The acoustic identification of Atlantic mackerel

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Calibrated, digitized data from multifrequency echosounders working simultaneously with nearly identical and overlapping acoustic beams were used to generate new, synthetic echograms which allow Atlantic mackerel (*Scomber scombrus*) to be identified acoustically. The raw echosounder data were processed stepwise in a modular sequence of analyses to improve categorization of the acoustic targets. The relative frequency response measured over as many as six operating frequencies, 18, 38, 70, 120, 200, and 364 kHz, was the main acoustic feature used to characterize the backscatter. Mackerel seemed to have a frequency-independent backscatter below ~100 kHz, but significantly higher levels of backscattered energy at 200 kHz. Synthetic echograms containing targets identified acoustically as mackerel are presented and evaluated against trawl catches. Although catching fast-swimming mackerel is difficult, trawl catches from three Norwegian research vessels confirmed that the targets identified acoustically as mackerel were indeed that species. Separate experiments performed on mackerel in pens support the findings.

Keywords: categorization, relative frequency response, species identification, synthetic echogram.

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Introduction

The backscatter from any fish is the amalgamation of that from components such as flesh, backbone, swimbladder, and head. However, between 90% and 95% of the acoustic backscatter from fish with a swimbladder are from that gas-filled organ (Foote, 1980). Atlantic mackerel (*Scomber scombrus*) do not have a swimbladder, and are weak scatterers at the most common operating frequency used in fisheries acoustics, 38 kHz. As the acoustic properties of mackerel are not well known, abundance estimates have been derived from labour-intensive egg production surveys carried out every third year. There is a need to estimate the abundance annually, however, and to determine the area of distribution of mackerel and how it changes throughout a year.

Although fishers have used horizontally orientated sonars with frequencies >100 kHz to identify mackerel subjectively, there has so far been no scientific proof that the fish can always be identified in this way. Korneliussen and Ona (2002) used empirical relationships between the backscatter at 18, 38, 120, and 200 kHz to identify selected schools of Atlantic mackerel based on the assumption that the relative frequency responses, $r(f)$, were reasonably constant. Korneliussen and Ona (2002) defined $r(f)$ as the backscattered energy at frequency f compared with 38 kHz, i.e. $r(f) \equiv s_v(f)s_v(38\text{ kHz})^{-1}$. Measurements of mackerel backscatter in a pen and during additional surveys at sea from 2003 revealed that the assumption of similar backscattering strength at 120 and 38 kHz was generally incorrect. The scattering properties were therefore investigated theoretically.

Gorska *et al.* (2005, 2007) modelled backscatter based on the suggestion that bone and flesh are the two main scattering components in mackerel. That model predicts that flesh backscatter from schooling mackerel (Gorska *et al.*, 2007) is essentially frequency-independent, although it does depend on fish orientation. It also predicts the backscatter from backbone to be weaker than that from flesh at and below 38 kHz, whereas backbone backscatter dominates the echoes at 120 and 200 kHz. The model of bone backscatter depends on a range of parameters, but currently does not take account fully of backbone morphology nor the contribution from the bone of the head. Adjusting model parameters within a credible range shows that there could be some variation in the transition frequency, where backbone backscatter becomes stronger than that from flesh. As the backscatter increases rapidly close to that frequency, it is here denoted as the "step frequency". One parameter that may influence the step frequency is the backbone radius, which depends on fish size. Measurements on a 10-cm section of mackerel backbone (Nesse *et al.*, 2009) are currently inconclusive in terms of the hypothesis that backbone is responsible for the increased backscatter at 200 kHz compared with 38 kHz. Backscatter from the skull has not yet been measured.

Further development of the mackerel-identification algorithm depends largely on estimating the typical value of the relative frequency response, $r(f)$, and its range of variation, $\Delta r(f)$, at each acoustic frequency, f. Trustworthy relationships for $r(f)$ and $\Delta r(f)$ are therefore essential to the reliable identification of mackerel, so the main objectives of the current work are to develop further the mackerel-identification algorithm with special focus on mackerel $r(f)$, and to test the robustness of the identification algorithm in different situations during a survey.

Material

Collection of acoustic data at sea

Acoustic data were collected in October and November in the North Sea and Norwegian Sea from RV "G. O. Sars (2)" during the years 1999–2002, RV "G. O. Sars (3)" from 2003 to 2005, and RV "Johan Hjort" in 2006 and 2007. Simrad EK500 or

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EK60 echosounders were operated at three, four, or six of the acoustic frequencies 18, 38, 70, 120, 200, and 364 kHz, and were calibrated using recommended methods (Foote 1982; Foote *et al.*, 1987) and appropriate standard targets for each frequency. The calibration spheres were typically 22 ± 1 m below the transducers. All the transducers on each vessel were mounted at essentially the same depth on the bottom of a protruding keel (Ona and Traynor, 1990). Figure 1 depicts the transducer mounting configuration, and Table 1 lists the 3-dB beam widths and the transmission power per unit area of the transducers. The internal echosounder noise-limit control was turned off to allow for noise quantification by software. Time was registered when the echosounder transmitter was triggered and data were stored with a resolution of 0.01 s for each ping.

RV "G.O. Sars (2)" used the EK500 during the years 1999–2002. The 18-, 38-, and 120-kHz transceivers were in the same EK500 echosounder, EK500(1), and modified to allow a pulse duration of 0.6 ms at a sampling interval of 2 cm. EK500(1) triggered its own frequencies simultaneously, and also triggered the other EK500, EK500(2), to transmit 0.6-ms 200-kHz pulses. The EK60 was used in 2003 and later, with the pulse duration set to 1.0 ms for all frequencies.

Biological sampling at sea

Pelagic trawling was conducted to sample echotraces that could be mackerel or other fish species. Fish were sampled from all three vessels using pelagic Åkra trawls, a midwater trawl of medium size. The trawl has a circumference of 539 m and was used with 7.5 m^2 doors manufactured by Egersund Trawl, sweeps of 160 m, and a 60-mm mesh bag. RV "G. O. Sars (2)" could not tow at high speed because of her low engine power. From 2003, both a single-net trawl and an additional Åkra trawl connected to an opening-and-closing "MultiSampler" system, with up to three codends (Engås *et al.*, 1997), were available. The trawl was towed at 4–4.5 knots, the design speed of the gear, in 2003 and subsequently. Tow duration was normally ~15 min with the trawl at fishing depth, though sometimes less.

The zooplankton was sampled from RV "G. O. Sars (2)" and "G. O. Sars (3)" by making horizontal tows at selected depths with the 1-m^2 MOCNESS (Multiple Opening and Closing Net Environmental System; Wiebe *et al.*, 1976, 1985), with its maximum of eight nets. For sampling zooplankton vertically, a 180 μm WP2 net (Anon., 1968) was used. It is a net that is always open and samples the entire water column up to the surface. The results were used to check that acoustic registrations of dense zooplankton aggregations were not mistakenly being interpreted as mackerel. Time constraints did not allow for zooplankton sampling during the 2007 survey with RV "Johan Hjort".

Acoustic and biological data from experimental pens

It was necessary to establish the relative frequency response, $r(f)$, for developing the mackerel-identification algorithm. In the pen measurements, only mackerel were present, except possibly for fish and plankton small enough to pass through the pen-net mesh size of 1.5 × 1.5 cm.

Two modified EK500 sounders with pulse duration of 0.6 ms and sampling interval 2 cm were used to collect acoustic data from captive mackerel at the IMR Aquaculture station at Austevoll, Norway. The pen was 21 m deep, and 10 × 10 m square. Different sizes of mackerel were introduced to the pen, and the backscatter was measured for 150 mackerel in each size class. For most size classes, extra backscatter measurements were made for 10 of the fish in the pen, then for 500 fish. Length and weight of each fish were determined after the experiments, and fat content was measured for 10–15 randomly selected fish after each measurement series.

The measurements were carried out on three size classes of mackerel. The captured mackerel were divided between two pens. One group was never fed, except for any plankton passing through the pen they may have consumed, whereas the other group was given food. Some of the fed mackerel were maintained for an additional season with the same treatment.

The transducers were mounted on a rig as shown in Figure 1d, ~1 m below the water surface. The calibration spheres were

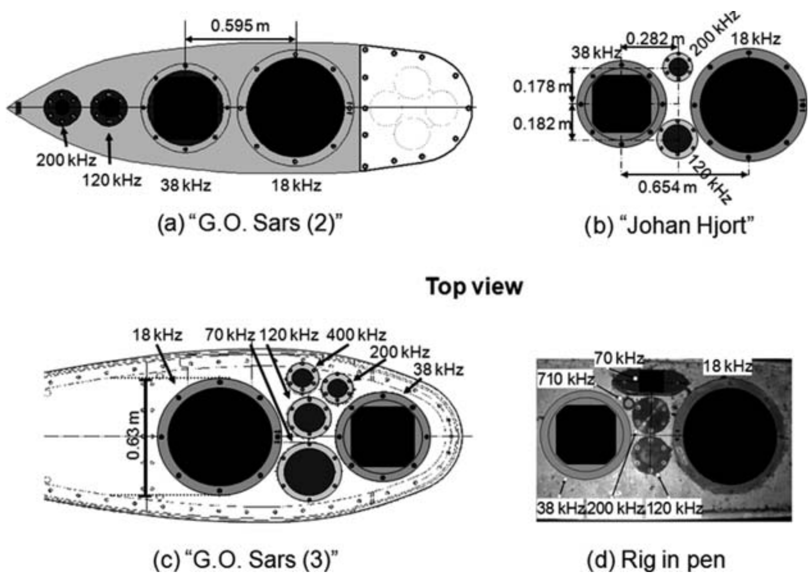

Figure 1. Positioning of the transducers (top view). (a) RV "G.O. Sars (2)". (b) RV "Johan Hjort". (c) Port keel of RV "G.O. Sars (3)". (d) Raft used in pen.

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Table 1. Transmission power (total and per unit active area of the transducer) for different echosounder systems.

Simrad echosounder	Frequency (kHz)	Power (W)	Power per area (kW m^{-2})	Beam width (3 dB) (°)
EK500	18	2000	10	11
	38	2000	20	7
	70	800	66	11[a]
	120	1000	100	7
	200	1000	227	7
EK60	18	2000	10	11
	38	2000	20	7
	70	1000[b]/800	30[b]/24	7
	120	250	25	7
	200	120	27	7
	364	60	56	7[c]

[a]Used in pen only.
[b]2003 and earlier.
[c]7° for 400 kHz. The calibration of the EK60 at 364 kHz (indicating 6° beam width) is doubtful.

~12 m below the transducers. The power and the beam widths of the EK500 systems are listed in Table 1.

Methods

Data processing

To secure objectivity and knowledge of the target species, a team of two experienced scientists and the chief instrument engineer conducted the manual scrutiny. Available knowledge of Atlantic mackerel biology, behaviour, and acoustic signatures was used in this process at sea, in addition to the results of biological sampling and temperature profiles. The biological samples were used to obtain species composition of the acoustic registrations and the size species distribution. The temperature profiles were used when there was a clear temperature gradient, as mackerel tend to stay at the warm side whereas herring (*Clupea harengus*) seem not to. The oceanic acoustic data were post-processed and scrutinized using the Bergen Echo Integrator (BEI; Korneliussen, 2004) until 2006, and the Large Scale Survey System (LSSS; Korneliussen *et al.*, 2006) was used for the 2007 data. In parallel with the manual scrutiny, mackerel and other acoustic categories were identified automatically by the post-processing systems through generating synthetic echograms. The results of the automatic mackerel-identification process were kept hidden until the manual scrutiny was finished.

The acoustic data from the experimental pen were collected and scrutinized using the BEI. Because of the possibility of non-linear acoustic effects (Pedersen, 2006), only mackerel appearing at depths near or below the depth of the calibration sphere at 12 m were considered.

Preparing acoustic data for combining frequencies

Noise was quantified and reduced according to the methods described by Korneliussen (2000) and was done entirely by post-processing; then the data were smoothed as described in Korneliussen and Ona (2003). This involved multiplying the noise-corrected acoustic data with a matrix of Gaussian weights that summed to unity. The averaging diameters were 10.0 m horizontally and 0.75 m vertically, i.e. vertical samples 0.75/2 m above or below the middle sample were multiplied by half the weight. The weights were skewed horizontally to take account of the transducer locations, and vertically to account for frequency- and bandwidth-dependent system delays (Korneliussen *et al.*, 2008).

Categorization

The acoustic properties of many similar species measured in small elementary volumes (pixels) are commonly too alike for automatic identification based solely on acoustic data, so multifrequency backscatter is grouped into broad acoustic categories such as "fish_with_swimbladder" or "target_resonant_at_18 kHz". Here, such acoustic categories are defined either through a scattering model, or using empirical data, or by a hybrid approach, i.e. a combination of model calculations and empirical data. The broad acoustic categories may or may not be refined into sub-categories (e.g. "fish_with_swimbladder" into "capelin" and "herring") at a later stage in the categorization process, depending on the available data. The acoustic category "mackerel" originated from empirical measurements of mackerel backscatter.

The categorization process involves multifrequency measurements and geographic information from the pixels of an echogram being evaluated in several stages. First (Stage 1), only the measurements are considered. Second (Stage 2), the requirements on the deviation from the measurements of $r(f)$ compared with the ideal values $r_i(f)$ are relaxed somewhat, as illustrated in Figure 2, but the categories of the neighbouring pixels resulting from Stage 1 are also considered. Finally, the requirements on the measurements themselves are relaxed further, but the requirement of belonging to the same acoustic category as the neighbouring pixels is strengthened, as illustrated in Figure 3.

Categorization speedup

A set of simple tests that are minimum requirements for a multi-frequency datapoint to be considered as the acoustic category "mackerel" was used to speed up the categorization process. For convenience, the following numbers were defined: $38_{weak} \equiv 0.1(4\pi 1852^2)^{-1}$ [m (nautical mile)$^{-2}$] and $38_{strong} \equiv 50\,000(4\pi 1852^2)^{-1}$ [m (nautical mile)$^{-2}$]. Then, the pixel was

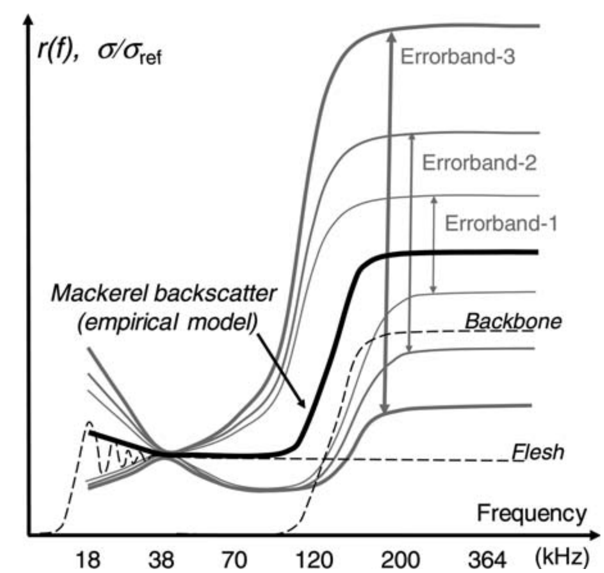

Figure 2. Illustration of the mackerel-backscattering model, showing the increasing error bands.

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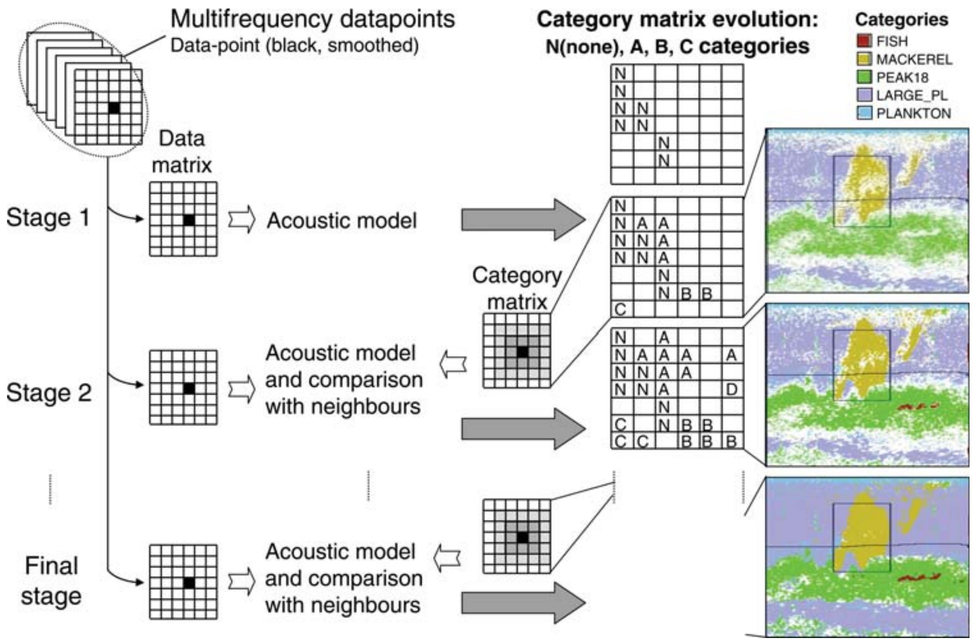

Figure 3. Clustering of the elementary volumes (pixels) during the categorization process. The colours show the different categories identified here. In Stage 1, the category of a pixel is found based on measurements only. In Stage 2, the requirements on the measurements are somewhat relaxed, but the categories of the neighbouring pixels resulting from Stage 1 are also considered. In the final stage, the requirements on the measurements are further relaxed and the requirement of belonging to the same category as the neighbour is strengthened.

deemed not mackerel if: (i) there were no data available or no data above noise threshold at either 38 or 200 kHz; (ii) $s_v(38) > s_v(200)$; (iii) there were 70 kHz data and $s_v(70) > s_v(200)$; (iv) there were 18 kHz data and $s_v(18) > s_v(200)$; (v) the echoes were very weak, i.e. $s_v(38) < 38_{weak}$; (vi) the echoes were very strong, i.e. $s_v(38) > 38_{strong}$. Here, s_v is the volume backscattering coefficient.

Similarity number

Data from each pixel (elementary measurement volume) were tested against the properties of known acoustic categories, and the most probable acoustic category was connected to that pixel. The resulting number is referred to as a similarity because, in a mathematical sense, it is not a probability. The similarity number, S, is defined by three components: relative frequency response similarity, S_r; geographic position similarity, S_{pos}; and backscattering-strength similarity, S_{sv}:

$$S \equiv S_r S_{sv} S_{pos}, \tag{1}$$

where $0 \leq S_r \leq 1$, $0 \leq S_{sv} \leq 1$, and $0 \leq S_{pos} \leq 1$.

Relative frequency response similarity (S_r)

S_r is a weighted sum of the individual $S_r(f)$ values at the frequencies where data exist, and is measured within the maximum range observed with each frequency. The implemented values of the ideal relative frequency responses, $r_i(f)$, for mackerel [Equation (2)] are based on measurements at sea and in pens during 2003 and earlier:

$$r_i(18) : r_i(70) : r_i(120) : r_i(200) : r_i(364) = 1.1 : 1.0 : 1.3 : 4.0 : 3.6. \tag{2}$$

The typical variation of $r(f)$ during one survey is $\Delta r(f)$, but the mean $r(f)$ also varies from year to year. The initial values of $e(f)$ in Equation (3) used by the algorithm is based on those measurements. The parameter $e(f)$ is used to calculate the lower $r_i(f)/1.5^{n-1}e(f)$ and upper bounds $1.5^{n-1}\,e(f)r_i(f)$ of the errorband at each frequency, as shown in Equation (4). Figure 2 illustrates $r(f)$ and how the errorband evolves. $S_r(f)$ in Equation (4) will generally have different values for different frequencies.

$$e(18) : e(70) : e(120) : e(200) : e(364) = 1.7 : 1.5 : 2.0 : 1.5 : 2.0. \tag{3}$$

For each individual frequency, $S_r(f)$ decreases according to the following equation:

$$S_r(f) = \begin{cases} 0.7^{n-1} & \text{if } \dfrac{r_i(f)}{(1.5^{n-1}e(f))} < r(f) < 1.5^{n-1}e(f)r_i(f), \\ 0 & \text{otherwise} \end{cases} \tag{4}$$

where $n = 1, 2, 3$.

The ability of $r(f)$ to identify mackerel differs between frequencies, so the $S_r(f)$ values are weighted according to the following equation. Note, for example, that $r(200)$ is weighted four times more than $r(18)$.

$$w(18) : w(70) : w(120) : w(200) : w(364) = 1.0 : 2.0 : 1.0 : 4.0 : 1.0. \tag{5}$$

S_r is calculated from Equation (6) using Equations (2)–(5):

$$S_r = \frac{\sum S_{r(f)} w(f)}{\sum w(f)}, \tag{6}$$

where f = 18, 38, 70, 120, 200, and 364 kHz.

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Backscatter strength similarity (S_{sv})

$S_{sv} \equiv S_{sv,L}S_{sv,H}$ is used to avoid very weak or strong s_v being associated with mackerel. $S_{sv,L}$ tests $s_{v,L}$, which is the mean of the s_v at 18, 38, and 70 kHz. The 38-kHz data will always exist as a result of the previous test.

$$S_{sv,L} = \begin{cases} 1 & \text{default;} \\ 1 & \text{if } 10 \times 38_{weak} < s_{v,L} < 38_{strong} \times 10^{-1}; \\ 0.5 & \text{if } s_{v,L} < 10 \times 38_{weak}, \text{ or } s_{v,L} > 8_{strong} \times 10^{-1}; \\ 0 & \text{if } s_{v,L} < 38_{weak}, \text{ or } s_{v,L} > 38_{strong}. \end{cases}$$

$S_{v,H}$ tests $s_{v,H} = s_v(200)$ in a similar manner, but 38_{weak} is replaced by $4.0 \times 38_{weak}$, because mackerel backscatter at 200 kHz is approximately four times stronger than at 38 kHz.

Geographical position similarity (S_{pos})

S_{pos} is quantified according to knowledge that is obvious to a scrutinizing team, such as the fact that Atlantic mackerel are not found in water where the temperature is close to zero, e.g. the Barents Sea in winter. For mackerel, the values are

$$S_{pos} = \begin{cases} 1 & \text{default;} \\ 1 & \text{if the position and time of year suggest that mackerel are very likely to be found, e.g. the North Sea and Norwegian Sea in September, October, or November;} \\ 0.9 & \text{for close positions and times, where mackerel are very likely to be found;} \\ 0.8-0.6 & \text{where mackerel are decreasingly likely to be found;} \\ 0 & \text{if the sampled position is in water far away from any location where mackerel have ever been observed.} \end{cases}$$

Algorithm

The categorization algorithm for mackerel is implemented in a function that runs in parallel with several other similar categorization functions. The similarity number (S) is calculated for each pixel for each acoustic category. One function does calculations for one category, and all the categorization functions return three similar flags $Q1-Q3$. Depending on the value of S, the subsequent flags $Q1-Q3$ are set to 'true' for mackerel:

$$\text{If } > 0.9\text{: } Q1 = \text{true: pixel almost certainly mackerel,}$$

$$\text{If } 0.5 < S < 0.9\text{: } Q2 = \text{true, } Q1 = \text{false: pixel likely to be mackerel,}$$

$$\text{If } 0.2 < S < 0.5\text{: } Q3 = \text{true, } Q1 = Q2 = \text{false: may be mackerel.}$$

Flags $Q1-Q3$ for different acoustic categories are compared as follows:

Stage 1: For all pixels (one pixel at a time), if only one function returns $Q1 = \text{true}$, or $Q2 = \text{true}$, the pixel is marked by that category. As an example for one pixel, $Q1_{mackerel} = \text{true}$, and all others $Q1 = \text{false}$ ($Q1_{R18} = \text{false}$, $Q1_{swimbladder} = \text{false}$, $Q1_{category\_X} = \text{false}$, etc.), that pixel is marked to contain mackerel.

Stage 2: If the measurements from one pixel are accepted by the test criteria for more than one category at the same level, e.g. $Q2_{mackerel} = \text{true}$ and $Q2_{swimbladder} = \text{true}$, the categories of the neighbouring pixels are examined too. The use of neighbouring pixels is justified by the fact that many species cluster in shoals or schools. (i) If the most common category in the 5×5 surrounding pixels is mackerel, and at least 15% of them are categorized as such, the examined pixel is set to mackerel. (ii) If the examined pixel is categorized as strong target (which is either mackerel or other fish with a swimbladder), the pixel category is set to mackerel if at least 15% of the surrounding pixels and at least 25% of the surrounding categorized pixels are identified as mackerel. (iii) If none of the neighbouring pixels are categorized as mackerel, the category of the examined pixel is considered doubtful, and is changed to 'uncertain'.

Stage 3: If the acoustic category of the pixel is still uncertain, it is tested at the lowest level for some categories. First, flag $Q3$ has to be $Q3 = \text{true}$. Then, the same tests as in Stage 2 are performed, but at Stage 3 there will of course be more categorized neighbouring pixels than in Stage 2.

The results of the categorization process can be visualized as identified categories by generating a synthetic echogram, or they can be used to mask selected categories at a single frequency, i.e. to keep some categories and remove others at that frequency. Figure 3 illustrates how the results from neighbouring pixels are used to refine the categorization. The intermediate categorization results evolve from the first to the final stage of categorization. In Figure 3, mackerel marks are coloured in ochre.

Verification

The automatic identification of mackerel is verified by trawl samples. The catch compositions are used only as a qualitative indication of the species presence; many or few mackerel in the catch indicate, respectively, many or few mackerel in the acoustic data. The verification from biological samples of the acoustic data categorized as mackerel is done in the following way:

(i) for a dense school identified as mackerel, a successful attempt to trawl that school is expected to catch a significant amount of mackerel;

(ii) for a dense school identified as not mackerel from the acoustic data, the trawl is expected to catch no mackerel;

(iii) if there is a mixture of mackerel and other fish identified from the acoustic data, a larger quantity of the other fish is expected to be caught rather than mackerel, because of its fast swimming speed;

(iv) if a trawl with three opening–closing codends is used to sample three schools identified acoustically as mackerel in the first and fish with swimbladders in the second and third schools, and each bag is opened before the trawl reaches a school and closed when that school is passed (as indicated by the acoustic registrations), mackerel could be found in all three codends because of its fast swimming speed.

Results

The relative frequency response of mackerel

Table 2 lists calculations of $r(f)$ from the oceanic acoustic data. Only acoustic registrations interpreted as pure mackerel formed

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Table 2. The relative frequency response and associated uncertainty, $r(f) \pm \Delta r(f)$, measured at sea in different years from acoustic registrations interpreted as mackerel schools.

Year	*r*(18)	*r*(38)	*r*(70)	*r*(120)	*r*(200)	*r*(364)
1999[a]	1.2 ± 0.9	1.0	–	1.2 ± 0.8	4.3 ± 2.1	–
2000[a]	1.2 ± 0.4	1.0	–	1.1 ± 1.1	3.7 ± 1.5	–
2001[a]	1.6 ± 0.9	1.0	–	–	4.5 ± 1.8	–
2002[a]	1.4 ± 0.5	1.0	–	1.4 ± 0.7	3.2 ± 1.4	–
2003[b,c]	1.3 ± 0.4	1.0	1.0 ± 0.3	1.7 ± 0.6	3.5 ± 1.1	–
20–100 m	1.2 ± 0.3	–	0.9 ± 0.2	1.6 ± 0.3	3.2 ± 0.7	2.9 ± 0.6
2004[b,c]	1.3 ± 1.1	1.0	0.8 ± 0.3	1.8 ± 0.6	3.1 ± 0.9	–
20–100 m	1.1 ± 1.1	–	0.8 ± 0.6	1.9 ± 1.3	3.7 ± 1.8	4.7 ± 2.2
2005[b]	1.3 ± 1.0	1.0	0.8 ± 0.2	1.3 ± 0.8	2.8 ± 1.5	–
2006[b]	1.0 ± 0.4	1.0	–	1.4 ± 0.6	2.9 ± 1.4	–
2007[b]	0.9 ± 0.5	1.0	–	1.8 ± 1.6	4.4 ± 2.6	–
Mean $r(f)$	1.2 ± 0.2	1.0	0.9 ± 0.1	1.5 ± 0.3	3.6 ± 0.7	3.8 ± 1.3
Mean $\Delta r(f)$	0.7	–	0.3	0.7	1.6	1.4

[a]Simrad EK500 was used from 1999 to 2002.
[b]Simrad EK60 was used from 2003 to 2007.
[c]Numbers of 364 kHz restricted to 20–100 m depth owing to its limited range.

Table 3. Values of $r(f)$ related to the average size and fat content of Atlantic mackerel from pen experiments and surveys.

Group	Weight (g)	Length (cm)	Fat (%)	*r* (18)	*r*(38)	*r*(70)	*r*(120)	*r*(200)	*r*(364)
Cage N	255 ± 80	32 ± 2.5	15 ± 7	1.5	1.0	0.8	1.3	4.1	
Surveys	320 ± 120	34 ± 5.0		1.2	1.0	0.9	1.5	3.6	3.8[b]
Cage F	385 ± 80	33 ± 2.0	30 ± 5	1.5	1.0	0.8	1.6	4.3	
Cage SFF	665 ± 75	38 ± 2.5	37 ± 3	1.3	1.0	1.0	2.0	4.0	
Average[a]				1.3	1.0	0.9	1.5	3.8	3.8[b]

[a]Measurements from surveys weighted 67%, i.e. double that of the pen measurements.
[b]Measured at depths of 20–100 m owing to the limited range of the 364 kHz transducer.

by schools with clear borders were used in the calculations. Registrations interpreted as mackerel mixed with other scatterers at one or more frequencies were not used in the calculations, nor were registrations with unclear borders. The bottom rows of Table 2 show the values of $r(f)$ for schools 20–100 m below the surface. The values of $r(f)$ for various school sizes were not significantly different from the results in Table 2. The uncertainty was, however, somewhat greater for the smaller schools. Note that r(364 kHz) derived from the 2004 mackerel survey in the North Sea had great uncertainty associated with it, so may not be trustworthy. Note also that the 364 kHz data were applied at ranges of $<$90 m from the transducers.

Table 3 lists the calculations of $r(f)$ from three size groups of mackerel measured in a pen, and also the mean value of $r(f)$ from all oceanic surveys.

Mackerel identification verified against trawl catches

Acoustic signals were identified under several conditions of varying complexity: simple, fairly complex, very dense, and mixed registrations. Two of the most difficult, a fairly complex situation (Figures 3 and 4) and one with mixed registrations (Figure 5) are displayed. The trawl catches of RV "G. O. Sars (3)" and RV "Johan Hjort" are thought to be more representative than those of RV "G. O. Sars (2)" owing to the faster trawling speed of the first two vessels. Figures 4c–e and 5c show the results from trawl catches made by RV "G. O. Sars (3)". Table 4 shows the average length and weight of the mackerel catches.

The 200-kHz echogram is shown in Figure 4a, the retained mackerel at 200 kHz in Figure 4b, the results of the trawl samples from the three bags for the same distance in Figure 4c–e, respectively, and values of $r(f)$ which, according to the categorization, is mackerel only, in Figure 4f. The last nautical mile of the echogram is also used for Figure 3. Note that the polygons drawn in Figure 4a show which schools the trawl was assumed to catch, although this is uncertain because the trawling was carried out after the ship turned and the schools originally detected might have moved in the meantime. Further, the trawl may not always be directly behind the ship. The contents of the three trawl codends are shown in Figure 4, and are compared with the acoustically identified targets as described in the "Verification" section above. The features of the trawl catches marked by polygons in Figure 4 compared with the acoustic data are described below.

Codend 1 (Figure 4). The identified categories contain mainly fish with swimbladders resonant at 18 or 38 kHz. This is consistent with the 128 kg of the fish with swimbladders, herring (*Clupea harengus*) and saithe (*Pollachius virens*), and with the 0.05 kg of pearlside (*Maurolicus muelleri*) caught. Note that mesh sizes in the trawl are large compared with the pearlside. The pearlside has a small swimbladder, which could be resonant at 18 or 38 kHz.

Codend 2 (Figure 4). The trawl is assumed to have passed through regions that, according to the categorization results, contain mainly mackerel and pearlside, but only a small proportion of fish with swimbladders. The existence of mackerel and pearlside is confirmed by the trawl catches, but the proportion of fish with swimbladders seems rather large compared with the acoustic categories identified.

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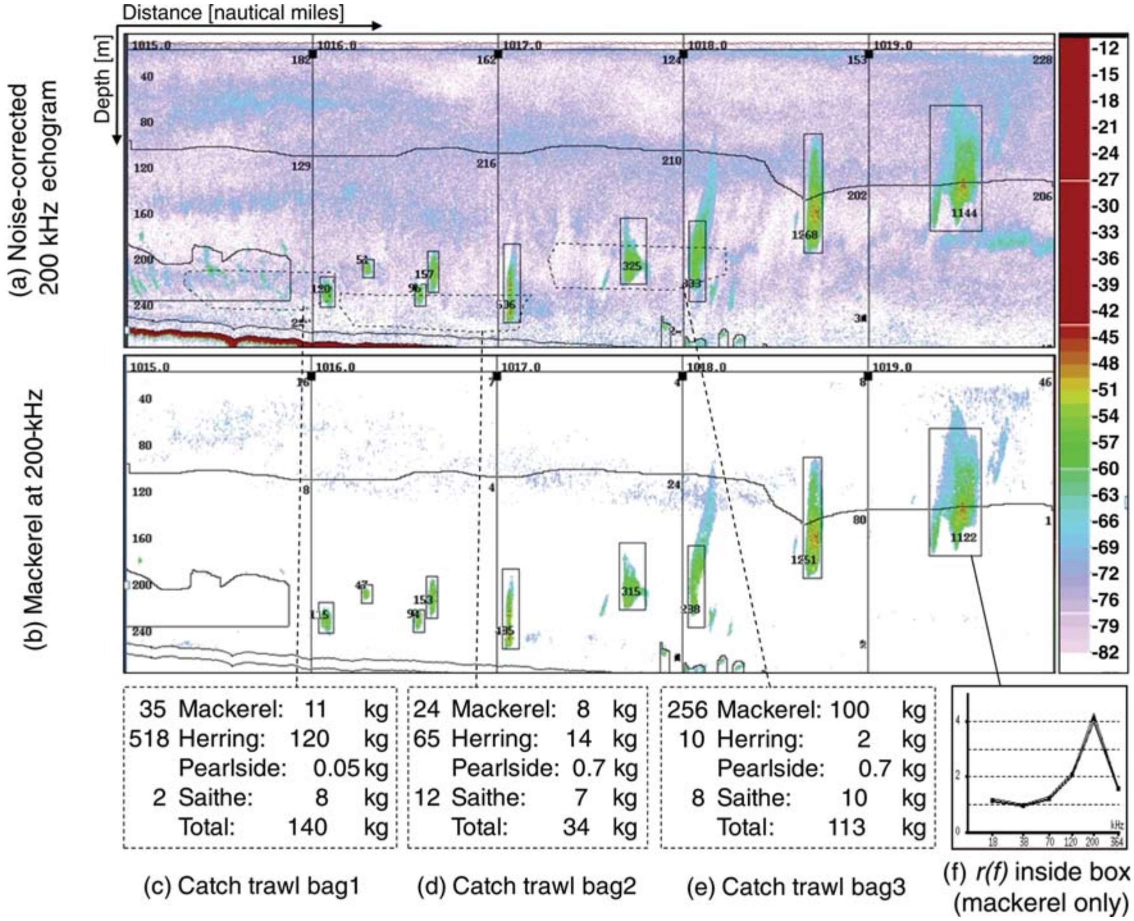

Figure 4. Trawl catches and echograms from the same five nautical miles of a fairly complex situation. The three stippled polygons in the 200-kHz echogram show acoustic registrations assumed to be sampled by each codend (bag) of the opening-and-closing trawl system. The three boxes connected to the trawl polygons show the catches of each codend in the trawl.

Codend 3 (Figure 4). The catch was mainly mackerel, is consistent with the identified acoustic categories, and also the quantity of pearlside. The small proportions of herring and saithe do not contradict the categories identified.

The echograms in Figure 5 show mixed registrations with large proportions of mackerel, pearlside, and fish with swimbladders, according to the acoustic categorization. The large school at ship-log 1233.2 and depth 200 m is identified by the system as containing both mackerel and fish with swimbladders, whereas the acoustic layer starting just below that depth is identified as fish with swimbladders only. The trawl catches contained mackerel, fish with swimbladders (herring and saithe), and pearlside, which seem to be consistent with the categorization.

Protocols for mackerel identification

The identification algorithm for mackerel applies the relative frequency response, $r(f)$, based on data collected up to 2003, and the implementation is verified using data collected in 2004. Comparing automatic identification of acoustic data with manual scrutiny tests the precision of the algorithm.

Figure 6 compares manual scrutiny and the results of applying the implemented algorithm on 2004 data. The blue diamonds show the result of scrutinizing the acoustic data with a resolution of 0.1 nautical mile, aided by trawl samples. The square root of the acoustic abundance at 200 kHz is plotted as a function of distance. The automatic categorization, shown as orange diamonds, gave a total acoustic mackerel abundance of 94% of the abundance found through manual scrutiny.

Figure 7 shows the same acoustic data as in Figure 6, and at the same resolution. The results of the manual scrutiny are plotted against the automatic categorization (correlation 0.99). The stippled line indicates the same acoustic abundance for manual scrutiny and automatic categorization. The closeness of many observations to the stippled line in Figure 7, and the lack of statistical outliers, clearly demonstrates the validity of the algorithm. Note that $r_i(f)$ values calculated from data before 2004 were used in the algorithm. The $r(200)$ values were slightly lower using the EK60 rather than the EK500, but in the data used to calculate $r_i(f)$, most data (except 2003 and some test data in 2002) were collected using the EK500. Tests show that the precision of the algorithm applied on 2004 data improves when $r_i(200)$ is reduced slightly from 4.0, the average before 2004, to $r_i(200) = 3.8$, the average over all years (Table 3). Note that in 2004 unusually, there were many schools at depths >250 m in the Norwegian Trench, compared with the earlier years (1999–2003). At greater depth, there is a tendency for $r(200)$ to reduce, although that may be attributable to the limited useful range of the 200 kHz data.

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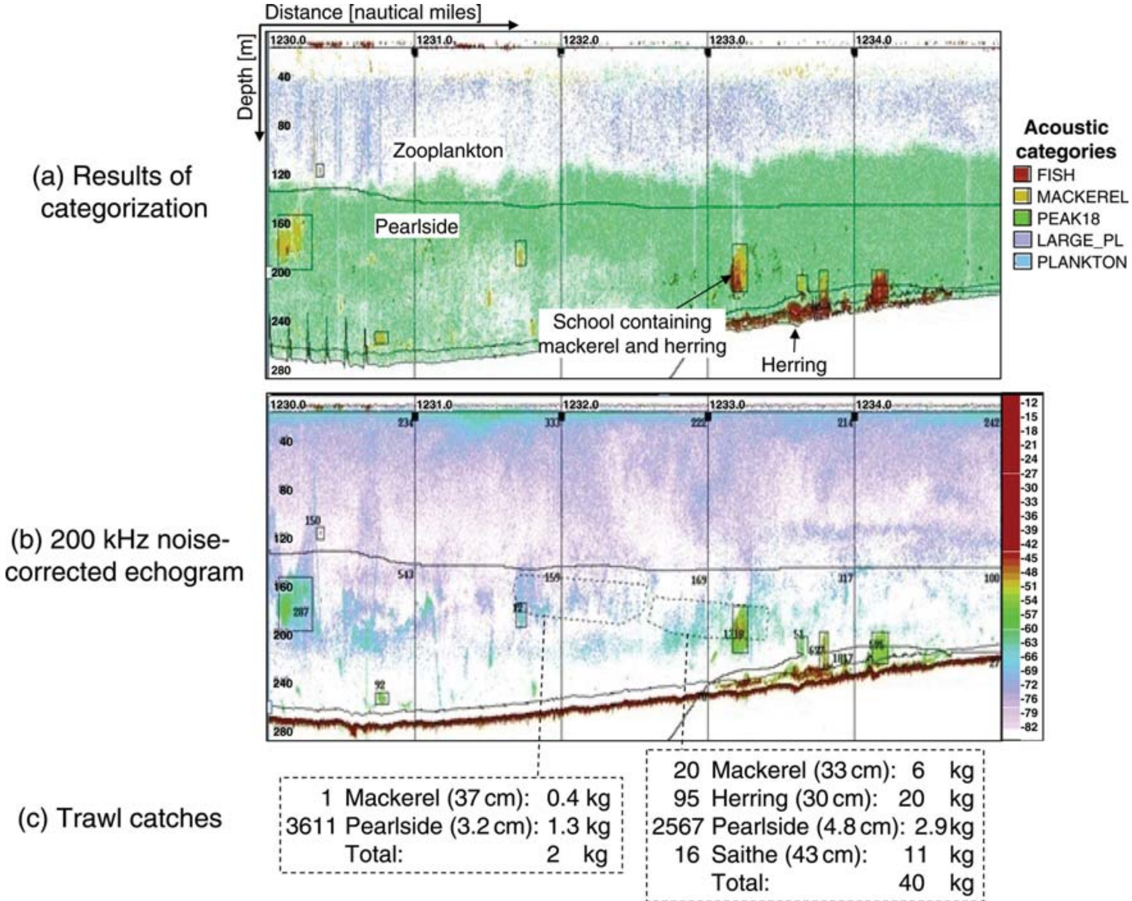

Figure 5. Mixed registrations in contaminated schools, showing trawl catches and echograms over 5 nautical miles, indicating both mackerel and another schooling fish, collected from RV "G. O. Sars" (3) on 27 October 2004. The two stippled polygons in the 200-kHz echogram show the particular acoustic registrations assumed to be sampled by the trawl.

Table 4. Lengths and weights of Atlantic mackerel caught during oceanic surveys. Lengths are measured from the nose to the end of the tail.

Year	Weight (g)	Length (cm)
1999	358	34.9
2000	286	32.8
2001	418	36.3
2002	295	33.3
2003	296	33.0
2004	322	34.1
2005	282	31.6
2006	368	34.1
2007	270	32.1
Average	322	33.6

Discussion

Components of the algorithm

S_{rf} is the most important component of the algorithm, whereas S_{pos} and S_{sv} serve to exclude very unlikely identifications of mackerel. Table 2 shows that the values of $r(f)$ measured at sea varied somewhat from year to year. Unlike the oceanic acoustic measurements, there is no doubt about the species identification and size distribution in the controlled conditions of the pen experiments. The measurements of mackerel $r(f)$, however, were performed with high transmission power, so substantial non-linear sound would be generated at harmonics (240, 400 kHz, etc.) of the 120 and 200 kHz transmissions (Pedersen, 2006). This, in turn, leads to backscatter at 120 and 200 kHz that is weaker than predicted by linear theory. Most of the non-linear loss at 200 kHz is within the calibration depth of 12 m and is accounted for through the calibration. However, the non-linear loss at 70 kHz and lower frequencies is negligible, and it is approximately <0.15 dB at 120 kHz and approximately <0.25 dB at 200 kHz, between 12 m and the 20-m maximum depth of the pen. Therefore, the results in Table 3 should be representative measures of $r(f)$ values for Atlantic mackerel.

Tests of the identification algorithm with the available acoustic frequencies conclude that $r(200)$ at least, i.e. the comparison of 200 and 38 kHz data, must be available for reliable identification of mackerel, although 38 kHz could probably be replaced by 70 kHz with slight modification of the algorithm, because 38 and 70 kHz are both in the frequency-independent scattering region below 100 kHz, as postulated in Figure 2, supported by Gorska *et al.* (2007) and verified here (Tables 2 and 3). The additional frequencies 18 and 120 kHz are also valuable for identifying mackerel, but they may be even more useful in identifying marks that are definitely not mackerel.

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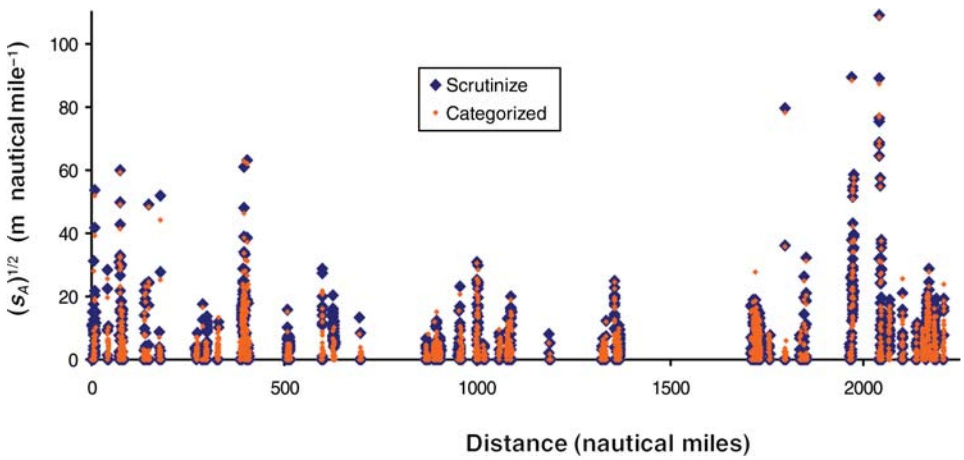

Figure 6. Validation of algorithm precision by comparing acoustic data from the 2004 North Sea survey at a resolution of 0.1 nautical miles. The blue diamonds are the acoustic mackerel abundances from traditional scrutiny aided by trawl samples. The orange diamonds are the equivalent results of automatic categorization. In all, 94% of the original acoustic abundance at 200 kHz was determined by categorization. In addition, inspection of the uncertain category easily identified which of the data were mackerel, so increasing the mackerel identifications to 98%.

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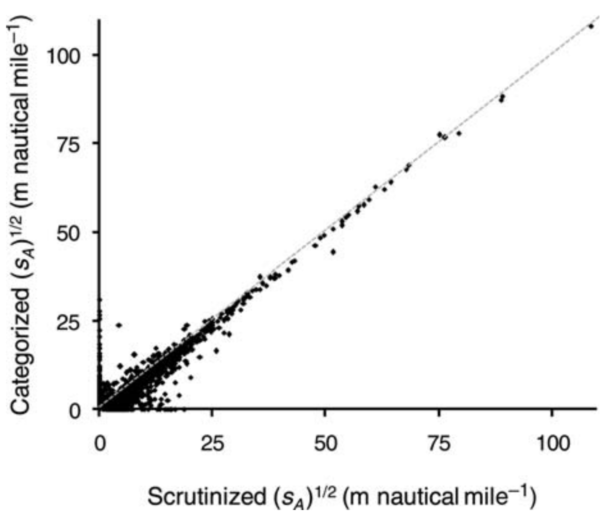

Figure 7. Validation of algorithm precision by comparing the same acoustic data from the 2004 North Sea survey at a resolution of 0.1 nautical miles, as in Figure 6. The *x*-axis is the square root of the acoustic mackerel abundance resulting from traditional scrutiny at 200 kHz; the *y*-axis shows the results of automatic categorization of acoustic data from the same survey. Correlation between manual and automatic scrutiny is 0.99.

Verification and precision

The identification algorithm is verified in small-scale scenarios by trawl catches, and it correctly identifies mackerel in situations of varying complexity, of which some examples are shown in Figures 3–5. As the catchability of mackerel by trawling is poorly understood, Norway's Institute of Marine Research has not adopted any quantitative measure to verify the identification, but relies instead on qualitative observations. The trawl speed is thought to be too slow for representative sampling of mackerel because of the species' strong avoidance behaviour and fast swimming speed.

On the larger scale of a survey, the algorithm identifies 94% of the mackerel abundance when compared with manual scrutiny of the acoustic data by a team of experts. The mean value $r(200) = 3.1 \pm 0.9$ calculated from the 2004 data was significantly lower than $r_i(200) = 4.0$, based on measurements from previous years and implemented in the algorithm. The high success rate of the algorithm suggests that it is probably robust for the annual variations in $r(f)$. Some data remained uncertain after automatic categorization and, for the 2004 data, that usually meant fish with swimbladders or mackerel. Inspection easily identified which of these data were indeed mackerel, increasing mackerel identifications to 98%. There were no cases in the tested data where the implemented identification algorithm missed intermediate or large registrations of mackerel, nor were there situations where the identification algorithm found intermediate or large registrations that were not mackerel according to manual scrutiny (Figures 6 and 7). To conclude, therefore, no serious failures and a high success rate show that the algorithm can identify Atlantic mackerel in situations of varying complexity.

Application of the results in abundance estimation

Measurements at 364 kHz showed an average backscatter comparable with that at 200 kHz, but technical problems and uncertainties in the measured $r(364)$ makes it difficult to draw any conclusion as to whether backscatter >200 kHz is essentially frequency-independent, as postulated (Figure 2). Note that the 364 kHz transceiver of the EK60 echosounder was connected to a transducer resonant at 400 kHz, and that the beam became asymmetrical and hence was not optimal when used at 364 kHz. A new transducer operating at 333 kHz has now been installed, which hopefully will overcome these technical problems. The main reason for using an acoustic frequency >300 kHz was to verify that 200 kHz is on the stable, flat region (Figure 2), where a relationship between target strength (*TS*) and size of the form established at 38 kHz, i.e. $20 \log 10 L - B$, would apply. As the backscatter of mackerel at 200 kHz is approximately four times stronger than at 38 kHz, and because many fish with swimbladders are weaker targets at the higher frequency (Foote *et al.*, 1993), the *TS* of mackerel relative to fish with swimbladders could be as much as 8 dB higher at 200 kHz. The consequences of wrongly identifying herring, for example, as mackerel would then be less severe when estimating the acoustic abundance using 200 kHz transmissions.

The increased backscatter at 200 kHz relative to 38 kHz may be explained by the backscatter from the flesh and backbone of schooling mackerel (Gorska *et al*., 2007). Moreover, Gorska *et al*. (2005, 2007) predicted that changes of temperature and fat content may alter the scattering properties of flesh, and therefore also the values of $r(200)$, but this statement cannot be verified by the data shown here. If flesh backscatter depends more on water temperature and fish fat content, then backscatter at 200 kHz would be more stable than at 38 kHz, which is yet another reason to use 200 kHz as the acoustic frequency for abundance estimation.

Future work

A natural development from changing the main frequency for abundance estimation to 200 kHz is to recalculate previous estimates of mackerel abundance that were originally based on 38 kHz via the 200 kHz data collected at the same time. Thereafter, automatic mackerel identification should be used always to support manual scrutiny.

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