Aquat. Living Resour. 20, 377–384 (2007)

DOI: 10.1051/alr:2008016
www.alr-journal.org

Aquatic Living Resources

Technical Note

Adaptation of fisheries sonar for monitoring schools of large pelagic fish: dependence of schooling behaviour on fish finding efficiency

Patrice Brehmer[1,a], Stratis Georgakarakos[2], Erwan Josse[3], Vasilis Trygonis[2] and John Dalen[4]

[1] University of the Aegean/Co IRD-UR109, Centre de Recherche Halieutique Méditerranéenne et Tropicale, 1 avenue Jean Monnet, BP 171, 34203 Sète, France
[2] University of the Aegean, Fisheries and Sonar Laboratory, University Hill, 81100 Mytilini, Greece
[3] Institut de Recherche pour le Développement, US004, Centre de Bretagne, BP 70, 29280 Plouzané, France
[4] Institute of Marine Research, P.O. Box 1870, Nordnes 5817, Bergen, Norway

Received 11 October 2007; Accepted 29 January 2008

Abstract – Multibeam omnidirectional sonars are tools currently used by fishers, but also allow the monitoring of pelagic fish schools surrounding a platform. Multibeam processing methods now offer improved capacities for raw data storage. The Simrad SP90 sonar was used for the detection of fish schools associated with drifting fish aggregating devices (FADs), and digital systems developed for the acquisition and processing of volume backscattering echoes and position data. Data sampling methods were defined based on two modes: one for periods searching for FADs and associated schools, and one for school monitoring in drifting mode. Validation of the detection of several FAD-associated schooling species was made by simultaneous visual observations or/and cross-checking with echosounder recordings. The characteristics of schooling behaviour in the targeted fish species are fundamental for the correct interpretation of acoustic data. Sonar detection threshold is the result of a compromise between fish number, size, species and the nearest neighbour distance (NND) of individuals per dynamic structure (school or shoal). Tuna schooling dynamics mean that NND can sometimes be too large to allow the presence of these fish to be detected, despite their number. Sonar data should be analysed and interpreted in a holistic manner, in combination with behaviour pattern and dynamics of all species around the drifting FADs. An autonomous sonar buoy prototype equipped with 360° scanning sonar coupled to video cameras will increase our understanding of tuna behaviour around drifting or anchored objects. A similar methodology can be applied to different kinds of platforms, either anchored or in permanent positions. This would improve the monitoring of fish schools around artificial reefs, open sea aquaculture farms, and across estuaries, channels or straits; applications which are undoubtedly essential for progressive fisheries management.

Key words: Autonomous system / Behaviour / Buoy / FAD / School / Sonar / Tuna

1 Introduction

Omnidirectional acoustic data is of broad interest in fisheries science, but this kind of approach is particularly valuable when addressing behavioural questions about pelagic fish schools (Brehmer et al. 2006). Horizontal 2D omnidirectional sonar data can usefully compliment information from echosounders and high resolution 3D sonars (Mackinson et al. 1999; Brehmer et al. 2002). Studies have led to several important findings concerning fish schools, such as avoidance behaviour (Diner and Massé 1987; Goncharov et al. 1989), kinematics (Misund 1990), migration (Hafsteinsson and Misund 1995), spatial structure (Petitgas et al. 1996), and residence time around an artificial reef (Brehmer et al. 2003). Limitations to the use of multibeam sonars are usually due to the lack of direct access to the acoustic signal and the implications that this has for quantification of the acoustic measurement.

This paper presents results on the analysis of raw sonar data, made within the European research project FADIO, using a Simrad SP90 omnidirectional sonar system (Brehmer et al. 2005). The overall aim of the FADIO project is to create observatories of pelagic ecosystems by developing prototypes of new autonomous instruments: electronic tags and instrumented buoys (www.fadio.ird.fr). Five acoustic surveys were conducted for the development of an methodology adapted for the detection of pelagic schooling species, mainly tropical tuna, known to associate with Fish Aggregating Devices

[a] Corresponding author: pbrehmer@ifremer.fr

(FADs). FADs can be artificial structures such as those set by fishers, typically made of a bamboo raft and net, or natural objects like coconuts, pieces of wood or any other floating object (Fedoryako 1988; Dempster and Taquet 2004; Dagorn et al. 2007). In the context of worldwide fish exploitation using these structures (Fonteneau et al. 2000), and to examine questions on fish school behaviour (Marsac et al. 2000; Fréon and Dagorn 2000; Castro et al. 2001), there is a need for solid data, gathered efficiently *in situ*.

The present experiments were designed to produce results on the definition of specific sonar parameters, sampling methodology, data storage protocols and processing methods; particularly in the context of an autonomous sonar buoy system, where real-time data transmission and analysis is needed. Acoustic information from the sonar system was compiled using a dedicated software tool (developed by the Fisheries and Sonar Laboratory of the University of the Aegean), and thus provided quantitative descriptors of the pelagic schools aggregated around FADs. The schooling behaviour of target species plays a key role in the correct understanding of sonar data, a point which was underlined by this work and is essential for avoiding erroneous interpretations.

2 Materials and methods

2.1 Digital raw data collection

The acoustic device used was a Simrad SP90 medium-range multibeam omnidirectional sonar, identical to equipment used by the principal fishing fleets in the Indian Ocean to detect tuna schools. The SP90 acoustic transmission is similar to the Simrad SR240 (Simrad 1992); however, its emission frequency can be selected from 20 to 30 kHz, and the 32 horizontal beams of 11.25 (Fig. 1; pulse lengths: 8 ms at a range of 800 m and 12 ms at 1200 m) are split into two parts (Simrad 2004). Moreover, the SP90 offers direct access to the acoustic signal through a new scientific digital output (Simrad 2003, 2004) that was used in the present project. This last improvement and the availability of protocols for multibeam sonar calibration (Foote et al. 2005) make the unit a valuable acoustics device for fisheries research.

All procedures of the built-in test system were checked (target and ship marker, view menu, bridge function and the sonar room functions when tested according to the manufacturer's instructions, Simrad 2004). The self-noise test was performed, producing a measured echo level of –43 dB, which matched the expected value. The alignment of the sonar picture was validated, peripheral equipment was tested, and the signals from all the external sensors were successfully interfaced with the sonar system (speed log, course gyro and Global Positioning System – GPS) (Palud and Brehmer 2004). In this new version (in contrast with the SR240 model) a GPS is used for the location of geographic markers, replacing the traditional gyrocompass reference. The vertical echosounder acoustic transmission rates (Table 1) were not synchronised with the SP90, however the sonar data did not show any interference during full operation. Nonetheless, the sonar caused interference rays on the sounder echograms at 38, 70 and 120 kHz, which could be avoided by the use of a central synchronisation system.

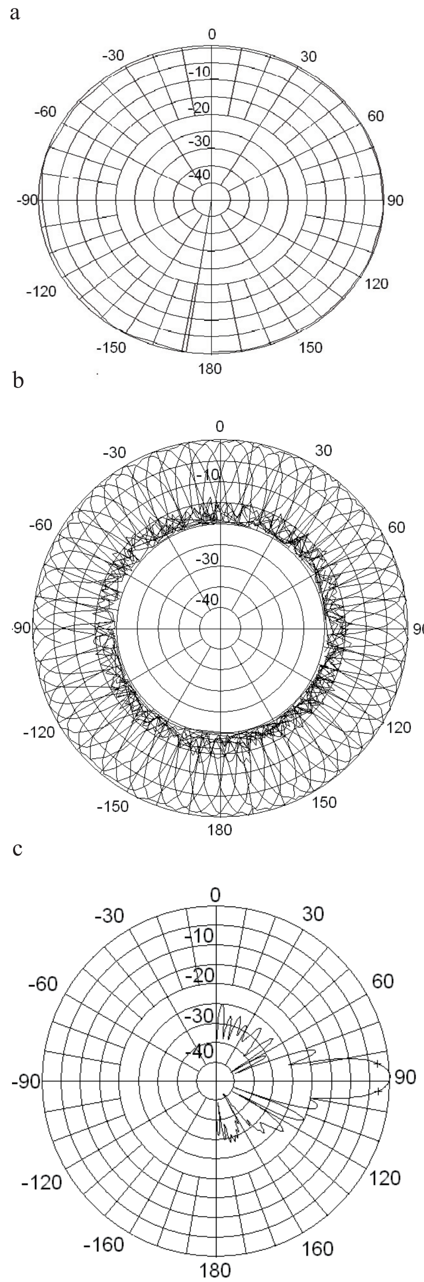

Fig. 1. Representation of the beam pattern for the SP90 omnidirectional sonar, at 26 kHz, (a) as transmitter and (b) receiver in an omnidirectional horizontal plane and, (c) as transmitter single beam with its sidelobes (from C. Corbières, Simrad Europe 2004).

Due to the narrow tilt angle used during the operation of the SP90 transducer, a spectacular emission was expected from tuna schools and therefore the commonly applied for acoustic integration 20 Log R time varied gain (TVG) function was replaced by 30 Log R, which is more appropriate for this particular situation.

The scientific output of the SP90 sonar is one binary file per ping transmission, containing one data block with the acoustic data telegram and certain blocks with metafile and sonar settings information. These blocks hold variables such

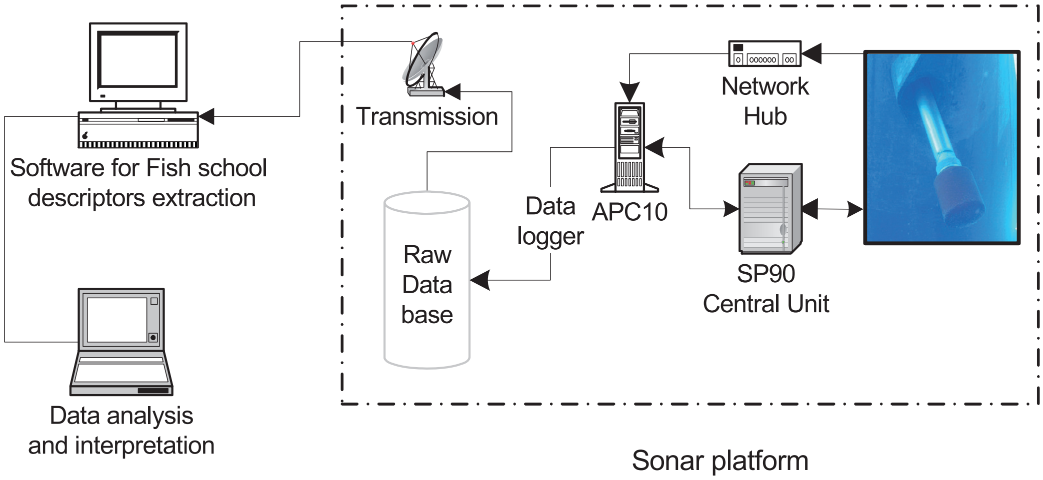

Fig. 2. Description of the tools and methods used to exploit (i.e. acquire, store/transmit, extract and analyse) the raw data from the Simrad SP90 sonar. The dotted rectangle denotes the system components that were used during the surveys, and can be mounted either on a fixed or on a drifting platform.

Table 1. List of the surveys conducted during the FADIO project in the western Indian Ocean, using pole or hull mounted omnidirectional sonar to detect schools of tuna and other associated species around drifting floating objects in the open sea. Other acoustic devices used simultaneously were three "VES" Vertical EchoSounders (Simrad EK60) and one "MBS" Multi-Beam Sonar (Reson Seabat 6012).

Survey	Date	Installation	Other acoustic devices (kHz)
FADIO 1	2003	Pole mounted	VES: 120
FADIO 2	2004	Hull mounted	VES: 38, 70, 120
FADIO 3	2004	Hull mounted	VES: 38, 70, 120. MBS: 455
FADIO 4	2005	Hull mounted	VES: 38, 70, 120
FADIO 5	2005	Hull mounted	VES: 38, 70, 120. MBS: 455

as range, transmission power, pulse length, tilt angle, stabilization, GPS, etc. (see Simrad 2003 for extended list of parameters). The data block consists of a 256 × 64 matrix (256 cells per beam) of the digitized backscatter coded in 64 logarithmic scale levels [0–63]. The detailed data acquisition flow diagram is illustrated in Figure 2. The video (bitmap) and digital form (binary files) of the sonar output were concurrently stored, for validation of sonar telegram extraction.

The main targeted fish species during FADIO acoustic surveys were the exploited tropical tuna: skipjack *Katsuwonus pelamis*, yellowfin *Thunnus albacares*, and bigeye tuna, *Thunnus obesus*, which represent more than 200 000 tons of annual landings in the western Indian Ocean. The sonar experiments of this study were conducted during five acoustic surveys carried out in the western Indian Ocean around the Seychelles Islands, onboard the "Indian Ocean Explorer" (35 m). On a regular basis during sonar observations, echosounder multi-frequency records were logged simultaneously (38 kHz, 2000 W; 70 kHz, 1000 W; 120 kHz, 1000 W), with a pulse duration of 0.512 ms and a beam angle of 7° for the three transducers. During the first cruise (Fadio 1), the sonar was pole-mounted alongside the vessel, it was then hull-mounted for the next four surveys (Table 1).

2.2 Sampling method and adapted sonar parameters

The primary goal of the surveys was to use the sonar system in order to reach the FADs. The underwater structure of a FAD is usually voluminous, covered by heavy biofouling and always accompanied by individual fish and schools at short distance (Fedoryako 1988). The second goal was to look for biological echoes of associated fish schools. Sonar scanning was carried out by applying two different groups of settings: "searching mode" during periods searching for fish schools and FADs, and "FAD and school mode" when monitoring fish schools around FADs.

- The "searching mode" was applied during vessel cruising. Full automation was selected i.e. automatic frequency modulation "FM mode", automatic gain control filter (AGC), reverberation gain control (RCG) and echo interpolation were all enabled. The sonar range was set to 3000 m, aided by visual detection using long-range binoculars for spotting sea birds or floating objects. The sonar tilt angle was set according to sea conditions between 0° (in good condition i.e. low wind and swell) to –6°.
- In "FAD and school mode" the vessel was stopped near the FAD at a distance of 50 to 300 m, except for special experiments during the (Fadio 2) cruise where the sonar vessel was moored alongside the FAD in drift mode (Brehmer et al. 2000), to imitate the behaviour of a buoy and continuously observe fish schools. In contrast to the 'searching mode', all automation was disabled and the transmission form was set on continuous wave mode. The sonar range was limited to 1200 m under good sonar conditions (Misund et al. 1992), and 800 m under bad conditions. The tilt angle followed the vertical displacement of the school in cases of single-school monitoring. In order to maximize the success of school detection, the tilt angle varied between 0° to –25°, according to the typical depth of the targeted fish species. In case of high current speed, the vessel had to be stationed in a position allowing passage near the FAD, in order to maximize the duration of target presences in the beam field.

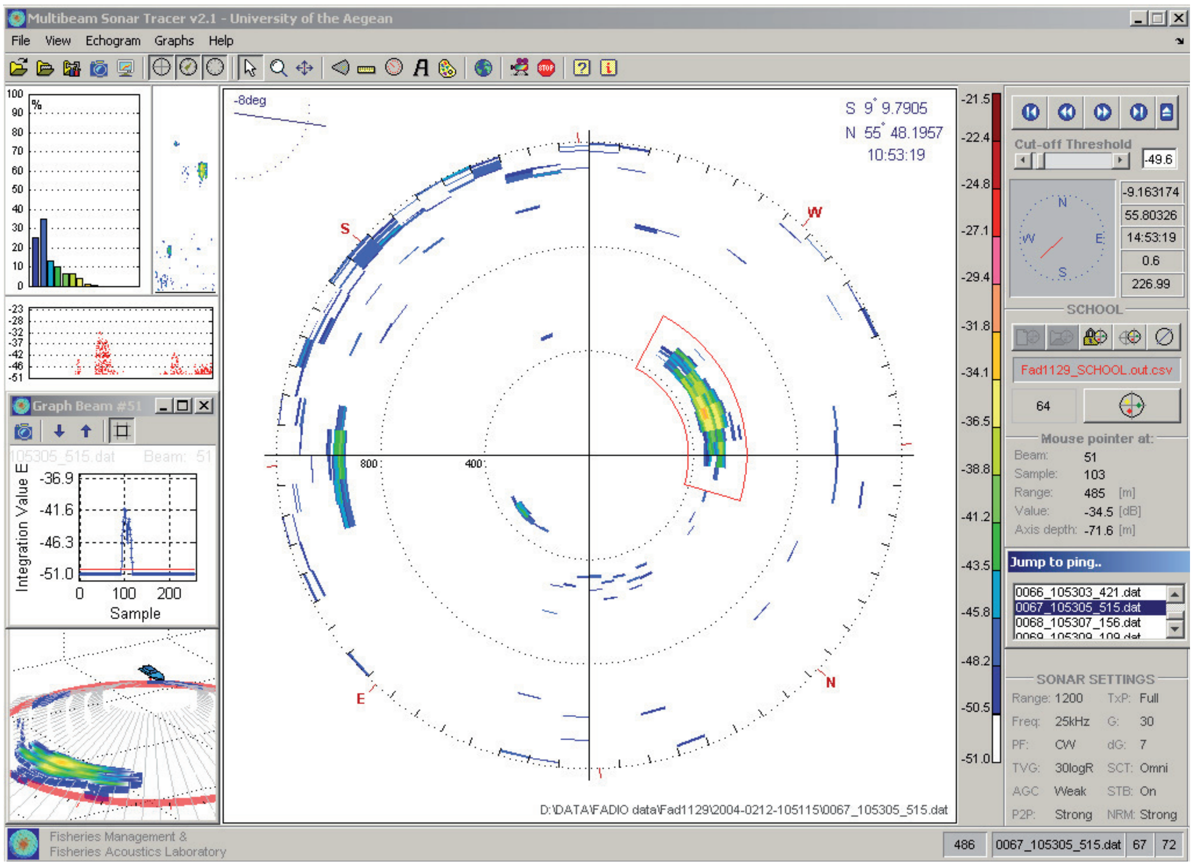

Fig. 3. Graphical user interface of the Multibeam Sonar Tracer software, illustrating the main panel, the multibeam echogram and statistical analysis results of fish schools around a fish aggregating device (refer to Table 2 for school descriptors results).

2.3 Data analysis

Using existing knowledge on sonar picture analysis (Gerlotto et al. 2001), specific software Multibeam Sonar Tracer (MST) was developed in Matlab and C++ to process SP90 binary files (Fig. 3). MST integrates algorithms for school identification and tracking, and 3D visualisation of school and vessel trajectories, and produces output of the respective sonar telegrams (beam data, sonar settings, GPS status) in ASCII-formatted files.

School dimensions (Figs. 4a,b) are calculated using algorithms from Misund (1990): (Eq. (1)) the corrected "corr" along- beam dimensions Lw and (Eq. (2)) across beam dimension Cw (Fig. 3), according their apparent dimension "a", as:

$$Lw_{\mathrm{corr}} = Lw_{\mathrm{a}} \cos T - (ct/2) \quad (1)$$

$$Cw_{\mathrm{corr}} = Cw_{\mathrm{a}} - 2Rn \tan(B/2) \quad (2)$$

with T: tilt angle, c: sound celerity (m s^{-1}), t: pulse length (ms), Rn: distance to the target (m), B: horizontal beam width (degree).

The distance to the schools encountered (average school range – ASR in m) is measured according to sonar accuracy, which is always 1/256 of the operation range (Fig. 4c). Two school swimming speeds can be estimated based on the SP90 telegram data: the instantaneous speed and the exploration speed (Brehmer et al. 2006; Trygonis and Georgakarakos 2007). The fish school acoustic density is calculated per school and for the whole echogram according to a user-defined threshold, adapted to the environment and the sonar acquisition settings.

The underlying assumption of the tracking algorithm is that although fish schools do change shape, size and position with time, these changes are expected to be minor in the limited time interval between two successive insonifications. Thus, the tracking routine is able to recognize identical schools in successive pings (under the assumptions that pitch and roll is efficiently compensated by the stabilization system (SIMRAD 2004) and that all ping transmissions are synchronized), applying appropriate ping-to-ping school matching criteria such as the distance from the sonar, horizontal displacement per unit time and area difference. The tracking algorithm of the MST software identifies the corresponding traces of each moving target in each ping, and calculates a log protocol of the school tracking paths (Trygonis and Georgakarakos 2007). The data processed represent a total of 728 successive insonifications, which correspond to approximately 20 min of continuous data logging. The number of acoustic detections per ping varies with time in data sets, especially if small echoes (area < 100 m^2) are not filtered out during the execution of the algorithm (Fig. 5). For the very low school-area filter used during the scanning, the majority of the echoes encountered in the specific dataset are below 300 m, while larger echoes are detected in ranges between 500 and 1100 m. We present an

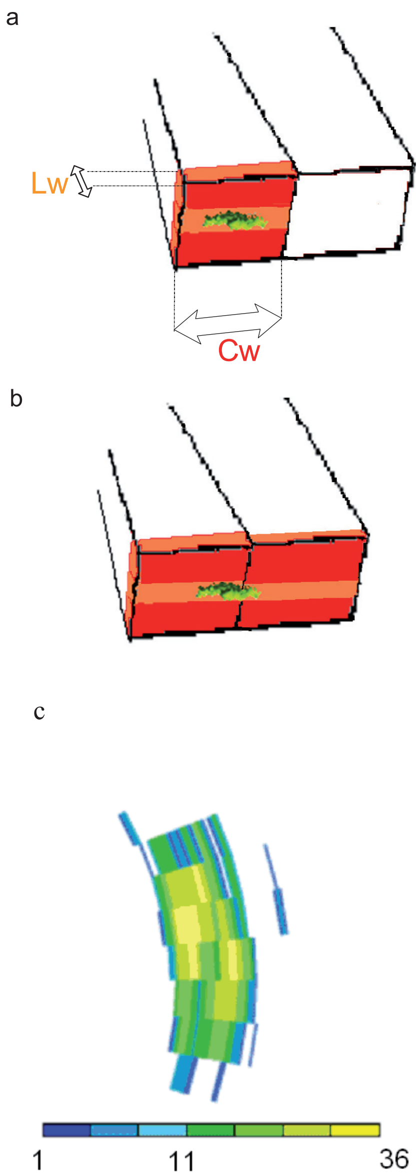

Fig. 4. Representation of the two sonar dimensions "Lw" along and "Cw" across the beam axis. (a) A school detected inside one of the 64 beams (in orange) that cover the whole beam volume detection area (in red). (b) The effect on the sonar echoes representation when a school crosses two beams: there is an extension of the Cw school dimension. (c) Zoom on a large school echo shape showing the heterogeneity of such biological structure (scale in acoustic intensity = 64 levels).

example of the information extracted on a tuna fish school near a FAD (Table 2). The software calculates the average school density Sv in dB if the automatic gain control (AGC) is disabled, otherwise the density estimator is expressed in relative values, representing the 64 colour levels of the raw beam data.

3 Results

Detection of the three main exploited tuna species *K. pelamis*, *T. albacares* and *T. obesus* was confirmed during our

Table 2. Example of school descriptor software extraction from the omnidirectional sonar during the FADIO surveys (FAD number 958). (*) Estimated in dB if the sonar internal automatic gain control (AGC) filter is disabled.

School descriptors by each ping			
Code	School Descriptor	Value	Unit
SID	School ID by each ping	25	-
NS	Number of acoustic samples	186	-
ASR	Average school range	524	m
ASD	Average school density *	–49	dB
AVEDPTH	Average school depth	–68	m
AVELw	Average along-beam width	83	m
AVECw	Average cross-beam width	276	m
LAT	Latitude	4.158135 S	degree
LON	Longitude	56.400461 N	degree

surveys. Large isolated tuna fish schools were usually observed together with several small schools (in a sampling area of more than one km^2). Tuna differ in this way from small pelagic fish that usually occur in school clusters (Haugland and Misund 2004), i.e. by including several large compact fish schools on the same sampling surface (around one km^2).

Compact pelagic fish schools were characterised by small nearest neighbour distance (NND) (approx.1 body length BL; i.e. 10 to 30 cm) between the members of the same school. For schools of exploited tuna species, BL was longer (in absolute value), typically lying between 40 and 100 cm: more than twice that of small pelagic species. The NND in 'shallow schools' (Josse et al. 2000) was also around 1 BL, in "intermediate scattered fish" it was over 30 BL and in "deep scattered fish" it was over 240 BL (Josse et al. 2000). The presence of low density tuna schools was not indicated using the "FAD and school" sonar mode setting, which corresponds to "deep scattered fish" rather than the easily detected "shallow schooling fish". We encountered a small school (<6 m diameter) of *K. pelamis* (fish without swimbladder i.e. low fish target strength), in the surface layers, observed visually at the surface during bad sea conditions, but not detected at a sonar range of 800 m (hand line caught specimen: FL 25–30 cm; com. pers. D. Itano). According to tuna schooling dynamics, NND can be too large to generate target density (a target = a group of several individual fish i.e. a fish school or a shoal) above the detection threshold. The fish school could also be too small (Diner 2007), and therefore under the detection threshold. Nevertheless, according to observations of professional fishing operations around FAD (Miquel et al. 2006), the tuna caught occur in detectable schools.

The school detection threshold, which in part defines the "fish finding" efficiency, is the result of a compromise between fish number, size and NND, which generate the acoustic response characteristics of the targeted schools; knowing that acoustic responses depend on the school species composition. The position of a school inside the beam obviously has an impact on sonar detection (Fig. 4), depending whether its centre of gravity is situated on the –3dB acoustic beam or not. Consequently, only large and/or dense tuna fish schools could be

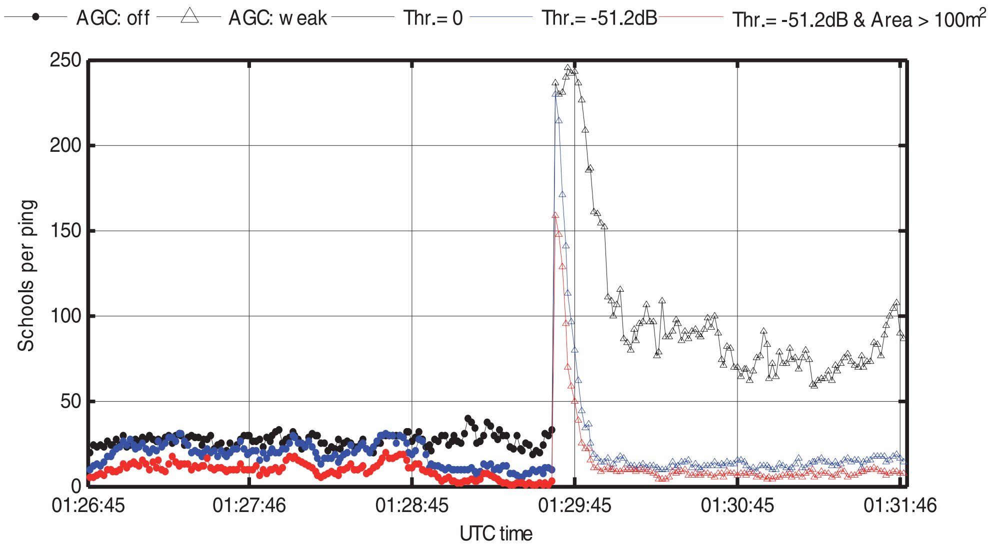

Fig. 5. Number of schools per ping for two automatic gain control "AGC" filter modes: disabled: • and enabled: △ within a range of 600 m (frequency of 26 kHz and a tilt angle of 0°); the peak at time, 01:29:30, represents the change from disabled to enabled (in weak position). The black line represents the number of detected schools per ping if no threshold is used; the blue line is with a colour threshold 6 = –51.2 dB, the red line is with the same colour threshold and with small targets (artefacts) smaller than 100 m^2 filtered out.

detected: these schools constituting the main part of the fish biomass. It was not possible to detect very large tuna schools (i.e. those targeted by fisher) around FADs during our five surveys (except for a single occasion, when however the experiment was interrupted by an operating fishing vessel, since the coordinates of artificial FADs are known to fishers). An alternative would be to use areas that are less visited by fishing fleets, or to increase speed and autonomy of the research vessel.

Apart from tuna, dense schools of flying fish were detected (verified by visual sightings at short range). To our knowledge, this is the first time that dense concentrations of flying fish have been observed by sonar. Other species such as triggerfish and clupeoids were detected around the FAD. More interesting was the detection of whale and dolphin groups (confirmed visually), both observed as distinct sonar echoes close to drifting FADs while cruising. Such results suggest that this medium sonar range would be suitable for mammal studies and monitoring. During transit between FADs, other interesting observations were also recorded, which could be of ecological value, such as free swimming fish schools of unidentified species. Lastly, observations by echosounders of a deep scattering layer at a relatively shallow depth (>50–100 m) in some areas during late evening and night could generate misleading echoes of fish schools, when not cross checked with echo sounder detections (Misund and Coetzee 2000) or another complementary method of fish observation.

4 Discussion

Medium-range omnidirectional sonar can be used to record large tuna aggregations encountered in the pelagic environment under various conditions, and to describe their relationships to an object; in this particular case is a drifting FAD. Species discrimination is obviously an important objective in the achievement of this goal, since there are multiple associated fish species in schools, shoals or as individual fish (Pitcher 1986). Such groups could be monospecific, multispecific, or could switch from one to the other. Therefore, it is sometimes difficult to correctly identify which species are being observed by the sonar. In these cases nevertheless, the observations can be used in terms of acoustic populations (Rose and Legget 1988; Gerlotto 1993), where the main part of the fish biomass is already known. Visual observations above and below the surface, qualitative echosounder recordings, and underwater visual post-observation (by video) were necessary for the accurate identification of the species observed. Even so, the combination of the two acoustic devices used during the FADIO surveys (i.e. multi frequency scientific echosounders and multibeam sonar) can allow the presence of tuna to be confirmed in the case of high abundance. In our case study, this was performed via echosounder target strength analysis (Josse and Bertrand 2000) and empirical knowledge of echo trace characteristics such as shape and depth, coupled with the sonar school detection.

Tang et al. (2006) have shown that omnidirectional sonars provide more accurate results in a fixed position rather than in cruising mode, which supports the choice of a buoy system for sonar monitoring. Such an autonomous system would offer valuable information concerning the behavioural characteristics of tuna schools, i.e. (1) the mean time spent near the FAD, (2) the mean speed of schools moving around, towards or away from the FAD (Miquel et al. 2006), and (3) their aggregative behaviour.

Directly around the FAD, small aggregations and individual fishes, are situated at very close proximity to the sonar FAD buoy. The intranatant fish, usually <50 cm length (Castro et al. 2001), and the closer part of extranatant (Parin and Fedoryako 1999) ones, are very small and not observable at the usual sonar resolution, outside or inside the near-field signal. Due to the transparency of tropical oceanic waters, visual census permits the investigations at close distance to the buoy system (Relini et al. 2000; Taquet 2004). A 360° video camera system could carry out this task, as fish diversity and abundance are usually very low and they remain close to the surface (depth < 10 m) even in clear water (Brehmer et al. 2005). For this reason it would be interesting to install a web of three video cameras with the sonar buoy system. The sonar resolution chosen in our case was selected to focus on large fish schools (extranatant and circumnatant fishes), which represent the bulk of fish biomass targeted by fishers, around FADs (i.e. for an anchored FAD 0.3 nautical mile (Josse et al. 2000; Doray et al. 2006)). In any case the sonar data should be analysed and interpreted in a holistic way, in combination with the behavioural pattern and the dynamic of all species in schools and shoals present around the drifting FADs, bearing in mind that some of these fish structures could be multi-specific.

5 Conclusion

The sonar system is a valuable tool for the detection and behavioural observations of pelagic fish schools, which represent the main pelagic fish biomass in the world. According to empirical *in situ* observations, fish schooling behaviour (Brehmer et al. 2007) plays an important role on fish detection validity. This is particularly so with tuna species around FADs, where three distinct types of aggregations occur, and the packing density (Misund et al. 1992) is highly variable (Josse et al. 2000). Algorithms for efficient detection threshold, school tracking and species identification are highly necessary for biological data interpretation; such research also requires *in situ* behavioural observations at sea, adapted to the particular situation (i.e. according to weather condition and biomass quantity and diversity). The next step in data processing will be to convert a sonar system mounted on a drifting (or fixed) buoy into an "intelligent" autonomous observatory of the pelagic ecosystem i.e. biological target recognition below ambient acoustic noise and interferences (Brehmer et al. 2006). The validation of sonar settings also requires additional experiments at sea, so that the capacities of sonar detection can be optimized and not limited to the pulse length value. Accurate sonar technology is now operational (Andersen et al. 2006); this technology however needs large vessels, and cannot yet operate autonomously. A new pulse form in hyperbolic frequency modulation, introduced on modern fisheries sonar (SIMRAD 2007), should improve the accuracy of school definition (compared with continuous wave pulse form). Power consumption is a serious limitation in the case of an open ocean drifting buoy system, so use will be made of a 360° scanning sonar system at higher frequencies that reduces power consumption, with the drawback of reducing the scale and the advantage of increasing the resolution. Data storage of raw binary fisheries omnidirectional sonar data is now operational and complemented by the development of dedicated software for data extraction. The problem of picture data storage can be overcome in this way, enabling continuous data collection via internal hard disks, or data transmission by radio or satellite systems (GSM, UMTS, Argos etc.) according to the environment (open sea, coastal or inshore areas). The application of the methodology presented – oriented towards schools associated with a drifting FAD – can be used to study the effect of artificial reefs on fish attraction (Brehmer et al. 2003) or effects of an aquaculture sea-cage farm on local fish distribution (Dempster et al. 2002). This technology could also be applied to other field studies such as school passage inside large estuaries and channels (Pedersen and Trevorrow 1999), or the migration process occurring in straits (such as *Thunnus thynnus* in Gibraltar, com pers. J.-M. Fromentin), where it will provide information on phenomena of major importance that are presently poorly documented.

Acknowledgements. This work was supported by the European Union; project FADIO (contract QLRI-CT-2002-02773). We are grateful to Laurent Dagorn (IRD), who offered us the valuable opportunity to transfer knowledge from small pelagic fish monitoring to tropical tuna species, and to François Gerlotto for his corrections and comments. We also are grateful to the crew of the "Indian Ocean Explorer", Captain Francis Roucou, and the helpful technical support of Pierre Palud and Christophe Corbières (SIMRAD Europe France).

References

Andersen L.N., Berg S., Gammelsæter O.B., Lunde E.B., 2006, New scientific multibeam systems for fisheries research applications. In: Rodriguez J.SM. (Eds), Proc. 8th Eur. Conf. Underwater Acoustics, pp. 385-386.

Brehmer P., Gerlotto F., Samb B., 2000, Measuring fish avoidance during surveys. ICES CM 2000/K:07.

Brehmer P., Gerlotto F., Rouault A., 2002, *In situ* inter-standardisation of acoustic data: an integrated database for fish school behavioural studies. Acta Acoust.88, 730-734.

Brehmer P., Gerlotto F., Guillard J., Sanguinède F., Guénnegan Y., Buestel D., 2003, New applications of hydroacoustic methods for monitoring shallow water aquatic ecosystems: the case of mussel culture grounds. Aquat. Living Resour. 16, 333-338.

Brehmer P., Lafont T., Georgakarakos S., Josse E., Gerlotto F., Collet C., 2006, Omnidirectional multibeam sonar monitoring: Applications in fisheries science. Fish Fish. 7, 165-179.

Brehmer P., Gerlotto F., Laurent C., Cotel P., Achury A., Samb B., 2007, Schooling behaviour of small pelagic fish: phenotypic expression of independent stimuli. Mar. Ecol. Prog. Ser. 334, 263-272.

Castro J.J., Santiago J.A., Santana-Ortega A.T., 2001, A general theory on fish aggregation to floating objects: an alternative to the meeting point hypothesis. Rev. Fish Biol. Fish. 11, 255-277.

Dagorn L., Holland K.N., Itano, D.G., 2007, Behaviour of yellowfin (*Thunnus albacares*) and bigeye (*T. obesus*) tuna in a network of fish aggregating devices (FADs). Mar. Biol. 151, 595-606.

Dempster T., Taquet M., 2004, Fish aggregation device (FAD) research: gaps in current knowledge and future directions for ecological studies. Rev. Fish Biol. Fish. 14, 21-42.

Dempster T., Sanchez-Jerez P., Bayle-Sempere J.T., Giménez-Casalduero F., Valle C., 2002, Attraction of wild fish to sea-cage fish farms in the south-western Mediterranean Sea: spatial and short-term temporal variability. Mar. Ecol. Prog. Ser. 242, 237-252.

Diner N., Massé J., 1987, Fish school behaviour during echo survey observed by acoustic device. Internat. Symp. Fisheries Acoustics, 21-24 June, 1987, Seattle.

Diner N, 2007, Evaluating uncertainty in measurements of fish shoal aggregate backscattering cross-section caused by small shoal size relative to beam width. Aquat. Living Resour. 20, 17-121.

Doray M., Josse E., Gervain P., Reynal L., Chantrel J., 2006, Acoustic characterisation of pelagic fish aggregations around moored fish aggregating devices in Martinique (Lesser Antilles). Fish. Res. 82, 162-175.

Fedoryako B.I., 1988, Fish accumulations in the open ocean near stationary buoys. J. Ichthyol. 28, 667–669.

Fonteneau A., Ariz J., Gaertner D., Nordstrom V., Pallares P., 2000, Observed changes in the species composition of tuna schools in the Gulf of Guinea between 1981 and 1999, in relation with the Fish Aggregating Device fishery. Aquat. Living Res. 13, 253-257.

Foote K.G., Chu D., Hammar T.R., Baldwin K.C., Mayer L.A., Hufnagle L.C., Jech J.M., 2005, Protocols for calibrating multibeam sonar. J. Acoust. Soc. Am. 117, 2013-2027.

Fréon P., Dagorn L., 2000, Review of fish associate behaviour: toward a generalisation of the meeting point hypothesis. Rev. Fish Biol. Fish. 10, 183-207.

Gerlotto F., Hamitouche C., Simmonds E.J., Georgakarakos S., Fernandes P., 2001, Analyse et visualisation tri-dimensionnelle des images sonar. Final report, Fair CT 96 1717, CRHMT, Sète.

Gaertner D., Pagavino M., Marcano J., 1996, Utilisation de modèles linéaires généralisés pour évaluer les stratégies de pêche thonière à la senne en présence d'espèces associées dans l'Atlantique ouest. Aquat. Living Resour. 9, 305-323.

Gerlotto F., 1993, Identification and spatial stratification of tropical fish concentrations using acoustic populations. Aquat. Living Resour. 6, 243-254.

Goncharov S.E., Borisenko E.S., Pyanov A., 1989, Jack mackerel schools defence reaction to a surveying vessel. Proc. Inst. Acoust. 11, 74-78.

Hafsteinsson M.T., Misund O.A., 1995, Recording the migration behaviour of fish schools by multi-beam sonar during conventional acoustic surveys. ICES J. Mar. Sci. 52, 915-924.

Haugland E.K., Misund O.A., 2004, Evidence for a clustered spatial distribution of clupeid fish schools in the Norwegian Sea and off the coast of southwest Africa. ICES J. Mar. Sci. 61, 1088-1092.

Josse E., Bertrand A., 2000, *In situ* acoustic target strength measurements of tuna associated with a fish aggregating device. ICES J. Mar. Sci. 57, 911-918.

Josse E., Dagorn L., Bertrand A., 2000, Typology and behaviour of tuna aggregations around fish aggregating devices from acoustic surveys in French Polynesia. Aquat. Living Resour. 13, 183-192.

Mackinson S., Nøttestad L., Guénette S., Pitcher T.J., Misund O.A., Fernö A., 1999, Cross-scale observations on distribution and behavioural dynamics of ocean feeding Norwegian spring spawning herring (*Clupea harengus* L.). ICES J. Mar. Sci. 56, 613-626.

Marsac F., Fonteneau A., Ménard F., 2000, Drifting FADs used in tuna fisheries: an ecological trap? In: Le Gall J.Y., Cayré P., Taquet M. (Eds.), Pêche thonière et dispositifs de concentration de poissons. Ed. Ifremer, Actes Colloq. 28, 537-552.

Miquel J., Delgado de Molina A., Ariz J., Delgado de Molina R., Déniz S., Díaz N., Iglesias M., Santana J.C., Brehmer P., 2006, Acoustic Selectivity in Tropical Tuna (Experimental Purse-seine Campaign in the Indian Ocean). Western and Central Pacific Fisheries Commission, 'WCPFC-SC2', FT WP-8; IOTC-2006-WPTT-06, Manila.

Misund O.A., 1990, Observation of schooling herring: school dimensions, swimming behaviour and avoidance of vessel and purse seine. Rapp. P.-v. Réun. Cons. Int. Explor. Mer 189, 135–146.

Misund O.A., Aglen A., Beltestad A.K., Dalen J., 1992, Relationship between the geometric dimensions and biomass of schools. ICES J. Mar. Sci. 49, 305-315.

Misund O.A., Coetzee J., 2000, Recording fish schools by multi-beam sonar: potential for validating and supplementing echo integration recordings of schooling fish. Fish. Res. 47, 149-159.

Palud P., Brehmer P., 2004, Montage du sonar multifaisceaux omnidirectionnel de longue portée SIMRAD SP91–160; Navire: Indian ocean explorer (Belize) EU project: FADIO, 5th Framework Programme, Research Directorate General; Contract #QLRI-CT-2002-02773. Rapp. Techn. CRHMT, Sète.

Parin N.V., Fedoryako B.I., 1999, Pelagic fish communities around floating objects in the open ocean. In: Scott M.D., Bayliff W.H., Lennert-Cody C.E., Schaefer K.M. (Eds.), Proc. Int. Workshop on the Ecology and Fisheries for Tuna Associated with Floating Objects. Inter-Am. Trop. Tuna Comm. Spec. Rep. 11, La Jolla, CA, pp. 447-458.

Pedersen B., Trevorrow M.V., 1999, Continuous monitoring of fish in a shallow channel using a fixed horizontal sonar. J. Acoust. Soc. Am. 105, 3126-3135.

Petitgas P., Monimeau L., Brehmer P., Gerlotto F., 1996, Characterizing the spatial distribution of fish schools with a point process approach: a first application on sonar recordings. ICES CM 1996/B:31.

Pitcher T. J., 1986, The behavior of teleost fishes. John Hopkins University Press, Baltimore.

Relini G., Relini M., Montanari M., 2000, An offshore buoy as a small artificial island and a fish-aggregating device (FAD) in the Mediterranean. Hydrobiologia 440, 65-80.

Rose G.A., Legget W.C., 1988, Hydroacoustic signal classification of fish schools by species. Can. J. Fish. Aquat. Sci. 45, 597-604.

Simrad 1992, Operator Manual Simrad SR240, Fishery sonar. P2291E Software Version 5.0X.Mar, Simrad AS, Horten, Norway.

Simrad 2003, New Sonar Scientific Data Logger. News Bulletin, Fishery 11, Horten, Norway.

Simrad 2004, Simrad SP90 Low frequency long range fishery sonar; Operator manual. 850-164511 / Rev. E, Simrad AS, Horten, Norway.

Simrad 2007, Operator Manual SX90, Fish finder sonar, Simrad AS, 307672 / Rev. A, Horten, Norway.

Taquet M., 2004, Le comportement agrégatif des dorades coryphènes (*Coryphaena hippurus*) autour des objets flottants. Thèse Doct. Univ. Paris 6.

Tang Y., Iida K., Mukai T., Nishimori Y., 2006, Estimation of fish school volume using omnidirectional multibeam sonar: scanning modes and algorithms. J. Acoust. Soc. Am. 45, 4868-4974.

Trygonis V., Georgakarakos S., 2007, Investigation of school speed measurement errors by simulation. In: Report, the Working Group on Fisheries Acoustics Science and Technology (WGFAST), ICES Fish. Technol. Comm. ICES CM 2007/FTC:09.