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Multi-Frequency Analysis of Seabed Echoes Using Wavelet Transform

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The methods based on analysis of bottom backscatter data from a single-beam echosounder have achieved special attention in the seabed identification problem, due to their simplicity over other more sophisticated acoustic techniques like side scan sonar or multibeam surveys. The majority of these methods analyses the scattering phenomena mostly in time domain (echo envelope). However, the frequency echo components carry concurrent information, which can be also used in bottom characterisation. The paper proposes the time-frequency approach to the bottom characterisation and presents the application of Wigner-Ville Distribution and wavelet transform of bottom backscatter data. The examples of continuous and discrete wavelet transforms of actual echo envelopes received at three bottom types for three different operating frequencies (38, 120 and 420 kHz) are shown. Their characteristic features are compared and parameters for classification schemes are proposed. The results of classification procedure are good with comparison with those of other simple acoustic methods.

1. Introduction

The problem of sea bottom identification and classification is important in many fields including marine geology, hydrography, marine engineering, environmental sciences, and fisheries. Acoustic methods of bottom characterisation have known advantages, as they are non-invasive and more cost effective than other methods, e. g. geological cores. The methods of so called normal incidence – which use the backscatter data from a single-beam echosounder – have achieved special attention, due to their simplicity and versatility. They can involve several approaches [2, 4, 5, 6, 8, 9] and the majority of them analyses the scattering phenomenon mostly in time domain. However, the frequency spectrum of echo components carries concurrent information, which also can be used in bottom characterisation. Some distinctive echo features, as for instance, the irregularity of decaying echo part, have straightforward description in frequency domain and are also localised in time domain. The wavelet transforms, as suitable for 2^D time-spectral analysis are specially useful for extracting properties of that kind. Moreover, temporal and spectral properties of echo may be related to spatial and spatial frequency features of seabed scattering properties [4].

The paper presents the application of continuous and discrete wavelet transform for time-frequency analysis of bottom backscatter data for different echosounder frequencies. The analysis and comparison of extracted wavelet coefficients for echoes from particular bottom types constitutes the formulation for seabed classification schemes.

2. Time-frequency analysis

The well-known techniques for signal analysis are Fourier related transforms, which convert the signal waveform in time domain to its spectrum in frequency domain. For broad class of signals, Fourier analysis is extremely useful because the frequency content of the signal is of great importance. However, when transforming to the frequency domain, time information is lost. Many interesting signals contain numerous non-stationary or transient characteristics, which are the most important part of the signal and Fourier analysis is not suited to detecting them. To overcome this deficiency, the technique based on windowing a small section of the signal at a time may be used. The so called Short Time Fourier Transform (STFT) maps a signal into two dimensional function of time and frequency and provides some information about both temporal and spectral features. But still, the drawback is that once one choose a particular size for the time window, that window is the same for all frequencies. Moreover, when the signal is represented by small number of samples, it is not possible to implement this approach due to the same size of the signal and the window. In such a case, much better results are achieved when using time-frequency analysis called Wigner-Ville Distribution (WVD) defined as [1]:

$$W_x(t,f) = \\ = \int_{-\infty}^{\infty} x(t+\tau/2)x^*(t-\tau/2)\exp(-j2\pi f\tau)d\tau \quad (1)$$

An interpretation of this expression can be found in terms of probability density function as the Fourier transform of an acceptable form of characteristic function for the distribution of the energy. This distribution satisfies a large number of desirable properties. In particular, it is always real-valued, preserves time and frequency shifts and satisfies marginal properties. In practice the Eq. (1) is not calculated in the range from $\tau = -\infty$ to $\tau = +\infty$, but in a regular window leading to the new distribution called the pseudo Wigner-Ville distribution (PWVD). This leads to smoothing in frequency domain and can be also extended by thresholding technique. An examples of such analysis are presented in Fig. 1 and 2 for the echoes collected by 120 kHz digital echosounder. Fig. 1 shows PWVD of the sample echo from rocky bottom and Fig. 2 – the sample echo from muddy bottom. Both spectral density functions do not allow for differentiating the type of the bottom easily. The time-frequency charts show precisely the changes of frequency components in particular moments.

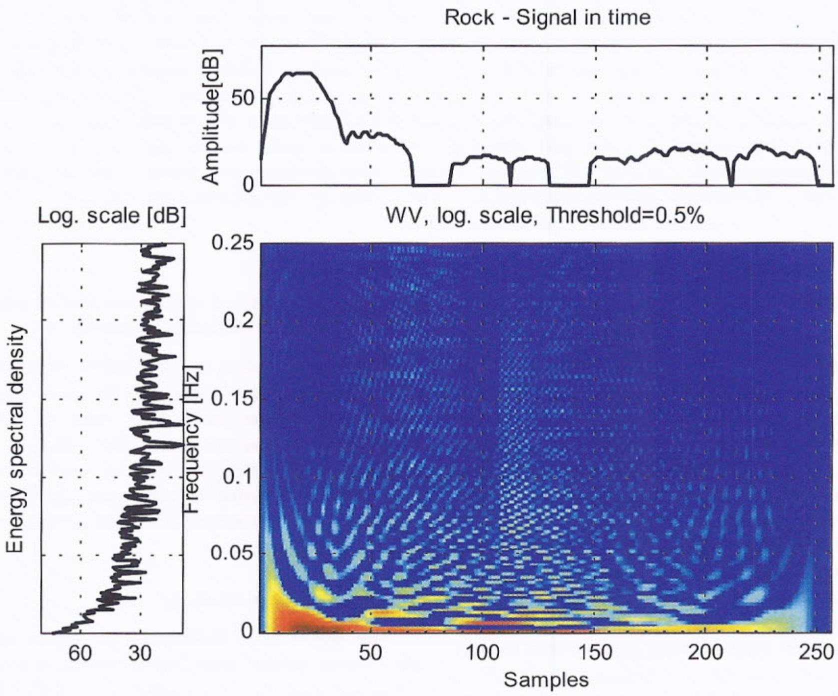

Fig. 1. Pseudo Wigner-Ville distribution of echo from rocky bottom (120kHz system)

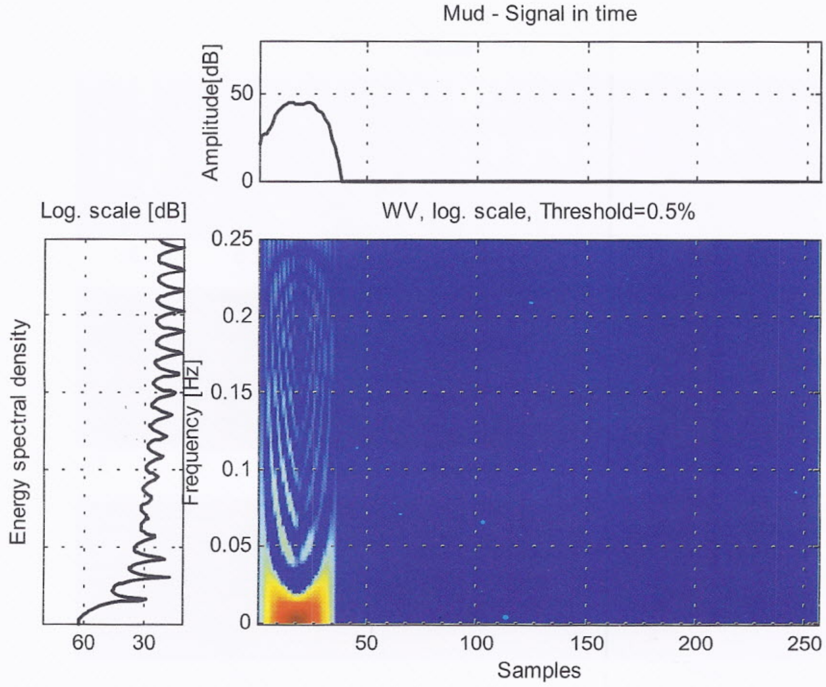

Fig. 2. Pseudo Wigner-Ville distribution of echo from muddy bottom (120kHz system)

3. Wavelet analysis

Wavelet analysis represents particular windowing technique with variable-sized regions, which allows the use of long time intervals where one wants to extract more precisely low frequency information, and shorter regions of high frequency information. Mathematically, the continuous wavelet transform (CWT) of signal $x(t)$ is defined similarly to Fourier transform as a projection of a signal x on a family of zero-mean functions derived from an elementary function (mother wavelet) by translations and dilations [3, 7]:

$$C(a,b) = \int_{-\infty}^{\infty} x(t)\psi(a,b,t)dt \;, \qquad (2)$$

where $C(a,b) \equiv C_{a,b}$ - set of wavelet coefficients, $\psi(a,b,t) \equiv \frac{1}{\sqrt{a}}\psi\left(\frac{t-b}{a}\right)$- wavelet function, a – variable representing scale, and b – variable representing position. By definition, the wavelet transform is more a time-scale than time-frequency representation. However, for wavelets which are well localised around a non-zero frequency f_0 at a scale $a=1$, a time-frequency interpretation is possible due to the formal identification $f = \frac{f_0}{a}$.

Fig. 3 shows sample CWT analysis of echoes reflected from three bottom types: rock, sand and mud, where data were collected by the same 120kHz echosounder. In this experiment the 128 consecutive echoes, each having 256 samples were organized in a one matrix and transformed. The three types of bottom can be nearly perfectly differentiated.

Continuous Wavelet Transform shows its attractiveness in recognition of the bottom types. However, its computation is time consuming so for actual implementation the Discrete Wavelet Transform (DWT) is used. The discrete version of this transform consists of $\log_2 N$ stages (levels) for a signal containing N samples. In every step, two sets of coefficients are obtained by convolution with a low-pass filter for approximation coefficients and a high-pass filter for detailed ones, followed by downsampling. In the next step, the same procedure is used for approximation coefficients only. This tree algorithm developed by Mallat can be implemented very efficiently and allows a real-time computation during measurement. The results of computation carried out by using this algorithm for one sample echo from mentioned bottom types are presented in Fig. 4.

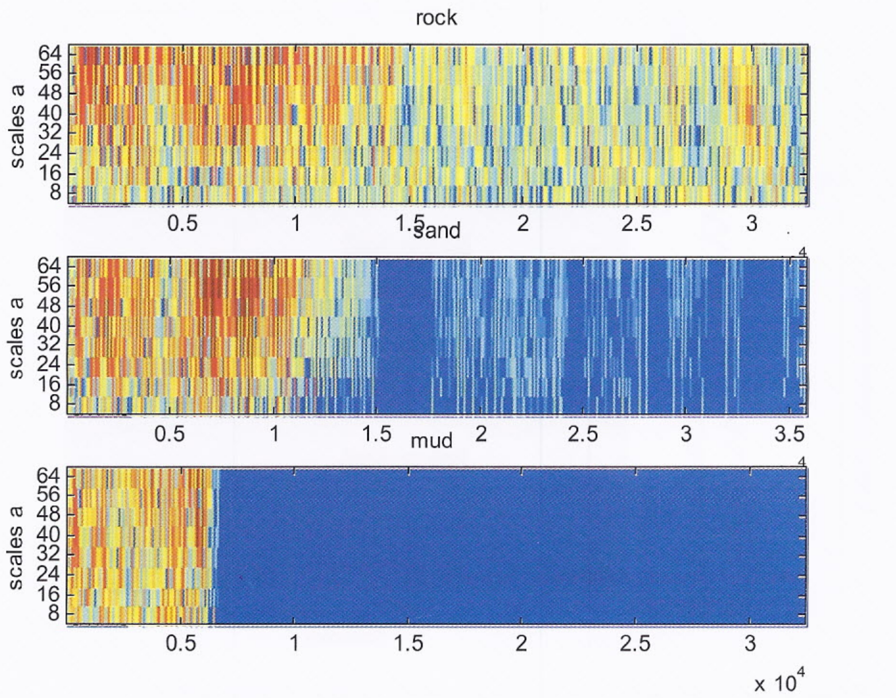

Fig. 3. Continuous Wavelet Transform of echoes from rocky, sandy and muddy bottom (120 kHz system)

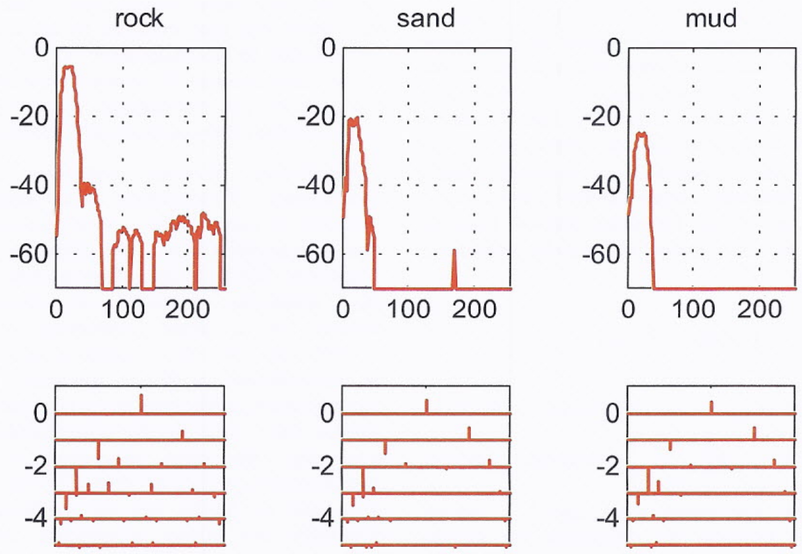

Fig. 4. Discrete Wavelet Transform of echoes from rocky, sandy and muddy bottom (120 kHz system)

4. Experimental results

The application of DWT for three sets of first echo envelopes from muddy, sandy and rocky bottom was investigated for classification purpose. The data were acquired on Lake Washington with use of the digital DT4000 echosounder with three different operating frequencies: 38, 120 and 420 kHz. Bottom characteristic parameters based on wavelet coefficients were proposed.

Fig. 4 presents the examples of one echo from each bottom type (a, b, c) together with its wavelet transform (d, e, f) for echosounder frequency 120 kHz. The differences between particular bottom types are visible and they are in line with theoretical predictions. For instance, the echo from rock is longer and more corrugated, what causes it to have significantly greater wavelet coefficients for less scale in second half of echo. The values of these coefficients decrease when going from harder to softer bottom. What is more, the coarsest scale wavelet coefficient, which is related to total backscattered echo energy, also decreases in the same way and is the smallest for muddy bottom.

As it is known, that bottom echoes received at different frequencies have different characteristic features, the DWT was performed and compared for three echo frequencies for the same acquisition sites. As a result, some parameters defined on the basis of wavelet coefficients were selected to seabed type classification procedure. First parameter P_1 was defined as the coarsest scale wavelet coefficient for 120 kHz echo. The second P_2 was defined as the sum of absolute values of wavelet coefficients for the second half of echo in time domain and the half of smaller scales in scale domain. P_3 was defined as the wavelet coefficient corresponding to the first quarter of echo in third scale level, for 420 kHz. It is related to echo maximal amplitude.

Fig. 5 shows the 2^D and 3^D plots of distributions of these parameters. It is visible that while on P_1 vs. P_2 plot the classes of mud and sand partially overlap, the use of third parameter P_3 which originates from different frequency 420 kHz, allows for clear distinction between them. P_3 is strictly related to the 420 kHz echo maximal amplitude and its values are more different for muddy and sandy bottom than in the case of the same parameter for other frequencies. It is probably due to the fact, that 420 kHz signal scatters only on the water-bottom interface and its maximal amplitude possess the information mainly about bottom hardness.

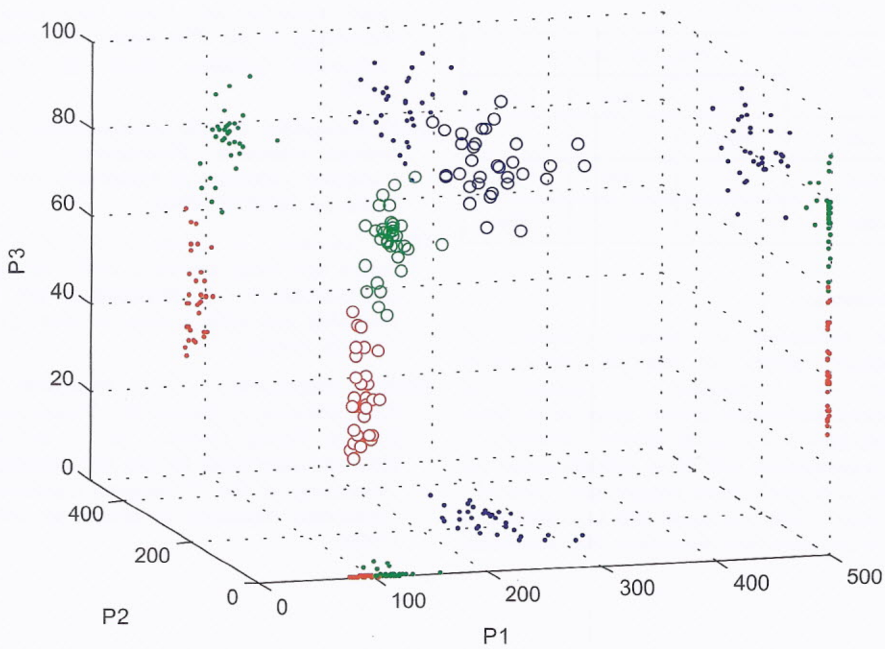

Fig. 5. 3^D plots of wavelet parameters P_1, P_2 and P_3 and their 2^D projections

The test of classification procedure was performed using data shown on Fig.5. 5% of data was selected as a training set and the mean values of parameters for its contents became the cluster centres. The rest of data was used as a test set. The assignment to a class was performed on the basis of minimal Euclidean distance in 2- or 3- parameter space from a data point in test set to particular cluster centres in training set. Table I shows the percentage of correct and incorrect classification assignments with use only the P_1 and P_2 parameters, while Table II contains the results of classification based on three parameters P_1,, P_2 *and* P_3. It is clear, that application of three parameters originating from more than one operating frequency improves the classification results.

Table I. Classification results with use of P_1 and P_2 parameters

True class	Assigned class (%)		
	mud	sand	rock
mud	**88.4**	11.6	0
sand	7.4	**92.6**	0
rock	0	0	**100**

Table II. Classification results with use of P_1, P_2 and P_3 parameters

True class	Assigned class (%)		
	mud	sand	rock
mud	**96.8**	3.2	0
sand	0	**100**	0
rock	0	0	**100**

5. Conclusions

The application of wavelet transform of echosounder echoes for seafloor classification purposes was investigated. The accuracy of developed classification schemes based on the time-frequency approach using the wavelet coefficients is better in comparison with other methods which use the data from single-beam echosounder, especially with methods analysing signal only time domain. It is due to including both temporal as well as spectral characteristics of echo features in classification procedure. What is more, the use of multifrequency data instead of single-frequency, additionally improves the classification results.

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