From two dimensions to three: the use of multibeam sonar for a new approach in fisheries acoustics

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Abstract: We present a methodology applying multibeam sonar for three-dimensional (3D) observation of fish schools that enhances the conventional use of vertical scientific echo sounders. The sonar we employ has 60 beams of 1.5° each. Its working frequency is 455 kHz. It is applied on a vertical plan normal to the vessel route, observing from the surface line to the bottom with a range set to 100 m. The sampled volume is 14 times larger than the volume observed with vertical echo sounding. The contribution of this new methodology to fisheries acoustics is detailed for school classification, internal school structure, spatial distribution of schools, fish behaviour, and biomass estimates. For each of these points, we present some preliminary results with the aim of defining the real progress in fisheries acoustics research as a result of 3D acoustics. Finally, we present a list of technical and methodological improvements that we are developing in order to make multibeam sonar fully adapted to fisheries acoustics.

Résumé : Nous présentons une méthodologie faisant appel au sonar multifaisceaux pour l'observation tridimensionnelle (3D) des bancs de poissons, ce qui améliore l'utilisation classique des échosondeurs verticaux scientifiques. Nous avons utilisé un sonar à 60 faisceaux de 1,5 degré chacun, émettant à 455 kHz. Il est appliqué dans un plan vertical, normal à la route du navire, ce qui permet d'effectuer des observations de la ligne de surface jusqu'au fond avec une portée fixée à 100 m. Le volume échantillonné est 14 fois plus important que le volume observé avec les appareils d'échosondage vertical. L'apport de cette nouvelle méthode à l'acoustique sous-marine appliquée à la pêche est décrit en détail pour les principaux points suivants : classification des bancs de poissons, structure interne des bancs, distribution spatiale des bancs, comportement du poisson, estimations de la biomasse. Pour chacun de ces points, nous présentons quelques résultats préliminaires dans le but d'établir le progrès réel que constitue l'acoustique 3D pour la recherche dans le domaine de l'acoustique appliquée à la pêche. Finalement, nous énumérons les perfectionnements techniques et méthodologiques que nous apportons au sonar multifaisceaux pour bien l'adapter au domaine de la pêche.

[Traduit par la Rédaction]

Introduction

Fisheries acoustics is one of the few direct methods of observation adapted to the study of coastal pelagic fish stocks such as clupeids, carangids, or engraulids. Echo sounding tools (MacLennan and Simmonds 1992) increase significantly both the sampled volume and the sampling resolution compared with conventional sampling (trawling, eggs and larvae).

Despite its capabilities, vertical acoustic methodology has limitations. The sample is two dimensional (2D) (one horizontal, one vertical), and the extrapolation of the results on a surface requires some assumptions on isotropy and stationarity of the fish spatial distribution (Petitgas 1993). The soundings provide information on the fish targets beneath the vessel inside the volume most disturbed by noise and visual disturbances. This implies that the fish reaction to the boat be measured (Diner and Massé 1987; Soria et al. 1996). Echo sounders present a continuous sampling in the vertical dimension, but a discontinuous one in the horizontal dimension, due to the ping rate (distance in space and in time between two pings). The horizontal dimension is actually spatial and temporal. Some drift or variability with time may interfere with the spatial structure (Fréon et al. 1993; Misund 1997).

The echo sounder beam angle is usually between 5 and 10°, which implies that the sampling volume becomes quite wide even at a rather short distance from the transducer. Therefore, the spatial resolution decreases dramatically with distance.

These limitations become more critical when there is a need for an understanding of the spatial behaviour of fish aggregation. The three-dimensional (3D) structures are affected by the influence of environmental and biological conditions and avoidance reactions to research and fishing vessels. Moreover, it is now known that the way in which fish aggregate has a strong influence on the catch and the fisher's strategy. A correct understanding of the fishery and of derived indices of abundance requires a good knowledge of aggregation patterns at different spatial scales (Fréon and Misund 1998).

The only way to overcome these limitations is to apply a methodology that incorporates the third dimension (i.e., not

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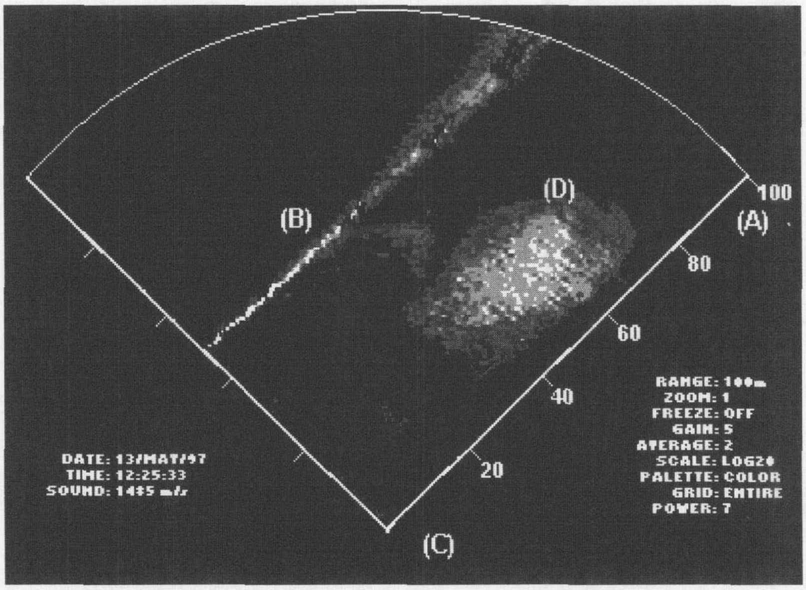

Fig. 1. Example of image acquired from the conventional video output of the sonar Reson Seabat 6012 (the sonar head is oriented 45° downward). A, sea surface; B, sea bottom; C, position of the vessel; D, fish school detection.

only vertically below the vessel, but also horizontally). This looks to the use of multibeam (or omnidirectionnal) sonars with very narrow individual beams. Two main approaches using multibeam sonars have been described in the literature. The first is the use of a sonar in a complementary way to the vertical echo sounder, as developed mainly by Misund and Aglen (1992). The multibeam sonar scanning plan is set horizontally and the observer may obtain a wide view of the horizontal distribution of the fish around the vessel for a given depth interval (increasing with the distance). This method gives detailed data on the horizontal school shape, behaviour, and distribution. Its primary limitation is the difficulty in relating the horizontal observation to the vertical data (Misund 1997). The second, first explored by Rusby et al. (1973), Gunderson et al. (1982), and Ona and Toresen (1988), consists of applying a scanning sonar on a vertical plan, perpendicular to the route of the boat. Although the system presents some limitations (mainly due to the single-beam scanning sonar operated by some of these authors and to the limited computation capabilities available at this time), the methodology appeared to be able to overcome the 2D problems.

This paper describes how the use of this multibeam side-scan sonar can resolve most of the problems identified above. Examples of the type of information that 3D acoustics are able to provide to scientists are detailed throughout the paper.

Materials and methods

The ideal sonar to be employed in order to fulfil 3D acoustic requirements should have some particular characteristics, such as a large set of very narrow beams (less than 2°), covering ideally 180° and at least 90°, a very short pulse length, and a high ping rate. This leads to the use of high frequency (>200 kHz), which in turn limits the maximum range to a few hundred metres. In the examples we give in this paper, the sonar is a Danish Reson Seabat 6012, covering a total receiving beam angle of 90° with 60 beams of 1.5° each and 15° in the perpendicular direction (at the –3 dB point). The sonar operating frequency is 455 kHz (bandwidth 20 kHz) with a pulse length of 0.06 ms. The 60 beams are updated simultaneously seven times per second when using the most appropriate range of 100 m. The time-varied gain (TVG) function is set to 40 log *R* (firmware). There are two sonar outputs: conventional and digital. The conventional output consists of video images reconstructed from the 60 beams to produce a real-time observation (Fig. 1). These are recorded on videotapes during the survey and postprocessed in the laboratory. The postprocessing is done either by eye, to produce a database containing the main geometric data, or after digitization in a matrix of 240 × 320 pixels using image analysis software developed by ORSTOM. The second output is the digital data provided by the sonar. For each ping, a matrix of 60 columns (representing the 60 beams) and 2040 lines is generated. At the moment, this kind of information is not easy to collect, due to the enormous amount of data (aboug 50 megabytes/min). Once these raw digital data are extracted, it becomes possible to reconstruct the 2D and 3D images with a much better definition than when using the video image. Processing beyond this point is similar for both the digital and digitized data sets. The usual survey parameters (i.e., the vessel speed, pitch and roll, latitude, longitude, sonar settings, etc.) are recorded in the database.

The sonar scans the side of the vessel route and exhaustively explores the water volume (Fig. 2). During the surveys, the sonar head is directed at 45° downside, which allows scanning from the vertical (underneath the boat) to the horizontal (parallel to the sea surface) on one side of the vessel. The range is fixed at 100 m, and the image is a smoothing of two or four successive pings (Soria et al. 1996). The third dimension is obtained through the succession of pings along a transect, as in conventional vertical echo sounding (Gerlotto et al. 1994). Five surveys were performed in the Mediterranean Sea during the European AIR program "TECHO".[2] The dominant pelagic species observed were sardine (*Sardina pilchardus*) and anchovy (*Engraulis encrasicholus*).

Several geometrical and statistical characteristics are extracted from each image of schools (Fig. 3): position of the school in the

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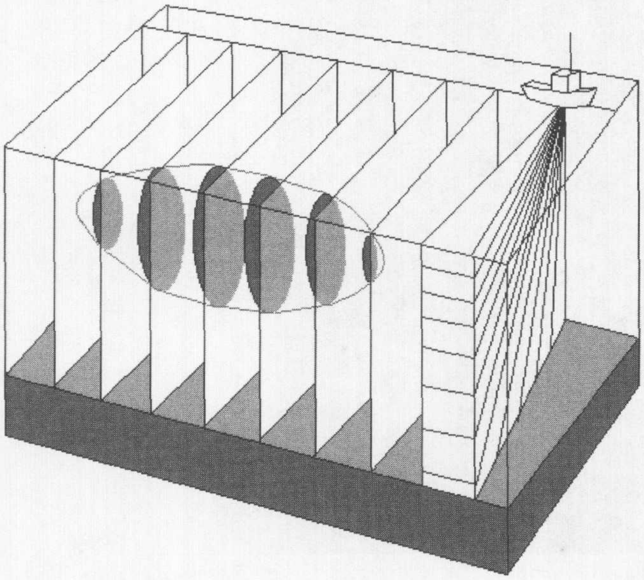
[2] Surveys performed aboard the Spanish R/V *Garcia del Cid* in the Catalan and Adriatic seas from May 1993 to September 1995. These surveys are part of TECHO, Project AIR1 CT92 0314.

Fig. 2. Diagram of the sonar sampling methodology. The image of the school is built up by plotting each successive beam detection.



water volume (depth, altitude, "lateral distance," i.e., distance to the vertical line underneath the vessel); geometrical dimensions of the school (length, height, width, surface, perimeter, circularity); coordinates of the rectangle including a school of fish; index of mean density (grey levels), which is assimilated to the mean density in fish in a vertical profile; standard error $\sigma = (1/n[\Sigma I(i)^2 - (\Sigma I(i))^2/n])^{0.5}$, where n is the number of pixels in the school and $I(i)$ is the brightness of a pixel inside the school; and index of density heterogeneity (variograms, which are calculated inside each single cross section using the conventional geostatistical formula) (Matheron 1970).

Characteristics extracted from the complete set of cross section images include, for instance, the school length (metres), calculated from the number of cross sections per second and the vessel speed and corrected by a beam-width correction factor (Johannesson and Losse 1977), and the indices of asymmetry. In order to estimate the disymmetry of the school (random or due to time or vessel influence), we compute the ratio of the mean of the first half image series to the second half image series for most of the above variables (surface, perimeter, circularity, mean density, standard error).

These data sets were used to calculate volume and 3D surface, total density, and a roughness index for each school. This allows extraction of a new set of data on school shape and typology, which is then used for school characterization, classification, behaviour, and clustering studies.

Results

We will list and review the fields where multibeam sonar can bring valuable pieces of information to fisheries acoustics through the presentation of some results obtained during TECHO surveys. They concern mainly school classification, internal school structure, spatial distribution of schools, fish behaviour, and biomass estimates.

Fig. 3. Diagram of the three successive images of a school detected by the sonar Reson Seabat 6012 showing the main morphological and bathymetric descriptors one is able to extract: *Z*, bottom depth; *D*surf, school depth; *D*vert, distance from the vertical line below the vessel; *H*, height; *W*, width; *L*, length.

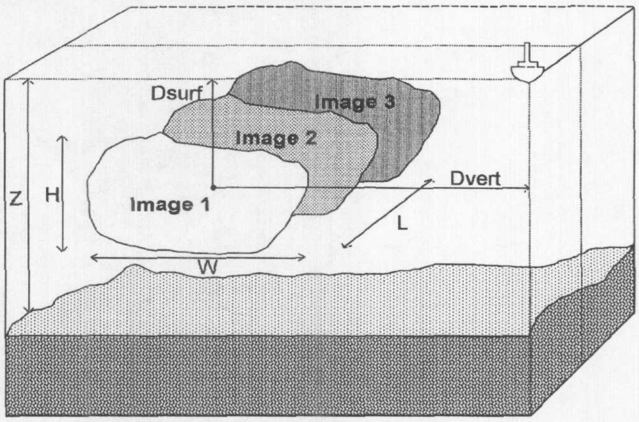


Table 1. Variation of three geometrical values of some schools (daytime, volume >4.5 m^3) observed during TECHO surveys in the Mediterranean Sea.

Survey	Mean length/width	Mean length/height	Mean volume (m^3)
GICS1 coverage 1	1.3	2.86	638.9
GICS1 coverage 2	0.45	0.88	418.8
GICS2 coverage 1	0.88	1.12	357.2
GICS2 coverage 2	0.9	1.17	409.6
GICS3 coverage 1	1.26	1.84	275.9
GICS3 coverage 2	0.79	1.31	629.2
GIAS2	1.9	3.26	870.7
GIAS3	1.71	3.93	991.5

Note: The GICS1, GICS2, and GICS3 surveys were performed in the Catalan Sea in 1993, 1994, and 1995, respectively, and the GIAS2 and GIAS3 surveys were performed in the Adriatic Sea in 1994 and 1995, respectively, using the same vessel (R/V *Garcia del Cid*).

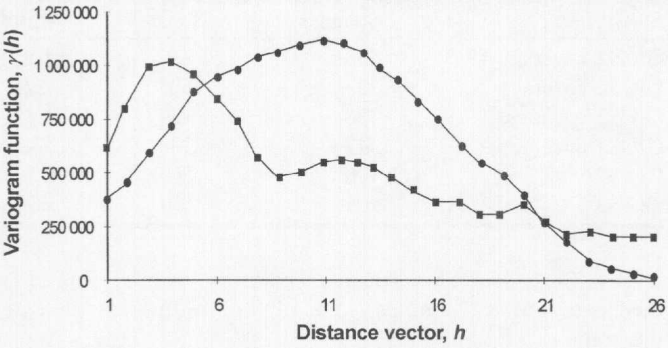
Multibeam sonar and school classification

School classification is a new and important goal in fisheries acoustics, as it is one of the ways to identify the species. There are usually two sets of parameters to be considered. The first concerns the geometrical characteristics of the school and the second its packing density distribution. In the first case, geometrical parameters extracted from the echogram are processed using different techniques (Souid 1988; Scalabrin and Massé 1993; Haralabous and Georgakarakos 1996; Scalabrin et al. 1996; Scalabrin 1997). All of them can benefit from 3D acoustics, which overcome the limitations of a random 2D cross section of the school provided by conventional sounders. The following example demonstrates the types of information that can be studied. The results obtained during the five TECHO surveys are presented in Table 1.

Table 1 shows that schools appear to be significantly flatter (ANOVA, $p < 0.001$) and longer (ANOVA, $p < 0.001$) in the Adriatic Sea than in the Catalan Sea. Their mean volume is also greater (ANOVA, $p < 0.001$). By using the new set of 3D data, the schools may be more easily classified through their own characteristics than when using 2D data.

As far as packing density is concerned, some previous work was done directly on the echo sounder signal analysis

Fig. 4. Variograms of the internal density (pixel brightness) in the horizontal direction of two schools detected during TECHO surveys.



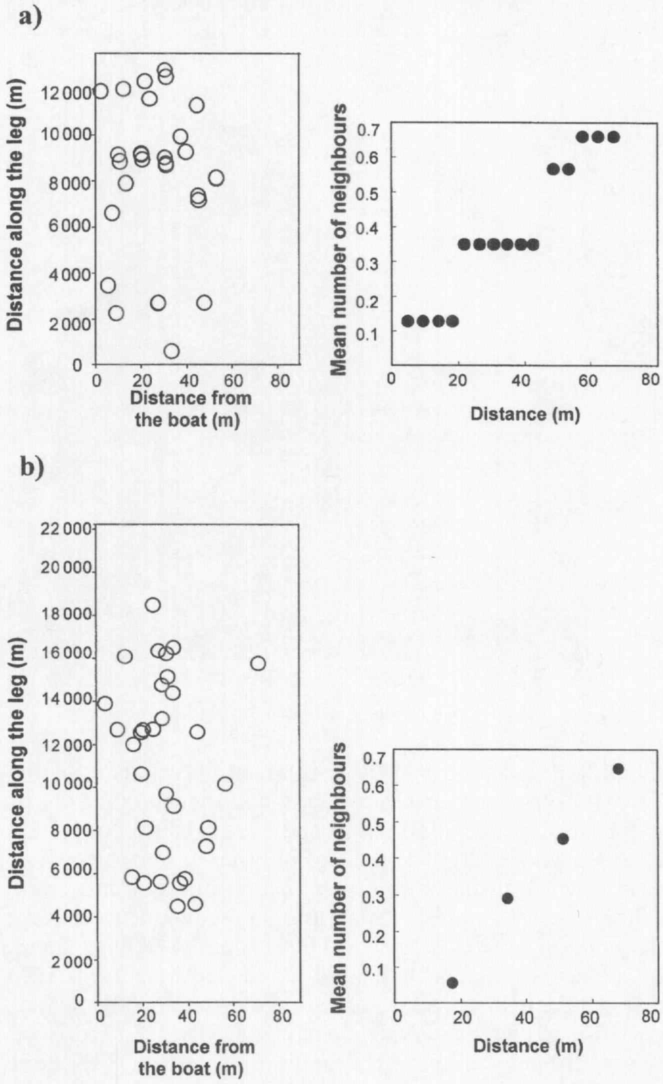
(Rose and Leggett 1988), and other work refers to geostatistical studies. Regarding this type of information, multibeam sonar is not yet completely efficient for some of the reasons presented above (background noise, calibration, etc.). Nevertheless, we obtained some results on the variograms calculated inside the schools. Figure 4 shows two typical variograms calculated on the central cross section of two different schools. Although it is probably too soon to routinely use these instruments, this example demonstrates that 3D distribution of echo energy inside a school could be a promising way to classify echo traces.

Description of spatial distribution of schools

Schools are distributed in clusters, whose characteristics may depend on several factors: overall biomass and mean density of the fish stock, species, and environment or fishing activities. The use of 2D data presents two limitations: one is the representativity of what is observed below the vessel (avoidance and limited sampling capabilities for the surface layers), and another is the fact that the school echogram represents only a given cross section of the school (e.g., an irregularly shaped school section may misleadingly show several schools). These problems do not exist with 3D acoustics, which makes it easy to draw an exhaustive horizontal 2D spatial distribution of the schools along the vessel path and allows definition of the “aggregative law” that the stock is obeying. An example is taken from M. Soria and P. Petitgas (unpublished data). They used a point process approach for structural analysis (Diggle 1983). The minimum of the nearest neighbour distances (NND) was computed and used as the distance lag, after taking into account the edge effect (Ripley 1981).

In the first plot provided in Fig. 5*a*, the distribution is characterized by steps and means that schools are distributed in patches surrounded by large empty areas. The second plot shows a linear pattern (Fig. 5*b*): around an arbitrary school, there is on average fewer schools than what a pure random process would generate. This suggests coalescence and (or) repulsion between schools. Therefore, we assume that the exhaustive horizontal 2D spatial distribution of schools obtained by multibeam sonar should be helpful in characterizing and classifying the different patterns of aggregation observed in relation to environmental and biological factors.

Fig. 5. Examples of spatial distribution of fish schools along the starboard side of the vessel during TECHO surveys and the corresponding *I* function plot. (*a*) $N = 32$; (*b*) $N = 30$.



Fish behaviour as observed by 3D acoustics

Fish behaviour may be considered from two points of view in fisheries acoustics: as general information on the status of a stock and as a source of bias. We already described how 3D could help to classify schools, and thus to relate their spatial behaviour to different parameters, such as species, and reaction to environmental characteristics. Avoidance is certainly one of the most important sources of bias in fisheries acoustics, as underlined by earlier workers using either sounder (Olsen 1971) or single-beam sonar (Lamboeuf et al. 1983). Avoidance can be vertical (Olsen et al. 1983; Gerlotto and Fréon 1992) as well as horizontal (Diner and Massé 1987; Fréon et al. 1992; Soria 1994). Side-scanning using a multibeam sonar allows for the calculation of a correction factor for vertical echo sounding. Soria et al. (1996) showed that the effect of the vessel on school distribution can be demonstrated and evaluated.

Figure 6 shows the daytime frequency of the horizontal projection of the distance between the geometrical centre of

Fig. 6. Daytime frequency histogram of the horizontal projection of the distance between the geometrical centre of the school and the sonar head during TECHO surveys. The broken line is the expected average frequency under H_0 (no avoidance).

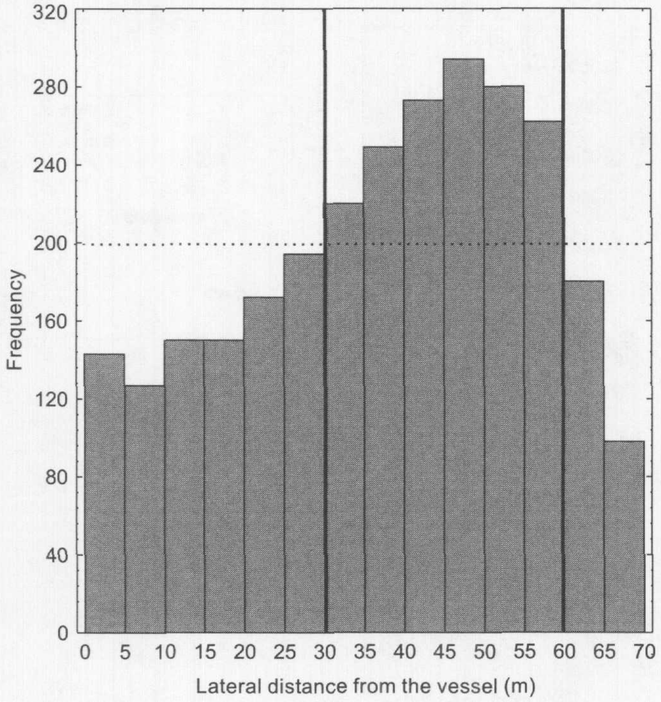


Table 2. Results of school counting (daytime, volume >4.5 m^3) from echo sounder and sonar in TECHO surveys and corresponding ratio (sonar/sounder).

Survey	Sounder	Sonar	Ratio
GICS2 coverage 1	233	452	1.9
GICS2 coverage 2	223	603	2.7
GICS3 coverage 1	128	139	1.1
GICS3 coverage 2	247	344	1.4
GIAS2	120	563	4.7
GIAS3	208	1081	5.2

the school and the sonar head obtained during three of five TECHO surveys. Because of the radial orientation of the sonar beams, we set horizontal and vertical limits (at 70 m from the boat and at 55 m deep) in order to obtain equal areas in each distance interval. Within these limits, 4201 schools were counted. The histogram shows a nonuniform distribution ($\chi^2 = 262.78$, $p < 0.001$) contrary to what should be expected under a nonlateral avoidance hypothesis (H_0). Comparing with the expected average under H_0 (199 schools per 10-m distance interval), there is a gap of 258 schools between distances 0 and 30 m and an excess of 384 schools between 30 and 60 m.

Biomass estimates

The evaluation of fish abundance is one of the first and most important results that acoustics are supposed to produce. Simmonds et al. (1992) showed that the accuracy of the results depended on methodological and sampling errors and on a series of biases. The 3D sonar method seems to be able to decrease both the errors and the biases: it increases the sampled volume, which could improve the precision of the estimate, and allows counting of the schools far from the boat, which limits the bias due to lateral avoidance.

The increase in sampling volume is one of the main interests of 3D acoustics. For simple and approximate calculation, let us admit that all the transmissions are partly overlapping (which is effective at a distance of 4 m from the transducer, with the speed ping rate and average used in the surveys). For a flat bottom at a depth of 55 m along 1 nautical mile, the sampling volume of a vertical echo sounder with the usual 10° beam is 0.49×10^6 m^3. The volume sampled by the sonar in the same bathymetric conditions at a 70-m range is 7.13×10^6 m^3. Therefore, in this usual case the echo sounder samples 6.9% of the volume sampled by the sonar.

The results of school counting by sonar and echo sounder for several surveys are presented in Table 2. The schools were counted on the sounder data using MOVIES-B, a school identification software (Weill et al. 1993). Only data collected during the day are taken into consideration. Some thresholds (namely minimum values for dimensions, surface, and energy) have been set for defining what is a school in the databases.

In this data series, the ratio between the number of schools counted by the echo sounder and the sonar varies from 19.2 to 92.1%. This is very different from the theoretical expected result of 6.9% if fish schools are randomly distributed and not reacting to the survey vessel.

Concerning density estimates, it is theoretically possible to evaluate fish density inside a given area using the sonar. At present, such a result is still out of reach due to the lack of a proper calibration procedure, significant background noise, and the meaning of target strength data at several angles. Until such time as sonars can be properly calibrated, direct estimates of densities are meaningless. Another point that will need particular attention is the likely difference in terms of packing density between disturbed schools observed close to the vessel and undisturbed schools observed at a greater horizontal distance.

Discussion

The advantages of a 3D survey are obvious when compared with 2D echo soundings. A simple example is the impact of depth on the significance of echo soundings on schools. We saw that using echo sounders, the sampling volume becomes wide at a rather short distance from the transducer. The echo sounding methodology makes it impossible to reduce very much the beam angle for both sample efficiency and acoustical reasons. The implication for school structure studies is obvious: all the descriptive tools suffer the fact that the pixels on the echogram (Reid and Simmonds 1993) or the digital samples of the acoustic signal (Weill et al. 1993; Scalabrin 1997) do not have the same spatial meaning according to the depth. The only way to decrease the beam angle and at the same time keep an efficient sampling volume is through multibeam techniques. This possibility was explored by Diner and Marchand (1995), who conceived a vertical multibeam echo sounder, which theoretically overcomes part of this drawback. Nevertheless, at the moment, many questions have yet to be addressed before the methodology can be considered operational. For instance, the optimal beam angle should be defined. In our examples, the beam angle is 1.5 × 15°; having a 1.5 × 1.5° beam angle would likely allow a more accurate description in the three dimensions, but would affect the representativity of a single ping image.

Fish avoidance is critical for fisheries acoustics, and from our results, it is necessary to give details on this point. In the examples presented above, the sonar underestimated the number of echoes because of the 40 log R TVG setting. This setting implies that the sonar overcorrects the echo energy according to the distance, which makes it difficult to count small schools close to the transducer and affects the signal to noise ratio at longer distances. Therefore, it is likely that a bias is present at the shortest and longest distances, mainly from 0 to 5 m and above 60 m. The first class and the last class of the histogram on Fig. 6 should be considered with caution. In the future, the sonar firmware will allow operation with a 20 log R TVG function.

On the other hand, the criteria used for school identification using 2D data, such as an echo sounder and the MOVIES-B algorithm, cannot compare with the visual criteria used in the counting method from sonar images: any patch of echoes above the defined thresholds is considered as a school by MOVIES-B, while the sonar requires in addition a succession of images (i.e., a volume). As the elementary sample of the echo sounder is much bigger than the elementary sample of the sonar (10 × 10° instead of 1.5 × 15°), a small school will appear much larger on the echogram than on the sonar images. It will be considered a school by MOVIES-B and discarded by the sonar. Another point that induces an overestimation of the number of schools in the echo sounder data is that a school often presents very irregular borders and could be seen as several schools if the vertical profile cuts several "pseudopods." This bias does not exist in the sonar data, as the complete 3D structure of each school is identified. This series of undocumented points and these differences in the school definition limit the conclusions we can draw from our first results. The main interest is to suggest that the definition and counting of the schools will be greatly improved once the sonar is adapted to fisheries acoustics: the method is the very first one that is able to provide information on the magnitude of school avoidance at any place and at any time.

Another serious problem related to the use of multibeam sonars in a vertical plan is the impact of side lobes on the images: the bottom echo received through the side lobes is often equal to or higher than the fish echoes. Depending on the settings and the hardness of the bottom, a "ghost" echo will appear on every beam at the depth distance, and the part of the image concerning distances higher than the depth will be affected by these ghost echoes. At present, we can overcome this problem in two ways: first, by considering only the data recorded at shorter distances than the vertical depth, but this dramatically decreases the sampled volume in shallow waters, and second, by considering only the school geometrical structure, which is less affected by the noise than energy-related data. But in order to apply correctly 3D acoustics to biomass estimates (echo integration), this technical problem must be taken into account and specific sonars with low side lobe effects have to be designed for fisheries research.

The technical adaptation of existing multibeam sonar systems to biological research is a complex process, but must bring the advantages described above. ORSTOM, in collaboration with other institutes,[3] submitted a project to the European Commission, which was approved in December 1996, with three main objectives: technical, methodological, and biological.

Technical research will enhance the use of multibeam sonar systems for biological purposes, particularly adaptation for recording data at rate orders of magnitude higher than conventional survey systems. Development of visualization and data analysis software for extracting the main characteristics of the spatial structures is also undertaken. The software should permit a complete 3D reconstruction of observed schools. Methodological research will investigate procedures on the validation of the data collected through an appropriate calibration. Such a procedure requires an on-axis calibration and thorough scan sensitivity, including sensitivity mapping of all parts of the main lobes of all the beams. Biological initiatives include the application to different 3D structures, the selection of the main relevant parameters extracted from the images, and the design of school characterization and classification statistical methods.

At the moment, very little appropriate fishery multibeam equipment is available on the market (G.D. Melvin, Department of Fisheries and Oceans, Pelagic Fisheries Section, Marine Fish Division, Biological Station, St. Andrews, NB EOG 2XO, Canada, personal communication), although numerous multibeam sonars have already been designed for bathymetry imaging. Two additional outputs are expected. The first will be to define the optimal system configuration (frequency, power, total angle, number and angle of beams, etc.), and the second will be to define a list of research for the application of sonar in stock assessment. For instance, the meaning of fish echoes in very narrow beams and at several tilt angles will have to be investigated.

Fisheries research is moving toward new approaches in most of its fields. The principal change in this discipline is that the spatial approach is becoming of major interest (Petitgas and Lévénez 1996; Fréon and Misund 1998). Information on the way a stock is occupying a given space, depending on its dimensions, behaviour, and the impact of environment and human pressure, is nowadays considered essential. Furthermore, spatial data can be analysed in a much better way than a few years ago, thanks to several tools and methods, such as GIS or geostatistics. Fisheries acoustics using 2D methods is one of the few methods able to provide spatial information on a stock, but is unable to provide precise data on the actual school structure and behaviour. Other spatial data are biased by the methodology itself (impact of a survey vessel). Therefore, and considering that the schooling behaviour is a fundamental characteristic

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[3] Project AVITIS, FAIR PL96 1717. The partners are ORSTOM, the Scottish Office of Agriculture and Fisheries Department (Marine Laboratory, Aberdeen, Scotland), RESON A/S (Slangerup, Denmark), the École Nationale Supérieure de Télécommunications de Bretagne (Brest, France), and the Institute of Marine Biology of Crete (Heraklion, Greece).

of the pelagic species as far as fishery research is concerned (ecology, capture processes, and stock assessment), it was necessary to conceive new methods to provide unbiased 3D data. Although there are still many conceptual, material, and methodological limitations, we may conclude that the 3D approach presented in this paper will address many of these aspects.

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