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Echotrace classification and spatial distribution of pelagic fish aggregations around drifting fish aggregating devices (DFAD)

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Abstract – This work presents a method to observe pelagic fish around drifting fish aggregating devices (DFADs). A triple-frequency vertical echosounder was employed to observe fish distributions in the vicinity of DFADs. Surveys were conducted in a star pattern that was centred at the DFADs. The objective of the study was to define a methodology for future acoustic studies. This goal was pursued by (i) studying the spatial distribution of fish aggregations, (ii) developing concepts for the grouping of observed aggregations and (iii) developing specifications for future autonomous acoustic tools. For this purpose 5 cruises were carried out in the western Indian Ocean. The multi-frequency approach proved useful as a means of separating acoustic detections into sound-scattering layers (e.g. plankton and micronekton), fish aggregations and individual fish. Fish target strength (TS) was measured. Four types of aggregations were found near DFADs: (i) dense structure (ii) medium structure (iii) loose structure and (iv) structure consisting of separated targets. More than 90% of these structures were found within a radius of 400 m and about 75% within 200 m of the DFADs. The spatial configuration of DFAD fish aggregations appeared to be more dynamic compared to aggregations near moored FADs. The spatial distribution and structure of DFAD aggregations have direct implications for their catchability by tuna purse-seiner. We have carried out the first quantitative acoustic recordings around DFADs, and obtained a better understanding of the spatiotemporal dynamics of fish aggregations around DFADs in the Indian Ocean. Based on this knowledge we are now working on specifications for instrumented buoys that are intended as autonomous data recording observatories for such pelagic environments.

Key words: Drifting Fish Aggregating Devices / Survey design / Multi-frequency / Tuna behaviour / Schooling behaviour / Pelagic ecosystem / Echotrace classification

Résumé – Classification des échotraces et distribution spatiale des agrégations de poissons pélagiques autour de dispositifs de concentration de poissons (DCP). Cette étude présente une méthode permettant d'observer les poissons pélagiques autour de DCP dérivants. Un échosondeur vertical multi-fréquence est utilisé pour observer la distribution des poissons autour des DCP. Les prospections sont réalisées en suivant un parcours en étoile centrée sur le DCP. L'objectif de l'étude est de définir une méthodologie en vue de futures études acoustiques afin (i) d'étudier la distribution spatiale des agrégations de poissons, (ii) de développer des concepts sur la structuration des agrégations de poissons et (iii) de définir les spécificités pour de futurs outils acoustiques autonomes. Cinq campagnes de recherche sont réalisées dans l'ouest de l'océan Indien. L'approche multi-fréquence s'est révélée être une méthode très utile pour discriminer les différents réflecteurs acoustiques : couches diffusantes (plancton et micronecton), agrégations de poissons, ou cibles individuelles. Les indices de réflexion des cibles individuelles (TS, target strength en anglais) sont mesurés. Quatre types de structure ont été observés près des DCP : structures denses, moyennes, lâches, ainsi que des structures formées de cibles isolées. Plus de 90 % de ces structures ont été trouvés dans un rayon de 400 m et environ 75 % dans un rayon de 200 m, autour des DCP. Les agrégations de poissons apparaissent plus dynamiques autour de DCP dérivants que de DCP ancrés. La distribution spatiale des agrégations des poissons autour des DCP dérivants

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a une application directe sur leur capturabilité par les thoniers-senneurs. Il s'agit des premières données acoustiques quantitatives obtenues autour de DCP dérivants, permettant une meilleure compréhension de la dynamique spatiale de ces agrégations dans l'océan Indien. Ces données permettront de définir les caractéristiques techniques d'observatoires instrumentés autonomes destinés à enregistrer automatiquement des données dans de tels environnements pélagiques.

1 Introduction

Tropical tuna and other large pelagic fishes such as dolphinfish and billfish are known to aggregate around Fish Aggregating Devices[1] (FADs) (Fréon and Dagorn 2000). Since the late eighties purse seine fisheries that exploit fish concentrations that are attracted by DFADs have shown a massive development worldwide (Fonteneau et al. 2000). Although the number of DFADs has risen, especially in the Western Indian Ocean where thousands of DFADs are utilised (Moreno et al. 2007), basic questions regarding the mechanisms underlying this associative fish behaviour are still unanswered (Fréon and Dagorn 2000). Most scientific studies have been carried out on anchored FADs (Dempster and Taquet 2004), as fish aggregations near DFAD are more difficult to access. A variety of techniques have been used that include: acoustic telemetry (Holland et al. 1990; Brill et al. 1999; Dagorn et al. 2007), tagging (Adam et al. 2003), fishery statistics (Cillaurren 1994; Kakuma 2000), and visual census (Taquet et al. 2000; Dempster 2005). These studies have provided valuable information about individual fish behaviour and near-surface pelagic fish communities around moored FADs. However, none of these results can be directly extrapolated to DFADs without new *in situ* observations of DFADs fish aggregations. Moreover, in spite of these studies, the underlying biological mechanisms of the association between pelagic fish aggregations and FADs (Fréon and Dagorn 2000; Castro et al. 2002), as well as spatial distribution patterns and biomass levels (Doray et al. 2006) remain undetermined.

Direct observations are required in order to understand behavioural patterns and the dynamics of aggregations around FADs. Acoustic observations near DFADs allow us to identify (i) spatial fish distribution, (ii) school types, (iii) school morphology and patterns, and (iv) number or volume density of different fish species.

Scientific echosounders and sonars were used for the first time to study DFAD fish aggregations in the Western Indian Ocean, in the framework of the European FADIO project (http://www.fadio.ird.fr). The general aim of this project was to develop new instrumented autonomous buoys and new electronic tags for the study of fish aggregations. Before designing a new autonomous acoustic buoy system, it was necessary to obtain basic information on the horizontal and vertical range needed to observe the aggregated biomass around DFADs. Our acoustic research was part of this project. It had the following objectives:

(i) study the spatial and temporal distribution of aggregations around DFADs;

(ii) classify the observed aggregations into distinct types;

(iii) develop the methodology for future echosounder surveys that are aimed at monitoring and understand pelagic fish aggregations around DFADs.

[1] In this paper the term FAD refers to any object floating at the surface that can attract pelagic fish, such as natural logs or man-made structures such as buoys and rafts.

Table 1. Day-time echo-surveys performed around DFADs in the Indian Ocean during FADIO4 and FADIO5 cruise program in 2005. For each survey, the DFAD No, date, hour (local time: UTC+4) and the position of the beginning of the survey are given.

DFAD Number	Date	Hour (UTC)	Lat. (S)	Long. (E)
FADIO4				
888	3 Feb.	04:02	3°04'	55°05'
	3 Feb.	09:24	3°03'	55°13'
	4 Feb.	11:24	3°00'	55°48'
	8 Feb.	11:55	2°46'	56°51'
	12 Feb.	02:55	3°24'	58°04'
1165	6 Feb.	09:16	2°16'	55°45'
	13 Feb.	02:45	2°44'	57°13'
881	9 Feb.	02:53	3°58'	56°49'
	9 Feb.	09:53	4°00'	56°53'
	11 Feb.	05:38	4°03'	57°27'
468	14 Feb.	06:56	3°18'	55°01'
FADIO5				
154	11 Oct.	06:31	5°21'	54°53'
	11 Oct.	10:58	5°20'	54°53'
	21 Oct.	04:46	4°15'	53°17'
917	13 Oct.	07:20	3°13'	53°38'
	14 Oct.	03:42	3°14'	53°50'
	15 Oct.	05:15	3°15'	53°58'
	15 Oct.	09:28	3°14'	54°00'
	15 Oct.	04:31	3°20'	54°05'
	20 Oct.	09:06	3°14'	54°15'
	20 Oct.	12:13	3°13'	54°17'
186	18 Oct.	06:41	2°46'	55°06'
	18 Oct.	11:10	2°46'	55°09'
	19 Oct.	03:50	2°48'	55°21'
	19 Oct.	09:53	2°48'	55°26'

2 Materials and methods

Data were collected during the 1st, 2nd, 4th and 5th FADIO cruise in the Western Indian Ocean off the Seychelles Islands with the chartered 35 m vessel "Indian Ocean Explorer". The first two cruises were designed to test survey patterns, data collection procedures and echosounder settings. These observations were used to determine the methodology for the 4th and 5th cruise that are reported here. A total of 25 daytime echo-surveys from two cruises (February and October 2005) were analysed (Table 1). Seven DFADs were investigated and all but one were visited repeatedly to study the persistent presence of tuna.

Table 2. Results of the calibration performed for the 38, 70 and 120 kHz transducers before the FADIO4 cruise.

	Transducer type		
	ES38B	ES70-7C	ES120-7C
Frequency (kHz)	38	70	120
Pulse duration (ms)	0.512	0.512	0.512
Transmit power (W)	1000	1000	1000
TS Reference target (dB)	–33.65	–39.30	–40.45
Depth of sphere (m)	8.9	7.9	8.4
Absorption coefficient (dB km^{-1})	8.6	23.0	43.8
Sound velocity (m s^{-1})	1510	1510	1510
Angle sensitivity alongship	21.9	23.0	23.0
Angle sensitivity athwartship	21.9	23.0	23.0
Gain (dB)	23.41	27.15	26.76
Sa correction (dB)	–0.66	–0.51	–0.35
Two-way beam angle (dB)	–20.6	–21.0	–21.0
3dB Beam width alongship (°)	6.86	6.54	6.42
3dB Beam width athwartship (°)	6.81	6.52	6.42
Angle offset alongship (°)	0.03	0.01	–0.14
Angle offset athwartship (°)	–0.01	–0.01	–0.13
RMS-error (dB)	0.19	0.18	0.14

2.1 Echosounder specifications for DFAD monitoring

The vessel was equipped with a SIMRAD EK60 scientific echosounder working at three frequencies (38, 70 and 120 kHz). All transducers (ES38B, ES70-7C and ES120-7C) were split-beam, with 3 dB beam width of 7°. The three transducers were mounted on the end of a pole, which was deployed on the starboard side of the vessel at two meters depth. Each transducer was connected to a General Purpose Transceiver (GPT). The GPTs were connected through an Ethernet switch (HUB) to the Processor Unit (laptop computer) running EK60 software. A pulse length of 0.512 ms and a transmit power of 1000 W were employed (Table 2). Acoustic observations were performed from the surface down to a depth of 250 m. The ping interval was set to maximum (about 1 ping every 0.44 s). The echosounder configuration allowed the acoustic pings to be synchronized at the various frequencies. Vessel position and navigation parameters (heading and speed) were recorded from a Global Positioning System (GPS).

Calibration of the echosounder was performed before each cruise for all frequencies in an experimental tank. Pulse length and other parameters were the same as used during the cruises. Reference copper calibration spheres were used (Foote 1982). The procedure described in the EK60 Scientific Echosounder Instruction Manual (SIMRAD 2001) was used to adjust the following transceiver settings: Gain, Sa correction, 3 dB Beam width alongship and athwartship and Angle offset alongship and athwartship (Table 2). We used 1000 W transmit power at 38, 70 and 120 kHz. Recent work by Tichy et al. (2003) suggests that reduced power should be used at our highest frequency to avoid the non-linear acoustic effects they observed. Following a reviewing of the situation we feel that the effect will be negligible for the purposes of our study.

The system Noise Level (NL), i.e. the sum of receiver noise, local noise and ambient noise, expressed in dB re 1 μPa was measured at sea with disabled transmitter at different vessel speeds according to the operational procedure described

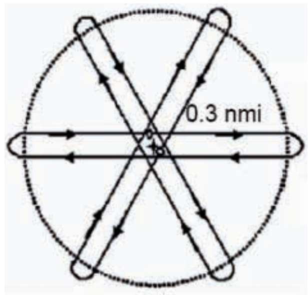

Fig. 1. Star shaped survey pattern with 0.3 nmi branches that are centred on a DFAD. The diameter of the circle is 0.6 nautical mile.

in the EK60 Instruction Manual. As the "Indian Ocean Explorer" has two engines with very different characteristics, and because during the acoustic surveys either one might be in use, measurements were carried out for each engine. The results obtained showed that the noise level for each frequency did not vary with vessel speed (between zero and seven knots) or engine used, and was in agreement with values found in other surveys (Bertrand 1999). The measured NL at 38, 70 and 120 kHz was 55.9, 49.5 and 48.5 dB re 1 μPa, respectively. On the basis of these results, the vessel speed was set at around seven knots during the acoustic surveys.

2.2 Survey design: star pattern centred on DFAD

During the first cruise, we started by performing a star survey pattern with eight, 0.8 nautical mile (nmi) long branches. The same pattern was used around moored FADs in French Polynesia by Josse et al. (1999) and more recently in La Martinique, in the French West Indies by Doray et al. (2006). However, one of the difficulties of carrying out acoustic surveys around DFADs is that they can drift very rapidly, depending on the local wind and current conditions. This is not the case for moored FADs, which remain within a very restricted area. To achieve a star pattern relative to the moving DFAD it was therefore necessary to continuously modify the course of the vessel according to the DFAD's changing position. On each pass we attempted to return as closely as possible to the DFAD position. Distances of a few metres were typical. This survey pattern was difficult to apply. At a distance of more than 0.3 nmi from the DFAD, visual contact was usually lost and it was often difficult to find it again with accuracy. We therefore decided to reduce the length of each branch from 0.8 to 0.3 nmi on the basis of observed fish detections around DFADs during the two first FADIO cruises. The number of branches to be followed was also reduced to six, in six different directions (Fig. 1). One branch was chosen to coincide with the drift direction of the DFAD, the remaining branch directions were chosen to obtain a symmetric pattern. Each branch was repeated twice to complete the star survey pattern. At a speed of seven knots each star survey pattern was completed in about two hours. As the DFADs were drifting, the trajectory of the vessel (Fig. 2a) differed from the proposed scheme (Fig. 1). In order to interpret acoustic data, we needed to know not only the absolute position (latitude, longitude) of the acoustic detections, but also their position relative to the DFAD. For this

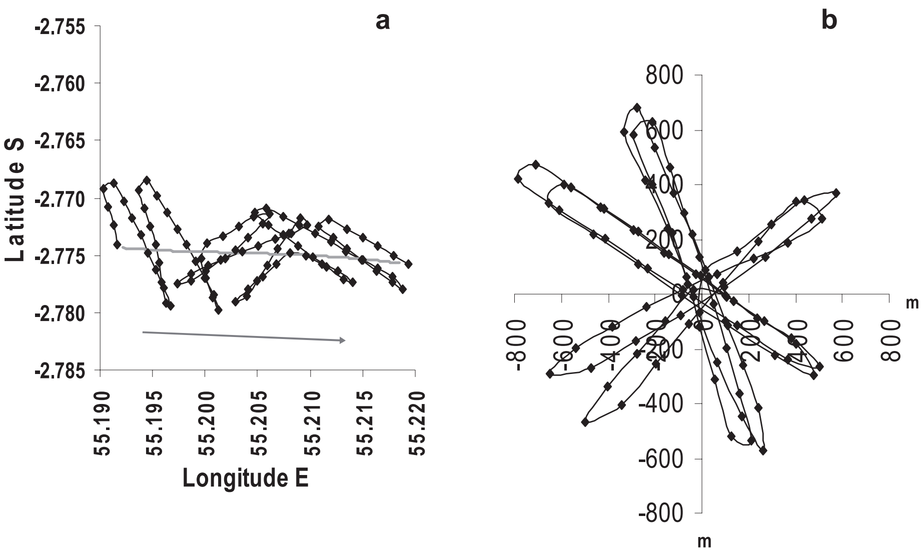

Fig. 2. a) Course of the vessel (in black) and of the DFAD drift (in grey) during an acoustic star survey (DFAD 186, FADIO5). The arrow indicates the approximate direction of drift of the DFAD; b) the same survey pattern described in the Lagrangian coordinate system with fixed North orientation that is centred on the DFAD (distances in m).

purpose, we used a 2D Lagrangian coordinate system similar to that use by Greene et al. (1998) to describe oceanographic observations from a drifting platform. Here the Lagrangian coordinates are in the horizontal plain, the origin is fixed to the centre of the DFAD and North-South orientation is maintained.

Vessel and DFAD positions are required to give the survey pattern in Lagrangian coordinate (Fig. 2b). Vessel position during each survey was stored in MaxSea software package. This software was also used to perform the 0.3 nmi branches of the star pattern. The position of the DFAD was estimated as follows: every time the vessel was close to the DFAD, generally a few metres on the starboard side, and perpendicular to it, an annotation was generated using the EK60 software, which noted which side of the vessel the DFAD was located and the distance between the transducers and the DFAD. The captain and two scientists on the bridge produced independent visual estimates of this distance. These data were written on the echogram. Time and position data as well as the course and speed of the vessel were continuously stored in the raw data files produced by the EK60 software (SIMRAD 2001). For each survey of a DFAD we thus had a set of values (time, latitude and longitude of the vessel, course, distance between the boat and the DFAD), which enabled us to estimate the geographical co-ordinates of the DFAD (Fig. 2a gray line).

2.3 Acoustic data processing of shoals and detection of individual fish

Unprocessed transceiver data (Raw data) were stored by the EK60 software during surveys. These Raw data were then replayed (with the EK60 software) and analysed with Movies + software (Weill et al. 1993; Berger et al. 2001). This included validation and archiving in the international hydroacoustic data format (HAC) (Simard et al. 1997) at a –80 dB S_v (volume backscatter cross section) threshold.

The analysis of single echo detections with Movies+ software was done from the echotrace datagram delivered by the EK60 (Diner and Berger 2004). The following settings were used for all frequencies to select single-echo detection with the EK60: minimum echo length: 0.8, maximum echo length: 1.8, maximum phase deviation: 8, maximum gain compensation: 6 and TS threshold: –55 dB. This TS threshold was selected with reference to TS values available in the literature for tuna (Bertrand et al. 1999a; Josse and Bertrand 2000).

2.3.1 Fish school structure types found in DFAD aggregations

A preliminary visual analysis of the echograms showed that DFAD aggregations did not appear as homogeneous assemblages, but rather as a juxtaposition of different structures. We here understand the term DFAD aggregation to include all acoustically observed shoals and separated targets that are observed near a DFAD. Thus, there is only one aggregation around one DFAD. Due to the loose configuration of the aggregations, different types of structures were often observed within DFAD aggregations. Generally a structure includes elementary acoustic shoals and/or a group of scattered fish. Elementary acoustic shoals are defined as a set of samples that form a distinct patch on the echogram, i.e. a set of samples with amplitude greater than a predetermined threshold which in our case was set to –80 dB. Samples also obeyed a certain law of contiguity; both within a single ping and from one ping to the next. An elementary acoustic shoal identified by the Movies+ software does not necessarily represent a real school (Appendix). It could happen that two distinct real schools could be detected as only one elementary acoustic shoal and also the reverse, identifying two elementary acoustic shoals when there is only one real school. Echograms were first scrutinized in order to identify and visually classify acoustic structures observed within DFAD aggregations. Different types of structures were

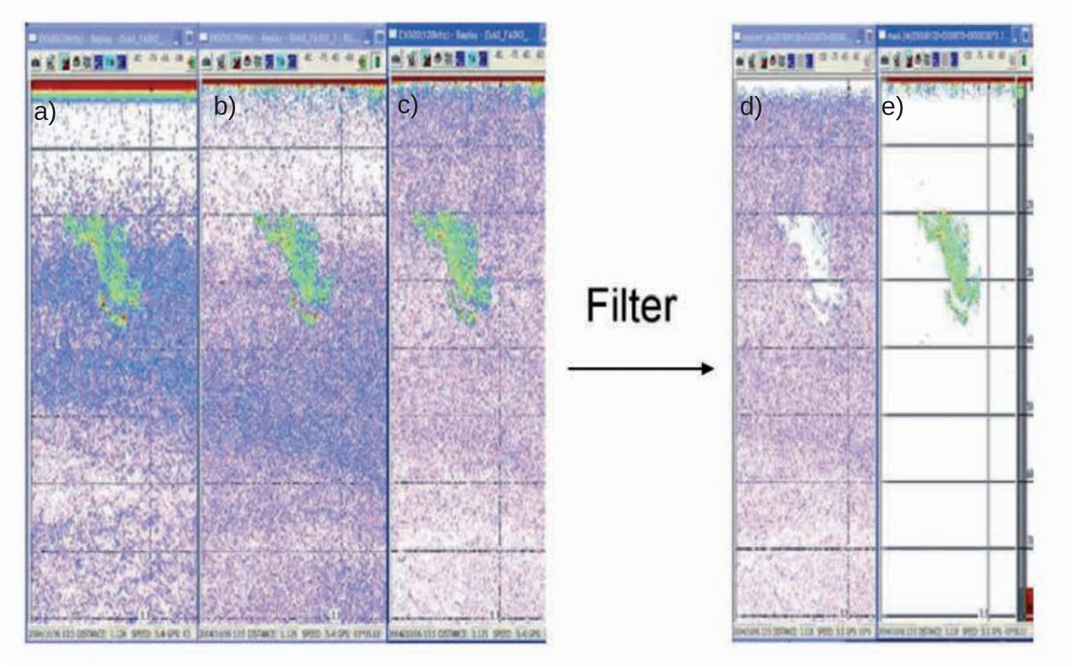

Fig. 3. Discrimination of fish and scattering layers; a, b and c) echograms from the three original frequencies; 38, 70 and 120 kHz respectively. After filtering the 120 kHz frequency, two new virtual echograms emerge; d) scattering layers; e) fish.

identified according to the methodology proposed by Petitgas and Levenez (1996). This classification was based on the following criteria: the depth of the detection, its shape and degree of scatter.

2.3.2 Echo-integration by shoal

The echointegration or "EI by shoal" algorithm implemented in Movies+ software (Weill et al. 1993; Diner et al. 2006) was applied to the acoustic data. It was used to define sets of samples that formed a patch or shoal on the echogram and to measure its EI value.

Tuna aggregations are often mixed with zooplankton, micronekton and other scattering layers (Fig. 3). Acoustic discrimination between fish and plankton is not always easy, especially when plankton layers are dense and fish are dispersed. Working with several frequencies allowed us to discriminate between fish and scattering layers as fish and plankton backscatter cross sections change differently with frequency (Fernandes et al. 2006). We used the multi-frequency module of the Movies + software (Berger 2006) to create filters used as masking operators on one of the frequencies. As Fig. 3 shows, the application of the filters to one frequency allowed two new virtual echograms to be generated; one with only the scattering layers, the other with fish detections. The application of the EI by shoal algorithm on these virtual echograms was more informative than applying it on the original echograms.

EI by shoal was used to estimate the geographical, energetic and morphological parameters of each elementary shoal forming a structure (Scalabrin 1997; Doray et al. 2006). 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, 2007).

We used the aggregate backscattering cross-section of shoal as energetic parameter of detected shoals. Using standard notation proposed by MacLennan and Fernandes (2000) and MacLennan et al. (2002) the aggregate backscattering cross-section of a shoal is defined as (Diner 2007):

$$\sigma_{\mathrm{ag}} = \sum \sigma_{\mathrm{bs}}$$

where σ_{bs}, sigma (bs), is the backscattering cross-section of an individual target (fish) and the sum is over all targets in the entire volume of the shoal intercepted by the sound beam, that is, it includes all echoes received from the shoal (Diner 2007). The σ_{bs}, σ_{ag} sigma (ag) is expressed in m^2 (MacLennan and Fernandes 2000).

Morphologic descriptors such as maximum height and length, energetic parameters such as aggregate backscattering cross-section (σ_{ag}) and positional descriptors such as geographical centre position, depth of the geographical centre and distance and depth of backscatter centroid (the average of X and Y values weighted by backscatter energy) were obtained for each shoal that formed a given structure. Since in most cases, several shoals formed a structure, descriptors were calculated from the contributing shoal descriptors. Structures were thus characterized by their maximum height, maximum length, position and depth of their geographical centre, and distance and depth of backscatter centroid. We approximated the backscatter centroid of the structure from the geographical centre of each shoal configuring the structures, as weighted by their aggregated backscattering cross-section (σ_{ag}). As for these analyses we were dealing with the shoals geographical centre we calculated the difference in metres from the

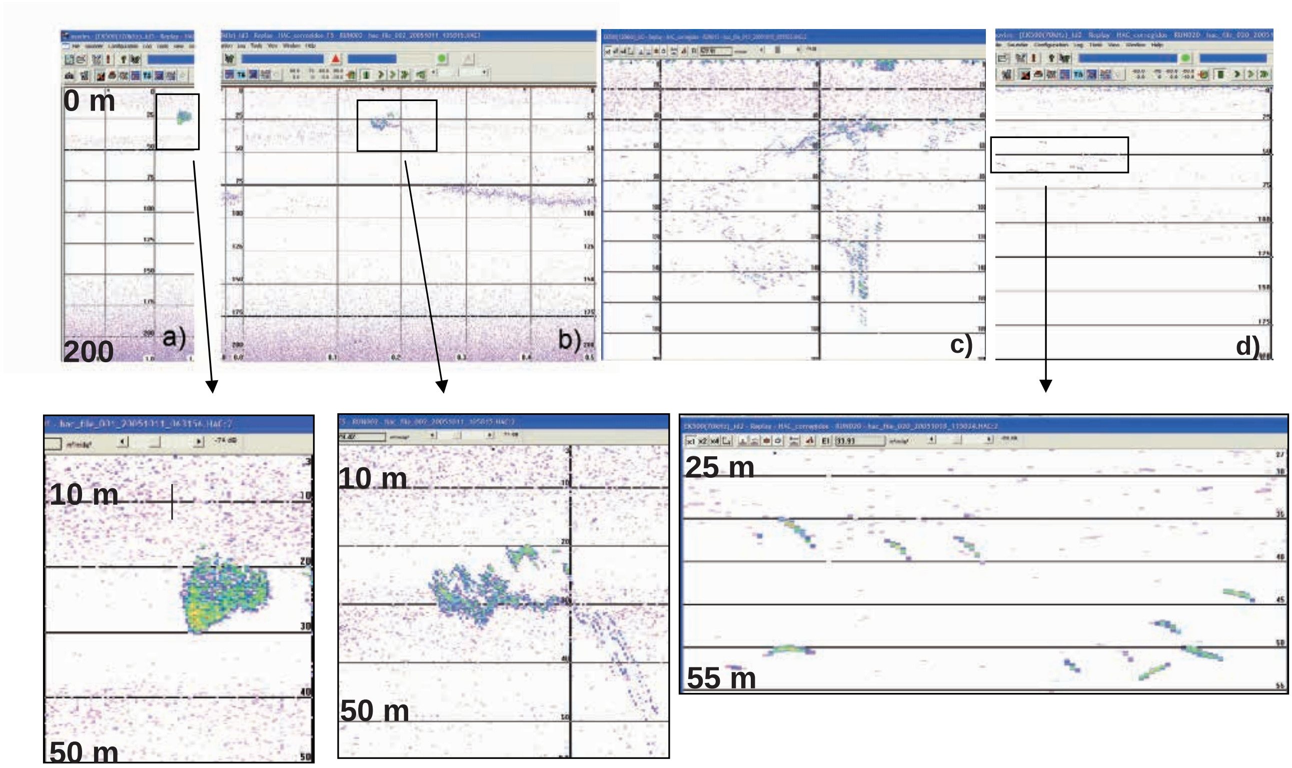

Fig. 4. Results of the visual discrimination of aggregations; a) dense structure; b) medium structure; c) loose structure; and d) structures of separated targets. Echogram ranged from 0 to 200 m and zoom captured from 0 to 50 m depth for dense and medium structures and from 25 to 55 m depth for structure of separated targets, respectively.

backscatter centroid to the geographical centre for each shoal to test whether the distances between the two were sufficiently significant to affect our results. As the position of the DFAD was known, the distance of the geographical centre of each structure to the DFAD could be calculated.

2.3.3 Target strength (TS) analysis

TS is known to be highly variable (Barange et al. 1994; Simmonds and MacLennan 2005) and differences in TS of more than 15 dB are frequently observed for the same fish, for example in yellowfin tuna, *Thunnus albacares* and bigeye tuna, *Thunnus obesus* (Bertrand et al. 1999a). In order to take this high TS variability into account, we followed the approach of Josse et al. (1999) and Doray et al. (2006), which favoured the selection of high level, good quality echoes at the expense of quantity. The individual echoes which had been selected as individual targets by the echosounder, were filtered with the tracking function included in the TS data-analysis module of the Movies+ software (Diner and Berger 2004). This tracking function enabled us to retain only fish that had been tracked for at least three consecutive pings. The number of missing pings allowed in a track was set at 1 and the maximum depth variation between two pings in a track was 1 m. This value was chosen with reference to the maximum vertical velocities recorded for tuna during ultrasonic tracking experiments around moored FADs (Cayré and Chabanne 1986; Marsac and Cayré 1998). This analysis was performed using a TS analysis threshold of –55 dB, which is identical to the threshold used to select individual echoes during the conversion of the EK60 data into the HAC format.

TS values were extracted for each structure configured either from separated targets and/or from individual fish echoes from elementary shoals. Most analyses were performed at 120 kHz, as pelagic fish appeared to have better detectability at this frequency compared to 38 or 70 kHz, due to strong scattering layers at these frequencies. Information about the time, position, depth, number of pings and mean TS were available for each fish that had been tracked, as well as all the information on individual echoes (TS_i), which made up a track. The average TS_i was calculated for each single fish track. TS_i values were pooled by structure type to obtain in situ TS distributions for each structure this resulted in Gaussian-like distributions, which were assumed to correspond to a single species and/or size range (Ona 1999).

3 Results

3.1 Classification of acoustic structures found in DFAD fish aggregations

At the end of the visual classification based on depth, shape and criteria of degree of scatter, four types of structures were found in DFAD fish aggregation: dense structures, medium structures, loose structures and structure of separated targets (Fig. 4). A total of 358 structures were observed, comprising

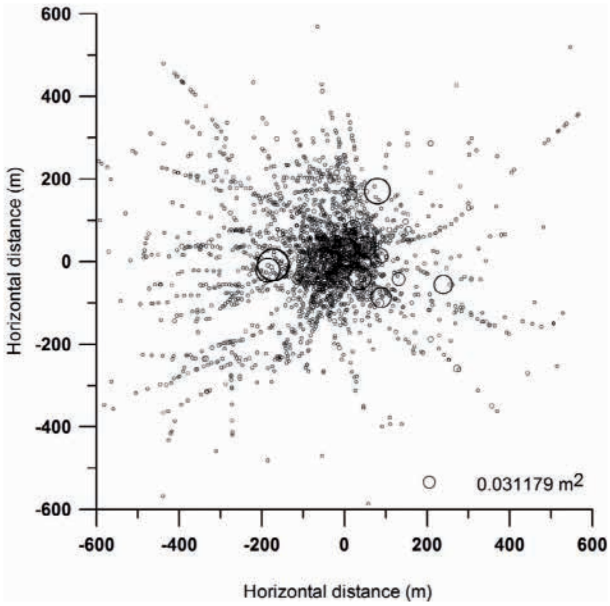

Fig. 5. Distribution of all elementary acoustic shoals observed around surveyed DFADs. DFAD is centred in (0,0) position. Circle diameter is proportional to aggregated backscattering cross-section for each elementary acoustic shoal.

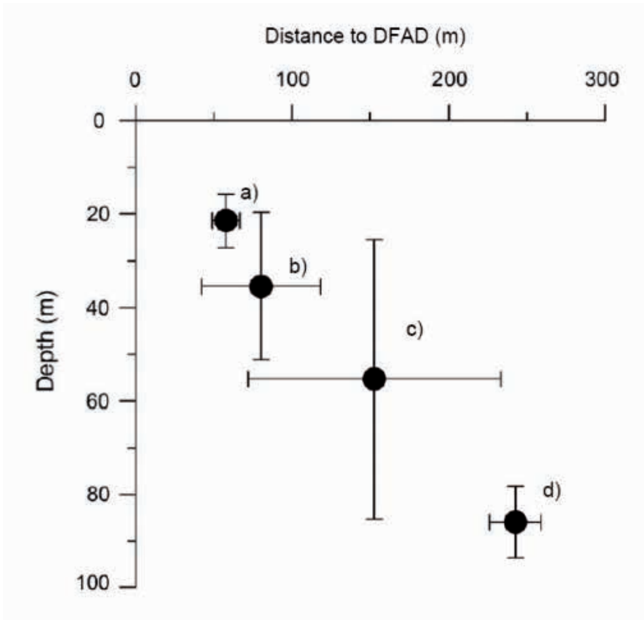

Fig. 6. Spatial distribution of defined structures related to the distance from the DFAD and according to their depth; a) dense structure; b) medium structure; c) loose structure; d) structures of separated targets. Horizontal and vertical bars correspond to average maximum length and height, respectively.

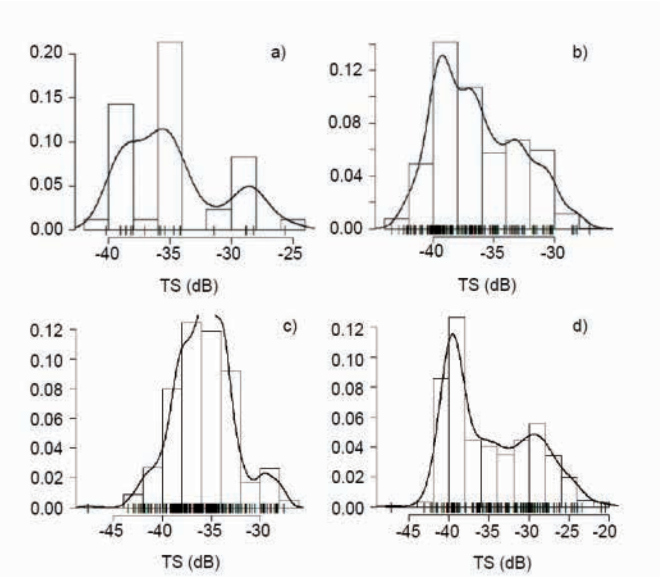

Fig. 7. Histogram and TS distribution for the four structure types; a) dense structure; b) medium structure; c) loose structure; d) structures of separated targets.

a total of 2546 elementary acoustic shoals (Fig. 5). A total of 92% of the structures were detected within a radius of 400 m of a DFAD and around 75% within 200 m. The morphological, positional and energetic parameters of each type of structure are shown in Table 3. All of the structures identified were observed in 36% of the 25 DFAD surveys.

3.1.1 Characteristics of dense structures

This type of structure was seldom observed; only 16 times (4.5% of observed structures) in 44% of the surveys, and it corresponded to dense fish shoals that usually were circular in shape, internally compact and with clear boundaries on the echogram (Fig. 4a). The spatial distribution of this type of structure was characterized by their location in shallow waters with mean backscatter centroid and geographical depths of 21.6 m, (standard deviation, SD 7.9 m) and 21.4 m (SD 8.4 m) respectively; and an average horizontal distance from their geographical centre to the DFAD of 61 m (SD 34 m) and 57.8 (SD 29.4 m) from the backscatter centroid (Fig. 6). The mean distance from the geographical centre to backscatter centroid was 1.8 m (SD 1.9) for shoals configuring this type of structure (Table 4). Average number of acoustic shoals forming this type of structure was 1.79 (SD 1.0). Morphological parameters found had an average maximum length of 18 m (SD 16 m) and 11 m (SD 7.0 m) of maximum height. The mean target strength value of the fish configuring this type of structure was –34.19 dB (Fig. 7a). This type of structure contributed 5.4% of the total observed acoustic energy, and had an aggregated backscattering cross-section (σ_{ag}) of 0.04 m^2.

3.1.2 Characteristics of medium structures

This structure was observed 105 times (29.3% of observed structures) in 76% of the surveys, and it was always observed in the presence of “loose structure”. This type corresponds to a well-defined structure, usually observed with a tail, irregular borders, with variable internal density appearance and different shapes due to the dynamics of the species of fish

Table 3. Morphologic, energetic and positional parameters for each type of structure. The latter are related to DFAD position. Structures from all DFAD surveys are pooled.

	Dense structure		Medium structure		Loose structure		Structure of separated targets	
	Mean	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
Number of shoals	1.7	1.0	5.4	3.9	9.7	6.2	2.2	1.8
$L_{\max}$ (m)	17.9	16.6	76.5	66.7	161.3	116.1	33.1	43.8
$H_{\max}$ (m)	11.3	7.2	31.5	20.2	59.9	33.8	15.5	23.8
Mean distance from geographical centre to DFAD (m)	61.4	34.3	94.4	59.3	160.0	111.4	242.8	181.1
Mean distance from backscatter centroid to DFAD (m)	57.8	29.4	80.2	48.0	152.6	114.3	242.5	174.8
Geographical centre depth (m)	21.7	7.9	37.8	14.6	60.6	27.8	86.5	58.4
Backscatter centroid depth (m)	21.4	8.5	35.4	13.1	55.3	29.3	85.9	59.1
Mean target strenght (dB)	–34.2		–35.7		–34.5		–29.9	
σ_{ag}	0.04 (5.4%)		0.5 (67.6%)		0.17 (23.0%)		0.03 (4.0%)	
Number of detections	16 (4.5%)		105 (29.3%)		128 (35.7%)		109 (30.5%)	

Table 4. Statistical descriptors for the distance in meters from the backscattering centroid to the geographical centre position.

Structure type	Mean	SD	Max
Dense structure	1.79	1.90	7.84
Medium structure	2.77	4.78	44.55
Loose structure	1.51	2.32	26.42
Structure of separated targets	0.93	1.19	8.2

involved (Fig. 4b). We observed a mean backscatter centroid depth of 35 m (SD 13 m) and a geographical centre mean depth of 37.7 m (SD 14.6 m), with an average 94 m (SD 59 m) of horizontal distance from the geographical centre to the DFAD and 80.2 m (SD 48.0 m) from the backscatter centroid (Fig. 6). Mean difference between the geographical centre and the backscatter centroid was 2.8 m (SD 4.8) (Table 4). The average number of acoustic shoals forming this type was 5.4 (SD 3.4) and they were in 95% of the cases within a radius of 200 m from the DFAD. The maximum length was on average 77 m (SD 67 m) and maximum height 32 m (SD 20 m). Mean TS value was –35.71 dB (Fig. 7b) and this type contributed 67.6% of the total energy observed, with a σ_{ag} of 0.50 m^2.

3.1.3 Characteristics of loose structures

This type was present in 80% of the surveys and was the most frequently observed one (35.7%), appearing 128 times in the course of the 25 surveys. This macro structure corresponded to aggregated fish that occupied a large volume of water, giving an aspect of aggregated but also scattered biomass (Fig. 4c). This structure had an average maximum length of 161 m (SD 116 m) and an average maximum height of 60 m (SD 34 m), which indicated that this was the structure that occupied most space. On average, the horizontal distance to the DFAD was 160 m from the geographical centre (SD 111 m) and 152.6 from the backscatter centroid (SD 114.3). Mean backscatter centroid depth of 55 m (SD 29 m) and geographical centre depth of 60.6 m (SD 27. 8) (Fig. 6). The mean distance from the geographical centre to backscatter centroid was 1.5 m (SD 2.3) (Table 4). The average number of acoustic shoals forming this type of structure was 9.7 (SD 6.2) and in 75.7% of cases they were within a radius of 200 m from the DFAD.

This structure had a mean value of –34.5 dB of target strength (Fig. 7c) and the σ_{ag} of 0.17 m^2, corresponding to 22.9% of the total energy observed.

3.1.4 Characteristics of structures consisting of separated targets

These isolated fish did not form any structure by themselves, but made up isolated acoustic shoals of a few individuals (Fig. 4d). These were very common, being identified in 92% of all the surveys. This structure was the only one that was found alone without any other structure present. In 50% of cases, acoustic shoals configuring these structures were within a radius of 200 m from the DFAD. The average number of acoustic shoals that made up these structures was 2.2 (SD 1.8). The morphological parameters for structures of separated targets were an average maximum length of 33 m (SD 44 m) and an average maximum height of 15 m (SD 2 m). Their spatial configuration around the DFAD was a mean horizontal distance of 243 m (SD 181 m) to the geographical centre and 242.5 m (SD 174.8 m) to the backscatter centroid, with a mean backscatter centroid depth of 86 m (SD 59 m) and mean depth of the geographical centre of 87 (SD 58 m) (Fig. 6). The

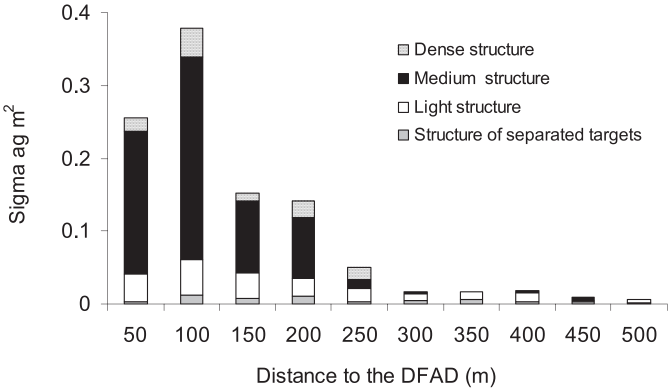

Fig. 8. Sigma ag (σ_{ag})-aggregated backscattering cross-section, in m^2 by structure type and horizontal distance strata to the DFAD.

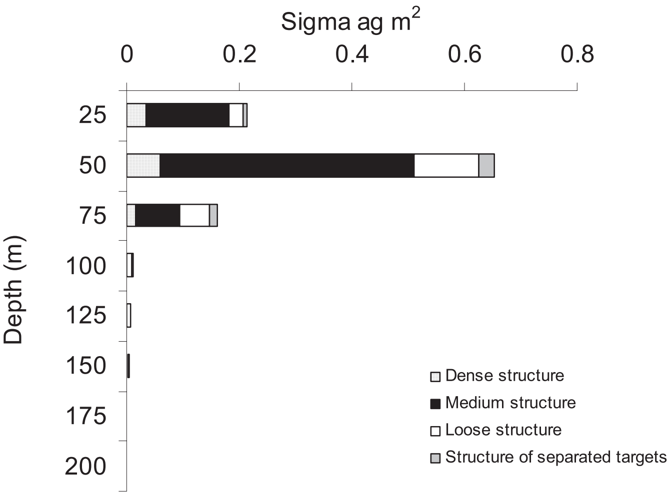

Fig. 9. Sigma ag (σ_{ag})-aggregated backscattering cross-section, in m^2 – by structure type and depth strata to the DFAD.

mean distance from the geographical centre to the backscatter centroid was 0.9 m (SD 1.2) for shoals with this type of structure (Table 4). The mean TS value was –29.9 dB (Fig. 7d) and the energy that they contributed to the total acoustic energy observed from the shoals was 4.0%, with a σ_{ag} of 0.03 m^2.

3.2 Spatial distribution of acoustic energy

The acoustic energy distribution relative to the distance from the DFAD and the depth distribution are shown in Figures 8 and 9, respectively. The greatest contribution to the total acoustic energy came from medium structures. Maximum values of σ_{ag} were found at a horizontal range of 50 to 100 m from the DFAD, while maximum depth values were found within the first 75 m. Energy decreased abruptly with water depth. Below 100 m, the energy corresponded only to loose structure and mainly to structures of separated targets. In contrast, this sharp decline in acoustic energy was not observed at the horizontal range, where the energy declined more gradually.

4 Discussion

4.1 Survey pattern

The star survey pattern was chosen because it allowed the vessel to pass frequently close to the DFAD (Josse et al. 1999). Moreover, it always sampled an area that was well centred on the device. The transect radius was initially set to 0.8 nmi. Surveying in parallel transects is not suitable for floating objects that can drift quickly (drifting speeds were measured up to 0.8 m s^{-1}, as the drifter soon would leave any reasonably sized survey area. A star survey pattern is effective with increased coverage near the DFAD. Moreover, the star survey pattern was particularly suitable for studying pelagic fish aggregations around DFADs, as the greatest effort was applied to the area with the highest biomass.

According to simulations performed by Doonan et al. (2003), the best survey pattern for estimating the density of a localised aggregation with reduced dimension would be a star pattern with six branches. In French Polynesia (Josse et al. 1999) and the French West Indies (Doray et al. 2006) a star survey pattern with eight branches was used. Having modelled the distribution of the aggregated fish around moored FADs, Doray et al. (2006) simulated various sampling strategies in order to study the accuracy of the estimation variance of the aggregated biomass. They concluded that star survey patterns with 4, 6 or 8 branches produce low estimation variance. The survey pattern we used in this study was a star survey with 6 branches repeated twice.

The position of the DFAD during the survey could be precisely estimated as a function of time. The method we used appeared to be satisfactory, in that the distance between the boat and the DFAD did not exceed 20 m. Under these conditions, the latitude and longitude through time as estimated for the DFAD were very close to the adjusted values. The positions of acoustic shoals or individual fishes could thus be precisely calculated with reference to the position of the DFAD and any error made in estimating the distance to the DFAD was low. However, it would be preferable to have an uninterrupted recording of the DFAD position to minimise the risk of systematic bias or errors. Moreover, the real-time availability of this information on the bridge during a survey could allow us to increase the radius of the prospected area and/or to increase the number of branches. It would be possible to know the relative position of the DFAD to the vessel in real time, and thus be able to adapt the course of the latter.

4.2 Acoustic data analyses

Fish do not occupy their space at random. Each species and each community tends to use space in a particular way, depending on their typical patterns of behaviour. Such spatial behaviour should make possible to extract from the echoes more than simple density values (Rose and Leggett 1988). However, we consider acoustic communities instead of species, which results in the following limitations: we consider global variations rather than specific characteristics. Using this information, Gerlotto and Marchal (1987) introduced a more generalized concept, which they called "acoustic population".

Basically, an acoustic population is a population of echoes, which may be gathered into a single group on the basis of their common acoustic characteristics (Gerlotto 1993).

A first attempt to classify aggregation structures was made using regression trees from acoustic shoal parameters such as morphology, position and acoustic energy. The results were not satisfactory, mainly due to the high degree of dispersion of the fish, which makes the EI shoal software identify many small shoals as a single shoal (see Appendix for an example of an EI-shoal result on acoustic shoal discrimination).

We therefore coded the morphological structures according to the method suggested by Petitgas and Levenez (1996), once again adopting the concept of acoustic population (Gerlotto and Marchal 1987; Gerlotto 1993). This approach has primarily been used to characterize populations of small coastal pelagic fish (Petitgas and Levenez 1996; Brehmer et al. 2007), but also to characterize micro-nektonic communities (Bertrand 1999; Bertrand et al. 1999b). We also wished to apply the method to tuna aggregations associated with DFADs, and four types of structures were therefore defined on the basis of shape and spatial distribution criteria and observed fine-scale movements.

TS analysis and EI by shoal was applied to each structure in order to extract the parameters that characterize acoustic shoals, to study the structure of aggregations as provided by Doray et al. (2006). The TSs of dense structures should be interpreted with caution, since TS analyses cannot be carried out if shoals are too dense, which was the case in most of the shoals of this type. However, we conducted the analyses primarily in order to explore the values for fish at the edge of or close to the dense shoals.

4.3 Aggregation structures

At our observed spatio-temporal small scales (two-hour surveys at ranges of 500 m horizontal and 250 m depth), aggregations of tuna and other pelagic species appeared as complex and dynamic structures around DFADs. Although the aggregations were very dynamic and surveys were performed at different times of day, the same type of structures turned up in most cases. Classifying the typology enabled us to identify different spatial behaviours within aggregations. Some structures evolved and were transformed into others (Brehmer et al. 2007), depending on the biomass present, or time of day. This variability in structure needs to be further studied and elaborated with regard to biomass.

Dense structures corresponded to fish schools of undetermined species. Due to the low reliability of TS analysis for such dense structures, it was difficult to identify the species or sizes of fish that formed these fish schools. According to the spatial classification of species around FADs by Parin and Fedoryako (1992) and later modified by Fréon and Dagorn (2000), dense structures corresponded to *circumnatants*. The smallest members of this group are balistids such as *Canthidermis maculatus* and schooling carangids such as *Decapterus macarellus*. In the course of our underwater visual observations, small pelagic fish and balistidae species were seen to rapidly form dense schools as a behavioural response to predator attacks. The few observations of this type of structure may be due to a short-lasting behavioural response of certain species associated with DFADs or to the presence of species that are not usually found at DFADs.

The dynamics of medium structures, echo-trace characteristics and acoustic energy all showed that various species of tuna, i.e. skipjack, bigeye and/or yellowfin, might be present in this type of structure. Echotraces of these structures showed different types of acoustic shoals (Fig. 4b) where two main acoustic shoals can be clearly distinguished as one large acoustic shoal with a tail and another smaller acoustic shoal above it. Depending on the proportion of each species, TS can vary significantly, making it difficult to estimate in real time without complementary data, the quantity of the various species present. Fishing and underwater visual observations helped to identify the species. While the depth range is suitable for diver or ROV based underwater visual observations, as maximum energy values for this structure were found within the first 50 m depth, the horizontal range should be extended to 50–100 m from the DFAD.

Loose structures and medium structures had common characteristics for shoals occupying the upper layers (0–40 m). The most important differences were found in spatial occupation and vertical distribution, which suggests that structures could evolve from one type to another, depending on their biomass or the size of the individual fish. Loose structures occupied deeper layers (Fig. 6) and were also more scattered around the DFAD. Mean TS values and the spatial distribution of acoustic shoals for this type of structure suggest that larger tuna were more frequently present in this type of structure than in medium structures. Large bigeye tuna were likely present in the deep shoals observed within this structure.

Structures of separated targets displayed the highest TS values with a maximum of –30 dB. Small isolated shoals of few individuals were present throughout the water column (0–250 m) and scattered around the DFAD (Fig. 9). The distribution of TS values was made up of two modes, one with the highest TS values observed and the other with lower TS values. This bimodal distribution showed that either two species or two different sizes of the same species comprised this type of structure. Taking into account the echotrace characteristics, spatial behaviour and TS distribution, we assume these two modes to be different species rather than different sizes of the same species. One of them corresponded to the highest TS observed around DFADs could be identified as tuna and the other was identified as small pelagic fish.

We did not study the temporal evolution of these structures but it is likely that the schooling behaviour of these aggregations might be highly variable depending on the time of day, as all structures evolve continuously, depending on several biotic and abiotic parameters (Brehmer et al. 2007). We therefore treated each survey on a given DFAD as being independent of the following one. Independence was assumed on the bases of the high temporal variability of the fish biomass and the spatial distribution of structures from one survey to the next, and because surveys were not performed immediately after each other (Table 1).

Classifying the typology of aggregations was useful as a way of identifying patterns of TS distribution. It was found a relation between spatial behaviour of different structures and

TS distribution. High TS values corresponded to the most highly scattered structures, those structures occupying a larger volume of water and farther away from the DFADs. Medium TS values corresponded to medium structures that were closer to the DFAD and nearer the surface than the other two more scattered structures.

Anchored FADs had quite stable aggregations with a nested structure, comprising a central part surrounded by a layer of scattered fish (Doray et al. 2006). Aggregation structures were quite predictable around anchored FADs, as they returned similar echotraces throughout the study. In the case of DFADs, although the most highly scattered structures such as medium, loose and structure of separated targets could also be nested or evolve from one structure to another depending on the biomass, the configuration of the DFAD aggregation, the spatial distribution and shoal morphology appeared to be more dynamic in association with DFADs than around moored FADs.

4.4 Implications for research tools and tuna catchability around DFADs

Tuna aggregations around DFADs are complex, dynamic and highly variable structures, localised predominantly within a radius of 400 m around the DFAD (Fig. 5). As most of the acoustic shoals were within a horizontal range of 400 m and at a depth of 250 m from the DFAD, we regard this range as suitable for the study of tuna and pelagic fish associated with DFADs. However, in view of the different structures that make up aggregations around DFADs, observation ranges should be adapted to the species of interest.

Future autonomous instrumented buoys to study tuna around DFADs should be equipped with sonar with a minimum range of 400 m. The 120 kHz frequency appears to be the most appropriate frequency for the study of fish aggregations around DFADs, offering the best compromise between spatial range, echo quality and portability (transducer size) compared to 38 kHz and 70 kHz echosounders. Future studies of non-tuna species dynamics, which are also important for a better understanding of tuna dynamics around DFADs, should consider a different sampling method for species that occupy the space close to the DFAD and close to the surface (0–10 m). Results on the structure and the dynamics of aggregations observed with a vertical echosounder need to be complemented by observations made by other tools such as multibeam sonar (Brehmer et al. 2006), acoustic telemetry (Dagorn et al. 2007) and visual observations (Taquet et al. 2007) in order to determine the species and size composition of pelagic fish aggregations, at both the scale of the aggregation and individual fish.

This study has also demonstrated that the detection ranges of acoustic receivers of sonic tags implanted on fish associated to DFADs are adequate for the study of associated population movements. The limited sensitivity of telemetry receivers, which is on average 400–1000 m and depends on local conditions, made studies of the presence and absence of fishes tagged with acoustic tags around DFADs somewhat uncertain. This was due to the fact that, when an acoustic signal was not received, the fish were assumed to be absent from the DFAD. As shown in this study, 90% of shoals were within 400 m of the DFAD. The 400–1000 m range of acoustic receivers thus appears to be sufficient, from a behavioural point of view, to permit us to assume that non-detected individuals are absent from the DFAD (Klimley and Holloway 1999; Ohta and Kakuma 2005; Dagorn et al. 2007).

When we look at the structure and spatial configuration of DFADs aggregations in the context of the purse-seine gear employed to exploit DFADs, we found that fishermen usually set their nets with the DFAD in the centre, configuring a circle with average diameter of 200 m and a depth range of 150 m around the DFAD. If we encircle the structures observed in this study with such a net, we predict a catch of 95% of the observed medium structure and 75% of observed loose structures. These two types of structures are the most likely to include skipjack tuna representing a target species for fishermen together with small yellowfin and bigeye tuna. Small bigeye and yellowfin tuna by-catches are at the same time the major species of interest for tuna management organizations. However for structure of separated targets, which returned greater TS values, representing larger tuna and main target species for fishermen, only about 50% of the larger tuna was within the 200 m radius from the DFAD. Due to the configuration of the shoals observed within structures, it was clear that the characteristics of current purse seine gear would make it difficult to catch only one target shoal without also taking the other species present in the same structure. Thus, when we have the three tuna species within the same medium or loose structure, even if they occupy different shoals, it will be difficult to catch skipjack as a target species without catching the other two, a drawback that also applies to other non-tuna species. We have not studied the temporal evolution of the structures and we do not know whether different shoals disperse during different times of day, which would enable fishermen to predominantly target desirable species and size groups. This is a topic future studies should address.

5 Conclusion

This work presents the first acoustic study of fish aggregations near DFADs that uses vertical echosounders and it describes a methodology for future studies. The star survey pattern used in French Polynesia (Josse et al. 1999) and in La Martinique (Doray et al. 2006) was successfully adapted to surveys of pelagic fish aggregations around DFADs in the western Indian Ocean. The creation of virtual echograms after combining acoustic observations made at three frequencies and filtering the data obtained, permitted satisfactory discrimination between fish aggregations, individual fish and scattering layers. Four different types of fish structures are defined in this work: dense structure, medium structure, loose structure and structure of separated targets, seem to be related to different sizes of tuna as shown by the TS values. Knowing the spatial distribution and structuring of fish aggregations around DFADs is of key importance for the development of future research tools and experiments. The results also suggest that purse seiners experience problems and challenges with considerable bycatch of non-target species and under-sized fish when targeting tuna associated with DFADs, and these aspects are important to resolve in order to improve the management of our vulnerable living marine resources.

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Appendix (see next page)

Appendix. Results of echo integration by shoal on acoustic shoals identification and numbering; a) echogram of the 120 kHz frequency, from 0 to 60 m depth; b) the same echogram after performing echo-integration on shoals, when the contours and number of shoals are identified.