USE OF THE HILBERT-HUANG TRANSFORM FOR CHARACTERIZATION OF GASSY SEDIMENTS IN ECKERNFÖRDE BAY

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The bottom top layer of the central part of the Eckernförde Bay (Germany) consists of soft muddy sediments containing free methane gas. Locations of gas bubbles trapped in the sediment and gas seeps visualised with hydroacoustic data have been reported. The main goal of our study was to examine whether it was possible, using a singlebeam echosounder with relatively high frequency of the transmitted signal (120 kHz), to detect echo properties that could be indicative of the occurrence of free gas in the bottom sediments. During three days of measurements organised by Leibniz Institute of Marine Sciences (IFM-GEOMAR) in Kiel (Germany), the acoustic data were collected from boards of r/v Polarfuchs and r/v Littorina. The Hilbert-Huang Transform was applied to detect 'gassy' anomalies in backscattered signals from the bottom. The transformer decomposes signal into finite and small number of Intrinsic Mode Function (IMF) components with time-dependent amplitudes and frequencies. Certain IMF components carry information on variability of geoacoustic parameters, which can be indicative of presence of gas bubbles in the acoustically penetrated sediment as well as in the water column. Based on the shape of the echo signal envelope and its fading with range we characterized the signal attenuation in areas where gas was present. The rapid increase in acoustical wave attenuation in areas of intensive gas ebullition demonstrates good applicability of the method proposed.

INTRODUCTION

Acoustic methods are used to study occurrence of free gas in the shelf bottom sediments. Deep layer subsurface profiling techniques [e.g. 1] as well as swath methods [e.g. 2] deliver qualitative information on gas presence and its escape from the bottom. Moreover, the nonlinear acoustic methods [e.g. 3, 4] can be used for quantitative description of bottom sediments containing free gas bubbles or gas pockets and estimation of its volume in sediments [e.g. 5].

Gas in sediments has been discovered in many shallow locations in marine and fresh water environments, both in form of gas dissolved in the pore water and as free gas bubbles [e.g. 5, 6, 7]. The main and most frequent source of gas bubbles in the surficial bottom layer is biologically mediated methanogenesis associated with bacterial decomposition of buried organic matter. Other important sources of free gases in upper sediments can be bubbles escaping from deeper layers containing gas hydrates or from deep methane gas pockets/caverns. In areas of geothermal and submarine volcanic activity massive gas seepages and plumes can also be detected [8]. The main forms of gas accumulated in the sediments are methane, carbon dioxide, hydrogen sulphide, or nitrogen. Gas caverns can have different sizes and possess various, often complicated and irregular shapes shown through X-ray scanning of frozen bottom cores [9]. Gas bubbles trapped in sediment undergo considerable changes in their compressional features demonstrated by acoustic attenuation and sound speed.

An example of a known gassy area is the central part of the Gulf of Gdansk characterised by decrease of the acoustic signal in the layered structure of sediments at a depth greater than 40 meters below the bottom surface [5]. Gas bubbles create the specific screen for acoustical wave and making it hard to penetrate the volume of deposits. The most known and well researched place of gas occurrence is the Eckernförde Bay located in the German North-West part of the Baltic Sea. In the last fifty years there were many scientific projects which used various techniques for investigation of features of the gaseous sediment layer in the bay [e.g. 7, 10]. The average depth of the Eckernförde Bay is 26 meters. The shallower part with depth less than 20 meters is covered by sandy sediments. The bottom areas below 20 meters are covered by very soft mud. The central part of the bay contains organic-rich silt-clay sediments with notable acoustic turbidity indicating the presence of gas bubbles.

The main goal of our study was to examine, whether using singlebeam echosounder with relatively high frequency of the transmitted signal, 120 kHz, is possible to detect echo properties that could be indicative for the occurrence of free gas in the bottom sediments. We used the Hilbert-Huang transform for characterization of "gassy" anomalies in the bottom sediments and water column, which can be indicative for the appearance of gas bubbles. Based on the shape of the echo signal envelope and its fading with range we specified signal attenuation in areas of gas presence.

1. EXPERIMENT METHODOLOGY

At the end of June and beginning of July 2010 the Leibniz Institute of Marine Sciences (IFM-GEOMAR, Kiel, Germany) organised a sampling campaign aimed to study sediment characteristics in the Eckernförde Bay. Acoustic measurements were conducted from boards of research vessels Polarfuchs and Littorina. All experimental points are shown on the map (Fig. 1).

Acoustic measurements were carried out with Simrad's EK-500 single beam echosounder with hydroacoustic transducer working at frequency of 120 kHz (ES120-7) and parameters listed as follow: 3 dB beam width – 7.1°, peak transmit power – 1000 W (during experiment was established 674 W), pulse duration – 0.7 ms, sampling distance – 0.03 m (number of samples per 1 m – 33.33). The transducer was deployed ~2 meters below the water surface during the time of vessel drift.

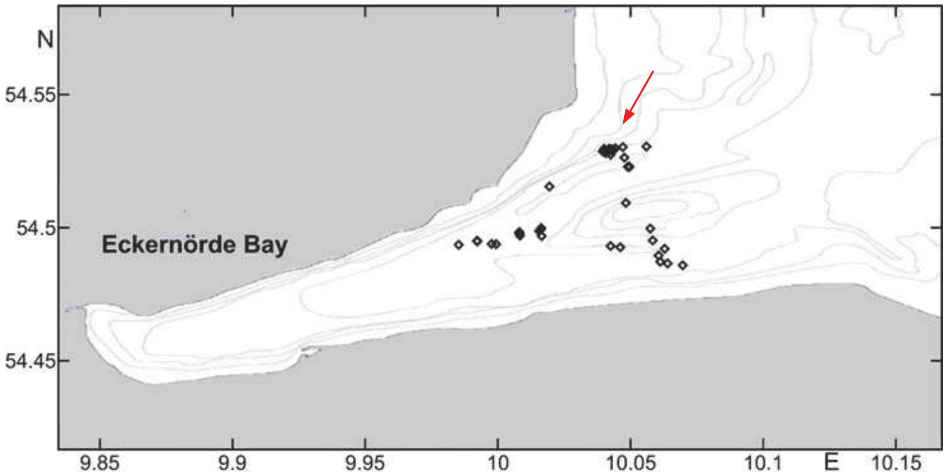

Fig. 1. Map of Eckernförde Bay showing the positions of acoustic measurements

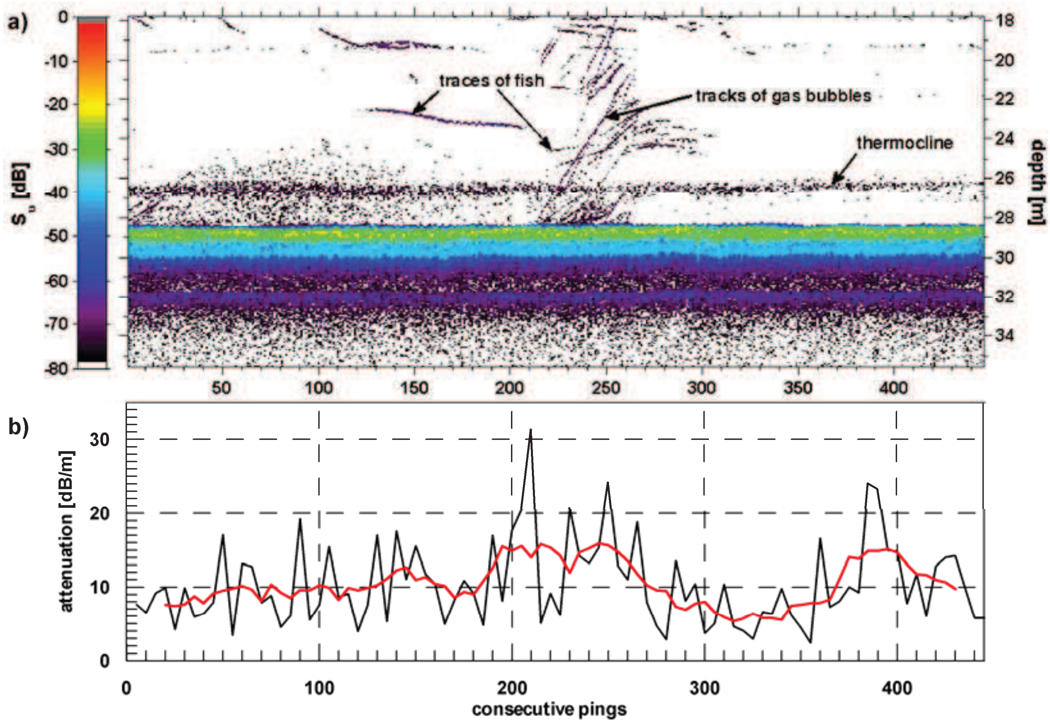

Fig. 2. Example of flowing up gas bubbles in the water (a), compressional wave attenuation in sediment estimated along the echogram (b). The red arrow in the Fig.1 indicates the location of echogram registration

Sea state during the measurements varied from 0 °B to 3–4 °B and resulted in the movement of the vessel relatively to the bottom at a speed of 0.1–0.5 knots. The example of 120 kHz echogram containing gas outflow from the gas-saturated deposits is presented in Fig. 2, where tracks of rising bubbles are clearly seen as inclined lines. The horizontal noisy layer in the middle part of the water column (at ~26 m depth) represents the position of the thermocline containing various acoustic scatterers (plankton, suspended particles, etc.).

2. DATA PROCESSING – HILBERT-HUANG TRANSFORM

This study was done in order to examine, whether using singlebeam echosounder with relatively high frequency of the transmitted signal – 120 kHz is possible to depict certain echo properties that can indicate the occurrence of free gas in surface sediments. To perform this task, we used the Hilbert-Huang transform, which represents relatively new mathematical approach for data analysis. Unlike wavelet analysis, the Wigner-Ville distribution, empirical orthogonal function expansion, and other approached, this transformation method can be adapted to nonlinear and non-stationary data. A Hilbert-Huang application in speech and acoustic signal processing has been well described earlier [11, 12]. Also the other research areas, which use time series analysis, are interested in applications of the Hilbert-Huang transformation to extract new information from the recorded signals [e.g. 13, 14].

The Hilbert-Huang transform consists of two processes. In the procedure of Empirical Mode Decomposition (EMD), the signal is adaptively decomposed into finite and often small number of Intrinsic Mode Function (IMF) components with time-dependent amplitudes and frequencies [15]. The IMFs are the form of the amplitude and frequency modulated oscillation modes included in the signal.

Inside the signal the lower and upper envelopes can be distinguished. The mean of envelopes is defined as m_1. The first component h_1 is determined in procedure called sifting as the difference between the signal $x(t)$ and m_1:

$$h_1 = x(t) - m_1 (1)$$

The above procedure allows obtaining an IMF by elimination of riding waves. Moreover, the transformed signal is more symmetric. In the next k steps the sifting process must be consecutively repeated until the transformed signal is fully decomposed. Obtained h_{1k} indicates the first IMF component c_1 received in the sifting procedure, which was repeated k times. The residue r_1 of the component c_1 is obtained by subtracting component c_1 from the signal $x(t)$. Next the same sifting process is applied to obtain all subsequent residues:

$$\begin{aligned} r_1 &= x(t) - c_1 \\ r_2 &= r_1 - c_1 \\ &\vdots \\ r_n &= r_{n-1} - c_n. \end{aligned} \tag{2}$$

General equation takes a form:

$$x(t) = \sum_{j=1}^{n} c_j + r_n \tag{3}$$

where c_j are the IMF components (j=1, …,n), r_n is the residue after repeating the sifting procedure n times.

Hilbert transform applied to each of IMFs convert signal to the frequency and the amplitude domains dependent on time. The output signal can be expressed as:

$$x(t) = \mathrm{Re} \sum_{j=1}^{n} a_j(t)\ e^{i\int \omega_j(t)\ dt} \tag{4}$$

In this paper we consider the empirical mode decomposition for bottom acoustic signal collected with singlebeam echosounder EK500. The continuity of the conditions for decomposition on the modes has been obtained by shifting the signal with a mean value. Next the signal was normalised according to the formula:

$$x'(t) = \frac{x(t) - \min(x(t))}{\max(x(t)) - \min(x(t))} \quad (5)$$

where $x(t)$ and $x'(t)$ are input signal and signal after normalization respectively.

Also, the attenuation coefficient β of compressional acoustic wave in bottom was estimated [16]. The computation procedure of β coefficient is based on the assumption that for the limited quasi-linearity interval of the dependence $< S_\upsilon(z) >= f(z)$, the coefficients of a linear regression can be calculated. The value of attenuation coefficient β is estimated from the slope of $< S_\upsilon(z_i) >$. For computation of the β coefficient the speed of sound both in the water and sediment was taken as 1500 m s^{-1}.

3. RESULTS

Example of Huang-Hilbert transform applied to the echo signal scattered at muddy sediment is presented in Fig. 3. In this example we used ping no. 225 (see the echogram on Fig. 2a), which depicts scattering at the chain of rising gas bubbles and fish, for further analysis. Normalisation and shifting the pulse on the average causes that its minimum and maximum values are uniformly distributed in the signal (i.e. the first requirement of modal decomposition is satisfied) and the average of the values of local minima and maxima is equal 0 (i.e. the second requirement of modal decomposition is satisfied). Below the echo signal (Figure 3, top) are shown its four consecutive forms of the intrinsic mode function obtained in the sifting process. The first IMF (c_1) represents the signal oscillation in a short time phases occurring evenly throughout the pulse period. In the second IMF (c_2) signal, the anomalies are observable caused by the presence of acoustic scatterers in the water column (e.g. from bubbles and fish). Differences in the acoustic signal corresponding to the bubbles and fish traces result in the oscillation of the decomposed signal with varying frequency. Third IMF (c_3) represents greater oscillations in the signal, which correspond to the reflection of the pulse from the bottom. In the last IMF (c_4) once again reveals the presence of fish (except the pulse reflection from the bottom) and to a lesser extend the traces of gas bubbles.

Hilbert-Huang transform can also be used to analyze the texture of two-dimensional images [e.g. 17]. The echogram (Fig. 2a) has been treated with algorithm of the Bidimensional Empirical Mode Decomposition (BEMD). Thus, its spatial characteristics were extracted in the 2D-sifting process (comparable to sifting process). Fig. 4 shows the second (C_2) and third (C_3) mode of performed decomposition and the residue mode R_1. Each decomposed echogram represents the specified scale of scattering phenomena. First echogram shows only low signal fluctuations, which evidently have changed after the next step of the BEMD procedure (2D-sifting process). Thus, the boundary between water and bottom, the top layer of sediment and all the phenomena occurring in the water (fish and gas bubbles traces) became easily observable. The residue (R_1) finds the filtered image of the coarest structure reflecting fluctuations occurring in the signal.

The result of estimation of compressional wave attenuation in sediment, computed along the echogram is presented in Fig. 2b. The rapid changes in attenuation coefficient of the acoustic soft, muddy sediments can indicate the evidence of gas bubbles. The red line on Fig. 1 depicts value of attenuation coefficient after moving average filtration.

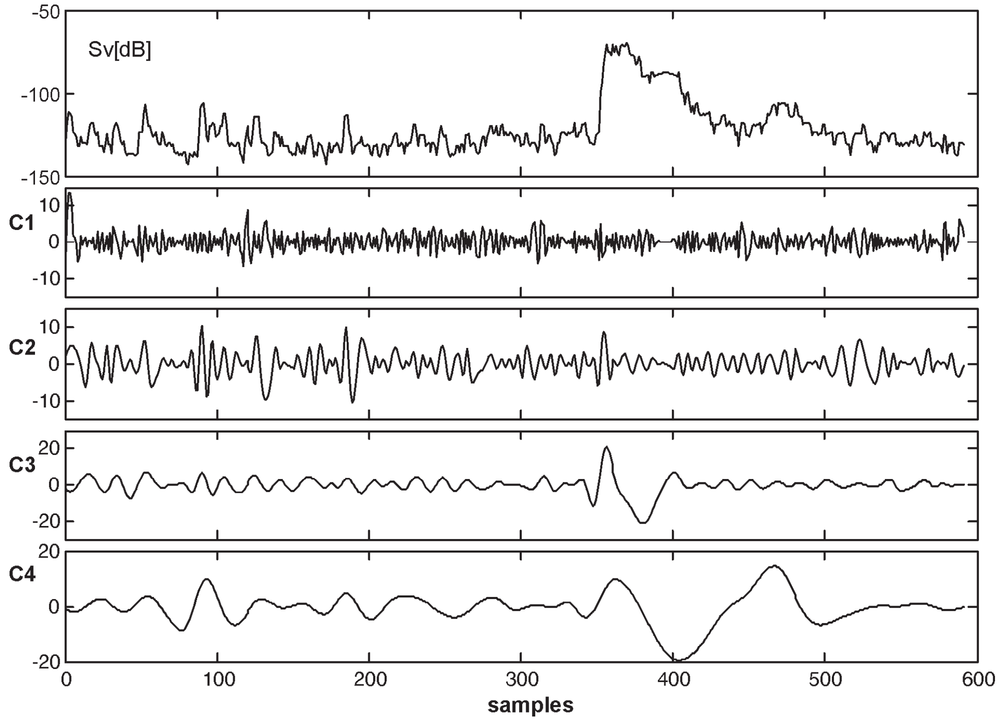

Fig. 3. Example of echo signal scattered at muddy sediment (top figure) and its consecutive four IMF components

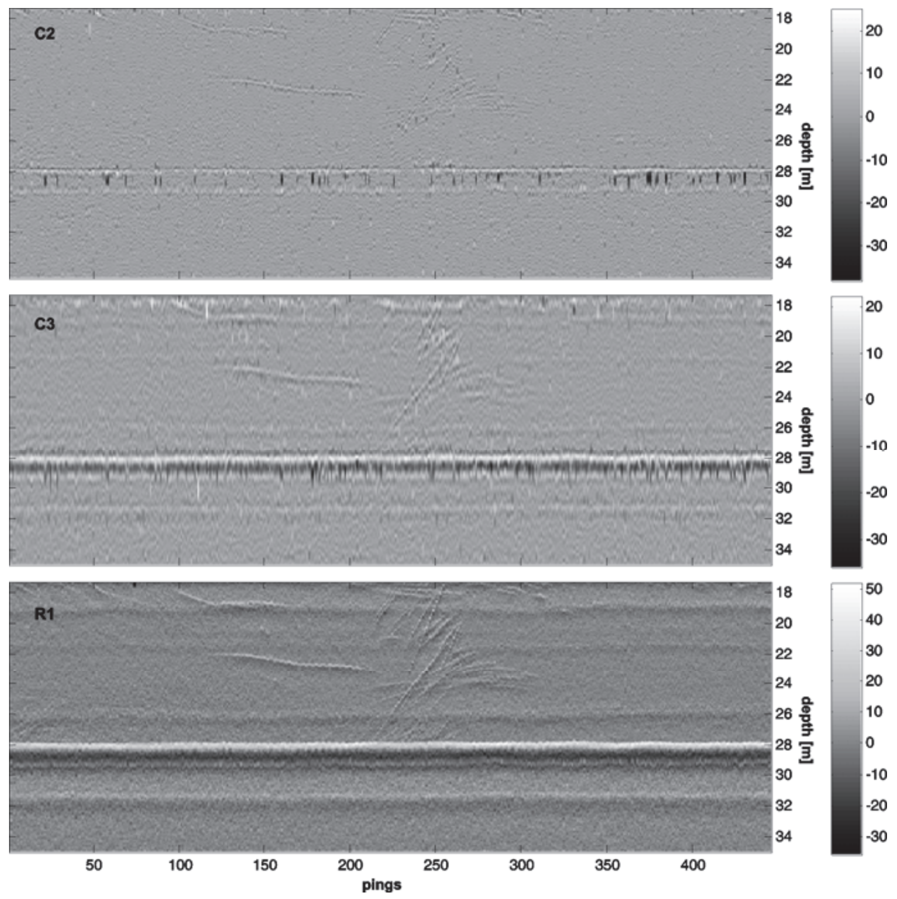

Fig. 4. The result of 2D decomposition of the echogram (Fig.2a) using BEMD algorithm

4. CONCLUSIONS

The use of the novel mathematical tool, the Hilbert-Huang transform, allowed for detection of anomalies in the bottom backscattered signals registered in the Eckernförde Bay. The transformation is able to depict from the signal various modes responsible for the interaction of the acoustic pulse with the bottom, gas bubbles travelling in the water column and marine organisms. The 2D-sifting procedure used for the echogram delivers information on spatial characteristics of phenomena observed in the measured environment. Moreover, on the basis of the shape of the echo signal envelope and its fading, one can define the attenuation of sediments in the areas of gas presence. The rapid increase of acoustical wave attenuation in areas of intensive gas ebullition demonstrates sensitivity of the proposed method.

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