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An acoustic approach to study tuna aggregated around fish aggregating devices in French Polynesia: methods and validation

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Abstract — The behaviour and spatial distribution of tuna, aggregated beneath fish aggregating devices (FADs), have been studied through ultrasonic tagging experiments but, surprisingly, very few studies on FADs have used underwater acoustic devices. We present techniques, and their limits, incorporating a scientific echo sounder connected to a split-beam transducer to observe and characterise tuna aggregations around FADs, and propose a general approach for future studies. Experiments were conducted in French Polynesia between December 1995 and February 1997. Two methods, echo-counting and echo integration, were used. Echo-counting is possible when individual fish are sufficiently scattered so that each target can be discerned. On the other hand, echo integration can be used with both scattered and aggregated fish schools. The knowledge of tuna target strength is useful for separating targets for echo-counting, and essential for obtaining absolute estimates of densities by echo integration. Sonar performances and settings should be considered when choosing the most suitable method to determine fish density or assessing spatial structure of a tuna aggregation. These techniques allow one to study an entire tuna aggregation, its behaviour in space and time at very fine time–space scales (about a nautical mile and over a few hours), and open up a new scientific field to study the spatial structure and behaviour of tuna aggregations around anchored or drifting FADs. © 1999 Ifremer/Cnrs/Inra/Ird/Cemagref/Éditions scientifiques et médicales Elsevier SAS

Acoustic survey / FADs / aggregation / tuna / fish density / behaviour

Résumé — Une approche acoustique pour étudier les thons agrégés autour de dispositifs de concentration de poissons en Polynésie française : méthodes et validation. Le comportement et la distribution spatiale des thons agrégés à proximité de dispositifs de concentration de poissons (DCP) ont été étudiés à l'aide de marquages acoustiques, mais de rares études ont utilisé les méthodes d'acoustique sous-marine. Cet article présente des techniques, ainsi que leurs limites, permettant, à l'aide d'un écho-sondeur scientifique connecté à un transducteur à faisceau scindé, d'observer et de caractériser les agrégations de thons autour des DCP. Les expériences ont été menées en Polynésie française entre décembre 1995 et février 1997. Deux méthodes : l'écho-comptage et l'écho-intégration ont été utilisées. L'écho-comptage n'est possible que lorsque les poissons sont suffisamment dispersés pour que chaque individu puisse être distingué. En revanche, l'écho-intégration peut être utilisée à la fois pour des poissons dispersés et des poissons agrégés en bancs. La connaissance de la réponse acoustique individuelle des thons est utile pour séparer les individus par écho-comptage, et indispensable en écho-intégration, pour obtenir des estimations absolues de densité. Les performances du sondeur et les réglages utilisés doivent être pris en considération avant de choisir la méthode la plus appropriée pour déterminer une densité de poisson ou étudier la structure spatiale d'une agrégation de thons. Ces méthodes permettent d'étudier l'ensemble d'une agrégation de thons, son comportement dans l'espace et dans le temps à très fines échelles spatio-temporelles (de l'ordre du mille nautique et sur des périodes de quelques heures). Elles ouvrent de nouveaux champs d'expérimentations scientifiques sur la structuration et le comportement des agrégations de thons autour de dispositifs de concentration de poisson ancrés ou dérivants. © 1999 Ifremer/Cnrs/Inra/Ird/Cemagref/Éditions scientifiques et médicales Elsevier SAS

Prospection acoustique / DCP / agrégation / thon / densité de poissons / comportement

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1. INTRODUCTION

Tuna are mainly found, and thus exploited, far from shore by industrial fishing fleets. The accessibility of this resource is difficult for artisanal fisheries, which are generally characterised by a limited operating range. As a consequence, the development of artisanal tuna fishing activities in most of the islands of the Indian and Pacific oceans, is dependent upon the use of fish aggregating devices (FADs), which can aggregate tuna at a known geographical location.

FADs have been the subject of many studies: 1) technological aspects [7, 14]; 2) fishing techniques [23, 24]; 3) socio-economic aspects [28]; 4) catches around FADs [11]; 5) diet of associated tuna [6, 8]; and 6) behavioural processes using ultrasonic telemetry [1, 5, 9, 10, 15, 17, 20, 21]. However, aggregations themselves have not really been studied.

Tuna aggregations are difficult to study because optical equipment and diving observations are greatly limited as light is quickly absorbed in the aquatic environment. The use of artificial lighting can disturb the behaviour of tuna, invoking avoidance or attraction reactions. Acoustic signals appear to offer a great advantage over optics because sound absorption is much lower in the aquatic environment (at least at the frequencies used in fish sonar). Because the auditory perception of tuna is below approximately 2 kHz, sound should not disturb the fish.

Acoustics appear to be an appropriate tool to observe and characterise tuna density and biomass associated with FADs. Two methods (echo-counting and echo integration) were used to determine tuna densities around FADs anchored at more than 1 000 m in depth in French Polynesia. The purpose of this paper is to discuss and validate each one of these methods according to 1) the spatial structuring of aggregations and 2) the characteristics and performances of the acoustic instrumentation used.

The experiments were conducted between December 1995 and February 1997 within the framework of the ECOTAP programme. ECOTAP (studies of tuna behaviour using acoustic and fishing experiments/ *étude du comportement des thonidés par l'acoustique et la pêche*) is a joint programme between two French research institutes (Ifremer: Institut français de recherche pour l'exploitation de la mer and IRD: Institut de recherche pour le développement), and a French Polynesian institute (SRM: Services des ressources marines). The purpose of this programme is to study the distribution and behaviour of bigeye tuna, *Thunnus obesus* (Lowe, 1839), yellowfin tuna, *Thunnus albacares* (Bonnaterre, 1788) and albacore tuna, *Thunnus alalunga* (Bonnaterre, 1788). The programme's research is directly related to tuna stocks exploited by a local longline fishery in more offshore water, and the drop-stone fishery associated with FADs located in more nearshore waters in French Polynesia [23].

Table I. Main settings of the SIMRAD EK500 echo sounder used during echo-surveys around fish aggregating devices (FADs).

Operation menu	ping interval	0.0
	transmit power	normal
	noise margin	10 dB
Transceiver menu	transducer depth	3.00 m
	absorption coef.	10 dB/km
	pulse length	medium
	bandwidth	auto
	max. power	2 000 W
	2-way beam angle	–20.9 dB
	Sv transducer gain	27.7 dB
	Ts transducer gain	27.8 dB
	angle sensitivity	21.9
	3 dB beamwidth	6.9 deg
	alongship offset	–0.07 deg
	athw.ship offset	0.21 deg
TS detection menu	min. value	–55 dB
	min. echo length	0.8
	max. echo length	1.8
	max. gain comp.	6.0 dB
	max. phase dev.	2.0

2. MATERIALS AND METHODS

2.1. Data acquisition

Experiments were conducted aboard the 28-m IRD Research Vessel Alis, using a SIMRAD EK500 echo sounder (version 4.01). The sounder was connected to a SIMRAD ES38B hull-mounted, split-beam transducer producing pulse duration of 1.0 ms at 38 kHz. The beam angle was 6.9°. The on-axis calibration of the acoustic equipment was performed with a 60-mm copper calibration sphere as described in the EK500 operator's manual [25]. The SIMRAD-supplied beam-plotting software (LOBE) was used to measure the beam characteristics of the transducer. *Table I* gives the results of the calibration and the main settings used during echo surveys.

The system noise level, i.e. the sum of receiver noise, local noise and ambient noise, expressed in acoustic relative units (dB ref. 1 μPa) was measured at various vessel speeds, between 0 and 10 knots, using the procedure recommended by SIMRAD [25]. Measurements were carried out in deep waters (more than 1 000 m deep). Results (*figure 1*) were used to define an optimal survey speed (7 knots), which represents a compromise between a higher speed producing greater coverage of an area and lower acoustic noise providing better sonar performance.

Three survey patterns were defined based upon a maximum survey time fixed a priori to 2 h (*figure 2*).

Transect 1: a star survey pattern with eight branches, each 0.8 nautical mile long and repeated twice (*figure 2a*).

Transect 2: a star survey pattern with 12 branches, each 1.0 nautical mile long, without duplicate (*figure 2b*).

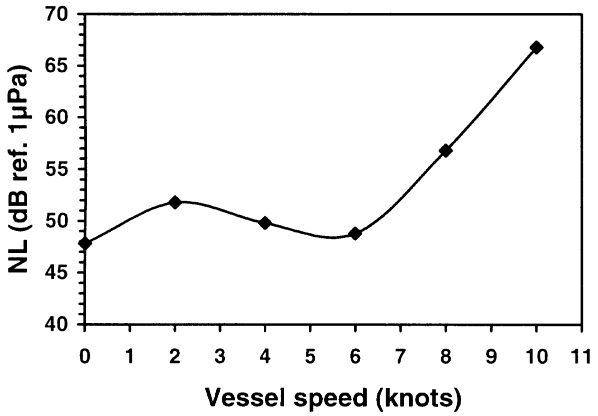

Figure 1. Acoustic system noise level (NL) as a function of the vessel speed.

Transect 3: a star survey pattern with eight branches, each 1.2 nautical miles long, without duplicate (*figure 2c*).

Star survey patterns allow a sampling effort all the greater since one is close to the FAD. The transect 1 pattern was used during previous acoustic surveys around FADs in French Polynesia [1, 13, 16] and was the most used pattern during the present experiments. Transect 1 increased the survey effort close to a FAD while allowing us to prospect an a priori area wide enough to encompass an entire aggregation. Transect 2 and 3 patterns produced fewer observations close to a FAD but made navigation easier, particularly when survey conditions were difficult (poor visibility, agitated sea, strong current, rain, etc.), and allowed us to extend the area prospected.

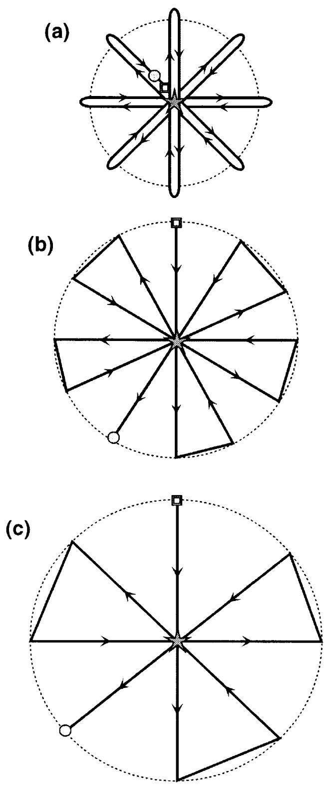

Figure 2. Survey patterns used during acoustic surveys around FADs in French Polynesia. ★, FAD position; □, start of the survey; ○, end of the survey.

SIMRAD EP500 software [26] was used to record, via ETHERNET on a personal computer (PC), acoustic and navigation data from the EK500 echo sounder. Acoustic measurements were extended down to 500 m in depth, because tuna are known to inhabit this vertical range within the region [12, 17]. Echo-trace (single echo) and echo integration data were processed and stored separately.

Single echos were selected using EK500 (see Soule et al. [27] for a review of the SIMRAD algorithms) when their target strength (TS) was higher than a minimum threshold value. We used a –55 dB threshold, selected a priori, from data available in the literature for various pelagic and bottom fish species of various sizes [19]. Additional operator-selected criteria, mainly concerned with the shape of the received signal, were defined during data acquisition [4, 25, 27]. We used the standard parameters recommended by SIMRAD [25] (*table I*). Target strength data were then recorded by EP500.

For echo integration the EP500 software allows the storage of 250 values of Sv (Log volume backscattering coefficient) from each acoustic ping. A vertical depth range of 0–500 m, therefore, corresponds to an elementary sample unit of 2 m in depth.

2.2. Data processing

In order to estimate tuna densities associated with a FAD, surveyed areas were partitioned into 30 or 45° angular sectors based upon the survey pattern used (*figure 3*). Each angular sector was then subdivided into volumes, using the distance of the sector from the FAD (0.1 nautical mile increments) and an arbitrary depth category. Depth categories included one 40-m layer for depths between 10 and 50 m, and nine 50-m layers for depths between 50 and 500 m.

For each elementary sampling volume, densities, expressed as a number of fish per volume unit, were determined by 1) echo-counting in the presence of scattered fish, or 2) echo integration in the presence of aggregated fish. We limited our analyses to a radius of 0.8 nautical mile around a FAD for comparison of fish densities between transect patterns and surveys.

An accurate estimate of the acoustic target strength of a fish, which may vary with species, size and depth, is necessary when using either the echo-counting or echo integration techniques to estimate biomass. Echo-counting requires that only echoes from tuna are counted and all other echoes are excluded. To convert acoustic densities into tuna densities with the echo

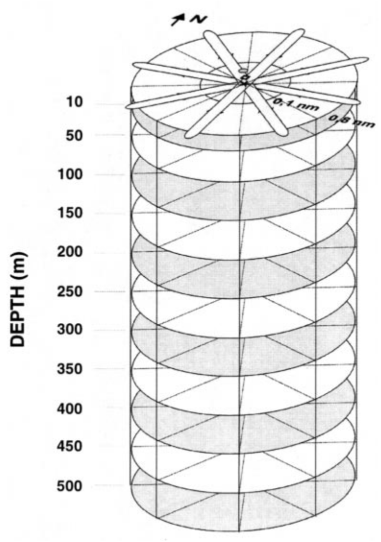

Figure 3. Elementary sampling units used to estimate the densities of fish around FADs.

integration method requires calculation of a mean TS value for the species of interest. Target strength values for yellowfin tuna (*Thunnus albacares)* and bigeye tuna (*T. obesus)* are shown in *table II*, from data collected during other ECOTAP programme experiments ([2, 3]; Josse, pers. comm.). Since the TS threshold used during data acquisition (–55 dB) appeared too weak, we used these tuna target strength references to determine a threshold value of –46 dB for the extraction of individual targets in our analysis.

2.2.1. Echo-counting

Echo-counting is a relatively simple technique for obtaining quantitative estimates of density and biomass [18], provided individual fish are sufficiently distant from one another to allow their individual echoes to be discriminated. The EK500 settings we used determined a vertical resolution of 0.75 m (i.e. half the pulse-length) and a horizontal resolution greater than the width of the acoustic beam. Beam width varies with the depth of the target and the beam angle (6.9° in theory). The split-beam system allowed us to directly apply this technique [22], following three steps.

The first step involves identification and counting of all fish using the EP500 ‘trace tracking’ software [26], which provides automated recognition of a single fish detected over one or more successive pings. In the second step, each identified fish is allocated to an elementary sampling unit corresponding to its spatial location referenced to depth and distance from a FAD. Although this information is not directly available, the EP500 software provides the depth of each identified target and serial numbers of acoustic pings associated with each target. The geographical location of each ping is available in the raw data files. Using these data, we calculated the geographical location of each fish and its distance from a FAD. The third step involves converting the number of fish detected in a basic sampling unit into a density value (number of fish per m^3). This step requires knowledge of the water volume sampled by the acoustic beam. In single-echo detection mode (TS detection), transducer directivity and EK500 settings (see *table I*: maximum gain compensation) determine the sampling angle of the acoustic beam. This angle can be determined using either the beam pattern of the transducer or the angular coordinates associated with individual echoes. This last method was used as a split-beam system allows a continuous recording of these angular coordinates [22]. The water volume sampled was then calculated for each basic sampling unit.

Table II. Target strength values (TS) for yellowfin (*Thunnus albacares*) and bigeye tuna (*T. obesus)* from the literature.

Species	Fork length (cm)	Estimated weight (kg)	Average TS (dB)	References
Thunnus albacares	60	4	–34.8	Bertrand et al. [2, 3]
	90	14	–33.0	
	108	25	–30.4	
	120	30	–26.1	
Thunnus obesus	49.9*	3	–32.8	Josse (pers. comm.)
	50.1*	3	–31.9	
	110	30	–24.4	Bertrand et al. [2, 3]
	130	50	–21.4	

* Mean value.

2.2.2. Echo integration

The distance between fish targets is not a concern using the echo integration technique, and this method is applicable when fish are closely spaced (packing density is high). Acoustic density values were extracted from each sampling unit using the EP500 software. Individual target strengths were extracted from each survey using the EP500 ‘trace tracking’ procedure. An average target strength was then calculated (TS data were transformed to acoustic cross section, i.e. in arithmetic values, when used in calculation) and used to transform acoustic density values into absolute densities (number of fish per volume unit).

The EP500 software uses an integration threshold to extract the acoustic density values. This integration threshold must be set high enough to minimise non-target acoustic noise, emanating from other organisms or the vessel, which could result in an overestimation of tuna biomass. A too high threshold, on the contrary, can result in an underestimation of biomass. Thus, choosing an integration threshold involves both theoretical and empirical considerations. We determined, as recommended by SIMRAD [25], that there was no integration of acoustic system noise above a Sv threshold of –80 dB to a depth of 500 m, at a vessel

Table III. Densities (d) in number of fish per km^3 and numbers of fish (n), per depth and distance to the FAD strata.

Depth strata (m)		Distance to the FAD strata (nautical mile)								
		0.0–0.1	0.1–0.2	0.2–0.3	0.3–0.4	0.4–0.5	0.5–0.6	0.6–0.7	0.7–0.8	0.0–0.8
10–50	d	246								4
	n	1								1
50–100	d	1 381	223	186	60					53
	n	7	4	5	2					18
100–150	d	667	51	19	7	7		25	36	30
	n	4	0.8	0.5	0.3	0.4		2	3	10
150–200	d	111	31	20	35	20	11		13	16
	n	0.6	0.5	0.5	1	1	0.6		1	6
200–250	d	41	34	19	24	15	8	6	31	18
	n	0.2	0.5	0.5	0.9	0.7	0.5	0.4	2	6
250–300	d	56	17	13	8	3	5	7	23	12
	n	0.3	0.3	0.3	0.3	0.2	0.3	0.5	2	4
300–350	d	10		3		3	9		11	5
	n	0.1		0.1		0.1	0.5		0.9	2
350–400	d					2				0.3
	n					0.1				0.1
400–450	d									
	n									
450–500	d									
	n									
10–500	d	251	36	27	14	5	3	4	12	14
	n	13	6	7	5	2	2	3	9	47

Mean values were calculated from the 44 surveys processed by echo-counting.

survey speed of 7 knots. We used three integration threshold values during the data extraction (–70, –65 and –60 dB) depending on micronecton abundance. We used a –60 dB threshold during nocturnal surveys in order to separate tuna from micronecton, which share the same depth strata at night.

3. RESULTS

During the ECOTAP programme, 87 acoustic surveys were carried out around 17 FADs. A visual analysis of the echograms coupled to a search of the individual targets with the EP500 software showed that tuna echoes were detected in 60 surveys. Echo-counting was used, only when fish were scattered, otherwise the echo integration technique was applied. The mean number of fish and density per unit of volume, by depth and distance to the FAD, are shown in *table III* for scattered fish and *table IV* for aggregated schools.

3.1. Echo-counting

This technique was used for 44 surveys. An average density of 14 fish per km^3 (i.e. an average of 47 fish per survey) was observed between depths of 10 and 500 m in a radius 0.8 nautical mile around FADs (*table III*). Densities were greatest near FADs, decreasing quickly with increasing distance from the FADs. Tuna were detected to depths of 400 m, but more than 60 % of the fish were observed between depths of 50 and 150 m. Measured target strengths for individual fish varied between –40.3 and –18.7 dB, with an average TS value of –25.7 dB. One broad distribution was observed with modes between –34 and –36 dB, –26 and –28 dB, and –20 and –22 dB (*figure 4a*).

3.2. Echo integration

Sixteen surveys were analysed using this technique. When tuna schooling fish were aggregated around FADs, target strength data were extracted on the periphery of the aggregation where fish are more scattered. Target strengths varied between –45.9 and –18.8 dB, with an average value of –32.6 dB. The distribution of target strengths is bimodal with modes between –40 and –42 dB, and –28 and –32 dB (*figure 4b*). An average density of 801 fish per km^3 (2 708 fish per survey) was observed between 10 and 500 m of depth in a radius 0.8 nautical mile around FADs (*table IV*). Densities were greatest close to FADs at depths between 10 and 50 m. Densities decreased very quickly as the distance from FADs, and depth, increased. A few small schools of tuna were observed near the edge of the survey areas, mainly in the surface layer (*table IV*). More than 70 % of fish were detected between depths of 10 and 50 m within 0.1 nautical mile of the FADs.

Table IV. Densities (d) in number of fish per km^3 and numbers of fish (n), per depth and distance to the FAD strata.

Depth strata (m)		Distance to the FAD strata (nautical mile)								
		0.0–0.1	0.1–0.2	0.2–0.3	0.3–0.4	0.4–0.5	0.5–0.6	0.6–0.7	0.7–0.8	0.0–0.8
10–50	d	451 425	2 309	339	8		161	405	1 338	7 612
	n	1 946	30	7	0.2		8	23	86	2 100
50–100	d	55 219	2 020	361			201			1 020
	n	298	33	10			12			352
100–150	d	18 233	5 597	1 070	10	5				633
	n	98	90	29	0.4	0.2				218
150–200	d	2 687	329							57
	n	14	5							20
200–250	d	42	232		113					24
	n	0.2	4		4					8
250–300	d	618	60							12
	n	3	1							4
300–350	d	600	51							12
	n	3	0.8							4
350–400	d	387								6
	n	2								2
400–450	d									
	n									
450–500	d									
	n									
10–500	d	44 788	1034	174	13	0.5	34	33	109	801
	n	2 365	164	46	5	0.2	20	23	86	2 708

Mean values were calculated from the 16 surveys processed by echo integration.

4. DISCUSSION

Although both methods (echo-counting and echo integration) used in the current research have previously been used by others, we feel we made significant advances in successfully adapting these techniques to the study of tuna aggregations. Three major elements must be carefully evaluated when choosing the most appropriate method: 1) performance of the sounder on individual fish, 2) performance of the sounder on groups of fish, and 3) the three-dimensional spatial structuring of the fish school. Echo-counting is appropriate when fish are scattered. Echo integration can be used for both scattered and aggregated fish.

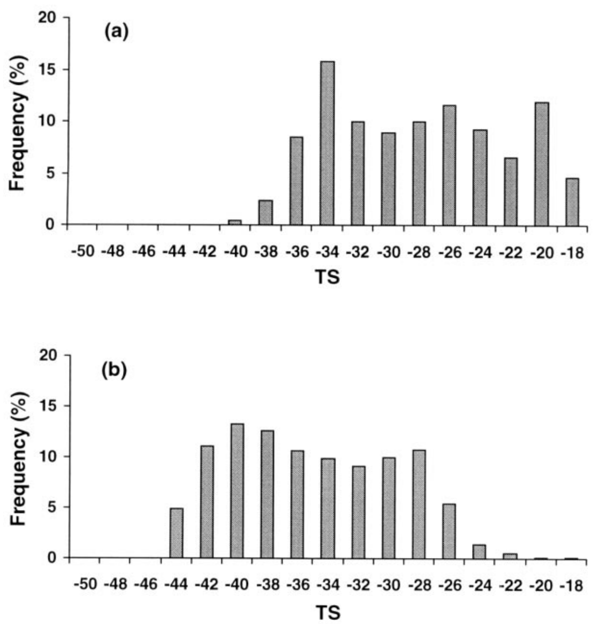

Figure 4. Frequency distribution of target strength (TS) values for the two different types of detection: (a) scattered fish; (b) aggregated schools.

4.1. Maximum depth-of-detection of an individual target (echo-counting)

We calculated a maximum depth-of-detection for a single target located within the acoustic axis of the beam (see Appendix), using the equipment's acoustic parameters, standard settings and the acoustic noise we measured at a vessel speed of 7 knots (*figure 5a*). Based on our analysis, we do not expect to detect a fish with target strength less than –46 dB (threshold value used for extracting the TS data) beyond a depth of 275 m. Bertrand et al. [2, 3] reported a TS value of –34.8 dB for a 60-cm fork length yellowfin tuna. We predict that echo-counting can detect a –34.8 dB target to a depth of 440 m. All targets with TS superior to –31 dB should be detected down to 500 m.

The risk of underestimating fish densities with this technique depends upon the size and depth of the targets, because small fish produce smaller acoustic target strength returns, and the fish must be within the

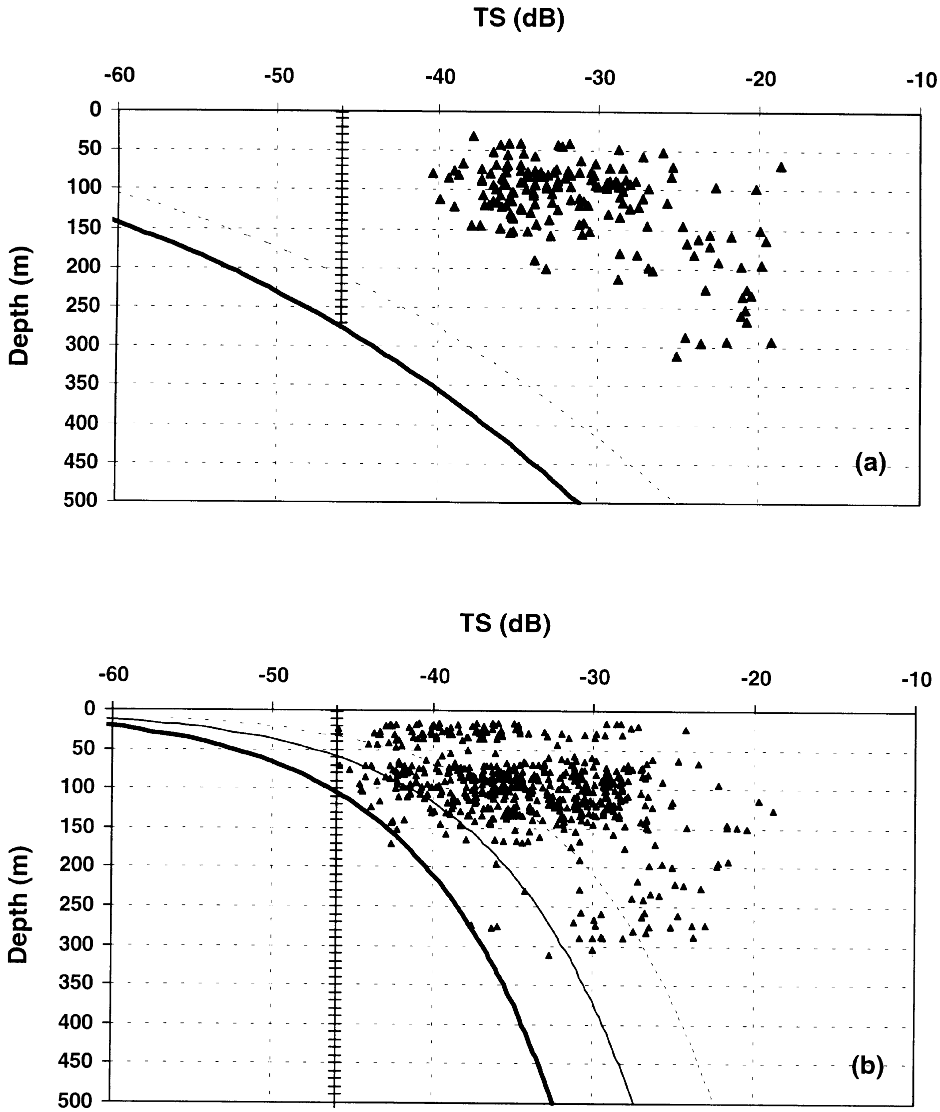

Figure 5. Acoustic limits of the echo sounder in (a) echo-counting (individual target detection mode); and (b) echo integration at a vessel speed of 7 knots. a) Echo-counting: ······, theoretical maximum depth to detect an individual target located outside the acoustic axis, at the maximum angle authorised for the detection of an individual target; ▬, theoretical maximum depth to detect an individual target located in the acoustic axis; +++++, threshold value used to extract target strength (TS) data with the EP500 software; ▲, (TS–depth) data from echo-counting. (b) Echo integration: ······, Sv threshold = –60 dB; —, Sv threshold = –65 dB; ▬, Sv threshold = –70 dB; +++++, threshold value used to extract target strength (TS) data with the EP500 software; ▲, (TS–depth) data observed during echo integration.

maximum depth-of-detection of the equipment. Acoustic tracking experiments have been conducted on skipjack (*Katsuwonus pelamis*), yellowfin and big-eye tuna [1, 10, 12, 17]. These studies suggest the maximum depths these species inhabit are within the theoretical limits of detection we calculated.

The beam angle is constant until a depth dependent on the TS of the target, then progressively decreases to null at the maximum depth-of-detection (*figure 6*). Due to the transducer directivity, the maximum depth-of-detection of a target decreases as the distance from the acoustic axis increases. The maximum beam angle of detection of individual targets was defined during TS data acquisition. The maximum depth-of-detection for a target, at the maximum angular distance from the acoustic axis, can be calculated taking into account the 6 dB (see maximum gain compensation in *table I*) losses due to the receiving directivity index of the transducer (*figure 5a*). Therefore, the acoustic beam angle is gradually reduced between the maximum depth-of-detection of a target, at maximum angular distance from the acoustic axis, and the maximum

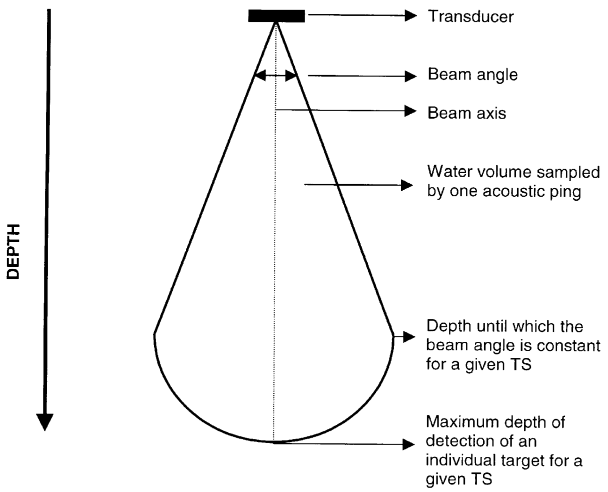

Figure 6. Schematic representation of the maximum depth of detection of an individual target and of the sampled volume by the acoustic beam.

depth-of-detection of the same target located in the acoustic axis. There is a risk of overestimating the sampled volume, which would result in underestimating density, if targets are detected between these two depths. We evaluated this risk by plotting all paired values (depth and TS) observed during echo-counting surveys (*figure 5a*). Because observed paired values are all located outside the limits where bias occurs, the risk of underestimating biomass appears very low.

4.2. Minimum detectable fish density (echo integration)

The lowest density of organisms that can be detected with this technique depends upon both the Sv integration threshold chosen and the average target strength (TS) value associated with the organisms. It can be easily determined (*figure 7*) using the relation:

$$\rho_v = \frac{S_v}{\sigma}$$

where ρ_v is the density (number per unit of volume), S_v, the volume backscattering coefficient (Sv = 10 $\log_{10}(S_v)$) and σ, the acoustic cross section (TS = 10 $\log_{10}(\sigma/4\pi)$).

For example, with a –60 dB Sv integration threshold, a density lower than 1 individual per 100 cubic metres could not be detected if their mean TS is lower than –40 dB.

Elementary volumes sampled by the acoustic beam increase quickly with depth because of the beam angle. Using EP500 software with a vertical depth range of 0–500 m, each elementary volume corresponds to a cell 2 m high. Knowing the beam angle (6.9°), we can measure the volume of each cell according to the depth. Therefore, we calculated the minimum number of targets (per elementary volume) exceeding the corresponding integration threshold at depth (*figure 8*). Then, the minimum number of targets of a given TS, necessary to exceed the integration threshold according to the depth can be calculated (*figure 8*):

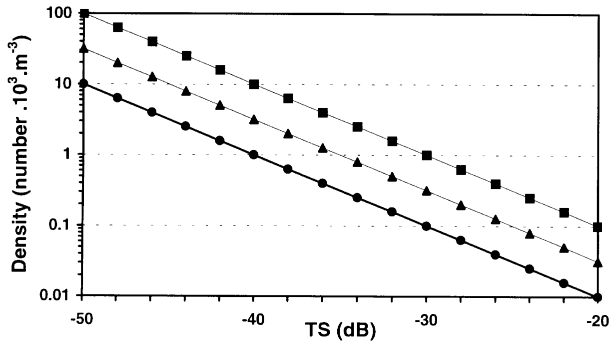

Figure 7. Minimal densities (number·10^3·m^{-3}) for echo integration as a function of mean target strength (TS) values for three integration thresholds (Sv): –60 dB (—■—), –65 dB (—▲—) and –70 dB (—●—).

$$N = \rho_v \cdot V(R)$$

where N is the number of targets, ρ_v, the minimum density per unit of volume (which is related to Sv and TS) and $V(R)$ the volume of an elementary cell at depth R.

Density estimates for large, scattered fish (TS superior to –20 dB) are reliable up to depths of 500 m, even if a high integration threshold is used. For smaller fish, there is a risk of underestimating densities if fish are widely scattered in deeper water. For example, a 60-cm fork length yellowfin tuna with a TS value of –34.8 dB [2, 3], theoretically cannot be detected below a depth of 125 m with a –60 dB integration threshold. The same fish is capable of inhabiting deeper waters down to 300 m during daytime, as shown by a sonic tagging experiment in French Polynesia [17]. Thus, it is advisable to decrease the integration threshold for targets at greater depths. Using a –70 dB threshold, the depth limit for echo integration of this same, isolated fish increases to around 380 m. Although a –70 dB threshold appears more suitable, there is increased risk for integrating organisms other than tuna using the lower threshold. Processing acoustic data with the echo integration method requires an adjustment of the integration threshold according to fish size, packing density and depth. We evaluated the risk of overestimating densities of small tuna, scattered in deep waters, by calculating the integration limits of an isolated fish, by TS and depth, for the three integration thresholds used during data processing. Observed pairs of values (depth–TS), and their calculated threshold limits, were plotted (*figure 5b*). The risk of underestimating densities of small tuna in deeper water is

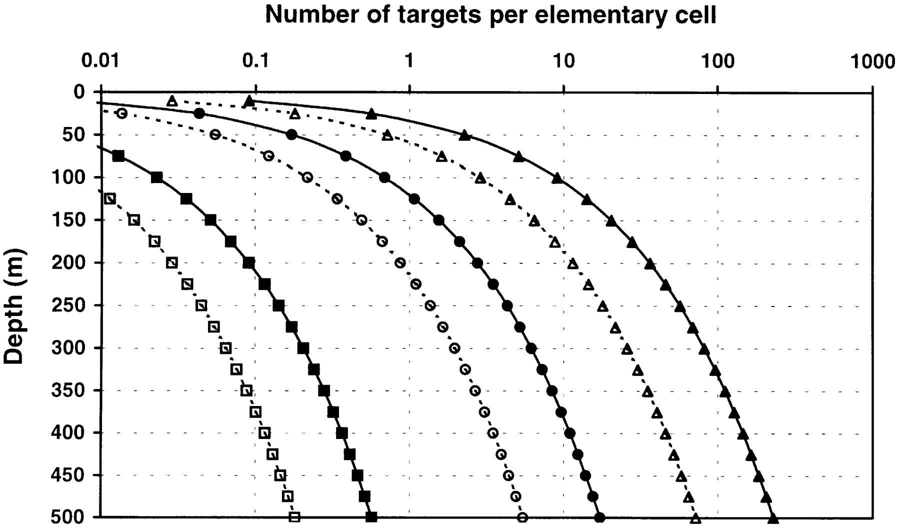

Figure 8. Minimum number of targets per elementary units for echo integration for different integration thresholds (Sv) and target strength (TS) values. —▲—, Sv = –60 dB, TS = –46 dB; —●—, Sv = –60 dB, TS = –34.8 dB; —■—, Sv = –60 dB, TS = –20 dB; —△—, Sv = –65 dB, TS = –46 dB; —○—, Sv = –65 dB, TS = –34.8 dB; —□—, Sv = –65 dB, TS = –20 dB.

dependent upon the correct application of adjustments to the integration threshold during data analysis.

4.3. Mean TS value used to convert acoustic density into fish density

Relative density values provided by the EP500 software require an estimate of average TS to convert the relative values into absolute density values. An average TS for each elementary sampling unit is desired, because aggregations are generally not homogeneous in either species composition or fish size. MacLennan and Simmonds [19], advise using in situ TS values obtained during the acoustic survey. TS values are generally obtained from the periphery of an aggregation where tuna are most scattered. We assume the TS values we used are valid, although the number of TS values measured for any elementary sampling unit is limited. Because we did not measure TS values for each elementary sampling unit, we calculated an average TS value for each series of surveys around the same FAD. We assume that the species composition and fish lengths of observed aggregations, and the behaviour of aggregated fish, did not change between surveys around the same FAD. Josse (pers. comm.) analysed results from various experiments conducted around an oceanographic buoy anchored far from shore and reported relative stable TS values, providing the basis for this assumption.

4.4. Comparison of results with literature

A literature review provided very few studies where acoustic methods were used to estimate tuna biomass associated with FADs. Three experiments have been conducted in French Polynesia [1, 13, 16], but it is difficult to compare results between these experiments and our study. During the first two series of experiments [13, 16], a SIMRAD EYM echo sounder connected to a towed single beam transducer was used at a frequency of 70 kHz. The SIMRAD EYM sounder used was incapable of detecting targets at depths below 100 m, which precluded analysis of any dispersed fraction of the tuna aggregation in deeper water. The echo integration method was used during data analysis, but because TS data were unavailable, it was not possible to evaluate tuna biomass. During the third series of experiments, a Model 102, Biosonics sounder was used at a frequency of 120 kHz [1]. This sounder provided acoustic data to a depth of 250 m. Despite the use of a dual-beam system and detection of scattered fish, they were unable to extract TS data and the results were only expressed in acoustic units. Since information about echo-sounder settings, performances or integration thresholds is not available, a comparison between all these experiments is difficult.

5. PERSPECTIVES AND CONCLUSION

We have shown that it is possible to estimate tuna densities and biomass around FADs if one carefully monitors the spatial distribution of fish, properly adjusts sonar parameters and chooses the appropriate echo-counting or echo integration method for data analysis. Both the echo-counting and echo integration techniques provide useful data for studies on spatial structuring of fish around FADs, as well as the temporal evolution of the aggregations on a daily basis. Acoustic tracking techniques have been used to study tuna behaviour around FADs. The two methods we describe should also be useful for studying the biological environment associated with tuna [17], the behaviour of individual fish within an aggregation, and temporal evolution and behaviour of the aggregation itself.

A measure, or estimate, of TS is a major parameter needed to estimate biomass, because TS allows conversion of acoustic density values into absolute values of density using the echo integration method. Data on tuna TS are only available for yellowfin and bigeye tuna ([2, 3]; Josse, pers. comm.).

The acoustic methodologies we applied to estimate tuna biomass around anchored FADs can also be used to study tuna aggregated around drifting objects, if these objects do not drift too fast. Research on fish aggregations and behaviour beneath anchored, and drifting, floating objects is needed to characterise differences in species and fish size composition around both structures, and to obtain a greater sample of TS values for tuna.

The echo-counting technique appears particularly well adapted to estimate densities when fish are scattered in deep waters anywhere in the open ocean, (e.g. large bigeye tuna occupying deeper water during daytime) as reported in Dagorn et al. [12].

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APPENDIX

Maximum on-axis depth-of-detection of an individual target

To detect a target, its echo level (EL) (in dB·1 μPa^{-1} ref. 1 m) must conform to the relation:

$$EL \geqslant NL + SNR + NM \quad (1)$$

where NL is the system noise level (in dB ref. 1 μPa), SNR the signal-to-noise ratio (in dB, SNR is automatically set to 20 dB by the SIMRAD system) and NM the noise margin (in dB) which can be introduced into the SIMRAD EK500.

The echo level of a target depends on the source level of the transducer (SL in dB·1μPa^{-1} ref. 1 m), on the two-way transmission loss (TL in dB) and on its acoustic characteristics (target strength: TS in dB):

$$EL = SL - 2\,TL + TS \quad (2)$$

TL can be calculated as follows:

$$TL = 20 \text{ Log } R + \alpha R \quad (3)$$

where R is the distance to the transducer (in m) and α is the sound absorption coefficient in the sea (α = 0.01 dB·m^{-1} at 38 kHz).

SL can be calculated as follows:

$$SL = Si + 20 \text{ Log } I \quad (4)$$

where Si is the transmitting response of the transducer (Si = 210.7 dB ref. 1 μPa·A^{-1}, SIMRAD references for the ES38B transducer used).

The intensity I (in A), can be calculated as follows:

$$I^2 = Pt \cdot Z^{-1}$$

where Pt is the transmitter output power (Pt = 2 000 W) and Z the transducer impedance (Z = 15 Ω).

From equations (1) and (2):

$$SL - 2\,TL + TS \geqslant NL + SNR + NM \quad (5)$$

Therefore to be detected a target must check the relation:

$$TS \geqslant 2\,TL - SL + NL + SNR + NM \quad (6)$$