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An operational system for processing and visualizing multi-frequency acoustic data

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Calibrated and digitized data from two or more discrete echosounder frequencies can be combined for the purpose of separating and extracting the acoustic scattering from zooplankton and fish in mixed recordings. This method is also useful for quantifying the relative contribution of each frequency to the total acoustic-backscattering when scrutinizing records in large-scale, acoustic surveys. Echosounder hardware requirements are defined which would permit the ideal extraction of such information. These include calibration, transducer specification, pulse resolution and digital representation of the signals. During this initial study a special version of the Simrad EK500 multi-frequency, split-beam echosounder and the Bergen Echo Integrator (BEI) post-processing system were used. The echosounder transmitted pulses simultaneously at four frequencies, 18, 38, 120 and 200 kHz and transferred the received signals to the post-processing system in calibrated, raw, digitized format. 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 the method is discussed.

Keywords: scrutinize, echo integration, multi-frequency, combined-frequency echogram.

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Introduction

Acoustic methods are used widely now for estimating fish abundance (Nakken and Ulltang, 1983; Jakobsson, 1983; Aglen, 1989; MacLennan & Simmonds, 1992) and echo integration at one frequency, supported by biological sampling, is the general method used (MacLennan, 1990). Scrutiny of acoustic data is generally done by analyzing and correcting echograms in digital format using a dedicated post-processing system, e.g. Bergen Echo Integrator (Foote *et al.*, 1991; Korneliussen, 1993), BI500 (Anon., 1993a, b), EP500 (Lindem *et al.*, 1993), EchoView (Anon., 1999) or ECHO. Within these systems echogram recordings are subject to manipulation, thresholding, error-checking and noise removal. During the scrutinizing process it is possible to re-arrange and control the depth layers for which the fish density is to be measured. A team of experienced operators interprets acoustic data by drawing lines and encircling schools on the echogram screen. Supported by data from biological and oceanographic measurements this process allows them to separate, isolate, and allocate the different acoustic structures to species and groups of scatterers. In most surveys identification and separation of one or two target species is the main goal with the rest of the recordings of less importance.

Within acoustic-surveying methodology there is an incessant call for improvement in order to reduce ambiguity in the interpretation of acoustic data and thereby reduce the uncertainty of acoustic abundance estimates. "Species identification" was seen by MacLennan and Holliday (1996) as "The grand challenge of fisheries and plankton acoustics". Considerable potential for improvement may be derived from the echogram interpretation process of Mathisen *et al.*, 1974; Korsbrekke and Misund, 1993; Misund, 1997. An enhancement of the echogram interpretation process is desirable by utilizing multi-frequency information for

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species discrimination. Concurrently collected multi-frequency data, combined with an improved knowledge of the backscattering properties of the observed animals, a typical species mix, and the size distribution, may be used to characterize acoustic returns and thereby improve the scrutinizing process. Multi-frequency data have been used since the late 1970s to identify and quantify the scattering from zooplankton (Greenlaw, 1977; Holliday 1977; Holliday and Pieper, 1980). Madureira *et al.* (1993) used 38 and 120 kHz data to discriminate between Antarctic krill and other scatterers. Stanton and his co-authors have on several occasions investigated backscattering from three different zooplankton groups; gas bearing, hard elastic-shelled, and fluid-like, both experimentally (Stanton, 1994, 1998a) and theoretically (1998b) to categorize and reduce some of the great diversity in scattering by zooplankton. The models incorporate the orientation distribution of euphausiids (Chu *et al.*, 1993). Models for acoustic classification of zooplankton have been incorporated into two algorithms by Martin *et al.* (1996). These were applied with reasonable success on high-frequency, broadband data. For fish the multi-frequency information has been utilized only on rare occasions (Love 1971, 1977; Løvik *et al.*, 1982; Løvik and Hovem, 1979; Foote *et al.*, 1992; Foote *et al.*, 1993; Simmonds *et al.*, 1996) but seldom for stock assessment surveys.

For improvements under practical survey conditions the operator of the post-processing system needs tools for analysing combined multi-frequency echograms and sequences of single frequency [s(f)] echograms. Most of the available systems were originally intended for either s(f) analysis, or sequential analysis of several frequencies, although a few examples designed for the combined analysis of two frequencies have recently appeared (Socha *et al.*, 1996; Higginbottom *et al.*, 2000). In some systems, layer lines and parameters for scrutiny, which are selected during s(f) analysis, can be transferred readily between echograms along the survey track (Foote *et al.*, 1991). These can also cross frequencies (Korneliussen, 1993, 2000a), but few attempts have been made to combine the information in real-time, or near real-time, for direct presentation to the operator.

A practical approach is to incorporate into the post-processing system both the empirical relationships of frequency-dependent backscattering and, as a start, simple models of backscattering from spheres (Johnson, 1977) or cylinders (Stanton *et al.*, 1994), to discriminate between acoustic categories. The extraction of basic differences in the acoustic-scattering properties of various size groups, or species of fish and zooplankton, from simultaneous, multi-frequency recordings, as well as synthesis of this information numerically and visually, have been investigated (Korneliussen, 1999).

The main objective of the present work was to develop a system for near real-time analysis of multi-frequency acoustic data. Its focus was the need for rapid scrutiny during large-scale acoustic surveys because this is a very time-consuming task. For fish stock assessment purposes the Institute of Marine Research (IMR) Bergen, collects acoustic data continuously during about 2000 research vessel survey-days each year. Developing systems for improving survey efficiency, as well as accuracy and repeatability, is therefore of significant importance.

Materials and methods

System description – outline of processing modules

Acoustic data are recorded from one or more Simrad EK500 echosounders with vertically-directed transducer beams (Bodholt *et al.*, 1989). Each echosounder may include three transceivers with different operating frequencies. Selected, continuous-wave bursts are transmitted at all frequencies, synchronized to a common trigger pulse. A single BEI recording process handles all data sent from each echosounder to the local area network.

Design of the acoustic data flow for the post-processing system is shown in Figure 1. It includes five modules: (1) data collection; (2) data processing; (3) display and scrutiny; (4) data report and (5) archive. In addition there is a quality-assurance system (Korneliussen, 1996; Hansen *et al.*, 1999).

In module 2, recorded data are processed to make multi-frequency data suitable for the generation of synthetic combined-frequency [c(f)] echograms. The actual number of processing steps needed to achieve sufficient quality of the combined-frequency data depends on the echosounders, data resolution, transducer mounting, etc., and is described below. Increased efficiency of the process is achieved by quantifying and removing noise, smoothing data and, automatically generating c(f) data prior to each scrutinizing session, even though this may also be done stepwise during the session. Some default key parameters are set at the beginning of each survey to reduce the number to be set during scrutinizing. In addition to nation, ship and survey ID needed by the recording process to generate file-names, these parameters are: acoustic category (species), primary frequency, depth-channel thickness, and upper integration depth.

During the scrutinizing process s(f) acoustic data are read from the noise-corrected files and c(f) data are read from the generated files as indicated in Figure 1. All data for a selected distance, or time, are first read into the computer memory. Only the echogram at the pre-selected primary frequency is shown initially but data from any frequency can be loaded directly from memory.

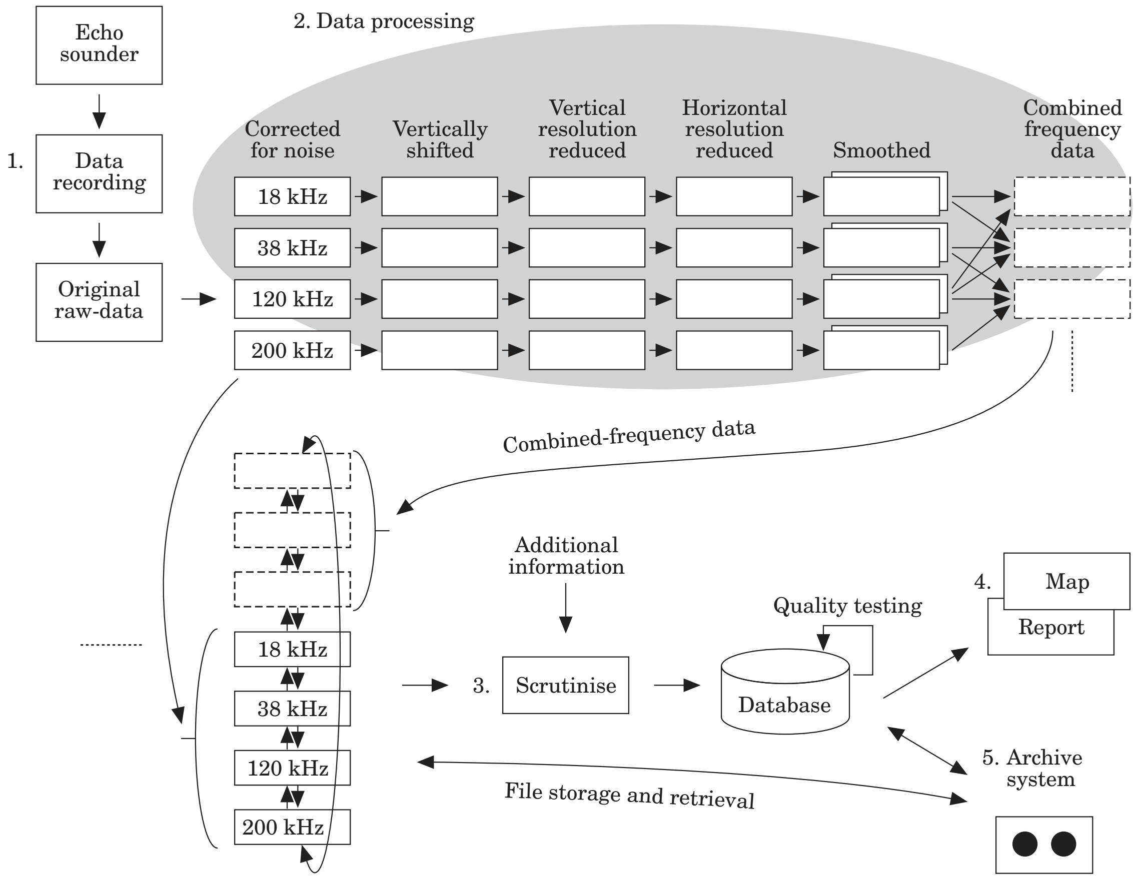

Figure 1. Data flow and data processing. The echosounder and post-processing system were set according to instructions. The BEI processor records data into files (1). Noise at each frequency is computed from the recorded data and removed. Data are shifted vertically if required provided there is sufficient vertical resolution. Reduced vertical resolution increases the vertical overlap whenever necessary to achieve proper spatial overlap 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). (See Figures 4 and B1 for generation of categorization c(f) data.) Noise-compensated data and c(f) data have an identical start time and cover the same distance; these data are interpreted and their quality rated by the program Scrutinize (3). When a new start-time is selected, the echogram for the pre-selected primary frequency is shown. Switching between frequencies is immediate. Scrutinized results at one frequency are overlaid onto the display for the next frequency. Database report programs present scrutinized data either in lists or charts (4). The archive system saves or restores both the database and the data-files to media, e.g. tape media, (5). All data-files may be archived, both original noise-corrected and the generated synthetic combined-frequency data-files. The content of the media is stored in the database for faster retrieval of archived data because the data-files itself are too large to be online continuously.

We define the relative frequency response, r(f) to describe the frequency-dependent backscattering as:

$$r(f) \equiv \frac{s_v(f)}{s_{v,38kHz}} \quad (1)$$

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

The r(f) response for a particular layer or school may be studied in a separate window to decide whether sufficient quality can be achieved by scrutinizing echograms at a single frequency. If not the process is aided by c(f) echograms which may be more time-consuming. Decisions resulting from scrutinizing, as indicated by layer and school selections on the primary echogram, are automatically transferred to displays for different frequencies. During the scrutinizing process c(f) echograms are also directly available to the operator. The echograms are then examined for the best possible quality during the time available and the results stored in the database.

An overview of scrutinized data can be visualized through an interactive map system. Data can also be stored to ASCII files for external software systems. Currently nineteen selectable print formats can be generated for each of the available frequencies 18, 38,

Table 1. Transducers, transducer mounting and echosounder parameter settings.

EK500 software version	5.30 SPECIAL			5.30 STANDARD
Frequency [kHz]	18	38	120	200
Transducer (Simrad)	ES18-11	ES38B	ES120-7	200-28
3 dB beam width [degrees][1]	11.0	6.9	7.1	7.0
2-way beam angle [dB][1]	− 17.1	− 21.0	− 20.6	− 20.4
Pulse duration [ms]	0.6	0.6	0.6	0.6
Bandwidth [kHz]	1.8	3.8	1.2	2.0
Distance between transducer centres [m]	0	0.595	0.99	1.27
Digital sampling distance [cm][2]	2	2	2	2

[1]Mean value from several measurements.
[2]The EK500 manual gives the sampling distance, not the sampling frequency.

120 and 200 kHz at each of the horizontal distance resolutions of 0.1, 0.5, 1.0 and 5.0 nmi. by pressing a single button of the database-report generator.

The current tape-archiving module stores the original and the processed data files, the database and information about decisions made through the scrutinizing process. This database also contains a reference to each data file on each tape for the efficient retrieval of any stored data, making data stored to tapes an extension of the online database. A quality-assurance system labels scrutinizes data for quality and marks the species for which the biological sampling was optimized.

Multi-frequency data collection

Defining ideal multi-frequency data

Multiple s(f) data may be collected in various ways on board research and fishing vessels. For detailed analysis the physical and spatial characteristics of acoustic data should be as similar as possible. While direct comparability is impossible in all aspects we define ‘‘Ideal data’’ as a reference point for the collection and analysis of multiple s(f) data. Acoustic data from several single frequencies are defined as ‘‘Ideal’’ in this context if they can be used to generate c(f) data at the same resolution as the original. This requires comparable physical measurements, done simultaneously from identical volumes, limited only by the effective range of the higher frequencies. We therefore propose the following requirements as necessary for ideally-recorded, multi-frequency acoustic data.

Requirements for physically comparable data are as follows (1) all echosounder and transducer systems must be calibrated; (2) insignificant noise, that is: (2.1) measurements should not be biased by noise and (2.2) noise should not reduce the sampling volume (see point 6); and (3) insignificant interference between frequencies.

Requirements to make data spatially comparable are as follows: (4) identical pulse lengths and pulse shapes at all frequencies; (5) individual pings identifiable in the data files at all times; (6) similar acoustic-sampling volumes at all frequencies for comparable ranges to the scatterers, i.e., targets of interest should be acoustically visible in all parts of the sampled volume for the ranges used (Foote, 1991). Providing there is insignificant noise, this implies: (6.1) similar half-power beam widths; (6.2) all transducers should have the same centre (including identical transducer depth) and (6.3) same acoustic axis for the transducers; and (7) the simultaneous transmission of pulses.

Several of these items in the ideal specifications above are not achievable using current systems. When working with hull-mounted transducers on research or fishing vessels it is particularly difficult to obtain spatially comparable data. The different transducers are often mounted separately on the hull and may be several meters apart, so that 6.2 and 6.3 are far from being fulfilled. Moreover transducer size, beam width and selectable pulse length are generally optimized for target detection at each frequency rather than for a combined analysis.

Collection of multi-frequency data on RV ‘‘G. O. SARS’’

During this specific study two Simrad EK500 echosounders operating at 18, 38, 120 and 200 kHz were calibrated using recommended methods (Foote, 1982; Foote *et al*., 1987) and standard targets for the particular frequencies. Noise was quantified and reduced according to methods described by Korneliussen (1998, 2000b). Noise reduction was done entirely by post-processing data and not by using the internal echosounder noise-limit control.

The first of the utilized sounders, EK500a, included three transceivers that operated split-beam transducers at 18, 38 and 120 kHz. The second sounder, EK500b, included a single transceiver which operated a single-beam, 200 kHz transducer. Simrad's standard operating software, version 5.30, was installed in EK500b, while a specially modified version 5.30 was installed in EK500a. Software modifications were made so that the pulse duration and the digital sampling-rate could be set to the same values for all operating frequencies (Table 1). Time

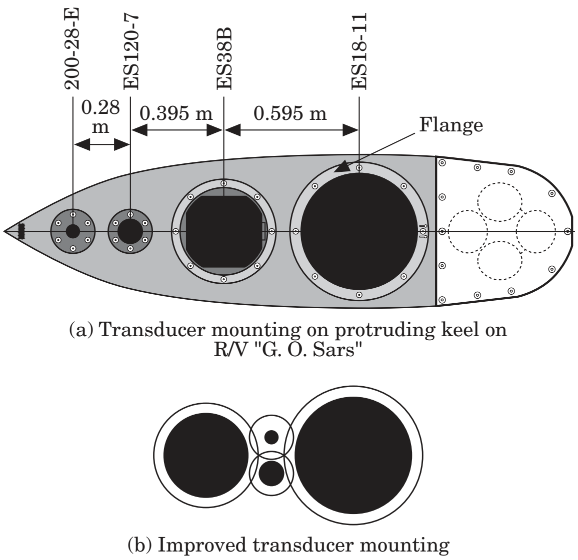

Figure 2. Transducer mounting on the instrument keel of RV "G.O. Sars". (a) Current mounting. (b) Proposed mounting for improved spatial overlap in acoustic data.

was registered when the EK500 transmitter was triggered and was stored with a resolution of 0.01 s for each ping.

For the 38, 120, and 200 kHz transducers the beam widths were close to 7°, whereas for the 18 kHz transducer it was 11^0. All transducers were mounted at the same depth on the bottom of a protruding instrument keel (Ona and Traynor, 1990) with the 18 kHz transducer in front of those at 38, 120 and 200 kHz. Transducer geometry is shown in Figure 2(a) and specifications are in Table 1, along with the specific EK500 parameter settings. The EK500 parameter "noise margin" is set to 0 dB on both echosounders.

Mounting transducers on the instrument keel of RV "G. O. Sars" (Figure 2(a)) is appropriate for multi-frequency analysis. Because of practical limitations related to these mountings and "filtering" effects in the echosounder and transducer systems both vertical and horizontal offsets are seen in recorded data as illustrated in Figure 3 for the two arbitrary frequencies Frequency 1 and Frequency 2. Horizontal offsets stem from the distance between the transducers while total system filtering causes the vertical offsets. The effect of the horizontal offsets is reduced with increasing range from the transducers (Table 2). Distances between the transducer centres are computed from Table 1. Beyond a range of 36 m from the transducers the 38 kHz, 120 kHz and 200 kHz beams are completely overlapped by the broader 18 kHz beam.

In a personal communication H. Nes of Simrad has derived two theoretical expressions for the nominal combined delay of the EK500 and the transducer. Calculation of the delays related to the EK500 internal trigger pulse is straightforward. They are dependent on frequency but independent of pulse length and are valid for the standard and the special version of the EK500. Ona *et al.* (1996) measured the delays with a standard version of the EK500 software (Table 3). The digital sampling distance in the standard version of the echosounder software, especially at 18 kHz (25 cm), reduces the accuracy of the delay measurements but the calculations should be valid both for the standard and for the EK500 special version. Here the delays are converted to vertical offsets in units of meters using sound speed $c = 1480\ \mathrm{m\ s^{-1}}$. Depths associated with the measurements of the volume-backscattering coefficients s_v are not corrected in the echosounder output data.

(1) Delay in seconds for WIDE bandwidth; 10% of the centre frequency f[Hz]: 14.8/f
(2) Delay in seconds for NARROW bandwidth; 1% of the centre frequency f[Hz]: 44.6/f

The percentage vertical overlap [pvo] between the frequencies is defined as: $\mathrm{pvo} = 100[1 - \mathrm{abs}(\Delta v_1 - \Delta v_2)/\Delta z]$ where Δv_1 and Δv_2 are the calculated vertical-offset distances found in Table 3 and Δz is the vertical resolution in these data. As an example, the pvo between 120 and 38 kHz is 98% for $\Delta z = 0.5$ m and 89% between 120 and 200 kHz for $\Delta z = 1.0$ m. Percentage horizontal overlap is pho. The percentage spatial overlap [pso] between the beams at different frequencies is defined as: $\mathrm{pso} = 100(\mathrm{pvo}/100)(\mathrm{pho}/100)$.

Generation of combined frequency data

Post-processing of each single-frequency data set

The measurement system is modified as described above to adapt to the requirements of ideal acoustic data but collected data still needs to be processed to adjust it for the generation of c(f) data. After noise correction, data may be shifted vertically to compensate for the frequency-dependent filter delays appearing as vertical offsets. This step is only performed if the vertical resolution of data is higher than the actual offset. Following this it may be necessary to standardize the vertical resolution of data. The latter may also be reduced to ensure appropriate overlap between the beams. Further, averaging several consecutive pings may reduce the horizontal resolution. For a number of "n" pings each of the processed data points at any depth is then the mean of "n" values. Averaging over several pings reduces the inherent fluctuations expected in acoustic data from multiple targets and provides better discrimination between acoustic target categories.

As an alternative to the reduction of resolution data may be smoothed in depth and distance (Figures 1 and 4) before generation of any type of c(f) data. Default weights of the two-dimensional moving average filter

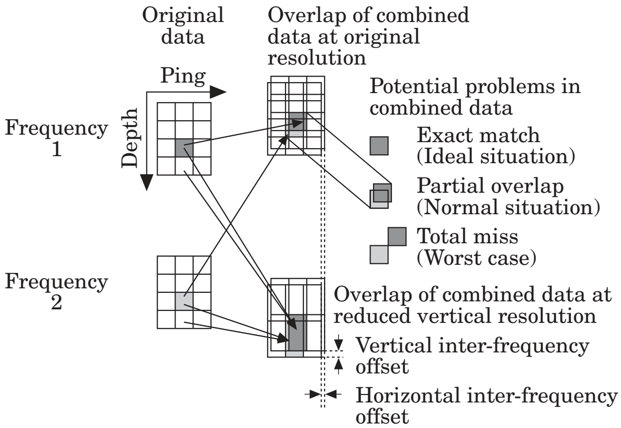

Figure 3. An illustration of some of the spatial problems for the generation of high-resolution c(f) echograms from data at two arbitrary acoustic frequencies, Frequency 1 and Frequency 2. Partial overlap, or at best horizontal offset, is the normal situation. The effect of horizontal offset decreases with increasing depth, while the effect of vertical offset remains. Reduction of the vertical resolution may reduce the problem of vertical offset.

Table 2. Percentage horizontal overlap (pho) between beams with 7° opening angles.

Distance between transducer centres	Depth below transducers 25 m	36 m	50 m	75 m
d=0.28 m (120 and 200 kHz)	88	92	94	96
d=0.675 m (38 and 200 kHz)	72	81	86	91
d=0.395 m (38 and 120 kHz)	84	89	92	95

used to smooth data are computed from a Gaussian series with 0.75 m vertical depth, while the weights used horizontally are 0.25, 0.5 and 0.25. These parameters may be changed by the operator. The Gaussian series is truncated when it calculates weights less than 0.15, and the remaining weights are then normalized to sum to unity. In the examples shown below only the Categorization system uses smoothed data. Figure 4 shows the original data points of a vertical resolution of 0.3 m smoothed using default filter weights.

Generation of combined-frequency data from multi-frequency data

Several methods may be used to generate c(f) data, provided that these are directly comparable with respect to digital resolution. Some c(f) methods have been tested and the two most promising of these are listed below. In the notation used, s_v is the volume-backscattering coefficient and the index 1, 2, . . ., n, indicates increasing frequencies. The s(f) and c(f) echograms are linked together as shown in Figure 1, with scrutinizing decisions made transferred between each of the s(f) and c(f) echograms.

Division (dB difference): $X = \frac{s_{v,2}}{s_{v,1}}$

Categorization (example): $s_v =$

$$\begin{Bmatrix} s_{v,\text{NO TARGET DUMMY}} & \text{if} & f_{\text{NO TARGET}}(s_{v,1},\cdots,s_{v,N}) = \text{TRUE} \\ s_{v,\text{CATEGORY 1 DUMMY}} & \text{if} & f_{\text{CATEGORY 1}}(s_{v,1},\cdots,s_{v,N}) = \text{TRUE} \\ s_{v,\text{CATEGORY 2 DUMMY}} & \text{if} & f_{\text{CATEGORY 2}}(s_{v,1},\cdots,s_{v,N}) = \text{TRUE} \\ \cdots & \cdots & \cdots \\ s_{v,\text{CATEGORY N DUMMY}} & \text{if} & f_{v,\text{CATEGORY N}}(s_{v,1},\cdots,s_{v,N}) = \text{TRUE} \end{Bmatrix}$$

For the "Division" method, data from two frequencies are pair-wise compared. This method attempts to enhance the difference in backscattering of a target at two specific frequencies.

Unlike the "Division" method, "Categorization" is not a well-defined single mathematical operation but rather a combination of several mathematical operations. The "Categorization" method groups volume segments of scatterers into acoustic-scattering categories, currently those in Table 4. Empirical data and various acoustic-scattering models are inspected to define simple and efficient rules for discrimination between the categories. To categorize the system presently uses the volume-backscattering coefficient, s_v, the nearest neighbours, and, in particular, the r(f) response. The volume-backscattering coefficient s_v relates directly to the backscattering cross-section, σ_{bs}, and to the volume, V, as $s_v = \Sigma\sigma_{bs}/V$ (see MacLennan *et al.*, 2001 for definitions). For each volume segment the categorization process results in a number, $s_{v,\text{CATEGORY\_N\_DUMMY}}$, that suggests which acoustic category the volume segment belongs to. Note that s_v requires several measurements to obtain stable results comparable to average backscatter calculated from models. One single

Table 3. Calculated and measured vertical offsets in transmitted pulses for a standard EK500.

Frequency [kHz]	18	38	120	200
Transducer	ES18-11	ES38B	ES120-7	200-28
Pulse duration [ms]	0.7	1.0	1.0	0.6
Bandwidth [kHz]	1.8	3.8	1.2	2.0
Calculated vertical offset [m]	0.61	0.29	0.28	0.17
Measured vertical offset [m]	0.46	0.30	0.24	—

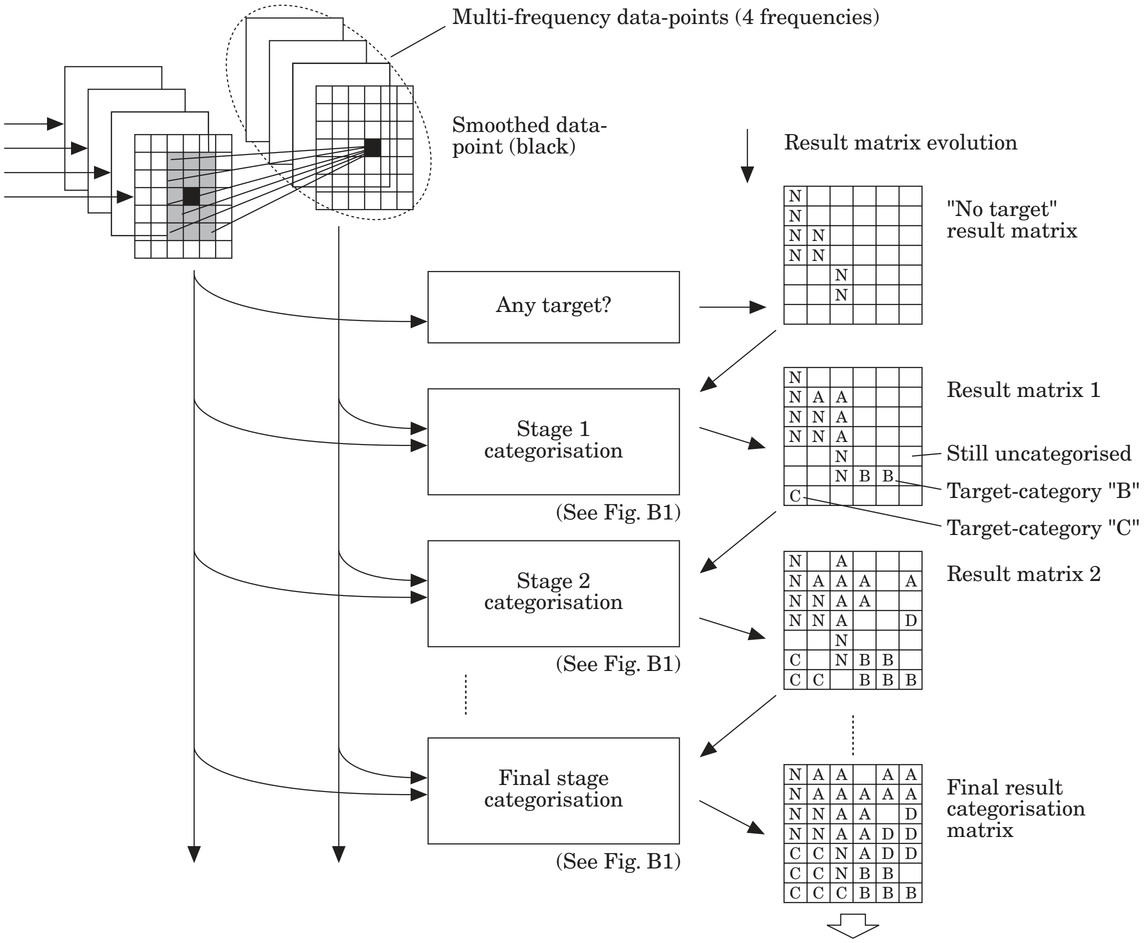

Figure 4. Data flow through the categorization system. (See Figure 1 for data flow through the post-processing system in general and Figure B1 for detailed data flow through the categorization system.) Both the original and smoothed multi-frequency data-points are used to discriminate between the target classes. If the default weights are used on data with 0.3 m vertical resolution, the smoothed point is generated from the indicated 15 points with the filter weights reduced from 0.18 in the centre to 0.025 in the corners. In Stage 1 categorization, strong model-based or empirical requirements must be fulfilled by a multi-frequency data-point in order to put the corresponding volume segment into one of the specific acoustic-target categories. The requirements on the data-point become weaker for each of the categorization stages that follow but results from the previous categorization stage are also used as new input.

measurement on an acoustic target will generally not follow the categorization scheme in Table 4.

Table 4 is a guideline for the implementation of an operational system and is partly based on features of the scattering models, e.g., zooplankton and juvenile swim-bladder fish and partly on features of empirical data, e.g., Atlantic mackerel. Some tests in the table are used to determine if there are non-resonant zooplankton present and these will extract both fluid-filled and elastic-shelled zooplankton according to the scattering models (e.g. Stanton *et al.* 1994). Additional tests distinguish large and small zooplankton. Discrimination

Table 4. Current acoustic-scattering categories in the frequency range 18–200 kHz. Only one acoustic category is allocated to a volume-segment. The term "target" means swimbladder, oil-filled sack, or the entire animal, depending on which is acoustically most important. The terms "small" and "large" refer to the size of the target compared to the acoustic wavelength.

Acoustic category, "category_name" and example of target		Model	Eq. spher. dia. [mm]	s_v and its frequency dependence r(f)	
0 – "NO_TARGET"; No target		—	—	No measurement above noise at any frequency	
I/II "PLANKTON" Fluid-like zooplankton	I – "SMALL_PL"; copepods	Fluid-filled sphere or bent-cylinder	0–2	$s_{v,18}<s_{v,120}/3$ $s_{v,18}<s_{v,38}$	dr(f)/df increase from 18–200 kHz
	II – "LARGE_PL"; euphausiids (krill)		4–10	$s_{v,38}<s_{v,200}$ $s_{v,18}<t^1$	dr(f)/df increase from 18–120 kHz dr(f)/df decrease from 120–200 kHz
III – "PEAK18"; juvenile fish, zooplankton with encapsulated gas		Gas-filled resonant sphere	0.5–2[2]	s_v peaked at 18 kHz (or 38 kHz)	
IV – "PEAK18_38"; unknown[3]				$s_{v,18}>2s_{v,120}$; $s_{v,38}>2s_{v,200}$; $s_{v,18}>2s_{v,120}$; $s_{v,38}>2s_{v,200}$	
V – "FISH"; cod, herring, saithe; fish with swimbladder		Gas-filled prolate spheroid	>20	Weak or weakly decreasing s_v with increasing frequency.[4]	
VI – "BOTTOM"; bottom		Empirical	—	Not investigated in detail	
VII – "MACKEREL"; Atlantic mackerel – fish without swimbladder		Heuristic empirical	—	s_v essentially frequency independent at 18–120 kHz, but peaked at 200 kHz.[5]	

[1] t is the largest value of s_v at 18 kHz accepted as zooplankton.
[2] $6500(1+0.1\ z)^{0.5}/f$, for air-filled sphere. z[m] is depth and f[Hz] is frequency.
[3] Occurs often in real acoustic data. Could be caused, e.g. by resonance between 18 and 38 kHz, or by fish tilted at an angle.
[4] Valid for pure backscatter from fish with normal tilt angle. A large number of samples are needed for swimming fish.
[5] Based on measurements of several hundred schools of Atlantic mackerel on two dedicated surveys. See also Figure 5(e).

between small fluid-like and the elastic-shelled species could be done at a later stage by comparing the derivative dr(f)/df which will be larger for the elastic-shelled zooplankton. The underlying model of the category "PEAK18" is based on scattering from a resonant target but the resonant peak is generally not exactly at 18 kHz. This category is often found to be associated with layers of fish larvae. Backscattering of the category "MACKEREL" is based on empirical data for the r(f) response of Atlantic mackerel (*Scomber Scombrus* L.).

The categorization system is implemented as a rough "expert system" with several stages in order to handle natural fluctuations and uncertainties in s_v data. Multi-frequency data resulting from noise reduction, vertical shifting of data, and the reduction of resolution are always used as input to the categorization system, in addition to a smoothed version of these same data (Figure 1). Data propagates through the categorization system as shown in Figure 4. Each stage in the process is shown detailed in Figure B1. In Stage 1 strict requirements are set for both the smoothed and non-smoothed versions of the multi-frequency data-point before a volume segment is accepted to belong to a specific acoustic category. In Stage 2, the acoustic requirements on the data-points are weaker than in Stage 1, whilst the requirement to belong to the same category as its closest neighbours, i.e. the same school, (found in Stage 1) is also used. In the following stages, the acoustic requirements on the data-points become weaker, whilst the requirement to belong to the same category as its closest neighbours is strengthened.

Collection of field data from RV "G.O. Sars"

Data from two separate surveys were used to test the c(f) analysis system on acoustic data. In the North Sea in October 1999 the main purpose was to test multi-frequency acoustic methods for the abundance estimation of mackerel during an ordinary survey where the time needed to scrutinize data is a limiting factor. Here biological sampling was mainly targeting mackerel. In Balsfjorden in northern Norway in September 1999, 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 bottom 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* sp.

Acoustic sampling

Two Simrad EK500 split beam echosounders were used to collect multi-frequency data. These systems were calibrated at least twice at two different locations (see Appendix A). 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 (Foote and Knudsen, 1994; MacLennan *et al*., 2001).

Raw data were stored in files as volume-backscattering coefficients s_v, together with spatial data having 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.

Vertical profiles of conductivity, temperature and pressure were made during calibration and at the biological stations with a standard SEA-BIRD 911 plus CTD probe. This information is used for computing sound speed during calibration and as supporting information to the operator during the scrutinizing process.

Biological sampling

Fish sampling in both surveys was done with a pelagic, single-net "Harstad" trawl because the "Multi-sampler" system for trawling (Engås *et al*., 1997) was temporarily out of order. During the North Sea trials the trawl sampling was targeted against mackerel and schools of other species but no sampling for zooplankton was conducted.

All biological sampling during the 24 h survey in Balsfjorden started close to the same position in the middle of the fjord. Sampling of zooplankton was done horizontally at selected depths with the 1 m^2 MOCNESS (Multiple Opening and Closing Net Environmental System, Wiebe *et al*., 1976, 1985) having a maximum of eight nets. Each net was opened and closed for sampling at four depth ranges, 158–101 m, 101–49 m, 49–24 m and 24–1 m. For vertical sampling of zooplankton a 180 μm WP-II net (Anon., 1968) was used. The WP-II stations were always taken at two depth ranges viz. from 100 m depth up to the surface and from the bottom to the surface. Because the WP-II net is always open it samples all the way to the surface. The first two trawl hauls were done as close in time as was practically possible, the first at 40 m depth and the second at about 140 m. These were just after a WP-II sample. The last two trawl hauls were both taken at about 130 m depth.

Results

North Sea

The categorization system was used to generate a masking matrix multiplied with the 200 kHz data to show only the acoustic category "MACKEREL" in Figure 5(f). The comparison with biological samples confirmed

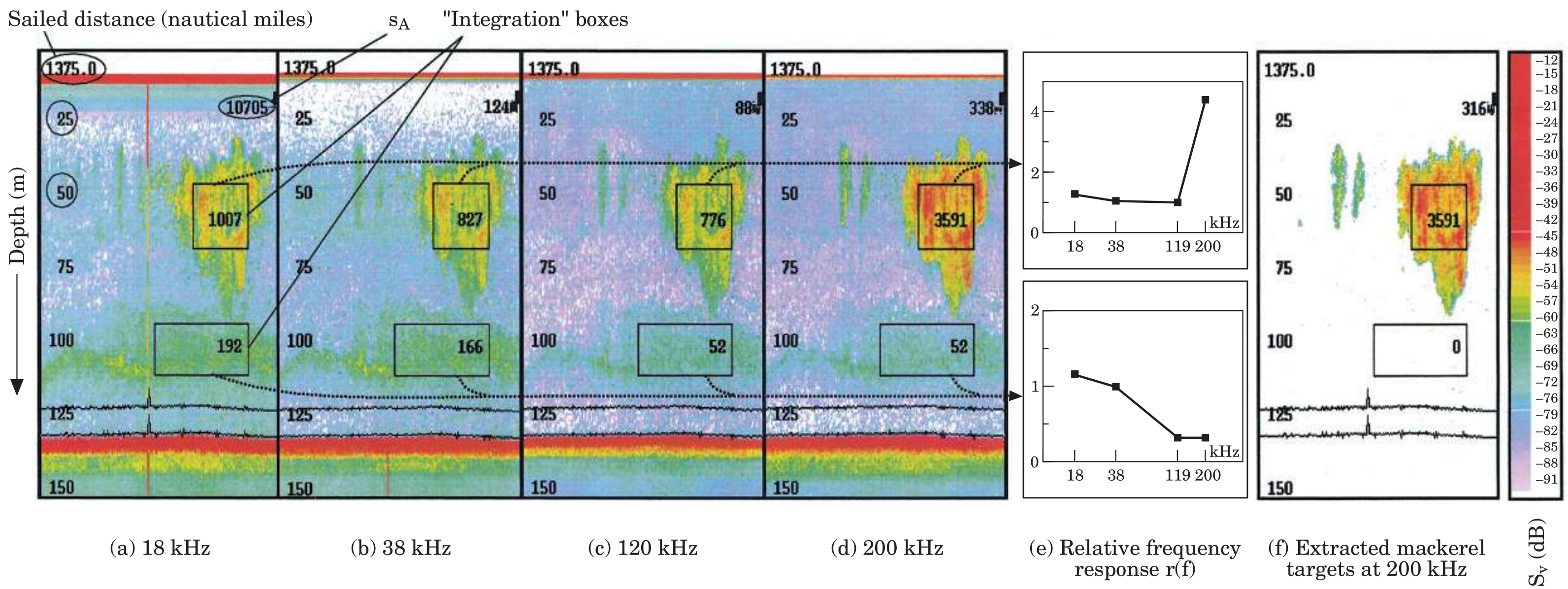

Figure 5. Original echograms from the North Sea after noise removal (a–d) and a synthetic 200 kHz echogram (f) where only the acoustic category "MACKEREL" is retained. (e) shows the r(f) response measured for mackerel and for Norway pout. Correspondence between colours and S_v is given by the scale.

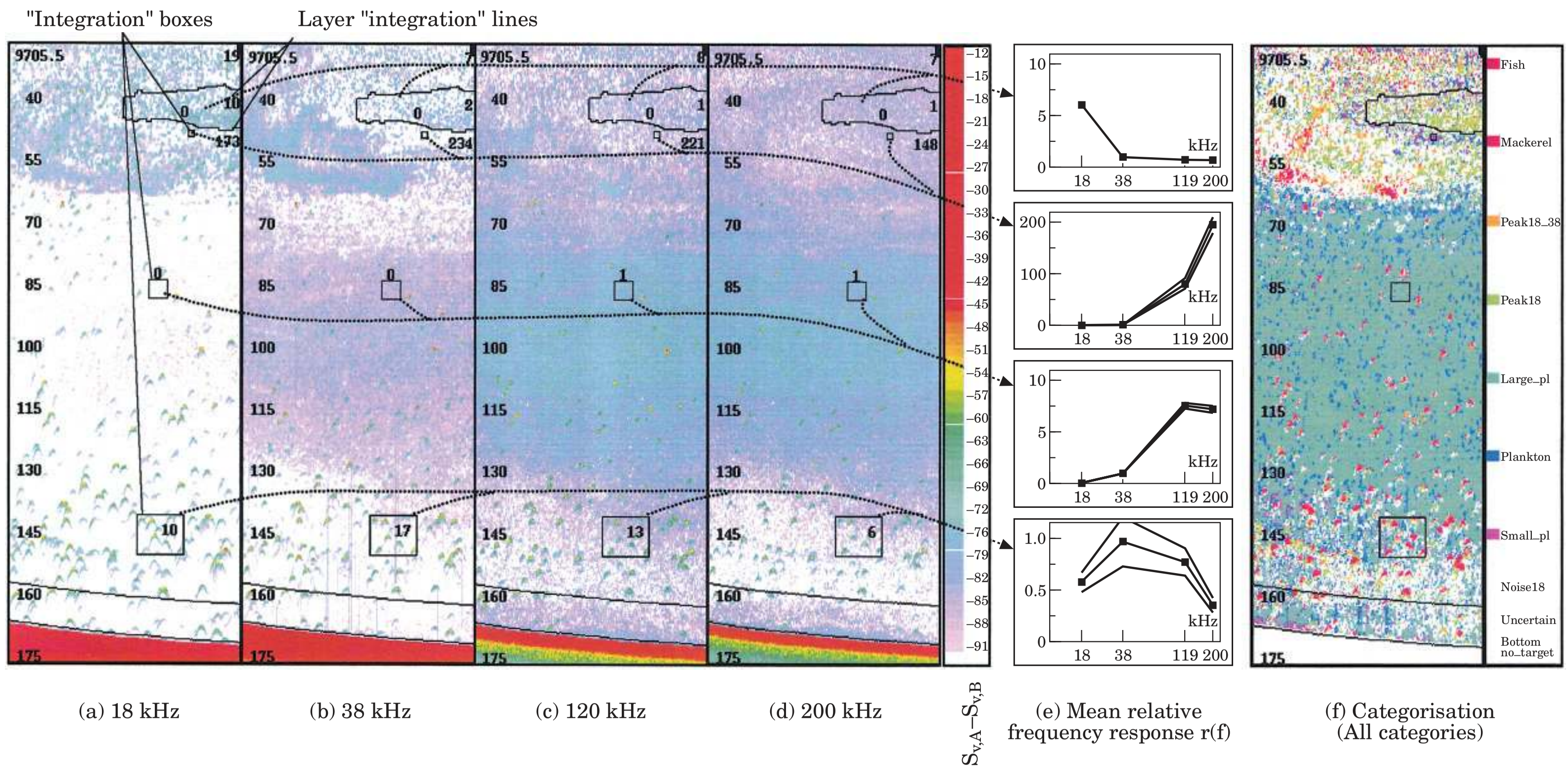

Figure 6. Original and synthetic echograms from Balsfjorden covering 0.5 nmi., collected during 700 seconds starting 1999.10.05 20:40 UTC. (a–d) and the accompanying colour scale show the original echograms after noise removal. (a) is used to explain lines and numbers in the figures. The colour scale shows the correspondence between colours and S_v. The r(f) response shown in (e) for selected regions is essential for the categorization system. (f) is a synthetic echogram generated from the categorization system using noise-corrected data as input, both smoothed and at their original vertical resolution (see Figure 4). The colour scale accompanying (f) shows the correspondence between the acoustic categories and the colours.

that the schools retained were mackerel. Trawl samples from the North Sea survey were made within the main fishing area for mackerel, and showed large amounts of these fish in all catches when the r(f) response indicated mackerel targets. Data used in Figures 5, 6 and 7, are merged over 3.5 s at each depth to avoid the natural fluctuations of such data, i.e., the s_v values at each depth are averaged over about three subsequent pings, but the result of the categorization is nearly as good for the original resolution of the acoustic data.

Balsfjorden

The acoustic data used to generate c(f) data, visualized in Figures 6 and 7, were selected from a time of day when suitable biological samples had been obtained. Collection of acoustic data occurred 0–1.5 hours after the fish (Figure 8(a–b)) and zooplankton (first column in Figure 9) were sampled.

Figures 6(a–d) show original, noise-corrected data. The mean r(f) response shown in Figure 6(e) indicates different species compositions in each of the four marked regions. These regions are selected from areas where acoustic data indicates different species composition but in all other respects are selected arbitrarily. According to Table 4 and supported by the biological samples, the curves in Figure 6(e) 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 at the surface level, are resonant at 18 kHz somewhere between 25–70 m depth. The standard error of the mean is calculated for all curves. Gas-filled zooplankton and mackerel are not present in Balsfjorden.

The final categorization matrix (Figure 4) is used to present the acoustic categories in Figure 6(f) in false colours. General impressions of the spatial distribution of the acoustic categories in Figure 6(f) agree largely with the biological samples. Cod and large capelin are found in the trawl samples at 40 m (Figure 8(a)) and 148 m depth (Figure 8(b)), and are seen as the acoustic category "FISH". The acoustic category "PEAK18" above 65 m is recognized as 0-group capelin found in the shallow trawl sample. WP-II zooplankton samples above 100 m (Figure 9, first column) showed mainly copepods and euphausiids, recognized in Figure 6(f) as respectively "SMALL_PL" above 60 m and "LARGE_PL" below. "SMALL_PL" is also seen at depths below 160 m in Figure 6(f). 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 above 70 m depth 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.

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 (Table 4). Above 60 m depth 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 according 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 (Figure 4) of the categorization system is categorized as "PEAK18_38" since that category contains additional information as compared to "FISH". Some features in Figure 6(f) also require closer examination: in the lower part of the figure some targets categorized as "PEAK18" are obviously larger fish as 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 extent 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 echosounder. The hypothesis that the category "PEAK18" is "in this case" fish is in agreement with the trawl samples.

Examples of echograms calculated from the "Division" method are shown in Figure 7. The depth resolution of the original echograms is 0.3 m, but is reduced to 0.9 m in some of the c(f) echograms (Figure 7(a,c)) mainly for improving the spatial overlap. A first impression of the division echogram in Figure 7(a) is that it is almost as informative as the categorization echogram in Figure 6(f). This has 0-group capelin, zooplankton and fish visible but with the same problems as in Figure 6(f) for larger targets in the outer extent of the 18 kHz beam. Moreover, some zooplankton seem to be missing in Figure 7(a) as compared to Figure 6 and Figure 7(b,c,e). 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. However, 0-group capelin ("PEAK18" in the upper part of Figure 6(f)) are obviously not present in the echograms based on the frequency combination 38 and 120 kHz. Figure 7(b,d and e) all show $s_{v,38}/s_{v,120}$, but with different colour scales. Figure 7(e) emphasizes zooplankton and Figure 7(d), fish.

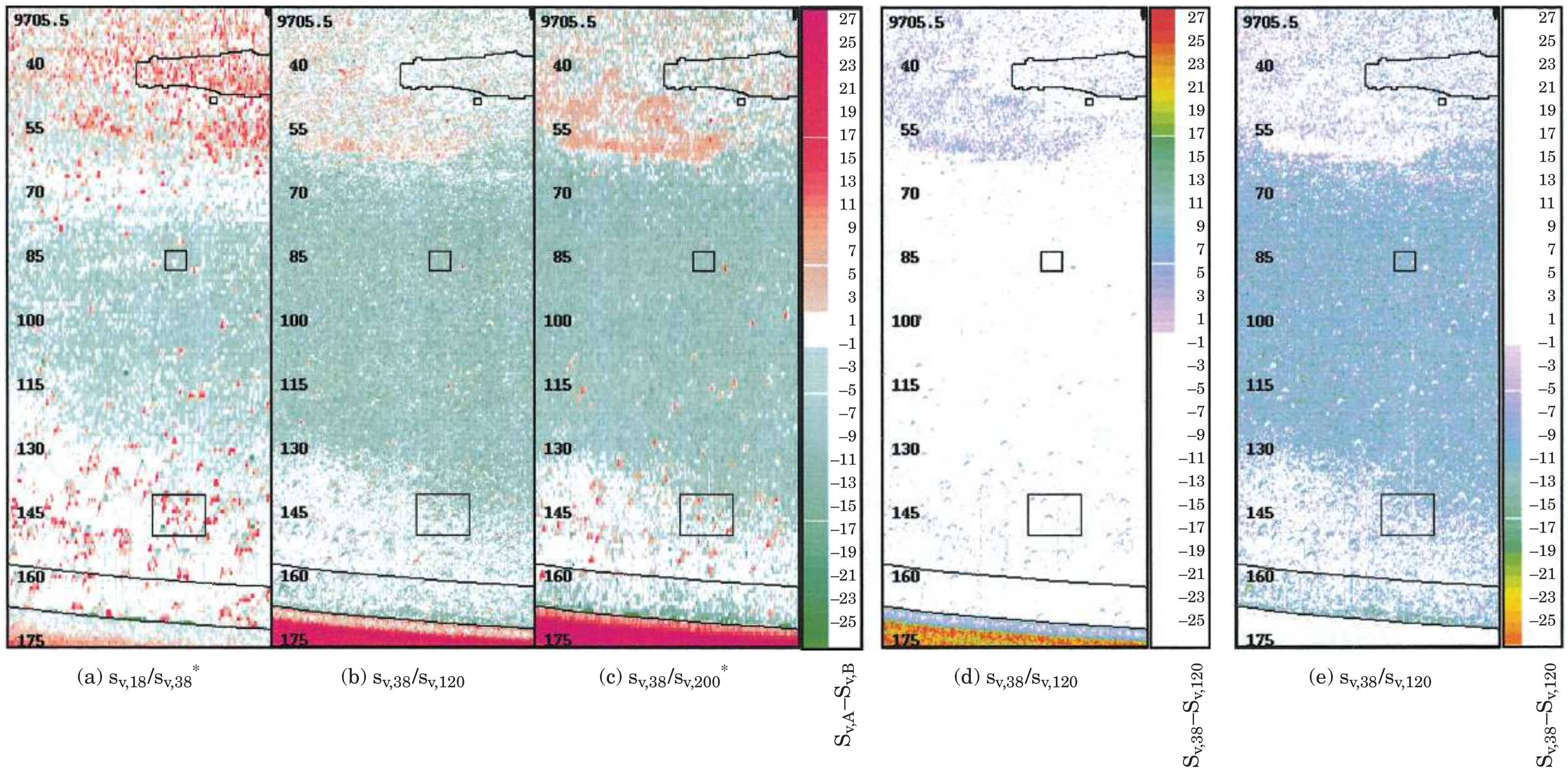

Figure 7. Division echograms derived from data shown in Figure 6(a–d). The colour scale shows the correspondence between colours and the dB difference, $S_{v,38}$–$S_{v,120}$. In (a), and (c) marked "*" the vertical resolution is reduced from the original 0.3 m to 0.9 m to reduce the effect of the vertical, inter-frequency offset (see Figure 3). The vertical, inter-frequency offset between the 38 and 120 kHz pulses is sufficiently small to defend the use of the original 0.3 m vertical resolution where only the 38 and 120 kHz data are used. (b), (d) and (e) all show $s_{v,38}/s_{v,120}$, but with different colour scales. The colour scale to the right of (c) is common to (a–c).

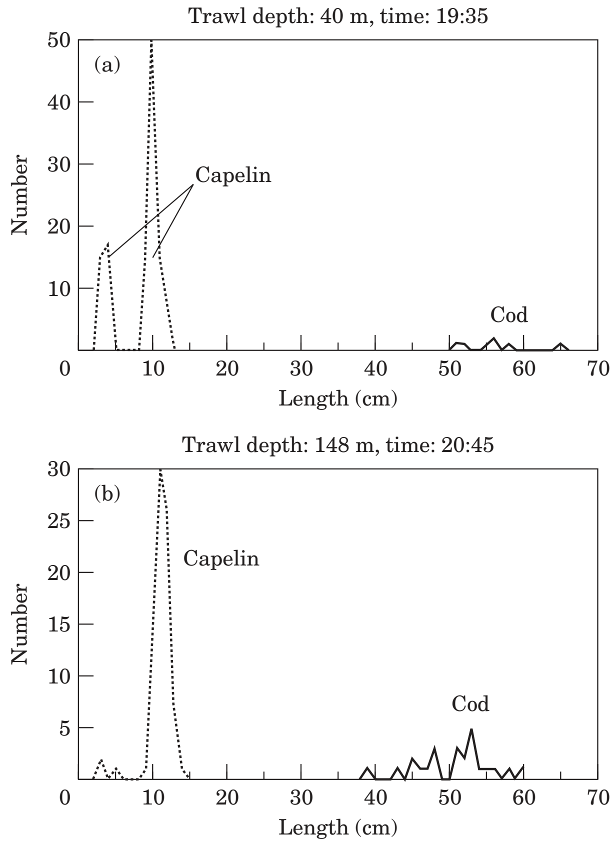

Figure 8. Number and length distribution of the fish caught in the two trawl samples in Balsfjorden 5 October 1999 closest in time to the analyzed acoustic data. The two trawl samples from 6 October at 140 and 135 m depth were very similar to (b). All trawl samples started at the same position.

Pelagic-trawl catch efficiency is reasonably good for cod, capelin and herring so the trawl samples are expected to reflect the fish population depicted in the echograms. All trawl samples in Balsfjorden contained individual cod (50 ± 10 cm) (*Gadus morhua* L.), and many large capelin (11 ± 2 cm) (*Mallotus villous* L.) as shown in Figure 8. The only trawl sample taken at a shallow depth (Figure 8(a)) also caught a relatively large number of 0-group capelin (3 ± 1 cm). Visual inspection showed that the swimbladders of 0-group capelin were about 1–2 mm diameter in the near-surface level. The trawl sample at approximately 150 m depth in Figure 8(b) shows less 0-group capelin but similar results in all other respects. Two trawl samples at 140 and 135 m depth showed very similar results as Figure 8(b). This indicated that the fish population was stationary during the full sampling period, at least at this location in the fjord. As the trawl could not be opened and closed at specified depths the small catches of 0-group capelin seen in Figure 8(b) are presumed to have occurred during the shooting and retrieval of the trawl.

WP-II zooplankton samples showed mainly copepods (*Calanus finnmarchicus* L.) and euphausiids (*Thyssanoessa sp.*) of 21.5 ± 1.5 mm length. Figure 9 shows the WP-II samples from 100 m depth to the surface and from the bottom at about 180 m depth to the surface. The WP-II net is known to have a low catch efficiency for all euphausiids because of animal avoidance but this is especially so for large species. When the biomass in the samples contained more than 30% euphausiids in the total water column, the euphausiids were probably strongly under-represented. Copepods dominated the size-fractionated biomass with specimens less than 2 mm, and also the biomass for specimens larger than 2 mm (except for euphausiids). Five of 18 zooplankton samples from Balsfjorden contained one or two small (less than 1 mm) specimens of the elastic-shelled pteropod *Limacina sp.*, which has much stronger target strength than soft-shelled zooplankton. Samples containing *Limacina sp.* are marked with "L" in Figure 9. The MOCNESS samples (Figure 10) confirm the results of the WP-II samples with respect to the

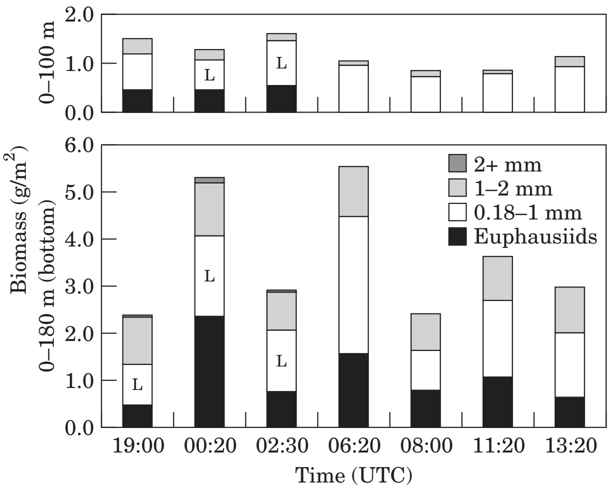

Figure 9. Dry-weight, size-fractionated biomass from zooplankton samples with the WP-II net 5–6 October 1999 from the same location in Balsfjorden as the trawl samples. Most of the biomass in all size groups is the copepod *Calanus finnmarchicus* (except for euphausiids). The five samples containing individuals of the elastic-shelled pteropod *Limacina* sp. are marked with L.

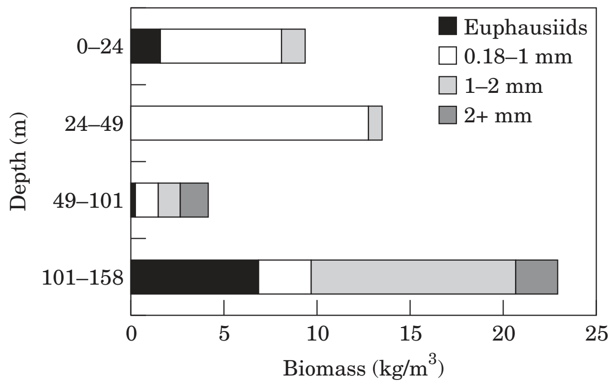

Figure 10. Dry-weight, size-fractionated biomass from zooplankton samples with the 1 m^2 MOCNESS 1999.10.06 14:20–14:40 UTC at four depths from the same location in Balsfjorden as the trawl samples. Most of the biomass in all size groups is the copepod *Calanus finnmarchicus* (except for euphausiids).

dominating organism groups. There is no indication of a patchy distribution for any zooplankton species either in the acoustic or in the biological samples.

Discussion of the methods

By avoiding unnecessary inspection and scrutinizing of echograms at all frequencies the average time to scrutinize 24 h of multi-frequency acoustic data has been reduced from more than 4 hours per day in 1999 to less than 2.5 hours on a similar mackerel survey in 2000 and to 1.5 hours in 2001.

Multi-frequency data processing methods

Many c(f) methods have been tried and a large number of possible echogram combinations with data from four frequencies are found, even with the two methods described here. Methods related to these two have been tried earlier (Socha *et al*., 1996; Korneliussen, 1999; Higginbottom *et al*., 2000) but there is still a need to optimize the extraction of information for practical use on large-scale surveys. More effort should be allocated now to improving echosounder systems and transducer platforms to make the multi-frequency observations better suited for combination into synthetic combined-frequency echograms on the post-processing side.

Division method

The power of the "Division" method to discriminate between acoustic categories is dependent on the frequency combinations but there is a need to inspect the echograms generated and this is a time-consuming task. On the other hand, the calculation of "Division" echograms can be done quickly, since raw data from the echosounder are already available in logarithmic units and this allows the subtraction of original data. Combined with the visualization of the mean r(f) response (Figure 5(e), Figure 6(e)), the ''Division'' echograms might often give the extra information on the spatial distribution of the scatterers needed to improve the quality of scrutinized survey data. One of the advantages for practical surveying work is the implementation of direct visualization of the r(f) response for an arbitrarily selected area of echogram. This is useful when scrutinizing s(f) data but it also indicates whether echograms at other frequencies add new information.

Categorization method

The ''Categorization'' echogram is the most useful of the suggested types of c(f) echograms since it can show simultaneously several scattering categories independent of the frequency combination. However generation of the ''Categorization'' echograms is slower than that of ''Division'' echograms and so offline generation of these synthetic echograms is desirable as illustrated in Figure 1. Acoustic categories can be visualized in false colours, as in Figure 6(f), to give a quick 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. Removing back-scattered echoes from zooplankton is often desirable if the purpose is fish-abundance estimation, e.g., Figure 5(e). The categorization system also provides help in extracting a proper value for the area-backscattering coefficient s_A needed for abundance estimation. This gives a result generally superior to single frequency methods, since contributions from unwanted targets are removed without amplitude thresholding. Use of the categorization method for the removal of unwanted targets also helps in the computation of the abundance of the remaining targets. This is as important as the withholding of desired targets. Without this method estimation of zooplankton abundance based on acoustic data would be difficult when fish and zooplankton are mixed.

The main problem in a practical categorization system is not the lack of backscattering models, since many models exist, but rather the quality and the comparability of the measurements as well as their natural fluctuations. A limiting factor in our present system is the few frequencies available. Nevertheless, at these discrete frequencies, backscattering properties at some or all frequencies are used to allocate backscattering from a volume segment into one of the general acoustic categories. Since it is the volume segments that are categorized, not single scatterers, the result of the categorization process obviously gives some ambiguity for volumes containing species belonging to different scattering categories, or even for volumes containing a wide size-distribution of one species.

Our categorization system is feature-based. Martin *et al*. (1996) concluded that a feature-based classifier performed better on most acoustic data than their model parameterization classifier. For classification of zooplankton they had access to broadband data in the frequency region 350–750 kHz, while we currently have access to only four specific frequencies. On the other hand they did not use the low frequency region to discriminate between the three acoustic scattering classes of zooplankton. In our system the low frequency and medium frequency region is efficient in discriminating between copepods and euphausiids. Categorization rules for zooplankton in Table 4 are largely based on such models. The greater calibration uncertainty of the 120 and 200 kHz systems compared to the 18 and 38 kHz systems is a problem but it does not change the general picture of the c(f) echograms. However, for euphausiids of 22 mm length found during this survey, Stanton *et al*. (1994) do not predict a reduction in r(f) response from 120 to 200 kHz. This apparent anomaly could be explained by a large calibration uncertainty. On the other hand the reduction in r(f) was also found in many other surveys where euphausiids were apparent. On those surveys, however, the acoustic returns have not been systematically compared to model predictions.

For our current implementation of the categorization system we use only the acoustic properties of the animals and this seems to work reasonably well, especially for species in clusters, e.g., schools or layers. The apparently successful identification and extraction of mackerel from North Sea data can be explained by their schooling behaviour and distinctive acoustic signature. In Balsfjorden, the composition of the target species is more complex. Nevertheless, the backscattered echo calculated from mixed species biological samples does not contradict the result in Figure 6.

The model of Stanton *et al*. (1994) shows that euphausiids represent more than 90 % of the relative backscatter at any of the four available frequencies; from a mixture having one *Thyssanoessa* sp. of 21.5 mm length, seven hundred *Calanus finnmarchicus* of 2 mm length and two *Limacina* sp. of 0.9 mm diameter. Because the backscattering from *Limacina* sp. increases rapidly with size, the size used in the calculation is intentionally larger than that found in the biological samples of this species. The calculation shows that backscatter from the acoustic category ''LARGE_PL'' in this case should dominate ''SMALL_PL''.

Once the targets in a cluster are categorized, better methods can be used for refining acoustic categories and, perhaps, even for the identification of single species. When this stage is reached existing methods for discriminating between particular species could be incorporated in the system to refine the acoustic categories. For example, the method developed by Brierley *et al.* (1998) could be implemented to discriminate between some types of zooplankton; or an artificial neural network used for species identification of fish schools (Haralabous and Georgakarakos, 1996).

There are a large number of uncategorized volume segments seen in Figure 6(f), especially above 60 m. This is partly caused by the mixture of several acoustic categories in the same volume but also by the use of smoothed data in the categorization system. Reduction of the region, or volume, from which data are smoothed does not increase the number of categorized volume segments because of the lack of spatial overlap (discussed below). Improved acoustic data is necessary to raise the percentage of volume segments achieving a reliable acoustic category. This will happen when collected acoustic data are closer to the ideal.

Although the use of c(f) "Categorization" echograms are especially helpful during the scrutinizing sessions they do not solve all problems. The experienced operator of the system still needs to make the key decisions.

Comparison of measurements between frequencies

Even though the generated c(f) echograms are useful tools they are not perfect. Different half-power beam widths pose a problem which leads to the question of how much percentage spatial overlap (pso) is needed to compare data from two frequencies. The effect of a horizontal offset is reduced with increasing range from the transducers because of the conical shape of the beams. There is no strict requirement with respect to overlap needed to defend the generation of c(f) echograms, but pso $\approx$ 85% seems 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 categorization method involves comparison of data at different frequencies but, since a smoothed version of input data is always used, this method is less sensitive to the lack of spatial overlap in schools than, e.g., the division method. However a pso closer to 100% would remove the need to always use a smoothed version of the input data in combination with the original.

Even when the 38 and 120 kHz data from RV "G. O. Sars" has 0.25 m vertical resolution they can be combined at ranges greater than 35 m since pso > 85%. At the same range the 120 and 200 kHz data can be combined with slightly less vertical resolution. The 38 and 200 kHz data have pso < 85% and should only be used at longer ranges, or with lower vertical resolution. As mounted on RV "G. O. Sars" the broader beam at 18 kHz completely overlaps all the other beams beyond 36 m range from the transducers.

The data used here collected with a vertical resolution of 0.3 m and 18 kHz data can therefore be shifted vertically to increase the spatial overlap, while maintaining all data at the original resolution. However the pulse envelopes differ from an ideal square pulse, especially at 18 kHz, and there are still problems of defining the exact spatial overlap between the wider 18 kHz beam and any of the others. This makes the result of vertical shifting of data at 18 kHz more uncertain. For the data used here the correlation of vertically-shifted data at 18 kHz to that at any of the other frequencies does not provide a significant improvement.

Future developments

Both the echosounder and the transducer mounting on the current RV G.O. Sars could easily be modified to provide better quality of c(f) data and on the planned new IMR research vessel a mounting that meets the requirements suggested earlier in this paper will be installed. Frequencies of 70 and 350 kHz will be added to those of the 18, 38, 120 and 200 kHz used at present and this will reduce some of the uncertainty in the present categorization of biological scatterers. If the half-power beam widths are increased pso increases but this is not a preferred solution since the signal-to-noise ratio is reduced. Compared to the original mounting seen in Figure 2(a), mounting the smaller transducers between the larger ones, Figure 2(b), will reduce the mean distance between transducers on the instrument keel. (Note the partly overlapping transducer flanges in Figure 2(b).) The horizontal overlap between any two transducer beams exceeds 85% beyond 21 m range. Provided that no pulse-transmission delay occurs the percentage horizontal overlap is equal to the percentage spatial overlap. Compensation for the combined delay of the echosounder and the transducer could be made before sound transmission or, alternatively, data vertical there could be increased resolution which would allow compensation to be made via the in software. A drawback to this option is the large amount of data storage needed.

The next steps in the project are for improvements to be made to the categorization method and for new echosounders may be adapted to the requirements of multi-frequency operation. Experience gained from the continued use of this system on routine surveys will show in which direction its development of the system should take.

The minimum range for the described methods is limited by the requirement pso > 85%, and the maximum range is limited by the effective range in the higher frequency, here 100–200 m for the 200 kHz system, on weak targets from vessel-mounted transducers. A very important part of the water column may therefore be investigated at full survey speed. However deeper fish and zooplankton populations must either be investigated by a combination of lower frequencies, or from towed vehicles equipped with similar instrumentation. Calibration of multiple transducers over the pressure range then becomes a new challenge (Ona and Svellingen, 1999).

Summary and conclusions

The time needed to scrutinize acoustic data to achieve optimal accuracy on oceanic surveys can impose a restriction on their overall efficiency. To overcome this a helpful new tool for improving the accuracy of the scrutinized data and, at the same time reduce the time spent on the task is the visualized r(f) response described in this paper. Using the technique to scrutinize multi-frequency acoustic data, it has been possible to reduce the average time spent on the task from 4 h in 1999 to less than 2.5 h per day in 2000 and to 1.5 h per day in 2001. For analyzing multi-frequency acoustic data, categorization, visualized in a single echogram, seems to be the most efficient of the proposed methods. The categorization scheme is also used to generate masking matrixes to withhold or remove selected data at single frequencies.

In order to implement the methods described in this paper it has been possible to use hardware and software currently available, albeit with some relatively small changes. Further detailed improvements that can be made to improve accuracy in the estimates from fish abundance surveys have been suggested. The preliminary results of the work described in this paper have already been made available to echosounder manufacturers. We conclude that the technique presented here has been shown to have significant potential.

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Appendix A

Calibrations

All four systems were calibrated using recommended standard targets for the particular frequencies. These are 64 and 60 mm copper spheres for the 18 and 38 kHz echosounders and a tungsten carbide, WC 38.1 mm sphere for 120 and 200 kHz (Foote, 1982). The echosounder systems were calibrated at least twice at two different locations (Table A1). Calibration conditions on the 7th and 13th of October were very good with calm weather. Conditions on the 22nd of October were also good.

Table A1. Calibrations.

Frequency [kHz] Calibration sphere	18 CU64		38 CU60		120 WC38.1					200 WC38.1		
Transducer depth [m]	7.5	5.0	7.5	5.0	7.5		7.5		5.0[3]	7.5	7.5	7.5
Date in October 1999	7	13	7	13	7		13		22	7	13	22
Calibr. sphere range [m]	21.50	20.50	21.30	20.50	20.85		20.94		23.07[4]	20.94	20.32	23.62
S_v transducer gain [dB]	23.4	23.4	27.4	27.4	24.8	25.7	25.7	26.0	25.8	26.1	25.2	25.7
TS transducer gain [dB]	23.3	23.3	27.8	27.8	24.7	26.0	26.2	26.0	25.6	26.1	25.2	25.7
Acoustic axis athwartship offset angle [degrees]	0.02[1]	NM	−0.09[1]	NM	NM[2]			−0.62	−0.52	NP	NP	NP
Acoustic axis alongship offset angle [degrees]	−0.04[1]	NM	−0.02[1]	NM	NM[2]			0.33	0.52	NP	NP	NP

NM, Not measured.
NP, Not possible to measure.
[1]Confirmed by calibrations of standard EK500.
[2]The acoustic axis offset angles were not measured but were erroneously set to 0.90° (alongship) and −0.62°.
[3]Calibration controlled with drop keel at maximum depth, i.e. transducers at 7.5 m below surface.
[4]Calibration controlled by lowering the sphere 2.5 m. The sphere depth was adjusted when the drop keel was lowered.

EK500 calibrations at 18 kHz and 38 kHz are consistent with earlier measurements and considered to be very good. An uncertainty in the (EK500-termed) "S_v transducer sensitivity" of 25.6 ± 0.5 seems to be a reasonable value for both the 120 and the 200 kHz systems. The figure of ±0.5 gives an uncertainty of more than 25% in the calculated volume and area backscattering coefficients s_v and s_A. Several 120 kHz systems are reported to be difficult to calibrate and the system on RV G. O. Sars" has been no exception.

Appendix B

Detailed description of each stage of the categorization system

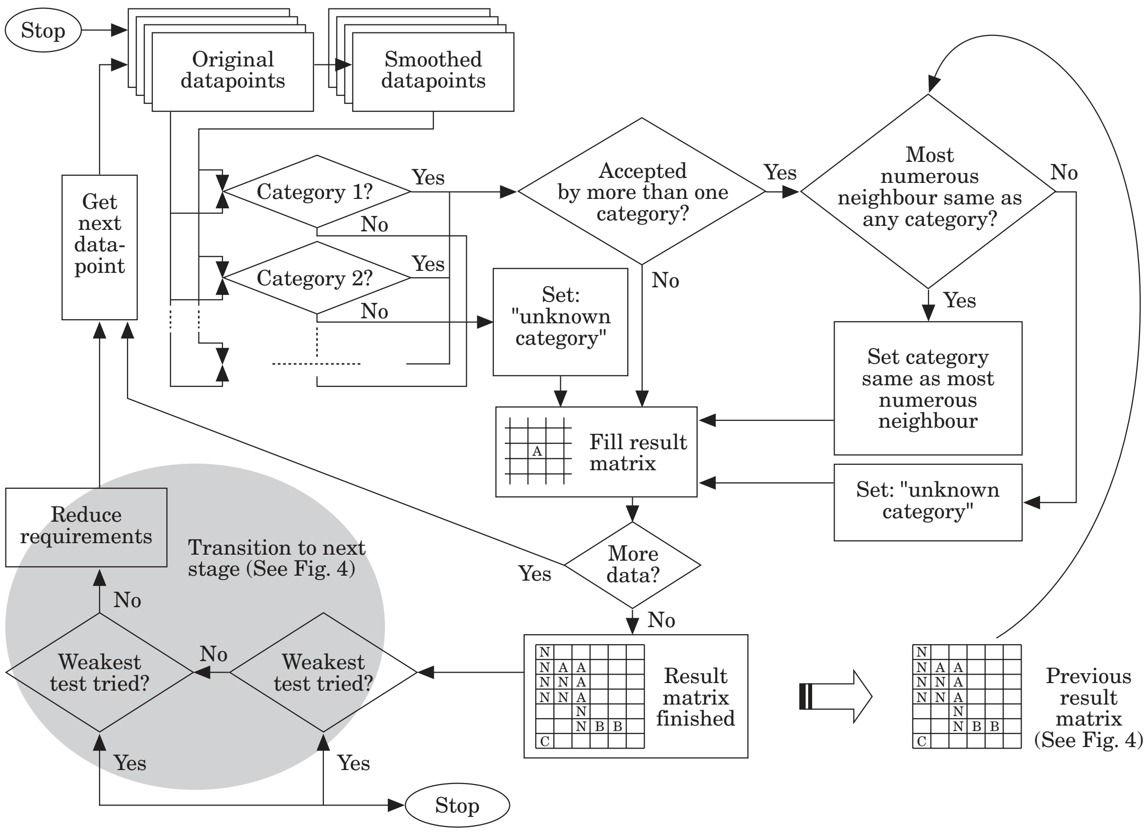

Figure B1. Detailed description of data flow through each stage of the categorization system. (See Figure 4 for overview of the data flow through the categorization system, and Figure 1 for general data flow through the post-processing system.)