Acoustic remote sensing for seabed archaeology

Crescenzo Violante[1]

[1] *Institute of Science of Cultural Heritage, CNR, Via G. San Felice, 8, Naples, Italy, crescenzo.violante@cnr.it*

***Abstract* – In maritime archaeology, acoustic remote sensing technology has traditionally been used to locate and document inundated archaeological sites and shipwrecks. These methods are constantly evolving as technology advances, allowing for detailed spatial investigation and interpretation of submerged archaeological features. In the last decade, the advent of ultra-high resolution sonars has enabled to solve the three-dimensional (3-D) shape of submerged objects providing a valuable tool for recognizing and describing archaeological resources at the seabed.**

Remote sensing for seabed archaeology developed from sonar systems used in military applications and geological prospection. Modern echo sounders measure physical properties of the seafloor (mainly backscatter) and water depth by transmitting acoustic energy toward the bottom and detecting the arrival times and directions of the acoustic energy that returns from the bottom. Such approaches are rapid in terms of acquisition and provide results that are repeatable and quantifiable, although post-processing is often required to optimize the information.

I. INTRODUCTION

Underwater archaeology has long relied on technology to locate and document inundated archaeological sites or shipwrecks. Until the early 1990s, the majority of marine archaeo-geophysical survey was reconnaissance in nature [1], [2], [3], where the principal objective of the investigation was to locate an archaeological site close to navigational hazards or ports [1], [3], [4]. In the last decades, rapid advances in marine geophysical techniques have provided the maritime archaeological community with significant opportunities for re-defining the procedures for site mapping, evaluation and monitoring. The techniques that offer most potential for high-resolution survey include side-scan sonar and multibeam echo sounder (MBES). Side-scan sonar systems differ from MBES systems because their main purpose is to provide acoustic images from backscatter of the seafloor rather than measurements of depth. Since the beginning of the 21st century, several underwater archaeological projects employed these systems for site characterization and mapping [5], [6], [7], [8].

Multi-beam echo sounder can also deliver high resolution side-scan like images. MBES forms multiple acoustic beams across track at reception using digital beamforming techniques. For each direction, a temporal signal is obtained, and a detection algorithm is used to extract the time of the first echo reflected by the seabed. Samples inside a time window before and after the seabed time echo are also stored. These signals, called snippet, correspond to the amplitude signals reflected from the beam footprint.

Modern echo sounders cover a relatively large area from a safe distance above the target, while resolving the three-dimensional shape of the object with centimeter-level resolution. These techniques generates results that are of high spatial resolution, repeatable and quantifiable, and that can be easily integrated with other scientific and terrestrial data. They are employed as much on discrete sites, such as shipwrecks [9], [10], [11] as they are on large tracts of seabed in order to reconstruct ancient submerged landscapes of archaeological interest (Fig. 1) [8], [12], [13]

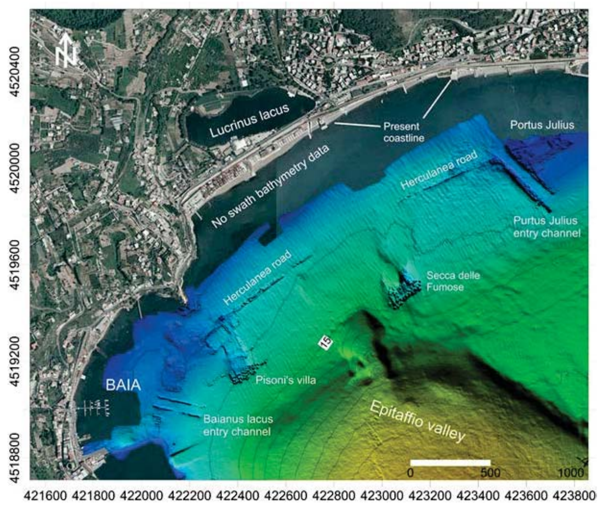

Fig. 1. Colored shaded relief map of the inundated Roman site of Baiae (southern Italy) obtained from high-resolution multibeam data, merged with aerial photograph and topography of the on-land areas [8].

Today, multibeam systems are a primary tool for deep water archaeologists [14]. Sonar technology has allowed to study submerged archeological sites not previously accessible, and its non-intrusive nature allow to preserve the artefacts and landscape sites in the context in which they are found with significant implications for archaeological conservation.

Multibeam bathymetry and backscatter data have been successfully used for studies on site formation, or how a site changes through time. These studies examine the physical, biological, and chemical processes impacting an archaeological site over time [15], [16] providing significant clues for quantitative assessment of submerged cultural resource degradation and risk analysis. Although acoustic systems will never completely replace diver surveys, they do provide baseline data at rates far exceeding those of experienced dive teams.

Marine geophysical techniques are usually complemented by Autonomous or Remotely Operated Vehicles (AUVs or ROVs) that provide ground truth inspections based on the maps produced from multibeam and side scan sonars. ROV systems properly equipped with high-resolution cameras have been also used to generate underwater 3D models of archaeological features based on structure-from-motion (SfM) photogrammetry [17], [18]. These models incorporate precise control points obtained from ultra-high resolution multibeam echosounding bathymetry that allowed for accurate positioning at depth [19].

The aim of this paper is to discuss the geophysical techniques (mainly multibeam and side-scan sonar systems) that are currently used for imaging archaeological features at the seabed. Sediment profiler systems designed to penetrate the seafloor also known as sub-bottom profilers (SBPs) are not discussed.

II. SONAR SYSTEMS

In underwater applications, sound waves are the most efficient means thanks to their long travel distance (up to kilometers) without significant attenuation. The level of attenuation depends on their frequency and is more important in the high frequency. While traveling, these waves carries a certain amount of acoustic energy and can be measured via their amplitude or their intensity (proportion to the squared of amplitude).

When an acoustic wave encounters a sudden change in the properties (specifically the product of sound speed and density) of the material in which it propagates a part of the acoustic wave will change its direction of propagation. As a result, as a sound wave encounters an interface between two different media with different impedance, it will be reflected, transmitted and scattered. The portion of the acoustic wave that reverses its propagation direction is the echo which echo sounders are designed to exploit for depth and seafloor backscatter strength.

Sonar systems are designed in a way to generate electrical signals that are converted to acoustic energy via a transducer thereby transmitting into the water column a pulse of acoustic energy at a particular frequency. The acoustic energy of the returning echoes is then converted into electrical energy via a receive transducer. Additionally, these systems require the ability to measure the arrival time of the returning echoes. The details of the transmit transducer, receive transducer, and the processing/ interpretation of the echo returns are what distinguishes a particular sonar as multibeam echo sounders (MBES) or side scan sonar (SSS).

Sonars may either be mounted to the hull of a vessel or incorporated into a tow fish. Side scan sonars are generally incorporated into a tow body, or in one of the types of sub-sea vehicles. However, when mounted to the hull of a small surface craft, side scan sonars are also capable of providing satisfactory imagery in water depths less than 20 meters [20].

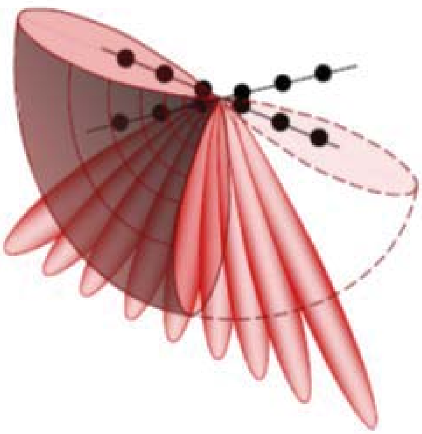

Fig. 2. 3D Beam patterns of both transmitter and receiver arrays arranged in a Mill's cross. Black dots are acoustic elements.

In order to identify which specific section of the seabed generated a particular echo, it is necessary to estimate the vertical and azimuthal angle of arrival of that echo. Sonar systems use groups of isotropic acoustic elements (acoustic arrays) to transmit non isotropic waves whose amplitude varies as a function of angular location, allowing projected pulses to have a degree of directivity. The characteristics of the main lobe and associated side lobes of a transmit/receive transducer depend on the actual frequency and physical size of the transducer (Fig. 2).

Element arrays of a sonar are constructed such that the transmit/receive transducers have negligible response in one hemisphere and finite response in the other hemisphere so that acoustic energy can be confined to a singular narrow angular sector. For this configuration, the detection of an echo provides both the range and bearing to the point in space where the echo was generated.

Measuring the local configuration of the seabed with acoustic survey systems is achieved by transmitting acoustic energy toward the bottom and detecting the arrival times and directions of the acoustic energy that returns from the bottom. The measured ranges and 3-dimensional directions to points where the echoes were generated are converted into 3-dimensional locations, relative to the transducer. Then the echo generation locations are transferred from the transducer frame of reference into the ship's frame of reference and finally into the appropriate reference frame for presenting the survey results.

Spatial resolution

For sonar data, resolution means the minimum distance by which two objects must be separated to be recorded as distinct entities. When measuring depth, the vertical resolution is of primary importance. In modern sonar systems, vertical resolution depends on the pulse length (bandwidth) and the transmitted beam width. Following the Nyquist theorem two objects must be separated by more than half the pulse duration (color band in Fig. 3 lower left) to be recorded distinctly, otherwise they will be recorded as a single object.

Higher frequencies typically result in shorter pulse lengths and greater vertical resolution. In hull-mounted systems, higher frequencies are commonly used for shallower waters, whereas lower frequencies are needed at increasing depths, with the subsequent reduction in vertical resolution.

The horizontal resolution of a sonar survey is governed by several factors that include the sampling density, the beam footprint and the mode of bottom detection (e.g. amplitude, phase). The sampling density correspond to the number of pings per unit area of the seafloor, which depends on the transmission method, vessel speed and ping rate. Modern sonar systems sample the digital returns at rates high enough to represent the signal accurately and therefore sampling should not limit the horizontal resolution. However, along-track sampling rates, which are determined by the ship speed and sonar firing rates, can limit the horizontal resolution and detection of targets on the seafloor. Moreover, beam footprints depend on the water depth and the wavelength, thus the achievable resolution of the system will degrade linearly with depth.

III. MULTIBEAM ECHO SOUNDER

Multibeam sonars are primarily designed to produce quantitative information about the water depths by measuring the acoustic time of flight to the seabed as a function of angle from nadir. Using trigonometric functions, the travel times are converted to a set of points, each with a vertical and horizontal coordinate, relative to the multibeam transducer (depth and position). Water depths are finally obtained by applying the speed of sound in the water column (i.e. the sound/ velocity profile; SVP). Because of the non-vertical measurement geometry, it is absolutely essential that full X-Y-Z inertial motion sensors be installed and operated on the survey platform along with the multibeam sonar.

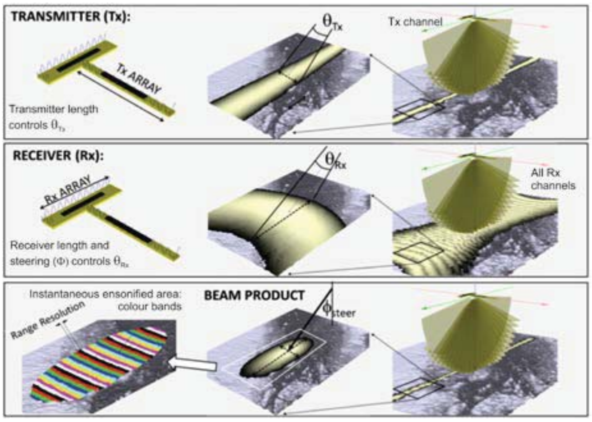

Fig. 3. Combination of the transmitter (Tx) and multiple receiver (Rx) beam footprints to generate multiple narrow beams across track. The projection of the two narrow axws of the Tx and Rx beams form a single elliptical footprint. Modified from [21].

A multibeam sonar consists of a pair of orthogonally mounted linear acoustic arrays of transmitter and receiver (hydrophones) acoustic elements (the Mill's cross; [21] see Fig. 2). The transmitter (Tx) is usually oriented along the fore-aft axis of the bottom of the vessel whereas the receiver (Rx) is mounted athwartship. The system may be broken into its transmit geometry and reception geometry (Fig. 3).

The width and length of the transmitter are such that a corridor across track is illuminated with the same acoustic transmit pulse (swath) that is narrow in the fore-aft direction (horizontal plane) and broad in the cross track direction (vertical plane). By applying time delays, or alternatively equivalent phase delays, to hydrophone readings and summing them to provide one composite electrical signal (beam steering technique; Fig. 2 and 4), multiple channels are simultaneously formed on receive transducer, each with its own main lobe that is relatively broad in the along-track direction (horizontal plane) and narrow in the cross-track direction (vertical plane). Where the illumination pattern on the seafloor is matched with the reception pattern, a series of small beam footprints are formed (Fig. 3). Within each of those footprints, using the imaging geometry (azimuth and incident angle of the beam) and correcting for the refracted ray path (i.e. the SVP), a depth measurement can be obtained.

Besides hydrographic quality depth data, MBES systems can provide high-resolution seafloor sonar images by acquiring the amplitude signals reflected from the beam footprint before and after the seabed time echo (footprint time-series/snippet). A snippet is a window of intensity values reflected from a beam's footprint on the seafloor, centered around the bottom detect point (Fig. 4) [22]. These values combined with the known bathymetry profile can be precisely compensated to compute absolute backscatter values versus incidence angle. By combining all of the snippet series from each beam, a full backscatter profile can be reconstructed for each swath.

IV. SIDE SCAN SONAR

Side-scan sonar systems allows obtaining backscatter images of the seafloor at high resolution rather than measurements of depth. These systems are usually towed at a short distance from the seafloor in a tow-fish, which keeps attenuation and spreading losses through the water column to a minimum [23], [24].

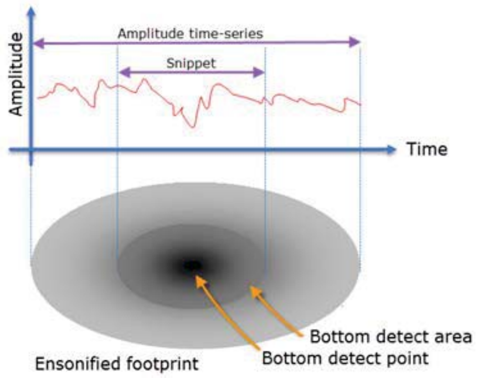

Fig. 4. Footprint time series (snippet) used for construction of backscatter profiles from MBES data. Modified from [22]

A side scan sonar insonifies the entire measurement swath with two simultaneously transmitetted acoustic pulses, one transmitted from a continuous line array transducer looking to port and one from a continuous line array transducer looking to starboard (side scan). The main lobe of the (port and starboard) transmit transducer is narrow in the along track direction (horizontal plane) and broad in the cross track direction (vertical plane). Conventional side scan sonars use the same transducer for receive and for transmit. This provides a high degree of confidence, but not an absolute guarantee that the echoes received by the side scan sonar originated from points that are located in the direction that the transducer is pointing.

The sound beams intersect the seafloor along a thin strip and use a very short pulse that spreads outward with time. As the survey vessel travels, the tow-fish transmits and listens to the echoes of a series of pulses. The echoes of each pulse are used to build up an amplitude versus time plot (or trace) for each side of the vessel recording a time series of backscatter of the seafloor along the swath. To adjust for the decline in the strength of echoes due to attenuation, a time-varying gain is applied to the amplitude values so that sea floor features with similar reflectivities have similar amplitudes. Each recorded reflectivity swath is geo-referenced and added to the previous swath. An image of the seafloor can therefore be generated by colour coding or grey shading the backscatter values (Fig. 5).

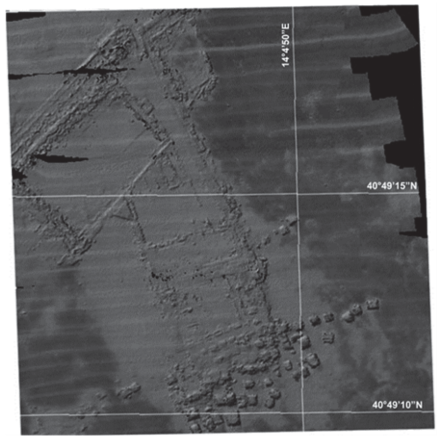

Fig. 5. Side-Scan backscatter image of the Villa dei Pisoni complex from the submerged Roman site of Baiae (Pozzuoli, southern Italy). Data courtesy of of Italian Ministry for Heritage and Cultural Activities.

The backscattered signal strength depend on the seafloor characteristics, which consist of both seafloor nature (material hardness) and seafloor interface (surface roughness). At high frequency, upon a few tens of kilohertz, only the first layer of the stratified seabed will contribute to the backscatter signal.

The strength of the scattering of the seafloor is characterized by the scattering cross section σ defined using equation (1) [25]. The scattered energy, proportion to mean-square scattered pressure $< |Ps|^2 >$, is proportional to the incident energy $|Pi|^2$ and the insonified surface *As*, and inversely proportional to the square of distance from the insonified seafloor to the measure point r^2_s.

$$< |p_s|^2 >= |p_i|^2 \, As\sigma \frac{1}{r_s^2} \quad (1)$$

In this equation, we notice the mean operator < . > in the scattered energy. This operator signifies an idealized average over the ensemble of individual scatters inside the insonified area (the footprint).

A major advantage of the side-scan sonar technique is the low incidence angle that enhances the generation of "shadows" behind areas of the seabed that distinctly rise above the surrounding area. The object shadow provides acoustic images that allow to discriminate with an high-level resolution manmade objects and other target that may lie on the surface of the seabed. This makes side-scan sonar systems particularly suitable for maritime archaeology investigations.

Because the side-scan sonar instrument uses two transducers directed away from each other, there will always be a narrow strip of the seafloor directly below the tow-fish (at the nadir) with no data. This strip will become wider as the distance of the tow-fish from the seafloor increases, but may be edited away at the interpretation stage to produce more accurate and better looking mosaics. The integrated arrivals at both sides and closest to the central strip with no data also provide an indication of the bathymetric profile along-course.

The resolution of a side-scan sonar system is difficult to quantify because it is inhomogeneous and varies along the ensonified swath both along- and across-track. If not compensated for, this results in elongated pixels with varying aspect ratios along each swath. However, modern side-scan sonar systems use electronic phase steering of the transducer elements in the array to focus the received signals from each part of the swath [24]. Heading variations in the tow-fish will turn the swath horizontally, causing geometrical problems. For the highest possible accuracy, these can be compensated for using ancillary navigation and motion-control devices.

V. CONCLUSIONS

Creating accurate maps and visualizing underwater sites is important for the future preservation, long-term study, and use of underwater archaeological resources. Seafloor bathymetry and 3D model archaeological features that can be obtained from MBES DEMs provide the primary record of the current state of the submerged archaeological sites and allow for the investigation of the site formation process, and the establishment of various measures for its future preservation and monitoring. Moreover, these approaches makes it possible to share information on submerged sites that are difficult to physically move or recover (i.e. shipwreck sites). These potential applications of acoustic remote sensing technologies to seabed archaeology are important for the management of sites that are currently known, and for the future assessment of sites that will continue to be found as climate changes and increased leisure activity puts pressure on the near-shore zone.

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