High-frequency seafloor acoustic backscatter from coastal marine habitats of Australia

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ABSTRACT

Backscatter strength versus incidence angle has been measured from a variety of seafloor types from Australian coastal waters using a Reson Seabat 8125 multibeam echo-sounder (MBES) operating at 455 kHz. MBES surveys were carried out at six sites around Australia (between 2004 and 2006). Seafloor habitats surveyed in this study included: seagrass meadows, rhodolith beds, coral reef, rock, gravel, sand, muddy sand, and mixtures of those habitats. The highest backscatter strength was observed not only for the hard and rough substrate, but also for marine flora, such as rhodolith and seagrass. The main difference in acoustic backscatter from the different habitats was the mean level, or angle-average backscatter strength. However, additional information was also obtained from the rate of change (or slope) of backscatter strength with incidence angle. Overall, analysis of MBES backscatter data found at least six different seafloor habitats could be identified, in descending order of their average backscatter strength: 1) Rhodolith, 2) Coral, 3) Rock, 4) Seagrass, 5) sand-dominated bare (i.e. no epibenthic cover) sediment, 6) mud-dominated bare (i.e. no epibenthic cover) sediment.

INTRODUCTION

Multibeam echo-sounder (MBES) systems are one of the most effective tools available to map the seafloor (Kenny *et al.* 2003). This is because MBES systems are capable of collecting data from a wide swath of the seafloor. The MBES backscatter signals are primarily used to derive high-resolution bathymetry; however, the backscatter intensity is also provided by some systems (de Moustier, 1986; Hughes Clarke, 1994, Parnum and Gavrilov, 2011a). Backscatter intensity is influenced by seafloor properties, such as acoustic impedance (relative to the water above it), surface roughness and volume heterogeneity (Jackson and Richardson, 2007). Hence, MBES backscatter intensity measurements have been used to infer seafloor properties and segment the seafloor into different acoustically different regions; see more details the review by Parnum and Gavrilov (2011b) and references there in.

It is well known from various theoretical models and experimental observations that acoustic backscatter from the seafloor is dependent on incidence angle (de Moustier, 1986; Hughes Clarke, 1994; Canepa and Pace, 2000; Jackson and Richardson, 2007; and Kloser *et al.*, 2010). In addition, the backscatter intensity and its statistical properties measured with MBES systems depend on the insonification area and footprint size of the receive beams (Hellequin *et al.*, 2003; Gavrilov and Parnum, 2010). The relationship between backscatter intensity and incidence angle, referred to here as angular dependence of backscatter, is a useful property that can be used to discriminate between different seafloor habitats (Hughes Clarke, 1994; Canepa and Pace, 2000; Kloser *et al.*, 2010 and Hamilton and Parnum, 2011).

One of the most used theoretical models of seafloor backscatter was developed by Jackson *et al.* (1986) and others at the Applied Physics Laboratory (APL, 1994), referred to here as the APL model. Bentrem *et al.* (2006) and Kloser *et al.*, (2010) have both demonstrated the application of the APL model to predict the sediment composition from backscatter

data collected with a Simrad EM1002 MBES, operating at 95 kHz. The APL model is considered only valid for backscatter measured at frequencies of less than 100 kHz (APL, 1994), while most shallow-water MBES systems operate at hundreds of kHz (e.g. Reson Seabat 7125, Simrad EM 3002). A theoretical model that has been shown to predict seafloor properties satisfactorily from high-frequency (> 100 kHz) MBES backscatter data is the Angular Range Analysis (ARA) developed by Fonseca and Mayer (2007). The ARA method is based on the effective density fluid model derived from the Biot theory (Williams, 2001) with some modifications for the calculation of the volume scattering contribution. For sedimentary beds, the ARA method has demonstrated some promising results (Fonseca and Mayer, 2007). However, one of the main limitations of using theoretical models is that, at present, there is no universal high-frequency backscatter model available to adequately describe the backscatter angular response from all shallow water seafloor types, including seagrass, rhodolith, coral reef, etc. This study presents some experimental results from a variety of seafloor habitat found around the Australian coast that could help in the development of backscatter models.

Coastal Water Habitat Mapping project

MBES data were collected as part of the Coastal Water Habitat Mapping (CWHM) project, which was an initiative of the Cooperative Research Centre for Coastal Zone, Estuary and Waterway Management (Coastal CRC). It was one of the largest programs related to shallow water benthic habitat mapping in Australia (Penrose, 2007). This paper presents MBES data collected from six sites around the Australian coast (Figure 1). These sites represent a wide range of the coastal-benthic habitats found in Australia, including coral reefs, seagrass, rocky reefs and various grades of sediment from mud (7 phi) to gravel (-4 phi). The primary MBES system used for this study was the Reson SeaBat 8125, which operates at 455 kHz.
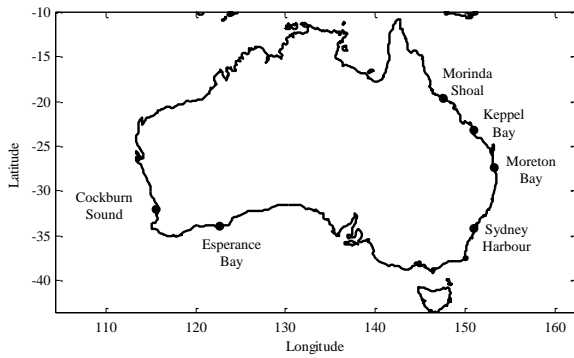
Figure 1. Location of data collected with the Reson Seabat 8125 multibeam echo-sounder.

METHODS

Data collection

A Reson Seabat 8125 MBES was used to collect data from Cockburn Sound, and Esperance Bay in Western Australia; Moreton Bay, Keppel Bay and Morinda Shoal in Queensland and Sydney Harbour in New South Wales (Figure 1). Data were collected using an over the side mount for the MBES off vessels of opportunity. Ancillary systems were a FUGRO Starfix DGPS for position, DMS05 motion sensor for heave, roll and pitch and Meridian Surveyor gyrocompass for heading.

Data processing

MBES data were processed using CMST's multibeam sonar processing toolbox, which was developed in MATLAB® (Parnum, 2007). CMST's processing toolbox calculates the surface scattering coefficient from the energy of backscatter returns by integrating the squared amplitude of the beam time series data (referred to by Reson as 'Snippets'). The resulting numbers were reduced to the width of the transmitted pulse, giving the pulse-averaged intensity, and were corrected for the transmit power and receive gain, which makes the backscatter estimates independent of the system settings (Parnum and Gavrilov, 2011a). The Reson system applies a Time Varied Gain (TVG) correction to the backscatter data, which is not always adequate to the actual conditions of acoustic propagation. So the TVG correction was removed and the backscatter data corrected for the actual spreading and absorption loss, and then reduced to the footprint size of each beam to obtain estimates of the surface scattering coefficient (Parnum, 2007); expressed here in the logarithmic scale and referred to as backscatter strength. However, these processed measurements were in relative units and required calibration to determine the fixed gain of the system to obtain absolute values.

Calibration

A calibration experiment was carried out to determine the fixed gain applied by the Reson 8125 MBES system. The calibration was made in a large swimming pool using a rectangular aluminium plate of known acoustic reflectivity (Parnum, 2007). The plate was 40 by 40 cm wide, which was large enough to make sure that it reflected the sonar signal from the whole footprint of the sonar beams at the measurement distance of 6.5 m. The calibration results showed that this particular model had a fixed receive system gain of 1.86×10^{-5} Analogue-to-Digital Converter units per μPa that

was reasonably uniform across all beams. The calibration was carried out at 20° C. The effect of change in temperature on the calibration was not considered for this paper.

Data analysis

Backscatter strength versus incidence angle data were collated into the different seafloor habitats encountered at the different sites. Ground-truth information, such as underwater video and grab samples was used to verify the seafloor habitats. The angle average (i.e. the mean) and slope of backscatter strength over 5-60° was also calculated.

RESULTS

Mean backscatter strength versus incidence angle measurements collected with the Reson 8125 for a variety of seafloor habitats are shown in Figure 2. The data represent a wide variety of seafloor types typical for the shallow coastal waters of Australia. The mean backscatter strength was lowest for the fine sediments (e.g. mud and flat sand) and, in general, as the sediment grain size and surface roughness increased so did the backscatter strength. The highest backscatter strength values were recorded not only from hard and rough substrates such as rock, coral reef and gravel, but also from marine flora, such as rhodolith and some seagrasses. The mean values of backscatter strength measured from seagrass were found to be generally much higher than those from areas of bare sand observed in the same survey area (Figure 2). Also, the backscatter strength from temperate seagrasses (e.g. *Posidonia sp.*) in Cockburn Sound) was found to be, in general, higher than that from the shorter and less dense tropical seagrasses (e.g. *Halophila ovalis* in Moreton Bay).
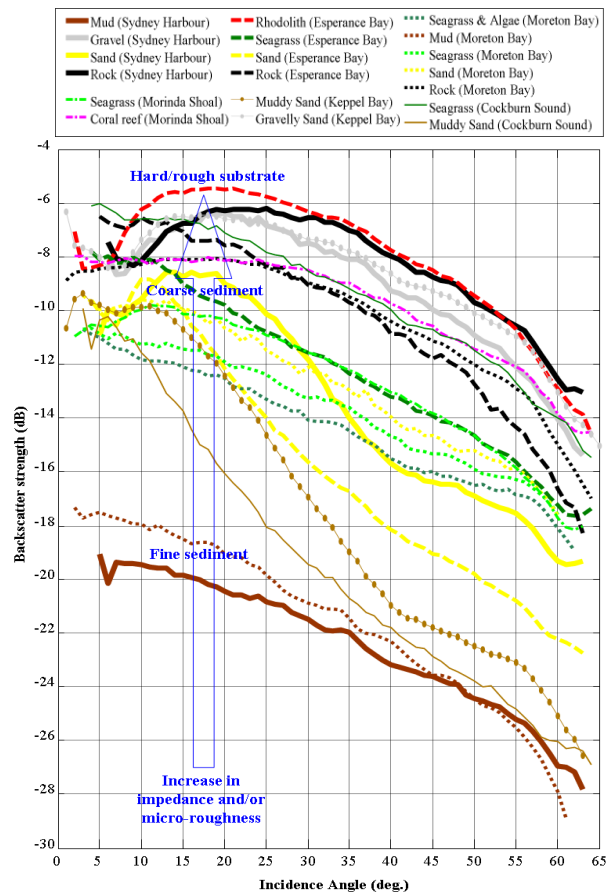
Figure 2. Mean backscatter strength (dB) versus incidence angle (deg.) for a variety of seafloor habitats from around the Australian coast measured using a Reson SeaBat 8125 MBES system (operating at 455 kHz).
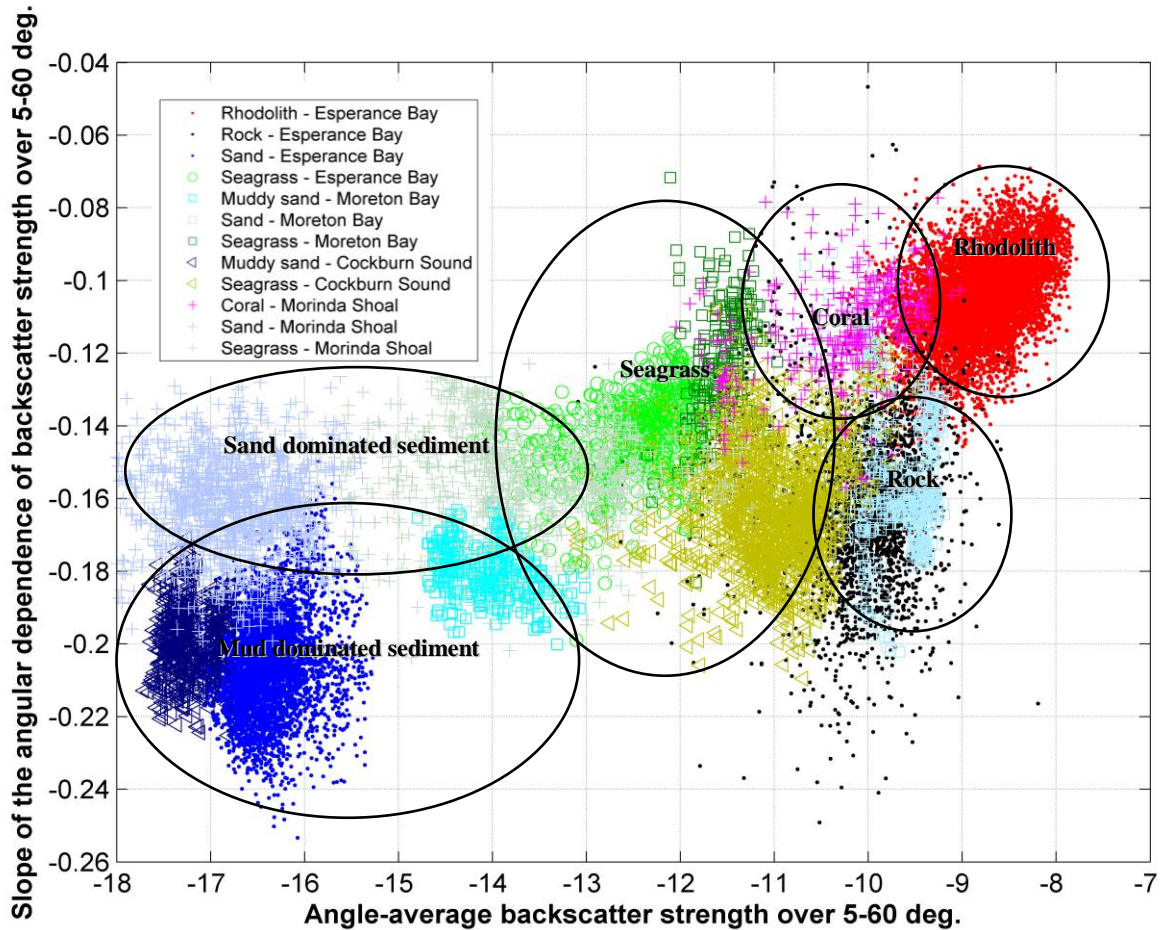
Figure 3. Slope of angular dependence of backscatter strength (dB/deg.) versus angle-average backscatter strength (dB) over 5-60 deg. for a variety of seafloor habitats from around the Australian coast measured using a Reson SeaBat 8125 MBES system (operating at 455 kHz).

Figure 3 shows the relationship between the slope of angular dependence and the angle-average backscatter strength measured within some of the selected training areas representing different habitats from the different case studies. An analysis of such relationships between different backscatter characteristics is useful for identifying the similarity and differences between habitats acoustically observed in different regions. For instance, in Moreton Bay the class labelled *sand* has a much higher angle-average backscatter strength than other soft sediment classes and is similar to the values obtained from *rock* (in Esperance Bay) and *coral* (in Morinda Shoal). This could be due to a number of reasons, such as the presence of larger sized sediments, such as pebbles or shell, or of hard surfaces (e.g. bedrock) or gas content present in the sediment. Further investigation of habitats in such areas by means of direct probes would be necessary to establish the actual reasons for anomalous backscatter. In addition, the direct measurement of surface roughness would also aid the interpretation of results.

DISCUSSION

Comparison with other studies and theoretical models

The field measurements are comparable with the theoretical predictions of backscatter from rock and bare sediments (i.e. no flora) at 455 kHz using the APL model shown in Parnum (2007), but also show some discrepancies. For instance, at nadir where backscatter is dominated by contributions from specular reflection, the APL model predicts quite accurately the values measured for rock and fine sediment. However, the values of backscatter measured at nadir for some sandy beds were noticeably higher than predicted. Except for some sedimentary habitats, the majority of seafloor types surveyed, the mean slope of the angular dependence at angles from 20 to 60° was not significantly different, revealing a decrease of the order of 6-8 dB over this angular sector. This is comparable to that measured with a lower frequency (95 kHz) system by Kloser *et al.* (2010). However, at the drop in seafloor backscatter from nadir to 20° at 455 kHz (results presented here) were typically 2-3 times smaller than at those at 95 kHz observed by Kloser *et al.* (2010). This is consistent with the theoretical models that predict levelling of the angular dependence of backscatter as the Rayleigh number increases

(Broschat & Thorsos, 1997). However, some areas of mixed sand and fine sediment did show noticeably different slopes of the angular dependence, which could be due to variations in geomorphological features of the seafloor surface (e.g. presence of sand ripples) and actual sediment content (e.g. presence of seashell debris, gas content, etc). Also, for some areas of rock, gravel and rhodolith, the backscatter strength exhibited a small decrease towards nadir. Such dips in backscatter strength at nadir have been observed previously for some other highly rough gravely /pebble-like surfaces (Beaudoin *et al.*, 2002). In addition, model results suggest there a theoretical basis for scattering regimes where the Rayleigh Parameter is >> 1 (Gragg *et al.*, 2001), such is the case as this study. However, further work is required to determine the reasons behind these features in the angular dependence curves.

Scattering from marine flora

The reasons for higher backscatter strength from hard substrates are apparent, and are large roughness and high acoustic impedance. These are also the most likely reasons for stronger backscatter from rhodolith. The reasons for the stronger scattering recorded from seagrass (than surrounding bare sediment), however, are less obvious but are consistent with other studies (de Falco *et al.*, 2010; Torres-Medina *et al.*, 2010). Backscatter strength from temperate seagrasses (e.g. *Posidonia sp.*) in Cockburn Sound) was found to be, in general, higher than that from the shorter and less dense tropical seagrasses (e.g. *Halophila ovalis* in Moreton Bay). This could imply that the size and density of canopy influences the amount of acoustic energy scattered back to the sonar, which is supported by laboratory experiments (Wilson & Dunton 2007). It is unknown to what degree gas filled channels within the seagrass and gas bubbles generated by the plants during photosynthesis dominate the acoustic behaviour (Wilson & Dunton 2007). A study of backscatter strength from seagrass collected at vertical incidence at 38 and 200 kHz by Torres-Medina *et al.* (2010), found no significant fluctuations over a 5 day period. However, further study is still required to determine the relative contribution of acoustic energy that is scattered from gas micro-bubbles produced by both seagrass and rhodolith, as well as the effect of epiphytes.

Implications for seafloor classification

The results presented here indicate that at least six coastal seafloor habitat classes were distinguished through an analysis of MBES backscatter data: 1) Rhodolith, 2) Coral, 3) Rock, 4) Seagrass, 5) sand-dominated bare sediment, 6) mud-dominated bare sediment. Further 'acoustic' classes are potentially possible through analysis of more parameters of the angular response such as those suggested by Hughes Clarke (1994), or by using the whole of the angular response curve (Hamilton and Parnum, 2011). In addition, other studies have found that higher statistical moments (e.g. variance and other descriptors of distribution) of backscatter are also useful (Hellequin *et al.,* 2003), but these can also be dependent on the beam geometry (Gavrilov and Parnum, 2010). However, it is unclear whether increasing the number of 'acoustic' classes will result in an increase in the number of distinctive geological or biological seafloor habitat classes, e.g. different types of seagrass, etc. Terrain analysis of bathymetry data combined with ecological modelling can provide some additional information about the spatial distribution of seafloor habitats and biota (Holmes, 2008). As shown in other studies (e.g. Hughes Clarke, 1994; Canepa and Pace, 2000; Kenny *et al.*, 2003; de Falco *et al.*, 2010) combined high-resolution

bathymetry and seafloor backscatter can adequately map important coastal seafloor habitats.

Current and future research focus

Improvements in acoustic modelling have shown the potential for predicting seafloor properties (Fonseca and Mayer, 2007). However, acoustic scattering from shallow water coastal marine environments, such as from marine flora, is still not completely understood and requires further investigation.

Repeat surveys to indentify and quantify changes in the seafloor environment are an important part of coastal zone management. However, in order to adequately carryout these types of studies using MBES backscatter, an understanding of MBES measurement repeatability and sensitivity is required, which includes, but is not limited to:

- Calibration drift;
- System settings;
- System frequency.

Even if the same MBES system is used to carry out repeat surveys, consideration needs to be given to change in response of the MBES system over time and in different temperature regimes, which is something that is not well understood and requires further investigation. In addition, it is important to understand the effect of system settings, such as pulse width. For instance, Parnum and Gavrilov (2011a) found that if the pulse width becomes shorter than the Nyquist sampling interval then backscatter measurements cannot be adequately corrected for pulse width, making comparison between different datasets a challenge, especially if different pulse widths are used. Moreover, carrying out repeat surveys with different MBES systems operating at different frequencies can make comparison between datasets a nontrivial task. Integration and comparison of MBES backscatter collected at different frequencies is an important research topic in seafloor mapping.

ACKNOWLEDGEMENTS

REFERENCES
Applied Physics Laboratory 1994,' UW High Frequency Ocean Environmental Acoustic Models Handbook', Technical Report APL–UW TR-9407, Applied Physics Laboratory, University of Washington, Seattle.

Beaudoin, JD, Hughes-Clarke, JE, Van Den Ameele, EJ & Gardner, JV 2002, 'Geometric and radiometric correction of multibeam backscatter derived from Reson 8101 systems', *Canadian Hydrographic Conference*, Canadian Hydrographic Association, Ottawa, Ontario.

Bentrem, FW, Avera, WE & Sample, J 2006, 'Estimating Surface Sediments Using Multibeam Sonar', *Sea Technology*, vol. 47, no. 6, pp. 37-40.

Broschat, SL & Thorsos, EI 1997, 'An investigation of the small slope approximation for scattering from rough surfaces. Part II. Numerical studies', *Journal of the Acoustical Society of America,* vol. 101, no. 5, pp. 2615-25.

Canepa, G & Pace, NG 2000, 'Seafloor segmentation from multibeam bathymetric sonar', *Proceedings of the Fifth European Conference on Underwater Acoustics*, ed. ME Zakharia, Lyon, France, pp. 361-6.

de Falco, G, Tonielli, R, Di Martino, G, Innangi, S, Simeone, S & Parnum, IM 2010, 'Relationships between multibeam backscatter, sediment grain size and *Posidonia oceanica* seagrass distribution', *Continental Shelf Research,* vol. 30, pp. 1941–1950.

de Moustier, CP 1986, 'Beyond bathymetry: mapping acoustic backscattering from the deep seafloor with Sea Beam', *The Journal of the Acoustical Society of America,* vol 79, No.2 pp. 316-31.

Fonseca L & Mayer, L 2007, 'Remote estimation of surficial seafloor properties through the application of angular range analysis to multibeam sonar data'. *Marine Geophysical Researches*, vol. 28, no. 2, pp. 119–26.

Gavrilov, AN, & Parnum, IM 2010, 'Fluctuations of seafloor backscatter data from multibeam sonar systems'. *IEEE Journal of Oceanic Engineering*, vol. 35, no. 2, pp. 209–219.

Gragg, RF, Wurmser, D, and Gauss, RC, 2001, 'Small-slope scattering from rough elastic ocean floors: general theory and computational algorithm', *The Journal of the Acoustical Society of America,* vol 110, No.6 pp. 2878-2901.

Hamilton, LJ & Parnum, IM 2011, Acoustic seabed segmentation from direct statistical clustering of entire multibeam sonar backscatter curves, *Continental Shelf Research*, 31 (2011), pp. 138-148.

Hellequin, L, Boucher, JM & Lurton, X 2003, 'Processing of high-frequency multibeam echo sounder data for seafloor characterization', *IEEE Journal of Oceanic Engineering,* vol. 28, no. 1, pp. 78-89.

Holmes, K, Niel, KV, Radford, B, Kendrick, G, & Grove, S 2008, 'Modelling distribution of marine benthos from hydroacoustics and underwater video', *Continental Shelf Research*, vol. 28, pp. 1800–1810.

Hughes Clarke, JE 1994, 'Towards remote seafloor classification using the angular response of acoustic backscatter: a case study from multiple overlapping GLORIA Data', *IEEE Journal of Oceanic Engineering,* vol. 19, no. 1, pp. 112-27.

Jackson, DR, & Richardson MD 2007, *High-frequency seafloor acoustics*, 1st Ed., Springer.

Jackson, DR, Winebrenner DP & and Ishimaru, A 1986, 'Application of the composite roughness model to high-frequency bottom backscatter', *Journal of the Acoustical Society of America,* vol. 79, pp. 1410-22.

Kenny, AJ, Cato, I, Desprez, M, Fader, G, Schuttenhelm, RTE & Side, J 2003, 'An overview of seabed-mapping technologies in the context of marine habitat classification', *ICES Journal of Marine Science,* vol. 60, no. 2, pp. 411-8.

Kloser, RJ, Penrose, JD, & Butler AJ 2010. 'Multi-beam backscatter measurements used to infer seabed habitats', *Continental Shelf Research*, vol., 30, no. 16, pp. 1772-1782.

Parnum, IM, 2007, 'Benthic habitat mapping using multibeam sonar systems'. PhD thesis. Curtin University, Perth, Australia, pp 208.

Parnum, IM, & Gavrilov, AN 2011a, 'High-frequency multibeam echo-sounder measurements of sea floor backscatter in shallow water: Part 1 - Data acquisition and processing', *International Journal of the Society for Underwater Technology*, vol. 30, no. 1, 3-12.

Parnum, IM, & Gavrilov, AN 2011b, 'High-frequency multibeam echo-sounder measurements of sea floor backscatter in shallow water: Part 2 - Mosaic production, analysis and classification', *International Journal of the Society for Underwater Technology*, vol. 30, no. 1, 3-12.

Penrose, JD 2007, 'Coastal water habitat mapping', in R Souter (ed.), *Building the bridges: seven years of Australian coastal cooperative research*, Cooperative Research Centre for Coastal Zone, Estuary and Waterway Management, pp. 75-9.

Torres-Medina, M, Gavrilov, AN, Parnum, I 2010, 'Theoretical and Experimental Studies of Seafloor Backscatter', *ECUA 2010 Conference*, Istanbul, 5-9 July 2010.

Williams, KL 2001, 'An effective density fluid model for acoustic propagation in sediments derived from Biot theory', *Journal of the Acoustical Society of America*, vol. 110, no. 5, pp. 2276–2281.

Wilson, PS & Dunton, KH 2007, 'Seagrass acoustics: results of an experimental laboratory investigation', *Proceedings of the Second International Conference "Underwater Acoustic Measurements: Technologies & Results*, Crete, Greece.