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Use of SDWBA predictions for acoustic volume backscattering and the Self-Organizing Map to discern frequencies identifying *Meganyctiphanes norvegica* from mesopelagic fish species

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ABSTRACT

To acoustically assess the biomass of multiple species or taxa within a survey region, the volume backscatter data should be apportioned to the constituent sound scatterers. Typically, measured backscatter is attributed to certain species using predictions at different frequencies, mostly based on the difference in scattering at the frequencies of 38 and 120 kHz (dual frequency method). We used the full version of the stochastic distortedwave Born approximation (SDWBA) model to predict backscatter spectra for *Meganyctiphanes norvegica* and to explore the sensitivities of ΔMVBS to the model parameters, e.g. acoustic frequency and incidence angle, and animal density and sound speed contrast, length, and shape. The orientation is almost the unique parameter responsible for variation, with fatness affecting longer lengths. We present a summary of ΔMVBS that can serve as the basis for identification algorithms. Next, we simulate the scenario encountered in the Balearic Sea (western Mediterranean) where Northern krill are mixed with mesopelagic fish species (bristlemouths and lanternfishes), which are modeled with a prolate spheroid model. Simulated numerical data are employed to emulate the discrimination process with the most common identification techniques and typical survey frequencies. The importance of using density-independent techniques for acoustic classification is highlighted. Finally, an unsupervised neural network, the Self-Organizing Map (SOM), is used to cluster these theoretical data and identify the frequencies that provide, in this case, the most classification potential. The simulation results confirm that pairs of frequencies spanning the Rayleigh and geometric scattering regimes of the targets are the most useful for clustering; a minimum of four frequencies are necessary to separate the three species, while three frequencies are able to differentiate krill from mesopelagic fish species.

1. Introduction

The ecosystem approach to fisheries management highlights the importance in concurrently exploring the various components of the trophic chain and evaluating the biomass contribution of the relevant species. Acoustic sampling tools offer this opportunity, especially if systematic acoustic surveys with scientific echosounders are performed in the areas of interest. However, the acoustic method requires correct identification techniques to separate echoes from the different species that need to be validated with net or optical sampling. In this context, the case of krill is of particular interest. While in Antarctic waters the *Euphausia superba* (Antarctic krill) is a key ecosystem species and has been a target of acoustic surveys for a long time, the acoustic data from recent surveys in the Northern hemisphere have been also used to investigate distribution and acoustic properties of the local krill species (De Robertis et al., 2010; Ressler et al., 2012; De Robertis and Cokelet, 2012; McQuinn and Dion, 2006; Peña et al., 2014).

Single frequency acoustics have been widely used in the past to generally describe patterns as swarms or layers of krill in some specific region, especially for Antarctic krill studies (Pieper, 1979; Cram et al., 1979; Sameoto, 1980; Macaulay et al., 1984; Greene et al., 1989; Wiebe et al., 1996; Hewitt and Demer, 2000; Kirsch et al., 2000; Lawson et al., 2004). However, the relationship between target strength, size and frequency has a non-monotonic form and varies with the scatterer's shape and aspect angle. Hence, it is not possible to uniquely distinguish any change in size or in abundance for even mono-specific aggregations using a single acoustic frequency (Holliday and Pieper, 1995) or between mixtures of different zooplankton species (Wiebe et al., 1990; Holliday and Pieper, 1995), or between zooplankton and collocated turbulent microstructures scattering (Stanton et al., 1994).

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Multifrequency acoustic methods have been proposed to overcome these ambiguities. Since the acoustic properties of individual species are known to vary with frequency, the variation in scattering strength between operative frequencies can be used for identification and discrimination purposes. Typically, a frequency-dependent identification technique uses the difference between mean volume-backscattering strength (ΔMVBS; dB re 1 m^{-1}) received at two or more frequencies to identify portions of the echograms occupied by particular scatterers or acoustic group (Madureira et al., 1993b; Watkins and Brierley, 2002). The higher number of frequencies is employed the more information about the general tendency of scattering with frequency (spectrum) is obtained, and thus the easier is to identify different species. However, investigators have mostly used the ΔMVBS technique involving the two common operative frequencies 38 and 120 kHz, the so-called dual-frequency method, defining ΔMVBS (dB) as

$$\Delta MVBS_{120-38} = \text{mean}(Sv(120) - Sv(38)) = TS(120) - TS(38) \quad (1)$$

where

$$Sv = 10_{*}\log 10(N) + 10_{*}\log 10(\sigma_{bs}) = 10_{*}\log 10(N) + TS \quad (2)$$

with TS being the Target Strength (dB re 1 m^2), Sv the volume backscattering strength (dB re 1 m^{-1}), N the numerical density (individuals per m^3) and σ_{bs} the backscattering cross-section (m^2) of the scatterers.[1]

The dual-frequency method has been applied for discriminating between zooplankton species (Greenlaw, 1979; Brierley and Watkins, 1996; Madureira et al., 1993b; Mitson et al., 1996), jellyfish and small pelagic fish (Lynam et al., 2004), small pelagic fish and plankton (Madureira et al., 1993b; Cochrane et al., 2000; Kang et al., 2002; Onsrud et al., 2004), mesopelagic fish species and krill (Watkins and Brierley, 2002; Fielding et al., 2012), and squid from finfish (Goss et al., 2001). However, it cannot distinguish between animals of very similar sizes or scattering type. Moreover, in order to render the ΔMVBS technique optimally effective, the frequencies should span the transition from Rayleigh to geometric scattering for all the organisms present in the survey area rather than just those of interest (Holliday and Pieper, 1995).

Ballon et al. (2011) and Lezama-Ochoa et al. (2011) proposed to apply the sum of MVBS rather than the difference by using $\sum MVBS_{120+38} = \text{mean}(Sv_{120} + Sv_{38}) = 20_{*}\log 10(N) + TS_{120} + TS_{38}$ where the numerical density term N remains, leading to changes in the ranges. Another technique used in the past employs Sv scatterplots of one frequency against another to visualise clusters of different species (Madureira et al., 1993a,b; Brierley et al., 1998; Simard, 1998; Griffiths et al., 2005). Both these techniques were employed for discrimination but, in contrast to the difference in frequencies of Eq. (1), changes in numerical density influence the results.

Recent papers warn on the use of common ranges of ΔMVBS for all krill lengths or in different areas with dissimilar krill characteristics (Watkins and Brierley, 2002; Woodd-Walker et al., 2003; Fielding et al., 2012). Woodd-Walker et al. (2003) employed a combination of ΔMVBS ranges with morphologic and energetic descriptors of schools or layers in a single frequency (as it was common for small pelagic fish, Reid, 2000), which provide further characteristics of the organisms and thus facilitate the classification. However, morphologic and energetic features can also vary with season, abundance, area, etc., as seen for krill schools (Tarling et al., 1998) and can be highly affected by vertical migration (Sourisseau et al., 2008), hence becoming dependent on sex and maturity stage (Watkins, 2003). Conti and Demer (2006) proposed a size-adaptive algorithm taking into account the changes of volume backscattering with krill length averages and demographics in the surveyed area. Changes in fatness and related material due to reproduction and diet may also lead to changes in ΔMVBS range and consequently biomass estimation (Hewitt et al., 2003). As for many fluid-like species, individual krill scattering (TS) is generally expected to increase within the typical frequency working band, i.e. from 18 to 200 kHz. However outside the Rayleigh scattering, length and specific behaviour (i.e. orientation) may result in maximum response at 120 or 70 kHz (Korneliussen and Ona, 2003; Calise and Skaret, 2011; Calise and Knutsen, 2012).

The TS of organisms are frequently estimated by using theoretical acoustic scattering models. Generally, the zooplankton models are based on shape approximations with simple geometric forms (Stanton and Chu, 2000) and are commonly parameterized using key reflection contrasts (speed of sound and specific mass density between the animal and surrounding seawater). In the early 1990s,a theoretical approach based on the distorted wave Born approximation (DWBA, Morse and Ingard, 1968) was adapted to predict the acoustical scattering from an elongated fluid-like organism such as krill (Chu et al., 1993; McGehee et al., 1998; Stanton et al., 1998). The actual shape of the organism is idealised by a discretised-bent tapered cylinder form and the result is obtained by coherent summation of scattering from discrete cylinders of varying radius representing the animal body shape when juxtaposed. Other parameters, such as the orientation and the scattering random phase, which take into account the stochasticity of the phenomena, may be introduced on the basis of empirical investigations to validate the model for specific species, size and frequency. At present, among the physics-based models the stochastic version of the distorted wave Born approximation (SDWBA) is recognised as the state-of-the-art in predicting TS from fluid-like zooplankton such euphausiids, and since 2005 it has been endorsed with its improvements by the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR) as standard for the acoustical estimates of Antarctic krill (SC-CMLAR, 2005).

The aim of this paper is to employ the SDWBA model, set with the most common parametrisation, to analyse the opportunity in identifying the Northern krill (*M. norvegica*) from mixed species aggregations with other detected scatterer types. For this purpose, we recreate a scenario encountered in the Balearic Sea (western Mediterranean) near Mallorca in late autumn 2009 and summer 2010 where *M. norvegica* individuals are mixed with mesopelagic fish species (Peña et al., 2014). We first review the $\Delta MVBS_{120-38}$ identification algorithm used for krill in other areas; then we study the influence of the different parameters on the theoretical $\Delta MVBS_{120-38}$ ranges estimated from the model using general levels for different krill species. The model is then restricted to *M. norvegica* parameters, with four distributions of orientation. Other techniques employed in the literature (scatterplots and sum of frequencies) are analysed to highlight the importance of removing abundance dependency. Finally, an unsupervised neural network, which takes advantage of all pairs of frequencies available simultaneously, is employed to study the frequencies responsible for a suitable acoustic separation in a mixing scenario of *M. norvegica* and mesopelagic fish species. All data used in this paper are theoretically inferred from the corresponding model.

2. Material and methods

2.1. Literature review ($\Delta MVBS_{120-38}$)

A summary of krill $\Delta MVBS_{120-38}$ presented in the literature is listed in Table 1. When comparing these results, it should be taken

[1] Note that this is a simplistic scenario, considering that all scatterers in each pixel are the same (in size, composition, and orientation), cancelling out the density term.