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Combined algorithms for detection of acoustic categories

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There is a current desire to harvest marine resources by managing total marine ecosystems rather than single species of the ecosystems. By means of algorithms applied on high-quality multi-frequency acoustic data, species, or rather acoustic categories, of the ecosystem can be identified. This information may significantly increase the accuracy of acoustic survey estimates of fish and to some extent also for zooplankton. Multi-frequency split beam echo sounders with nearly identical and overlapping acoustic beams have been regularly used in acoustic surveys for fish stock abundance estimation at Institute of Marine Research for the last five years. Calibrated raw data from up to six simultaneously working echo sounders at 18, 38, 70, 120, 200 and 364 kHz was used as input to a stepwise, modular sequence of analysis, like bottom detection, noise quantification and removal, target categorisation and school detection in near real-time. Direct generation of new, synthetic echograms, based upon the measured or modelled relative frequency response of the targets is one of the most useful features of the systems. The result of the categorisation process can be used to show the spatial distribution of different acoustic categories in a single synthetic echogram, or to keep some and remove other acoustic categories in echograms at a single frequency.

Key words: categorisation, species identification, synthetic echograms, relative frequency response

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Introduction

There are many species in any aquatic ecosystem, and these can be investigated by means of acoustic scattering. Multi-frequency data have been used since the late 1970's to identify and quantify the scattering from zooplankton (Greenlaw, 1977; Holliday 1977; Holliday and Pieper, 1980) and, more recently, fish (Kang *et al.* 2002). Martin (1996) used different models to classify zooplankton, and concluded that a simple feature-based model worked best. In 2002, Korneliussen and Ona drew the attention to the data collection process, as the acoustic data was not optimal for use in identification of acoustic categories at high resolution. They were able to split the acoustic categories into several classes. Like Martin et al. (1996), they also concluded that simple feature based models worked well. In 2003, Korneliussen and Ona simplified the data processing, and developed further the techniques to process the data prior to combination. The categorisation process was also simplified, and made the results more reliable and efficient than previously. Korneliussen et al. (2004a) documented in detail the identification of the acoustic category "mackerel", which in practise is Atlantic mackerel (*Scomber scombrus* L.) and the verification by trawl samples.

The techniques described here are based on the work of Korneliussen and Ona (2002, 2003). The principle in the categorisation process is as follows:

- Use good data as input to the categorisation system.

- Use simple scattering models to identify simple and broad acoustic categories.
- The broad acoustic categories may or may not be refined into finer categories at a later stage.
- Do not trust the automatic categorisation system blindly – the result may be wrong. (The scientist should take the final decision in the interpretation of the acoustic data.)

Material and methods

The principle of categorization

The acoustic data is collected according to the recommendations of Korneliussen et al. (2004b). Noise is corrected according to Korneliussen (2000, 2004). The acoustic data is smoothed and pre-processed according to Korneliussen and Ona (2002, 2003). The smoothed acoustic measurements are used as input to the categorization system, as initially described by Korneliussen and Ona in 2002, and later significantly improved by the use of better scattering models and by the use of smoothed and shifted data in 2003.

The general idea 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. The principle of the categorisation system is based on identification of three scattering classes as illustrated in Figure 1. The scattering classes are: (1) resonant, (2) fluid-like and (3) elastic-shelled. Since the frequencies are fixed, the size of the target decides where on the curve in Figure 1 a target is.

The resonant scattering is due to gas-inclusion, e.g. as found in siphonophores or as the swim-bladder of fish. For gas-inclusions of 1 – 2 mm diameter, resonant scattering is likely to happened between 18 – 38 kHz depending on depth below the surface, while resonant s scattering from swim-bladder will often be below 1 kHz, which is far below the frequencies used here.

The fluid-like targets are characterized by small difference between sound speed and density of the target and seawater as is the case for euphausiids, copepods and fish flesh. Common sizes of copepods will have backscatter that increase with frequencies in the frequency range used, while adult euphausiids will typically have maximum backscatter between 70 – 200 kHz.

Backscattering from hard targets like hard-shelled zooplankton and fish backbone are characterized by the increase of backscatter with frequency to a asymptotic level.

The details of the scattering models differs slightly from the illustrations of Figure 1, e.g. for the high frequency region which in practice is not frequency independent, but on averade often tend to decrease with increasing frequency.

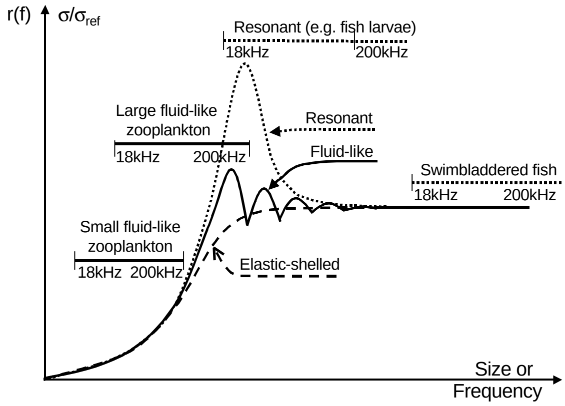

Figure 1. Three general scattering classes

Some targets is composed by components of several of these, e.g. fish where the swim bladder is resonant, the bones are elastic-shelled and the flesh is fluid-like. For swim bladder fish, the swim bladder dominates the backscatter at most frequencies, so that the other scattering mechanisms can be ignored. In Figure 2a-c, Atlantic mackerel is used as an example.

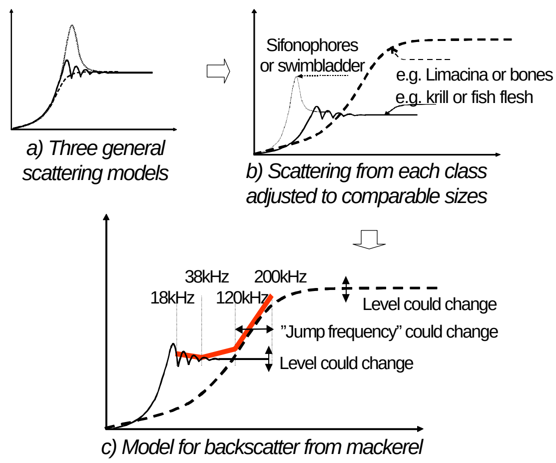

Figure 2. The three scattering classes used to describe backscatter from mackerel.

An acoustic category as used by the categorization system 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.

The categorisation system currently tests the following acoustic categories:

FISH (strong target – swimbladdered fish)
CAPELIN (sub-category of FISH)
MACKEREL (fish without swimbladder)
PEAK18 (resonant at 18 kHz)
PEAK18_38 (resonant between 18-38 kHz)
PEAK_38 (resonant at 18 kHz)
PEAK38_70 (resonant between 18-38 kHz)
PEAK70 (resonant at 18 kHz)
PLANKTON (fluid-like plankton)
LARGE_PLANKTON (e.g. krill – sub-category of PLANKTON)
SMALL_PLANKTON (e.g. copepods – sub-category of PLANKTON)

Behind each of these categories there is a simple acoustic model as described above, and a belonging error-band. The most important of the acoustic features used by the categorization system is the relative frequency response, r(f), which describes the frequency dependent backscatter, and of course its belonging uncertainty Δr(f). Figure 3 shows the error-bands of the "mackerel" category as used in each stage in the categorisation process. The upper grey region of Figure 4 shows the r(f) of some other acoustic categories.

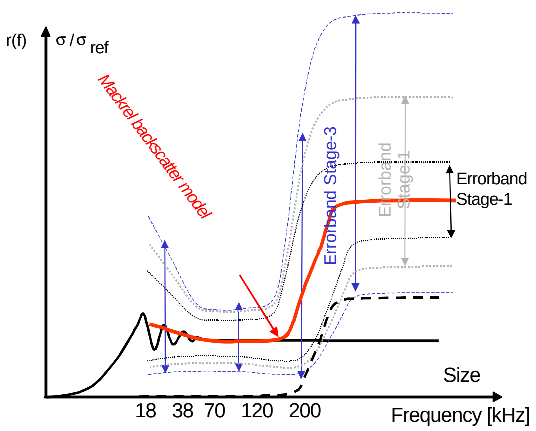

Figure 3. Backscatter of mackerel and error-band evolution in each categorisation stage.

In addition to the acoustic categories, there are some "help-categories". These are:

NOISE18 (acoustic noise at 18 kHz)
UNCERTAIN (uncertain – no category)
BOTTOM (bottom, or below bottom)
NO_TARGET (no measurement above noise)

Elements of categorization

Together with the major acoustic feature, r(f), some 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 all other categories is small, the more likely it is for correct identification.

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:

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

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

Depending on the value of S, the following flags, which are by default FALSE, are set to TRUE by the function categorizing the multi-frequency data-point to belong to a single acoustic category:

- If S>0.9: *"pixel-is-categoryX"*
- If 0.5<S<0.9: *"pixel-is-possibly-categoryX"*
- Pre-categorization test OK: *"cannot-exclude-pixel-to-be-categoryX"*

Pre-categorization

Each multi-frequency data-point is tested against all acoustic categories. The categorization process starts with the pre-categorization to speed up the total process. This is a set of simple tests that is considered the minimum requirements for a multi-frequency data-point to be considered as belonging to the tested category.

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 quantifiable information. One of the possible components of $S_{behavior}$ is $S_{position}$., which can be set as illustrated in Figure 4.

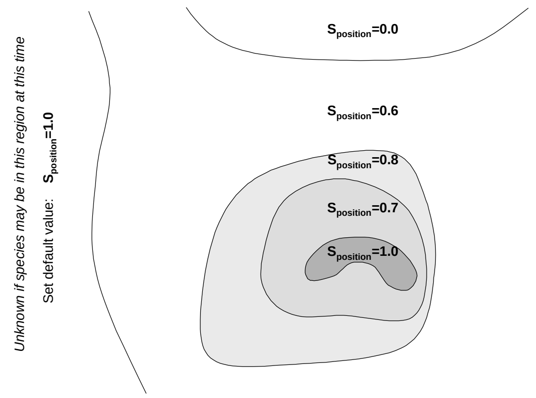

Figure 4. Setting the position component of the similarity $S_{behavior}$.

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: $S_{sv} \equiv S_{v,L} * S_{v,H}$.

$s_{v,L}$ is the mean backscatter at existing low frequencies that, and $s_{v,H}$ is the mean of the backscatter at the high frequencies that exist. Which frequency is considered to be high and low depends on the acoustic category. $S_{v,L}$ is the similarity result of testing the backscatter at the low frequencies, and $S_{v,H}$ is the similar for testing backscatter at high frequencies. $S_{v,L}$ and $S_{v,H}$ are set to the default value one, 1, if it is not possible to test the acoustic category for this acoustic feature. Note that there is set a range limitation for each frequency, which inherently means that the data are not tested beyond that range.

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

Figure 3 illustrate the frequency dependency of the backscatter of mackerel, and how the error-band evolves through different stages of the categorization process.

Implementation of the categorization system

Figure 5 gives an overview of how the categorization system works. The acoustic data at several frequencies are processed to be suitable for combination between the frequencies. The multi-frequency data is used

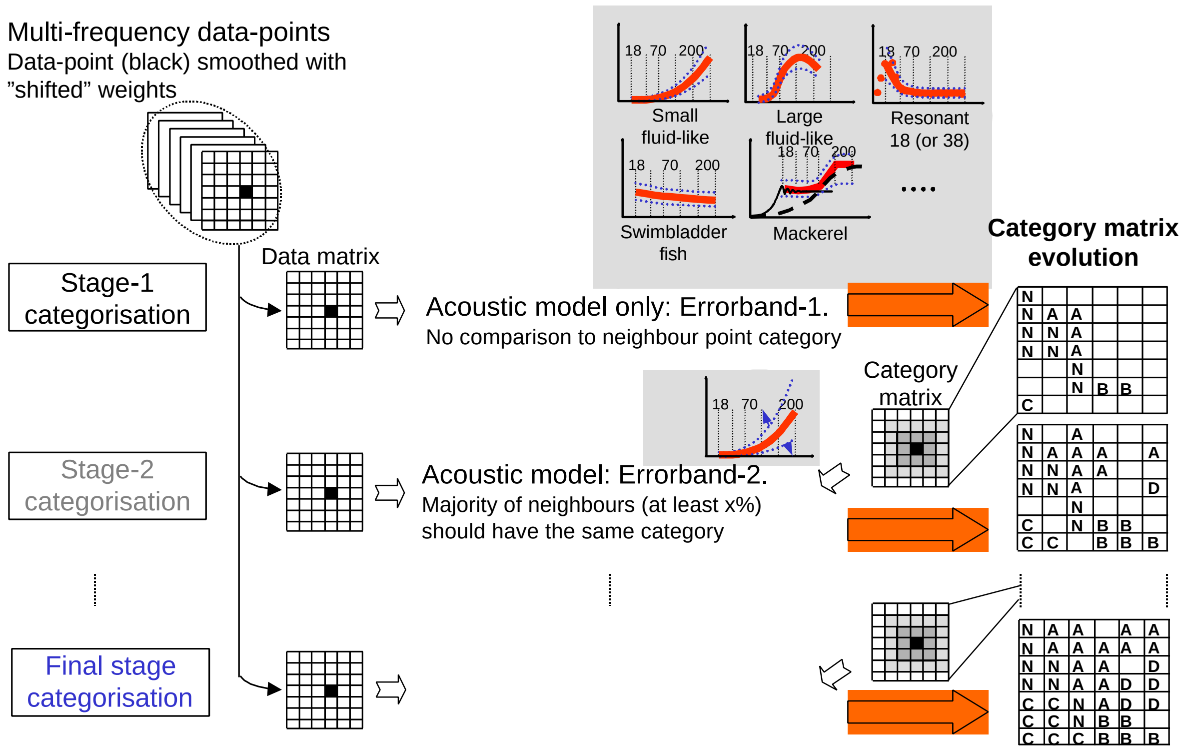

Figure 5. Categorisation of multi-frequency data

as input to the categorisation system. If this multi-frequency data is zero, the element of the categorisation matrix is marked NO_TARGET. Further, the multi-frequency data-point is tested against all available models, of which some are illustrated in the upper grey part of Figure 5.

The acoustic data are used as input to a function testing one category only. The function internally calculate a similarity number, S, as described in equation (1), and then returns a value telling if the data-point is "very-likely", "possibly", "not-likely" or "not-at-all" to belong to the tested category.

In the first stage of testing, all multi-frequency data-points in the echogram are tested to be "very-likely" to be long to each category. If the acoustic data is accepted within the specified error-band of one and only one model, the element of the categorisation-matrix is assigned to the belonging acoustic category. The measured relative frequency response, r(f), is tested aginst the idealized relative frequency response, $r_i(f)$ given by equation (2) for the acoustic category to be tested.

(2) $r_i(f_1) : \ldots : r_i(38\text{kHz}) : \ldots : r_i(f_n) \ldots = x_1 : \ldots : 1.0 : \ldots : x_n$

where $f_1 - f_n$ are acoustic frequencies.

The measurements r(f) are checked against the error-band of $r_i(f)$. The error-band is based on the measured or estimated uncertainty of $r_i(f)$, namely $\Delta r_i(f)$. These are used to define the error-band relation as given by equation (3):

(3) $e(f_1) : \ldots : e(38\text{kHz}) : \ldots : e(f_n) \ldots = y_1 : \ldots : 1.0 : \ldots : y_n$

$r(f_n)$ is tested, and the sub-similarity $S_{r(fn)}$=1 if

(4) $r_i(f_n)e(f_n) < r(f_n) < r_i(f_n)/e(f_n)$

If it is not accepted, the error-band $e(f_n)$ is increased for the frequency f_n by a pre-defined factor d, typically d=1.5, i.e. 50% increase. $r(f_n)$ is tested again as shown by equation (5).

(5) $r_i(f_n)\, d\, e(f_n) < r(f_n) < r_i(f_n)/(d\, e(f_n))$

The sub-similarity $S_{r(fn)}$=0.9 if accepted in second pass. Similar development for third pass.

The available acoustic frequencies are given different weights w(f) for their ability to identify a defined acoustic category. The final r(f)-similarity, $S_{r(f)}$, then becomes:

(6) $S_{rf} = (S_{r(f1)}w(f_1)+\ldots+S_{r(fn)}w(f_n))/(w(f_1)+\ldots+w(f_n))$

The r(f)-similarity, $S_{r(f)}$, is one of the components in the total similarity, S, as given by equation (1). S is used as described to set several flags for how likely a multi-frequency data-point is to belong to a category. These flags are then used in the first stage of categorization. In the first stage, the categories are tested against the value of the flag *"very-likely"* to belong to a category. Note that an identification of a multi-frequency data-point as "belong to category_X" is inherently also interpreted as "does not belong to category_Y".

In the second stage of categorisation, the measured multi-frequency data-points are tested against the values of the flag "possibly" to belong to each acoustic category. This is similar to increase the error-band of the tested category. In this pass the results of the previous categorisation are also used as input. If the acoustic multi-frequency measurement is only accepted by one acoustic model with the increased error-band used in Stage-2 testing, the pixel is assigned to the belonging category. If the acoustic multi-frequency measurement is accepted by more than one acoustic model, the categories of the nearest neighbours in space are checked. The pixel is then assigned to the most common neighbour provided that at least 15% of the neighbours have that category, and those 15% are at least 25% of the categorised pixels.

In the third and last stage of categorisation, the multi-frequency data of the remaining uncategorized pixels are tested against a few acoustic models (FISH, PEAK18, PEAK_38, PEAK70). The pixel is assigned a category if the multi-frequency data fit one and only one of the belonging models. The still uncategorized pixels remain uncategorized.

Figure 6 shows the principle for testing the acoustic categories in each stage.

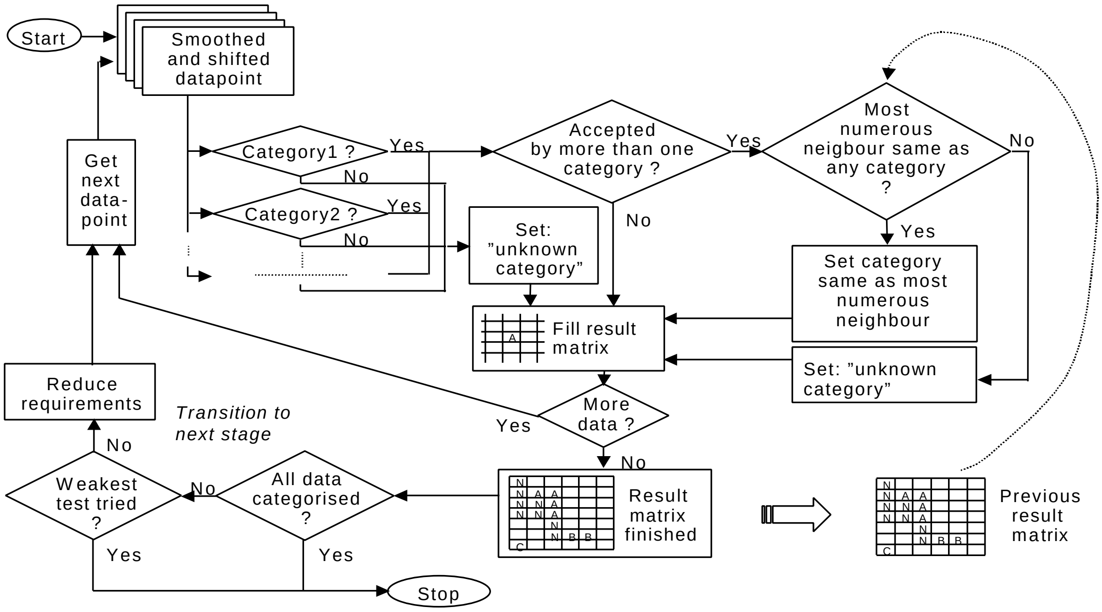

Figure 6. Testing of data against models in each stage of categorisation

Results and discussion

The results of the categorization process is visualised in Figure 7. A detailed description of the algorithm for identification of one acoustic category, mackerel, and verification of the identification of Atlantic mackerel is found in e.g. Korneliussen and Ona 2004. One weakness of the categorization principle is that the multi-frequency measurements of a small volume-segment can be assigned to only one acoustic category. Thus, dominant scatterers are likely to be over represented if weak and strong scatterers are mixed in a volume. To reduce the possible domination of scattering from a few scatterers, the acoustic measurements should represent as small volume-segments as possible. This puts high requirements on the acoustic data (Korneliussen et al., 2004b). On the other hand, the acoustic measurements are in nature stochastic, and should therefore be smoothed to reduce the inherent fluctuations in the measurements. In the case of many scatterers in the observation volume, this smoothing is done naturally. As a compromise between high spatial resolution in the data and stable measurements, the categorization system smooth the measured data slightly. This is done also with the data in Figure 6b), and with the data used to generate Figure 6d) and e). Another possibility is to use broad categories, and to split these by other means than high spatial resolution.

During many years the results of the categorisation system has been verified against biological samples. Although verification often is qualitative rather than quantitative, the performance of the categorisation system of the Bergen Echo Integrator, BEI, seems reasonable.

One of the obvious applications of the result of the categorization is to keep wanted categories and to remove unwanted categories. This is illustrated in the 5five sections of Figure 6c, but can also be seen in Korneliussen and Ona (2002, 2003) and in Korneliussen et al. (2004a). The final decision during the scrutinizing process should not be left to an automatic system, but is an useful aid. To quantify mackerel backscatter, it is possible to keep mackerel and trust the automatic identification, or to keep both the acoustic category MACKEREL, FISH and UNCERTAIN and scrutinize the data the traditional way as e.g. described by Korneliussen (2004).

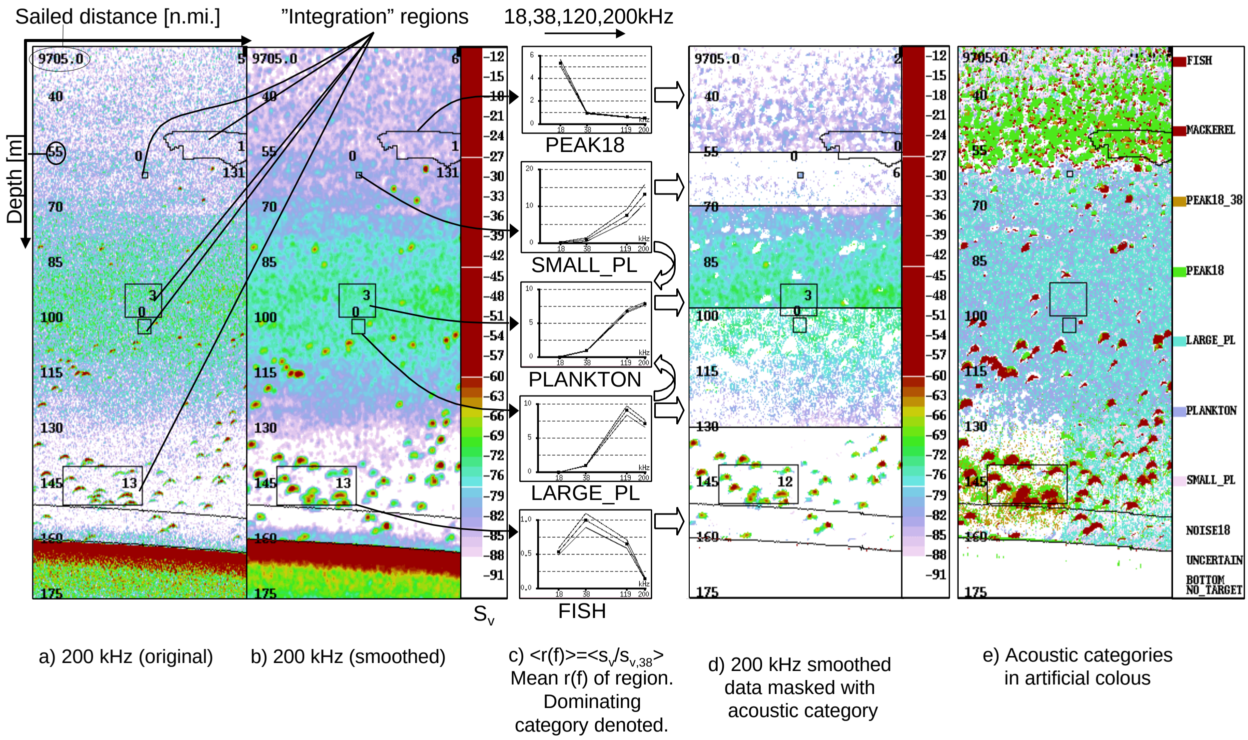

Figure 7. Results of categorisation

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