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SCALED TANK EXPERIMENTS: SEABED AND TARGET SCATTERING AT HIGH FREQUENCIES

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Abstract: *Emergent technologies such as Autonomous Underwater Vehicles and bistatic sonars offer immense leverage to the modern applications of underwater acoustics. However, high-frequency scattering processes need to be better understood, especially in complex, multiple-target environments (e.g. dumpsites or highly cluttered seabeds). Sea trials are paramount in providing acoustic measurements to validate scattering models and show the different processes involved, but they are expensive, difficult to conduct, and fraught with difficulties. Laboratory experiments are complementary, because of the fully controlled environment and the repeatability of the measurements. The imaging frequencies (> 10 kHz) to be investigated, and the finite dimensions of the tanks usually employed, mean that these experiments need to be scaled. Our article will first present the differences between sea trials and tank experiments, the various parameters that need to be scaled, and the physical validity of the choices made in each case. We shall then illustrate this by presenting some scaled experiments conducted in our facilities at the University of Bath, in a large water tank containing several sediment trays representative of continental margin seabeds. The first series of scaled experiments correspond to acoustic propagation and penetration in the sediments. The second series of experiments is concerned with monostatic imaging and the influence of seabed parameters on the full scattered waveform. The third series of experiments studied bistatic imaging geometries, and the relative influence of seabed types and different targets, proud or buried. In the latter case, the scaled targets were comparable to the toxic waste containers found in many dumpsites at sea. Both monostatic and bistatic tank experiments were used in conjunction with sea trials. Similar experiments around the world are discussed. Scaled tank experiments can be used for the design of future surveys and instruments, as well as for the in-depth analyses of past and future acoustic datasets*

Keywords: *sonar, scaled experiments, multistatic scattering, monostatic scattering*

1. RATIONALE

The last decades have shown acoustic instruments were paramount in mapping the seabed and detecting structures at its surface or in its immediate sub-surface. The spatial resolutions now available range from a hundred metres down to a few centimetres, spanning four orders of magnitude and a whole range of physical, geological and anthropological processes (e.g. [1,2]). The theory of acoustic scattering is now well understood, but applications in complex, real-world environments often reveal the limits of scattering models. In geological surveys, for example, no single model can at the moment describe unequivocally the seabed only from its acoustic characteristics. In other types of applications, small or man-made objects located on or below the seafloor are still rather difficult to find. Important and on-going research efforts are devoted to their acoustic detection and recognition (e.g. [3]). Multiple-target environments (e.g. dumpsites, or cluttered zones) are particularly difficult to investigate, and often only the location and extent of the largest targets can be determined. Further details, such as their physical state (integrity/corrosion) or the numbers/positions of smaller targets, are still generally inaccessible. Scaled experiments can be used to address these problems in controlled environments, where different parameters can be varied as desired.

2. EXPERIMENTAL FACILITIES

The University of Bath tank facilities consist of one large underground tank (Figure 1) and several smaller, above-ground tanks. The walls of the main tank are made of concrete, and the top of the tank is at floor level. The water level can be varied, from 1.8 m to a few millimetres. The bottom of the tank is occupied by several trays filled with sediments, at least 14 cm deep and carefully emplaced after centrifuged degassing. These sediments have been left in place for several decades and are free of gas or bubbles, which have limited the validity of some other tank experiments in the past. These sediments are typical from the European continental margins and exhibit small variations around their acoustic properties. They consist in, respectively (Figure 1): silt (mean grain size 50 μm; density 1.20; sound speed 1503 m/s), sand (mean grain size 1-2 mm; density 2.42; sound speed 1926 m/s), fine gravel (average diameter 5 mm) and coarse gravel (average diameter 20 mm). Acoustic attenuation in the sediments is larger than 100 dB/m at the high frequencies generally used. A computer-controlled gantry system is used to accurately position sonar systems of varying sizes, which can be emplaced with a heavy-lifting crane (Figure 2). The accuracy of the gantry positioning system has been systematically measured for all degrees of freedom, for small-amplitude movements, for large-amplitude movements, and its variations with time have also been investigated. *XY* positioning shows millimetric accuracy or better, depending on the translation stage used, whereas *Z* positioning is accurate to 1 mm [4]. The rotation stage, most often used in the horizontal plane (ϕ direction, i.e. bistatic angle) is accurate to better than 0.1° [5]. The physical parameters that need scaling are associated to signal transmission (e.g. the acoustic wavelength), its propagation, its scattering on targets (*ka* values and target shapes) and on sediments (e.g. grain sizes). Some parameters cannot be scaled easily; for example sound velocity variations cannot be scaled to recreate deep sea conditions, unless changing related parameters (temperature, salinity). As an illustration, in the bistatic scattering experiments presented in Section 5, a scaling factor of approximately 10:1 was used. The targets were designed to match the types of targets likely to be encountered at the Möja Söderfjärd trial site (oil drums, cylinders, boxes). Silt can be considered as a scaled-down version of the soft muddy sediments, with a minute content of gas, present at the site. This was confirmed by [6], whose previous inversions at nearby sites yielded values of 1.047 for the sound speed ratio and 1.1 for the density of the sediments, quite close to the values for the silt tray (1.024 and 1.20 respectively). The scaling choices will be based on the experiments to perform. They can be roughly divided into propagation and penetration experiments (Section 3), monostatic scattering experiments (Section 4) and multistatic scattering experiments (Section 5).

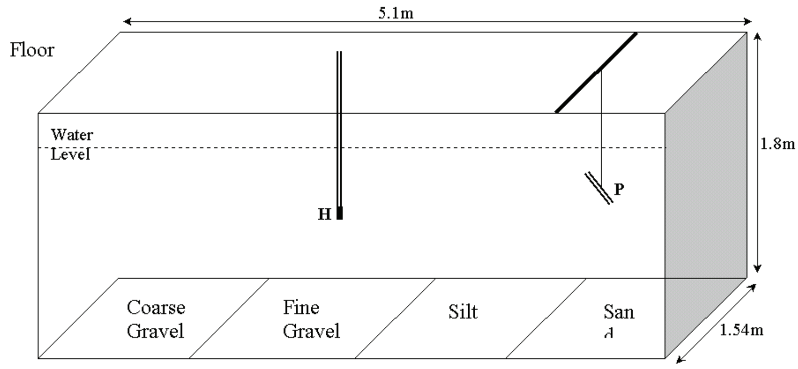

Fig.1: The University of Bath tank facilities include a large underground tank. The walls are made of concrete, and the top of the tank is at floor level. The sediments in the trays are 14 cm deep in average. The acoustic projector and hydrophone(s) can be positioned anywhere in the tank, enabling access to all geometries.

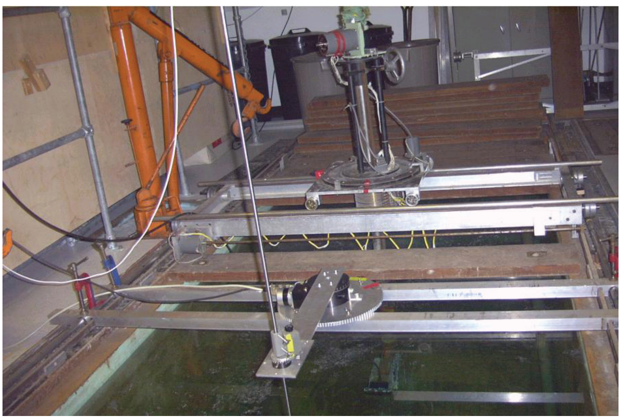

Fig.2: A view of the gantry system used in the main Bath tank. Computer-controlled positioning yields millimetric accuracy; the rotation stage is accurate to 0.1°.

3. ACOUSTIC PROPAGATION AND PENETRATION

Over the years, many experiments have been performed in the laboratory tank(s), some as scaled versions of at-sea situations and others as investigations in their own right. Bubbles and bubble clouds play an important role in underwater acoustics, and as such have been the subject of many studies (e.g. [7]). A number of experimental studies have been carried out to attempt to describe how acoustic absorption and backscatter depend on the duration of the driving force. They usually focused on specific conditions and frequencies, and often gave conflicting results. To this effect, a comprehensive programme of experiments measured the acoustic attenuation through well-defined bubble clouds (e.g. [8]). In these experiments, the frequency range spanned 20–200 kHz and the pulse lengths varied from 20 cycles down to a single cycle, using a parametric transmitter. The experiment simulated the conditions for which a decrease in attenuation with decreasing pulse length might have been expected. No effect was observed for two different but well-defined bubble distributions [8]. Scaled tank experiments were also very useful to investigate propagation in shallow water [9,10]. Two different propagation models (IFD and SNAP) were used to investigate transmission loss for four different bathymetry profiles: a control flat-bed case, two trough shapes and a ridge. Experimental verifications were highly consistent with the predictions [9]. The latter study also showed the feasibility of performing very small scale laboratory experiments with various bathymetries, scaling the system with a high frequency (500 kHz) so that a water depth of only a few millimeters was sufficient to sustain several modes, making it possible to achieve a realistic aspect ratio in a tank less than 2-m long. This complements the tank experiments investigating the influence of water column fluctuations on acoustic performance [11]. The University of Bath tank facilities were also used in scaled experiments intending to clarify the confusion surrounding the acoustic penetration of the seabed by a terminated parametric array [12]. These experiments (using frequencies of 1.39 MHz and 2.25 MHz) focused on the time domain and showed the importance of the imaging geometry. Theoretical calculations of the far-field secondary pressure in the sediments due to a parametric array truncated at the water-sediment interface were derived by [13]. They were checked with experiments in our tank facilities [14]. One of the results was the demonstration that the performance of parametric array differs significantly from a conventional array only when the array was truncated in its primary near-field. These experiments and several later ones were very important in developing the field of parametric arrays in underwater acoustics.

4. MONOSTATIC SCATTERING

Acoustic backscattering experiments using these facilities have been reported in many articles over the years, and they have addressed a wide range of topical problems. In one particular case, broadband scattering studies were performed for rough surfaces, at frequencies of 20-300 kHz and 600-1200 kHz [15]. Another series of scaled experiments addressed the range dependence of the backscatter coefficient as defined in terms of near and far regimes of the scatter patch [16]. These experiments used two rough surfaces; a low-density polyurethane foam constructed with Gaussian height statistics and a Gaussian autocorrelation function and a plaster cast from the coarse gravel tray (Fig. 1). Two circular transducers operating at 250 kHz and 1 MHz were used, validating theoretical calculations. These experiments also showed that in a range interval between the nearfield and farfield, the backscattering coefficient depends on both the surface statistics and the measurement geometry. These experiments were extended by [17], measuring backscatter coefficients from three types of marine sediments between 10° and 90° grazing angle at the same frequencies. Predictions based on the Helmholtz-Kirchhoff integral were in moderate accord with the actual measurements, and the relative importance of surface scattering vs. volume scattering was directly brought into evidence. Simulations and practical use of high-frequency acoustic scattering show the potential offered by bistatic geometries to detect small targets on/in the seabed, and sometimes to identify some of their smaller details or characteristics (e.g. [4,18]). The emergence of new technologies, such as Autonomous Underwater Vehicles, adds to the growing interest for bistatic sonars. But for a long time there were few published bistatic scattering experiments. For these reasons, it was germane to examine what information about bistatic scattering strength one could obtain using a simple monostatic geometry. This was the path followed by [19]. This work made use of low-frequency sources (< 2.5 kHz), in deep water (down to 5000 m). But there is no reason why this should not be transposable to higher-frequency sources in much shallower waters. The advantage is that data from older experiments could be reanalysed to extract some bistatic scattering information. The disadvantage is that this would be restricted to in-plane bistatic scattering, and that the geometry of the initial acquisition should be known with great accuracy. A similar approach was presented by [20] with echo-sounder data.

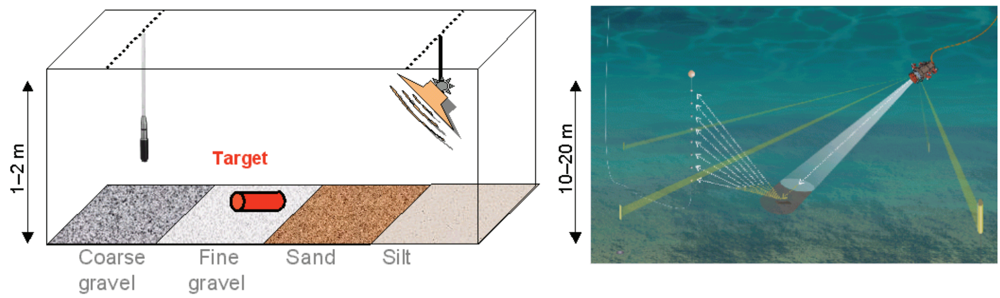

Fig.3: In scaled tank experiments (left), the scattering geometry, the seabed types and the target characteristics can all be measured with high accuracies, the water column and imaging conditions are stable and the experiments can be easily replicated. In typical sea trials (right, adapted from FOI), the seabed and ocean usually exhibit significant variability, whilst the imaging platform and receiver are in constant movement.

5. MULTISTATIC SCATTERING

Multistatic scattering has been studied theoretically and experimentally with our facilities. The experiments reported in this Section are all using a scaling factor of 10:1, dictated by the types of applications. The first studies were concerned with the scattering from different types of seabed at 240 kHz [21]. They used different types of computer simulations to assess the importance of the experimental uncertainties on the interpretation of the results, and define the optimal imaging geometries (combinations of the incidence, scattering and bistatic angles). Because the comparison of these models with actual data is hampered by the lack of actual measurements, especially at higher frequencies (above 100 kHz), these measurements were also used to validate some of the models (e.g. [4]) and their extensions to higher frequencies. These experiments and simulations were particularly useful in showing the role of the bistatic angle. The comparison with full-scale sea trials performed by NATO/SACLANTCEN near Elba demonstrated the synergy between sea trials and tank experiments [22]. Results obtained during the tank experiments [4] matched very well those acquired independently in the sea trials [18]. Building on these studies, we decided to investigate experimentally the bistatic scattering from proud and buried objects, and how it could be used to reconstruct their characteristics. The incentive for this work was the investigation of risks caused by buried toxic waste, as part of the SITAR project (funded by the European Commission) and the preparation of sea trials in the Stockholm Archipelago in 2003. The scaled tank experiments aimed at understanding the optimal imaging geometries to detect/identify targets, and at refining the sonar signal processing techniques that would later be used at sea. In this case, a parametric array flown on a Remotely-Operated Vehicle was used to fly lines at a fixed altitude above the seabed and circle around objects of interest, whilst a hydrophone chain was positioned to record the scattering at different angles (Fig. 3).

A scaling factor of approximately 10:1 was used in the design of the scaled tank experiments. The targets were designed to match the numerical models used during the SITAR project and the types of targets likely to be encountered at the trials site. The sediments used in this study are silt and fine gravel. The former are a scaled-down version of the soft muddy sediments, with a minute content of gas, expected at the sea trials site (as confirmed later by [6]). A single hydrophone was positioned at different depths to simulate a hydrophone chain. In the case of the sea trials, the transmitter and receivers needed to be accurately positioned with a long-baseline transponder net. The positioning accuracy was scaled down in the tank experiments, and its influence assessed using earlier work [4,22]. The acoustic waveforms collected at different ensonifying geometries can be used to first detect the presence of a potential target, second to locate it and even reconstruct its acoustic characteristics. The first task is based on an adaptive implementation of the non-recursive Wiener filters traditionally used in seismic processing, while the localisation of the target(s) uses multidimensional search routines based on a downhill simplex algorithm [23]. Results from the tank experiments show the good agreement between the actual and inferred locations of the targets (as well as their characteristics) [5]. We performed a wealth of bistatic scattering measurements on different types of seabeds. Significantly, we also investigated the scattering from multiple targets (up to 4 at the same time). These results are summarised in [5,23,24]. Single targets are easily identified, by inspection of the different scattering angles at a fixed bistatic angle; they are characterised by a single region of high scattering. An additional target, in line with the source, induces interference, but the two targets are still visible. When adding a third target, one must view the measurements at different bistatic angles. In this case, the interference patterns give a clue to the presence of multiple targets. The effect of adding a fourth target is not very apparent in the images as a function of scattering angle. This may be due to the fourth target being just outside the acoustic beam, and its orientation relative to the other targets. However, its presence is revealed by generating images as a function of bistatic angle at a fixed scattering angle. First analyses of the individual scattering patterns show effects similar to those observed for bare seabeds [4,22], or for targets at lower frequencies or suspended in water [25,26]. Mainly, our experiments show that, by carefully selecting the ROV tracks and the positions of the hydrophone chain, it is possible to identify individual targets in a multiple-target environment. The large dataset acquired over the silt and fine gravel was also analysed by [27]. A suite of algorithms was developed, inspired by spectral distances used in speech processing and aiming at distinguishing between targets [27]. By comparing the acoustic power scattered as a function of the grazing angle, for different bistatic angles, an automatic classifier can be designed. This is particularly advantageous because of the simplicity in data processing requirements (data autocorrelation and standard signal enhancement filtering at the pre-processing stage) [27].

6. CONCLUSIONS

Scaled tank experiments offer an attractive complement to full-scale sea experiments. The latter are often plagued by unanticipated difficulties: unexpected variations in the seabed or the water column, unexpected effects (e.g. ship hull reflections, target burial during the time of the experiment), etc. Because of their complexity, the results of many experiments are still being fully analysed. They have however revealed the complex interactions between targets and their environments. Conversely, laboratory experiments are easier to perform, at least in theory: the environmental variations can be controlled; the target emplacement is known with very high accuracy; the target-background interactions can be directly measured and the experimental uncertainties (e.g. transducer positions) are tightly controlled. This article aimed at showing the advantage of scaled tank experiments, and their synergy with the sea trials. The results presented here have indeed often been corroborated by the direct comparison with similar experiments (e.g. [4] with [18], [5] with [6]). Scaled tank experiments allow investigating the influence of parameters not directly accessible at sea, or not easily changed. They allow feasibility experiments to test new concepts or techniques, or to decide between competing theories. The experiments presented here intend to span a representative portion of what has been achieved at the University of Bath (and in other places) over the last decades. We have for example used scaled tank experiments in studies of acoustic propagation, penetration into sediments, high-frequency scattering (monostatic and multistatic), multiple-target target environments, and, although it was not presented here, basic time-reversal techniques. Scaled tank experiments can be used to design of future surveys and instruments (e.g. bistatic sonars), as well as for the in-depth analyses of past and future acoustic datasets.

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