HIGH-FREQUENCY BISTATIC SCATTERING ON SEABED AND TARGETS: COMPARISON OF SCALED AND FULL-SCALE EXPERIMENTS WITH SEA TRIALS

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1 RATIONALE

Recent uses of bistatic sonars show the advantages of decoupling transmitter and receiver(s) to optimise the information from seabed and target scattering. However, high-frequency scattering needs 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 (decametre-scale usually), mean that these experiments most often need to be scaled. Laboratory experiments are ideal to understand the role of each physical process in the overall scattering, and to optimise data collection strategies depending on the objectives. Experiments can be scaled, using higher frequencies, smaller tanks and smaller targets. But how does it influence bistatic scattering (and its interpretation)? How does the transition to full-scale experiments work out? This is particularly relevant as sea trials are expensive and difficult to conduct. We compare here the results from: (1) scaled experiments of bistatic scattering on bare seabed and targets, performed at Bath; (2) full-scale experiments in the GESMA submarine pens during the EC-SITAR project, with targets in a sand box and (3) sea trials from similar bistatic experiments performed in Elba (for a bare seabed) and Möja Söderfjärd (on a well documented dumpsite). Each series of experiments revealed particular experimental issues, or solved specific questions related to the conduct of the experiments and/or the physical scattering processes. The three approaches prove to be complementary, with advantages and drawbacks related to their distinct objectives. The comparison of these experiments with acoustic simulations shows agreement increasing with the sophistication of the models. Tank experiments, scaled or not, can be used for the design of future surveys and instruments, as well as analyses of past and future acoustic datasets[1]. Comparing their analyses with those of sea experiments show future trials can now be devoted to more focused investigations, or more complex generic problems.

2 SCALED EXPERIMENTS

2.1 Seabed Scattering Experiments

Simple laboratory experiments were conducted in Bath in 1999-2001 to investigate bistatic scattering in a highly controlled and stable setting[2,3]. Scaled experiments were conducted in a large water tank containing several sediment trays representative of continental margin seabeds (Figure 1, left). The trays are respectively filled with silt (average grain size of 50 μm), sand (1-2 mm), fine gravel (5 mm) and coarser gravel (20 mm), reproducing different types of genuine seabeds. For a scaling factor of 10:1, the silt tray corresponds for example to soft muddy sediments found in Möja Söderfjärd (see Section 4.2). Careful preparation ensured all sediments were water-saturated and their surfaces smooth and horizontal. The sediments had not been disturbed for several years, ensuring their stability and homogeneity[1]. A robotics system is supported above the tank, and provides positioning of the acoustic source and hydrophone(s) over its whole area along the *x*–, *y*– and *z*–directions, and around the vertical *z*–axis. This allows acquisition of a range of bistatic geometries (Figure 1, right): incidence angle, scattering angle and bistatic angle (deviation from in-plane geometry, where the source, target and receiver are aligned). Positioning accuracies are around 0.01 m. The acoustic source can be pan-tilted over a large range of angles, accurate to 0.1°. The centre frequency is 238 kHz, and the half-intensity beam width is 9°. Full 3-D calibration also assessed the position of the secondary sidelobes, non-symmetrical[2]. The hydrophones are omnidirectional and positioned in the far field, with similar degrees of accuracy.

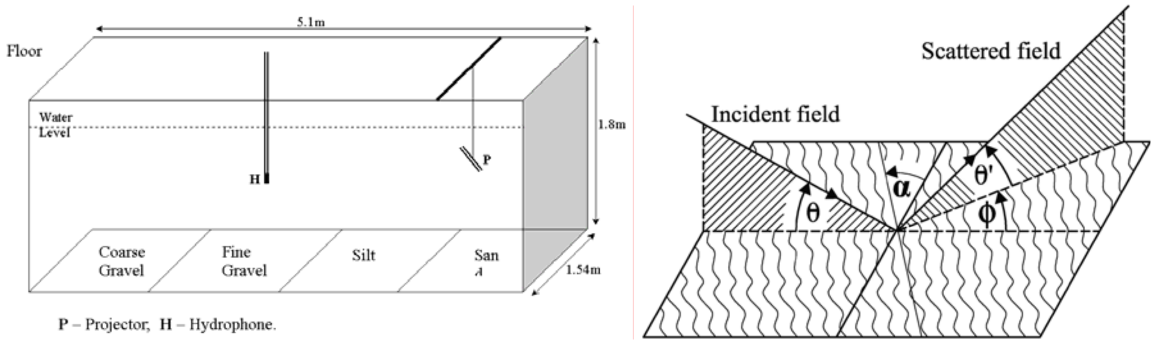

Figure 1. Left: scaled experiment facilities at Bath. The tank walls are made of concrete, and its top is at floor level. The sediments are 14 cm deep in average. The water level can be varied. Both acoustic projector and hydrophone(s) can be anywhere in the tank. Right: all bistatic geometries can be investigated, as a function of the incidence, scattering and bistatic angle ϕ.

Bistatic scattering measurements from the bare silt seabed were compared with predictions from the “Jackson” model[4]. It was found[2] that the model’s predictions for in-plane scattering agree very closely with the experiments. Away from in-plane scattering, at bistatic deviations of 30°, 60° and 90°, the “Jackson” model consistently overestimates the return signal strengths. The experimental results have also often shown a small increase in return strength for specular geometries ($\theta = \theta'$). This is not always predicted by the “Jackson” model, especially away from in-plane. Most likely causes for model/data discrepancies were assessed as the actual interface roughness (not measured directly, but inferred from the grain size using the relations given with the “Jackson” model) and, to a lesser extent, to the approximation of scattering areas as constant. Extensions of the “Jackson” model above its intended range of 10-100 kHz were independently shown to be physically valid (for different terrains and frequencies[5,6]) and this study confirms that, at least in the forward direction, the agreement between measured and modelled bistatic scattering is fair.

2.2 Target Scattering Experiments

These experiments were extended in 2002-2005 with measurements of the bistatic scattering strength of silt and fine gravel, with targets placed proud, half-buried or flush-buried and at different orientations[7]. A much larger range of scattering angles was measured, but bistatic measurements were restricted to deviations of 40° or less from in-plane. The scaled targets were intended to be versions of typical waste found in marine dumpsites like oil drums and boxes. Nearly identical targets were selected, some filled with air or fluids, others solid. The scaling of these experiments was designed to match later sea trials on an actual dumpsite (see Section 4.2) and the configurations tested influenced the design of the surveying strategies at sea[8] (Figure 2).

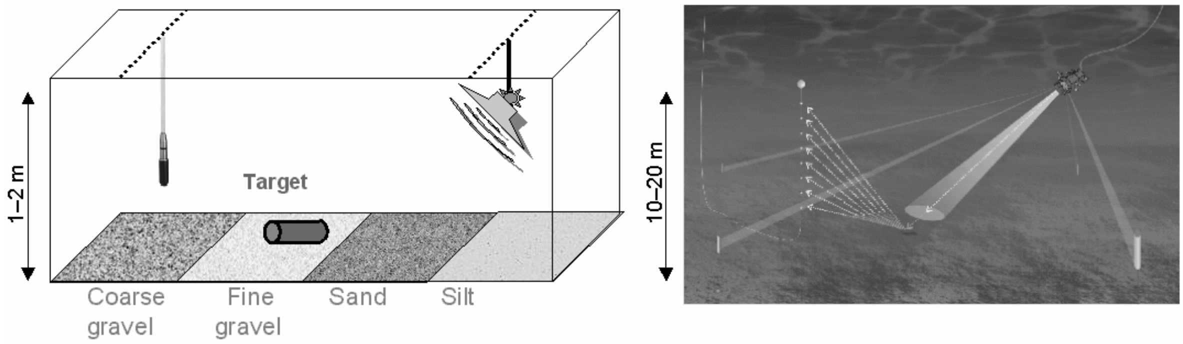

Figure 2. SITAR. The targets are oriented relative to the *X* axis (lengthwise), the *Y* axis (along the 1.54-m width of the tank), or the *Z* axis (vertically). They were also placed diagonally (*XY* orientation). Right = scaled version of the sea trials planned later (cf. Section 3.2).

The influence of bare silt was already known from earlier studies (see Section 2.1) and this study therefore concentrated on the detection and identification of the individual targets[7,10]. The silt tray was a scaled-down version of the soft muddy sediments, with a minute content of gas, expected at the sea trials site and later confirmed[8]. Conversely, the scaling-up of the fine gravel matches it with very rough terrain, covered with rubble (and acoustically challenging). The first aim of these scaled experiments was to design an optimal strategy for the surveying of buried waste. Line scans, where the bistatic system (transmitter + receiver(s)) surveys the object at a variety of incidence and scattering angles, proved useful to detect objects and variations within, measuring the acoustic field in regions of most variable (and important) scattering[7]. They showed in detail the role of target orientation and target burial in the processing[10]. Rotation scans, where the bistatic system moves around a particular object of interest, showed how differences in the multistatic scattering could be used to differentiate objects[11]. The handful of published bistatic experiments using targets had so far focused primarily, if not only, on mine-like objects. The SITAR experiments focused instead on buried waste, and extended traditional experiments by looking at targets not simply on their own, or in simple settings, but also in clusters of different sizes[7,12]. Figure 3 shows for example the difference between scattering from a simple target, and a cluster made from two nearly identical targets, one fluid-filled and the other solid. Using simple spectral distances often used in speech processing, significant differences in the received signal power at bistatic angles different from the forward direction were systematically observed. They enabled some recognition of individual targets in silt, even when organised in close clusters. For larger clusters (5 targets), acoustic interference between targets is visible at distinct scattering angles, and amplified at different bistatic angles.

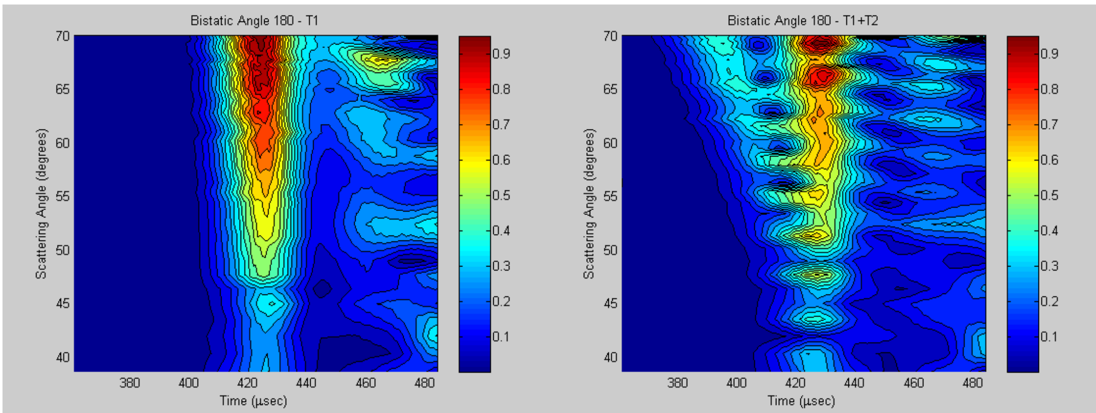

Figure 3. SITAR. Results Contour maps of the normalised amplitude as a function of the scattering angle for a bistatic angle of 180° (in-plane), for a single fluid-filled target on a silt seabed and (left) and the same target laid close to a solid equivalent (right).

These scaled experiments on target scattering confirmed that the 3-D acoustic field scattered by targets provides additional information that can be exploited successfully in target classification, as already observed theoretically and computationally by several other studies[13]. In addition to previous studies, they showed that sometimes even the bistatic configuration may not be sufficient, and that multistatic configurations should be preferred. The role played by the sea bottom is non-negligible, but even in rough terrain (e.g. the fine gravel here), it is possible to detect targets and identify them using the right metrics and surveying approach.

3 FULL-SCALE EXPERIMENTS

Full-scale tank experiments were also conducted in 2004 as part of the SITAR activities[14], using a former submarine hangar lent by GESMA and the French Navy. Its large dimensions (80 m long, 10 m large, 9 m deep) allowed the investigation of bistatic target scattering at full-scale, i.e. 1:1. A 15-kHz transmitter with a narrow beam (9° at 3 dB) was used to image a sandbox (10 m long, 5 m large, 0.3 m deep) in which different targets had been set up (proud and flush-buried spheres, air-filled cylinders of different dimensions). The equipment was placed in the tank when dry and then the tank was gradually filled with seawater. The scattering was analysed with a fixed hydrophone chain, each hydrophone accessing a different scattering angle. Several transmitter positions and tilt angles allowed access to a range of bistatic configurations (Figure 4).

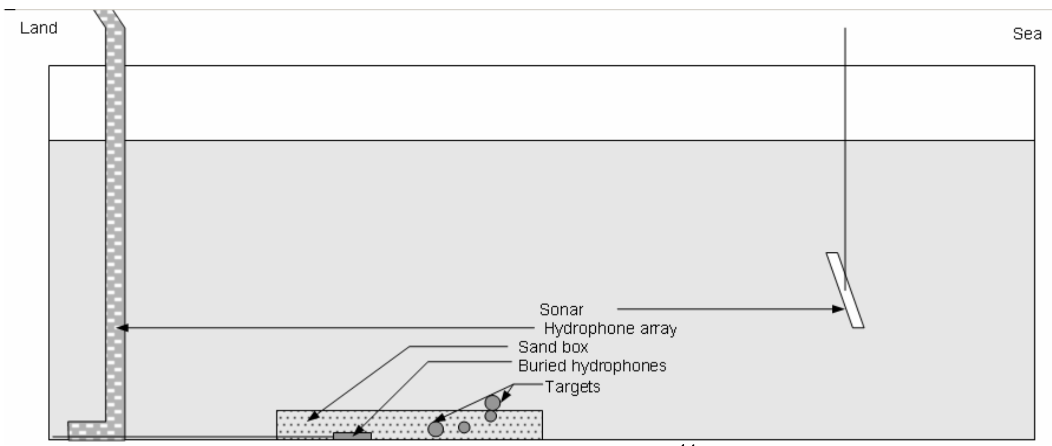

Figure 4. Sketch from the SITAR-GESMA full-scale trials[14]. The narrow-beam sonar can be tilted to image the targets in the sandbox at different angles of incidence. The hydrophones in the array at the end of the tank allow access to different angles of scattering.

Preliminary, unpublished results from these experiments confirm earlier results from the scaled tank experiments (Section 2.2). The achievable range of scattering angles was rather limited (~7-36°), reaching slightly beyond specular angle in most cases. The flush-buried sphere revealed similar scattering to the proud sphere, whereas the buried cylinders showed a lower acoustic response (due to sediment attenuation) but similar variations with the scattering angle. This rapid experiment (1 day) revealed several limiting issues. First, the sand box was entirely contained within the sonar beam. This precluded the easy calculation of an effective scattering area, as it would correspond to the box, its walls and the bottom of the submarine pen around the box. The exact scattering strengths of each target could thus not be directly compared with those measured in other experiments or in simulations. Another limitation was the distance between targets: in most of the configurations studied so far, the targets are placed too close to each other, and the scattered signal shows only the main reflections from each target. Any secondary reflections (e.g. within the target) or surface waves are irreversibly mixed with the main reflections from the next target in the acoustic line of sight. A result with experimental significance, though, is that short acquisition times are achievable. It is definitely possible to identify scattering from targets at different depths, even below each other, and detect differences between targets from the variations of acoustic returns with the scattering angles alone.

4 SEA TRIALS

4.1 Seabed Scattering

Field measurements of bistatic scattering strength (BSSS) are difficult and expensive to acquire at sea, in real conditions. At most, one can expect to obtain data for a small set of the possible combinations of angles (incidence, scattering and bistatic) involved. Even for homogeneous sediments (and not considering non-sedimentary seabeds like rock outcrops or vegetation-covered areas), different statistical realisations of the seabed of the desired type are required to obtain a value of BSSS close to the expected value. A recent experiment was conducted by the NATO Undersea Research Center[15] in Golfo Biodola (Island of Elba, Italy) (Figure 5). A nearly flat sandy seafloor, ~12 m deep, was extensively measured, first with an EM-3000 bathymetric sonar to ensure the same depth accuracy throughout, and in some selected places with stereo-photogrammetry[16]. A circular transducer was placed on a tower positioned on the seabed, and pan-tilted to achieve different angles of ensonification. With a beamwidth of 7° at –6dB, it was transmitting at 118 kHz. The signal scattered from the seabed was measured with a hydrophone chain, placed on a pole on a vessel circling the area of interest. The source and receiver positions were calculated (with a standard deviation of the residual errors of ~ 0.1 m) using a kinematic differential GPS (RTK), a motion reference unit (MRU) and an inclinometer. The same instruments ensure accurate calculation of grazing and azimuthal angles.

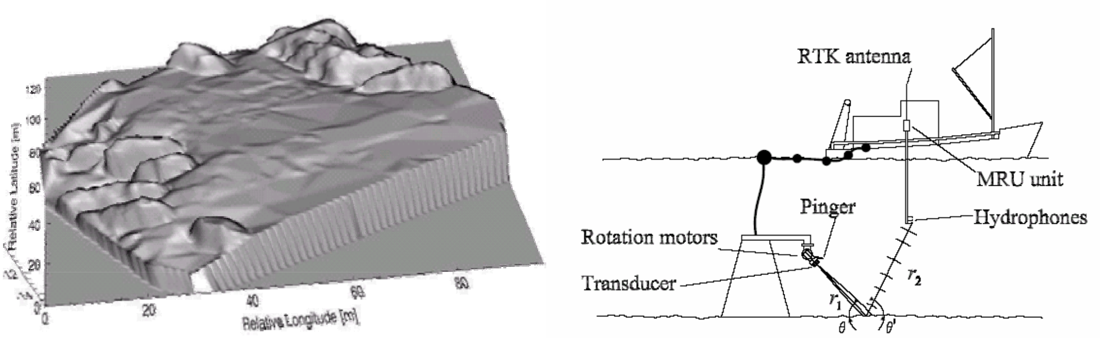

Figure 5. Bistatic measurements of seabed scattering at Elba Island[16]. Left: 3-D bathymetry of the site, with clumps of *Posidonia* and a nearly flat sandy seafloor (with a few ripples). Right: experimental configuration, showing the transmitter on its tower (fixed on the seabed) and the hydrophones on a pole (moving with the ship).

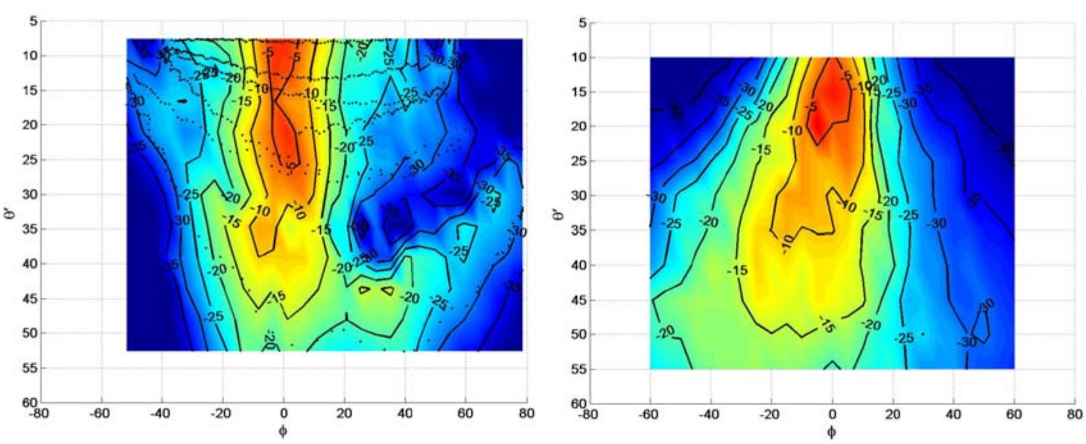

Figure 6. Measurements of bistatic seabed scattering strengths (BSSS) at Elba Island[15]. Comparison between measured BSSS (left) and simulated (right) for the Elba data[20] show variations of BSSS with scattering angle θ' and bistatic angle ϕ for α=45° and incidence angle θ=15° (see Figure 1 for explanation of the geometry; in this case, α refers to the angle of seabed ripples).

In shallow water, the need to transmit short pulses directly limits the size of the scattering patch. Analyses of these experiments[16] quantified the role of the Instantaneous Scattering Area, and how its accurate calculation could drastically affect the calculation of the BSSS. In some configurations, the signal received from the seabed was shown to be a mixture of both the main beam and the sidelobes of the transmitter. Calculations of the Instantaneous Scattering Areas[16] showed the scattering from the sidelobes was actually higher than that associated to the main beam, limiting potential interpretation of the BSSS. In other configurations, reflections from the hull of the ship were received at the same time as the signal from the seabed. This showed the necessity to place hydrophones further from large reflectors, i.e. hanging in the water column or moved on underwater vehicles. To explain the behaviour observed in the data, the experiments were simulated using the time-domain snapshot model BORIS-SSA[17,18,19] (Figure 6). The conclusion[20] is that the BSSS computed using BORIS-SSA are in good agreement with the BSSS acquired at sea. Thus, potentially, the need for the difficult and expensive sea experiments has receded.

4.2 Target Scattering

The SITAR sea trials[21] extended the scaled target scattering experiments presented in Section 2.2. They took place in 2003 over a known dumpsite in Möja Söderfjärd, in the Stockholm Archipelago (Sweden). This dumpsite was well documented and the likely distribution of buried targets was mapped with the new Parametric Synthetic-aperture Sidescan Sonar[22]. The bistatic part of the sea trials focused on several targets of interest. The transmitter was a TOPAS-120 parametric array (beamwidth 3-4°, 120 kHz primary frequency, 2-18 kHz secondary frequency band), placed on a Remotely-Operated Vehicle. The scattering was recorded on a 6-hydrophone chain in a fixed mooring (Figure 7). The ROV could be controlled to keep the incidence angle accurate to 1°, and the depth was accurate to 0.1 m. It was navigated with a 4-transponder network on the seabed, referenced to the DGPS navigation of the surface vessel. Each target, or field of targets, was first surveyed with a line scan, similar to that presented in Section 2.2, and targets of interest were further surveyed with rotation scans.

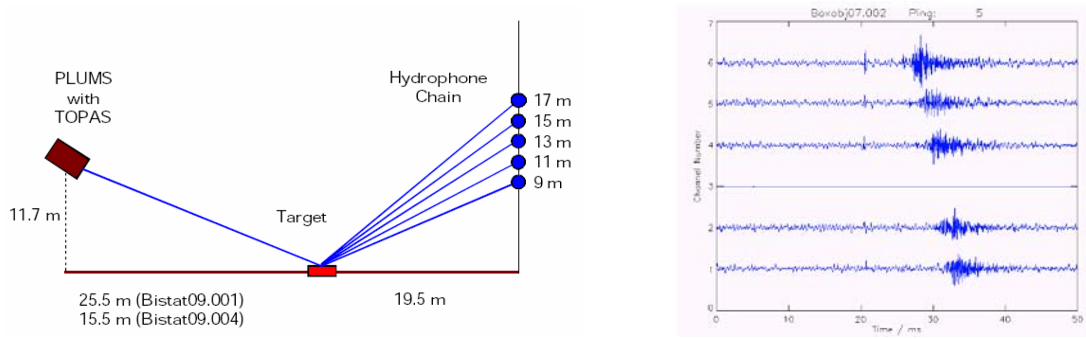

Figure 7. Left: typical bistatic setup used during the SITAR sea trials; the TOPAS-120 transmitter is mounted on the research ROV PLUMS. Right: typical signals recorded on the hydrophone chain.

These sea trials proved the success of scaling up the strategy originally designed in the laboratory (Section 2.2). Line scans could be used to detect the targets, and rotation scans to investigate the scattering from each target or group of targets. Individual half-buried targets could be identified acoustically, as validated with visual inspection, and their acoustic characteristics could be inverted successfully[23]. Issues revealed during these trials were the importance of synchronising transmitter and receiver acquisition (even if the direct arrival could still be used as a common reference), and of knowing their respective positions as accurately as possible (the ROV was accurately tracked with a four-transponder network, but the hydrophones were mounted off-axis on the chain, and individual/group movements were not monitored). The overall methodology proved nonetheless rather successful, as the identification of targets worked well with a range of pulse types and with both distorted and noisy signals[23].

5 CONCLUSIONS

The previous sections have summarised the main aspects of several types of scaled and full-scale experiments: laboratory experiments, in controlled environments, and sea trials, in different settings. Some experiments were performed with bare seabeds, others with targets on/in homogeneous seabeds. These approaches are complementary. Laboratory experiments allow measuring a much larger range of bistatic geometries than attainable at sea, in controlled and repeatable conditions, whereas sea trials are direct applications of bistatic sonars in complex and changing environments.

Scaled tank experiments of seabed scattering enabled a more quantitative understanding of the different sources of uncertainties in interpreting experimental results, e.g. positioning accuracy and the role of sidelobes. They strongly hinted that the largest sources of disagreement between measurements and models of high-frequency bistatic scattering would be miscalculating the instantaneous scattering area, and inaccurate measurements of seabed roughness and its variations. The full-scale tank experiments mostly corroborated the results from scaled tank experiments, showing the importance of careful design over size considerations. Sea trials demonstrated clearly the early conclusions from tank experiments, showing as well the increasing agreement between measurements and sophisticated models of bistatic scattering.

Investigations of target scattering were also conducted in scaled and full-scale laboratory settings, and further tested at sea on a real dumpsite. All series of experiments confirmed that the scattering from targets is not separable from the scattering on enclosing/neighbouring sediments, as shown both theoretically[24] and experimentally[25]. For example, scattering from flush-buried targets is often much larger than for half-buried targets, and on a par with the same targets placed proud on the seabed. The laboratory experiments helped design (or test) the surveying strategy employed at sea (i.e. line scans for detection and rotation scans for identification), and the optimal configurations of the bistatic system (transmitter + hydrophones).

In summary, each series of experiments revealed particular experimental issues, or solved specific questions related to the conduct of the experiments and/or the physical scattering processes. The three approaches reveal complementary, with advantages and drawbacks related to their distinct objectives. The comparison of these experiments with acoustic simulations shows agreement increasing with the sophistication of the models. Tank experiments, scaled or not, can be used for the design of future surveys and instruments, as well as analyses of past and future acoustic datasets. Analyses of sea experiments show future trials can now be devoted to more focused investigations, or more complex generic problems. Refinements to the experiments, better models, and in general more bistatic experiments are still required. But comparisons show how much confidence one can now have in bistatic scattering measurements of seabeds and targets. Bistatic sonars are increasingly proving to be useful and versatile tools for the detection and classification of underwater targets, in particular when coupled with new technologies such as Autonomous Underwater Vehicles. Bistatic sonars can now be used in an increasingly wider range of applications, from buried waste monitoring to underwater archaeology to habitat mapping.

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