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Verified acoustic identification of Atlantic mackerel

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Calibrated, digitised data from simultaneously working multi-frequency echo sounders with nearly identical and overlapping acoustic beams have been used to generate new, synthetic echograms where only targets identified as Atlantic mackerel are retained. Echo sounder raw data are processed stepwise in a modular sequence of analysis to improve the ability to categorise acoustic targets. The relative frequency response measured over up to six acoustic frequencies, 18, 38, 70, 120, 200 and 364 kHz, is the main acoustic feature used to characterise acoustic backscatter. Mackerel seems to have a frequency-independent backscatter below approximately 100 kHz, and above approximately 200kHz, but at 4 times higher level of the backscatter. Results from numeric modelling explaining the measured relative frequency response of mackerel are shown. Synthetic echograms containing targets identified acoustically as mackerel are presented and evaluated against trawl catches. Even though catching of the fast-swimming mackerel is difficult, the trawl catches from two Norwegian research vessels confirm that the targets identified acoustically as mackerel is really mackerel.

Key words: mackerel, multi-frequency, combined-frequency, categorization, synthetic echogram.

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Introduction

The swim bladder is the dominant scatterer of those fish that have such. Atlantic mackerel (*Scomber scombrus L*) does not have a swimbladder, and is a weak scatterer on the most common acoustic frequency used within fisheries acoustics, 38 kHz. Since the acoustic properties of mackerel are not well known, abundance is estimated from labour intensive egg-fertility surveys every third year. There is a desire to estimate mackerel abundance every year, and also a desire to survey the distribution area of mackerel throughout the year.

Although fishermen have used horizontally oriented sonars of frequencies above 100 kHz to identify mackerel, there have so far not been any scientific proof that mackerel can always be identified this way. Early measurements in experimental pen and from ships indicated that the backscatter was stronger at 120 kHz than at 38 kHz when measured with vertical oriented echo sounders. Institute of Marine Research, IMR, did systematic studies of mackerel from RV “G.O. Sars” (2) in 1999 – 2002. The backscatter of mackerel was expected to be larger at 120 kHz than at the lower frequencies, but seemed surprisingly to be essentially frequency-independent in all of the frequency range 18 – 120 kHz, but 4 times larger at 200 kHz. Korneliussen and Ona (2002) used these empirical relations at the 4 acoustic frequencies 18, 38, 120 and 200 kHz to identify Atlantic mackerel. Their method was, however, based on the assumption that the empirical relation did not change much. Measurements of mackerel backscatter in pen and on additional surveys show that the assumption of similar backscattering strength at 120 kHz and 38 kHz is generally not correct. The mackerel identification algorithm is therefore developed further here and is discussed in detail.

Gorska and co-authors (Gorska et al. 2004a,b, Korneliussen et al., 2004b) have modelled backscatter from mackerel based on the suggestion by Korneliussen that the bone and the flesh are the two main scattering parts of mackerel. The model predicts that backscatter from flesh of mackerel schools are essentially frequency independent, although it depends on orientation and acoustic frequency (or fish size) for individual fish. The model predicts backscatter from backbone to be weaker than backscatter from flesh at 38 kHz and below, and that backscatter from backbone dominates at 120 and 200 kHz. The model of bone backscatter depends on a range of parameters, and has currently not fully implemented the backbone morphology or backscatter from the head-bone. Variation of the model parameters within the limited acceptable range lead to a possible variation in the frequency-range where the backbone backscatter starts dominating over flesh backscatter. One of the parameters that may change the "step-frequency" is the backbone radius, which depends on the mackerel size. The model also shows the possibility for a relatively frequency-independent region at 200 kHz and above. In 2003, the frequencies 70 and 364 kHz became available onboard the new RV "G.O. Sars" (3) in addition to 18, 38, 120 and 200 kHz. These new frequencies gave the possibility to test the model predictions.

Further development of the Norwegian algorithm for identification of Atlantic mackerel depends largely on the relative frequency response, r(f), for mackerel and its typically and possible range of variation at each frequency, f. Establishing trustworthy relations of r(f) and Δr(f) is therefore essential. If the region at and above 200 kHz is verified to be frequency independent, acoustic data at 200 kHz should be used to calculate abundance rather than 38 kHz.

The mackerel backscatter of 200 kHz relative to the 38 kHz found during the Scottish acoustic mackerel surveys starting in 2001 were similar to the Norwegian, while the mackerel backscatter at 120 kHz was slightly larger than at 38 kHz. The Scottish identification algorithm was based largely on the much stronger backscatter at 200 kHz than at 38 kHz.

Both the Norwegian and Scottish acoustic registrations of mackerel have been verified by pelagic trawl samples. The catching of mackerel, however, have been a limited success, especially for the Norwegian research vessels, assumable due to the ability of mackerel to swim fast and avoid the trawl.

Material and methods

Collection of acoustic data at sea

Acoustic data was collected from the middle of October to the beginning of November in the North Sea and Norwegian Sea from RV "G.O. SARS" (2) in 1999 - 2002, and RV "G.O. Sars" (3) in 2003. In addition, there was cooperation with the Scottish RV "Scotia" some of the years. The data collected from RV "G.O. Sars" (2) and (3) was post-processed with the Bergen Echo Integrator system, BEI (Korneliussen, 2004). Noise was quantified and reduced according to methods described by Korneliussen (2000) and was done entirely by post-processing data, not by using the internal echo sounder noise limit control. Time was registered when the EK60 transmitter was triggered and was stored with a resolution of 0.01 s for each ping.

During this specific study, the Simrad echo sounders EK500 or EK60 operating at three, four or six of the approximate acoustic frequencies of 18, 38, 70, 120, 200 and 364 kHz were calibrated using recommended methods (Foote 1982; Foote et al., 1987) and standard targets for the particular frequencies. The ranges from the transducers to the spheres used during the calibration of the echo sounder systems of RV "G.O. Sars" (2) and (3) were typically 22 ± 1 m. The acoustic transducers used were similar on all vessels. All transducers on each vessel were mounted at the same depth on the bottom of a protruding instrument keel (Ona and Traynor, 1990). Figure 1a-c shows the transducer mounting, and Table 1 shows the 3 dB beamwidths and the input power per area of the transducers

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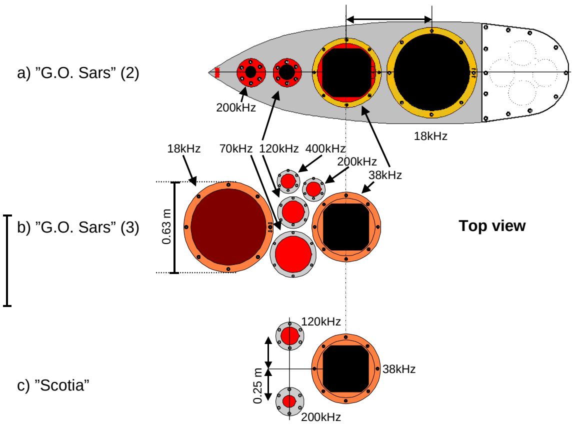

Figure 1. Positioning of transducers mounted on the protruding instrument keels of the research vessels. a) RV "G.O. Sars" (2). b) Port keel of RV "G.O. Sars" (3). c) RV "Scotia"

Table 1. Transmitting power and power per area on different systems

Echo sounder / frequency [kHz]	Transmit power [W]	Power per area [kW/m^2]	Beam width (3dB)
EK500/18	2000	10	11^0
EK500/38	2000	20	7^0
EK500/120	1000	100	7^0
EK500/200	1000	227	7^0
EK60/18	2000	10	11^0
EK60/38	2000	20	7^0
EK60/70	1000	30	7^0
EK60/120	250	25	7^0
EK60/200	100	23	7^0
EK60/364	60	56	$7^{0\,*}$ (6^0)

* *7^0 for 400 kHz. Calibration, which gave 6^0 of EK60/364 kHz, is doubtful.*

RV "G.O. Sars" (2) used EK500, although EK60-Mk1 was also tested. The 18kHz, 38kHz and 120 kHz transceivers were put in the same EK500 echo sounder, EK500S(1), which were specially modified to allow for pulse duration of 0.6 ms, and a sampling distance of 2 cm. EK500S(1) triggered its frequencies simultaneously for sound transmission, and triggered also the other EK500, EK500(2), to transmit 0.6 ms 200 kHz pulses.

The pulse duration of the EK60 echo sounder was set to 1.0 ms for all frequencies. EK60-Mk1 was used on RV "G.O. Sars" (2) in 2002, and EK60-Mk2 on RV "G.O. Sars" (3). Note that the EK60/364kHz echo sounder was connected to a transducer resonant at 400kHz that was not optimal although with 30% (120kHz) bandwidth.

Horizontal offsets are due to the distance between the transducers, while total system filtering causes the vertical offsets. Pulse transmission delays due to "filtering" effects in the echo-sounder and transducer systems similar to those found in the echo sounder Simrad EK500 was expected. The pulse transmission delay of EK500 can be found in Korneliussen and Ona (2002) and in Korneliussen, Diner and Fernandes (2004). For EK60, however, the theoretical calculations were not confirmed by measurements. The vertical shifting of the acoustic data was therefore set to zero in the further work. The percentage vertical overlap [*pvo*] between the frequencies using similar pulse lengths is defined as: $pvo = 100[1\text{-abs}(\Delta v_1 - \Delta v_2)/\Delta z]$ where Δv_1 and Δv_2 are the calculated vertical offset distances. Since the pulse transmission delay of EK60 could not be verified by measurements, *pvo* is set to 95% for EK60. The effect of the horizontal offsets is reduced with increasing range from the transducers. Thus, a requirement of percentage spatial overlap, $pso = 100(pvo/100)(pho/100)$, larger than 85% for combining acoustic multi-frequency requires percentage horizontal overlap [*pho*] $pho > 90\%$.

The distances between the 7^o transducers of RV "G.O. Sars" (3) and RV "Scotia" shown in Figure 1 allows for combination of data at different frequencies beyond approximately 40 m below the transducers, i.e. beyond 50 m depth, if $pso > 85\%$ is required, while RV "G.O. Sars" (2) requires a somewhat larger range due to the large distance between the two furthest 7^o transducers. The use of slight smoothing, shifting of the acoustic data and other techniques is expected to improve the comparability between frequencies somewhat, but it should be noted that the result of combining data at shallower depths than 30 m is doubtful.

Biological sampling

During the North Sea trials the trawl sampling was targeted against mackerel and schools of other species. The main strategy for trawling was to first let the ship first pass the acoustic registrations, and then turned to trawl on the desired registrations.

Fish was sampled from RV "G.O. Sars" (2) and (3) with pelagic Åkra trawls. RV "G.O. Sars" (2) was not able to tow at high speed due to the weak engine. In 2003, there was available both a single-net Åkra trawl, and an additional Åkra trawl connected to opening and close "Multi-sampler" system for trawling with up to 3 bags (Engås et al. 1997). RV "G.O. Sars" (3) has a strong engine, but the trawls showed signs of damages at speeds greater than 4 knots. The time used for the trawl in fishing operation was close to 15 minutes, but were sometimes less.

Sampling of zooplankton from RV "G.O. Sars" (2) and (3) was done horizontally at selected depths with the 1m^2 MOCNESS (Multiple Opening and Closing Net Environmental System, Wiebe et al., 1976; 1985) having a maximum of eight nets. For vertical sampling of zooplankton an 180µm WP-II net (Anon., 1968) was used. Because the WP-II net is always open it samples all the way to the surface. The sampling for plankton was to verify that dense aggregations of plankton were not by mistake interpreted as mackerel.

Acoustic data in experimental pen

Establishment of r(f) was necessary for the development of the mackerel identification algorithm. In the pen measurements, only mackerel were present, except for possibly fish and plankton that were small enough to pass trough the net-masks of approximate size 1.5x1.5 cm.

Two specially modified EK500 with 0.6 ms pulse duration and 2 cm sampling distance were used to collect acoustic data from mackerel in captivity at the IMR Aquaculture station in Austevoll, Norway. (The EK60 could not be used in the pen-experiments, as they were withdrawn from the market a few months to correct an error just prior to the start of the experiment.) The pen was 21 m deep, and 10x10 m wide. Different sizes of mackerel were introduced to the pen, and backscatter was measured for numbers of 150 mackerel in each size class, and for numbers of 10 and 500 for most size classes. The length and weight of each individual specimen were measured after the acoustic measurements. The fat-content were measured for a selection of 10 – 15 specimens after each of the measurement series.

The measurements were done on five different size classes of mackerel. The captured mackerel were split into two groups into two pens. One group were never fed, except for the plankton passing through the pen, while the other group were fed. Each of these groups was then manually split into two sub-groups, large and small unfed, and large and small fed. Some of the fed mackerel were fed an additional season.

The transducers were mounted on a rig as shown in Figure 2 approximately 1 m below the surface.

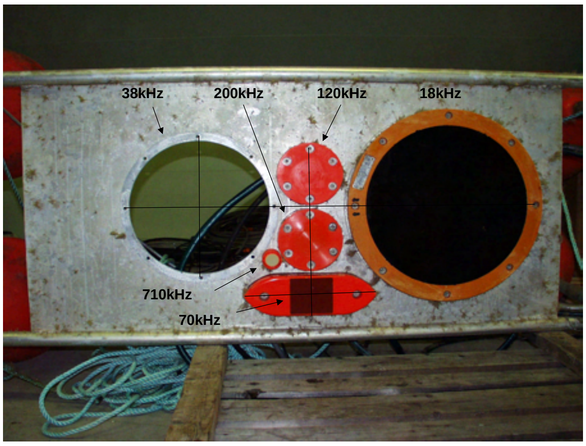

*Figure 2. Positioning of transducers of rig used during measurements at Institute of Marine Research Aquaculture station at Austevoll, Norway.*The calibration spheres were approximately 12 ± 1 m below the transducers. The EK500 systems at 18, 38, 120 and 200 kHz were as in Table 1. The EK500/70 kHz system used 800 W input power, 66 kW/m^2, and had 11^0 3dB beamwidth.

Data processing

The Norwegian data collected from RV "G.O. Sars" (2) and (3) were processed in two different manners. Firstly, the echograms were scrutinised in the traditional manner by a team of two scientists and the chief instrument engineer. All available knowledge of Atlantic mackerel was used in this process in addition to the biological samples from trawl. The scrutinising process is described in Korneliussen (2004). The results of this process were stored in a database, and were used to establish the relations of frequency dependent backscatter relative to 38 kHz, r(f).

Secondly, in parallel to the traditional scrutinising, mackerel and other acoustic categories were identified automatically by the system through the generation of synthetic echograms. This method improved through the years.

The acoustic data from experimental pen were collected and scrutinised using BEI. Due to the danger of non-linear effects, only mackerel appearing at depths larger or slightly less than the depth of the calibration sphere were used.

Preparing acoustic data for combination

The acoustic data of RV "G.O. Sars" (2) and (3) was processed generally as described in Korneliussen and Ona, 2002, 2003. First, the noise was removed as described in Korneliussen (2000) then the data was smoothed as described in Korneliussen and Ona (2003). The noise-corrected acoustic data was smoothed by multiplication with a matrix containing Gaussian weights (that sum to unity). The vertical averaging diameter was 0.75 m and the horizontal was 10.0 m, i.e. samples that is 0.75/2 m above or below the mid sample was multiplied by half the weight. The weights were skewed horizontally to take into account the horizontal offset of the transducers, and would generally have been skewed vertically to account pulse transmission delay due to filtering effects of the echo sounder if those delays had been known.

The relative frequency response of mackerel

The acoustic backscatter interpreted as mackerel during surveys as well as acoustic measurements from mackerel freely swimming in pen were used to establish r(f) and its uncertainty Δr(f).

Generation of synthetic echograms: the algorithm for automatic identification of mackerel

The smoothed acoustic measurements are used as input to the categorization system, as initially described by Korneliussen and Ona in 2002, and later by the use of smoothed and shifted data only in 2003. The idea of the system is to group the multi-frequency backscatter into broad acoustic categories that may or may not be refined into sub-categories at a later stage.

An acoustic category is defined either through an acoustic model, through empirical data, or through a hybrid, i.e. a combination of a scattering model and empirical data. Measured values is used to adjust the scattering models, but may also be used independently as was the case originally for mackerel. Each acoustic category is described through a few acoustic features, of which the relative frequency response, r(f), is the major feature used to generate synthetic echograms. To each acoustic category, there is a belonging r(f) and its initial measurement uncertainty or tolerance Δr(f) at the frequency f. Together with the major acoustic feature, r(f), the other features are used by the categorization system to generate a "Similarity number", S, for identification of each acoustic category. The larger S is for one of the tested acoustic categories, especially if S for the other categories is small, the more likely it is for correct identification. Note that an identification of a multi-frequency data-point as "belong to category_X" is inherently interpreteted as "does not belong to category_Y", i.e. that measurements identified as "large plankton" or "no target" inherently is interpreted as "not mackerel"

In addition to the acoustic categories, there are some "help-categories". Two of these are used to describe that: (1) there is no scatterer in the measured volume, and (2) the measurement is done below the bottom.

One of the acoustic categories has its origin from empirical measurements of backscatter from mackerel. These are later confirmed by modelling (Gorska et al., 2004). The Similarity number, S, is composed by the relative frequency response similarity, $S_{r(f)}$, the behaviour similarity, $S_{behavior}$, and the backscattering strength similarity, S_{sV}. S for mackerel is currently defined as:

$$S \equiv S_{r(f)} * S_{behavior} * S_{sV} \tag{1}$$

where
$$0 < S_{r(f)} < 1$$
$$0 < S_{behavior} < 1$$
$$0 < S_{sV} < 1$$

The mackerel-categorization starts with the pre-categorization to speed up the total categorisation process. This is a set of simple tests that is considered the minimum requirements for a multi-frequency data-point to be considered as mackerel (i.e. the acoustic category "mackerel").

Pre-categorisation

Mark all volume segments with no scatterers based on the non-smoothed data. The acoustic category "no target" cannot be changed later.

Further, the smoothed "pixel"-data are tested against a set of acoustic categories where r(f)±Δr(f) is known to estimate S_{rf} and S_{sV}, and when possible also $S_{behavior}$. For the acoustic category "mackerel", the calculation of S proceeds as follows:

S = 0, i.e. "pixel" cannot be mackerel if:

- Not data at both 38 and 200 kHz
- $s_v(38kHz)=s_v(38)>s_v(200)$
- If 70kHz data exist: if $s_v(70)>s_v(200)$
- If 18kHz data exist: if $s_v(18)>s_v(200)$
- $4\pi1852^2 s_v(38)<0.1$
- $4\pi1852^2 s_v(38)>50000$

Behavior, position and date similarity, $S_{behavior}$

This similarity can only be connected to acoustic categories that can be connected to a quantifiable behavior of some kind. $S_{behavior}$ can be set only if the acoustic category is identical to a known set of species as is the case for mackerel. The default value of $S_{behavior}$ is unity, 1, if there is no known information. Figure 3 illustrates how $S_{behavior}$ can be set. For mackerel, $S_{behavior}$ is:

- $S_{behavior} = 1$ default
- $S_{behavior} = 1$ if position and time of year is where mackerel is very likely to be, e.g. the North Sea and Norwegian Sea in September, October or November.
- $S_{behavior} = 0.9$ for close positions and time, where mackerel is very likely to be found.

- $S_{behavior}$ = 0.8 to 0.6 where mackerel is decreasingly likely to be found.
- $S_{behavior}$ = 0 if the position of the data is far outside waters where mackerel has never been observed.

If the above tests are passed, i.e. both the pre-categorization and the behavior testing, the mackerel-identification function will set a flag to indicate "cannot-exclude-pixel-to-be-mackerel".

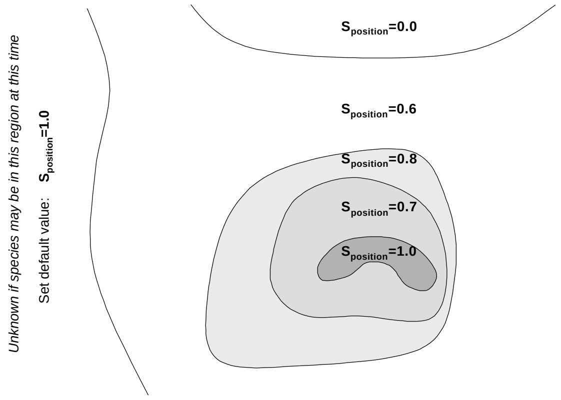

Figure 3. Illustration of setting the position and time similarity, $S_{behavior}$.

Backscatter strength similarity, S_{sv}

S_{sv} is used to avoid multi-frequency measurements to be associated with an unlikely acoustic category. Very weak s_v at all frequencies should as an example not be associated with mackerel or fish with swim bladder. S_{sv} is defined as: $S_{sv} \equiv S_{v,L} * S_{v,H}$

$S_{v,L}$ tests $s_{v,L}$, which is the mean of the 18, 38, and 70 kHz data that exist. The 38 kHz data will always exist due to previous test.

- $S_{sv,L}$=1 Default
- $S_{sv,L}$=1 If $10*0.1<4\pi1852^2 s_{v,L}<50000/10$
- $S_{sv,L}$=0.5 If $4\pi1852^2 s_{v,L}<10*0.1$ or $4\pi1852^2 s_{v,L}>50000/10$
- $S_{sv,L}$=0 If $4\pi1852^2 s_{v,L}<0.1$ or $4\pi1852^2 s_{v,L}>50000$

$S_{v,H}$ tests $s_{v,H}$, which is the mean of the 200 and 364 kHz data that exist. The 364 kHz data will only be used at ranges of 90 m or less from the transducer. The 200 kHz data will always exist due to previous test. The max range of 200 kHz data is set to 250 m for mackerel.

- $S_{sV,H}$=1 Default
- $S_{sV,H}$=1 If $3.3<4\pi1852^2 s_{v,H}<50000*0.33$
- $S_{sV,H}$=0.5 If 4p18522sv,H<10*3.3*0.1 or 4p18522sv,H>50000*3.3/10
- $S_{sV,H}$=0 If $4\pi1852^2 s_{v,H}<3.3*0.1$ or $4\pi1852^2 s_{v,H}>3.3*50000$

Relative frequency response similarity, $S_{r(f)}$

Figure 4 illustrate the frequency dependency of the backscatter of mackerel, and how the error-band evolves through different stages of the categorization process. Figure 5 illustrates how the results of the categorization of the neighbour pixels are used.

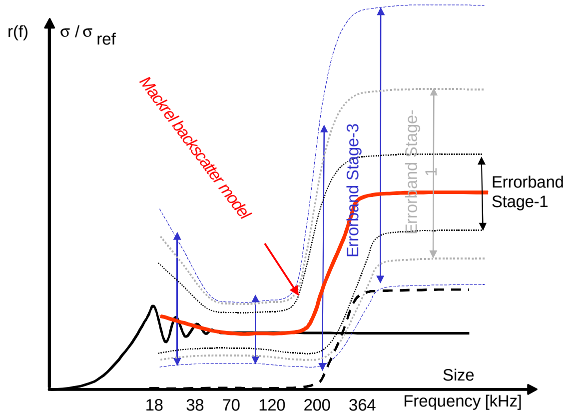

Figure 4. Illustration of mackerel backscattering model, with increase of error bands in each categorization stage shown.

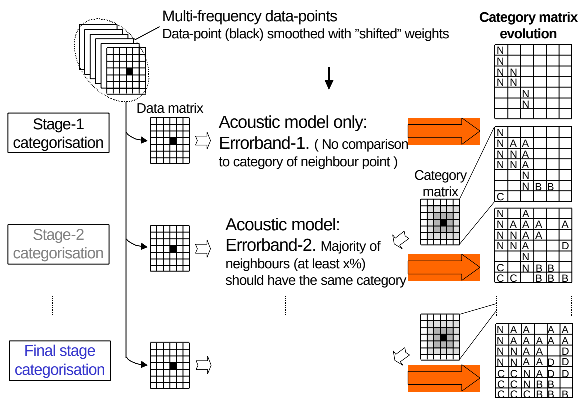

Figure 5. Clustering of the pixels (representing volume segments) during the categorization process.

The idealized frequency responses, $r_i(f)$, for mackerel at the frequency f is based on measurements (see below) and verified by models (Gorska et al., 2004) is set to:

(2) $r_i(18) : r_i(70) : r_i(120) : r_i(200) : r_i(364)$ =
1.1 :1.0 : 1.3 : 4.0 : 3.6

The uncertainties are also based on measurements. The minimum value accepted for r(f) in first pass is $r_{ideal}(f)/e(f)$, and the maximum is $r_{ideal}(f)e(f)$. If $r_{ideal}(f)/e(f) < r(f) < r_{ideal}(f)e(f)$, $S_{r(f)=}$1.0. The values if e(f) are:

$S_{sV,hi}$ $S_{sV,high}$ = 0.5

(3) e(18) : e(70) : e(120) : e(200) : e(364) = 1.7 : 1.5 : 2.0 : 1.5 : 2.0

For each pass of maximum 3, e(f) is increased by a factor 1.5. If accepted in second pass, $S_{r(f)=}$1.0*0.7, and in third $S_{r(f)=}$1.0*0.7*0.7=0.49.

The total S_{rf} is a weighted sum of the individual $S_{r(f)}$ at the frequencies f where data exist, and is measured within the maximum range of the frequency. The weights are:

(4) w(18) : w(70) : w(120) : w(200) : w(364) = 1.0 : 2.0 : 1.0 : 4.0 : 1.0,

which mean that the 200/38 data counts 4 times the 364/38 data. For data not used, the weight w=0. The result is then:

(5) $S_{rf} = (S_{r(18)} *w(18) + S_{r(70)}*w(70) + S_{r(120)}*w(120) + S_{r(200)}*w(200) + S_{r(364)}*w(364)) / (w(18)+w(70)+w(120)+w(200)+w(364))$

The resulting total similarity, S, for mackerel

The total similarity is then: S = $S_{mackerel}$ = S_{rf} * $S_{behavior}$ * S_{sV}. Depending on the value of S, the following flags are set to TRUE:

- If S>0.9: *"pixel-almost-certainly-mackerel"*
- If 0.5<S<0.9: *"pixel-possibly-mackerel"*
- Se above for: *"cannot-exclude-pixel-to-be-mackerel"*

All categorization functions returns three similar flags. The results of all categorization functions are compared as follows:

- If only one function return a flag like *"pixel-almost-certainly-category_X"*, the pixel is marked as Category_X. If there is only one function return a flag like *"pixel-possibly-category_X"*, the pixel is also marked as Category_X.
- If there are more than one category accepted at the same level, i.e. more than one *"pixel-almost-certainly-category_X"*, or if none accepted at the highest level, more than one *"pixel-possibly-category_X"* , the categories of the nearest neighbours in space is examined. If no other of the neighbouring pixels are categorised as "mackerel", the category of that pixel is considered doubtful, and is changed to "uncertain". If the most common category in the 5x5 surrounding pixels is "mackerel", and at least 15% of the pixels are categorised as "mackerel", the examined pixel is set to "mackerel". If the examined pixel is categorised as "strong-target" (i.e. mackerel or swim bladdered fish), the pixel category is changed to "mackerel" if at least 15% of the surrounding pixels and at least 25% of the surrounding categorised pixels are categorised as "mackerel".
- If the acoustic category of the pixel is still uncertain, it is tested at the lowest level for some categories, but not for mackerel.

The result of the categorization process can be visualised as identified categories in a generated synthetic echogram, or it can be used to mask selected categories at a single frequency, i.e. keep some categories and remove others at that frequency.

Methods of verification

The automatic identification is verified by means of trawl samples. Fernandes suggested during the ICES/WGFAST in Gdynia in 2004 to test the result of the identification by means of Similarity of Identification Index, S_{ID}, or Probability of Identification Index, P_{ID} as it was originally named.

(5) $$S_{ID} \equiv 1 - \left|\left(\Phi_t - \Phi_{f(x)}\right)\right|$$

where (6) $$\Phi_t = \frac{n_{(x)}}{\sum n_{(fish)}}$$

is observed proportion in the trawl

(7) $$\Phi_t = \frac{r_{a(x)}}{\sum r_{a(fish)}}$$

is observed proportion from the algorithm

(8) $$r_{a(x)} = \frac{s_{A(spp,x)}}{4\pi s_{bs(x)}}$$

is number of species "x" per area

(9) $$\sum r_{a(fish)} = \frac{s_{A(spp,x)}}{4\pi s_{bs(x)}} + \frac{s_{A(spp,y)}}{4\pi s_{bs(y)}}$$

is total area density of fish "x" and "y"

Mainly due to the unknown catch ability of mackerel by trawl, IMR has not suggested any quantitative measure to verify the identification, but relies on qualitative data. The trawl speed is thought to be too slow for the IMR surveys to be applicable. The verification from biological samples of the acoustic IMR data categorized as mackerel is done qualitatively the following way:

- For a dense school identified as mackerel, the trawl catches are expected to catch a significant amount of mackerel.
- For a dense school identified as not mackerel from the acoustic data, the trawl catches is expected to not catch mackerel.
- If there is a mixture of mackerel and other fish identified from the acoustic data, the other fish is expected to be caught in larger quantity relative to mackerel.
- If three opening-close bags are used to catch several schools identified as e.g. mackerel, herring, herring and herring, mackerel could be found in all three bags if the first school is mackerel.

Results

The relative frequency response of mackerel

The relative frequency response, r(f), and its uncertainty, Δr(f), has been measured at several frequencies during cruises starting in 1999. r(f) and Δr(f) has also been measured for different size classes of freely swimming mackerel in pen. Due to possible non-linear loss, frequencies at 120 kHz and above in the pen experiments, only the data at or slightly deeper than the depth of the calibration sphere was used to calculate r(f).

Table 2 shows calculations of r(f) from a subset of the data. Only acoustic registrations interpreted as pure mackerel forming with clear borders are used in the calculations. The registrations that were interpreted as mackerel mixed with other scatterers at one or more frequencies were not used in the calculations, and neither were acoustic registrations with unclear borders. The bottom row of Table 2 is r(f) for schools between 20 and 100 m below the surface.

r(f) for different sizes of the schools was not significantly different from the results of Table 2. The uncertainty was, however, somewhat larger for smaller school than for large.

Table 3 summarises all measurements of backscatter from mackerel. Note that r(364kHz) taken during the mackerel cruise in the North Sea in 2004 have a large uncertainty, and may not be trustworthy. Note also that the 364 kHz data is collected at ranges less than 90 m from the transducers.

Biological sampling

not thought to reflect the real proportions. The proportion of mackerel is thought to be generally too low due to the stronger avoidance due to the swimming speed. The catches of RV "G.O. Sars" (2) were therefore used as an indication of the species presence, with much mackerel indicating much mackerel in the acoustic data, and little mackerel in the catches indicating little

Table 2. r(f)±Dr(f) for different years for acoustic registrations interpreted as mackerel schools

SCATTER GROUP	r(18)	r(38)	r(70)	r(120)	r(200)	r(364)
1999 (EK500)	1.2 ± 0.9	1.0	-	1.2 ± 0.8	4.3 ± 2.1	-
2000 (EK500)	1.2 ± 0.4	1.0	-	1.1 ± 1.1	3.7 ± 1.5	-
2002 (EK500)	1.6 ± 0.9	1.0	-	-	4.5 ± 1.8	-
2002 (EK500)	1.4 ± 0.5	1.0	-	1.4 ± 0.7	3.2 ± 1.4	-
2003 (EK60)	1.3 ± 0.4	1.0	1.0 ± 0.3	1.7 ± 0.6	3.5 ± 1.1	
Average	1.3 ± 0.6	1.0	1.0 ± 0.3	1.4 ± 0.8	3.9 ± 1.8	
2003 (20-100m)	1.2 ± 0.3	1.0	0.9 ± 0.2	1.6 ± 0.3	3.2 ± 0.7	2.9 ± 0.6

Table3. r(f) of increasing average size of Atlantic mackerel from pen 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	330 ± 120	34 ± 5.0		1.4	1.0	1.1	1.1 – 2.0	4.1	3.6
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	
Total				***1.3±0.4***	***1.0***	***1.0±0.1***	***1.0 – 2.0***	***4.2±1.0***	***3.6±1.4***

mackerel in the acoustic data.

The trawl catches of RV "G.O. Sars" (3) is thought to be somewhat better than those of RV "G.O. Sars" (2). The results of some trawl catches of RV "G.O. Sars" (3) is found in Figures 8 - 10.

Automatic identification of mackerel

The Figures 6-8 show original acoustic data, results of categorization, and of the trawl samples. Figures 6a-f shows a noise-corrected 1 nautical mile echogram at the original frequencies. Figure i shows the average relative frequency response, r(f), of the connected quadrangle. Figure (g) visualizes all acoustic categories found during the categorization process. Figure (h) shows the 200-kHz echogram masked with the acoustic category "mackerel". Comparison of Figures (i) and (j) shown that r(f) of the retaining mackerel-category is slightly different from the original data used in Figure (i). Figure 7a-c show how the intermediate categorization results evolve from Stage-1 categorization to the final stage. The last 1 nautical mile of the 5 nautical miles echograms in Figure 7 is the one shown in Figure 6.

Figure 8 shows the original 200-kHz echogram, the retained mackerel at 200 kHz, and the results of he trawl samples for the same distance. Note that the polygons drawn in Figure 8a are assumed approximate positioning of the trawls, although there is no way to know this for sure.

The features of the trawl catches as compared to the acoustic data are:

1) The first trawl bag catches in a region which according to the identified categories contains mainly "swimbladdered fish" and "resonant at 18 or 38", which is consistent with the 128kg of the swim bladder fish herring (*Clupea harengus* L.) + saithe (*Pollachius virens* L.), and with the 0.05 kg of pearlside (…. L.). Note that masks in the trawl are small compared to pearlside. Pearlside has a small swim bladder, which could be resonant at 18 or 38 kHz.
2) The second trawl bag is assumed to go trough regions that according to the categorization results contains mostly mackerel and pearlside, but only minor portions of swim-bladder fish. The existence of mackerel and pearlside is confirmed by the trawl, but the portion of swim bladder fish seem to be somewhat large compared to the identified acoustic categories.
3) 1) The catch of last trawl bag was mainly mackerel, which is consistent with the identified acoustic categories, and so is the mount of pearlside. The small portions of herring and saithe do not contradict the identified categories.
4) Figure 9 shows a 3 nautical mile echogram with two very dense schools, and where the trawl catch showed very large amounts of pure mackerel. The categorization identifies the schools as being almost entirely mackerel, but also with some minor portions inside the last school as not being mackerel. The relative frequency responses, r(f), of the regions connected to Figure 9e and g is typically mackerel. The r(f) in Figure 9f is not typically mackerel. Note that both Figure 8b and 9c show mackerel in relative loose registrations outside the schools.
5) The echograms in Figure 10 shows large portions of mackerel, pearlside and swim bladder fish. Note that the large school at ship-log 1234 and depth 200 m is identified to contain both mackerel and swim bladder fish, while the acoustic layer starting just below is identified as swim bladder fish only. The trawl catches contained portions of mackerel, swim bladder fish (herring and saithe) and pearlside, which seem to be consistent with the identified categories.
6) The catch of last trawl bag was mainly mackerel, which is consistent with the identified acoustic categories, and so is the mount of pearlside. The small portions of herring and saithe do not contradict the identified categories.

Figure 9 shows a 3 nautical mile echogram with two very dense schools, and where the trawl catch showed very large amounts of pure mackerel. The categorization identifies the schools as being almost entirely mackerel, but also with some minor portions inside the last school as not being mackerel. The relative frequency responses, r(f), of the regions connected to Figure 9e and g is typically mackerel. The r(f) in Figure 9f is not typically mackerel. Note that both Figure 8b and 9c show mackerel in relative loose registrations outside the schools.

The echograms in Figure 10 shows large portions of mackerel, pearlside and swim bladder fish. Note that the large school at ship-log 1234 and depth 200 m is identified to contain both mackerel and swim bladder fish, while the acoustic layer starting just below is identified as swim bladder fish only. The trawl catches contained portions of mackerel, swim bladder fish (herring and saithe) and pearlside, which seem to be consistent with the identified categories.

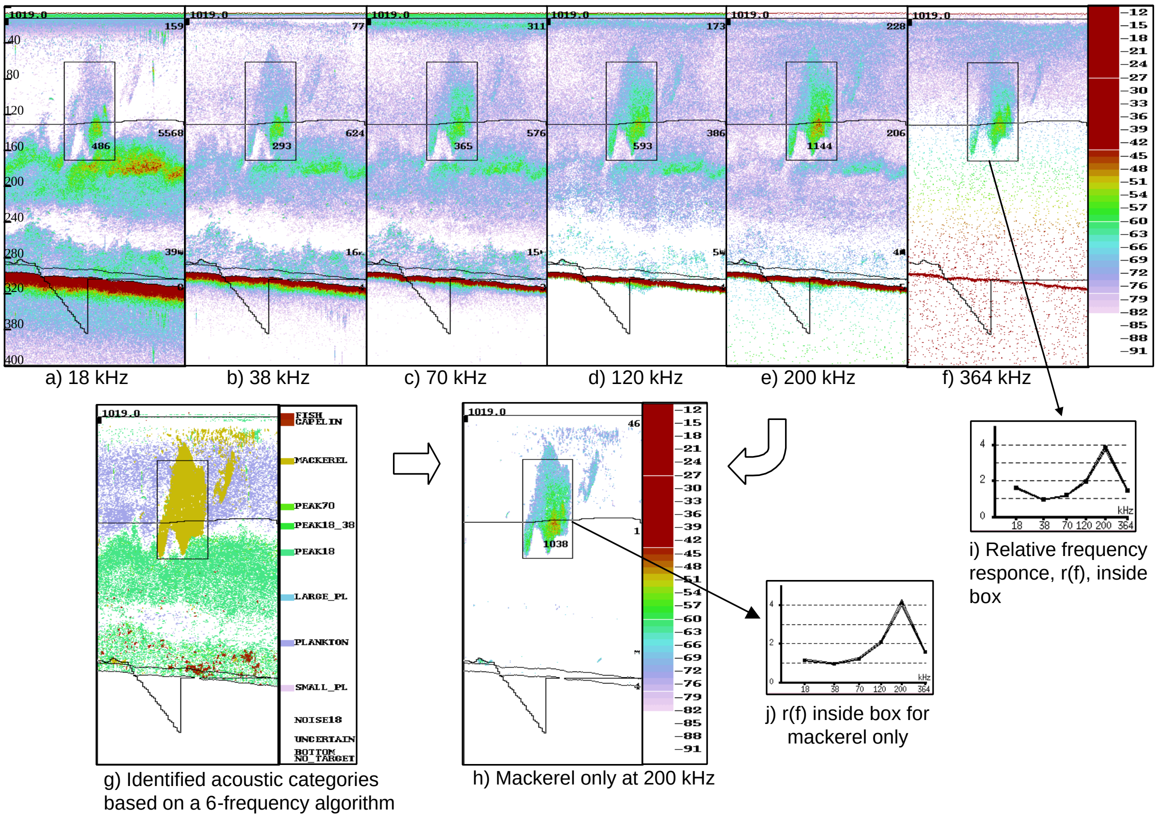

Figure 6. One nautical mile of 6-frequency acoustic data collected from RV "G. O. Sars" (3) 26 October 2004.

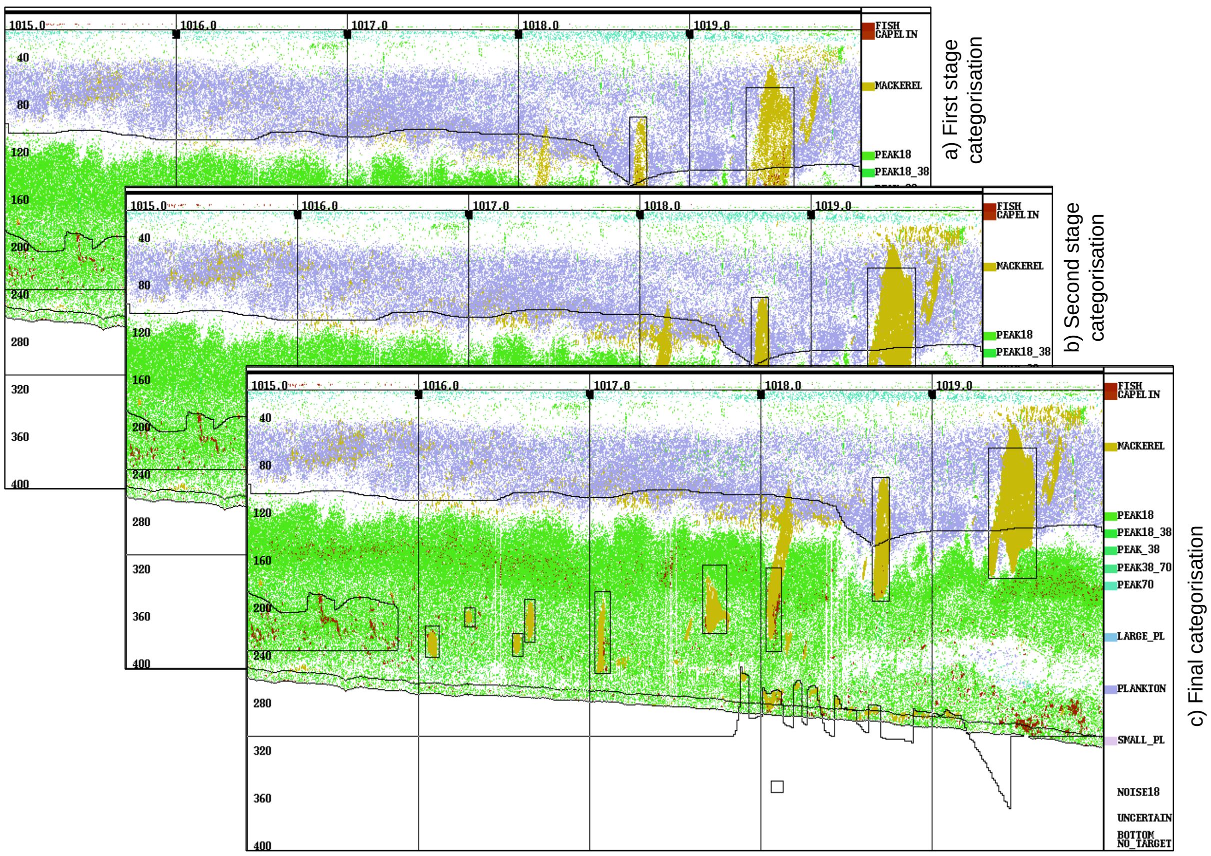

Figure 7. Progress of categorization in echograms of 5 nautical miles

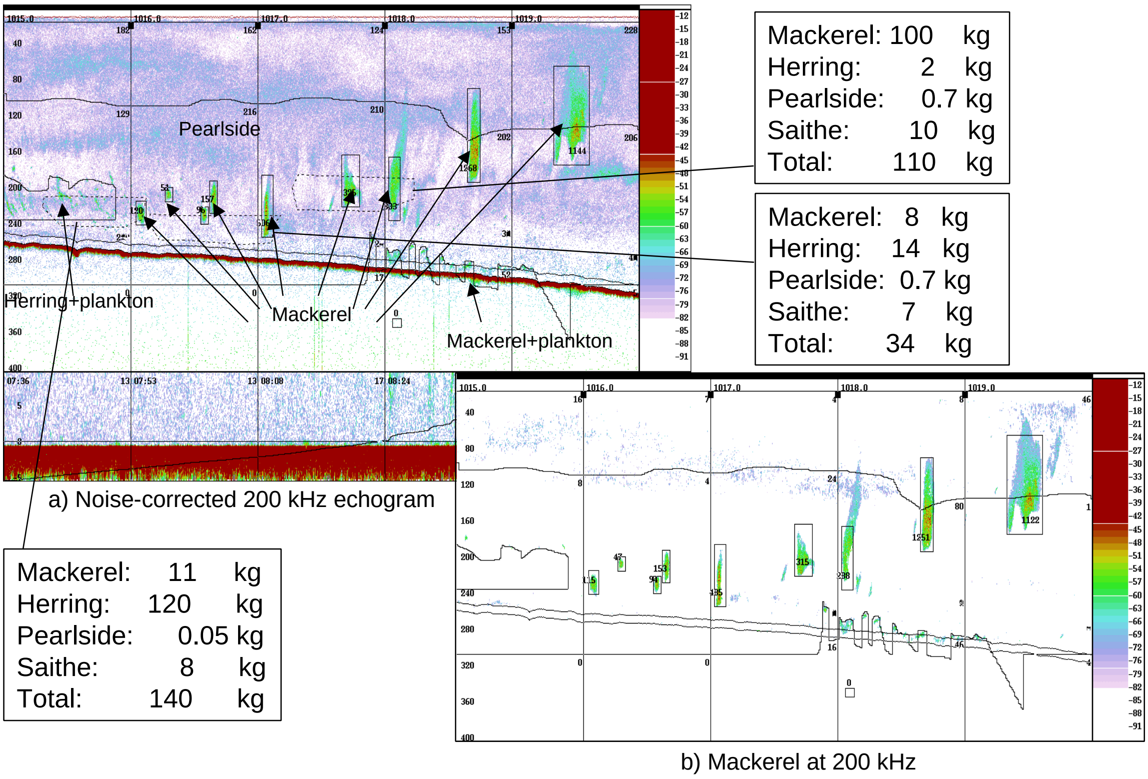

Figure 8. Trawl catches and echograms of the same 5 nautical miles as in Figure 7. The three stippled polygons in the 200-kHz echogram show acoustic registrations assumed caught by each bag of the opening-and-close trawl system. The three boxes connected to the trawl-polygons show the catches of each bag the trawl.

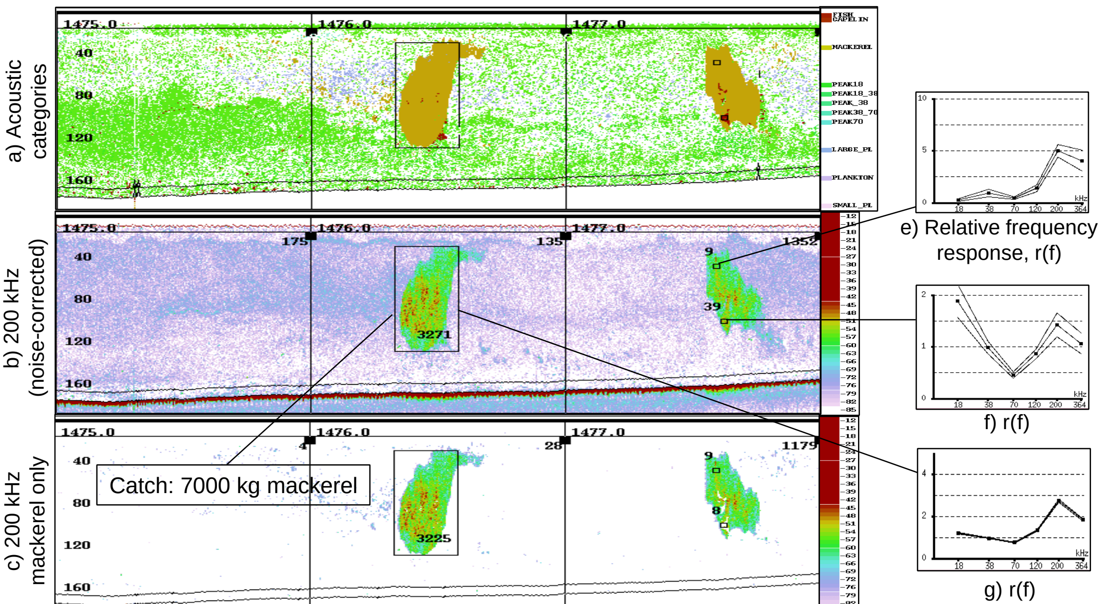

Figure 9. Trawl catch and 3 n.mi. 200kHz echograms from RV "G.O. Sars" (3) in North Sea 28 October 2003

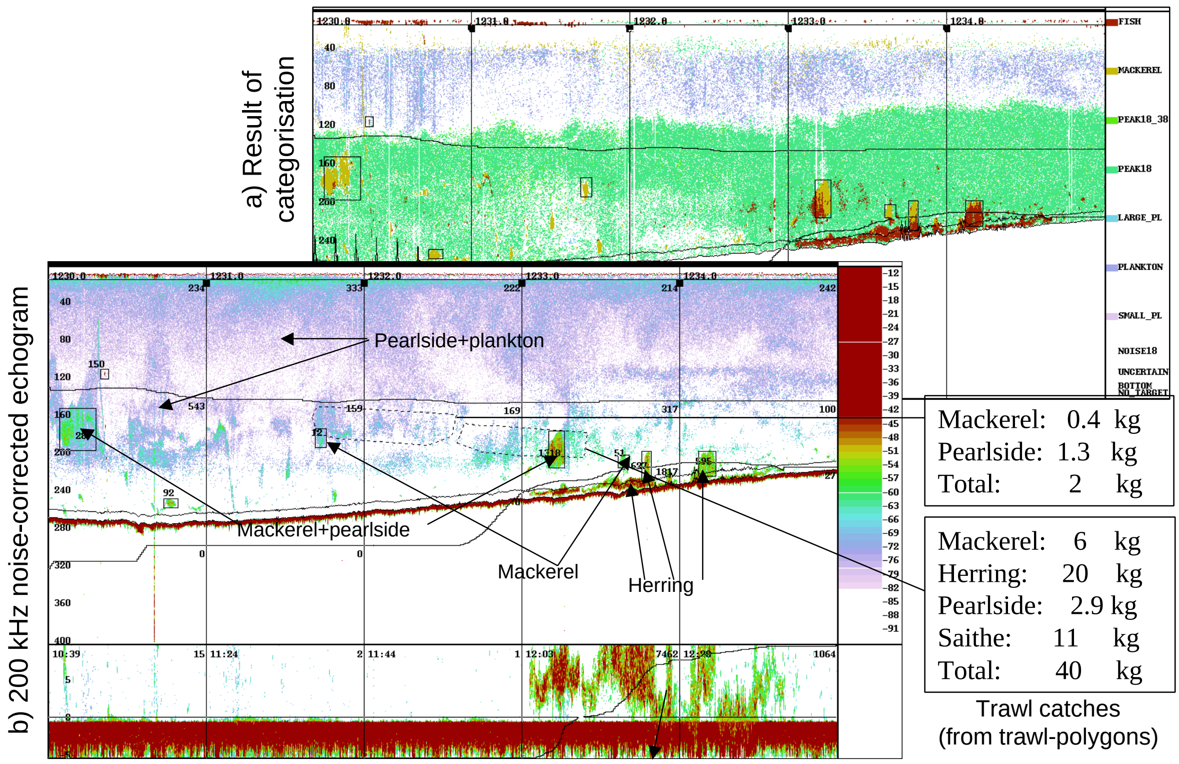

Figure 10. Trawl catches and echograms of 5 nautical miles, containing both mackerel and another schooling fish, collected from RV "G. O. Sars" (3) 27 October 2004. The two stippled polygons in the 200-kHz echogram show which acoustic registrations assumed caught by the trawl.

Discussion

The relative frequency response, r(f), has been used to identify mackerel during many years, and the result of the identification seems to be reliable. The r(f) has been investigated through many years, and it seems to be most stable at 38, 70 and 200 kHz. This is also confirmed by modelling (Gorska et al., 2004). The use of the additional frequencies 18 and 120 kHz is also valuable for the identification of mackerel, but may be even more valuable to identify what is definitely not mackerel.

To stabilise the inherent stochastic nature of the acoustic backscatter and make them more comparable between the frequencies, the measurements are slightly smoothed. The measurements are also shifted vertically and horizontally to account for the total echo-sounder system delay and the transducer positioning by using non-symmetric weights in the smoothing-matrix.

There may be several species in a volume segment, but the categorization system will assign maximum one acoustic category to a single volume segment, or to a pixel as it appears on the screen. Some acoustic categories are defined to allow for several species, i.e. "fluid-like-plankton" that may or may not be splitted into "small"- and "large-fluid-like-plankton". It is obvious that pixels that contain several species may be wrongly categorized. Korneliussen and Ona (2002, 2003) conclude that the categorization system works best for aggregations of the same species.

The Figures 6 – 10, and numerous examples not shown here, seem to confirm that the mackerel identification algorithm is really able to identify mackerel, at least in a broad sense. The trawl samples confirms largely the acoustic data, but due to the slow trawling speed of RV "G.O. Sars" (2) and (3), the fast swimming mackerel has a greater ability to avoid the trawl than most other fish. The common strategy of trawling is first to pass the acoustic registrations to assure that the collected acoustic data are largely undisturbed from avoidance reactions, and then to turn the ship for trawling. Mackerel, as other fish, may then be at another location than originally, so that the trawls hit different schools than expected. Even if the trawl hits the mackerel school as desired, mackerel is found from video-recordings to sometimes swim faster than the trawl, and may therefore also avoid it easily. The trawl speed of 4 knots is known to be too slow for efficient trawling of mackerel.

At some occasions, mackerel-schools seem to grow out of nowhere. Mackerel either being to close to the surface to be observed may explain this, or by mackerel forming loose layers mixing with other organisms. Within the upper layer identified as zooplankton in Figure 8b and 9b, there is also scattered some small regions identified as mackerel. It is not easy to verify such a mixture of species by biological samples. However, personal communication with biologists (Svein Iversen, IMR, and Johannes Hamre, IMR) confirms that it is possible that mackerel is distributed in that way.

In some echograms, e.g. Figure 10b, there are schools that contain scatterers partly identified as mackerel, and partly as another species of fish. Such mixtures of species are often verified by trawl catches, which is also the case for Figure 10b.

Sometimes, the identification process gives results, that although they may be correct; they are hard to believe in, e.g. minor portions in the centre of the second school of Figure 9. The r(f) of the lower part of the second school (Figure 9g) show that there may be large portions of something resonant at 18 kHz, or there may really be some swim bladder fish inside the school.

The main reason for using an acoustic frequency above 200 kHz was to verify that 200 kHz is on the stable, flat region illustrated in Figure 4. If the 200 kHz data are in this flat region, it is expected to follow a similar TS-size relationship as at 38 kHz, i.e. something close to $20\log_{10}L$-B. Since the backscatter of mackerel at 200 kHz is verified to be 4 times stronger than at 38 kHz, and since also many swim bladder fish has weaker average backscatter at 200 kHz than at 38 kHz (Foote et al., 1993), the TS of mackerel could increase as much as 8 dB compared to swim bladder fish. The consequence of wrongly identifying e.g. herring as mackerel will then be reduced in an acoustic abundance estimate.

Due to the problems of the 364-kHz data, the stable region is still not satisfactory verified. The original frequency of 400 kHz could not be used to verify the stable region since the strength non-linearly generated 400-kHz 2. harmonic of 200 kHz was large enough to make the linear 400 kHz data unusable. The frequency of the of the electronic part of the echo sounder was therefore reduced to 363.6 kHz, but it turned out that the 400-kHz transducer was not operating optimally at that frequency, partly due to a deformed beam-shape, partly due to the short range, and partly due to the 3. harmonic generated sound from the 120 kHz echo sounder (really 121.2 kHz). The solution seem to be to reduce the frequency further, e.g. to 333 kHz, and to make a new acoustic transducer resonant at 333 kHz.

Automatic identification of any acoustic registration should never be trusted blindly. Therefore, the categorization system is implemented in at least one acoustic post-processing system (BEI: Korneliussen, 2004) where the identified acoustic categories of each pixel (volume segment) may be turned on or off at will at the acoustic frequencies. However, the backscatter is sometimes so complex that such automatic categorization systems will be a good help.

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References

Anon., 1968. Smaller mesozooplankton. Report of Working Party No. 2. pp. 153-159 in: Tranter, D.J. (ed.) Zooplankton Sampling. (Monographs on oceanographic zooplankton methodology 2.). UNESCO, Paris. 174 pp.

Engås, A., Skeide, R. and West, C.W, 1997. The “Multisampler”: a system for remotely opening and closing multiple cod ends on a sampling trawl. Fish. Res.., 29: 295-298.

Foote, K. G., 1982. Optimizing copper spheres for precision calibration of hydroacoustic equipment. Journal of the Acoustical Society of America, 71: 742-747.

Foote, K. G., Knudsen, H. P., Vestnes, G., MacLennan, D. N., and Simmonds, E. J., 1987. Calibration of acoustic instruments for fish density estimation: a practical guide. ICES cooperative research report, 144, 69 pp.

Foote, K G., Hansen, K. A., and Ona, E., 1993. More on the frequency dependence of target strength of mature herring. ICES, C.M. 1993/B:30, Fish Capture Committee, Ref. H – Pelagic Fish Committee. 8 pp.

Gorska, N., Ona, E., and Korneliussen, R. J., 2004. ”On acoustic multi-frequency species identification and separation of Atlantic mackerel, Norwegian spring spawn herring and Norway pout”. ICES Annual Science Conference, Vigo, Spain, 22 – 23 September 2004, CM2004/R:18.

Korneliussen, R. J., 2000. Measurement and Removal of Echo Integration Noise. ICES Journal of Marine Science, 57: 1204-1217.

Korneliusen, R. J., 2004. The Bergen Echo Integrator post-processing system, with focus on recent improvements. Fisheries Research 68 (2004) 159-169.

Korneliussen, R. J., and Ona, E., 2002. An operational system for processing and visualising multi-frequency acoustic data. ICES Journal of Marine Science, 59: 293-313.

Korneliussen, R. J., and Ona, E., 2003. Synthetic echograms generated from the relative frequency response. ICES Journal of Marine Science, 60, 636 – 640.

Korneliussen, R. J., Diner, N., Ona, E. and Fernandes, P., 2004a. Recommendations for collection of acoustic multi-frequency data to be used for generation of combined-frequency data. ICES Annual Science Conference, Vigo, Spain, 22 – 23 September 2004, CM2004/R:16.

Korneliussen, R. J., Ona, E., and Gorska, N., 2004b. ”Verified acoustic identification of Atlantic mackerel”. Working paper presented on ICES Working Group Fisheries Acoustics Science and Technology, Gdynia, Poland, 20 –23 April 2004.

Ona, E., and Traynor, J., 1990. Hull mounted, protruding transducer for improving echo integration in bad weather. ICES C.M. 1990/B:31.

Wiebe, P.H., Burt, K.H., Boyd, S.H., and Morton, A.W., 1976. A multiple opening/closing net and environmental sensing system for sampling zooplankton. J. Mar. Res., 34, 313-326.

Wiebe, P.H., Morton, A.W., Bradley, A.M., Backus, R.H., Craddock J.E., Barber V., Cowles, T.J. and Flierl, G.R., 1985. New developments in the MOCNESS, an apparatus for sampling zooplankton and mikronekton. Marine Biology, 87, 313-323.