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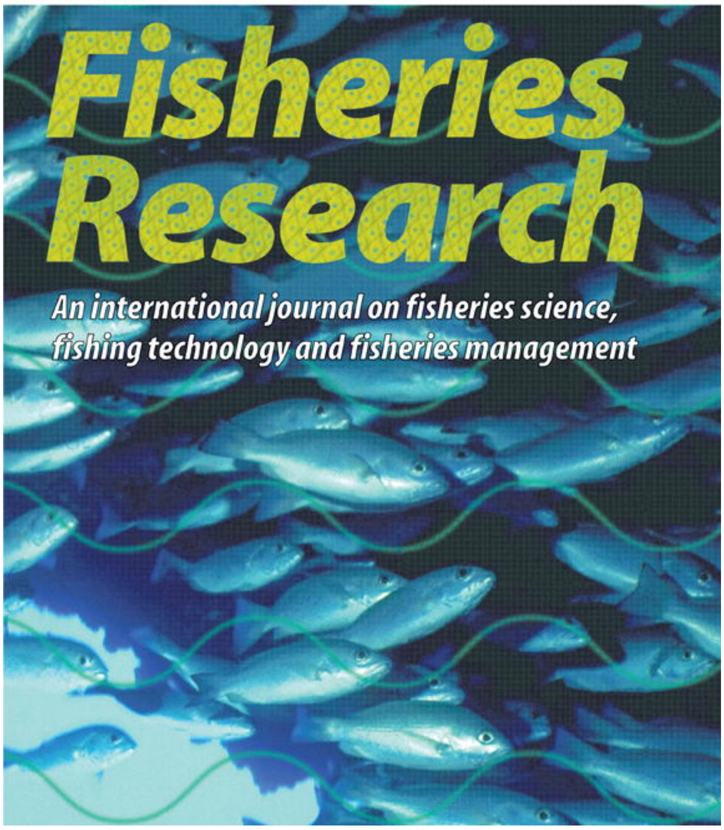

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Acoustic characterisation of pelagic fish aggregations around moored fish aggregating devices in Martinique (Lesser Antilles)

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Abstract

Sea cruises were conducted for 57 days over 16 months to characterise pelagic fish aggregations around two moored fish aggregating devices (FADs) in Martinique (Lesser Antilles). Echosounder surveys run in a star pattern were used in conjunction with obliquely beamed sonar observations. An echo-integration-by-shoal algorithm was implemented to isolate pelagic fish shoals from sound scattering layers and to compute mean morphometric, positional and density parameters. Tree regressions were used to select and classify pelagic fish target strengths (TS), with reference to their spatial and temporal characteristics. The main type of pelagic fish aggregation was a large sub-surface aggregation. It was observed during all daytime periods within a radius of 400 m of the FAD. A smaller type of aggregation was observed closer to the surface and to the FAD in 65% of daytime periods. Large scattered fish were observed in 16% of daytime periods. At night, a medium-sized aggregation was detected in the sub-surface in 75% of night-time periods. The sizes of the fish inside the aggregations (determined from TS values) were lower in the small near-surface aggregation than in the large sub-surface aggregation. Mean packing densities of sub-surface medium fish and near-surface small fish aggregations (determined from TS and shoal acoustic density) were respectively 0.2 and 1.3 fish per m^3. The acoustic methodology and results are discussed with reference to the characteristics and performance of the echosounder and to the spatial structure of pelagic fish aggregations around moored FADs in Martinique.

Keywords: Fish aggregating device; Acoustics; Target strength; Shoal density; Aggregative behaviour; Large pelagic fish; Tuna; Lesser Antilles

1. Introduction

Large pelagic fishes such as tuna, dolphinfish and billfish naturally aggregate around moored fish aggregating devices (FADs) (Fréon and Dagorn, 2000). Since antiquity, small-scale fishermen have deployed moored FADs near the coasts of their islands (Morales-Nin et al., 2000) to take advantage of this aggregative behaviour. Indeed, moored FADs have increased the vulnerability of large pelagic resources and particularly of juveniles (Fréon and Dagorn, 2000).

Studies on fish aggregated around moored FADs have been developed using various techniques: acoustic telemetry (Cayré and Chabanne, 1986; Holland et al., 1990; Cayré, 1991; Josse et al., 1998; Marsac and Cayré, 1998; Brill et al., 1999; Klimley and Holloway, 1999; Dagorn et al., 2000; Girard et al., 2004; Ohta and Kakuma, 2005; Schaefer and Fuller, 2005), fishery statistics (Cillauren, 1994; Kakuma, 2000; Doray and Reynal, 2003), conventional (Adam et al., 2003) and archival (Musyl et al., 2003) tags, experimental fishing and visual census (Taquet et al., 2000; Dempster, 2004, 2005). These studies have provided valuable information on individual fish behaviour (acoustic telemetry, archival tags), near-surface pelagic fish communities around moored FADs (visual census) or sub-stocks (fishing and tag and release data). However, the spatial distribution and biomass of major pelagic fish aggregations associated with moored FADs remain mostly unknown. This quantitative characterisation of pelagic fish communities associated with floating objects at the scale of aggregations is a prerequisite for implementing sustainable management of FAD fisheries. Designing specific surveying techniques is needed to achieve this goal. In this paper, we present a new methodology for acoustically characterizing the spatial distribution, size composition and packing density of pelagic fish aggregations around moored FADs. This technique was applied around moored FADs in Martinique.

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Martinique and Guadeloupe Islands (French West Indies) have shown significant and fast development of the moored FAD fisheries with high rates of juvenile catches (Doray et al., 2002). In Martinique, no fishery statistic collection system has been implemented. Current knowledge on pelagic resources aggregated around moored FADs is based on scarce commercial fishing data (Doray et al., 2002) and on a single experimental fishing cruise (Taquet et al., 2000). Josse et al. (1999) studied for the first time large pelagic fish aggregations in French Polynesia using an echosounder. We followed this pioneering work and conducted classical vertical acoustic sampling (with the echosounder pointing downwards) around two moored FADs in Martinique. We also conducted oblique beaming acoustic surveys (with an inclinable transducer looking sideward) to expand the volume and the number of angular sectors that were sampled. The morphology and position of large pelagic fish aggregations were characterised using an echo-integration-by-shoal (EI-shoal) algorithm. The backscattered acoustic energy of single acoustic targets (or target strength: TS) was analysed to (i) classify pelagic fish aggregations with reference to their individual acoustic targets and (ii) assess the pelagic fish aggregation density in combination with EI-shoal results. We discuss and validate this new methodology, with reference to the characteristics and performance of the echosounder and to the spatial structure of pelagic fish aggregations around moored FADs in Martinique.

2. Materials and methods

2.1. Temporal and spatial scale

From January, 2003 to April, 2004, data were collected during 16 monthly cruises aboard the 12 m fishing vessel "Béryx" within the framework of the DAUPHIN research project. Two moored FADs located on the leeward coast of Martinique, at 7 (coastal FAD) and 25 (offshore FAD) nautical miles from the coast were studied. The coastal moored FAD had one head (terminal floating group of buoys) and was derived from the Ifremer Martinican type (Guillou et al., 2000). The buoyancy of the offshore FAD was increased by adding a second head linked to the first one at about 150 m depth, so as to cope with rough sea conditions and strong seasonal currents. In order to cover a complete diel cycle and to estimate the day-to-day biomass variability over three 24 h periods, each leg began at about 12 a.m. on the first day and ended around 2 p.m. on the third day.

2.2. Acoustic data collection

2.2.1. Echosounder specifications

The vessel was equipped with a Simrad EK60 scientific echosounder (version 1.4.6.72) connected to two hull-mounted, spherical split-beam transducers (ES38-B and ES120-7G). The transducers emitted respectively at frequencies of 38 and 120 kHz (beam angles at −3 dB: 7°). An ellipsoidal ES 120-2.5×10 120 kHz split-beam transducer (2.5° vertical and 10° horizontal) was also used at the end of a telescopic steel tube (diameter 10 cm) at 3 m depth on the starboard side of the vessel. The transducer could be oriented from 0° to 90° below the sea surface to conduct horizontal observations near the surface or deeper oblique beaming surveys. The pulse length was set to 0.512 ms for both frequencies. The vertical resolution of the echosounder was therefore 9.6 cm (Simrad, 2004) and individual targets could be resolved if their range differed by at least 38 cm. *In situ* on-axis calibration of the echosounder was performed before each cruise using a standard methodology (Foote, 1982). Table 1 gives the results of the calibration and the main settings used during echo surveys.

A noise measurement experiment performed for different values of the vessel speed allowed us to define the optimal survey speed as 7 knots. At this speed, a good signal-to-noise ratio was obtained up to 600 m depth with the 38 kHz frequency and up to 180 m with the 120 kHz vertical transducer at a threshold of −75 dB. The signal-to-noise ratio of the ellipsoidal 120 kHz transducer operated at 5 knots was good up to 300 m depth at a threshold of −70 dB.

Acoustic surveys were replayed with the Movies+ software (Weill et al., 1993) and archived in the international hydroacoustic data format (HAC) (Simard et al., 1997) at a −80 dB threshold. All single echoes with a TS greater or equal to −55 dB were selected using the EK60 SIMRAD algorithms (Andersen, 2005). The TS threshold was selected with reference to TS values given in the literature for tuna (Bertrand and Josse, 2000).

2.2.2. Vertical beaming survey patterns

The survey pattern used during vertical beaming acoustic surveys was the star transect designed by Josse et al. (1999) to study fish aggregations around moored FADs (Fig. 1a). The transect radius was initially set to 1500 m (large star survey). The first preparatory cruises showed that pelagic fishes were aggregated very close to the FAD by day. As a result, the radius of the diurnal transects was reduced to 400 m (small star survey). In daytime, small star surveys were conducted every 2 h in succession around each head of the moored FADs. To determine whether the majority of the biomass was located within the radius of the small transects, large star surveys were conducted once around midday and once around midnight during each leg. For the two-heads FAD, a new survey pattern was used for large star surveys (Fig. 1b). A large star survey was completed within 2 h at 7 knots and a small one within 30 min at the same speed.

2.2.3. Horizontal and oblique beaming survey patterns

2.2.3.1. Horizontal beaming.

Horizontal beaming experiments were implemented to observe near-surface pelagic fish aggregations between 0 and 10 m depth. The acoustic beam was chosen with the smallest equivalent vertical angle available (2.5°) to allow horizontal observations to be made very close to the surface. The vessel completed several 600 m × 300 m rectangular transects around the moored FAD (Fig. 2). As the tube was deployed on the starboard side of the vessel, completing a rectangular transect clockwise allowed us to sample the near-surface layer inside the FAD area and an anticlockwise survey sampled the outer area. As the maximum echosounder range was 300 m, combined clockwise and anticlockwise horizontal beaming sur-

Table 1
Main settings of the Simrad EK60 echosounder used during the acoustic surveys around moored FADs

	Frequency		
	38 kHz spherical	120 kHz spherical	120 kHz ellipsoidal
Operation menu			
Ping interval (ping s^{-1})	1.1–1.2 (max)	1.1–1.2 (max)	1.1–1.2 (max)
Transceiver settings menu			
Transmit power (W)	2000	1000	1000
Pulse length (ms)	0.512	0.512	0.512
Advanced transceiver settings			
Gain	25.66	25.95	27.38
Sa Correction	−0.6	−0.42	−0.5
Bandwidth (Hz)	3275	5557	5557
Two-way beam angle	−20.6	−20.8	−24
Absorption (dB km^{-1})	6.16	45.9	45.9
Athw. angle sens.	21.9	21	15
Athw. beam angle (°)	6.85	7.2	10
Athw. offset angle (°)	−0.10	0.05	0.09
Along. angle sens.	21.9	21	61
Along. beam angle (°)	6.84	7.21	2.52
Along. offset angle (°)	0.12	−0.03	0
Transducer depth (m)	0	0	0
TS detection menu			
Minimum echo length	0.8	0.8	0.8
Maximum echo length	1.8	1.8	1.8
Maximum gain comp. (dB)	6.0	6.0	6.0
Maximum phase dev.	8	8	8

veys therefore allowed a near-surface layer of a rectangular area of 1200 m × 900 m to be sampled around the FAD.

2.2.3.2. Oblique beaming. Exploratory oblique beaming surveys revealed that there was only one large sub-surface pelagic fish aggregation within a radius of 400 m around the moored FAD. As a result, a 600 m × 300 m rectangular survey pattern (Fig. 2) was designed to routinely observe this sub-surface aggregation in oblique beaming, i.e. with the transducer set at 20° or 30°. Rectangle transects were repeated three or four times at different distances from the FAD to obtain sections of the aggregation at different depths. When sea conditions allowed the vessel to be attached to the moored FAD, oblique beaming observations were also performed to study the inner structure and dynamics of the sub-surface aggregation. The ellipsoidal transducer was set between 20° and 30° and 15 min recordings were made successively while rotating the tube from 0° to 360°, in increments of 45°. In order to establish the swimming pattern of pelagic fishes inside aggregations, vertical observations were made simultaneously at 38 kHz (Fig. 2).

2.2.4. TS surveys

TSs were recorded in daytime near or within pelagic fish aggregations when the vessel was slowly drifting for periods of about 1 h. TSs were also recorded when the vessel was attached to the moored FAD for periods of 1.75 h on average, by day and night. These fixed surveys were conducted when the weather conditions were favourable and when the number of TSs collected while drifting was too low.

2.3. Data processing

2.3.1. Echo-integration-by-shoal

The density of the majority of pelagic fish aggregations observed around moored FADs in Martinique was above the threshold that allows acoustic resolution of individual fish. An EI-shoal algorithm implemented in the Movies+ software (Weill et al., 1993) was therefore applied to vertical beaming acoustic data. This algorithm was used to define sets of samples, or acoustic shoals (Kieser et al., 1993), forming a patch on the echogram. The geometry of shoals whose width was more than 1.5 times the width of the acoustic beam was corrected for acoustic beam pattern effects by Movies+ (Diner, 2001). Shoals that did not fulfil this length requirement were not corrected. They were analysed together with corrected shoals. As vertical and oblique beaming surveys demonstrated that large pelagic fish were concentrated close to the moored FAD, we assumed that star acoustic surveys provided successive vertical acoustic cross-sections of single pelagic fish aggregations (Fig. 3). Due to the loose structure of aggregations, the acoustic cross-sections were often made of several acoustic shoals (Fig. 3). Echograms were scrutinized to (i) classify acoustic shoals as portions of sound scattering layers or portions of pelagic fish aggregation and (ii) allocate pelagic fish shoals to corresponding acoustic cross-sections. Actually, pelagic fish acoustic shoals were visually classified into several types of aggregations inside each acoustic cross-section, based on shape and position criteria (Fig. 3). Overall parameters were computed for each acoustic cross-section of each type of aggregation from the parameters of acoustic shoals. This was done with refer-

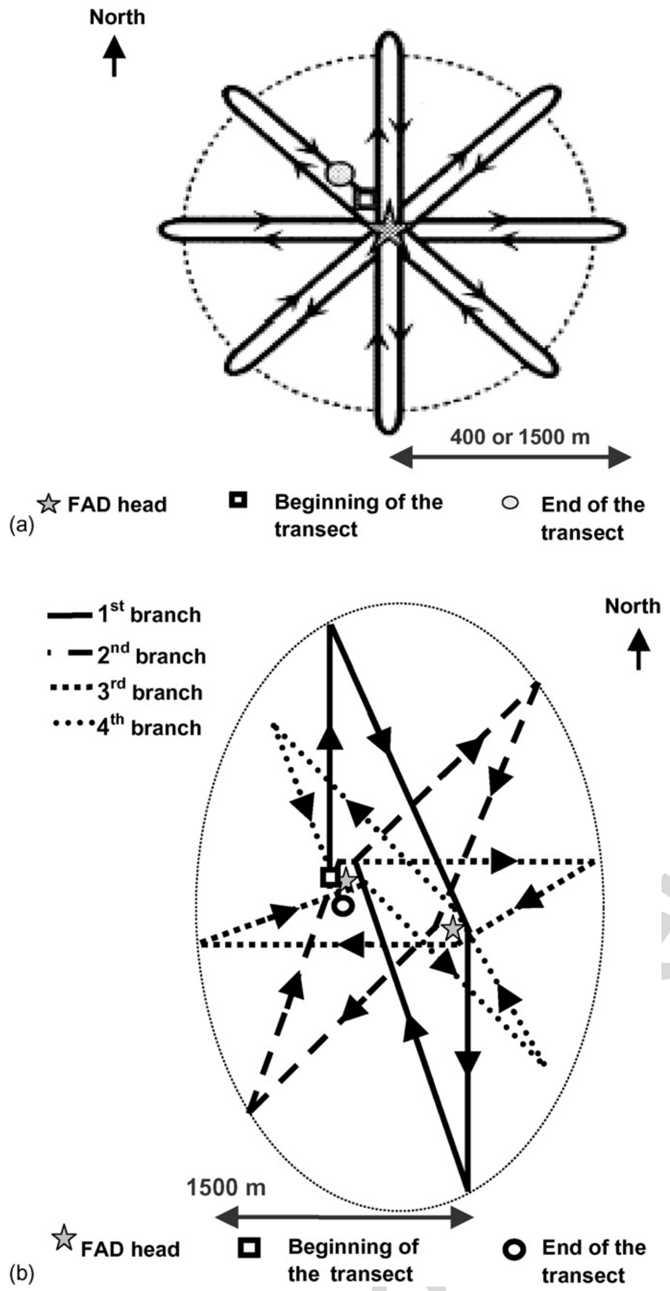

Fig. 1. Vertical beaming acoustic survey patterns used around (a) single head moored FAD (redrawn from Josse et al., 1999) and (b) two-heads moored FAD.

ence to standard protocols for school-based data analysis (Reid et al., 2000). The coordinates of the barycenter of an aggregation cross-section in the vertical plane (i.e. its distance to FAD and depth) were calculated from the mean of the coordinates of acoustic shoal barycenters weighted by their acoustic density (volume backscattering coefficient: S_v). Finally, descriptors of each type of aggregation observed during a star survey were computed from the average and standard deviation of the parameters of their respective cross-sections. The coordinates of the barycenter of aggregation types were computed from the mean of the coordinates of the aggregation cross-sections barycenters, weighted by their volume backscattering coefficient. Parameters retained for characterising the pelagic fish aggregations were: (i) morphometric parameters: maximum width, height and cross-sectional area, number of shoals in aggregation cross-sections; (ii) positional parameters: distance from aggregation barycenter to FAD, barycenter depth, minimum and maximum depth; (iii) a density parameter: volume backscattering strength (S_v).

2.3.2. *TS analysis*

We first checked that the theoretical performance of the echosounder allowed single tuna targets to be detected in the depth layers where pelagic fish aggregations were observed in acoustic surveys. We used the methodology proposed by Josse et al. (1999) for this purpose.

TSs were therefore used to (i) infer differences in the composition of pelagic fish aggregations and define types of aggregations and (ii) compute a mean TS value for each type of aggregation. TS is known to be highly variable (Barange et al., 1994; Simmonds and MacLennan, 2005) and TS variability of more than 15 dB has commonly been observed for the same fish in the case of yellowfin tuna, *Thunnus albacares* (Bonnaterre, 1788) and bigeye tuna, *Thunnus obesus* (Lowe, 1839) (Bertrand et al., 1999). To cope with this high TS variability, we followed Josse et al. (1999) and favoured the selection of good quality echoes at the expense of quantity. For this purpose, we set a minimum TS analysis threshold and only retained TS values of fish that had been tracked for at least three consecutive pings. The number of missing pings allowed in a track was set to 1 and the maximum depth variation between 2 pings in a track to 1.5 m. This last value was chosen with reference to maximum vertical velocities recorded for tuna during ultrasonic tracking experiments around moored FADs (Cayré and Chabanne, 1986; Marsac and Cayré, 1998).

For each survey, all TS values retained after filtering were pooled together. The resulting *in situ* TS distributions were analysed to identify Gaussian-like distributions, that were assumed to correspond to one species and/or size range (Simmonds and MacLennan, 2005). However, TS distributions were often mixtures of overlapping Gaussian distributions and isolating distinct modes was not straightforward. Using regression trees (Breiman et al., 1984), TS values were classified into clusters of minimum deviance with reference to ancillary variables (depth, time and distance to FAD). In this case, minimum TS deviance in a cluster corresponded to a rough normality of the TS distributions. For each TS survey, Gaussian-like TS distributions isolated by tree modelling were retained for further analysis if the presence of pelagic fish aggregations in their depth/distance cluster was confirmed by visual checking of the echogram. Gaussian-like TS distributions were therefore allocated to different TS categories based on their mean values.

The consistency of these TS categories was validated by implementing a global tree analysis on all TSs issued from Gaussian-like distributions. TS was the dependent variable and depth, distance to the FAD, hour of day, month and FAD name were descriptors. FAD name and month effects were introduced to validate the spatial and temporal consistency of the classification.

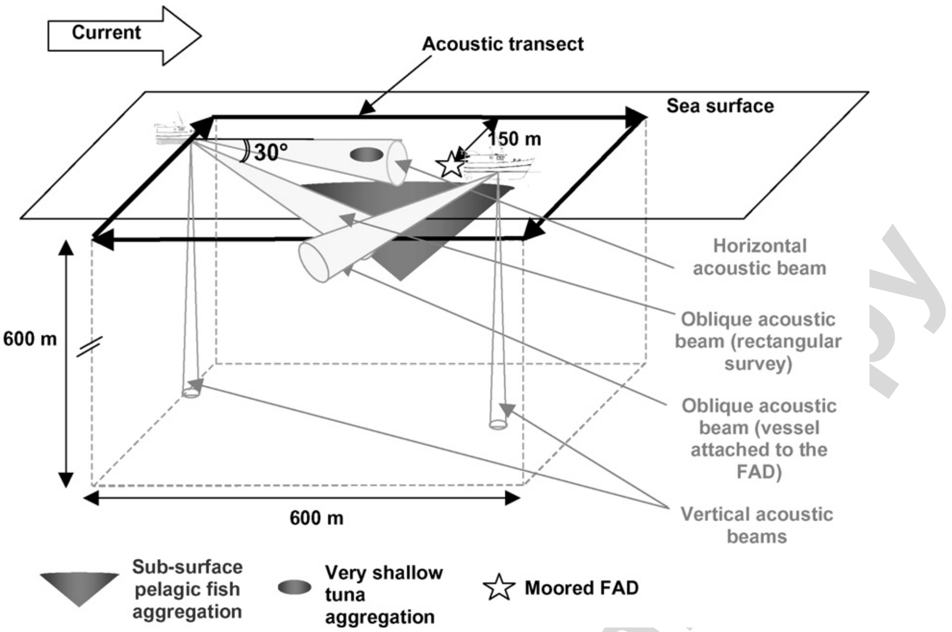

Fig. 2. Oblique beaming acoustic survey patterns used around moored FADs in Martinique.

2.3.3. Comparison of TS analysis and echo-integration-by-shoal results

The agreement between the classification of pelagic fish aggregations and TS values was evaluated while: (i) classifying all pelagic fish aggregations into spatial and/or temporal clusters defined by the overall TS tree regression and (ii) calculating the proportion of each type of aggregation in each TS cluster to identify corresponding TS/aggregation types.

The spatial distributions of the types of pelagic fish aggregations and TS categories were summarized by their center position and their average spread in the vertical plane. Dealing with aggregations, the center was defined as the barycenter, the vertical spread as the difference between maximum and minimum depths and the horizontal spread as half the maximum width. The TS center was the geographical center (i.e. the mean TS position) and horizontal and vertical spreads were defined as the standard deviations of the TS coordinates on both axis (Okubo and Chiang, 1974). Differences between the center position and spread of corresponding types of TSs and aggregations were tested with non-parametric Wilcoxon rank sum tests.

The mean fish packing density d_j of the average pelagic fish aggregation of type j was computed based on the following relation (Diner and Marchand, 1995):

$$d_j = 10^{(S_{\mathrm{vm}(j)} - \mathrm{TS}_{\mathrm{m}(j)})/10}$$

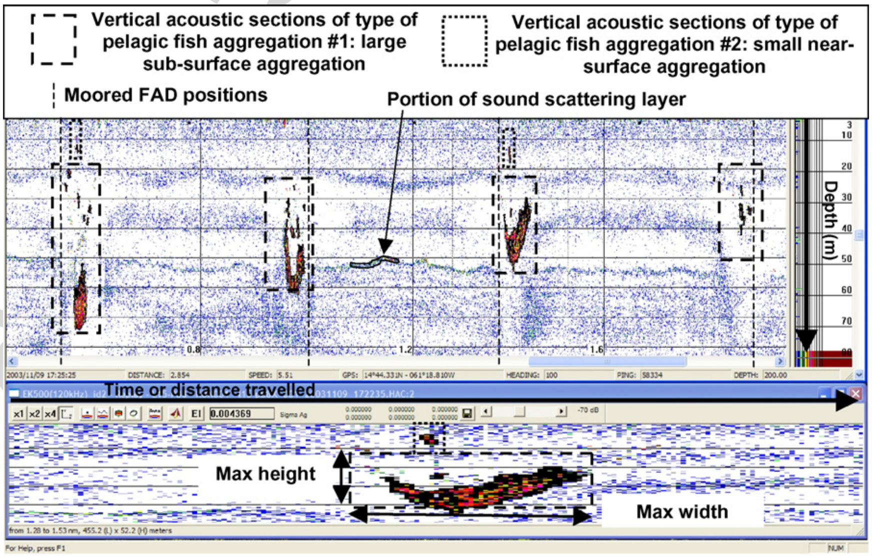

Fig. 3. 120 kHz echogram. Top panel: successive sections of pelagic fish aggregations during a star survey by day. Bottom panel: zoom on an aggregation section with real length/height ratio. Shoals identified by Movies+ outlined in black.

where $S_{\mathrm{vm}(j)}$ is the mean volume backscattering coefficient of the average aggregation of type j and $\mathrm{TS}_{\mathrm{m}(j)}$ is the mean value of the corresponding TS category.

All statistics were implemented using the R language (R Development Core Team, 2005) with the "tree" (Ripley, 2005) and "lattice" (Sarkar, 2005) packages.

3. Results

3.1. Acoustic data collection

3.1.1. Vertical beaming

Sound scattering layers (SSLs) exhibited a higher acoustic response at the 38 kHz frequency than at the 120 kHz frequency (up to 5 dB). Pelagic fish aggregations were generally well separated from SSLs at the 120 kHz frequency whereas they were barely distinguishable within the dense SSLs at the 38 kHz frequency. The 120 kHz frequency was therefore used for studying the large pelagic fish aggregations.

A total of 366 small and 150 large star surveys accounting for 523 h of vertical beaming acoustic recordings were collected over 57 days. In daytime, the main type of acoustic aggregation was a large, generally V shaped, aggregation distributed in the sub-surface (30–100 m) (Fig. 3). This aggregation was observed during all of the 12 cruises conducted around the moored coastal FAD. It was also observed around the two heads of the offshore FAD during the 10 cruises when the FAD was not submerged by current. This aggregation was always located within a radius of 400 m around the moored FAD heads. No other fish aggregation was observed outside the central area during the large star surveys. At night, deep SSLs migrated upward and mixed with sub-surface SSLs. Loose sub-surface aggregations were also observed close to the FAD with a frequency of 75%.

More than 24,000 TS values were recorded during 49 TS surveys (41 drifting and 8 fixed surveys) from May 2003 to March 2004. Isolated very strong acoustic targets were detected near the large sub-surface aggregation during 16% of the days sampled ($n = 9$). Numerous scattered single targets with TS values higher than −40 dB were observed in the whole water column every night.

3.1.2. Horizontal beaming

During the October 2003 cruise, 20 h of horizontal beaming experiments were conducted around the coastal and offshore FADs. The position of very shallow tuna aggregations could be visually identified when fish jumped out of the water. However, it appeared that quantitatively characterizing these aggregations around a moored FAD with an echosounder in horizontal beaming was not possible. The main problem was attenuation, dispersion, and scattering of sound by the air bubbles generated by waves that masked any biological target. Wave bubbles hindered the observations of very shallow tuna aggregations with wave heights as low as 0.5 m with the transducer set at 3 m depth. A single good acoustic observation of these tuna aggregations was made when the sea was exceptionally calm (Fig. 4a). No other pelagic fish aggregation was observed during rectangular horizontal beaming surveys.

3.1.3. Oblique beaming

A total of 60 rectangular oblique beaming surveys were conducted. These observations allowed us to record oblique cross-sections of the large sub-surface aggregation (Fig. 4b). The aggregation was mainly observed in the up-current direction when the vessel was attached to the moored FAD.

3.2. Characterisation of acoustic objects

3.2.1. Echo-integration-by-shoal

EI-shoal analysis was implemented on a dataset of 60 daytime and 13 night-time star surveys conducted during four cruises from May to August 2003. The structural variability of the aggregations was very high during transition periods (dawn and dusk). Surveys conducted during these periods were therefore discarded. Diel and seasonal changes of structure and density of both pelagic fish and portions of SSL acoustic shoals were observed. For this reason, EI-shoal parameters were adjusted for each survey to obtain a satisfactory extraction of pelagic fish shoals from SSLs.

Two types of pelagic fish aggregations were defined by EI-shoal in daytime: the large sub-surface aggregation and a small near-surface aggregation that was observed on 65% of the days sampled ($n = 37$) (Fig. 3). Quantitative descriptors of types of pelagic fish aggregations are presented in Table 2. The large sub-surface aggregation was characterised by a wide vertical and horizontal extension (mean width: 109 m, mean height: 52 m). Its inner structure was complex, as it was made on average of six acoustic shoals of different densities and shape (Fig. 3). It was distributed in the sub-surface, between 35 and 87 m depth, and at 80 m on average of the FAD. The near-surface aggregation was small (mean width: 24 m, mean height: 14 m). It was distributed above the large sub-surface aggregation (mean depth: 24 m) and in the vicinity of the FAD (mean distance to FAD: 36 m) (Fig. 3). A single type of aggregation was defined at night: the night-time sub-surface aggregation. Although its vertical distribution was roughly similar to that of the daytime large sub-surface aggregation, its horizontal extension was more limited (mean width: 54 m).

3.2.2. TS analysis

As pelagic fish appeared to be better detected at 120 kHz than at 38 kHz, we only analysed TSs recorded in 120 kHz. The diel migration of deep SSLs led to a sharp increase of the mean acoustic density of SSLs within the echosounder range at night. We assumed that this phenomenon hindered TS detection too heavily to include TSs recorded at night in the analysis. A limited number of fixed surveys ($n = 4$) were however conducted to record TSs in the vicinity of the night-time loose sub-surface pelagic fish aggregation. After implementing echogram scrutinizing and regression trees, 20,386 TSs were retained as pelagic fish TSs (17,967 by day and 2,419 at night). Tree classification led to the definition of three categories of pelagic fish TSs: scattered large fish only observed by day, sub-surface medium-sized

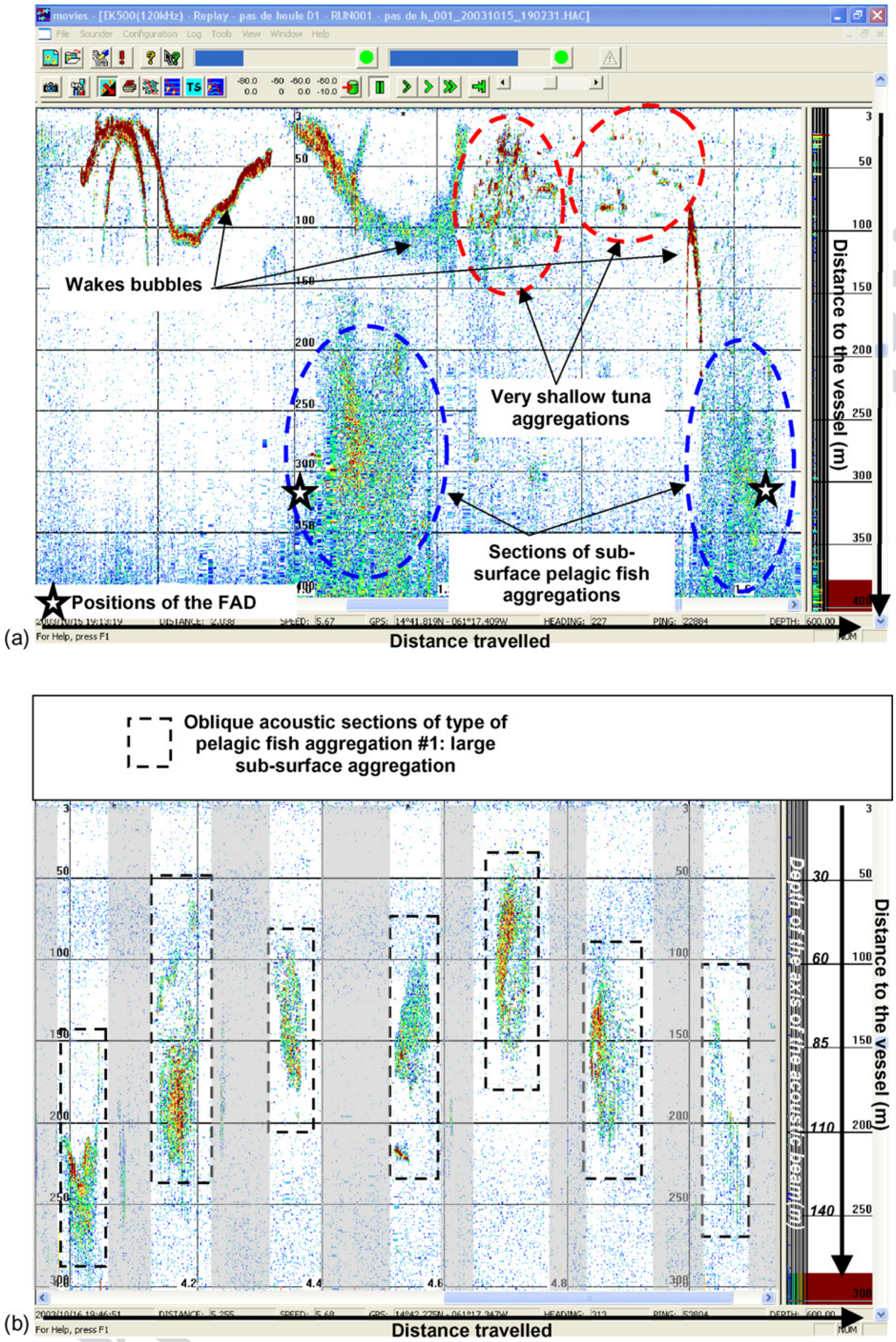

Fig. 4. (a) Horizontal beaming 120 kHz echogram of a daytime rectangular survey with no waves and (b) oblique beaming 120 kHz echogram of a rectangular survey with successive oblique sections of a sub-surface pelagic fish aggregation in green/yellow/red. Discarded sequences in grey.

fish and near-surface small fish observed by day and night. TS distribution histograms of the last two categories are presented in Fig. 5 and quantitative descriptors of all categories in Table 3.

As scattered large fish were very rarely observed, their TS distribution is not presented. They were isolated fish characterised by a very high mean TS value: −18 dB.

Sub-surface medium fish TSs were the most numerous in the database. They were distributed in the sub-surface (mean depth: 65 ± 25 m) at 95 m on average from the FAD. TS/length equations are available in the literature for yellowfin and bigeye tuna at 38 kHz (Bertrand and Josse, 2000). According to the yellowfin tuna equation, the TSs observed in the sub-surface could correspond to medium-sized fish of mean fork length (FL) 60 cm.

Near-surface small fish exhibited a superficial vertical distribution (mean depth: 31 ± 14 m) and the wider horizontal distribution (mean distance to FAD: 235 ± 179 m). The TS distribution of small near-surface fish was truncated on the left (Fig. 5) but the mode of this distribution was evident (−46 dB). We therefore used the mode instead of the mean as position parameter of this truncated TS distribution. A TS of −46 dB would correspond to a physoclistous fish of approximate length 12 cm (Foote, 1987).

Table 2
Descriptors of types of pelagic fish aggregations

	Diel period					
	Day				Night	
	Large sub-surface aggregation		Small near-surface aggregation		Sub-surface aggregation	
	Mean	S.D.	Mean	S.D.	Mean	S.D.
Maximum width (m)	109	41	24	8	54	18
Maximum height (m)	52	19	14	8	45	18
Cross-sectional area (m^2)	472	455	21	17	90	34
Number of shoals in aggregation slices	6	2	3	1	5	2
Distance from barycenter to FAD (m)	80	41	36	21	54	26
Barycenter depth (m)	55	15	24	4	42	17
Minimum depth (m)	35	12	18	3	25	12
Maximum depth (m)	87	22	32	6	71	26
Acoustic density: volume backscattering strength (dB)	−42	N.A.	−45	N.A.	−41	N.A.
Packing density (number of fish per m^3)	0.2	0.1	1.3	0.8	0.6	0.4

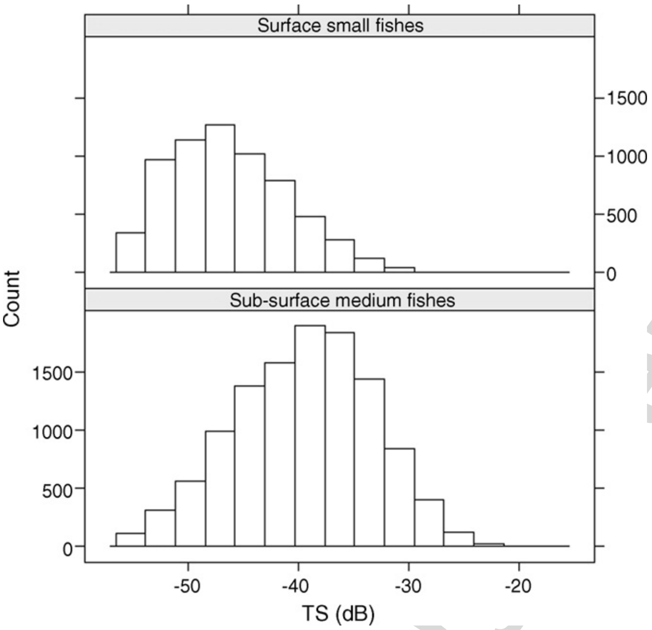

Fig. 5. TS distribution of near-surface small fish and sub-surface medium-sized fish around a moored FAD in Martinique.

The main structuring effect in the total pelagic fish TS dataset appeared to be the depth. The partitioning of all pelagic fish TSs into two depth clusters around 49 m led to the largest reduction of deviance (16%) in the overall tree model. Ninety-two percent of the sub-surface medium-sized fish were detected below 49 m and 82% of the near-surface small fish above this depth. This result validates the consistency of the classification of pelagic fish TSs.

3.2.3. Comparison of TS analysis and echo-integration-by-shoal results

Daytime TSs of sub-surface medium-sized fish and near-surface small fish were averaged in the vertical plane by elementary cells of 5 square meters and plotted in Fig. 6a and b, respectively. The distribution of all scattered pelagic fish is presented in Fig. 6c. The mean spatial distributions of pelagic fish aggregations were plotted on the same graphs as ellipses whose axis are the vertical and horizontal spread of the aggregations.

All barycenters of small near-surface aggregations were located above the depth limit defined in the overall TS tree regression. No significant differences were found in the Wilcoxon tests between their center position and spread (Table 4). Nonetheless, the center position and horizontal spread of near-surface small fish TSs were both significantly greater than those of small near-surface aggregations. The near-surface aggregation and small fish therefore appeared to be located in the same depth layer but scattered small fish were spread at a wider distance from the FAD than small near-surface aggregations.

The large sub-surface aggregation barycenter was located below the overall tree regression depth limit in 62% of the surveys. The sub-surface medium-sized fish center was signifi-

Table 3
Descriptors of TS categories of pelagic fish

	Diel period	Sub-surface medium fishes		Small near-surface fishes	
	Large scattered fishes, day	Day	Night	Day	Night
Number detected	9	13,497	1,997	6,889	422
Mean TS (dB)	−18	−35	−40	−46[a]	−46[a]
TS span (dB)	22	38	29	33	23
Mean distance to FAD (m) ± S.D.	35 ± 69	137 ± 81	NA	124 ± 87	NA
Mean depth (m) ± S.D.	74 ± 8	72 ± 20	26 ± 8	32 ± 14	49 ± 7
Mean detection time ± S.D.	16:20 ± 02:00	14:20 ± 04:00	05:42 ± 01:39	13:48 ± 03:30	06:01 ± 00:48

[a] Mode used instead of mean.

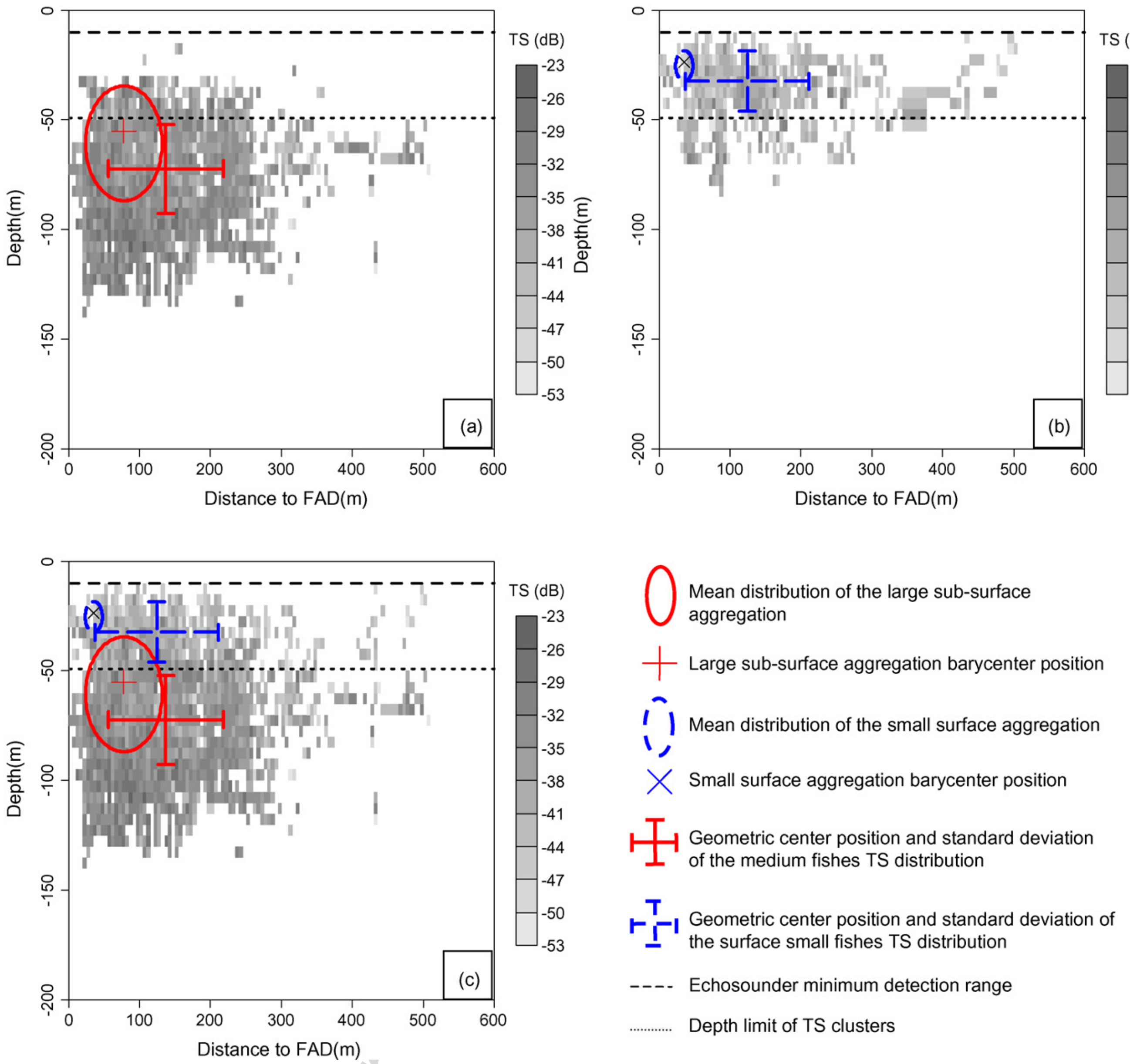

Fig. 6. Mean daytime spatial distribution of pelagic fish aggregations in the vertical plane and (a) mean sub-surface medium-sized fish TS distribution, (b) mean near-surface small fish TS distribution and (c) mean TS distribution of both categories.

cantly deeper and further from the FAD than that of sub-surface aggregation whereas their vertical spread was less than that of sub-surface aggregations. The large sub-surface aggregation therefore appeared to cover a larger depth range than the medium-sized fish and potentially included near-surface small fish in the upper part, as can be seen in the first aggregation cross-section in Fig. 3.

From this analysis, we assumed that the small near-surface aggregation was made of near-surface small fish whereas the large sub-surface aggregation was made on average of a majority of medium-sized fish mixed with small fish in its upper part. Dissimilarities in the structure of fish aggregations assessed by echogram scrutinizing hence appeared to reasonably match the vertical heterogeneity of TSs determined by the tree regression,

Table 4
Results of the Wilcoxon tests comparison of the mean spatial distributions of scattered and aggregated pelagic fish

TS category	Aggregation type	Center depth	Vertical spread	Center distance to FAD	Horizontal spread
Sub-surface medium fishes	Large sub-surface aggregation	>	<	>	×
Near-surface small fishes	Near-surface small aggregation	×	×	>	>

>, TS parameter significantly greater than aggregation parameter; <, TS parameter significantly less than aggregation parameter; ×, non-significant result. All significant results are highly significant ($p < 0.001$).

except in the boundary area between the two types of aggregation where mixing may occur.

Regarding this hypothesis, the mean packing density of daytime near-surface aggregations was calculated using the mode of the near-surface small fish TS distribution. The mean packing density of sub-surface pelagic fish aggregations was calculated using the mean of the daytime TS values of sub-surface medium-sized fish (Table 3). The packing density of night-time sub-surface pelagic fish aggregations was calculated based on the mean TS of all individual targets detected at night: −40 dB.

4. Discussion

4.1. Acoustic data collection

4.1.1. Influence of fishing activities

Two 7 m undecked commercial vessels were fishing on average around the moored FADs during acoustic surveys. No difference in the distribution or behaviour of pelagic fish aggregations was observed when the fishing vessels were present.

4.1.2. Vertical acoustic sampling

Pelagic fish aggregations located close to the surface were under-sampled compared to sub-surface aggregations, due to the acoustic beam geometry. First, echosounder near field and air bubbles produced by waves hindered both vertical and horizontal acoustic detection in an acoustic blind zone between 0 and 10 m depth. In fact, very shallow tuna aggregations detected during horizontal beaming experiments were never observed in vertical beaming. A blue marlin spends about 70% of the time between 0 and 10 m depth with reference to archival tag experiments (Graves et al., 2003; Saito et al., 2004). The acoustic sampling of this species was therefore biased. Acoustic surveying with an echosounder beaming upward (e.g. aboard an autonomous underwater vehicle) and/or combined scuba diving observations and ultrasonic tagging (e.g. Taquet, 2004) would allow a more efficient study of pelagic fishes in very shallow waters around FADs.

Below 10 m depth, the volume sampled by the echosounder with the use of vertical beaming was proportional to the diameter of the acoustic beam. The majority of near-surface and sub-surface pelagic fish aggregations were distributed below the depth at which successive acoustic beams overlap. For that reason, they were entirely sampled by the echosounder along the path of the vessel. However, near-surface aggregations were insonified by fewer beams than large sub-surface aggregations. The mean diameter of the acoustic beam within the depth stratum of the aggregations was low compared to their mean width. Therefore, errors in the geometry of pelagic fish aggregations that occur when the acoustic beam is not totally occupied might be very limited.

4.1.3. Horizontal acoustic sampling

Although horizontal beaming experiments did not provide a reliable quantitative sampling of the very shallow tuna aggregations, it provided additional information to the vertical beaming surveying of the area surrounding the FAD. In fact, if a large fish aggregation had been present in the superficial layer (0–10 m) sampled by the echosounder with the use of horizontal beaming, its presence would have been detected.

The star survey pattern was chosen because it allowed the vessel to pass frequently near the head of the moored FAD during a survey (Josse et al., 1999). Moreover, it always sampled an area well centered around the device. In addition, the star survey pattern was particularly well suited for studying pelagic fish aggregations around moored FADs in Martinique, as the highest effort was applied, more or less, to the area with the highest biomass. Oblique beaming was primary used to validate the hypothesis that only one large sub-surface aggregation occurred around moored FADs. Oblique acoustic sections of a sub-surface aggregation could however be combined in the future with vertical sections of the same aggregation to infer its mean 3D shape.

The positions of acoustic objects in the horizontal plane were located with reference to the position of the moored FAD head(s) to allow comparisons between surveys. As the length of the anchoring rope of the moored FAD was greater than the mooring depth, the moored FAD could sometimes drift over hundreds of meters during a single acoustic survey. The moored FAD position was noted each time the vessel passed near the FAD head during star surveys. Thereby, the position of the FAD during the survey could be precisely modelled as a function of time. In this way, positions of acoustic shoals were precisely calculated with reference to the FAD position. Therefore, any error made while estimating the distance to the FAD of pelagic fish aggregations was low. The positioning error was however greater in the case of TS surveys for which no precise FAD position was available. Mean FAD positions were used in this case to calculate the distance to the FAD of single acoustic targets.

Differences were noted in the results of drifting and fixed TS surveys: the mean TS and depth of targets detected during drifting surveys (−35 dB) were significantly higher ($p < 0.01$, Wilcoxon rank sum tests) than those of targets detected during fixed surveys (−39 dB). Moreover, the span of TSs recorded during drifting surveys (43 dB) was also significantly higher ($p < 0.01$) than that of fixed surveys (36 dB). During fixed surveys, TSs were only collected in a given area of the aggregation. Drifting surveys provided a more extensive sampling of pelagic fish aggregations, as the vessel passed over the whole aggregation during a survey. This sampling difference can explain the differences observed between TS of fixed and drifting surveys. As the mean target depth was lower in the case of fixed surveys, it may be assumed that fixed surveys mainly sample fish inhabiting the near-surface layer. Moreover, cases of association of small near-surface fish with the research vessel were observed during both drifting and fixed surveys. This associative behaviour could have biased the distances to the FAD recorded during some TS surveys and could partly explain the wide horizontal distribution of small near-surface fish. The horizontal distribution of small near-surface fish observed in this study is however consistent with the spatial distribution of commercial catches of small tuna caught with trolling lines previously reported around moored FADs in Martinique (Reynal et al., in press), in Vanuatu (Cillauren, 1987) and in Hawaii (Matsumoto et al., 1981).

Night-time TSs were only collected during a few fixed surveys and their mean TS seemed to be underestimated. The large difference (5 dB) observed between daytime and night-time sub-surface fish mean TS values is more likely to reflect differences in sampling than differences in composition and/or behaviour.

4.2. Acoustic data processing

4.2.1. EI-shoal

Josse et al. (1999) used classical echo-integration-by-depth-layer to estimate the density of shoaling pelagic fish aggregations around moored FADs in French Polynesia. This technique relies on the setting of a minimum EI threshold to discriminate between acoustic samples of species of interest and other echoes (e.g. Josse et al., 1999). In the case of Martinican moored FADs, patches in SSLs were often as dense as certain parts of pelagic fish aggregations. Relying only on a minimum echo-integration threshold for isolating pelagic fish from SSLs was therefore not possible. EI-shoal provided a visual control of the patches of acoustic samples that would be echo-integrated and hence permitted pelagic fish shoals to be efficiently extracted from SSLs. At the 120 kHz frequency, SSLs were most of the time interrupted around vertical sections of pelagic fish aggregations (cf. Fig. 3). Therefore, we considered that the positive bias introduced in the estimation of the acoustic density of pelagic fish aggregations by the mixing of pelagic fish and SSLs was very limited and negligible.

Applying EI-shoal to pelagic fish aggregations required setting EI-shoal parameters for each survey and was time consuming. Subjective visual setting of parameters can also produce bias in the shoal extraction and therefore in the calculation of shoal descriptors. However, we assumed that errors made at the scale of acoustic shoals were negligible when computing overall parameters for the whole aggregation.

In the same way, the aggregation descriptors presented in this paper were computed based on a subset of surveys. Nonetheless, aggregation morphological patterns were quite stable during all cruises. We therefore assumed that the mean descriptors calculated from the subset of surveys were representative of the average pelagic fish aggregations observed around moored FADs in Martinique between January 2003 and April 2004.

Classical echo-integration-by-depth-layer limits the study of shoaling pelagic fishes at the arbitrary scale of a large elementary sampling unit. EI-shoal allows pelagic fish to be studied at a finer scale that is meaningful in terms of behaviour: the acoustic shoal. Many studies on mono-frequency acoustic shoals of small pelagic fishes have been conducted for the purpose of species identification (Rose and Leggett, 1988; Nero and Magnuson, 1989; Nero et al., 1990; Richards et al., 1991; Reid and Simmonds, 1993; Barange, 1994; Diner et al., 1994; Haralabous and Georgakarakos, 1996; Scalabrin et al., 1996). The present paper showed that EI-shoal could also be used for the purpose of large pelagic fish acoustic identification.

4.2.2. TS analysis

Tree regression proved to be a convenient exploratory technique for quickly uncovering structures in large TS datasets. The advantage of this TS processing technique is that it uses ancillary experimental data for isolating a biologically meaningful Gaussian-like TS distribution.

Drifting slowly over loose pelagic fish aggregations allowed us to record TSs of fish located inside and outside the aggregations. A unimodal, Gaussian-like, TS distribution was isolated within the depth stratum of each aggregation during each survey. This indicates that, for a given type of aggregation, the TS values of aggregated or scattered fish were comparable. Moreover, this result shows that the size distribution of fish within the aggregation was homogeneous.

Josse et al. (1999) postulated that the species and size composition of the aggregations as well as the behaviour of aggregated fish, did not change much between surveys around moored FADs in French Polynesia. The mean TS values of our TS categories were consistent over 1 year around two different FADs. This finding therefore confirms the hypothesis of Josse et al. (1999).

However, TS analysis of single frequency data cannot provide a precise identification of the species and size classes observed around moored FADs. Partial sampling of catches indicates that small (30 cm FL) blackfin *Thunnus atlanticus* (Lesson, 1831) and yellowfin tuna dominated in terms of numbers the commercial catches around moored FADs in Martinique (Doray et al., 2002). Moreover, tropical tunas represent the great majority of worldwide catches around floating objects (Fonteneau et al., 2000). For this reason, we assume that the majority of pelagic fish aggregations we observed acoustically around moored FADs were comprised of tuna. In fact, TSs of sub-surface medium-sized fish are compatible with the values previously recorded for tuna (Bertrand and Josse, 2000; Josse and Bertrand, 2000).

4.2.3. Comparison of EI-shoal and TS analysis results

The joint analysis of the spatial distribution of daytime aggregated and scattered pelagic fish provided rough size composition of pelagic fish aggregation and interesting insights into the aggregative behaviour of pelagic fish around moored FADs. Pelagic fish aggregations appeared to be surrounded by clouds of scattered fishes, especially in the horizontal plane and in the near-surface layer. A “confusion zone” resulting from poor coordination of joining sub-schools has been described for sand-eel coalescing schools (Pitcher and Wyche, 1983). By analogy with this confusion zone, the layer of lower density and therefore of lower coordination surrounding pelagic fish aggregations could be interpreted in terms of aggregative behaviour as a boundary where fishes move inward to or outward from the aggregation.

This hypothesis is partially corroborated by the fact that significant mixing, i.e. exchange was evidenced at the interface between near-surface and sub-surface aggregations. In this way, pelagic fish aggregations around moored FADs should be viewed as dynamic structures partly maintained by flows of fish migrating inward to and outward from the aggregation, as suggested by an exhaustive analysis of yellowfin tuna ultrasonic tracking data (Girard et al., 2004).

4.2.4. Comparison of results with the literature

The only comparable study of pelagic fish aggregation characterisation by echosounding around moored FADs was conducted in French Polynesia by Josse et al. (2000). In this study, the dominant type of aggregation was deep scattered fish distributed between 100 and 300 m. Pelagic fish therefore appeared to be more densely aggregated and shallower in Martinique than in French Polynesia. Josse et al. (2000) observed that differences in the types of aggregations observed around moored FADs could be related to differences in fish size. In French Polynesia, smaller fish usually shoaled in shallow waters, whereas larger ones were scattered in deeper waters. We observed a similar size-dependent vertical stratification in Martinique but this time within the aggregations of shoaling fish.

References to packing densities of shoals of fish larger than small pelagic species are scarce in the literature (Pitcher and Partridge, 1979; Andreeva and Belousov, 1996). Assuming that fish comprising the daytime sub-surface and near-surface pelagic fish aggregations were respectively about 60 and 30 cm FL, our estimates of mean packing densities for these aggregations would be in reasonable agreement with the values given by Andreeva and Belousov (1996). Moreover, the packing density of the sub-surface pelagic fish aggregation is quite similar to the mean fish density estimated by Josse et al. (2000) in the same area around moored FADs in French Polynesia. However, our estimates of packing density for both types of aggregations would only account for 4% of the packing density predicted by the model of Pitcher and Partridge (1979). Given the high variability of fish shoal packing density depending on the origin of the observation (Gerlotto et al., 2005), the mean packing densities of large pelagic aggregations presented in this paper are in reasonable agreement with previous values and models.

5. Conclusion

This study showed that conducting echosounding surveys around moored FADs aboard a 12 m vessel was possible. The small size of the vessel allowed us to test a great variety of acoustic survey patterns, including fixed surveys, and was compatible with working amidst the commercial vessels fishing around moored FADs. The acoustic star transect used in French Polynesia around moored FADs by Josse et al. (1999) was successfully adapted to survey the Martinican pelagic fish aggregations. New oblique beaming techniques were developed to expand the area sampled around moored FADs with a scientific echosounder. However, sampling the very superficial layer of the sea (0–10 m) with an echosounder was shown not to be possible with the use of horizontal beaming. EI-shoal was for the first time applied to large pelagic fish aggregations and allowed quantitative information to be gathered on their morphology, position and density.

Our work confirms that moored FADs are convenient oceanic observatories for studying aggregative behaviour of large pelagic fish around floating objects (e.g. Fréon and Dagorn, 2000). The combination of EI-shoal and TS data showed that large pelagic fish aggregations around moored FADs were nested structures comprised of a relatively dense central part surrounded by a layer of scattered fish. This layer was interpreted as a boundary through which fishes could migrate inward to and outward from the aggregation. The area and acoustic density of pelagic fish aggregations provided by EI-shoal were combined with mean TS values to estimate for the first time *in situ* the acoustic packing density of shoals of large pelagic fishes.

Data collected with complementary identification tools could be used to specify the species and size composition of pelagic fish aggregations characterised by acoustics. This study has shown that it was possible to quantitatively assess the spatial distribution of the acoustic density of a large sub-surface aggregation around a moored FAD. It opens up new prospects for estimating the biomass of large sub-surface pelagic fish aggregation associated with FADs. Such biomass estimates are of prime importance for fishery management purposes and for quantitative studies of the aggregation of pelagic fish around FADs.

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