A REVIEW OF ACOUSTIC TECHNIQUES FOR HABITAT MAPPING

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Habitat mapping has become an increasingly important application of remote sensing. Active and passive acoustic techniques have greatly improved in the last decade, and their use extends into other spheres to show their economic, legal, political and environmental benefits. This paper reviews the current status of acoustic techniques for habitat mapping. Traditional techniques include echosounders, multibeam systems and sidescan sonars. Passive techniques are also presented, along with geoacoustic inversion and acoustic daylight imaging. The developments in new techniques such as non-linear acoustics, synthetic aperture and interferometry are reviewed. Some emerging techniques are showing increasing potential for habitat mapping, and bistatic sonar, parametric SAS and 3-D chirp profiling are briefly reviewed. Leading international programmes are now making use of these techniques, most often in combination, and their results inform the recommendations for future uses and desired technological developments.

INTRODUCTION

Habitat mapping is a term now commonly found in marine policy documents, at national and international levels, as well as in technical descriptions of efforts in a wide variety of settings. Habitat mapping is used for economic purposes, for example to assess viable resource exploitation areas; for environmental purposes, for example to assess the health of a particular ecosystem or the evolution after an environmental affect (either disasters, like oil spills, or intentional changes, like rerouting of shipping); for legal purposes, for example to define areas where fishing should be restricted or forbidden; and for many other uses, including recreational (e.g. use of pleasure craft in natural reserves). But the multitude of uses has spawned some confusion about what "habitat mapping" is exactly. If the definition of "mapping" is quite straightforward, it is still necessary to define what a "habitat" is. According to the *Oxford Dictionary of Science*, it is "the place in which an organism lives, which is characterised by its physical features or by the dominant plant type". The *New Oxford American Dictionary* defines it more widely as "the natural home or environment of an animal, plant or other organism". And the *Merriam-Webster Dictionary* defines it as "the place or environment where a plant or animal naturally or normally lives and grows". Habitat mapping can therefore be defined as the physical, complete description of a particular environment, both in space (seabed but also water column and sub-surface) and in time (e.g. through the tide cycles or the seasons). This description is not limited to the morphology or the species present, but can include parameters as varied as seabed type, salinity, currents, ecosystem variations or sub-surface geology. Marine habitats can cover all depths (Figure 1), particularly now that economic incentives (e.g. oil exploration) and national initiatives (e.g. EEZ mapping) move the focus to deeper waters, whereas the wider accessibility of mapping techniques allows access to very shallow water (e.g. surf zone, in-land waterways).

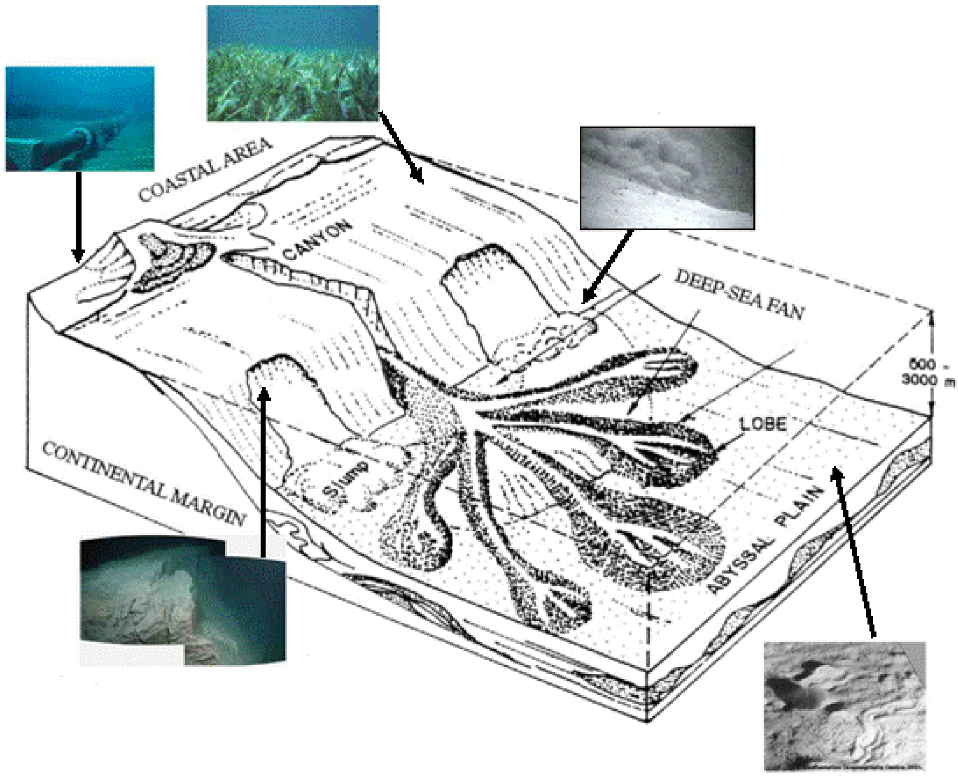

Figure 1. Acoustic techniques are the only way to map habitats from the surf zone to the abyssal plain.. Clockwise from top left: pipeline and seagrass in coastal areas; turbidite flow down the continental slope; *Spatangus raschi* sea urchin and burrowing path, 600 m deep (courtesy NOCS); fresh crack in a submarine canyon in a tsunami-generating area (courtesy JAMSTEC). The diversity of targets, depths and spatial scales emphasizes the need for different approaches to habitat mapping, tailored according to the objectives (e.g. survey area, survey speed, repeatability).

1. ESTABLISHED TECHNIQUES

Habitat mapping has existed long before the use of acoustic sensors. For example, mussel beds off Belgium were thoroughly mapped with lead-line soundings, grabs and visual observations at low tides in the late 19th Century (e.g. [1]). But the use and accuracy of habitat mapping only increased with the better accessibility and reliability of acoustic tools. Large-scale acoustic mapping of marine habitats started in the late 1970s throughout the world. Shortly before 1994-1996, collaborative research efforts of USGS, NOAA and other North American institutions led to the creation of national marine sanctuaries like Stellwagen Bank (e.g. [2]). Their approach decided to integrate biological and geological studies with sonar (sidescan and multibeam) imaging. These studies helped define the optimal range of tools necessary for habitat mapping on a range of scales, from the metre to the kilometre or more. Multibeam bathymetry is the main instrument, providing background topography and showing seabed features in relative detail. Sonar imagery can then provide indications of the types of materials on the seabed, in higher detail. And ground-truthing (using video, photo or in situ sampling) is generally conducted in more localised areas, collecting the data necessary for the final, interpretive maps of the seabed. Since then, marine habitat mapping studies have encompassed all depths (from tidal pools to the abyssal plains) and a variety of (sometime conflicting) objectives. Some surveys have focused on mapping large areas, even at the scale of a national coastline or continent (e.g. [3]). Other surveys have focused on the rapidity of data collection, for example in the case of military Rapid Environmental Assessment (e.g. [4]). And, for most of the modern environmental surveys, repeatability and time evolution have become key factors (e.g. [5]). Systematic reviews of habitat mapping techniques have all been keen however to emphasize that not one mapping system can quantify all required properties at the same time (e.g. [6,7]). Each system has its own advantages and limitations.

Single-beam, down-looking echosounders have long been the tool of choice for underwater habitat mapping, because they are simple to use and widespread on nearly all vessels. They transmit a single beam, oriented toward the ship's nadir. They generally use low-frequency signals (<20 kHz) transmitted in short pulses (< 2 ms). The first return from the seabed corresponds to points closest to the ship, and further as the cone spreads. Sub-surface penetration is often an issue in sedimentary areas, and so is overlying biota such as algae (e.g. [8,9]). Echosounders are not always calibrated, but often give a very good estimate of the depth and type of seabed. The shape of the echo can be analysed quantitatively (e.g. [10,11]) to derive more information about the local habitat. Innovative techniques were also developed to extract more information from the echoes of the secondary lobes (e.g. [12]). However, single-beam echosounders only provide information on the seabed immediately below the surveying vessel. The footprint on the seabed varies in size, depending on the water depth and the local slopes. Seafloor coverage is therefore highly variable and rather small.

Multibeam echosounders go one step further, by transmitting several narrow beams (up to 120 for some instruments) to cover a wide swath (up to 20 times the water depth in some cases) on each side of the ship. These instruments really became accessible in the late 1980s. These systems principally acquire bathymetry measurements for each beam, but, increasingly, backscatter strengths can also be derived from the individual measurements. Targets smaller than the footprint can now be resolved by some systems, using the "split aperture" method (picking of the zero-differential phase point). Multibeam echosounders have proved particularly attractive for the mapping of Exclusive Economic Zones. Because of the high standards of calibration usually attached to these systems (e.g. IHO-S44 for bathymetry), multibeam systems have proved particularly adapted to repeat surveys of near-shore areas. Processing is highly standardised, giving a good point of comparison between products from different systems. Knowledge of the local bathymetry, at each point where backscatter has been acquired, can be used to correct the imagery and represent it using the exact local incidence angles. Analysis of the imagery itself proves different from the sidescan sonar case, partly because the footprint on the seabed is generally much larger (100 m compared to a few metres), partly because of the difference in frequency and beam widths.

Sidescan sonars cover a much larger portion of the seabed away from the surveying vessel, from a few tens of metres to 60 km or more. This coverage is attained by transmitting two beams (broad in the vertical plane and narrow in the horizontal plane), one beam on each side. Using different frequencies (from 6.5 kHz to 675 kHz or higher), sidescan sonars achieve resolutions of 60 m down to 1 cm. The processing steps are less standardised, depending on the manufacturer, despite the consensus on the types of corrections desirable (e.g. [13]). Sidescan sonar imagery usually shows a "finer" resolution than multibeam imagery, as it is affected, in decreasing order of importance, by the local imaging angle, the surface and volume characteristics of the seabed.

Sub-surface penetration from sidescan sonars is not always well known, and usually only through experience with distinct systems (cf. the examples shown in [13]).

These instruments are generally used in combination. Multibeam echosounders give a general bathymetric map of the habitat. Shaded-relief topography shows seabed features in great detail, and backscatter imagery provides a "broad-brush" indication of the types of materials that constitute the seabed. This image is then "refined" with sidescan sonar imagery, which shows smaller features, generally at a higher frequency. Single-beam echosounder measurements, aligned along the track of the surveying vessel, provide point information about the immediate sub-surface (or, in some cases, the overlaying vegetation cover). These instruments are complementary: echo-sounder data can for example be used in the processing of the multibeam bathymetry, and multibeam bathymetry for sidescan sonar corrections. [1] and [9] show typical examples in a coastal area and in an Arctic fjord, respectively, where the different instruments are fully complementary and their measurements need to be interpreted together.

Because the amounts of data generated by these systems are usually very high, the compilation of interpretive maps showing seabed environments and habitats also requires the development of a computer-based sea floor classification system. An ideal system should cut the interpretation time and assist the human interpreter by providing insights into the acoustic patterns revealed by the different mapping tools. Geographic Information Systems can answer specific queries (e.g. health of seabed biotopes compared to prevailing currents and depth). The additional use of data-mining techniques can also reveal less obvious relations. Acoustic Ground Discrimination Systems (AGDS) can be a basis for comparing, managing, and researching characteristic areas of the seabed. Several solutions are available commercially (e.g. RoxAnn, QTC, GeoTexture) or academically (e.g. TexAn) (see [14] for a more complete review of seabed classification systems).

2. PASSIVE ACOUSTICS

The instruments presented in Section 1 are all active sensors, transmitting sound into the water and analysing its backscatter. But ambient noise can also be successfully used to map seabed habitats in general. Through its spectral characteristics and its time-domain evolution, ambient noise can be attributed to different sources (e.g. [15]). At the sea surface, shipping, weather processes (e.g. rain, wind, waves, thunder) and ice all have specific frequency characteristics (e.g. [16]). Deeper in the sea, marine mammals have distinct vocalisation patterns (e.g. [17]) and fish, as well as the famous "snapping shrimps" contribute significantly to the background noise (e.g. [18]). Like shipping, wind farms and deep-sea mining also add to the ambient noise. Finally, current-induced movements of sediments or vegetation on the seabed can also create noticeable acoustic noise (e.g. [19. 20]). All these changes contribute to the assessment of the marine habitat and its evolution. For example, [17] relate increased ambient noise to climate changes, whereas [18] identify environmental effects of anthropogenic activities on fish behaviour. Inversion techniques can be used to identify the geoacoustic properties of the seabed. This field benefits from an important body of scientific literature, including theory and experiments (e.g. [21,22]). Sources of opportunity such as surface noise, ships and marine mammals can also be used to great effect (e.g. [23]). In specific settings, "acoustic daylight imaging" to image objects on the seabed from their scattering of ambient noise on a large number of nearby receivers (e.g. [24,25,26]).

3. NEW APPROACHES

The instruments and approaches presented in Sections 1 and 2 are well established and have been the subject of many validation studies in different contexts of habitat mapping (e.g. [6,27]). They have often been adapted over the years to provide more information. For example, sub-bottom profilers work on the same principle as single-beam depth sounders, but are purposefully designed to get information from below the seabed. Recent improvements include the use of parametric sub-bottom profilers. They are based on the non-linear interaction of two high-frequency plane waves in the near-field (e.g. [28]). The two primary waves interact and thereby generate a sum and a difference frequency component. The difference frequency will be a low frequency secondary wave, if the two primary frequencies are almost equal. This will experience a low absorption and a narrow beam width. The TOPAS system is based upon this principle. The interaction with the seabed and the immediate sub-surface are well known, from controlled laboratory experiments (e.g. [29]) and validation at sea. Groups of parametric arrays can also be placed in very close proximity to the seabed to provide detailed measurements of its properties and the health of local habitats (e.g. [30]). Although the latter technique is limited to very local coverage, it can be used in key locations to validate more regional measurements.

Interferometric sonars provide bathymetry at the same resolution as the sidescan sonar imagery. Interferometric sonar records a time series of relative phase on several receiving transducer staves (e.g. 4 for the GeoSwath system). Each of the receiving staves records a time series of the ensonified area. The amplitude of the times series is used to determine the relative phase and phase difference between the four staves. The time from transmitting to receiving is used to determine the distance to the scatter location. Multiple staves ensure that the angular measurement and the overall phase resolution are measured with high precision. By receiving the acoustic signal on a pair of acoustic transducers, both range and phase measurements can be made [31]. The range and the phase angle pair enable us to determine the location of the ensonified seabed patch relative to the sonar transducer. Automatic and reliable phase-unwrapping still proves a problem in difficult terrains, despite its obvious advantages.

A limitation of both sidescan and interferometric sonars is their poorer spatial resolution parallel to the length of the acoustic arrays, varying along the full operational range (e.g. [32]). Narrowing the beam pattern by increasing the array length is not a satisfying solution, as it could lead to extremely long (and unwieldy) antennas. The same problem exists with airborne or satellite radars. Synthetic-Aperture Sonars are based on the same technique as Synthetic-Aperture Radars, and aim at addressing these limitations in a similar way. The basic principle is to record the signals received on a short ("physical") array as it proceeds along the track. The signals can then be combined to create an artificial ("synthetic") array independent of the physical length, only by post-processing the signals recorded [32]. The main challenge is the precise navigation of the surveying platform, as even changes small for other types of sonar surveys would preclude the formation of a synthetic array. This need for very high accuracy (typically better than 1/8 of the imaging wavelength) seems at the moment to preclude the easy use of synthetic aperture on Autonomous Underwater Vehicles. Amongst the few commercial systems available, one example is Shadows, a 100-kHz SAS capable of resolving targets of 15 cm at a maximum range of 300 m [33]. Similar results were obtained with the Kiwi-SAS experimental system by [34]. Recent developments in the field have been summarised in an extensive review by [35].

4. EMERGING TECHNIQUES

The ongoing developments of AUVs and UUVs were brought to profit by driving the investigation of other imaging geometries, in which the transmitter is physically decoupled from the receiver. These geometries are known as bistatic (for one receiver) and multistatic (for several receivers). Theoretical and experimental studies (e.g. [36,37]) have shown all the benefits in detection/characterisation that could be attained by looking at several directions, in particular away from the main beam. Examples of the application of multistatic sonars can be found in the articles in [38] and [39] *inter alia*. Two of the main challenges now facing multistatic sonars are the link with theoretical models of bistatic scattering, to gain a truly quantitative understanding of what the measurements represent, and the design of an easy way to submit these results to the practitioners and end-users (e.g. biologists) of habitat mapping.

A very recent development is the Parametric Synthetic-aperture Sidescan Sonar (PSSS), which aims at combining the advantages of a parametric source and of synthetic aperture processing (e.g. Zakharia and Dybedal, in [39]). Parametric and synthetic aperture sonar techniques are commonly considered as competing, as they both aim to obtain "virtual" low frequency arrays with a small angular aperture. The former is commonly associated to an echosounder-like geometry and the latter to a sidescan sonar configuration. Zakharia and Dybedal (in [39]) showed it was possible to use both simultaneously. They built a prototype Parametric Synthetic-aperture Sidescan Sonar (PSSS). Its architecture made use of the narrow beam of the parametric generation and complemented it with synthetic processing to improve the azimuthal resolution and maintain it constant with range (dynamic focusing). The SITAR PSSS was designed for resolving and detecting small, buried objects with dimensions down to 0.2 meters. The along-track beamwidths are 0.7° for the primary 100 kHz signal and 1.4° for the secondary 20 kHz signal. Synthetic processing of both primary and secondary bandwidths led to 3 different images for each frequency band. It was validated in experimental conditions in a submarine pen (with known targets) and at sea [39].

Techniques inspired from 3-D seismic surveying have shown their worth for large-scale mapping of marine habitats and their sub-surface (e.g. [40]). Similar techniques have been used to high effect with high-resolution acoustic measurements in shallow-water (e.g. [41]) and are now investigated for smaller-scale surveying. [42] show for example how chirp sub-bottom profilers can be used to produce 3-D images of the sub-seabed with decimetric resolutions. In their particular application, 4 profilers and 60 receiver elements can provide true 3-D imaging of the top 20 cm of the seabed.

Other emerging techniques include the adaptation of time-reversal techniques (e.g. [43]) to deduce the 3-D structure of sedimentary seabeds and their immediate sub-surface [44]. Finally, one should mention the pioneering work of [45] and [46] in measuring the acoustic variations of algae with time, as this can have important implications to small-scale, repeat mapping of shallow-water biota.

5. CONCLUSIONS

This short paper intended to review both traditional and emerging acoustic techniques for habitat mapping. It is impossible to do justice to the high amount of scientific literature devoted to the subject, either by acousticians or by end-users. Space limitations have also meant that the use of upward-looking sonars (including ADCPs: Acoustic Doppler Current Profilers) could not be presented. Direct measurements of the water column are an important part of habitat mapping and worth a review of their own, in particular because of the latest developments in mapping very small objects like plankton or detecting very small changes in the environmental parameters (e.g. [47]).

However rapid, this review showed there has been much progress in the last years, with a better integration of acoustic techniques with intended deliverables. This is particularly visible with the blossoming of successful European research programmes such as MESH (Development of a framework for Mapping European Seabed Habitats), HERMES (Hotspot Ecosystem Research on the Margins of European Seas) or BONUS (Baltic Organisations' Network for Funding Science), to cite but a few.

Several key issues are still being addressed, namely: developments in the new technologies (how can we measure this particular process? how can we adapt this promising technique to habitat mapping?), developments in their use by non-acousticians (e.g. increasing demand for calibration of sidescan sonars), advances in data interpretation (what are we actually measuring? how can this guide and further the analyses?), refinements in Acoustic Ground Discrimination Systems (and their parallels for non-sonar acoustic techniques), and finally the synergy between tools (what are the optimal tools to delineate and monitor this or that type of habitat?).

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