR bathymetric data underwent further processing using a semi-automated methodology designed to extract seafloor archaeological features from other seabed components (Abate et al., 2024). This involved slight modifications to the AFE (Archaeological Feature Extraction) method (Masini et al., 2023), which is based on the principle of reducing input data prior to unsupervised classification. The methodology uses a combination of machine learning and statistical techniques to generate a vector map that identifies archaeological features in a semi-unsupervised way (Fig. 5).

The dense point cloud obtained from the UHR bathymetric survey also enabled the application of specialized algorithms to generate a 3D mesh model with centimetre-level resolution. The optimized 3D model was then exported and integrated into the Web3D platform ATON for interactive visualization. This is an open-source platform (Fanini et al., 2021) based on Node.js and Three.js, designed, developed, and coordinated by CNR ISPC to create Web3D/WebXR applications for interacting with cultural heritage objects and 3D scenes on the Web (https://osiris.itabc.cnr.it/aton/).

3. Preliminary results

Bathymetric investigations conducted using a multibeam echosounder with UHR performances have enabled the generation of exceptionally high-resolution thematic maps that depict the archaeological and geomorphological characteristics of the study area. The main results focus on the three-dimensional modelling of the seabed and the detailed mapping of underwater archaeological features, achieving an unprecedented level of detail (fig. 6).

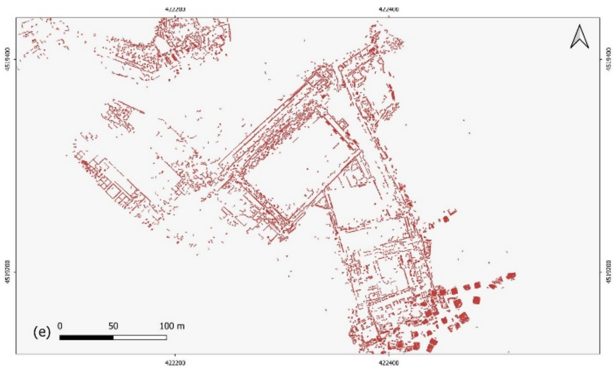

Figure 5. Archaeological map derived from UHR MBES data (modified from Abate et al., 2024).

The dense point cloud generated from the multibeam survey was processed utilizing advanced 3D modelling techniques for integration into spatial data visualization platforms, including web-based environments. This enabled the development of immersive installations aimed at enhancing communication and accessibility for the general public, which includes the production of 3D prints of the digital bathymetric model.

In particular, the post-processing of UHR bathymetric data was implemented using a semi-automatic Modified Automatic Feature Extraction (MAFE) method (Abate et al., 2024) to produce a vector map that delineates seabed features relevant to archaeology (see fig. 5). This methodology was conceived as a support tool for archaeologists, providing preliminary maps to inform subsequent investigations, while addressing potential unfamiliarity with advanced data types and visualization methods, rather than replacing expert interpretation.

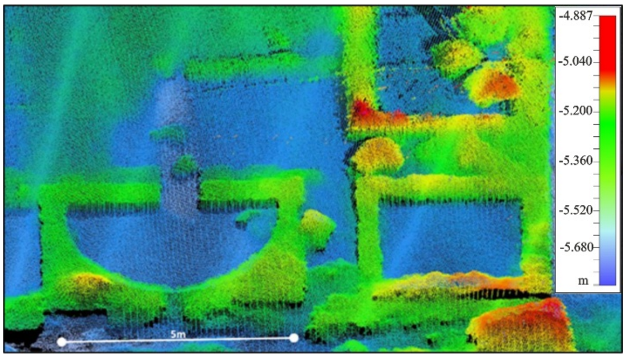

Figure 6. Remains of a thermal complex in the Baia submerged park. Point cloud from multibeam data. Color scale represents bathymetry.

Future developments include the implementation of the above methodological approach within the MOLAB (MObile LABoratory) platform of the European Research Infrastructure on Cultural Heritage Science (E-RIHS - www.erihs.eu), with the establishment of an open-access underwater acoustic remote sensing laboratory for researchers, scholars and professionals.

4. Potential for integrating UHR MBES bathymetry and optical methods

In underwater environment, light travels much shorter distances than sound waves due to significant attenuation by scattering and absorption as it passes through the water. This leads to a loss of information in low-light imaging. While light-based systems can provide very high resolution in clear water, they are greatly limited by the depth that can be mapped.

LiDAR systems and Structure-from-Motion (SfM) photogrammetry are among the most effective systems for 3D optical underwater mapping. These technologies can be used to generate bathymetric maps and orthomosaics of the seafloor with resolutions ranging from millimeters to centimeters under optimal conditions of water clarity, sea state and ambient lighting.

Airborne LiDAR technology has become a widespread methodology for conducting bathymetric measurements in shallow coastal and inland areas (Wehr and Lohr, 1999; Kandrot et al., 2022). When designed with both green and red laser sensors, LiDAR from drone allows for seamless mapping of both water and surrounding land in a single survey. It is therefore used in hydrography and the maritime cartography of coastal areas.
Compared to acoustic systems, this technology offers the advantage of acquiring topographic and bathymetric data providing dense and accurate measurements in transition zones that are challenging to cover using only shipborne or land-based methods. However, due to light attenuation in the water column, airborne LiDAR seabed scanning is typically limited to shallow water.

SfM is typically suited to the very high-resolution scanning of relatively small areas of seabed of natural and/or cultural interest. In underwater environments various image enhancement and restoration algorithms are typically required to compensate for optical degradation due to wavelength-dependent light absorption, chromatic aberration and dispersion (Marino et al., 2018; Wang et al., 2019). Furthermore, as photogrammetry alone cannot provide absolute positioning, additional sensor data must be integrated or an adequate spatial distribution of seafloor ground control points with surveyed coordinates has to be ensured in order to achieve georeferenced positioning and an accurate point cloud.

Compared to sonar and LiDAR bathymetry data, underwater photogrammetry has the advantage of producing highly detailed photographic textures while providing the highest resolution data on objects and structures. Such information can be used to identify benthic features and characteristics, as well as to recognize the surface conditions of underwater cultural objects, including damage and the characterization of sessile organisms. The integration of optical and acoustic mapping systems has been successfully employed for underwater archaeological prospections, and the 3D modelling and documentation of shipwrecks in shallow water (Kan et al., 2018; Prado et al., 2019; Wiseman et al., 2021; Solana Rubio et al., 2023).

In the case of the Baia submerged site, the shallow depths and the presence of archaeological remains along the coastline create optimal conditions for conducting optical-based surveys utilising LiDAR and photogrammetry techniques. Integrating photogrammetric data with the high-density measurements obtained from the UHR MBES survey presented in this study could further enhance the bathymetric dataset along selected transects of particular archaeological interest, producing ever-higher quality 3D models that incorporate colour imagery in the final products. Moreover, airborne LiDAR investigations could provide elevation data in areas of very shallow water not covered by MBES surveys, as well as along the adjacent land. This would enable the characterization and mapping of both cultural and natural resources throughout the coastal zone.

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