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Omnidirectional multibeam sonar monitoring: applications in fisheries science

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Abstract

Data exploitation, acquired by medium-frequency omnidirectional multibeam sonar, enables original studies in fisheries research but is seldom used despite the fact that such equipment is found on most fishing vessels and a number of research vessels. This is the only system for real-time monitoring of fish schools within a horizontal omnidirectional plane about a vessel or a buoy. Between 1996 and 2001, we used two standard omnidirectional sonars and developed new methodologies for exploiting their specific acoustic data according to two main sampling schemes: 'prospecting', including fishing and searching operations, and 'drifting', as with an instrumental buoy system or aboard a stationary vessel. We present a complete method for continuous data acquisition from aboard a research vessel or commercial boat, with automated data extraction by picture analysis and a data processing method. Two cases of data analysis are considered: the first on a school-by-school basis, the 'single school' mode; the second taking into account all fish schools detected within the sonar sampling volume, the 'cluster' mode. Elementary sonar information is divided into five categories that comprise 24 survey and sonar parameters and 55 school, cluster and fisher behaviour descriptors. We review the applications of these categories and discuss perspectives for their use in fisheries science. If the sonar system enables the evaluation of the effects of vessel avoidance on fish school biomass assessment, no accurate abundance estimate can be provided by a simple sonar echo-integration process. Omnidirectional sonar data can be used to analyse collectively the fish schools' swimming speed, kinematics in terms of diffusion and migration, aggregative dynamics as school splitting and merging indexes, spatial characteristics of clusters such as school density, 2D structure and fisher behaviour. The prospect of integrating such data into a fish school database, including multifrequency echo-sounder and lateral multibeam (3D) sonar data combined with a species recognition method, will enable a complete view of fish school behaviour and consequently the adoption of accurate fisheries management methods.

Keywords direct approach, fish behaviour, fish school, fish school cluster, fisher behaviour, multibeam omnidirectional sonar

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Introduction

Fisheries biology requires the use of new monitoring tools to overcome limitations in the management of stocks, where the limited use of fishing data makes it difficult to understand the complex mechanisms of stock evolution and its interaction with fishing and the environment. Efficient and sustainable fish population management is the challenge of fisheries scientists. However, this task has its limits (Christensen 1996; Bertrand *et al.* 2004; Cotter *et al.* 2004) and a new approach, i.e. ecosystem-based management (EBM), is now being considered (Pauly *et al.* 2002). Recently, original fisheries biology hypotheses have been integrated, where fish behaviour is taken into consideration, such as 'school trap' (Bakun and Cury 1999), 'meeting point' (Fréon and Dagorn 2000) and 'biological trap' (Marsac *et al.* 2000). The importance of fish behaviour in fisheries research has been reviewed by Fernö and Olsen (1994), Pitcher (1995) and Fréon and Misund (1999). In addition, special attention has also been paid to the tactics and strategy of fishermen (Hilborn and Walters 1987; Salas and Gaertner 2004).

Such developments, which mostly relate to fish and fishermen's behaviour, require the recording and evaluation of their dynamics by direct observations. Some heavily exploited fish populations (mainly *Clupeidae*, *Engraulidae* and *Scombridae*) commonly occur as fish shoals and schools, but few devices have been adapted for observing such shoals and schools *in situ* (Brehmer and Gerlotto 2002).

Medium-frequency multibeam omnidirectional sonar enables the observation of fish schools at reasonable spatial resolution, even when not captured by fishing nor detected by echo-sounder, as the latter instrument is limited to observations in the vertical plane. Omnidirectional sonar allows the observation of fish schools, in a horizontal plane at a long distance from the vessel, simultaneously with fishermen's behaviours (tactics and strategy). Unfortunately, such direct observations are rare (Goncharov *et al.* 1989; Misund and Aglen 1992) because of the difficulty in extracting useful information from omnidirectional sonar data. Data acquisition and processing using omnidirectional sonar is unusual for several reasons:

1. the acoustic signal is not directly available, as the common output that such a device provides is a VGA image (i.e. 2D omnidirectional view) of school distribution around the vessel;
2. the huge amount of data collected from this set of images requires special processing;
3. configuring the omnidirectional sonars requires an experienced operator (Diner and Marchand 1995); and
4. the propagation paths of sound in the sea with depth are seldom linear due to stratified water masses (temperature and salinity variations).

Historical reviews of data acquisition and processing in fisheries acoustics are provided by Misund (1997); Fréon and Misund (1999); Simmonds and MacLennan (2005), and Reid (2000). From these reviews and our own sea-based observations, we have determined the main advantages and limitations of two different omnidirectional fisheries sonar systems. The literature on sonar data analysis is mainly directed towards scientific scanning sonar (Misund 1990; Misund *et al.* 1994; Godø 1998; Farmer *et al.* 1999; Gerlotto *et al.* 1999; Pedersen and Trevorrow 1999; Simmonds *et al.* 1999; Dalen *et al.* 2000; Axelsen *et al.* 2001; Hamano *et al.* 2002; Mayer *et al.* 2002; Melvin *et al.* 2002). This paper presents the methodologies for continuous data acquisition, extraction and analysis from standard omnidirectional sonar systems, a review of their use and a proposal for new sampling schemes and applications in fisheries sciences.

Experimental surveys

We conducted a total of 11 surveys (Table 1), in five regions, targeting aggregative small pelagic fish (*Clupeids* and *Engraulids*). The bulk of the data came from a joint research project in the tropical Atlantic Ocean between 1996 and 1999, aboard the Research Vessel 'Antéa', carried out by IRD (France), ISRA (Senegal) and FLASA (Venezuela). The project surveyed three populations of the clupeid *Sardinella aurita* in continental shelf waters of Senegal, Venezuela and the Ivory Coast. Additional surveys, performed in cooperation with Ifremer (France) and IFOP (Chile), completed the study. Our approach is driven by observations that are dominated by tropical or subtropical fisheries, and is only relevant where fish are present in pelagic schools.

Omnidirectional sonar characteristics and settings

We used two commercial omnidirectional sonars, a Simrad *SR240* and a Furuno *CSH-20* (Fig. 1; Table 2), which are available onboard many fisheries and research vessels. Such devices require a system extension and adaptation to store, extract and analyse the relevant information from the display, because no digital data output is provided.

Omnidirectional sonars are characterized by medium frequencies, commonly between 15 and 50 kHz, long pulse length, τ, from 1 to 64 ms and medium (horizontal and vertical) beam widths, θ (i.e. around $11 \times 11°$), covering 360° in total, with tilt angle, T, varying from $+5$ to $-90°$. A constant frequency pulse (continuous wave mode) emitted simultaneously in all beam sectors was used to study a number of schools within sonar range. The 'heading up' mode was selected for its data-processing capability and efficiency when used in behavioural studies. The automatic gain control filter was switched off to avoid uncontrolled modification of the gain from the sonar preamplifier. The filter that controls sound reverberation was used to remove small signal variations (to avoid non-biological detection), but can delete small and scattered fish schools (Anonymous 1992). Lastly, a compar-

Table 1 Details of the 11 surveys undertaken for the collection of sonar data, with their main characteristics (i.e. data acquisition or experimental studies) carried out between 1996 and 2001 by five institutes (IRD[1], ISRA[2], FLASA[3], Ifremer[4] and IFOP[5]) aboard four different vessels.

Survey	Date	Research vessel	Location	Characteristics
Varget 2/96	1996	Antéa	Venezuela	Black and white video analogical
Varget 1/96	1996	Antéa	Senegal	Drift operations
Varget 1/97	1997	Antéa	Senegal	Analogical/digital signal converter
Varget 3/97	1997	Antéa	Ivory Coast	Kinematics
Calib 98	1998	Antéa/Hermano Gines	Venezuela	Standardization procedure
Varget 2/98	1998	Antéa	Venezuela	Echo-sounder records
Varget 3/98	1998	Antéa	Ivory Coast	Spatial structure
Varget 2/99	1999	Antéa	Venezuela	Aggregative dynamics
Varget 1/99	1999	Antéa	Senegal	Avoidance reaction
Dicamuf 01	2001	L'Europe	France	Shallow water observations
Reclan 0111	2001	Abate Molina	Chile	Digital video data collection

Location denotes where the data has been collected.
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Table 2 Main characteristics of the two standard omnidirectional sonars: Simrad *SR240* and Furuno *CSH-20*.

Sonar parameters	Simrad *SR240*	Furuno *CSH-20*	Common values
Frequency (kHz)	24	32	20–45
Vertical beam width – 3 dB (degrees)	11.5	11.5	10–15
Horizontal beam width – 3 dB (degrees)	11.25	12	10–15
Time-varied gain function	30 log *R**	30 log *R**	15–40 log *R*
Pulse length (ms)	8*	10*	1–64
Range (m)	800*	800*	200–8000
Colours	32	16	16

For most other types of omnidirectional sonar, the common setting values present a similar configuration. (*) Current values used.

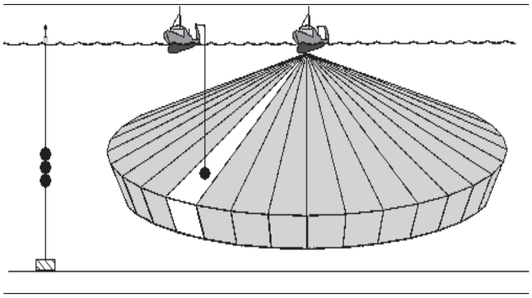


Figure 1 Representation of the omnidirectional multi-beam sonar sampling volume around the vessel. The white beam represents the vessel heading (forward-directed beam). An artificial pelagic target (black spheres) is used for validating the beam heading adjustment (submerged via a boat or a ground mooring, as shown in the figure).

Table 3 Summary of abbreviations and units of the survey data (eight parameters) and sonar settings (16 parameters) associated with sonar frame selection.

Parameter	Abbreviation	Unit
Survey parameters		
Sound velocity or 'Celerity'	C	m s^{-1}
Sea temperature	$T^{°C}$	°C
Sea salinity	$S_{‰}$	–
Observation time step	t_i	s
Total observation time	t_t	s
Bottom depth	D_b	m
Operation type	Op	alphanumeric
Calibration date	Cd	day/month/year
Sonar parameters		
Tilt	T	degrees
Sampling volume	V	m^3
Sampling surface	S_s	m^2
Sonar range	R	m
Display sonar range	R_d	pixel
Scale factors	s	m pixel^{-1}
Near field dimension	$R_{minimum}$	m
Source level (single beam)	SL_h	dB//1 μPa ref. 1 m
Source level (omnidirectional)	SL_o	dB//1 μPa ref. 1 m
Single beam width	θ	degrees
Pulse length	τ	ms
Frequency	F	Hz
Wave length	λ	m
Range resolution	R_r	m
Reference mark	RM_x	–
Greatest width of the transducer	d	m

All parameters are stored before analysis.

ison between the last eight pings was set (ping-to-ping filter) to reduce any unwanted noise or false echoes. The ping-to-ping filter alters the amplitudes/metrics of the fish schools by an unknown/uncontrolled magnitude and should not be used in quantitative studies of fish school.

Survey and sonar parameters are detailed in Table 3. Theoretical acoustic values can be calculated according to the instrument instruction manual (Anonymous 1992) and classical acoustic formulae (Diner and Marchand 1995; Lurton 2002). The results were stored, along with the sonar and survey parameters (Table 3), for later sonar data processing.

An important activity was the validation of the sonar heading adjustments. An underwater reference target (with diameter 'X' inferior to one beam width θ at observational distance R_n, as $X < R_n \times \tan\theta$) attached to a surface buoy detectable by the onboard radar was used to identify the target on the sonar screen. Once the sonar detected the target (Fig. 1), the target radar location was used as a reference to validate the sonar echo coordinates (Brehmer and Gerlotto 2001a).

The optimal sonar configuration needs knowledge on the ecosystem studied and must be adapted to the environment (fish size, behaviour, bottom relief, sound propagation, weather). The acoustic threshold could be adapted according to the study.

Sampling schemes: prospecting and drifting modes

The sonar data were recorded during normal acoustic surveys and fishing operations (Goncharov *et al.* 1989); this sampling scheme is referred to as 'prospecting mode'. In prospecting mode, fish schools are detected by following predefined transects (standard survey design) or by 'active tracking', where the vessel is free to adapt its route according to movement of the fish school (Misund 1991).

The main problem of the prospecting mode is perturbations of the behaviour of the fish school generated by the vessel (Mitson 1995; Mitson and Knudsen 2003). An important observation objective is to obtain data on fish school behaviour without these perturbations. Consequently, an alternative sampling mode was developed: the 'drifting mode'. During these experiments, the vessel was adrift with the engine clutch off (silent vessel) and lights switched off at night (Brehmer and Gerlotto 2000, 2001a).

Continuous monitoring

The data sets from our surveys were continuously recorded in a PAL professional video format (S-VHS), which has the advantage of no storage limitations and low cost, as data is stored onto videotapes. The sonar frames were then post-digitized at a minimum rate of one per second. In 2001 we used the alternative method of recording the sonar's RGB signal onto a digital videocassette recorder. This allowed professional digital video quality (DVcam format) and possible transfer onto all digital frame formats and/or digital movie formats without signal degradation. Fig. 2 shows the solutions for continuous sonar data storage and treatment, i.e. extraction and analysis that enables the collection of sonar information with any kind of sonar system.

Two geo-referenced marks, 'RM_x' (Table 3), must be set on the instrument display to establish a Euclidean reference mark (Brehmer *et al.* 1999) where the school and vessel position are to be projected. Sonar shadows and non-biological targets such as surface or bottom echoes, oceanographic discontinuities, vessel noise, wakes, buoys and seamounts were removed. Changes in sonar settings and navigation parameters were recorded automatically.

Data drawbacks

The use of built-in sonar signal algorithm analysis to avoid false echo (sea surface or sea bed reverberation) and interference (Anonymous 1992) is an efficient method; however, this algorithm has a drawback in that it can lead to an increase in the number of schools that are not displayed on the sonar screen, i.e. small schools with a dimension inferior to R_r and scattered fish schools. As in standard echo-sounder detection, the instrument

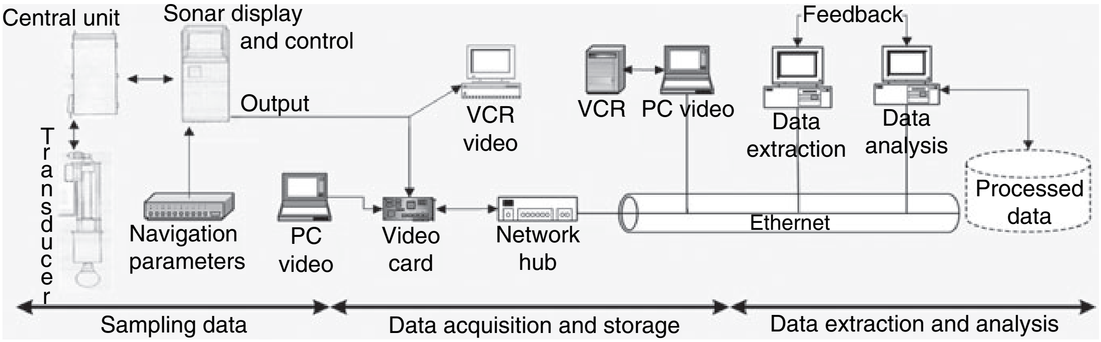


Figure 2 Methodological scheme of the complete process of video sonar data treatment: sampling, data acquisition and storage [using two modes: analog (S-VHS) or digital (DVcam)], and extraction and analysis.

cannot discriminate between two schools that are separated by a distance that is less than the range resolution, R_r, where $R_r = C\tau/2$ (m). It is important to distinguish the existence of two school categories, present in the beams field and not represented on the sonar detections. The 'cryptoschool' is a school detected by the sonar (with the current settings) but mixed up with another one if the minimal interdistance is $<R_r$ or if the schools are superposed vertically (inside the same beam). The second category, the 'deleted school' is a school not detected by the sonar, or which is not detected continuously on each sonar frame between each elementary time step, either because it is out of the sonar field or because of its too weak acoustic response [scattered school, small size ($<R_r$); out of beam on-axis].

Omnidirectional multibeam sonar has a conventional built-in self-test system that should be activated before a recording session (calibration date; Cd). The dimension, Lw and Cw (see Table 4) can be correlated to school descriptors by simultaneous recording (Brehmer *et al.* 2002) high-resolution sonar data (Gerlotto *et al.* 1999) and/or calibrated (Foote 1987) vertical echo-sounder data (Weill *et al.* 1993). Fortunately, a specific protocol for the calibration of multibeam sonar is now available (Brehmer and Gerlotto 2001b; Cochrane *et al.* 2003; Foote *et al.* 2005).

An amoeboid shape is a common fish school structure (Pitcher 1986; Misund *et al.* 1995; Coetzee 2000). Nevertheless, fish school properties can induce strong variability in Lw measurements because of their highly variable structure. The internal structure of a school is usually highly unstable (Misund *et al.* 1995; Couzin *et al.* 2002), as fish kinematics and aggregative behaviour are dynamic. In addition, there are uncertainties due to the position of the gravity centre of the school relative to the sonar beam axis. Lw values depend on the beam and school depth. As a consequence, during continuous recording Lw varies from a minimum value, usually the first and last detection, to a maximum value when the fish school is on a certain sonar beam axis where the depth D of the beam axis has the value $D = \tan(T)\times R_n$. According to initial results for Venezuelan tropical clupeids (Brehmer *et al.* 2002), the best estimator of the $\mathrm{Lw}_{\mathrm{corrected}}$ dimension is the average Lw value 'AvLw' in drift mode (for each school detection there are several values of Lw dimension) and the maximal Lw value 'MaLw' in prospecting mode. The Lw descriptors can be used to roughly classify the fish school in terms of size-classes. The school surface S is computed under the hypothesis of a spherical shape with the adapted Lw estimator as the school diameter.

In the presence of a high-gradient thermocline, a shift in the actual school position may appear (Smith 1977); this does not influence kinematic studies in drift mode, however, such a physical phenomenon can generate erroneous measurements of displacement relative to the vessel when conducting avoidance analysis at long range, for example, or produce blind areas on the sonar sampling volume in 2D school mapping studies. The direct observation can be corrected by an adapted sonar deviation model (Pedersen and Trevorrow 1999; Lurton 2002), which requires an efficient probe-sampling scheme (Urick 1983; Brekhovskikh and Lysanov 1991; Burdic 1992; Diner and Marchand 1995) (see Appendix).

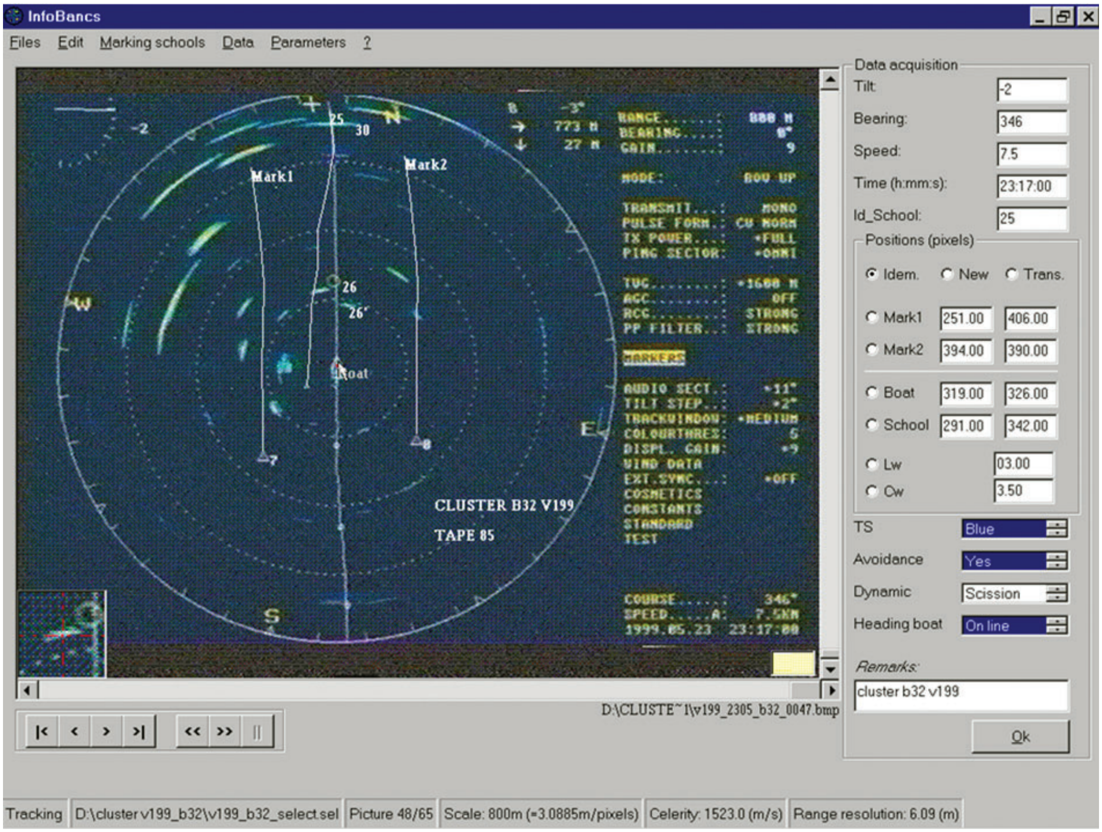
For accurate biomass estimation, there is a lack of knowledge concerning: (i) an adapted method for remote species identification (Haralabous and Georgakarakos 1996; Horne 2000); (ii) school acoustic intensity response at different tilt angles beyond what has been presented by Love (1981) and Hazen and Horne (2003) for individual fish; (iii) the presence of schools being deleted by a built-in signal processing algorithm; and (vi) the effects of acoustic extinction and shadowing when several fish schools are detected within the same sonar beam (Røttingen 1976; Zhao and Ona 2003).

Principles of data extraction and post-processing

The basic principle of data extraction is to calculate the observed target coordinates (sonar transducer, fish school) relative to an orthogonal reference mark, RM_x, created by two sonar reference tags positioned inside the sonar range, replaced regularly (according to the vessel speed) by a new reference mark where the previous data coordinate are converted. These both tags are calculated from vessel speed and heading (Fig. 3). For analysis, sonar video frame sequences are selected over a total time t_t, then divided into constant time periods t_i between successive sonar observations. Automatic data extraction for each sonar frame is then carried out, as for the sonar settings, navigation parameters, and boat and target Euclidian position, using optical character recognition (OCR) (Horst and Wang 1997) and image analysis (Ayat 2004)

Table 4 Summary of abbreviations and units of the descriptors delivered after omnidirectional sonar data analysis, as divided into three categories: school, cluster and navigation.

Descriptor	Abbreviation	Unit
Navigation descriptors		
Date, year	DY	day/month/year
Sonar frame name	Sf	alphanumeric
Vessel course	β	degrees
Course standard deviation	$\beta\sigma$	–
Vessel speed	V_{bi}	m s^{-1}
Euclidean boat position	$(x_{\mathrm{b}};\ y_{\mathrm{b}})$	m
Index of horizontal movement (boat)	IHM$_{\mathrm{b}}$	–
School descriptors		
School identifier	Si	alphanumeric
Time of the day	T_{d}	s
Latitude/Longitude	Lat./Long.	degrees
Number of observations	n	–
Along wise beam dimension	Lw	m
Along-beam dimension corrected	Lw$_{\mathrm{corrected}}$	m
Maximum along-beam dimension	MaLw	m
Average along-beam dimension	AvLw	m
Across beam wise dimension	Cw	m
Across-beam dimension corrected	Cw$_{\mathrm{corrected}}$	m
Maximum across-beam dimension	MaCw	m
Average across-beam dimension	AvCw	m
Fractal dimension	Fd	–
Surface	S	m^2
Number of echo pixels	n_p	–
Acoustic intensity	I_{cp}	dB//1 µPa ref. 1 m
Pixel echo colour code	Co(p)	–
Euclidean school position	$(x_{\mathrm{s}};\ y_{\mathrm{s}})$	m
Depth	D	m
Instantaneous speed	Vt_i	m s^{-1}
Exploration course	$\beta\tau\varsigma_{\tau}$	degrees
Exploration speed	Vt_{t}	m s^{-1}
Average instantaneous speed	AvVt_i	m s^{-1}
Minimum instantaneous speed	MiVt_i	m s^{-1}
Maximum instantaneous speed	MaVt_i	m s^{-1}
Standard deviation instantaneous speed	StVt_i	–
Distance to the transducer	R_n	m
Index of horizontal movement	IHM	–
Modality 1: splitting–merging	M_{SM}	$0 = 0;\ 1 = S;\ 2 = M$
Modality 2: avoidance	M_{AV}	0 = yes; 1 = no
Modality 3: on vessel heading	M_{VH}	0 = yes; 1 = no
Cluster descriptors		
Cluster identifier	S_{f}	alphanumeric
Exploration course	$\beta\Sigma_N$	degrees
Exploration speed	V_N	m s^{-1}
Number of schools	N	–
Global density	D_{a}	N m^{-2}
Density by ring	D_{torus}	N m^{-2} torus^{-1}
Averaged total surface	AvS	m^2
Standard deviation surface	σAvS	–
Averaged total echo colour	AvCo(p)	–
Standard deviation echo colour	σAvCo(p)	–
Number of splitting event	nS	–
Number of merging event	nM	–
Frequency of appearance	FA	–
Index of appearance	IA	–



RANGE......: 800 M
BEARING.....: 0°
GAIN.......: 9
MODE: BOW UP
TRANSMIT...: MONO
PULSE FORM.: CW NORM
TX POWER...: •FULL
PING SECTOR: •OMNI
TVG........: •1600 M
AGC........: OFF
RCG........: STRONG
PP FILTER..: STRONG
AUDIO SECT.: •11°
TILT STEP..: •2°
TRACKWINDOW: •MEDIUM
COLOURTHRES: 5
DISPL. GAIN: •9
WIND DATA
EXT.SYNC...: •OFF
COSMETICS
CONSTANTS
STANDARD
TEST
COURSE.....: 346°
SPEED.....A: 7.5KN
1999.05.23 23:17:00

D:\CLUSTE~1\v199_2305_b32_0047.bmp

Data acquisition
Tilt: -2
Bearing: 346
Speed: 7.5
Time (h:mm:s): 23:17:00
Id_School: 25

Positions (pixels)
● Idem. ○ New ○ Trans.
○ Mark1 251.00 406.00
○ Mark2 394.00 390.00
○ Boat 319.00 326.00
○ School 291.00 342.00
○ Lw 03.00
○ Cw 3.50

TS: Blue
Avoidance: Yes
Dynamic: Scission
Heading boat: On line

Remarks: cluster b32 v199

Tracking | D:\cluster v199_b32\v199_b32_select.sel | Picture 48/65 | Scale: 800m (=3.0885m/pixels) | Celerity: 1523.0 (m/s) | Range resolution: 6.09 (m)

Figure 3 Data extraction of a Simrad SR240 sonar frame. The vessel with heading up is in the centre of the picture, with fish school echoes all around and sonar parameters on the right. Each fish school is identified with an alphanumeric mark and tracked with their two associated geographic tags per frame.

(Fig. 4a). Finally, the extraction of intrinsic fish school parameters is processed:

1. referenced 2D position and time (x; y; t);
2. acoustic intensity translated to a colour scale (Anonymous 1992); and
3. along- and across-beam dimensions, Lw and Cw respectively (Fig. 4b).

Fish school dimensions are calculated by the scale factor s (m pixel^{-1}), equal to the sonar range divided by the display range R_d, then corrected ($\mathrm{Lw}_\mathrm{corrected}$ and $\mathrm{Cw}_\mathrm{corrected}$) according to the method described by Misund (1990). The acoustic intensity of individual or collective sonar echoes is estimated by the average colour class Co(p) of each pixel number n_p. Consecutively, the intensity related to colour classes of each pixel, denoted I_cp, is calculated as:

$$I_\mathrm{cp} = \frac{1}{n_p}\sum_{p=0}^{n_p} Co(p) \qquad (1)$$

Once the sonar parameters are extracted (Table 3), two process modes enable sonar data analysis over total time t_t in the same Euclidian reference mark:

1. school-by-school, referred to as ‘single school’ mode; or
2. all observed schools within the field of the sonar beams, referred to as ‘cluster’ mode (Table 4).

In single school mode, school swimming speed is calculated according to its vector displacement during time periods t_t and t_i. Two measures of school swimming speed are defined: the instantaneous speed, Vt_i, where

$$Vt_i = \left(\left(\sqrt{(x_{i+1}-x_i)^2 + (y_{i+1}-y_i)^2}\right)s\right)/t_i \qquad (2)$$

and exploration speed, Vt_t, where

$$Vt_\mathrm{t} = \left(\left(\sqrt{(x_n-x_i)^2 + (y_n-y_i)^2}\right)s\right)/t_\mathrm{t} \qquad (3)$$

An index of horizontal movement (IHM), which involves dividing the horizontal distance between the first and last school position by the sum of

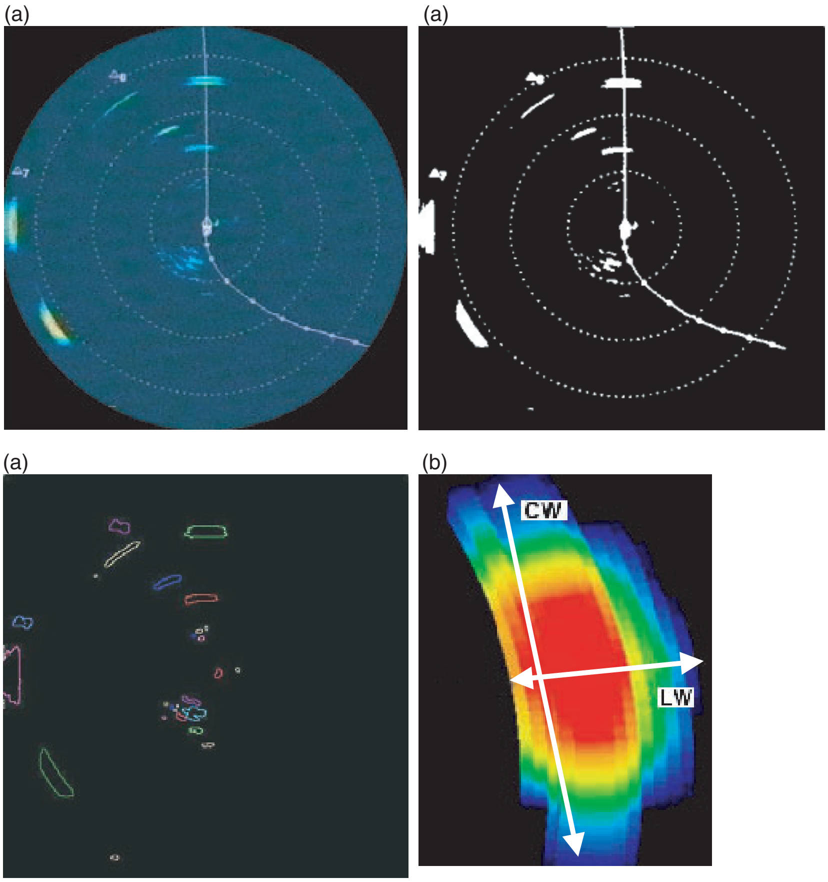


Figure 4 (a) Three-step sonar picture analysis for echo descriptor extraction. (b) Enlargement of a fish school echo, as represented on the sonar display, and the representation of their two sonar dimensions: Lw, along the beam dimension and Cw, across the beam dimension.

elementary distances recorded at time period t_i, has also been proposed by Misund (1991). For all fish schools recognized by a school identifier S_i and associated with a number n of sonar frames analysed, the following kinematics descriptors are computed: t_t, Vt_t, βVt_t, Vt_i, $\mathrm{Ma}Vt_i$, $\mathrm{Mi}Vt_i$, $\mathrm{St}Vt_i$ and $\mathrm{Av}Vt_i$ (Table 4). The distance to the boat R_n and school modality, e.g. splitting or merging events and the presence of a fish school on the vessel heading, are also automatically stored in a worksheet. The standard deviation of vessel course $\sigma\beta$ is computed for the total observation time t_t. The index of horizontal boat movement, $\mathrm{IHM_b}$ (calculated as for the school), which is related to boat speed V_bi and operation type 'Op' (fishing/searching/transit), provides the elementary information on fisher behaviour.

In cluster mode, the global displacement of all schools observed on one single cluster is obtained by vector addition of all their respective exploration vectors. The exploration vector, V, is measured from the school exploration speeds. The Vt_i vectors are added, by calculating their components, to obtain the resultant vector, which informs on the movement direction βV_N and amplitude V_N, as evident in Table 4. Global density D_a reflects the number of schools N per unit of surface area. D_torus gives the density per tore in terms of classes of distance (100 m) to the transducer in $\mathrm{N\ m^{-2}\ t^{-1}}$, as calculated using surface circles of radius R_x for boundary marks of 100-m intervals for x classes. An index of cluster compaction, I_c, based on the inertia moment divided by the number of schools (N) per sonar observation, can then be estimated. For each fish school cluster detection, S_f, the following descriptors are also calculated: NS_s, D_g, D_torus, I_c, $\mathrm{Av}S\sigma$, $\mathrm{Av}S$, $\mathrm{AvCo}(p)$ and $\sigma\mathrm{AvCo}(p)$ (Table 4). The aggregative dynamics is approached by the indexes of splitting

IA_S and merging IA_M events, processed by a count of splitting *n*S and merging *n*M occurrences, for a single school or the entire 'sonar cluster', for time period t_t. At the cluster level, the frequency of splitting and merging event appearances, *F*A, is equal to *n*S or *n*M divided by the number of schools, *N*, detected within the sonar range.

Current and future applications of omnidirectional sonar data

The large sampling volumes of omnidirectional sonar enables the tracking observation of large numbers of fish schools at large distances from the vessel, e.g. 800 m or more (3000 m in the case of optimal detection conditions). The behaviour of fish school migration has already been successfully recorded using other medium-frequency omnidirectional sonar (Hafsteinsson and Misund 1995; Misund *et al.* 1997). Misund (1990) showed the value of such data, particularly during purse seining, to improve and quantify this type of fishing operation. Goncharov *et al.* (1989) and Misund and Aglen (1992) used omnidirectional sonar to monitor fish school avoidance (Fernandes *et al.* 2000; Jorgensen *et al.* 2004) during trawling and purse seining operations respectively. In addition, this kind of sonar information enables a correction of the bias related to fish avoidance reaction (Misund and Coetzee 2000; Melvin *et al.* 2002) on echo-integration processes for assessment purposes (Fréon and Misund 1999; Simmonds and MacLennan 2005). Fig. 3 shows an avoidance reaction to starboard at 200 m from the vessel, where the school (no. 26) splits into two parts in front of the survey vessel. Omnidirectional sonar enables the recording of antipredator strategies (Nøttestad and Axelsen 1999) in front of the vessel. During our acoustic surveys, we have demonstrated that continuous recordings of sonar data overcome the drawback of horizontal avoidance during the behavioural assessment of small pelagic fish (Brehmer *et al.* 2000).

Continuous data acquisition also enables the study of fisher behaviour. The fish searching behaviour of fishermen aboard commercial fishing vessels can be documented from the start to the end of the cruise, including exploration area, searching attitude and fishing tactics. The operational setting can be directly associated with sonar detection, while vessel course characteristics (Table 4) can be used to monitor fishermen's decisions (Gaertner *et al.* 1999; Salas and Gaertner 2004; Bertrand *et al.* 2005). A combination of sonar detection, catch data and net sensors provides information on fishing efficiency. As observed in purse seine fisheries (e.g. tuna or sardine), skippers use these sonars before setting their nets.

The catchability coefficient can be considered in terms of two components. First, by measuring the reaction of individual fish schools to fishing gear, and secondly, by measuring their spatial distribution over the fishing area (Brehmer and Gerlotto 2001a; Mayer *et al.* 2002).

The two sampling scheme modes, static 'drifting' and dynamic 'prospecting', enable us to test whether the fish school kinematics are sensitive to vessel and gear perception. In particular, drift experiments are useful for measuring the swimming behaviour of fish schools, their *in situ* diffusion coefficient (Sibert and Hampton 2003) and classifying the swimming patterns of fish schools. The spatial structure of schools can be evaluated by omnidirectional sonar observations using spatial point process analysis (Petitgas *et al.* 1996). The analysis of fish school density within the same cluster, according to time of day, enables monitoring of the aggregative dynamics of a fish school cluster. At the level of a single school, splitting and merging dynamics can also be considered for large schools (diameter and nearest neighbour distance > range resolution). The limitation to large school sizes enables the observation of aggregative dynamics at the meso-scale (from a single school to a cluster of schools), but prevents the evaluation of one component of the behavioural dynamic that occurs at the micro-scale [e.g. the splitting of a single school into many small ones (Soria *et al.* 1998)]. A combination of high-resolution sonar and medium-frequency omnidirectional sonar in a small-scale study would enable the operator to determine which kind of behavioural dynamic component had been missed.

The possibility of data acquisition from shallow water (Brehmer *et al.* 2003) to open sea domains, and the combination of processing modes, enables the versatile application of long-range omnidirectional sonar. Acoustic data also enables the acquisition of comparable information from circadian to annual variations. The combined use during acoustic surveys of high-resolution multibeam sonar (Gerlotto *et al.* 1999) and echo-sounder detection (Reid and Simmonds 1993; Weill *et al.* 1993) with medium-frequency omnidirectional sonar (e.g. Varget mission, Table 2), provides a database for a global view of acoustic responses (Brehmer *et al.* 2002), morphology, 3D location and swimming pattern characteristics of fish schools; as a result, fish school behaviour can be accurately studied.

Perspectives

At a technological level, future omnidirectional sonar systems require the introduction of specific technology related to individualized beams for trace tracking. Narrower beam widths and smaller pulse lengths will provide more accurate results. Raw sonar data acquisition can now be considered with the new generation of Simrad omnidirectional sonar systems (Anonymous 2003).

Three-dimensional GIS-based representation of fish schools along transects sampled by omnidirectional sonar can now be developed (Melvin *et al.* 2002), and continuous monitoring by direct data analysis can also be considered. This will enable the adaptation of real-time survey design during fishery surveys according to observed fish behaviour. Geostatistical tools is used combined with echo-sounder data for estimating population abundance, estimation of survey precision, optimization of sampling strategy and models that could characterize spatial variation and temporal variability (Petitgas 2001). Similar analysis could be realized with omnidirectional sonar data. Pooled sources of both information (echo-sounder and sonar) will permit to obtain accurate results.

Data from medium- to long-ranging omnidirectional sonar can be used for the validation of the density-dependent model of fish shoaling (Seno and Nakai 1995), antipredator strategies (Vabø and Nøttestad 1997) or the modelling of fish school movement (Huth and Wissel 1994; Reuter and Breckling 1994; Couzin *et al.* 2002) at a meso-scale, i.e. from a single fish school to a cluster of schools. In addition, direct observations of fisher tactics can be useful in calibrating models presented in the literature (Dreyfus-Leon 1999; Gillis 2003).

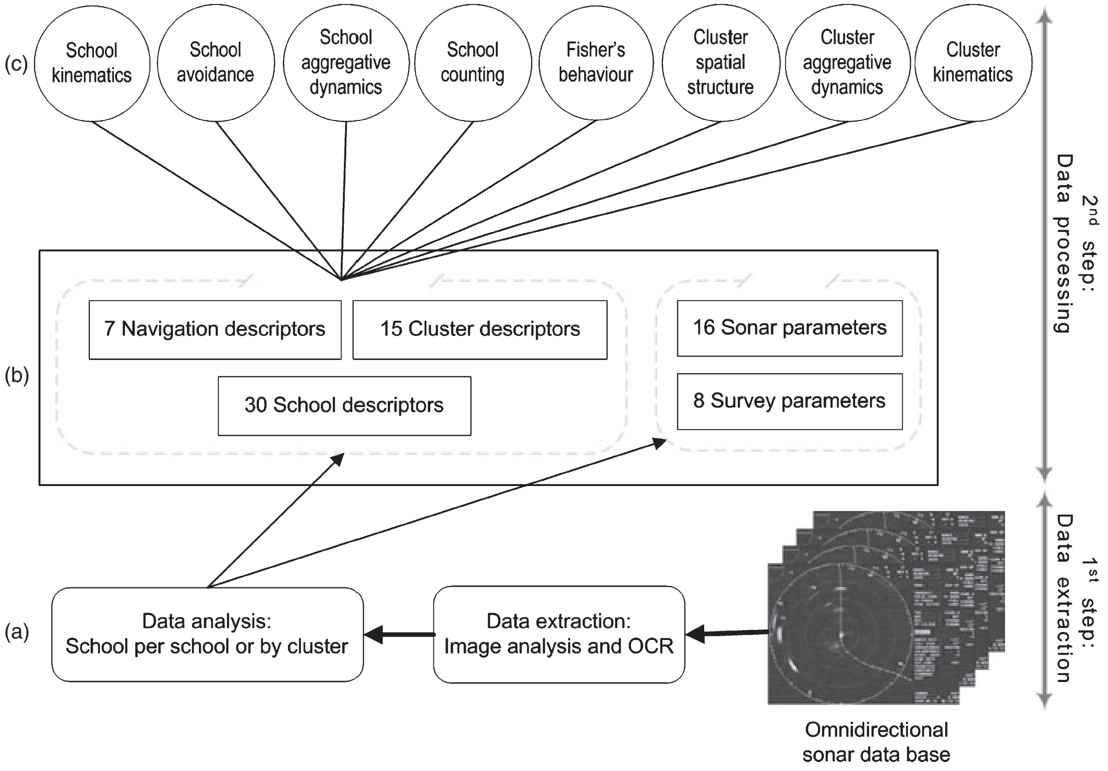


Figure 5 Scheme of sonar data treatment in two main steps: data extraction and processing. (a) Digital sonar frame extraction by video analysis and optical characters recognition. The worksheet obtained is processed in two analysing modes (school-per-school or by cluster). (b) Data analysis provides 77 variables across the navigation, school, and cluster descriptors, and the survey and sonar parameters. (c) Main study areas within fisheries sciences that could benefit from omnidirectional sonar data analysis.

A European project (FADIO) has been approved (Holland *et al.* 2004) with the aim of developing and utilizing a medium-frequency buoy-mounted sonar, including automated data-loggers, to study the aggregative behaviour of pelagic species at low cost compared with the cost of using a research vessel. The first trial of this project has been successfully undertaken in the Indian Ocean. This kind of tool will be particularly useful for studying the aggregative dynamics of tuna schools (Anonymous 2004) using fish aggregating devices (FADs) (Hunter and Mitchel 1967). The time of residence around a FAD and kinematics can be studied by omnidirectional sonar observations. This methodology could also be used in studies of artificial reefs.

Omnidirectional sonar holds promise for assessment purposes, however, as discussed above, its use in this area is prevented by a number of drawbacks. Nevertheless, monitoring within a horizontal omnidirectional plane around a fishing vessel offers the possibility of studying fisher behaviour, i.e. strategy and tactics, in relation to aspects of fish school behaviour such as kinematics, spatial structure, avoidance reaction, aggregative dynamics, migration and schooling behaviour (Fig. 5). Most fishing boats and several fisheries research vessels around the world are already equipped with sonar. The use of this technology in fisheries research, by applying our methodology of data acquisition and analysis, would provide access to an exceptional source of information on pelagic fish stocks. It should also be possible to integrate parameters resulting from direct observations into fisheries management models. The efficiency of the method has already been validated on engraulids and clupeids, and its application to other aggregative species, especially when combined with drift observations, will achieve original results and provide new perspectives on fish school behavioural studies and fisheries research.

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Appendix

Underwater acoustic ray deviation

The direct observation can be corrected by adapted sonar deviation model, which needs efficient probe sampling scheme. The basic Eqs (1–4) for geometrical propagation (Urick 1983; Burdic 1992; Brekhovskikh and Lysanov, 1991) have been used by Diner and Marchand (1995) for calculating the local ray deviation. Lurton (2002) summarizes practical formulae for ray refraction computations. In this method, $c(z)$ is the sound speed profile; z is 0 at the surface and is counted positively downwards. The profile is approached by a limited number of $W + 1$ points defining W layers inside which one makes the hypothesis of linear variations of the velocity. In the wth layer, the velocity gradient is g_w (5). The Snell–Descartes law is verified for all layers and is an invariant characteristic for a given ray path (6). A sound ray with angle T_{w-1} (sonar tilt) at a layer input undergoes a circular refraction of its trajectory of curvature radius R_{cw} (7).

$$\begin{cases} r - r_{w-1} = R_{cw}(\sin T - \sin T_{w-1}) \\ z - z_{w-1} = R_{cw}(\cos T - \cos T_{w-1}) \end{cases} \tag{4}$$

$$g_w = \frac{c_w - c_{w-1}}{z_w - z_{w-1}} \tag{5}$$

$$\frac{\cos T_w}{c_w} = \frac{\cos T_{w-1}}{c_{w-1}} = \text{constant} \tag{6}$$

$$R_{cw} = \frac{c_{w-1}}{g_w \cos T_{w-1}} \tag{7}$$