Chapter 2
Imaging of the Near-Surface

Abstract Acoustic sounding of the seabed and its immediate sub-surface produces different types of returns, based on aspect, roughness and physical characteristics of the different targets. This is presented within both seismic (low frequencies) and sonar (high frequencies) contexts. Both authors describe their own studies in controlled laboratory environments and at sea, contrasting larger-scale benthic habitats with lower-scale buried targets. The key results are then compared with existing research in acoustic Computed Tomography. Each example builds up to a set of recommendations, about the source(s) and signals; about the receivers and their spacing; about the hardware (constrained by the harsh realities of underwater environments); and about the requirements of bespoke signal processing drawing on a large range of independent techniques. The relative merits of standard projectors and parametric arrays are discussed and the important roles of acoustic attenuation within the seabed and non-specular returns are introduced.

Keywords High-frequency · Low-frequency · Broadband · Parametric arrays · Computed Tomography

2.1 Capturing the Relevant Characteristics of Near-Surface Sediments

The field examples in Chap. 1 highlight the important types of information provided by existing techniques, namely borehole, CPT, surface sampling and acoustic mapping with multibeam and/or sidescan sonars. These examples also show their limits in capturing sub-surface characteristics with a good enough resolution and a wide enough area/volume coverage. Acoustic techniques seem a promising approach (Sect. 1.4) but acoustic returns from the seabed and layers/objects below its surface will be complex, even more so by combining measurements at different frequencies, different horizontal resolutions and different vertical resolutions (with frequency-dependent attenuation). "Traditional" (i.e. sonar) data will therefore

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require bespoke processing and interpretation techniques. The solutions chosen are part of a rich field of possible approaches, detailed *inter alia* in Blondel (2009) and Montereale Gavazzi et al. (2016), but not discussed here for the sake of brevity.

The physical and geological characteristics modulating acoustic returns from the seabed are now pretty well understood, depending on the frequencies used and the imaging mode (monostatic, where the same platform is used to transmit sound and measure its backscatter along the same line of sight, as opposed to multi-angle, or multistatic, where the sound source and receivers are physically decoupled). Large-scale sonar approaches are highlighted in, for example, Blondel (2009) for sidescan and Blondel (2012) for multibeam. Multi-static approaches to sonar imaging of buried waste is also presented in Blondel and Caiti (2007). Research from the last decades has identified the main factors in sediment acoustics, in particular with the seminal SAX'99 and SAX'04 programmes in the US (e.g. Thorsos et al. 2005). Local topography, roughness and physical make-up all modulate the acoustic returns in predictable ways (Fig. 2.1). These principles are used in habitat mapping (e.g. Kenny et al. 2003), in site investigations before developments (e.g. OSIG 2014) and in similar activities.

Acoustic attenuation varies with sediment type and layer thickness. Not knowing *a priori* values, it is often determined with the spectral ratio method. Because it uses the geometric spreading of the sound waves as they travel through sediments, it relies on accurate knowledge of the beam patterns at different frequencies. Guigné et al. (1989a, b) showed the short and narrow-beam signals enabled by parametric arrays had the right characteristics to investigate variations in different sand layers, in a laboratory setting. This resulted in an adaptive determination procedure, further validated in the field, which provides an exact model of sound velocities in unknown seabeds.

Seabed surfaces are not always pristine geological environments. They are often affected and reworked by marine life (e.g. coral reefs, burrows) and anthropogenic activities (dumped objects or surface constructions, drill cuttings, trawling). Large-scale structures such as carbonates or corals are easily identified at the surface with sonar and conventional seismics (e.g. Hovland 2008). Pipe-lines, cables or well-heads are most often proud above the surface but sometimes buried, through sedimentation or as protection from trawling. Signatures of marine life can also be much more subtle (Fig. 2.2) but still contribute significantly to acoustic returns from different directions, especially if extending over large areas and at depth. Although dumping is generally prohibited, 6.4 Mt of marine litter are deposited every year (UNEP 2005). Legacy waste will also affect returns from the seabed and immediate sub-surface, e.g. toxic buried waste (Blondel and Caiti 2007) or oil spills (Parthiot et al. 2004; Medialdea et al. 2008). In areas of industrial activity, cuttings (solid materials from the well bore) will generally smooth the seabed's surface. Their disposal is stringently regulated and like drilling fluids, they require proof that vulnerable marine species or resources are not harmed (e.g. Storeng et al. 2009). In other places, previous dredging or scouring around structures will change the

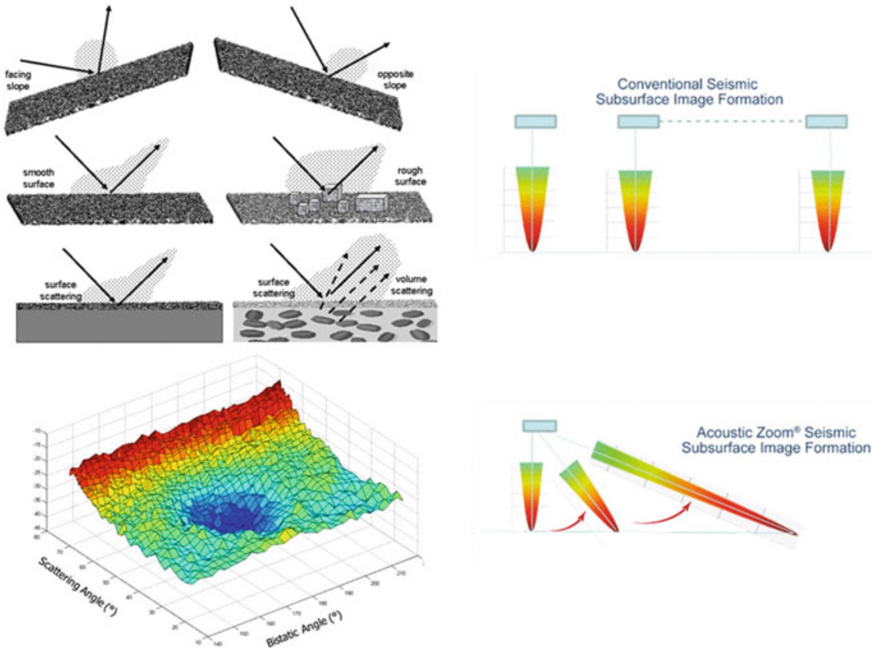

Fig. 2.1 Comparison of high- and low-frequency imaging at different angles. *Top left*, from Blondel (2009): acoustic scattering will be influenced by the relative slope of the surface or object of interest (with most of the energy scattering in the specular direction), by the roughness of the target relative to the imaging wavelength (rougher surfaces presenting more facets likely to scatter the energy in non-specular directions) and by the presence of heterogeneities (surface vs. volume scattering). *Top right*, from Guigné et al. (2014): similarly, conventional seismic imaging will use only the specular returns from horizons and discontinuities, if large enough relative to the imaging wavelength(s). *Bottom left*, from Howey and Blondel (2008): differences between the scattering expected at specific angles and the scattering actually measured can reveal buried targets. *Bottom right*: the multi-angle technique designed by Guigné (1986) makes use of all possible returns, revealing non-specular and diffuse scatterers

geotechnical characteristics of the surface (e.g. Wienberg and Bartholomä 2005). Correctly understanding the exact characteristics of near-surface sediments can therefore be challenging. It is also associated with very high costs. Clean-up costs from marine litter are for example ranging in the millions of USD (UNEP 2005). Benthic environmental surveys are now integral parts of assessments and consenting before offshore installations, and are estimated to cost around USD 0.75 M for a typical 500-MW wind farm (Crown Estate 2010). It is therefore important to "get it right", achieving the best accuracy and the best repeatability.

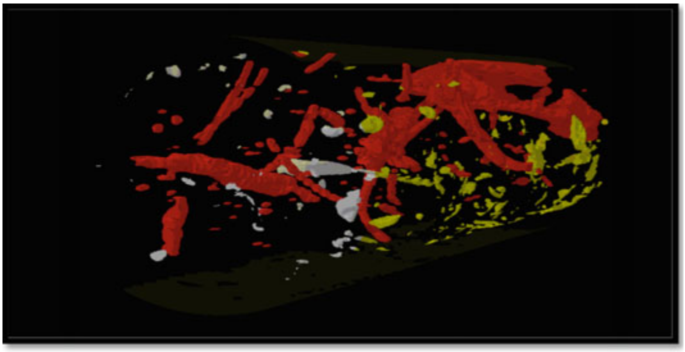

Fig. 2.2 X-ray CT scan of a horizontal core from a coastal seabed near Venera Azzura (Italy). The volume imaged (10 × 10 × 22 cm) matches the width of a borehole or the area of a high-resolution sonar pixel. Shell pieces (*yellow*), small rocks (*grey*), animal burrows and water pockets (both in *red*) penetrate the sediment (transparent) and contribute in different ways to high-frequency volume scattering. From Pouliquen et al. (2001)

2.2 Buried Objects and Benthic Habitats

To image the fine details and stratigraphy of the immediate sub-surface, acoustic instruments will require high frequencies, short pulses and ideally a broad bandwidth. Parametric arrays are ideally suited because of their very fine beam patterns and broad bandwidth signals (using the interaction between non-linear acoustic waves, they produce a set of primary and secondary frequencies).

One example of this approach is the use of bistatic sonars for the detection and identification of buried waste (Blondel and Caiti 2007). This was conducted as part of the European project SITAR ("Seafloor Imaging and Toxicity Assessment of Risks caused by buried waste"), and the approach was tested in the laboratory and validated over a known dumpsite in the Stockholm Archipelago (Blondel and Pace 2009). Conducted in shallow water and using a parametric array, decoupled from a hydrophone chain further away (Fig. 2.3), these tests allowed the careful exploration of the optimal geometries for imaging strong returns associated to man-made targets, of the size of oil drums and often with metallic walls. In this case, the TOPAS-120 parametric sonar transmitted primary frequencies centred on 120 kHz and generated secondary frequencies within the low frequency band 2–30 kHz. Repeat signals were stacked to decrease the signal-to-noise ratio, enabling detection of milllimetric details from up to tens of metres away. These experiments highlighted several important issues. In shallow water, or close to the intended target, the need to transmit short pulses directly limits the size of the scattering patch, and in some cases, sidelobes will contribute significantly to the overall scattering strengths. Transmitter and receiver acquisition need to be very accurately synchronised and positioned respective to each other. These experiments also showed the necessity to move receivers away from the strong reflectors. Other work (e.g. Schmidt et al. 1998) showed the role of recording

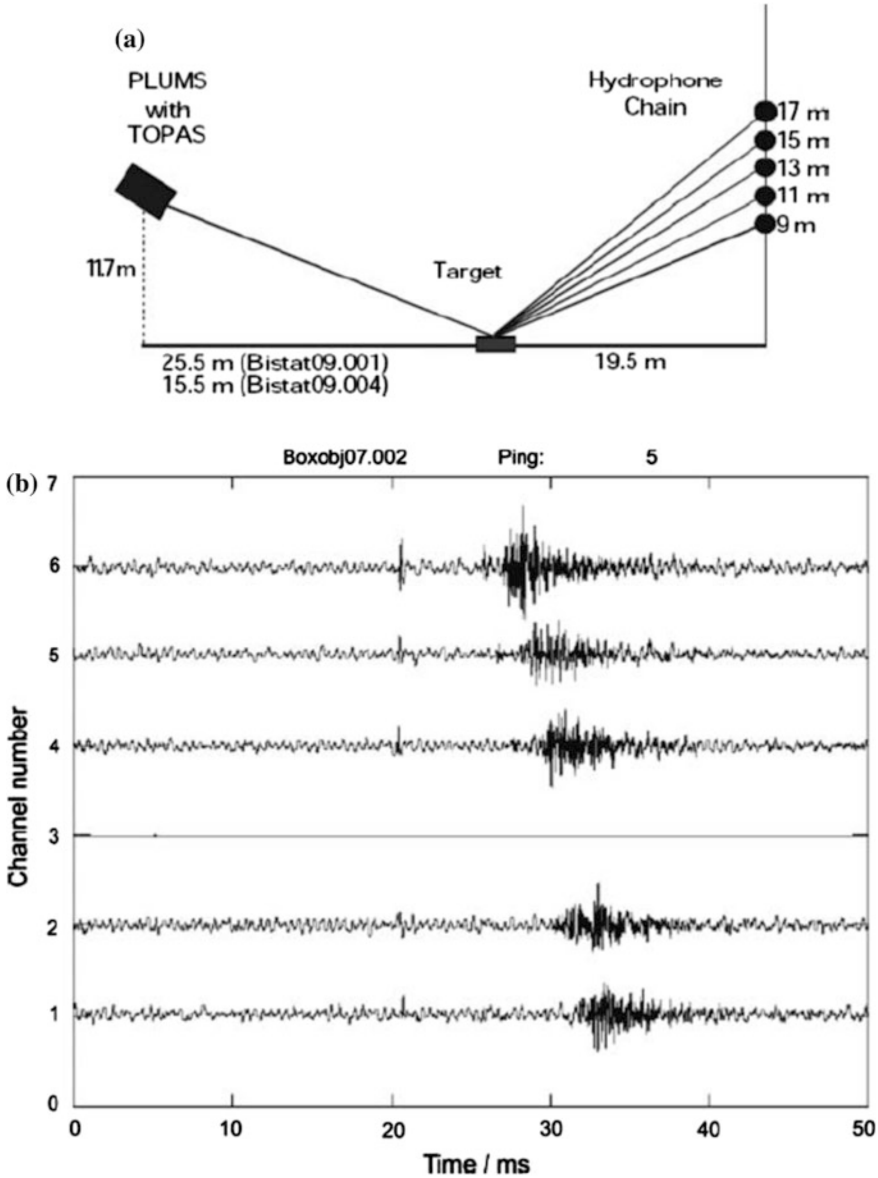

Fig. 2.3 Bistatic sonar setup: **a** the parametric array is positioned on an ROV, pointing at a target of interest, and the signal is recorded on a chain of receiving hydrophones; **b** each signal will carry distinct information, enabling reconstruction of scattering from below the surface (down to 10–20 cm) and from inside the target, highlighting toxic waste even if buried. From Blondel and Pace (2009)

at very distinct locations, for example by positioning receivers on moving AUVs. From a deployment perspective, the need to use several platforms at once makes this method more expensive and potentially more time-consuming.

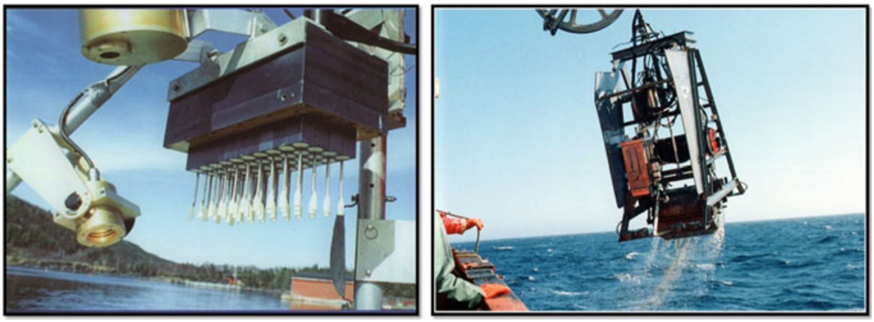

Fig. 2.4 *Left*: Details of the camera and 4 rows of transmitters (*circles* flush with the *black* face), next to the receivers (*white*-tipped probes). *Right*: for deployments, the instrument was combined with a frame grabber to directly sample seabeds of interest

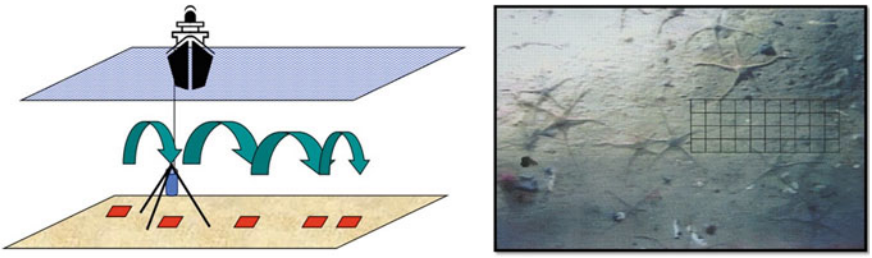

Fig. 2.5 *Left*: Sampling strategy, with a sequential transmit/receive script executed in seconds for each of the 40 positions, with hundreds of locally distributed soundings, giving a statistically significant series of measurements in the region of interest. *Right*: example camera picture, showing ground truth and the exact location of each area further sampled with acoustics (*black rectangles*, encompassing approximately 12 × 30 cm on the seabed)

A related approach by Guigné and co-workers (Schwinghamer et al. 1996) had been used slightly earlier to image the fabric and texture of benthic habitats, applying it to the environmentally sensitive Grand Banks area offshore Eastern Canada (Schwinghamer et al. 1996, 1998). In this case, the targets were much more subtle, akin to those presented in Fig. 2.2. The challenge in this case was to acquire information at high enough resolution (mm-sized voxels) to map potential habitats over large areas. Designed by the lead author, Benthic-DRUMS™[1] combined 4 rows of 10 independent, high-frequency, broadband parametric transducers, with co-located receivers (Fig. 2.4, left). This complex acoustic instrument was positioned in the same frame as a grab sampler with a camera (Fig. 2.4, right). To cover large areas of seabed in reasonable times, despite the varying water depths, a "leap-frog" sampling strategy was adapted (Fig. 2.5, left). The Benthic-DRUMS

[1]Dynamically Responding Underwater Matrix Sonar.

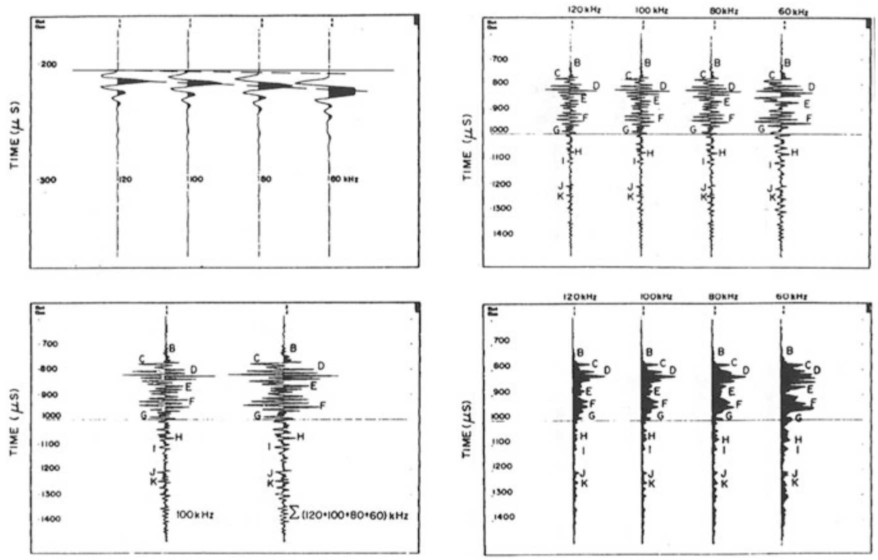

Fig. 2.6 Example data from a single transducer (from Guigné et al. 1991). *Top left*: dispersion test of the water column, for frequencies of 120, 100, 80 and 60 kHz (from *left* to *right*). *Top right*: acoustic returns from the seabed at the test site. *Bottom left*: frequency summation, highlighting different fine-scale stratigraphy levels (*B* to *K*). *Bottom right*: instantaneous amplitudes for the 4 different frequencies

was deployed from a cable over the side of the ship, taking a picture of the "ground truth" with accurate localisation of where the 40 detailed acoustic measurements come from (Fig. 2.5, right) and offering the potential to sample the seabed in locations of interest.

First tests in Hamilton Harbour, Ontario (Canada) showed the potential of the frequencies used (60–120 kHz) to delineate fine seabed stratigraphy (Fig. 2.6). As with the previous approach, stacking greatly increases the signal-to-noise ratio. Here, though, stacking was also used with different secondary frequencies, as recommended by Guigné et al. (1991). Hilbert transforms of the individual signals provide their envelopes (Fig. 2.7), and the derivation of each waveform's fractal dimensions measures its irregularity and roughness, using a modified box-counting method described in Schwinghamer et al. (1996). Combined with returns from 40 transducers at each sampling location, this technique provides cross-verification of measurements over very small spatial scales (Fig. 2.5, right), and allows for rigorous statistical treatment of returns from each transducer and their variations.

The instrument and the signal processing methodology were tested extensively during a 3-year experiment on the effects of otter trawling on benthic habitats on a sandy-bottom ecosystem from the Grand Banks area offshore Newfoundland (Schwinghamer et al. 1998). Each year, corridors 13 km long were trawled 12 times, over widths of 120–150 m, each year from 1993 to 1995. Acoustic measurements were taken before and after trawling, to document its effects and quantify sub-seabed

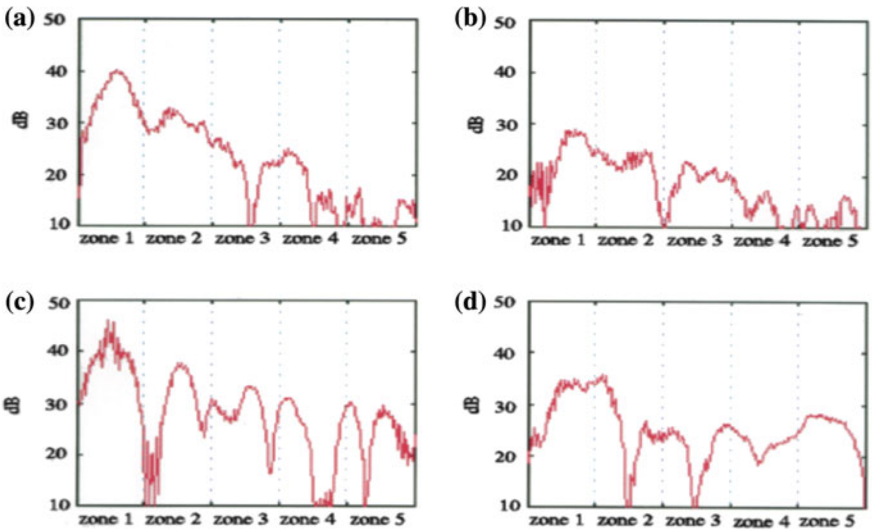

Fig. 2.7 Hilbert-transformed acoustic returns, for one transducer. They show the comparison between untrawled control areas (*left*, plots *A* and *C*) and trawled areas (*right*, plots *B* and *D*). Five depth zones are delimited each time (here, for the same intervals in time and for the upper 4.5 cm of sediments). Signal levels vary between and within zones, giving access to a very fine stratigraphy. From Schwinghamer et al. (1996)

changes (e.g. ecosystem recovery from year to year). The field data included systematic, high-frequency sidescan sonar surveys, to describe the surficial sediments. In 1995, the RoxAnn™ acoustic bottom classification system was also used. These two instruments were thoroughly compared with Benthic-DRUMS in 1994 and 1995. RoxAnn results, gathered with a footprint of 200 m^2, were mixed and sometimes contradicting the video evidence. Conversely, Benthic-DRUMS measurements were consistent with the video evidence, with the sidescan sonar imagery and with the many seabed samples (Schwinghamer et al. 1998), providing relevant high-resolution benthic information over the first 4.5 cm of sediments over very fine footprints. Typical results for a trawled area and a control area are shown in Fig. 2.8. This approach was assessed independently and is now recommended by the UN Food and Agriculture Organization (FAO) (Løkkeborg 2005) *inter alia*.

Similar challenges have been encountered in Computed Tomography, used for example with X-ray imaging of the human body. This typically uses tens of thousands of very closely spaced sensors, reconstructing 3-D and 2-D images from thousands of different projections. But how easy would it be to translate this approach to underwater environments, and buried objects? Acoustic Computed Tomography has been tested by many authors, including Younis et al. (2002) who investigated the imaging of shallow buried objects in a laboratory setting. Their study used landmine-type objects buried 10–50 cm deep in homogeneous wet sand, emplaced in an empty swimming pool (i.e. in air). 31 microphones emitted plane

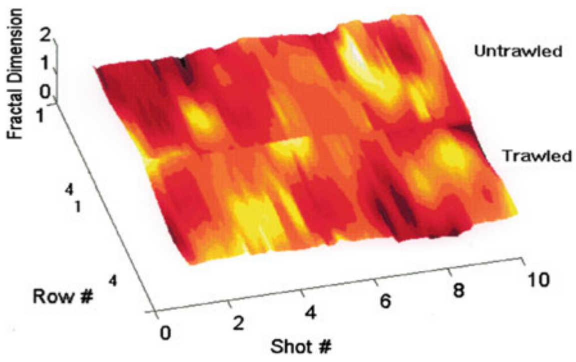

Fig. 2.8 Fractal dimensions (decreasing from *white* to *yellow*, *red* and *black*) for the 40 transducers, sliced by descending zones (1.6-cm thick). They show the clear differences between trawled and untrawled (control) areas. From Guigné and Pace (2007)

waves of frequencies 2000–3000 Hz. For each transmitted pulse, the reflected-refracted signals are received by a line array located diametrically opposite the source (Fig. 2.9), rotated at 1° intervals to cover a full horizontal circle. Pre-amplifiers (with a fixed gain setting) were used before digitising (at 8 kHz) and multiplexing the different signals. These were then used to provide individual time-series for each sensor, combined into CT reconstructed images. Their measurements showed: (1) the importance of coupling between sensors and the ground (arguably easier in water than in air); (2) how pulse design must guide the design of the source array;

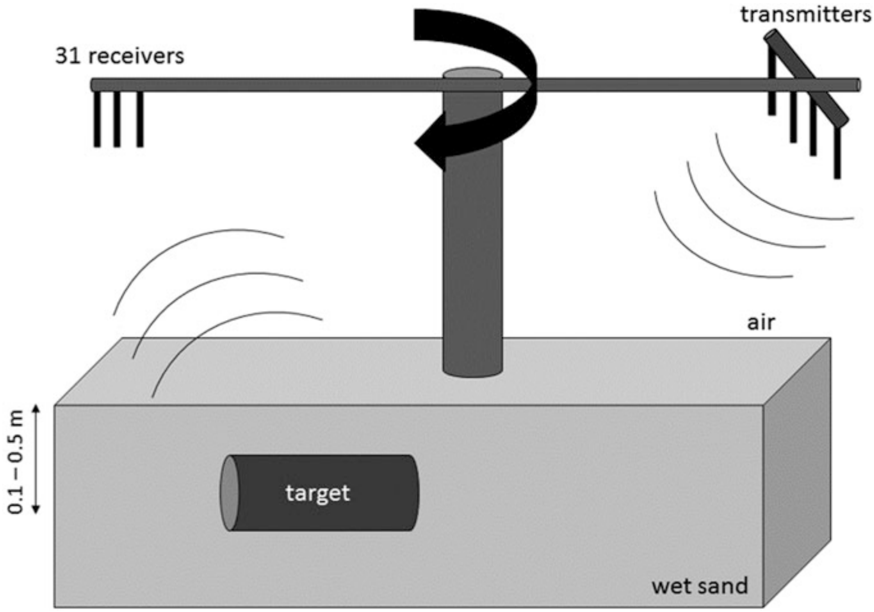

Fig. 2.9 Idealised view of the multi-transmitter, multi-receiver used by Younis et al. (2002) for acoustic Computed Tomography of shallow buried objects in wet sand and air (not to scale)

(3) the need for a higher number of receivers to achieve good resolution (even when the signal-to-noise ratio is good, which is less likely in complex sediments under water) and (4) the need for bespoke signal processing techniques to get the most of data, for example using adaptive interference cancellation.

These recommendations were carried out in independent studies later carried out by Raytheon and Guigné International Ltd. (GIL), investigating ways to detect targets buried in marine sediments (Raytheon/GIL 2004). A large pit (22 m long × 4 m wide × 7 m deep) was filled with relatively homogeneous marine sediments typical of a beach or of shallow water environments, to a thickness of 3 m. These sediments were carefully emplaced and made of 49% sand, 50% silt and 1% gravel, with a mean grain size of 75 μm and a measured high attenuation of 0.53 dB/m/kHz. A large variety of targets were emplaced at selected positions within the sediments, including an inert 81-mm mortar round (0.66 m long and 0.08 m in diameter). Like all other targets, it was supported with steel tubing (0.3 m below) to prevent movements as the sediments compact and the targets settle under their own weights. A DRUMS®-R200 parametric sonar, operating at 190 kHz, transmitted short broadband impulses with modulation frequencies of 15, 20, 26 and 35 kHz. It was used to image the targets at accurately controlled locations and tilt angles (Fig. 2.10) and distance to the seabed was monitored with a distinct depth sounder.

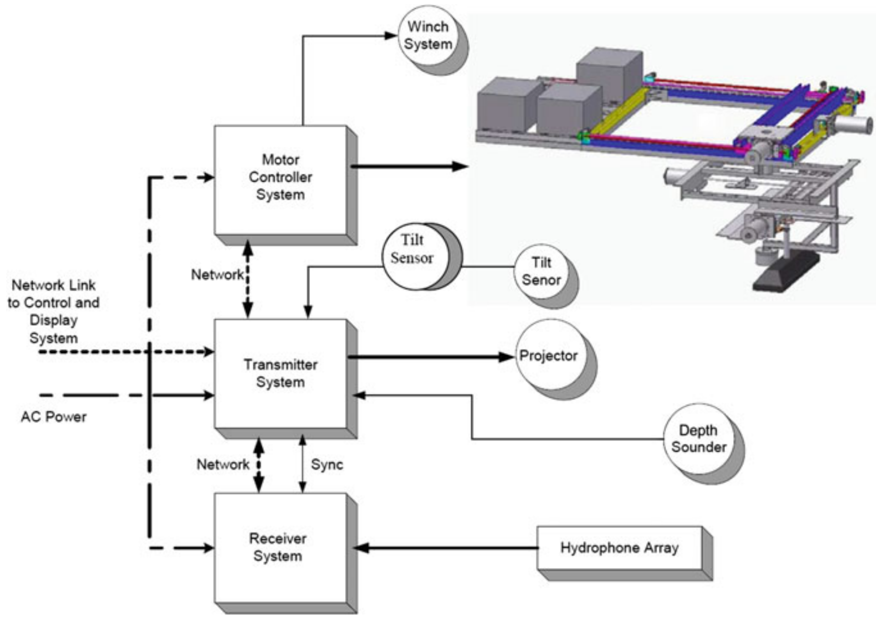

Fig. 2.10 Schematics of the DRUMS-200 parametric sonar (*light grey*, *top right* of the frame) and the ITC-6164 8-hydrophone array (*dark grey*, *bottom right* of the frame), with associated electronics. Modified from Raytheon/GIL (2004)

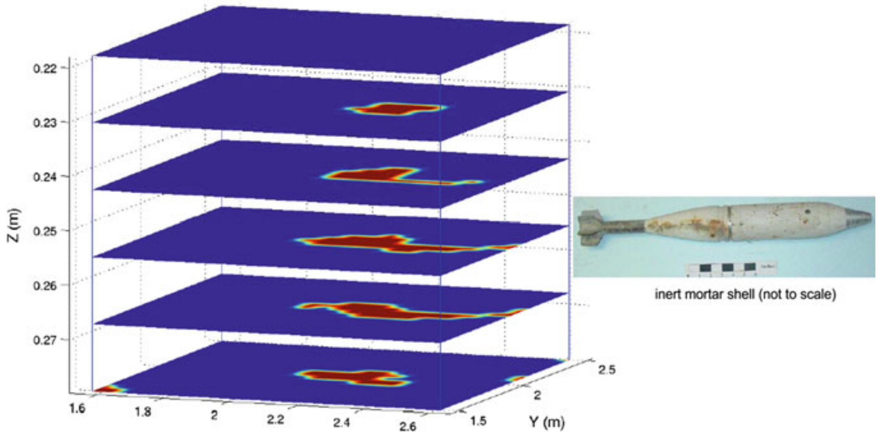

Fig. 2.11 Example results, corresponding to the acoustic detection (*left*) of an inert mortar shell (*right*) buried 50 cm deep. The 2-D slices at different (relative) depths show strong acoustic returns as *red*, *low* or background returns as *blue*. The bottom slice shows additional (real) targets at two of the corners. Adapted from Raytheon/GIL (2004)

Acoustic scattering from the water-sediment interface, from the individual targets (and supporting frames) and from the surrounding sediments was measured at 8 closely-spaced broadband hydrophones. Each received pulse included forward scatter, reverberation and potential out-of-plane returns from strong reflectors (like the targets). Signal processing included accurate positioning of the imaging and receiving transducers relative to the simulated seabed, and beamforming (focused at 1.0-m depth for this particular test). In this highly-controlled environment, it was possible to detect most targets and in particular the mortar shell (Fig. 2.11). 2-D slices of acoustic returns at different relative depths show the background return from the surrounding sediments (top slice), and for each slice, at 1-cm interval, the acoustic returns from the shell. Its shape is gradually revealed with depth, and it is largest 4 cm after the first slice, consistent with its 8-cm diameter. Some of the processing schemes used will be presented in Chap. 3 (“Imaging into the sub-seabed”).

2.3 Significance and Value—Moving Toward an Answer Product

Section 2.1 showed the importance of multi-aspect imaging, revealing more about the sub-surface and the targets within, by using the variations in scattering at different angles, and how this could be harnessed to detect subtle changes. The four examples highlighted in Sect. 2.2 showed, respectively; (1) high-frequency multi-aspect imaging of buried targets with a single parametric array and multiple receivers on a vertical line array; (2) multi-aspect imaging of subtle sub-seabed variations with multiple transmitters and multiple receivers organised along a 2-D array; (3) acoustic Computed Tomography of large objects buried close to the surface (in air) and (4) in water. Each of these approaches revealed much more than traditional tools, illustrating how some of their key innovations can be brought together in an answer product, consisting of carefully selected hardware/sensors and a bespoke signal processing solution. These can be synthesised in the following evidence-based recommendations:

Recommendation 1: The source(s) need to have a broad bandwidth combining low and high frequencies, and they need to transmit high-amplitude, short signals. The low frequencies are useful to detect discontinuities, and the high frequencies to detect individual targets. The frequencies need to be tuned to the spatial wavelengths of each type of structure or target, but also to the acoustic penetration they allow within the seabed. The signals transmitted need to be short, to improve image resolution and distinction of the different arrivals. They need to have relatively high amplitudes, to improve the signal-to-noise ratio as they get attenuated through the sediments and back to the receivers close to the seabed.

Recommendation 2: The receivers need to cover different spatial scales but they are necessarily limited in number. The spacing of the receivers needs to optimise the possibilities of detecting individual returns from sub-seabed targets (discontinuities or objects), with the potential aim of using beamforming to improve localisation accuracy. Some of them can be above the potential targets of interest; others will need to be far away, offering large scattering angles from the source(s) to the target and forward to the receiver(s). The line of receivers will need to cover large areas over the seabed, either by moving to cover a full circle (as in Younis et al. 2002) or by being deployed in a larger pattern (e.g. as a circle or a spiral). The total number of receivers is however limited and cannot be as high (typically tens of thousands) as in X-ray Computed Tomography, because underwater use puts severe constraints on the power available, multiplexing possibilities and data storage on the subsea platform (or even on-board surface vessels).

Recommendation 3: The hardware needs to be relatively portable, for repeated deployment in the harsh underwater environments. The relative positions of both source(s) and receiver(s) need to be carefully controlled and synchronised accurately enough to allow beamforming and other, more complex processing.

Recommendation 4: Bespoke signal processing will need to adapt to potentially low signal-to-noise ratios, and it will need to distinguish between forward scatter and out-of-plane returns. The resulting information will need to be presented as 2-D horizontal slices and 3-D volume plots, relating the acoustic measurements to parameters with a geophysical signification clear to the end-user. There should be clear indications of the resolutions achievable each time, to allow confident identification of targets of interest.

The next chapter will show how this can be achieved in practice, introducing the *Acoustic Corer*, the concept of the JYG-cross and the necessary signal processing stages.

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