ARCHIVES OF ACOUSTICS
34, 1, 95–109 (2009)

Bistatic Sonars: Sea Trials, Laboratory Experiments and Future Surveys

Philippe BLONDEL, Nick G. PACE

University of Bath
Department of Physics
Claverton Down, Bath BA2 7AY, UK
e-mail: pyspb@bath.ac.uk

(*received July 11, 2008; accepted January 14, 2009*)

Bistatic sonars use separate transmitter and receiver(s), optimising the information received from seabed/target(s) scattering. Laboratory experiments are ideal to understand scattering processes and to optimise data collection strategies. They can be full-scale or scaled down. In the latter case, the influence on bistatic scattering processes needs to be carefully weighed, to validate the transition to full-scale experiments. This is particularly relevant as sea trials are expensive, difficult to conduct, and generally impossible to repeat. This article presents the results from: (1) scaled experiments on bare seabed and targets, performed at Bath and other places; (2) full-scale experiments in the GESMA submarine pens during the EC-SITAR project and (3) sea trials from similar experiments in Italy and Sweden. These results are put into the wider context of other international efforts. These three approaches (scaled and full-scale experiments plus sea trials) can be used in synergy. This has important implications for future experiments, the design of surveys and instruments, and analyses of past/future acoustic datasets.

Keywords: bistatic sonar, tank experiments, sea trials, acoustic scattering.

1. The need for bistatic sonars

Traditional sonars use monostatic geometries: the transmitter and receiver are on the same platform (and sometimes correspond to the same instrument), and only the portion of acoustic energy that happens to scatter back in the direction of the imaging sonar is analysed. These sonars can create complete maps of the seabed with high accuracies (e.g. Blondel and Murton [7]) but their geometries limit the range of scattering processes observable. Conversely, bistatic sonars use decoupled transmitter(s) and receiver(s), optimising the gathering of acoustic information from seabed and potential targets. High-frequency scattering is getting increasingly better understood but work still needs to be done in complex, multiple-target environments (e.g. dumpsite 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. Tank experiments are complementary, because of the fully controlled environment and because measurements can be repeated as necessary. The imaging frequencies ($>$ 10 kHz) to be investigated, and the ranges at which multistatic surveys are usually conducted, mean that these tanks must be large (dimensions $>$ 10 m). Due to the limited number of such facilities available, it makes sense to scale down these experiments, 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? We compare here the results from scaled experiments, conducted at the University of Bath (Sec. 2) and investigating seabed and target scattering in a wide range of bistatic configurations, with full-scale experiments, conducted in the GESMA submarine pens during the EC-SITAR project (Sec. 3) and with sea trials performed in Elba, Italy (on a bare seabed) and in the Stockholm Archipelago, Sweden (on multiple targets from a documented dumpsite) (Sec. 4). Each series of experiments revealed particular experimental issues or solved specific questions relating to the conduct of the experiments and/or the physical scattering processes (Sec. 5). The three approaches, namely scaled tank experiments, full-scale experiments and sea trials, are complementary. Their comparison with acoustic models shows agreement increasing with the sophistication of the models used. Tank experiments, scaled or not, can be used to design future surveys and instruments, as well as to analyse past and future acoustic datasets [8]. Used in synergy, they mean that future trials can now focus on more demanding investigations or more complex generic problems.

2. Scaled experiments

Simple laboratory experiments were conducted in Bath in 1999–2001 to investigate bistatic scattering in a highly controlled and stable setting [9, 10]. A large water tank (5.1 m (L) $\times$ 1.5 m (W) $\times$ 1.8 m (D)), made of concrete and with its top at floor level, contained several sediment trays representative of continental margin seabeds. These trays are ~14 cm deep, ensuring good attenuation at the frequencies used. They are respectively filled with silt (average grain size of 50 μm), sand (1–2 mm), fine gravel (5 mm) and coarser gravel (20 mm). 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 [8]. A robotics system is supported above the tank, and provides positioning of acoustic source and hydrophone(s) along the x-, y- and z-directions, and around the vertical z-axis. This allows acquisition of a range of bistatic geometries: 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 [10]. The hydrophones are omnidirectional and positioned in the far field, with similar positioning accuracy.

Bistatic scattering measurements from the bare silt seabed were compared with predictions from the APL-UW model [2]. It was found [10] 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 APL-UW model consistently overestimates the return signal strengths. The experimental results have also often shown a small increase in return strength for specular geometries. This is not always predicted by the APL-UW 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 model) and, to a lesser extent, the approximation of scattering areas as constant. Extensions of the APL-UW model above its intended range of 10–100 kHz were independently shown to be physically valid (for different terrains and frequencies) [1, 14, 33] and this study confirms that, at least in the forward direction, the agreement between measured and modelled bistatic scattering is fair. 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 [11]. A much larger range of scattering angles was measured, but bistatic measurements were restricted to deviations of 40° or less from in-plane. These measurements were intended to prepare for sea trials in the Stockholm Archipelago (Sec. 4). For a scaling factor of 10:1 (Fig. 1), the silt tray corresponds for example to soft muddy sediments found in Möja Söderfjärd [5]. Conversely, the scaling-up of the fine gravel matches it with very rough terrain, covered with rubble.

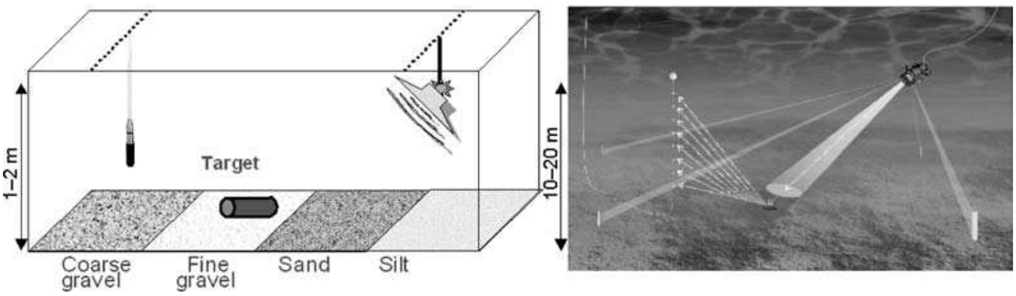

Fig. 1. Scaled tank experiments can be used to prepare for sea trials and/or to interpret their results.

The influence of bare silt was already known from earlier studies (e.g. Blondel *et al.* [10]) and the next studies therefore concentrated on the detection and identification of individual targets [6, 11, 16]. The scaled targets were intended to be versions of typical waste found in marine dumpsites like oil drums and boxes (Fig. 2). Nearly identical targets were selected, some filled with air or fluids, others solid. The first objective 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 [11]. They showed in detail the role of target orientation and target burial in the processing [6]. 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 [4]. 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 in isolation, or in simple settings, but also in clusters of different sizes [11, 15].

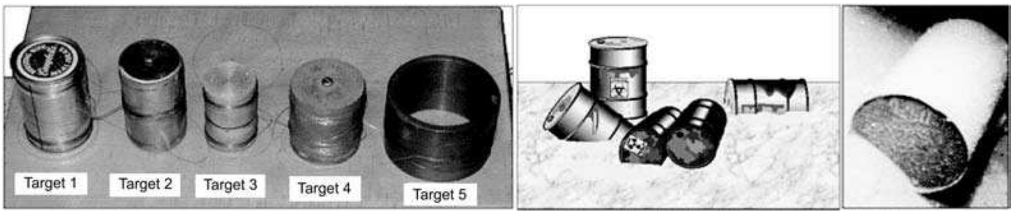

Fig. 2. Appropriately designed (and scaled) targets can be used to investigate the bistatic scattering from complex objects such as those found in dumpsites.

Typical results are shown in Fig. 3. The scattering from a simple target varies with the scattering and bistatic angles, and the time-domain evolution of the scattered waveform reveals information about the target and its contents (Fig. 3a). Similar information can be obtained for clusters of targets, provided their individual returns are not too close in space or time. 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 recognition of individual targets in silt and gravel [4, 15], even when organised in tight clusters. For larger clusters (5 targets), acoustic interference between targets is visible at distinct scattering angles, and amplified at different bistatic angles. Short-Time Fourier Transforms amplify these differences (Fig. 3b). These experiments confirm 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 (Pace and Blondel [24], and articles therein). In addition to previous studies, these experiments show that sometimes even one bistatic configuration may not be sufficient, and that multistatic configurations should be preferred (e.g. Blondel [4]). The role played by the sea bottom is non-negligible, but even in rough terrain (e.g. gravel), it is possible to detect targets and identify them using the right metrics and an appropriate surveying approach.

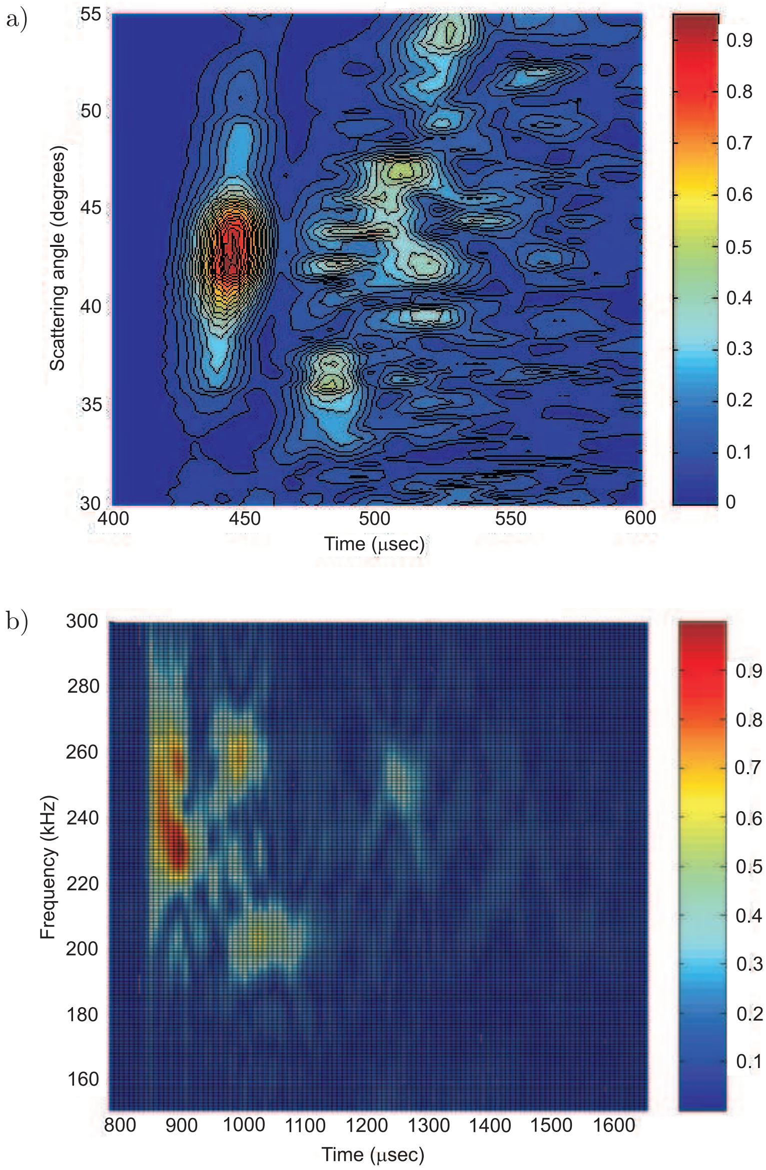

Fig. 3. a) time-domain scattering of a fluid-filled cylinder with ribs, proud and imaged broadside on, b) Short-Time Fourier Transform of a cluster of proud targets.

3. Full-scale experiments

Full-scale tank experiments were conducted in 2004 as part of the SITAR activities [5, 35], using a former submarine hangar lent by GESMA and the French Navy. Its large dimensions (80 m (L) × 10 m (W) × 9 m (D)) 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 (Fig. 4). Preliminary, unpublished results from these experiments confirm earlier results from the scaled tank experiments (Sec. 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 experiment 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,

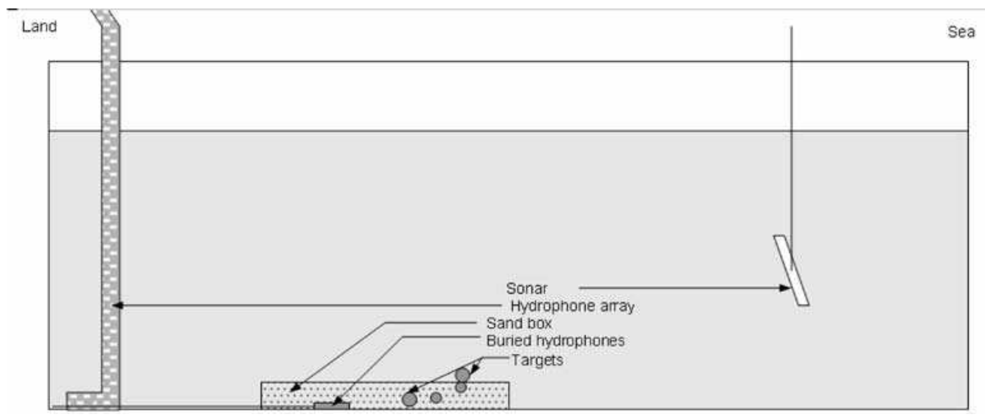

Fig. 4. Full-scale targets are placed in a sand box 10 m (L) × 5 m (W) × 0.3 m (D), in the middle of a test basin 80 m (L) × 10 m (W) × 8 m (D) later flooded with sea water. The sonar can be tilted to image the targets in the sandbox at different angles of incidence. The hydrophones in the array at the end of the tank allow access to different angles of scattering. Adapted from Zakharia [35].

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

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 [13] in Golfo Biodola (Island of Elba, Italy) (Fig. 5). A nearly flat sandy seafloor, ~12 m deep, was extensively mea-

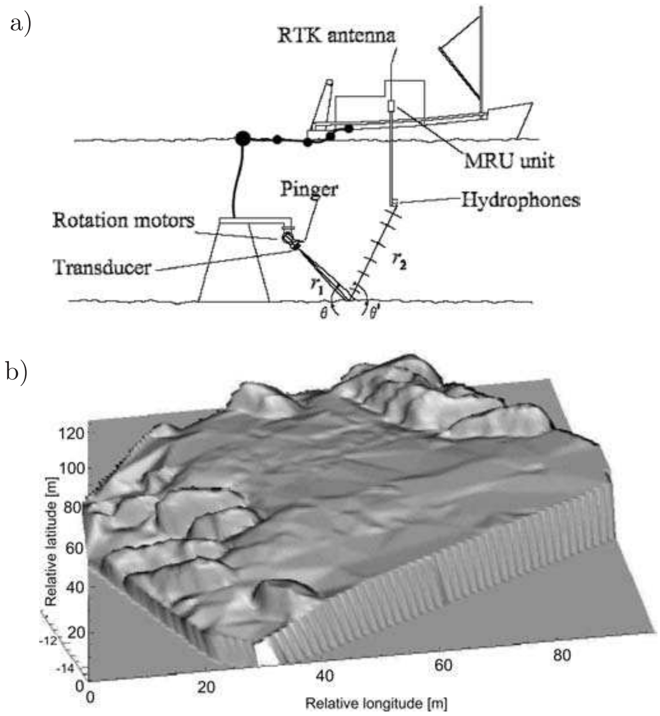

Fig. 5. a) general bistatic set-up used in the NURC experiments [13], b) measurements show the real seabed is not exactly flat, affecting the calculation of scattering strengths.

sured, first with an EM-3000 bathymetric sonar to ensure the same depth accuracy throughout, and in some selected places with stereo-photogrammetry [21]. A circular transducer was placed on a tower on the seabed, and pan-tilted to achieve different angles of ensonification. With a beamwidth of 7° at −6 dB, 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. Source and receiver positions were calculated (to ∼0.1 m) using RTK-GPS, a motion reference unit and inclinometer. These also yield accurate calculation of grazing and azimuthal angles.

In shallow water, the need to transmit short pulses directly limits the size of the scattering patch. Analyses of these experiments [13, 21] 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, and in some cases, the scattering from the sidelobes was actually higher than that for 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 [12, 23, 26] (Fig. 6). The conclusion of Canepa *et al.* [12] is that the BSSS computed using BORIS-SSA are in good agreement with the BSSS acquired at sea. Thus, potentially, the need for difficult and expensive sea experiments has receded.

Several sea trials have since looked at target scattering with bistatic geometries. The SITAR experiments [22] extended the scaled target scattering experiments presented in Sec. 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 [36]. The bistatic part of the sea trials focused on several targets of interest. The transmitter was a TOPAS-120 parametric array (beamwidth 3–4°), placed on a Remotely-Operated Vehicle. The scattering was recorded on a 6-hydrophone chain in a fixed mooring (Fig. 7). The ROV was 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 surface DGPS navigation.

These sea trials proved the success of scaling up the strategy originally designed in the laboratory (Sec. 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 (e.g. Karasalo *et al.* [19]). Issues revealed during these trials were

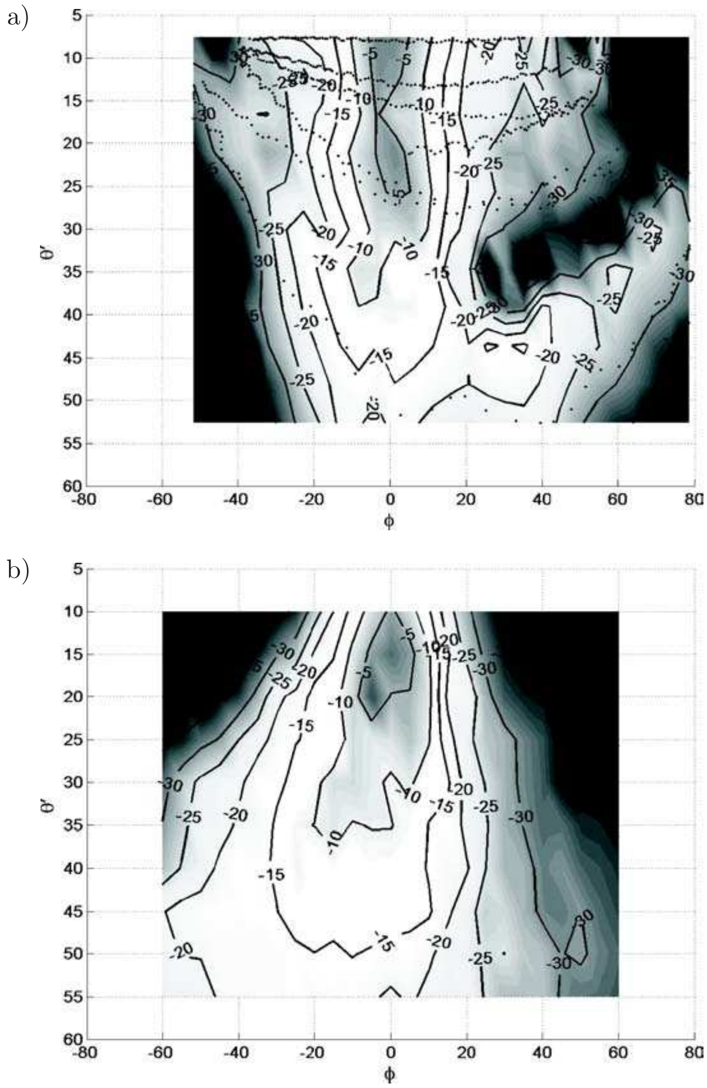

Fig. 6. Comparison between bistatic scattering strengths measured at sea a) and simulated b). From Canepa *et al.* [13].

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 [19].

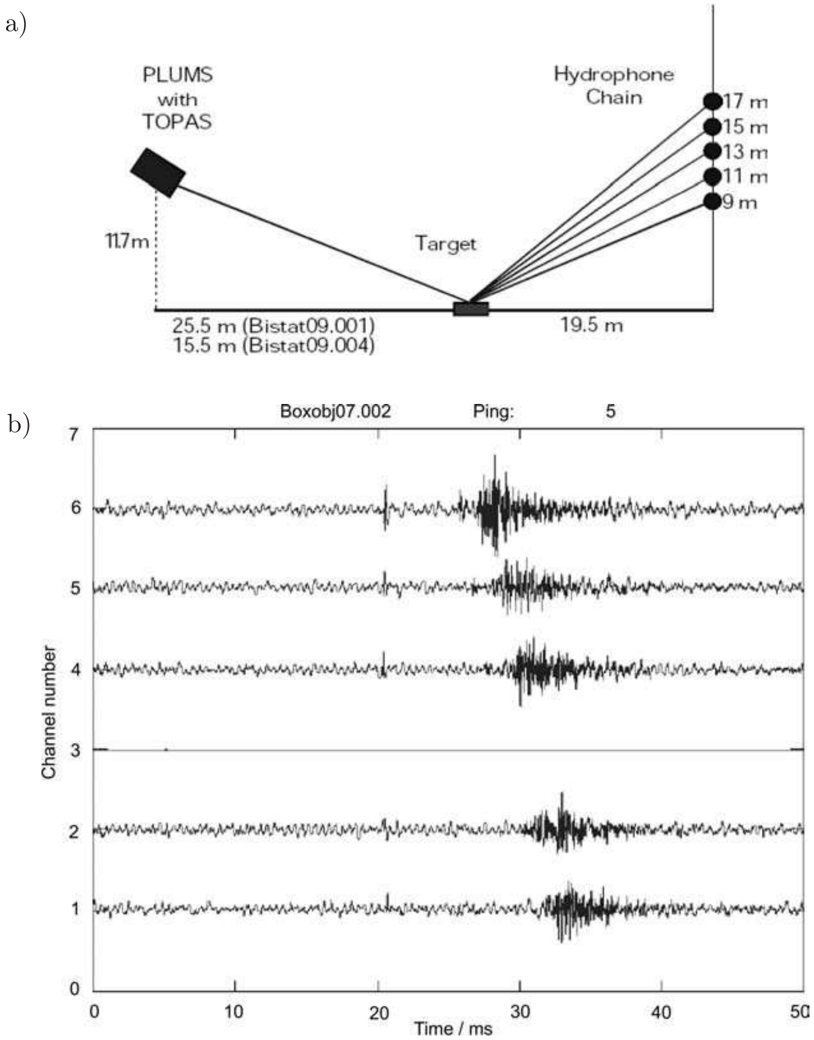

Fig. 7. a) typical bistatic setup used during the SITAR sea trials; the TOPAS-120 transmitter is mounted on the research ROV PLUMS, b) typical signals recorded on the hydrophone chain.

5. Discussion – conclusions

The different types of experiments presented here are a representative subset of many experiments performed, mostly during the last decade, by several research groups around the world. Simpson *et al.* [29] and Drevet [17] looked for example at the role of seabeds in tank experiments. Papadakis *et al.* [25] presented a series of scaled shallow-water tank experiments, and how these could be standardised for a better comparison of results from different tests. Full-scale tank experiments have also been performed with more complex targets, e.g. by Humphrey *et al.* [18], investigating the importance of the filling in partially fluid-filled cylinders. Biffard *et al.* [3] used the combination of a real test-bed, with exhaustive sampling of its seabed and acoustics properties, with a simulated test-bed (using BORIS). The library of data thus created can arguably be used to develop single-beam echosounder characterisation techniques, although these tests do not account for the high seasonal variability of the seafloor (e.g. with tides or storms, notwithstanding vegetation in shallower areas), taken into account in most other experiments. Zampolli *et al.* [38] showed how recent advances in high-performance modelling of scattering by complex objects can match both analytical treatments and, more importantly, actual measurements of real targets such as those used in the EVA'06 experiment [31, 38]. This follows up from the work done by Tesei *et al.* [32] at sea, for scattering by air-filled cylinders and during the GOATS'98 experiments [28] with monostatic sonars. Elegant and scientifically promising investigations of scattering within targets and the role of resonant frequencies (e.g. Tesei *et al.* [20, 30, 31]) can now be brought to bear on more complex targets (e.g. solid-filled fibreglass sphere and cylinder with hemispherical endcaps). Some early conclusions of the EVA'06 experiments show however that scaled and full-scale targets need to be simple enough to be computationally tractable with models at desired accuracy. Finally, no discussion of bistatic experiments cannot be complete without the mention of the SAX'99 experiments (e.g. Williams *et al.* [34]) and the SAX'04 trials (e.g. Richardson *et al.* [27] and other articles in Pace and Blondel [24]), which resulted in extensive publications. One point worth noting, however, is that most of these tests have been application-driven. Explicitly or implicitly, they have for the most part investigated targets of military interest, e.g. mines. Although their results could be used to address the same objectives, the SITAR sea trials were the first ones to explicitly consider the more general, and acoustically more complex problem of buried waste.

The previous sections summarised the main aspects of several types of experiments: scaled and full-scale 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. Scaled tank experiments of seabed scattering enable a more quantitative understanding of the different sources of uncertainties in interpreting experimental results, e.g. positioning accuracy and the role of sidelobes. They show that the largest sources of disagreement between measurements and models of high-frequency bistatic scattering consist in miscalculating the instantaneous scattering area, and inaccurate measurements of seabed roughness and its variations. Published (see references above) and unpublished (restricted technical documents and personal communications) reports show that full-scale tank experiments mostly corroborate the results from scaled tank experiments, showing the importance of careful design over size considerations. Sea trials demonstrate clearly the conclusions from tank experiments, showing as well the increasing agreement between measurements and sophisticated models of bistatic scattering.

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. Laboratory experiments help design (or test) the surveying strategies employed at sea (i.e. line scans for detection and rotation scans for identification), and the optimal configurations of the bistatic system (transmitter + hydrophones). Sea trials form the "ultimate truth", especially if adequately designed and performed for the objectives chosen.

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.

Acknowledgments

The Bath experiments were funded by DERA/QinetiQ and the European Community (SITAR project). Use of the GESMA facilities was organised by M. Zakharia (IRENAV) within the SITAR project. The Elba data was collected within the Joint Research Project "Wideband acoustic interaction with the seabed" between DERA and NURC. The Sweden data was collected as part of the SITAR project. Part of this presentation was presented at the Institute of Acoustics (UK) conference "Detection and Classification of Underwater Targets" in September 2007. It was greatly enriched through discussions with other experimenters worldwide, in particular N. Chotiros (ARL/UT), A. Tesei and M. Zampolli (NURC). We acknowledge the constructive comments of two anonymous reviewers.

References

[1] Anstee S., *Removal of range-dependent artifacts from sidescan sonar imagery*, Technical Report DSTO-TN-0354, 2001.

[2] *APL-UW High-Frequency Ocean Environmental Acoustic Models Handbook*, Applied Physics Laboratory, University of Washington, APL-UW TR 9407, AEAS 9501, October 1994.

[3] Biffard B.R., Bloomer S.F., Chapman N.R., Preston J.M., Galloway J.L., *Single-beam seabed characterization: a test-bed for controlled experiments*, Proc. 8th ECUA, 2006.

[4] Blondel Ph., *Rapid distinction of dumpsite objects using multiple-aspect scattering: Results from scaled experiments*, Acoustics'2008, p. 3948, J. Acoust. Soc. Am., **123**, 5, Pt. 2 (2008).

[5] Blondel Ph., Caiti A. [Eds.], *Buried Waste in the Seabed – Acoustic Imaging and Bio-toxicity (Results from the European SITAR project)*, Springer-Praxis 2007.

[6] Blondel Ph., Fang D., Smith A., Jayasundere N., *High-frequency bistatic imaging of proud targets – Influence of target orientation and type*, Proc. 2nd UAM, Heraklion 2007.

[7] Blondel Ph., Murton B.J., *Handbook of Seafloor Sonar Imagery*, p. 314, PRAXIS-Wiley & Sons, 1997.

[8] Blondel Ph., Pace N.G., *Scaled tank experiments: Seabed and target scattering at high frequencies*, Proc. 1st UAM. Heraklion 2005.

[9] Blondel Ph., Pace N.G., Heald G.J., Brothers R., *High-frequency bistatic scattering: comparison of tank and sea experiments*, Proc. IOA, **23**, 2, 276–282, SOC 2001.

[10] Blondel Ph., McCloghrie P., Pace N.G., Heald G.J., Brothers R., *High-frequency bistatic bottom scattering: Modelling and experimental studies*, pp. 21–29, Proc. 6th ECUA, Gdańsk 2002.

[11] Blondel Ph., Dobbins P.F., Jayasundere N., Cosci M., *High-frequency bistatic scattering experiments using proud and buried targets*, [in:] Experimental Acoustic Inversion Techniques in Shallow-Water, Caiti A., Chapman R., Jesus S., Hermand J.-P. [Eds.], pp. 155–170, Springer, 2006.

[12] Canepa G., Pouliquen E., Pautet L., Pace N.G., *Bistatic scattering from the seabed at high frequency*, Proc. 7th ECUA, pp. 595–600, Delft 2004.

[13] Canepa G., Pace N.G., Pouliquen E., *Field measurements of bistatic scattering strength of a sandy seabed at 118 kHz*, Proc. 6th ECUA, pp. 183–188, Gdańsk 2002.

[14] Choi J.W., Na J., Seong W., *240-kHz bistatic bottom scattering measurements in shallow water*, IEEE J. Ocean. Eng., **26**, 1, 54–62 (2001).

[15] Cosci M., Caiti A., Blondel Ph., Jayasundere N., *A potential algorithm for target classification in sonar bistatic geometries*, [in:] Boundary Influences in High-Frequency Shallow Water Acoustics, Pace N.G. and Blondel Ph. [Eds.], pp. 367–374, U. Bath, 2005.

[16] Dobbins P.F., Jayasundere N., Blondel Ph., *Multiple-Aspect Imaging of Seafloor Targets – Analyses of Tank Experiment Datasets*, pp. 469–474, Proc. 5th ECUA, Delft 2004.

[17] Drevet C., *High-frequency wave propagation of the fast compressional wave in fine to medium sand: Acoustic measurements in tank*, Proceedings of the Fifth European Conference on Underwater Acoustics ECUA-2000, 2000.

[18] Humphrey V.F., Jayasundere N., Dench M., Chinnery P.A., *Experimental and theoretical studies of scattering by partially fluid-filled cylindrical shells*, pp. 463–468, Proc. ECUA-2004, 2004.

[19] Karasalo I., Skogqvist P., Blondel Ph., Dobbins P.F., *Buried waste inspection: acoustical images and inversion from multiple-aspect scattering*, [in:] Buried Waste in the Seabed, Blondel Ph. and Caiti A. [Eds.], pp. 115–126, Springer-Praxis, 2007.

[20] Lucifredi I., Schmidt H., *Subcritical scattering from buried elastic shells*, J. Acoust. Soc. Am., **120**, 6, 3566–3583 (2006).

[21] Lyons A.P., Pouliquen E., *Advances in high-resolution seafloor characterization in support of high-frequency underwater acoustics studies: Techniques and Examples*, Meas. Sci.&Tech., **15**, R59–R72 (2004).

[22] Moren P., Caiti A., Zakharia M., Larsen M.A., Blondel Ph., Dybedal J., *Acoustic sea trial in the Möja Söderfjärd dumpsite*, [in:] Buried Waste in the Seabed, Blondel Ph. and Caiti A. [Eds.], pp. 87–102, Springer-Praxis, 2007.

[23] Pace N.G. *et al.*, *BORIS-SSA: Bottom Response from Inhomogeneities and Surface using Small Slope Approximation*, Technical Report M-152, NATO URC (2004).

[24] Pace N.G., Blondel Ph. [Eds.], *Boundary Influences in High-Frequency Shallow-Water Acoustics*, University of Bath Press, 2005.

[25] Papadakis P., Taroudakis M., Sanchez P., Sessarego J.-P., *Time and frequency measurements using scaled laboratory experiments of shallow-water acoustic propagation*, Proc. 8th ECUA, 2006.

[26] Pouliquen E., Bergem O., Pace N.G., *Time evolution modelling of seafloor scatter (1): Concept*, J. Acoust. Soc. Am., **105**, 6, 3136–3141 (1999).

[27] Richardson M.D. *et al.*, *The effects of seafloor roughness on acoustic scattering*, Boundary Influences in High-Frequency Shallow Water Acoustics, 2005.

[28] Schmidt H. *et al.*, *GOATS'98: bistatic measurements of target scattering using autonomous underwater vehicles*, SACLANTCEN Rep. SR-302, 1998.

[29] Simpson H.J., Houston B.H., Frederickson C.K., Lim R., *Measurements and analysis of scattering from proud and buried targets in a shallow-water laboratory environment*, Proceedings of the IEEE Conference Oceans'99, 1999.

[30] Tesei A., Maguer A., Fox W.L.J., Lim R., Schmidt H., *Measurements and modelling of acoustic scattering from partially and completely buried spherical shells*, J. Acoust. Soc. Am., **112**, 5, 1817–1830 (2002).

[31] Tesei A., Zampolli M., Canepa G., *At-sea measurements of acoustic elastic scattering by a 1.5-m long cylinder made of composite materials*, pp. 505–510, 2nd UAM Proc., 2007.

[32] Tesei A., Fox W.L.J., Maguer A., Løvik A., *Target parameter estimation using resonance scattering analysis applied to air-filled, cylindrical shells in water*, J. Acoust. Soc. Am., **108**, 6, 2891–2900 (2000).

[33] Williams K.L., Jackson D.R., *Bistatic bottom scattering: Model, experiments and model/data comparison*, J. Acoust. Soc. Am., **103**, 1, 169–181 (1998).

[34] Williams K.L. *et al.*, *Underwater sand acoustics: A perspective derived from the sediment acoustics experiment (SAX99)*, J. Acoust. Soc. Am., **113**, 4, 2298 (2003).

[35] Zakharia M., *Preparation des essais GESMA – Projet SITAR*, internal report, 2004.

[36] Zakharia M., *Full-scale tank parametric sidescan sonar test*, [in:] Buried Waste in the Seabed, Blondel Ph. and Caiti A. [Eds.], pp. 79–82, Springer-Praxis, 2007.

[37] Zampolli M., Tesei A., Jensen F.B., Blottman J.B., *Finite element and hybrid modelling tools for the detection and classification of buried objects in shallow water*, [in:] Boundary Influences in High-Frequency Shallow Water Acoustics, Pace N.G. and Blondel Ph. [Eds.], pp. 349–356, U. Bath, 2005.

[38] Zampolli M., Tesei A., Jensen F.B., Malm N., Blottman J.B., *A computationally efficient finite element model with perfectly matched layers applied to scattering from axially symmetric objects*, J. Acoust. Soc. Am., **122**, 3, 1472–1485 (2007).