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Tittel (norsk/engelsk):
SOME METHODS FOR GENERATION OF COMBINED-FREQUENCY ECHOGRAMS

Forfatter(e):

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Sammendrag:
Kalibrerte digitaliserte data fra to eller flere akustiske frekvenser på ekkolodd kan kombineres med formål å skille fra hverandre og trekke ut ekko fra zooplankton og fisk i blandede forekomster. Metoder for manipulering av ekkogram og for kombinering av akustiske data inn i nye syntetiske ekkogram blir beskrevet. Eksempler på hvordan ekko informasjon fra blandede registreringer av fisk og små organismer som kopepoder og krill vises, og potensialet til hver enkelt av kombinert frekvens metodene diskuteres.

Summary:
Calibrated and digitised data from two or more discrete echo sounder frequencies can be combined for the purpose of separating and extracting the acoustic scattering from zooplankton and fish in mixed recordings. Methods are described for echogram manipulation and for the construction of new synthetic combined frequency [*c(f)*] echograms. Examples of extracted scattering information from mixed layers of fish and small scattering organisms, such as copepods and euphausiids, are shown, and the potential of each of the different *c(f)* methods is discussed.

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SOME METHODS FOR THE GENERATION OF COMBINED-FREQUENCY ECHOGRAMS

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ABSTRACT

Calibrated and digitised data from two or more discrete echo sounder frequencies can be combined for the purpose of separating and extracting the acoustic scattering from zooplankton and fish in mixed recordings. Methods are described for echogram manipulation and for the construction of new synthetic combined-frequency [*c(f)*] echograms. Examples of extracted scattering information from mixed layers of fish and small scattering organisms, such as copepods and euphausiids, are shown, and the potential of each of the different *c(f)* methods is discussed.

Key words: Acoustic, interpretation, echo integration, multi-frequency, synthetic echogram.

1. INTRODUCTION

Korneliussen and Ona (2002) described the requirements for the collection of acoustic data at multiple frequencies and combined-frequency methods in a general, but only the two methods that seemed to be most effective in improving the quality of the scrutinised data were discussed. Several of the methods omitted by them have been presented in other papers by the same authors (Korneliussen, 1999, Korneliussen, 2000, Korneliussen and Ona, 2000, Korneliussen and Ona, 2001). All of the methods previously published by the two authors are described in this paper, as well as some that have not been published previously. All methods are described for the linear domain, i.e. not in the logarithmic domain. Each described combined-frequency [*c(f)*] method is employed on pre-processed (i.e. noise-corrected, smoothed, etc.) multi-frequency data measurement from a volume-segment. The data-flow for preparing single-frequency [*s(f)*] data prior to the generation of combined-frequency data is illustrated in Figure 1.

This paper is intended to be an extension of Korneliussen and Ona (2002) and therefore mainly refers to that paper or papers containing preliminary results to that paper, but except for that aspect, it should be possible to read this paper independently.

2. DATA COLLECTION

Two Simrad EK500 split beam echo sounders with vertically oriented transducer beams were used to collect multi-frequency data. These systems were calibrated at least twice at two different locations. Calibration of the 18 and 38 kHz systems was well within specification, with effectively no variation between the series. For the 120 and 200 kHz systems the calibration series varied substantially, resulting in more than 25% uncertainty in the calculated volume and area backscattering coefficients s_v and s_A at these frequencies.

Selected, continuous-wave bursts are transmitted at all frequencies, synchronized to a common trigger pulse. The special EK500 used transmitted pulses of 0.6 ms duration at all frequencies. A single Bergen Echo Integrator (BEI) recording process handles all data sent from each echo sounder to the local area network. Raw data were stored in files as volume backscattering coefficients s_v, together with spatial data which had a resolution of five hundred s_v echogram data values per ping per frequency. Horizontal data resolution varies with bottom depth and the EK500 processing speed but typical values were 1 ping per second. The depth resolution of the original echograms is 0.3 m and the average horizontal resolution approximately 2.5 m.

The acoustic data were collected in Balsfjorden in northern Norway in September 1999 by RV "G.O.Sars". The same data were also used by Korneliussen and Ona (2002). The purpose of the survey was to test the capacity of the system to discriminate between zooplankton and fish; therefore the biological sampling targeted a wider range of species, both zooplankton and fish. Balsfjorden has a typical depth of 150 m and it accommodates local stocks of cod, herring and capelin. The fjord is also known for large standing stock of euphausiids, mainly *Thyssanoessa spp.*

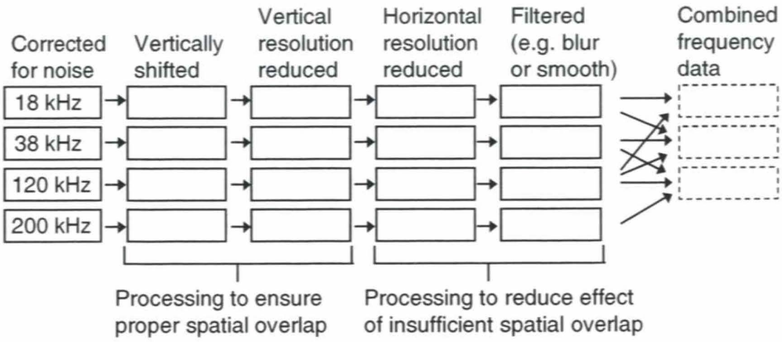
Data from essentially the same location were also used by Korneliussen and Ona (2002).

3. METHODS

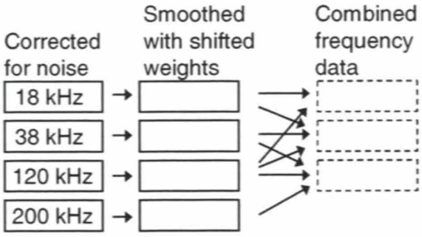
3.1. Data pre-processing

Recommendations for the collection of multiple-frequency data for the generation of combined-frequency data at its original resolution were described by Korneliussen (1999) and Korneliussen and Ona (2002) and were discussed by Korneliussen and Ona (2002). The actions required for the improvement of equipment and transducer-mounting as well as techniques for processing singe-frequency data prior to generation of c(f) data at its original resolution were also discussed by Korneliussen and Ona (2002). The most significant problem remaining is the spatial overlap.

The processing sequence, from noise-corrected acoustic data at its original resolution until the generation of *c(f)* data of combined-frequency data, is shown in Figure 1(a) and (b). The first processing steps in (a) are performed in order to ensure proper spatial overlap as described by Korneliussen and Ona (2002). The filtering step is introduced to smooth or blur the data at any frequency prior to generation of the combined-frequency data. All the steps after noise-correction are implemented in a single step as shown in Figure 1(b).



a) Principle for data processing



b) Implemented data processing

Figure 1. Data processing for the generation of combined-frequency echograms. The noise-corrected data are shifted vertically if required, provided there is sufficient vertical resolution. Reduced vertical resolution increases the vertical overlap whenever necessary to achieve proper spatial overlap in order to generate c(f) data. At each depth interval, data from several pings may be averaged to increase the number of samples needed to avoid natural stochastic fluctuations. Data may also be smoothed before c(f) data are generated (2). (a) Shows the principle for data processing, and (b) how this is implemented with a filter, using weights that are shifted vertically and horizontally.

The data presented here are smoothed vertically and horizontally with Gaussian weights with a 0.75 m average diameter vertically (truncated when less than 0.15) and 7.0 m horizontally (truncated when less than 0.3). For this vessel speed (11.3 knots), ping-rate and vertical resolution of the data, Table 1 shows the calculated weights for the 38 kHz data (where no vertical or horizontal shifting of the weights are necessary since the 38 kHz data are used as the reference):

Table 1. Weights used on the 38 kHz data (i.e. "unshifted" weights)

0.0113	0.0225	0.0334	0.0225	0.0113
0.0246	0.0488	0.0725	0.0488	0.0246
0.0404	0.0800	0.1189	0.0800	0.0404
0.0246	0.0488	0.0725	0.04877	0.0246
0.0113	0.0225	0.0334	0.02246	0.0113

The percentage spatial overlap [PSO] is defined as:

$$PSO = 100(PVO/100)(PHO/100) \qquad (1)$$

where PVO=100[1-abs(Δv_1-Δv_2)/Δz], Δv_1 and Δv_2 are the calculated vertical offset distances, Δz is the vertical resolution of the data, and *PHO* is the percentage horizontal overlap, i.e. the percentage common area of the two insonified beam disks at two frequencies at any depth.

The insonified disks used to calculate *PHO* are calculated from the 3 dB opening angles. For the 7° 3dB beams at 38, 120 and 200 kHz, *PHO*≈100–1040d/R for R>>d, where R is the range below the transducers and d is the distance between the transducer centres.

The 11° 3dB-beam at 18 kHz overlaps all the 7° beams for R>36 m. Note that the 18 kHz beam has a 3 dB angle of 11° as compared to 7° for the beams generated at the other freques. For a circular piston, only 56.6% of the backscatter that is measured within 11° at 18 kHz is (on average) also within 7° of the same beam. This is calculated from the two-way directivity functions of intensity times insonified area. For real beams, the level of the sidelobes is less than the Bessel directivity, so 60% within 7° may be a better estimate for real beams than 56.6%.

3.2. Visualisation of data

The "Linked echogram method" is a technique for processing either a set of single frequency echograms, or any of the combined-frequency echograms, but with scrutinising decisions made at one frequency used to assist the scrutinising process at the other frequencies (see Figure 1 in Korneliussen and Ona, 2002). All echograms are read into computer memory so that switching back and forth between the echograms at different frequencies is instantaneous. When only a single species is scrutinised at each of the frequencies, the stored single-frequency data can be used to extract more information on the dominant scatterers through inversion methods. The frequency-dependent backscattering is visualised through the relative frequency response, *r*(f), in a window. Korneliussen and Ona (2002), and Korneliussen (2002) described the "Linked Echogram" method and the relative frequency response.

Linked echogram at single frequencies: $s_{v,1}, s_{v,2}, s_{v,3}, \ldots, s_{v,N}$

Definition of the relative frequency response:

$$r(f) \equiv \frac{s_v(f)}{s_{v,38kHz}} \qquad (2)$$

where: s_v is the overall volume backscattering coefficient; *f* is the acoustic frequency; $s_{v,38kHz}$ is s_v at 38 kHz.

Echograms at the original frequencies or combined-frequency echograms may, as an alternative to the "Linked echogram combined with *r*(f)" method, be visualised in vertical or horizontal slices. The "Stripe" technique is used to visualise any type of *s(f)* or *c(f)* echogram in vertical slices with a common colour-scale for all slices. Any sequence of the synthetic echograms generated from any method described below or any echogram at the original single-frequency can be visualized in vertical slices in a single echogram with full vertical resolution. The instrument operators at IMR seem to prefer vertical slicing to horizontal slicing.

3.3. Generation of combined-frequency data from multi-frequency data

c(f) data may be generated by any of several methods. Some of the methods tested are listed below. In the notation used, s_v is the volume backscattering coefficient and the index 1, 2, …, N indicates rising frequencies. Results marked x_v have the same units as s_v and may be comparable in size, while results marked x do not have the same units as s_v. Each method has its own advantages and shortcomings.

3.3.1. Two-frequency methods

The "Difference" and "Division" methods are generated through well-defined mathematical operations. Using the "Division" method, only data from two frequencies can be visualised at a time, while with the "Difference" method this can be done only with data from a single frequency. The "Difference" and "Division" methods attempt to display certain targets, e.g. fish, and hide others, by using only two frequencies. "Difference" echograms were discussed by Korneliussen (1999) "Division" echograms by Korneliussen and Ona (2002) and an "Indicator" echogram by Korneliussen and Ona, 2000.

Difference:
$$x_v = s_{v,1} - s_{v,2} \quad if\ s_{v,1} \geq s_{v,2} \tag{3}$$

Division*:
$$x = \frac{s_{v,2}}{s_{v,1}} \tag{4}$$

Indicator:
$$s_v = \begin{cases} s_{v,1} & if\ \ s_{v,1} \geq const \cdot s_{v,2} \\ 0 & if\ \ s_{v,1} < const \cdot s_{v,2} \end{cases} \tag{5}$$

* To visualise the division data, none of the colour-scales used to visualise s_v data can be used.

3.3.2. Averaging multiple-frequency methods

The purpose of the "Mean" method is to display any targets within the observed volume. The purpose of the "Product" method is to develop large targets with a relatively frequency-independent backscatter. "Mean" and "Product" echograms were also shown byKorneliussen (1999). The results from the calculations below have the same units as s_v.

Mean (sum):
$$x_v = \frac{1}{N}\sum_i s_{v,i} \tag{6}$$

Product:
$$x_v = \prod_{i=0}^{N-1} s_{v,i}^{1/N} \tag{7}$$

RMS (Root Mean Square):
$$x_v = \frac{1}{N}\sqrt{\sum_{i=0}^{N-1} s_{v,i}^2} \tag{8}$$

3.3.3. Feature-based multiple-frequency method

The "Categorisation" method is not a well-defined single mathematical operation but rather a combination of several operations. The "Categorisation" method attempts to display certain targets, e.g. fish, and remove others, by using all frequencies. The method is based on acoustic features and on clustering of the categorised targets in several stages. In the first stage, strong acoustic requirements have to be fulfilled by a multi-frequency data-point. In the next stage, the acoustic requirements are reduced, but a further requirement of belonging to the same acoustic category as neighbouring data-points is imposed. In the following stages, the acoustic requirements are further reduced, while the clustering requirements are strengthened. The method was described in detail by Korneliussen and Ona (2002).

Note that the categorisation system uses data at their original resolution only to detect "no target", while smoothed data are used in all subsequent calculations. In Korneliussen and Ona (2002), both smoothed data and data at their original resolution were used in the further calculations.

$$\text{Categorise (visualise)}^{**}: \qquad x = \begin{cases} x_{NO\_TARGET} & \text{if } f_{NO\_TARGET}(s_{v,1},\cdots,s_{v,N}) = TRUE \\ x_{CATEGORY\_1} & \text{if } f_{CATEGORY\_1}(s_{v,1},\cdots,s_{v,N}) = TRUE \\ x_{CATEGORY\_2} & \text{if } f_{CATEGORY\_2}(s_{v,1},\cdots,s_{v,N}) = TRUE \\ \cdots & \cdots\ \cdots \\ x_{CATEGORY\_N} & \text{if } f_{CATEGORY\_N}(s_{v,1},\cdots,s_{v,N}) = TRUE \end{cases} \qquad (9)$$

$$\text{Categorise (mask)}^{**}: \qquad s_v = \begin{cases} s_{v,1} & \text{if } f_{CATEGORY\_1}(s_{v,1},\cdots,s_{v,N}) = TRUE \\ 0 & \text{if } f_{CATEGORY\_1}(s_{v,1},\cdots,s_{v,N}) = FALSE \end{cases} \qquad (10)$$

** The result of the categorisation may be visualised as a single echogram with each acoustic category coded by a value x, which for the purpose of visualisation is in the range of typical s_v values. Alternatively, the result of the categorisation may be used to generate a masking matrix to be multiplied by data at any frequency.

Categorisation: the idea

Figure 2 illustrates typical backscatter in a broad sense from three scattering classes. In practical oceanic situations, measurement uncertainties, the relative lack of available acoustic frequencies, and other reasons such as transducer positioning and known and unknown limitations of the equipment, combine to make it more convenient to split the measurements into broad acoustic categories before these are refined. The ideas of Figure 1 are incorporated into Table 4 in Korneliussen and Ona (2002).

Figure 2 shows that fluid-like objects have sound speeds and densities not very unlike those of seawater, and the backscatter shown as a solid line in Figure 1 is characterized by fluctuations between the low- and high-frequency regions. All gas-bearing objects, e.g. siphonophores or fish with swimbladders, produce resonant scatter at a frequency that depends on the size of the gas inclusion. Backscatter from elastic-shelled zooplankton is characterized by the smooth transition between the low- and high-frequency regions. Some scattering classes are marked in the figure, as is where these are expected to be found for the available frequency span. In real situations, the three curves will not follow each other in the low-frequency region since the rate of increase differs for the three classes, and the strength of the backscatter in the high frequency region will not be the same within each class. There will also be differences within each class, e.g. increase-rate, height and width of resonance top, frequency spacing of the fluctuations for fluid-like backscatter, and the strength of the backscatter in the high-frequency region.

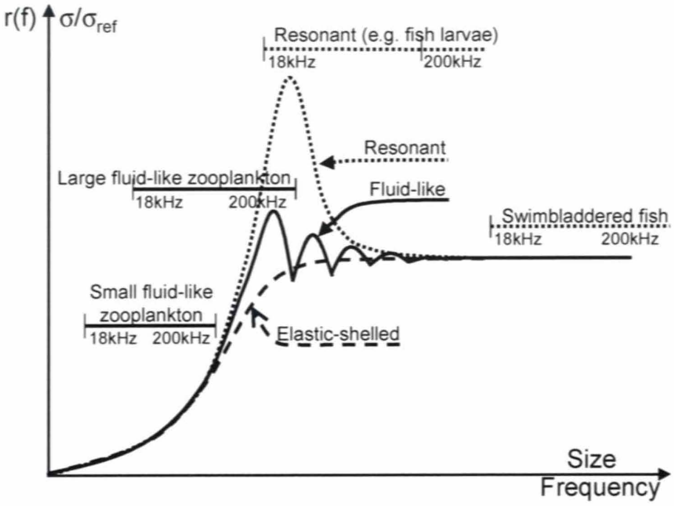


Figure 2. General schematic description of the relative frequency response, r(f), as expected from fluid-like, gas-bearing, and elastic-shelled objects. The typical position in the figure for selected acoustic categories when measured in the frequency range 18 – 200 kHz are indicated.

3.3.4. Mixed methods

In addition to the methods listed here, a long series of combined-frequency methods has also been tried out. The formulae for two of these are shown below. Although the visualisations derived many of these methods may appear attractive, the echograms generated from any of the methods tested so far are not easy to interpret.

Combined method (a):

$$x_v = \frac{2(s_{v,1}s_{v,2} + s_{v,3}s_{v,4})}{s_{v,1} + s_{v,2} + s_{v,3} + s_{v,4}} \qquad (11)$$

Combined method (b):

$$x = \frac{\prod_{i=0}^{N-1} s_{v,i}^{1/N}}{\frac{1}{N}\sum_{j=0}^{N-1} s_{v,j}} \qquad (12)$$

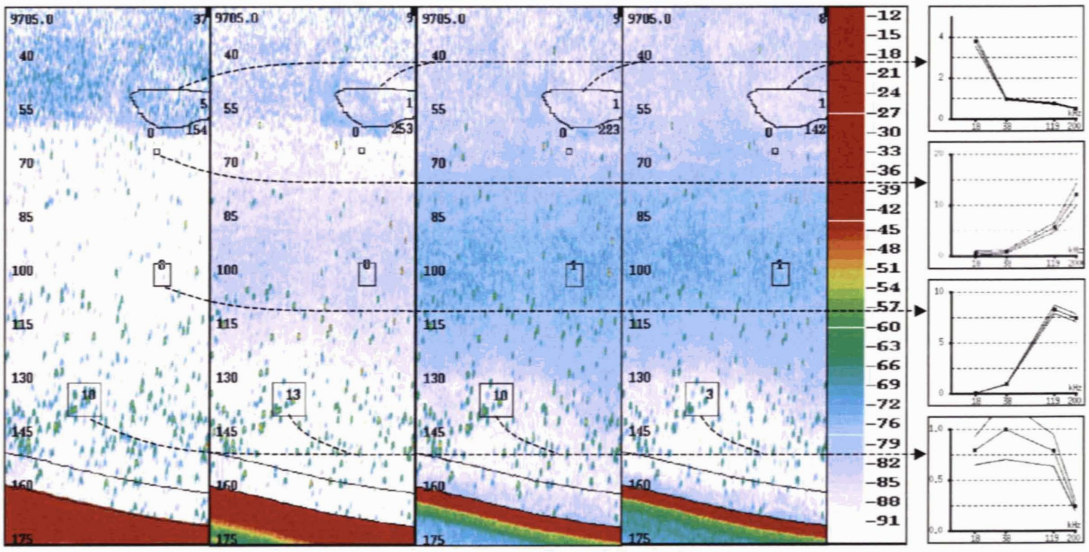
4. RESULTS

Details from the biological samples in Balsfjorden can be found in Korneliussen and Ona (2002). Pelagic trawl catch efficiency is reasonably good for cod, capelin and herring, so the trawl samples may be assumed to reflect the fish population as depicted in the echograms. All the trawl samples from Balsfjorden contained individual cod (50±10 cm) (Gadus morhua L.), and many large capelin (11±2 cm) (Mallotus villous L.). At shallow depths, a relatively large number of 0-group capelin (3±1 cm) were found. Visual inspection showed that the swimbladders of 0-group capelin were about 1 - 2 mm in diameter near the surface. WP-II and

MOCNESS zooplankton samples showed mainly copepods (Calanus finnmarchicus L.) and euphausiids (Thyssanoessa sp.) of 21.5±1.5 mm lengths. Copepods dominated both the size-fractionated biomass with specimens less than 2 mm, and the biomass of specimens larger than 2 mm (except for euphausiids). There is no indication of a patchy distribution for any zooplankton species, either in the acoustic or in biological samples.

The original noise-corrected and smoothed acoustic data at 18, 38, 120 and 200 kHz used to generate c(f) data, as visualized in Figure 3, were selected from a time of day at which suitable biological samples had been obtained. Acoustic data were collected 0 – 1.5 hours after the fish and zooplankton had been sampled. The mean relative frequency response, r(f), (with ranges of standard error of mean) shown in Figure 3e indicates different species compositions in each of the four marked regions. These regions are selected from areas in which the acoustic data indicated different species compositions, but in all other respects they were selected arbitrarily. According to Korneliussen and Ona (2002), the curves in Figure 3e from top to bottom indicate 0-group capelin, small zooplankton, large zooplankton and swimbladder fish. Juvenile capelin with 1-2 mm air-filled swimbladders, found in biological samples near the surface, were resonant at 18 kHz at depths of somewhere between 25 and 70 m. The standard error of the mean has been calculated for all curves. Gas-filled zooplankton and mackerel are not found in Balsfjorden.

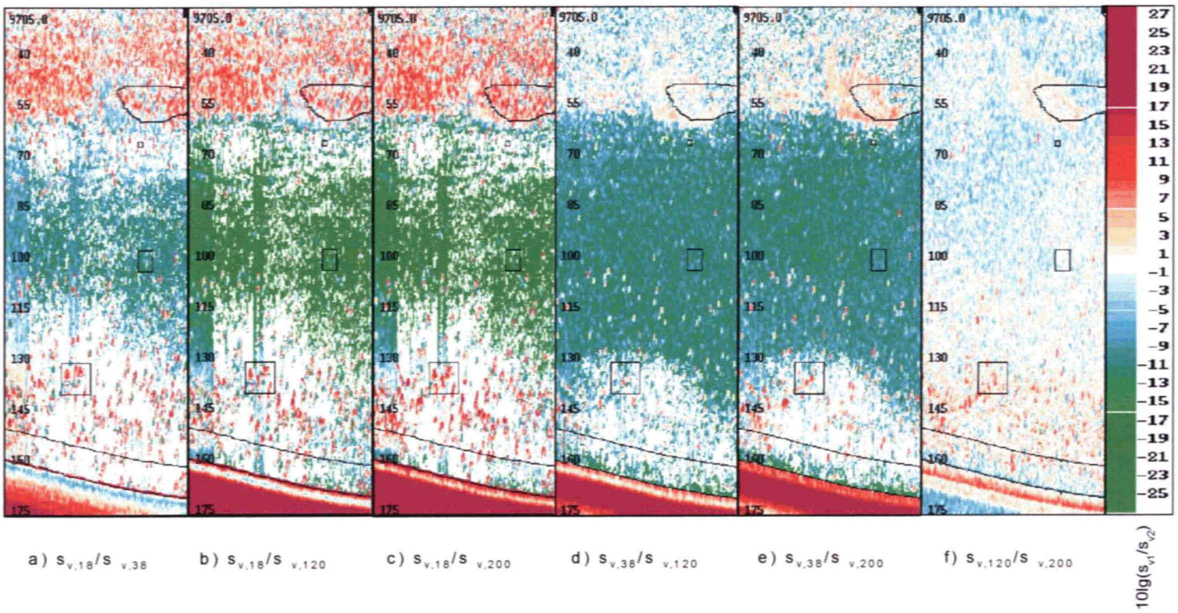
The echograms shown in Figures 3-7 cover one nautical mile and were collected in the course of 10 minutes.



a) 18 kHz b) 38 kHz c) 120 kHz d) 200 kHz S_v e) r(f)

Figure 3. Echograms generated from noise-corrected and smoothed data at their original acoustic frequencies. The colour scale is common to all echograms. The relative frequency response r(f) is shown in (e).

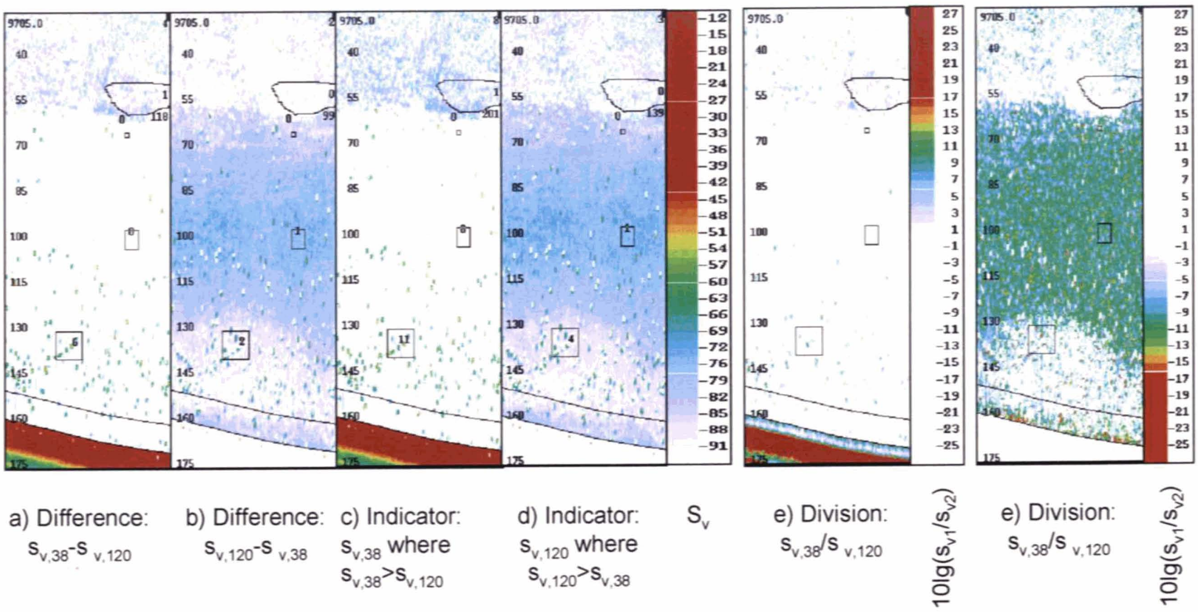
Echograms generated from the “Difference”, “Division” and “Indicator“ methods are shown in Figures 4 and 5. All available frequency combinations used to generate “Division” echograms are shown in Figure 4. The ability of a “Division” echogram to separate the acoustic categories depends on the frequency combination used. The zooplankton between 70-130 m are not equally visible at all frequency combinations, and it is not easy to distinguish 0-group capelin from fish above 70 m, or 0-group capelin from fish in the outer field of the wider 18 kHz beam. The use of two beams with similar half-power beam widths, e.g. the 38 kHz and 120 kHz systems, eliminates the problem of unequal sampling volumes, but since the backscatter from 0-group capelin peaks close to 18 kHz it is not easy to identify in the echograms generated from the 38/120 kHz frequency combinations. Calculation of the "Division" echograms is a fast operation since the raw data from the echo sounder are already available in logarithmic units, which gives a subtraction of the original data. Two disadvantages of the "Division" method are that data from only two frequencies at a time can be used and that the size of X is very sensitive to small $s_{v,1}$. For X very large or X=0, which may occur quite often when 18 and 200 kHz echograms are being compared, decisions on how to visualise X have to be made, whether as a white or an intensely coloured pixel.



a) $s_{v,18}/s_{v,38}$ b) $s_{v,18}/s_{v,120}$ c) $s_{v,18}/s_{v,200}$ d) $s_{v,38}/s_{v,120}$ e) $s_{v,38}/s_{v,200}$ f) $s_{v,120}/s_{v,200}$

Figure 4. Echogram generated from the "Division" method. The backscatter, which is strongest at the lowest frequency, is visualized in red.

Some "Division" echograms are shown in Figure 5 too, but with colour-scales that are more comparable to the "Difference" and "Indicator" echograms shown in the same figure. Echograms based on the "Difference" method shown in Figure 5 look good. However, as implemented here, only the acoustic data where either $s_{v,1}>s_{v,2}$ or $s_{v,1}<s_{v,2}$ are visualised at the same time, but not both simultaneously. The "Difference" method therefore has no significant advantages over the "Division" method. The Indicator method (see Figure 5) is a simple technique for retaining or removing data. The values used in the echograms are the measured s_v values (here: also noise-corrected and smoothed). The values removed from the echogram are the same as for the "Difference" method if the constant used in the "Indicator" method equals 1.0.



a) Difference: $s_{v,38}$-$s_{v,120}$

b) Difference: $s_{v,120}$-$s_{v,38}$

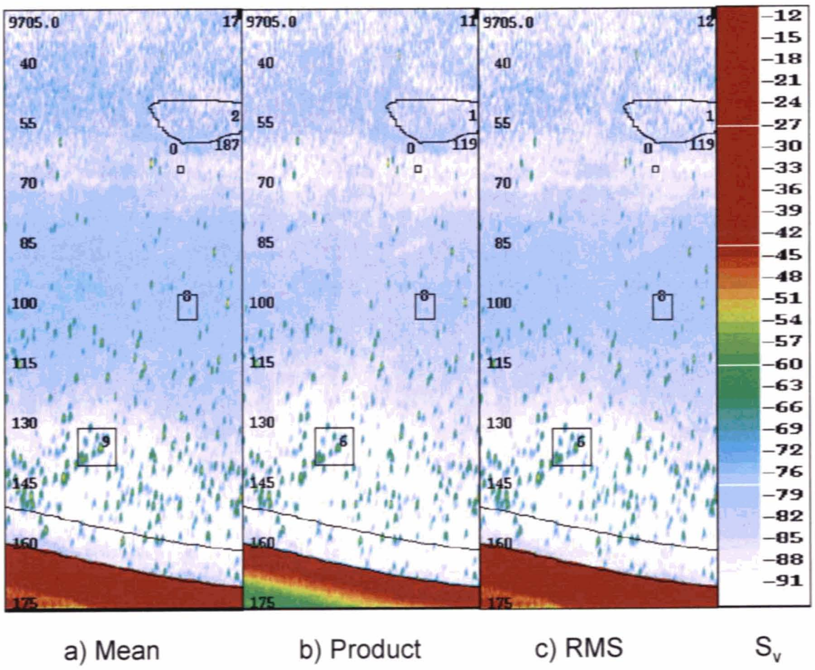
c) Indicator: $s_{v,38}$ where $s_{v,38}>s_{v,120}$

d) Indicator: $s_{v,120}$ where $s_{v,120}>s_{v,38}$

e) Division: $s_{v,38}/s_{v,120}$

e) Division: $s_{v,38}/s_{v,120}$

Figure 5. Echogram generated from the "Division", "Difference" and "Indicator" methods from 38 kHz and 120 kHz data. The "Difference" and "Indicator" echograms are visualized using same colour scale, and the "Division" echogram with different one. Figure (a), (c) and (e) emphasize the same features of the echogram. Note that the data visualized in Figure (e) and Figure 3 (d) are the same, but with a different colour-scale.



a) Mean

b) Product

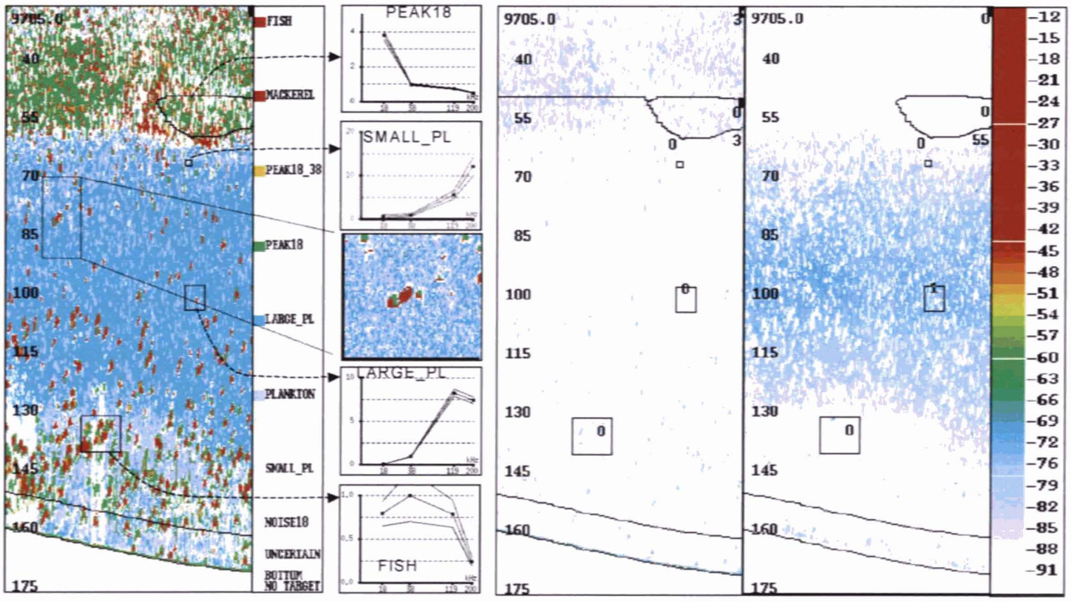
c) RMS

Figure 6. Echogram generated from 18, 38, 120 and 200 kHz data through the "Mean", "Product" and "RMS" method.

The "Mean", "Product" and "RMS" methods are different techniques for averaging backscatter at several frequencies. Echograms generated from these methods are shown in Figure 6. Spatial overlap is less important for the "Mean" method (Figure 6a) than for any other method, but the visual information of the echograms is not very clear, and information seems to be lost rather than improved. A small s_v generated using the "Mean" method is interpreted as no target at all in the insonified volume, while large values mean that some target does exist, large or small, plankton or fish. The generation of combined-frequency data through the "Product" method (Figure 6b) is dependent on the spatial overlap of the data at different frequencies. Large $s_{v,i}$ at each individual frequency and small frequency differences result in a large combined s_v. However, either small $s_{v,i}$ at each individual frequency, large differences between the frequencies, or poor spatial overlap will result in a small combined s_v. Thus, even though the echograms generated through the "Product" method look good, they are difficult to interpret.

"Indicator" echograms are simpler than "Categorise-mask" and faster to calculate, but have no other advantages over that method.

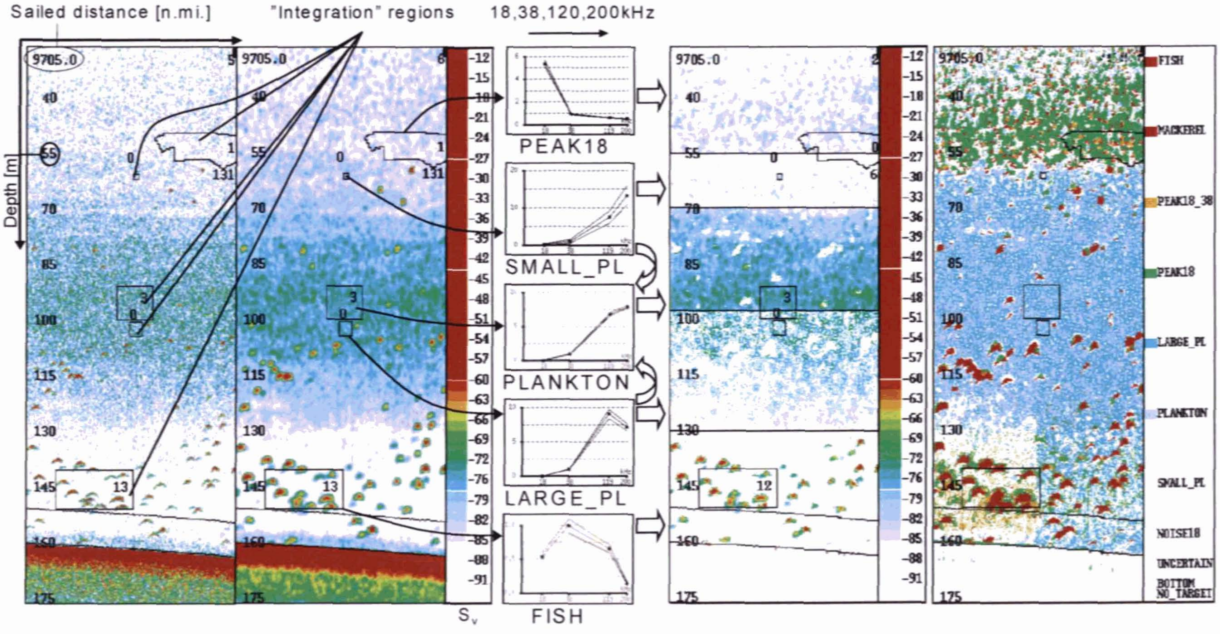
The result of the "Categorisation" method is shown in Figure 7. In (a), all categories are visualized in false colours, in (b) only the category "FISH" is kept at 38 kHz, and in (c) only the category "PEAK18" is kept at 38 kHz. General impressions of the spatial distribution of the acoustic categories in Figure 7 agree largely with the biological samples. Cod and large capelin are seen as the acoustic category "FISH". The acoustic category "PEAK18" above 65 m is recognized as 0-group capelin found in trawl samples. WP-II zooplankton samples above 100 m showed mainly copepods and euphausiids, recognized in Figure 7a as respectively "SMALL_PL" above 60 m and "LARGE_PL" below. "SMALL_PL" is also seen at depths below 160 m in Fig. 6f. The category "PLANKTON", with zooplankton specimens of unknown size, is scattered in between "LARGE_PL" and "SMALL_PL" and is probably a mixture of large and small zooplankton. Note that the uncategorized volume segments appearing mainly at depths of less than 70 m are visualized in white, the same colour as the categories "BOTTOM" and "NO_TARGET". Almost 40 % of the volume segments above 60 m are uncategorized.



a) All categories b) r(f) and section at full resolution c) PEAK18 at 200 kHz d) LARGE_PL at 200 kHz S_v

Figure 7. Echograms generated from the "Categorisation" method. (a) visualisation in false colours of all acoustic categories tested by the categorisation system. (b) r(f) for the four regions marked in the echograms. The dominating acoustic category is marked on each sub-figure; (b) also shows an echogram region at full resolution. (c) and (d) 200 kHz echogram masked by the acoustic categories PEAK18 and LARGE_PL respectively.

Cod, large capelin and 0-group capelin are found in the trawl samples from Balsfjorden. 0-group capelin should appear mostly as the category "PEAK18", but could also appear as "PEAK18_38" dependent on depth and swimbladder size. Acoustic category "PEAK18_38" has a much larger s_v at 18 and 38 kHz than at 120 and 200 kHz. At depths of less than 60 m, this category could be either 0-group capelin or diving fish (i.e. fish tilted at an angle). At depths below 100 m, the category "PEAK18_38" is most likely to be cod due to the results of the trawl catches and the shape of the traces. Volume segments that are accepted both as "FISH" and "PEAK18_38" in the same stage (Fig. 4) of the categorisation system are categorised as "PEAK18_38" since that category contains additional information compared to "FISH". Some features in Fig. 6f also require closer examination: in the lower part of the figure some targets categorised as "PEAK18" are obviously larger fish as can be seen from the shape of the traces, unlike the 0-group capelin found in the uppermost region for the same acoustic category. One reason could be that large fish are detected in the outer field of the 11° beam at 18 kHz but are barely visible in the 7° beams at the other frequencies. The strength of s_v measured at the individual frequencies was not sufficient for discrimination between the acoustic categories "FISH" and "PEAK18". No single targets suitable for further discrimination among the categories were detected by the echo sounder. The hypothesis that the category "PEAK18" in this case indicates fish is in agreement with the trawl samples.



a) Noise-corrected data at 200 kHz

b) Noise-corrected and smoothed data at 200 kHz

c) r(f) response from five selected regions.

d) Five depth-regions of smoothed 200 kHz data with one category retained.

e) All tested categories in a single echogram

Figure 8. Original, smoothed and synthetic echograms covering 0.3 n.mi., collected in the course of three minutes in Balsfjorden. The regions were selected to represent typical r(f) responses in (c) for five different acoustic categories dominating each region. The five categories retained in (d) are from top to bottom: PEAK18 (capelin larvae), SMALL_PL (calanus), SMALL_PL + PLANKTON + LARGE_PL (calanus + euphausiids), LARGE_PL (euphausiids), FISH (cod + capelin). All tested categories are visualized in a single echogram (e) where the adjacent colour scale denotes the categories.

Figure 8 show the result of the categorisation process over 0.3 nautical miles starting at the same location as Figures 3 - 7. Using smoothed and shifted data as input to the categorisation process generates Figure 8. The vertical and horizontal offsets at the other frequencies are given relative to the 38 kHz data. The horizontal offset is due to the transducer positioning, and the vertical offset is due to the combined effect of the transducer and the analogue filters in the echo sounder. The relative offsets of the 18, 38, 120 and 200 kHz data used to generating the "shifted" weights employed in Figure 8 are: -0.32, 0.0, 0.01, 0.12 [m] vertically and 0.60, 0.0, -0.40 and –0.68 [m] horizontally. The percentage of uncategorized volume segments is reduced when smoothed data alone are used as input to the categorisation system as in Figure 8, and not both original and smoothed as in Figure 7.

5. DISCUSSION

5.1. Comparison of the measurements between the frequencies

Combined-frequency echograms are useful tools, although they are far from perfect. One problem is the large number of echograms that need to be inspected in order to find the best method and frequency combination to extract the information desired. Another problem is the size of PSO that is required for a specific frequency combination and method to work properly with the equipment used.

There is no strict requirement regarding the size of PSO needed to defend the generation of combined-frequency echograms, but PSO>85[%] seem reasonable. For methods involving division or multiplication of data at two frequencies, PSO=85 gives an uncertainty of about 15 % in the result in addition to the measurement uncertainty. The categorisation system involves comparisons of of data at different frequencies, but since a smoothed version of the input data is always used, the categorisation method is less sensitive to lack of spatial overlap than, for example, the division method. A PSO closer to 100 will reduce the need to reduce resolution. Nevertheless, smoothing is still needed to some extentto reduce natural, stochastic, fluctuations in the measured acoustic data.

A combination of 38 kHz and 120 kHz data collected with EK500 onboard RV "G. O. Sars" (2) gives PSO>85 at ranges greater than 35 m from the transducers even at 0.25 m vertical resolution in the data, while any other frequency combination needs either a lower resolution, or can only be compared at a longer range. At ranges of greater than 36 m from the transducers as mounted on RV "G. O. Sars", the 18 kHz beam completely overlaps all the other beams due to its greater beam width. Due to the bandwidth-dependent nature of the pulse transmission delay, the vertical offset will be different at each frequency. Data collected at a sufficiently high resolution can be shifted vertically to increase PVO so that PSO≈PHO. The data used here were collected at a vertical resolution of 0.3 m, so the 18 kHz data can be shifted vertically to increase the spatial overlap, PSO, while maintaining all data at their original resolution. However, the pulse envelopes differ from an ideal square-wave pulse, especially at 18 kHz, and there is a problem of defining spatial overlap between the wider 18 kHz beam and any of the other beams, which makes the result of shifting the data vertically rather uncertain. For the data as collected, correlating vertically shifted data at 18 kHz with data at any of the other frequencies does not significantly improve the results as compared with unshifted data.

5.2. The methods: advantages and shortcomings

Each of the above methods for generation of combined-frequency echograms has its own advantages and shortcomings.

5.2.1. The Division, Difference and Indicate methods

The division of s_v values at two frequencies is easy to interpret, but the result is not volume back-scattering coefficients s_v. The calculation of $X=s_{v,2}/s_{v,1}$ is fast since the raw data from the echo sounder are already available in logarithmic units, which gives a subtraction of the original data. Two disadvantages of the "Division" method is that only two frequencies can be used at a time and that the size of X is very sensitive to small $s_{v,1}$. For X very large or X=0, which might occur quite often when comparing 18 and 200 kHz, decisions on how to visualise X has to be made, either as a white or an intensely coloured pixel in the echogram.

$X=s_{v,2}/s_{v,1}>>1$ for the available frequency combinations probably represents small zooplankton without encapsulated gas, and $X=s_{v,2}/s_{v,1}\approx 1$ for all reasonably close frequencies probably indicates swimbladdered fish. The interpretation is similar for the "Indicate" and the "Difference" methods. Calculations of "Indicate" echograms are also fast, and the result is in s_v, but the result from the "Categorise" method is generally superior to the "Indicate" method. The generation of "Difference" echograms is slower than "Division" echograms, but the interpretation of the results is similar to the "Division" methods. The preliminary conclusion is that the "Division" is the preferred method of the three two-frequency methods.

Table 2. Methods for combining data at two of four frequencies

	Indicate	Difference	Division
Spatial overlap sensitivity	High	High	High
Max no. frequencies in a single echogram	1	1	2
Echograms to be inspected (four orig. freq.)	12	12	6 – 12 [§]
Ability to discriminate between categories	Depends on frequency combination		
Greatest disadvantages	Large number of echograms to inspect		
Greatest advantages	Simple mathematically		* Fast to calculate * Simple mathematically
Improvement potential	Poor		None

[§] The number depends on whether data from one or two frequencies are visualised

5.2.2. The Mean, Product and RMS methods

Data from all frequencies can be used to generate combined-frequency echograms by means of the "Mean", "Product" and "RMS" methods. Spatial overlap is less important for the "Mean" method than for any of the other methods, but the visual information provided by the echograms is not very clear, and information seems to be lost rather than gained. For the "Product" method, the coordination of data collected at different acoustic frequencies is important. The resulting s_v is large if $s_{v,i}$ at each individual frequency is large. Even though the echograms generated through the "Product" method looks good, the echograms are not easy to interpret. Echograms based on the "RMS" method also give good-looking echograms, but like the "Product" method, the results are difficult to interpret and therefore not very valuable. At this time, it is difficult to envisage any obvious application of any of these three methods. Perhaps they could be used in combination with the "Division" method, for example.

Table 3. Methods for combining data at several frequencies

	Mean	Product	RMS
Spatial overlap sensitivity	None	High	None
Max no. frequencies in a single echogram	Unlimited	Unlimited	Unlimited
Echograms to inspect (four orig. freq.)	1 [§]	1 [§]	1
Ability to discriminate between categories	Low: only target or no target	Low/unknown: only large or low variability	Low: only target or no target
Greatest disadvantages	Poor ability to discriminate between acoustic categories		
Greatest advantages	Simle mathematically	Simle mathematically	Simle mathematically
Improvement potential	None	None	None

[§] 10 possible combinations, but only one needed to show data from all frequencies.

5.2.3 The Categorise method

The "Categorise" method enables several scattering categories in a single echogram to be visualised, or alternatively backscatter of selected acoustic categories to be retained or removed, i.e. back-scattered echoes from plankton can be removed if the purpose is abundance estimation of fish, and vice versa. Back-scattering at some or all frequencies is used to indicate whether data should be kept or rejected, but the actual algorithm used does not need to be as simple as the example used. The frequency dependence of the volume back-scattering coefficients, s_v, can be used to either place a target into one of the main acoustic categories, or even better; a species with well-known frequency dependent s_v can also be used for categorisation. Existing methods to discriminate between some selected species could be incorporated in the system, e.g. the method developed by Brierly et al. in 1999, or an artificial neural network as used to discriminate between schools of different species (Haralabous and Georgakarakos, 1996). The resulting values from the "Categorise" method can be converted to biological measures the same way as for single-frequency data, but since unwanted measurements are removed, the result is generally superior to single-frequency methods.

Table 4. Feature-based method for combining data at multiple frequencies

	Categorise
Spatial overlap sensitivity	Moderate [§]
Max no. frequencies in a single echogram	Unlimited
Echograms to be inspected (four orig. freq.)	1
Ability to discriminate between categories	Good: depends on models and empirical data.
Greatest disadvantages	* Complex mathematically * Slow to calculate
Greatest advantages	* Easy to interpret * Flexible in use
Improvement potential	Good

[§] Provided both original and smoothed data are used as input

There are approximately 40 possible combined-frequency echograms even with the methods described with data from four frequencies, but this large number of different combinations is a major drawback due to the time needed to inspect the echograms properly. It is therefore desirable to collect as much information as possible and select a few combined-frequency echograms for further use in the scrutinizing process. Some methods related to those described here have already been tried, but there is a need to optimise the methods for practical use on large-scale surveys. Several of the combined-frequency echograms give an impression of quality improvement over the single-frequency echograms scrutinised. Combined-frequency echograms generated by the "Division" method offer the operator valuable additional information . The frequency combination of 38 and 120 kHz is especially valuable, both because of large *PSO* and also because these frequencies have a greater ability to discriminate between plankton and fish. The power of the "Division" method to discriminate between target-categories is dependent on the frequency combinations, and it is necessary to examine several frequency combinations, which is a a time-consuming task. One of the greatest achievements on operational surveys at sea turned out to be the direct visualisation of the relative frequency response $r(f)$, and the use of this information to determine whether scrutinising echograms at more than one frequency adds valuable information. By eliminating the inspection and scrutinising of the echograms at all frequencies when this is not needed, the average time used to scrutinise the acoustic data collected in the course of a day is reduced from more than 3.5 hours to less than 1.5 hours.

The "Categorisation" echogram is the best of the types of combined-frequency echograms suggested, since it is able to visualise several scattering categories within a single echogram, unlike echograms generated from the other methods. The generation of "Categorisation" echograms is slower than generation of any of the other types of combined-frequency echograms, so off-line generation of the categorisation echograms as illustrated in Figure 1 is desirable. The target categories can be visualised in false colours to provide a rapid impression of the spatial distribution of the scattering organisms. Furthermore, target scatterers can be retained and unwanted elements removed from data at a single frequency, e.g. by removing back-scattered echoes from plankton if the purpose is abundance estimation of fish, so the categorisation system also provides assistance in extracting the proper value of the area backscattering coefficient, s_A, required for abundance estimation. The result is generally superior to single-frequency methods, since unwanted measurements are removed. Using the categorisation method to remove unwanted targets is also valuable for estimating the abundance of the remaining targets. This is as important as retaining desired targets. The estimation of plankton abundance based on acoustic data would be difficult without this method when fish and plankton are mixed.

Martin et al. (1996) concluded that a feature-based classifier performed better on most acoustic data than their model parameterization classifier. Our categorization system is also feature-based. They had access to broadband data in the frequency range of 350 – 750 kHz for classification of zooplankton, while we currently have access to only four frequencies. On the other hand, they did not use the low-frequency region to discriminate between the three classes of plankton. In our system, the low- and medium-frequency ranges are efficient at discriminating between copepods and euphausiids.

The categorisation system seems to work reasonably well, especially for species in clusters, e.g. schools or layers, in its current implementation, where only the acoustic properties of the animals are used. Once the targets in a cluster have been categorised, better methods for refining the target categories can be used, perhaps even methods for identifyingsingle species. For average measurements of the whole cluster, the spatial overlap between the data obviously becomes less important. When we reach this stage, existing methods of discriminating between species could be incorporated in the system to refine the acoustic categories, e.g. the method developed by Brierley et al. (1998) for discrimination between some types zooplankton, or an artificial neural network used to discriminate among schools (Haralabous and Georgakarakos, 1996).

The greater calibration uncertainty of the 200 and the 120 kHz systems as compared to the 18 and 38 kHz systems is a problem, but does not change the general picture of combined-frequency echograms. However, Stanton et al. (1994) did not predict a reduction in relative frequency response, *r(f)*, from 120 to 200 kHz for the euphasiids of length 22 mm found in this survey, but the reduction could be explained by the large calibration uncertainty. On the other hand, the reduction in *r(f)* is also found in many other surveys in which euphasiids have been seen, but in these surveys the acoustic returns were not compared systematically to models.

Even though the use of combined-frequency echograms, especially the "Categorisation" echograms is helpful during the scrutinising sessions, this does not solve all problems of interpretation, so an experienced operator of the system is still needed to make the decisions. The continued use of this system on routine surveys will show which direction the development of the system should take.

6 SUMMARY, CONCLUSIONS AND FUTURE WORK

The average time of 1.5 hours needed per day to scrutinise multiple-frequency acoustic data to the best quality using the system described above is acceptable.

So far, categorisation of acoustic data visualised in a single echogram is the most efficient of the methods proposed for visualising multiple-frequency acoustic data. The method generates an echogram type that makes scrutinizing much easier and therefore also better. The categorisation system is also used to generate masking matrixes to retain or remove selected data at individual frequencies, and is thus also able to extract the correct echo abundance, s_A, used for calculation of species abundance. The generation of echograms through the categorisation method is a slow operation compared to generation via the other methods, but generating the echograms prior to the scrutinizing process solves this.

The acoustic returns are allocated to acoustic categories, but of course only known categories can be used. Future work will aim to make improvements in the categorisation system. On the new, planned research vessel (RV "G. O. Sars" (3)), the transducer mounting will be better than on RV "G. O. Sars" (2) in order to adapt the system to the requirements described here. The 70 and 400 kHz frequencies will be added to the current frequencies of 18, 38, 120 and 200 kHz, and this will reduce the uncertainty in the categories identified by the current categorisation system. Echo sounders will also be modified to meet some of the requirements that have been identified to optimise them for multiple-frequency applications.

The Division method seems to be the most useful of the other methods. It generates the echograms rapidly, and a suitable combination of frequencies separates many acoustic categories reasonably well. One drawback compared with the categorisation echograms is that a relatively large number of echograms have to be inspected to find a frequency combination that separates species reasonably well. The method is sensitive to spatial overlap, and only two frequencies can be compared at a time. The number of frequencies that have to be inspected is reduced by using the relative frequency response, r(f). The visualised relative frequency response, *r(f),* is a helpful tool for keeping down the time required to scrutinize the data.

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