SEABED HABITAT MAPPING IN COASTAL WATERS USING A NORMAL INCIDENT ACOUSTIC TECHNIQUE

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Abstract

As part of the Coastal Water Habitat Mapping (CWHM) project of the Cooperative Research Centre for Coastal Zone, Estuary and Waterway Management (Coastal CRC), a set of bathymetry and acoustic backscattering data was collected in Cockburn Sound, Western Australia in March 2004 in order to develop acoustic methods for seabed classification. The acoustic recordings were made over seabed areas of different habitat types using a SIMRAD EQ60 echosounder operating at two frequencies of 38 and 200 kHz. A drop video camera was also used to provide groundtruthing for the acoustic results at selected stations. A RoxAnn-like technique was adopted for acoustic classification of the seabed habitat types. An analysis of the backscattered signals was also made to determine the backscatter characteristics which were more robust with respect to discrimination of seagrass on the seabed. Five different seabed habitats were derived from the RoxAnn-like technique, which agreed well with the video recordings. From the backscatter analysis, it was found that the effective pulse width of backscattered signals and the surface backscatter coefficient were the most suitable characteristics for distinguishing seagrass meadows from the other, seagrass-free bottom types.

Nomenclature

c_τ	Pulse length offset
$d_{\theta a}$, $d_{\theta b}$	Depths corresponding to θ_a, θ_b respectively
E1	Bottom roughness
E2	Bottom hardness
$f_i(j)$	Backscatter intensity level of ping j at sample i
$G(\theta_1)$	Transducer gain
i	Sample index
i_c	Sample index at the centre of mass of backscatter pulse
i_f	First sample index of the acoustic returns above the threshold
$I(i)$	Moment of inertia of ping i
$m_s(\theta_1)$	Acoustic scattering coefficient
p_0	Source pressure at a distance of 1 m from the source
R	Bottom depth/range
R_0	Reference range
$\Re$	Acoustic reflection coefficient
$\bar{s}_A$	Surface backscattering coefficient
$\bar{S}_A$	Surface backscattering strength
s_v	Linear volume backscattering coefficient
t	Time
T	Correlation length of the surface roughness
$T_{\Delta f}$	Difference between the arrival time of the first return signal at different frequencies
$W(i)$	Effective pulse width of ping i
δd	Distance sampling interval
δ_t	Sampling interval
θ_l	Beamwidth
θ_a, θ_b	Angular integration limits
σ	RMS height of the surface roughness
τ	Pulse length

Introduction

A survey was conducted in the Cockburn Sound area, Western Australia, on 25th, 26th and 29th March 2004 as a part of the CWHM project of the Coastal CRC. Various techniques were deployed in the survey, including single beam acoustic techniques. Single beam data collection was conducted from aboard *FV Sabrina* using the SIMRAD EQ60 echosounder operating at two different frequencies of 38 and 200 kHz.

This paper describes two different approaches to acoustic discrimination of seabed habitat types. In the first one, a RoxAnn-like method was adopted. This technique was successfully implemented in the North West Shelf region and the South East Fisheries region, and was described in [1,2,3]. Different acoustic backscatter characteristics were also analysed with respect of their capability of distinguishing different seabed habitat types, such as seagrass and sand.

Material and Methods

Study area

Cockburn Sound in Western Australia is a coastal shelf region bounded partly and protected from the open ocean by the Garden Island to the west with a narrow opening to the south under a bridge connecting the island to the mainland and the opposite, much larger opening to the north. The data were collected from 14 selected sites near the north opening to supplement the results of the previous survey of seabed habitat in this area [4]. The seagrass population in Cockburn Sound has declined since 1960s due to land developments and industrial activities around the area. At present, seagrass can be found only in water depth less than 10 m. *Posidonia Sinuosa* is the most dominant species (98%) and

Posidonia australis comes second (1.7%) [5]. The seagrass currently occupies only about 4% of the total Cockburn Sound area.

Data collection

The acoustic backscatter data were collected by SIMRAD EQ60 in two regimes: when *FV Sabrina* was running along selected tracks and while the boat was kept drifting at predefined stations. Fugro's Starfix DGPS navigation system was deployed along with the echosounder to provide positioning of the boat. Video footages were also taken simultaneously with acoustic measurements at the predefined locations for specific time intervals. The RoxAnn-like method was applied only to the 38-kHz backscatter signals. The acoustic backscatter analysis was applied to the signals at both frequencies.

Table 1 gives a summary of the EQ60 parameters and settings applied during the survey. For the beamwidth given in Table 1, the footprint size for a typical water depth of 5 m was about 0.5 and 0.1 m^2 at 38 and 200 kHz respectively.

Table 1. Parameters and settings of the SIMRAD EQ60 echosounder.

Parameters	Frequencies (kHz)	
	38.08	198.864
Beamwidth (degree)	15.2	7.2
Transducer draft (m)	2.14	2.14
Sample interval (sec)	0.000126	0.000025
Absorption coefficient (dB/m)	0.0098	0.0523
RoxAnn-like method:		
Transmit power (W)	1000	1000
Pulse length (ms)	1.024	1.024
Transducer gain (dB)	20	26.3
Acoustic backscatter analysis:		
Transmit power (W)	100 & 500	100 & 1000
Pulse length (ms)	0.256	0.1
Transducer gain (dB)	17.5	24.8

Acoustic data quality control

The ECHO*view* software tool developed by SonarData (based in Hobart, Tasmania) was used for data quality assessment. Faulty records due to aeration of the thin subsurface layer under wind and vertical mixing were marked as bad ones and excluded from the further analysis. This was only applicable to the RoxAnn-like technique. ECHO*view* was also used to export raw acoustic backscatter data into ASCII and MATLAB formats for the backscatter analysis.

Acoustic data analysis

RoxAnn-like technique

The RoxAnn system uses an echo-integration methodology to derive values for an electronically gated tail part of the first return echo (E1) and the whole of the second return echo (E2). While E2 is primarily a function of the gross reflectivity of the seabed surface and therefore it indicates the acoustic hardness of the seabed cover, E1 depends strongly on incoherent backscattering from the seabed and hence it can be used to estimate the roughness of the bottom. Acoustically different seabed types can be discriminated by clustering the backscatter signals by these two parameters E1 and E2 [6,7].

Heald and Pace [7] try to relate energy features from the first acoustic bottom returns and roughness parameters. For an incremental area dA_1 far from the axis, the first backscatter return becomes incoherent. Total backscatter return is a superposition of all backscatter signals from all areas. Following [7], the received acoustic pressure may be expressed as

$$p_{bs1}^2 = p_0^2 \int_{\theta_a}^{\theta_b} \frac{m_s(\theta_1) G^2(\theta_1)}{(R')^4} dA_1 \qquad (1)$$

where $dA_1 = 2\pi R'^2 \tan\theta_1 d\theta_1$, $R' = R\sqrt{(1+\tan^2\theta_1)}$, $m_s(\theta_1) \propto \Re^2$ and $m_s(\theta_1) \propto (\sigma/T)^2$. Heald and Pace further suggest that the integration limits of the intensity envelope of the first backscatter return from the seabed are to bound the region where the insonified area is an annulus within which $\sqrt{c(t-\tau)/R} \le \theta_1 \le \sqrt{c\tau/R}$

The acoustic energy of the second backscatter return from the seabed includes both coherent and incoherent components, and hence for calculation of the total reflection coefficient the integration limits must include the whole returned envelope. The acoustic scattering coefficient $m_s(\theta_1)$ for the first return is proportional to the square of the acoustic reflection coefficient $\Re$. The amplitude of the second backscatter return depends on the 4th power of $\Re$. The coherent component of the second backscatter pulse is estimated by integrating the signal envelope within $ct/2 \le c\tau/2$ and $ct/2 > c\tau/2$. [7]

ECHO*view* provides several algorithms including a constant angular algorithm (see equation (1)). This algorithm ensures that a constant angular sector of the incoherent field, irrespective of depth changes, is used for the integration of the first acoustic bottom backscatter. Following the procedure introduced in [1], the integration limits (θ_a and θ_b in equation (1)) were chosen between 16° and 45° after the falling edge of three times the acoustic pulse (c_τ = 1.6 m for the settings at 38 kHz). The depths (after the bottom) corresponding to θ_a and θ_b varied with changing water depths and were estimated by

$$d_{\theta i} = R/\cos\theta_i - R + c_\tau \qquad (2)$$

A constant depth algorithm was used for the integration of the complete envelope of the second backscatter pulse. The integration limits were defined starting from twice the water depth ($d_{\theta a}$) and ending at twice the water depth plus 3 m ($d_{\theta b}$). To reduce variability between pings in the backscatter returns, the integration was also performed over an along-track interval of 10 pings. The integration of acoustic volume reverberation resulted in the surface backscatter coefficients that stem from fisheries acoustics for biomass assessments and are adopted as a relative measure of acoustic energy for scattering from the seabed. In the discrete form, the estimate of the mean surface backscattering coefficient can be written as

$$\bar{s}_A = 4\pi \frac{\sum_{p=1}^{m} \delta d \sum_{d=d_a}^{d_b} s_{v(dp)}}{m} \tag{3}$$

The surface backscattering strength is simply

$$\bar{S}_A = 10 \times LOG_{10}(\bar{s}_A) \tag{4}$$

The parameters E1 and E2 were calculated using equations 3 and 4 with the summation in (3) within the limits d_a and d_b defined for the first and second backscatter returns as described above.

Seabed classification of the RoxAnn-like data

A cluster analysis (CA) was applied to the parameters E1 and E2. This study used the iterative relocation technique with Bayesian distance for clustering. A training set comprising distinct seabed habitat based on video footages was set up. The mean of E1 and E2, and the covariance matrix were estimated from the training set. The results from the training set then became the seeds of the initial centroids. Using these seeds of the initial centroids, the iterative relocation technique was eventually performed on the rest of the data.

Acoustic backscatter analysis

The volume backscattering coefficients exported from ECHO*view* were first converted into the surface backscattering coefficients. The further processing procedure was applied to the surface backscattering coefficients.

It was assumed that the detection of seagrass would be better at higher frequencies, and hence it was expected that the first arrival pulse at 200 kHz was backscattered by the top of the seagrass canopy, while at 38 kHz the signal was mainly reflected by the sediment interface.

The pulse front of backscatter signals was located by finding the first signal sample of which the intensity level exceeds a predefined threshold. The other parameters, such as the centre of mass and the moment of inertia of the pulse, were derived once the pulse front had been located. All signal parameters used for the analysis are described below:

Time difference between the arrivals of pulse fronts at two frequencies $T_{\Delta f}$

This parameter is assumed to be proportional to the height of the seagrass canopy, if the above assumption on the difference in backscattering at 38 and 200 kHz is valid. The estimate of this parameters is:

$$T_{\Delta f} = i_{f1} \cdot \delta_{t1} - i_{f2} \cdot \delta_{t2} \tag{5}$$

The sampling intervals δ_{t1} and δ_{t2} are 126 and 25 µs at 38 and 200 kHz respectively.

Centre of mass i_c

The centre of mass is a conventional characteristic to define the centre of pulses of a complicated form (see [8], for example). Its definition is similar to that given in classical mechanics. In the discrete form, the sample index of the centre of mass is defined as

$$i_c(j) = \mathrm{int}\left\{ \sum_i i \cdot f_i(j) \Big/ \sum_i f_i(j) \right\}, \tag{6}$$

where f_i are the backscatter pulse samples. Index j denotes the ping number.

Effective pulse width $W(j)$

The effective pulse width is defined as the square root of the moment of inertia calculated for the pulse magnitude and multiplied by the sampling interval δt, which can be written as follows

$$W(j) = \delta t \sqrt{I(j)} \tag{7}$$

where $I(j) = \sum_i (i - i_c)^2 \cdot f_i(j) \Big/ \sum_i f_i(j)$ is the moment of inertia. The smaller the effective pulse width, the more the backscattered energy will concentrate at the pulse centre.

Surface scattering coefficient s_A

According to Medwin and Clay [9], the surface backscattering coefficient is defined as

$$s_A = P_t R^4 \big/ P_r R_0^2 A, \tag{8}$$

where A is the insonified area. It is expected that the surface backscattering coefficient for seagrass is smaller at near-nadir angles of incidence than that for sand.

Results

RoxAnn-like technique

During the survey, areas with and without dense seagrass cover were easily recognised by comparing the echograms at two operating frequencies. In the areas free of seagrass, the bottom interface detected by the SIMRAD EQ60 built-in algorithm is almost coincident at 38 and 200 kHz. In the areas with a dense seagrass cover, the depth of the sounder-detected bottom is noticeably different at 38 and 200 kHz. As shown in Figure 1, the sounder-detected bottom observed on the 38 kHz echogram (left panel) is different from that on the 200 kHz echogram (right panel). At 38 kHz, the detected bottom interface was spike-like, so that the location of the bottom interface was not certain. The density of spikes was depending on how dense the seagrass was.

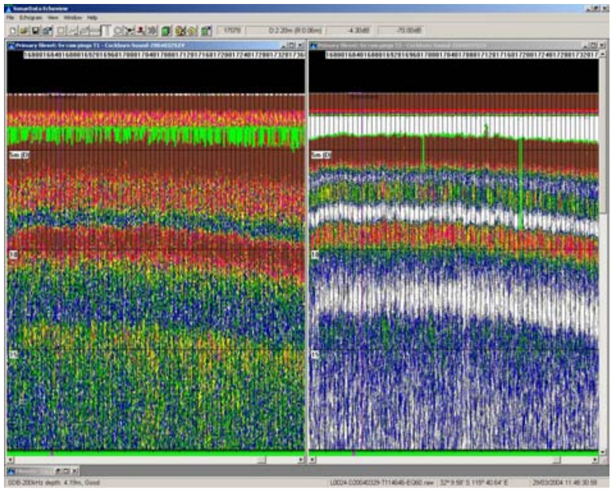

Figure 1. Representative examples of echograms from seagrass reproduced by ECHOview at 38 kHz (left) and 200 kHz (right).

A training data set was established from homogeneous areas within the reference (training) sites. The video footages taken over these areas were used to directly examine the seabed habitat. Three seabed habitat types, namely seagrass (×), sand (•) and no-seagrass (□) as shown in Figure 2, were defined from the video recordings. The two others shown in Figure 2 as ○ and + were defined from the echogram. It is obvious that the five classes in Figure 2 are well separated with a minor overlap.

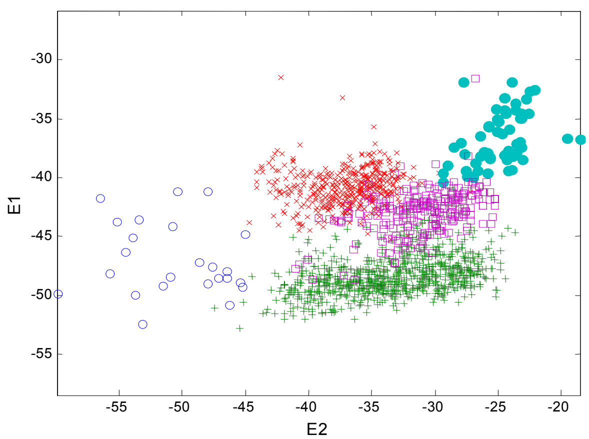

Figure 2. Scatter plot of E1 vs E2 showing five different classes defined from the training data set.

The arithmetic means and the covariance matrix of the five classes in Figure 2 were estimated and then used as seeds of the initial centroids for refining using the iterative relocation cluster analysis. As shown in Figure 3, overlapping between classes disappears after the refinement. The refinement process using CA reassigns overlapping data to new, appropriate classes to which the data belong most. As a consequence, new means and covariance matrix are produced. These new values become the seeds of the initial centroids that are used to perform CA for the entire data set. The ellipses in Figure 3 show the first standard deviation contours.

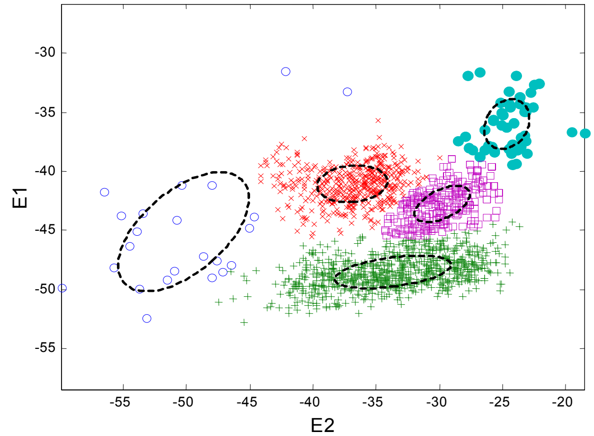

Figure 3. Scatter plot of E1 vs E2 for the refined classes derived from Figure 2.

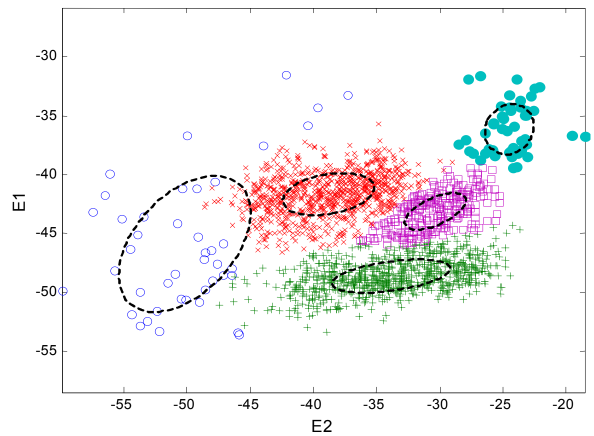

Figure 4. Scatter plot of E1 vs E2 for the entire data set. Five cluster domains are shown by the ellipses.

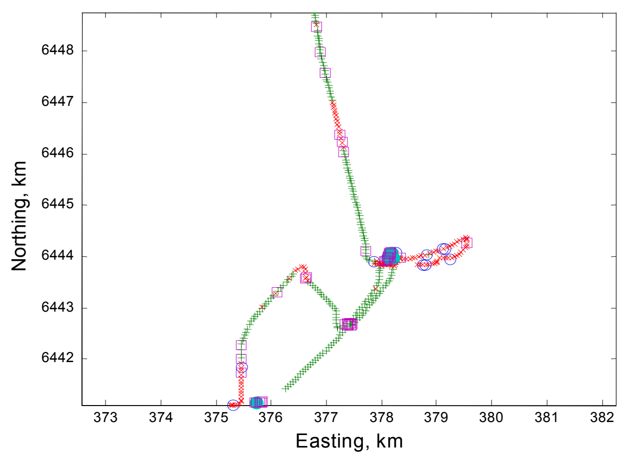

Figure 5. Acoustically derived seabed types along the track.

The CA results for the entire data are shown in Figure 4. E1 and E2 indices were also derived from the acoustic data collected in stations used in the acoustic backscatter analysis. When they were superimposed into Figure 4, they agreed well with those in the figure. Figure 5 demonstrates the acoustically derived seabed classes located along the vessel's track. Note that the number of data points shown in Figure 5 is reduced for better visualisation.

Acoustic backscatter analysis

As shown in the previous section, the bottom location derived from the echograms is different at 38 and 200 kHz when the seabed is covered by seagrass. The front of the backscattered pulse at 200 kHz arrives on the sonar receive array generally earlier than that at 38 kHz. However, the time difference $T_{\Delta f}$ varies substantially in a random manner and depends noticeably on the threshold level selected for locating the pulse arrivals, especially at 38 kHz. The arrival time difference can serve as a coarse indicator of the presence of seagrass on the bottom. However, this parameter is not robust enough for accurate estimates of the mean seagrass height, because of its instability. Further experimental studies are necessary to determine a more suitable set of sonar frequencies for acoustic measurements of the seagrass canopy height.

The seagrass canopy is a much rougher surface than a seagrass-free sandy bottom. According to the scattering theory, the rougher the surface, the less energy of acoustic waves will be reflected at the specular angle and the more energy will be scattered in the other directions. Scattering at non-specular angles increases with the increase of frequencies. This scattering feature is clearly seen in the results of the backscatter analysis for sand and seagrass. At 38 kHz, the intensity of acoustic backscattering from sand is somewhat higher than that from seagrass (Figure 6), but the difference is not large. At 200 kHz, the backscatter intensity for seagrass is much lower, 10-15 dB than that for sand. A small sand patch of about 5 m wide is clearly seen in the backscatter level at both frequencies. The backscatter intensity depends on the echosonder's parameters and the sea depth. Hence this parameter is not suitable for distinguishing seagrass on the bottom if the sea depth varies substantially. The surface scattering coefficient does not depend on the seabed, and hence the estimate of this coefficient is more robust with respect to acoustic discrimination of seagrass. The surface scattering coefficient can be calculated using equation 8 with an accurate estimate of the insonified area A and proper correction for the transducer power and receive gain of the echosounder.

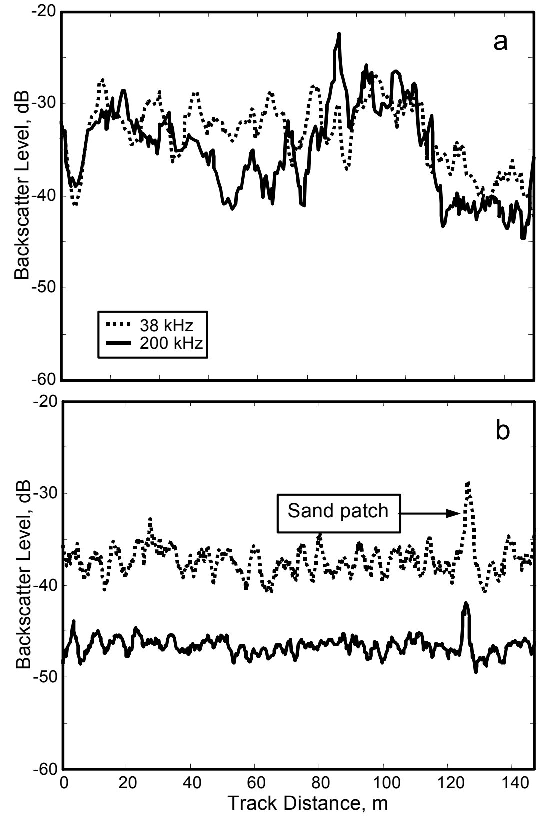

Figure 6. Surface backscatter level from sand (a) and seagrass (b) at 38 and 200 kHz.

The other backscatter characteristic that is capable of discriminating seagrass on the seabed is the effective pulse width of the echo signal. The sonar head transmits and receives the acoustic energy within a finite solid angle. When the RMS height and correlation length of the surface roughness are small relative to the wavelength of acoustic waves, the contribution of waves scattered back to the sonar at oblique angles of incidences to the received signal remains small comparing to the intensity of waves backscattered at the normal incidence, and hence the pulse width changes insignificantly. For rough surfaces, the contribution of oblique backscattering becomes substantial, which leads to spreading of the received pulse, because the two-way acoustic travel time at oblique angles is longer. The pulse width is commonly measured at a –3-dB level of the maximum amplitude. However, the signals backscattered by a rough surface of the seabed frequently have a complicated irregular shape of the envelope, so that the conventional method of estimating the pulse width is not applicable. In that case, the effective pulse width defined earlier is the only robust parameter to measure the pulse duration. Figure 7 shows the effective pulse width of the backscatter signals received at 38 kHz (dotted line) and 200 kHz (solid line) over a sandy bottom (upper panel) and a seagrass canopy (lower panel).

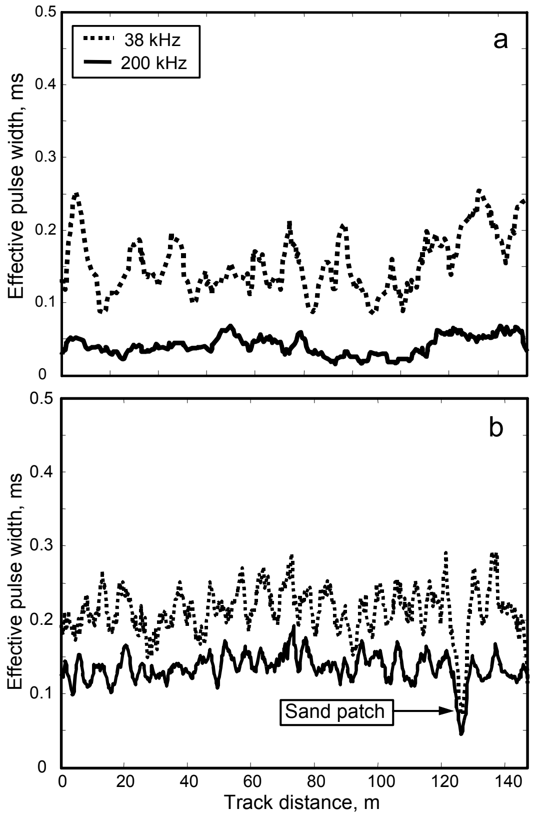

Figure 7. Effective pulse width measured for sand (a) and seagrass (b) at 38 and 200 kHz.

At 200 kHz, the backscatter pulse width is very sensitive to the presence of seagrass on the bottom, which is clearly seen when comparing the plots on the upper and lower panels. Also a sharp decrease of the pulse width is observed when the track crosses the sand patch in the seagrass cover. Within this patch the pulse width decreases approximately to the value observed at 200 kHz over sand. The pulse width at 38 kHz is less sensitive in general to the type of the bottom cover, but still demonstrates a noticeable decrease over the sand patch. It is assumed that the 38-kHz signal is scattered mainly by sediment inhomogeneities below the seabed surface rather than the top of the seagrass canopy.

Conclusions

The water depths in the Cockburn Sound area are much shallower than those in the areas for which the RoxAnn-like technique was developed [1,2,3]. Initially, this was of concern because the area for the integration reduced with depth. However, it turned out that this technique was indeed workable in the current study area. Nevertheless, some adjustments were required as a consequence of different beamwidth of the transducer being used and the water depth regime. Five different seabed habitats were derived. This agreed well with the direct video observations.

Comparing to the other parameters, the effective width of backscatter pulses and the surface backscatter coefficient are robust parameters that can be used to distinguish seagrass from sand on the seabed or seagrass-free meadows. It is necessary to test the robustness of these two parameters of acoustic backscatter for different seabed habitat types.

Acknowledgements

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