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Seabed sub-bottom sediment classification using parametric sub-bottom profiler

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Abstract Many studies have been published concerning classification techniques of seabed surfaces using single beam, multibeam, and side scan sonars, while few paid attentions to classify sub-bottom layers using a non-linear Sub-Bottom Profiler (SBP). Non-linear SBP is known for its high resolution images due to the very short pulse length and aperture angle for high and low frequencies. This research is devoted to develop an energy based model that automatically characterizes the layered sediment types as a contribution step toward "what lies where in 3D?". Since the grain size is a function of the reflection coefficient, the main task is to compute the reflection coefficients where high impedance contrast is observed. The developed model extends the energy based surface model (Van Walree et al., 2006) to account for returns reflection of sub-layers where the reflection coefficients are computed sequentially after estimating the geo-acoustic parameters of the previous layer. The validation of the results depended on the model stability. However, physical core samples are still in favor to confirm the results. The model showed consistent stable results that agreed with the core samples knowledge of the studied area. The research concluded that the extended model approximates the reflection coefficient values and will be very promising if volume scatters and multiple reflections are included.

1. Introduction

The increased human marine activities in the offshore environment, such as wind farms, dredging operations, studies of marine geology and morphology have led to an imperative demand for accurate seafloor maps. These applications require knowledge of the seafloor topography and detailed information about the seafloor composition, both at the sediment surface and in deeper layers. The conventional approach to obtain information about the seafloor composition is to take physical sediment samples. This procedure is extremely expensive and time consuming. A much more attractive technique, which provides high spatial coverage at limited costs within short time, is acoustic remote sensing. Such technique has been successfully developed that classifies the seabed surfaces using single beam, multibeam, and side scan sonars (Van Walree et al.,

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2006; Sternlicht Daniel and De Moustier Christian, 2003; Eleftherakis etal., 2012; Applied Physics Laboratory, 1994).

Underwater acoustic devices operate at frequencies between 10 Hz and 1 MHz. Frequencies lower than 10 Hz will penetrate deep into the seabed, whereas frequencies above 1 MHz get absorbed very quickly. Most systems used today for seabed mapping make use of a single acoustic frequency because different frequencies will require sophisticated sensor to capture the desired information (Anderson et al., 2008). Classical Sub-Bottom Profilers are single frequency sonars that aim to explore the first layers of sediments below the seafloor over a thickness commonly reaching several tens of meters. Sediment structure is directly observed by measuring the elapsed time of the received reflections of the acoustic energy when it encounters boundaries of different sediment layers.

Parametric SBPs are very compact transducers that exploit signal interference process to construct low frequency signal with a very narrow beam width $\pm 2°$. The consequence of such configuration is a very small footprint about 7% of water depth i.e. high spatial resolution. Basically, the transducer transmits two primary simultaneous high frequency signals that are slightly different e.g. 100–95 kHz at high sound pressure. Due to the high pressure, the sound propagation will be non-linear; water sound velocity is a function of water pressure, temperature, salinity, and density (Urick, 1982). The higher sound amplitudes will move faster than lower sound amplitudes. As a consequence, a number of secondary frequencies are produced such as harmonics, sums and difference of the emitted signals e.g. 100–95 = 5 kHz.

Acoustic remote sensing classification methods are numerous but can fall under two general categories: phenomenological approach and model based approach. Phenomenological approach is based on grouping echo like features together and labeling each group using the acquired ground truth samples. The aim is to extract some properties from the measured seabed echo that will allow the seabed to be classified into relatively homogeneous categories. Classifying the data in this way allows areas with similar seabed properties to be grouped together. The selection of grouping can be based on the similarity of amplitudes, skewness, energies, etc. This approach used the single beam echo sounder SBES echoes in Orłowski (1984) by grouping the square root ratio of the energy of second bottom echo to the first bottom echo. For the same device, Chivers et al. (1990), Heald and Pace (1996) and Siwabessy et al. (1999) grouped the energy summation of the first seabed echo tail and used it to represent the seabed roughness. Multibeam and side scan sonars echoes were also used by Preston et al. (2004) where the selective features were Mean, standard deviation, higher order moments, amplitude quintiles histogram and power spectral ratio. On the other hand, Hughes Clarke et al. (1997) exploited the Seabed backscatter strength.

Model based approach is a mathematical model to seek quantitative estimates of the geo-acoustic parameters that are incorporated in the model. This is achieved by modeling the received signal and optimizes its geo-acoustic parameters to match the acquired signal. Knowledge of transmitted pulse shape, duration, and power is needed. The unknown geo-acoustic parameters are estimated by minimizing the mismatch between the acquired and modeled acoustic signals. The advantage of this approach is that, in principle no independent measurements 'ground-truth' of the actual seabed is required. However, the ground truth is still recommended to assess the classification results. This approach is more complicated than the phenomenological approach since it requires full understanding of the physical process that the signal encounters.

2. Data description

The data consist of four sets of measurements that cover four areas characterized by various sediment types. The data used in this research were acquired by 'Innomar' in January 2007 in the Baltic Sea near Rostock. An SES-2000 standard SBP system is used for acquiring the data with filters set to a maximum bandwidth. The filter settings are experimental to ensure that the received signal is almost unchanged which consequently caused high noise level. Therefore, a filtering bandpass filter process is necessary to remove the presence of noise to increase the level of confidence within the analysis procedure.

Each area is acquired by four frequencies, the primary high frequency (± 100 kHz), and three secondary low frequencies $\pm$(5, 10, 15 kHz). Fig. 1 illustrates the echo prints of the four areas observed by the low 15 kHz. The first and second datasets, known as 'area 1' and 'area 2' have a survey length of 112 m and 128.5 m respectively with an average water depth of 20.5 m. The third survey line 'area 3' is approximately 118 m, with a starting water depth of 14 m that gradually increases to 15.5 m. Finally, 'area 4' is acquired over a survey length of 105.5 m and average water depth of 13 m. The acoustic survey for each survey is carried out at approximate speed of 10 km/h with ping rate of six pings/s.

A number of core samples were collected as ground truth. Unfortunately, no laboratory results were presented; however, the visual inspection indicated that 'area 1' and 'area 2' at the seabed surface are dominated by soft sediments, e.g. mud. 'Area 3' is dominated by medium mean grain size, e.g. sand, and 'area 4' is characterized by rough sediment such as pebble or rocks. The analysis done in this research will exploit the prior knowledge of sediment description as a guiding reference for the consistency of the classification results.

3. Time domain energy model

The nonlinear SBP can be considered as hybrid sonar system of SBES and classical SBP where the high frequency is also exploited to measure accurate seabed depth. As the transmitted acoustic signal travels downwards through the water column with a relative large beam width $\pm 30°$ such as in the case of SBES, the received energy will be a composite of reflections and backscatters from the seabed surface. On the contrary, nonlinear SBP operates with a very narrow beam width $\pm 1.8°$. This geometric configuration makes the received echo a function of the impedance contrast rather than interface micro roughness; 'SBP sees only echoes that come perpendicular from the seabed with very narrow beam width' (Lurton, 2002).

3.1. Seabed surface classification

The physics based model (Van Walree et al., 2006) describes the received echo energy as a function of the transmitted pulse energy, water column losses and seabed reflection. The aim here is to infer the sediment type from its reflection coefficient