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Synthetic echograms generated from the relative frequency response

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Calibrated, digitized data from multi-frequency echo sounders have been used to generate new, synthetic echograms. The relative frequency response measured at four acoustic frequencies (18, 38, 120, and 200 kHz) is the main acoustic feature used to characterize the acoustic targets. Synthetic echograms are used to enhance and colour-code sample volumes with similar acoustic properties. The method is invaluable during scrutinizing, particularly in areas with many types of target. Several broad acoustic categories can be clearly distinguished, and detailed examples based on different fish species and zooplankton are demonstrated. The limitations of the method are described and discussed.

Keywords: acoustic, relative frequency response, multi-frequency, synthetic echogram.

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Introduction

Korneliussen and Ona (2002) have described an operational system for the generation of synthetic echograms in which model-based and empirical features of the acoustic backscattering were grouped into acoustic categories and visualized in a new, synthetic echogram. These echograms were generated from multi-frequency data collected on ocean-going vessels with hull-mounted transducers and were used to aid the scrutiny of acoustic-survey data. Signals representing schools of Atlantic mackerel (*Scomber scombrus*) were extracted from other targets (zooplankton and swim-bladdered fish figured in one of the surveys presented). The system was tested further on mixed-species echo traces in Balsfjorden, northern Norway, using ground-truthed data in a local ecosystem. The main acoustic feature processed by the system was the relative frequency response r(f), defined as $r(f) \equiv s_v(f)/s_v\ (38\,\mathrm{kHz})$, where s_v is the volume-backscattering coefficient, and the response at the acoustic frequency f is normalized to that at 38 kHz. r(f) was determined for each pixel of the echogram, representing the elementary sampling volume or volume-segment in the stored digital data.

In most regions of the echograms from Balsfjorden, Korneliussen and Ona (2002) were able to categorize nearly all the volume segments with the identified categories matching the biological samples. In some regions, however, the percentage of uncategorized volume segments was as much as 40. This uncertainty was partly a result of imperfect spatial sampling but was also related to the complex mixture of species. The first analysis used the original acoustic data, and data smoothed vertically and horizontally with Gaussian weights as input to the original categorization scheme. It did not, however, correct for the pulse-transmission delay: see below for details of the smoothing process. The analysis described in this article uses smoothed data. The uncertainty of the resulting acoustic classification was reduced, and the discrimination between the categories was improved. We suggest that this method in general may also be useful in species-identification algorithms (Haralabous and Georgakarakos, 1996). The quality of the acoustic data is still a limiting factor, especially the spatial overlap at different frequencies, but arranging the transducers in a tight cluster will significantly improve the horizontal overlap and therefore also the spatial overlap of the data.

The expected relative frequency response from a few target-scattering categories is illustrated in Figure 1, with the region covered by our four discrete frequencies 18, 38, 120, and 200 kHz, as indicated. In practical survey conditions, measurement uncertainties, relative acoustic frequencies, and equipment limitations make it more appropriate, initially, to split the detected echoes into categories representing broad species types that may be refined later.

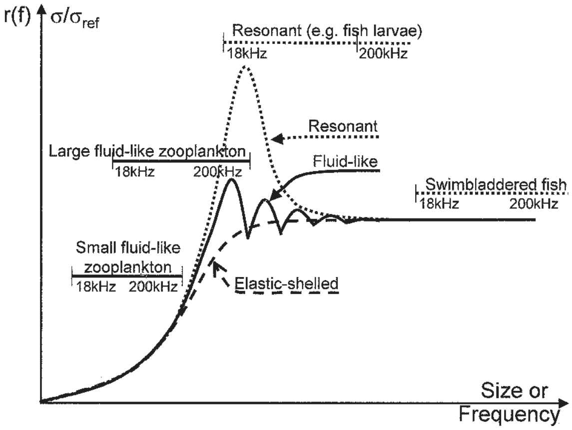


Figure 1. A general schematic description of the relative frequency response, r(f). Bands indicate typical positions of selected acoustic categories when measured at frequencies 18–200 kHz.

Fluid-like objects have sound speeds and densities not very different from those of seawater, and the backscatter shown as a solid line in Figure 1 is characterized by fluctuations between the low-frequency (Rayleigh) and high-frequency (geometric) scattering regions. All gas-filled objects, such as siphonophores and fish with swim bladders, display resonant scattering at a frequency that depends on depth and the size of the gas inclusion. Backscatter from elastic-shelled zooplankton is characterized by the smooth transition between low-frequency and high-frequency regions. Rough scattering classes are marked in the figure, along with the regions where these are expected for the stated frequency range. Under realistic conditions, the three curves will not follow each other in the low-frequency region, because the slope differs for the three classes. Furthermore, the backscattering strength in the high-frequency region will not be the same within each class. There will also be differences within each class, e.g. rate of increase, height, and width of resonance peak, frequency-spacing of the fluctuations for fluid-like backscatter, and the strength of the backscatter in the high-frequency region.

Materials and methods

Optimizing the collection of multi-frequency data

For detailed analysis, the physical and spatial characteristics of acoustic data should be as similar as possible at all frequencies. Consequently, special EK500 software giving equal pulse duration of 0.6 ms at all frequencies was used. The data were collected from RV "G. O. Sars", the Norwegian research vessel with the relative transducer-mounting and transducer-opening angles best suited for combination of acoustic data from multiple frequencies.

The smoothing process

To obtain the best resolution, the data should preferably not be smoothed. For large clusters of targets there is less need for smoothing, because the natural-backscatter fluctuations tend to cancel out. For volume segments containing only one or a few targets, however, smoothing is needed to reduce the expected stochastic variability in the measurements. The need for vertical or horizontal smoothing therefore depends on the number of objects in the measurement volume. The smoothing or reduction of resolution needed to increase spatial overlap is a different matter though, and it is essential to make measurements at different frequencies more spatially comparable.

The weights used to smooth our data always sum to unity, and have Gaussian distributions both vertically and horizontally. The weights that depend on the ping-rate and the vertical resolution of the data are shifted vertically to compensate for the bandwidth-dependent range offset at each frequency. They are also shifted horizontally to compensate partly for the relative positions of the transducers. The half-power averaging diameters used to compute the weights were 0.75 m vertically and 7.0 m horizontally. The horizontal offsets in the smoothing weights are those of Korneliussen and Ona (2002). Assuming a sound speed of $c = 1480\ \mathrm{ms}^{-1}$, the vertical offsets in EK500 were 0.61, 0.29, 0.28, and 0.17 m, corresponding to bandwidths of 1.8, 3.8, 1.2, and 2.0 kHz at 18, 38, 120, and 200 kHz, respectively.

Data collection and generation of categorization data

Data on mixed fish and zooplankton were collected during a 24-h survey in Balsfjorden, Norway, in September 1999, conducted from RV "G. O. Sars" as described by Korneliussen and Ona (2002).

For each frequency, the data were corrected for noise (Korneliussen, 2000) and smoothed as previously described. Data from multiple frequencies were combined to create a synthetic echogram, where each pixel was assigned a category. The resulting synthetic echogram was then stored as a single file including codes to identify the acoustic category. The categorization process was based on modelled or empirical acoustic features in the frequency range 18–200 kHz. The main acoustic feature used by the categorization scheme is the r(f) response. Only a single acoustic category is allocated to a volume segment.

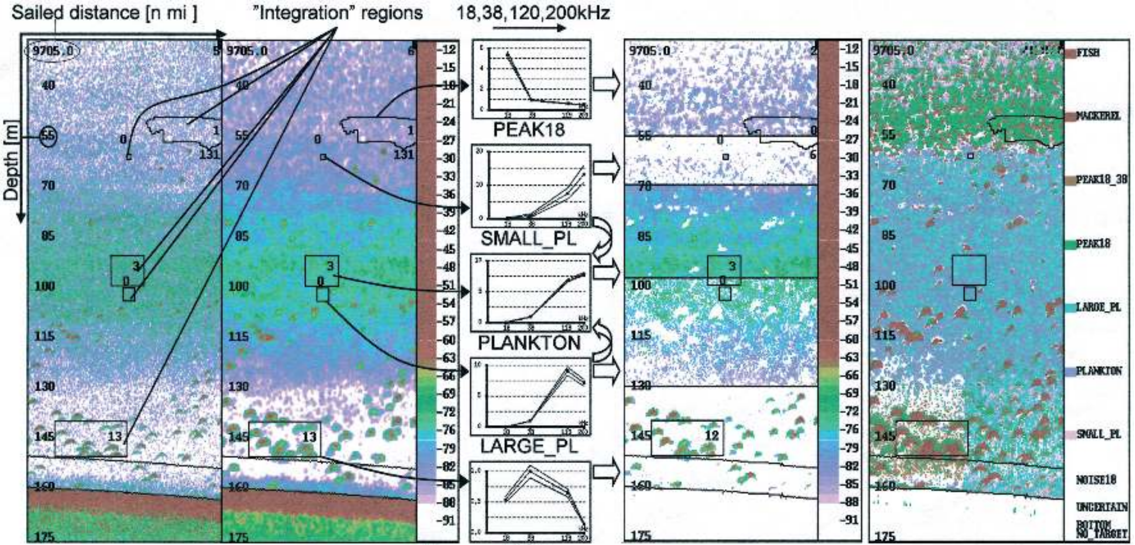
Results

The pelagic trawl is reasonably efficient at catching cod, capelin, and herring, and the trawl samples are expected to roughly reflect the fish population depicted in the echograms. Visual inspection of the capelin larvae of 3 ± 1 cm length caught at 40-m depth showed that, near the surface, the swim bladders were about 1–2 mm in diameter. All trawl samples showed capelin of length 11 ± 2 cm and cod of length 50 ± 10 cm. The zooplankton samples showed mainly copepods (*Calanus finnmarchicus* L.) and euphausiids (*Thyssanoessa* sp.) of 21.5 ± 1.5 mm in length. The vertical net used to sample zooplankton, WP-II, is known to have poor catch efficiency for euphausiids because of animal avoidance, especially for large specimens. Euphausiids comprised 25% of the total biomass according to the trawl samples, but this was probably an underestimate. Euphausiids were more abundant above 100 m (35%) than below (20%) during the night.

The combined frequency data used to generate new synthetic echograms were selected from a time of day (~22 MET) at which suitable biological samples could be obtained. Figure 2(a) shows the original acoustic data at 200 kHz, and Figure 2(b) shows the smoothed and shifted version of that echogram.

The mean r(f) response shown in Figure 2(c) indicates different species compositions in each of the marked regions. Figure 2(d) shows the smoothed 200 kHz echograms with only the denoted acoustic category retained. According to Figure 1, and supported by the biological samples, the echograms in Figure 2(d) from top to bottom indicate capelin larvae, small zooplankton, a mixture of large and small zooplankton, large zooplankton, and fish with swim bladders. The identified capelin larvae are resonant at 18 kHz at depths somewhere between 25 and 70 m. The standard error of the mean is computed for all curves in Figure 2(c) and is a good indication of the variability seen in the selected volume. The acoustic data are tested for all categories found in the "colour scale" and are visualized in Figure 2(e). Gas-filled zooplankton and mackerel were not present in Balsfjorden.

General impressions of the spatial distribution of the acoustic categories in Figure 2(d, e) are consistent with the biological samples. Cod and large capelin are seen as the acoustic category "FISH", and capelin larvae can be recognized as the acoustic category "PEAK18" above 65 m. The zooplankton samples showed mainly copepods and euphausiids, recognized in Figure 2 as mainly "PLANKTON" and "LARGE_PL", although also with some "SMALL_PL" above 60 m and below 160 m in Fig. 2(d, e). The category "PLANKTON", which included zooplankton of



a) 200 kHz (original)

b) 200 kHz (smoothed)

c) $\langle r(f)\rangle = \langle s_v/s_{v,38}\rangle$ Mean r(f) of region. Dominating category denoted.

d) 200 kHz smoothed data masked with acoustic category

e) Acoustic categories in artificial colours

Figure 2. Original, smoothed, and synthetic echograms covering 0.3 nmi collected during a period of 3 min: (a) noise-corrected data at 200 kHz; (b) noise-corrected and smoothed data at 200 kHz; (c) the r(f) response with standard error for the five selected regions. The regions (for example in (b)) are selected to represent typical r(f) responses for the five acoustic categories indicated below the five curves. The arrows to the middle curve indicate that the categories SMALL_PL and LARGE_PL are refinements of the category PLANKTON. (d) Five selected depth regions of the smoothed 200 kHz echograms at full resolution where the acoustic category in the connected r(f) response is retained. From top to bottom: PEAK18 (capelin larvae), SMALL_PL (*Calanus*), SMALL_PL + PLANKTON + LARGE_PL (calanus + euphausiids), LARGE_PL (euphausiids), FISH (cod + capelin). (e) All categories in a single echogram where the adjacent colour-scale denotes the category.

unknown size, is scattered in between "LARGE_PL" and "SMALL_PL" and is probably a mixture of large and small zooplanktons. The uncategorized volume segments are visualized in white, the same colour as the categories "BOTTOM" and "NO_TARGET".

Capelin larvae should appear mostly as the category "PEAK18" but could also appear as "PEAK18_38", depending on depth and swim bladder size. The acoustic category "PEAK18_38" has a much larger s_v at 18 and 38 kHz than at 120 and 200 kHz. At depths above 60 m, this category could be either capelin larvae or fish with swim bladders, while below 100 m, the category "PEAK18_38" is most likely to be cod, as inferred from the results of the trawl catches and the shape of the echo traces. Volume segments that are accepted both as "FISH" and "PEAK18_38" by the categorization scheme are categorized as "PEAK18_38".

In the lower part of Figure 2(e) some targets categorized as "PEAK18" are obviously larger fish, as seen from the shape of the traces, unlike the capelin larvae found in the uppermost region for the same acoustic category. This is probably a consequence of large fish being detected in the outer region of the 11° beam at 18 kHz, because these are barely visible in the 7° beams at the other frequencies. The categories "FISH" and "PEAK18" are, in this case, not separable using s_v. The hypothesis that the category "PEAK18" at this depth is also fish seems to be supported by the trawl samples. At depths below 115 m, many pixels on the left of Figure 2(e) are present with the noise at 18 kHz.

Discussion

The new synthetic echograms, with their algorithms for isolating and colouring categories with different acoustic-backscattering properties, may be useful tools for improving the quality and speed of the scrutinizing process. At this stage, however, neither the data nor the methods have been developed fully. The categorization system seems to work reasonably well for single targets. It is even better on clusters, schools, or layers of multiple targets. Using the categorization system, it is possible to visualize several acoustic categories simultaneously in one echogram so that all biological structures can be scrutinized together. It is, however, open to question whether the categorization system is useful for allocating the appropriate acoustic category to a volume segment. The uncertainty of the resulting acoustic categories will surely decrease if more frequencies were used to calculate r(f), given a good spatial overlap between the acoustic beams. Spatial overlap above 85% is suggested as a reasonable criterion for the direct generation of synthetic echograms from r(f). For the data presented in this article and pre-processed as described, this degree of overlap was achieved at depths beyond 30 m.

Even though the biological samples appear to support the results of the acoustic categorization, the accuracy of the identification process is difficult to assess. Separation of closely related categories may be difficult, and the separation of mixed aggregations of large and small fluid-like targets is demonstrated in the three middle r(f) curves in Figure 2(c). However, the proportion of successfully categorized volume segments is now more than 95%, a clear improvement on previous systems, which achieved less than 90%.

The generation of "categorization" echograms is a slow operation compared with "division" echograms, which is the same as "dB-difference" echograms (Socha *et al.*, 1996; Korneliussen and Ona, 2002), but this is overcome in practice by automatic generation of the synthetic echograms prior to the scrutinizing process. The strategy used in our method is to split the acoustic returns into broad acoustic categories by means of acoustic features. The broad categories initially give a crude indication of the content of a volume segment but they can be refined, as was done here, by splitting the acoustic category "PLANKTON" into "SMALL_PL" (small fluid-like plankton) and "LARGE_PL" (large fluid-like plankton, e.g. krill). The use of acoustic features is in accordance with the conclusion of Martin *et al.* (1996) that the classification of zooplankton from broadband acoustic signatures gave better results than the use of a stricter, model-based approach. Another example is Kloser *et al.* (2002), who used 12, 38, and 120 kHz data to identify three acoustic groups.

Categorization through the relative frequency response, r(f), can probably be improved by combining it with other methods and by improved mathematical modelling. On the other hand, in the current implementation only a single acoustic category can be allocated to a volume segment. Consider a 7° sound beam and a 1-m layer at 200 m depth. The ensonified volume is almost 500 m^3, and will probably contain several species. Thus, the strongest scatterers are likely to be overrepresented in acoustic registrations of mixed species, while the weakest scatterers will be underestimated.

The greatest advantage of the present synthetic echogram over other types of display is that the distribution of the biological structures is visualized in a single echogram at high resolution. The use of other types of combined echograms, such as "division", "product", or "mean", requires inspection of several echograms to find the most suitable methods and frequency combinations for the target category. The results of the categorization process described here can also be used to show or remove data for selected species at any single frequency, e.g. 38 kHz. The filtered data set can then be used to compute abundance.

The method described is general and may be further applied to broadband acoustic data and low-frequency acoustic systems. The lower detection range of the higher frequencies, however, limits the effective range of the complete system. For hull-mounted transducers, it is difficult to observe targets at depths below 150 m with the full combination of our four frequencies. The maximum observation depth is limited by the 200 kHz component. One solution would be to transmit from a deep-towed body, but then the performance of the transducers at depth becomes a new challenge.

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