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A pulse-length correction to improve energy-based seabed classification in coastal areas

Daniel Rodríguez-Pérez [a], Noela Sánchez-Carnero [b,c,*], Juan Freire [b,d]

[a] Departamento de Física Matemática y de Fluidos, Facultad de Ciencias, UNED, Paseo de la Senda del Rey, 11, 28040 Madrid, Spain
[b] Departamento de Biología Animal, Vegetal y Ecología, Universidad de A Coruña, Campus de A Zapateira, Rúa da Fraga, 10, 15008-A Coruña, Spain
[c] Kartenn Tecnologías Para la Gestión Ambiental y Territorial, S.L., Capitán Juan Varela, 35, 5 D, 15007 A Coruña, Spain
[d] Barrabés Next, Serrano 16-1, 28001 Madrid, Spain

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ABSTRACT

Sea bottom classification using echosounders is an active field of research, where many different methods (to define echo features or perform their statistical classification) have been proposed and tested. Here we propose a new echo correction method suitable for use in coastal waters, where large relative depth variations occur. The idea is based on scaling the pulse length with depth as suggested by Pouliquen (Preston et al., 2004. Proceedings of the Seventh European Conference on Underwater Acoustics, ECUA 2004), but instead of in real time, in postprocessing. We investigate, in particular, the benefits of this correction for a classification based on the energy integrals of first and second return echoes, relying on the correction to find an optimal definition for those energy integrals. The method is tested in a coastal area survey with substrates varying over small scales (less than 200 m) and with large relative changes in water depth (5–40 m and slopes of up to 0.2). We show that the unsupervised classification bears a good agreement with divers groundtruthing (85% agreement with a Cohen's kappa, $\kappa=0.74$ for a 4-class map) and with previous knowledge of the study area.

1. Introduction

Acoustic methods have been widely used for sea-bottom classification (Kenny et al., 2003). Currently, multibeam and side-scan sonar systems mark the standard of sea-bottom classification because both can provide full seabed coverage for reflectance and texture-based seabed discrimination, using quantitative analysis and, eventually, human interpretation. Single beam echosounders too have long been used for sea-bottom classification. In particular, digital scientific echosounders calibrated to provide accurate scattering strength measures (Manik et al., 2006) but also simpler models that integrate energy response allowing the estimation of scattering strength (Orlowski, 1984; Burns et al., 1985; Voulgaris and Collins, 1990) have been used. Single-beam echo shape responses have also been characterized using features (moments, wavelet coefficients, fractal dimension, etc.) that have been related to different seabed types within a study area (Tsemahman et al., 1997; Tegowski et al., 2003; Preston et al., 2004; van Walree et al., 2005). Studies that use Sidescan Sonar (SSS) have been popular for bottom classifications based on geomorphological characteristics that distinguish geological formations of the sea bottom, often through visual analysis (McRea et al., 1999; García-Gil et al., 2000; Brown et al., 2002). Multibeam methods have provided the most detailed results (Dartnell and Gardner, 2004; Lamarche et al., 2011). They are based on backscattering strength analysis and make the most of the total bottom coverage of the Multibeam echosounder (MBS), rendering classification accuracy percentages higher than 80% (Serpetti et al., 2011). Despite some criticisms regarding its accuracy (see the comparative study of Schimel et al., 2010), use of MBS could be considered the standard for bottom classification in deep areas (in shallow waters its coverage is limited by depth). Its use is still limited by its high cost and high technical requirements for the acoustic signal correction and the classification of sea bottoms (Lefebvre et al., 2009). Single-beam echosounders are cost effective methods, providing classification results almost as good as those obtained with SSS and MBS by Parnum et al. (2008), Schimel et al. (2010) and Hamilton and Parnum (2011).

Extensive research has been carried out on the acoustic response of seabed (Jackson and Ivakin, 1998; Bergem et al., 1999; Pouliquen et al., 1999; Pouliquen, 2004; Manik et al., 2006; Ainslie, 2008, to mention just a few). Roughly speaking, the seabed acoustic response corresponds to that of an interface between two liquids with different acoustic impedances; no relevant transversal waves propagate below the sea-bottom. The acoustic reflectance depends on

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* Corresponding author at: Kartenn Tecnologías Para la Gestión Ambiental y Territorial, S.L., Capitán Juan Varela, 35, 5 D, 15007 A Coruña, Spain.
E-mail address: noelas@gmail.com (N. Sánchez-Carnero).

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the acoustic impedance ratio between the two media, the incidence angle, the interface roughness and the seabed attenuation coefficient for sound. All these factors have been analyzed in the literature and the total acoustic response can be forward modelled (Pouliquen et al., 1999) but, despite some efforts (see Sternlicht and de Moustlier, 2003; Simons et al., 2009; Snellen et al., 2011) no method has been agreed on to solve the inverse problem of determining the type of seabed (sandy, rocky, muddy, etc.) from the acoustic response.

The main factors affecting backscattered echoes which are difficult to include or to invert from theoretical models are seabed roughness, seabed slope and the finite length of the ping emitted by the echosounder. The answer to this question is processing of the echo to partially remove these effects (echo correction). In order to isolate depth effects in the received echoes corrections based on the depth and slope dependence of echo duration have been proposed (Biffard et al., 2005, 2007, 2010; Preston, 2006). Also, methods of correction of the echo with respect to the ping duration, either during the acquisition (Pouliquen, 2004) or after it (Caughey and Kirlin, 1996) have been proposed. However none of these methods, to our knowledge, have been included in any software or echosounder currently in use.

This paper will focus on this latter problem, i.e., correcting the effect of the finite pulse length. Our approach will be a combination of Pouliquen (2004) and Caughey and Kirlin (1996) approaches, trying to combine the benefits of both approaches. This correction becomes most important in coastal areas where depth differences range from a few meters to tens of meters. In the following two subsections we review some corrections and give more details about our objective.

1.1. Echo corrections

A single-beam echosounder emits acoustic waves that propagate with spherical symmetry from its transducer, traveling at the speed of sound in water, $c_w \approx 1500\ m/s$. The emitted power lasts for a small time τ, producing a wave packet that reaches the bottom and the sub-bottom region beneath and is backscattered to the transducer. As the wave propagates, its intensity decreases due to spreading and water absorption and scattering.

Most acoustic energy is concentrated in what is called the acoustic beam which spans some angle θ_a around the main emission axis of the transducer, usually defined as the that angle at which the emitted power decays to one half (-3 dB) of the beam maximum, and this marks the acoustic footprint or insonification area on the seabed. For an infinitely thin spherical wavefront with no seabed penetration most of the bounce energy would be concentrated in a time interval lasting from the first contact of the wavefront until the last contact within the acoustic footprint determined by angle θ_a, given by:

$$t_{echo} = \frac{R}{c_w}\left(\frac{1}{cos\ \theta_a} - 1\right)$$

where R is the seabed depth (or range). For a finite ping length, this time interval will be roughly increased by τ. As the acoustic wave propagates, a second signal twice reflected from the bottom, and once from the air–water interface, can reach the transducer as a second bottom bounce (see Fig. 1 in Siwabessy et al., 2000, for a graphical description of the process). Also for this second bounce a time interval t_{echo2} can be defined in which most of the echo power is received by the transducer. These time intervals t_{echo} and t_{echo2} are usually termed echo lengths. However, for some situations the echo signal can be detected for longer intervals than these, t_{echo} and t_{echo2}, ranging from the echo onset until the next echo arrives (or power decays in the order of the background noise). We will call this time length the full echo length or duration, given geometrically by $T = 2R/c_w$.

Thus, echo duration and amplitude depend mainly on the sea bottom depth. In order to obtain acoustic seabed segmentation from its acoustic responses, those responses, i.e., the echoes, have to be made comparable. This is what power and time corrections attempt to do.

Let us consider an ideal zero-length pulse. As the single-beam wavefront intersects a flat bottom around the circumference of a circle, the backscattered power received as an echo, $H(t)$, will be proportional to (Pouliquen, 2004)

$$H(t) \propto W_0\ exp[-4\alpha_w R(t)]/R(t)^3$$

where W_0 stands for the emitted power, α_w, the sound attenuation coefficient in water, and $R(t) = c_w t$, the range corresponding to time t and sound velocity c_w. Hence, power level, defined as $10 \log_{10} H(t)$, will be corrected with a TVG of $+30 \times \log_{10} R(t) + 4\alpha_w R(t)$. The latter term becomes more important the larger the depth and the higher the frequency: for instance, $\alpha_w = 8.5$ dB/km for 38 kHz signal, and $\alpha_w = 75$ dB/km for 200 kHz (computed according to Ainslie and McColm (1998)).

Furthermore, in order to compare the shape of two echoes measured at different depths, their recording times will have to be scaled with the time t_0 where each echo begins (proportional to depth), introducing a new time variable $\xi = t/t_0$. This simple scaling (assuming α_w negligible) will render the power-corrected function $H(t)$ depth independent (that is, representing H with respect to ξ will give always the same graph). Nevertheless, α_w is not always negligible, which introduces a small distortion in the corrected echo.

According to Pouliquen et al. (1999), the pulse signal $s(t)$ appears as the structure element of a convolution with a pulse independent seabed response $h(t)$. This $h(t)$ is the pressure response of the zero-length pulse previously described:

$$p(t) = h(t) \circ s(t) = \int_{-\infty}^{\infty} h(t')s(t-t')dt'$$

Caughey and Kirlin (1996) identified the need to correct this effect: "[…] contains a component (the source ping $s(t)$) that is independent of depth. Therefore, it is inappropriate to resample the received signal to correct for depth effects (specifically, dilation). Furthermore, in shallow water the bottom response becomes sufficiently short that the distortion introduced by convolution becomes a significant, and can not simply be ignored". These authors proposed a least squares deconvolution operation in order to recover the theoretical $h(t)$ from $p(t)$. Despite commercial echosounders actually measuring pressure $p(t)$, the values they usually provide are acoustic power $I(t)$, or intensity level $LI(t)$ measured in dB. Thus the deconvolution approach (leaving aside the numerical problems involved) is not a practical postprocessing solution.

One problem arising from the existence of this convolution is that power correction cannot be written as a simple TVG compensation any more; at least, this approximation is not good at the beginning of the echo, although it holds approximately for the echo tail (which begins at a time one pulse length after the beginning of the echo). The other problem is that time correction does not work because $s(t)$ is usually fixed in the echosounder settings and does not scale with depth as $h(t)$ does.

In order to solve this latter problem, Pouliquen (2004) suggested going the opposite way: scaling the pulses with depth during acquisition, in order to avoid the need for time correction as far as possible, i.e., making $h(\xi)$ depth independent. Pouliquen formulates the problem in terms of $H(t)$ and $S(t)$, the equivalent power signal, and suggests an active transmission of pulses of varying length, a step that would be done during the survey.