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In situ acoustic target-strength measurement of bigeye (*Thunnus obesus*) and yellowfin tuna (*Thunnus albacares*) by coupling split-beam echosounder observations and sonic tracking

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A research programme was carried out in French Polynesia to study tuna behaviour using acoustics and fishing experiments. Acoustics are of great importance for the study of tuna behaviour and estimation of abundance but estimates of individual target strength that are available are particularly inaccurate. In this study, four yellowfin tuna (*Thunnus albacares*) and two bigeye tuna (*Thunnus obesus*) of weight 4–50 kg were individually caught, identified, and equipped with ultrasonic tags for telemetry experiments. While tracking the fish, simultaneous underwater acoustic data were recorded with a split-beam echosounder in order to estimate their *in situ* acoustic target strength. It was observed that target strength was stronger when fish were diving than when they were ascending toward the surface. This can be explained by the tilt angle orientation of the swimbladder. A target strength bias according to depth was also observed.

Key words: acoustics, target strength, swimbladder, tilt angle, *Thunnus albacares*, *Thunnus obesus*, acoustic telemetry.

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Introduction

Knowledge about individual target strengths (TS) is a principal requirement for the assessment of fish biomass and behavioural studies using acoustics. Target-strength ranges of most commercially important small pelagic fish have been extensively studied over the past 20 years (MacLennan and Simmonds, 1992) and generally show great variability. Unfortunately, tuna TS are almost unknown and the only values present in literature are estimates (Freeze and Vanselous, 1985).

Target-strength measurement is a difficult exercise, especially when the fish is distributed between the surface and 500 m of depth, as in the present study. It is already known that tethered fish studies (Nakken and Olsen, 1977) are not suitable for active fish and that *in situ* methods generally provide more accurate data (MacLennan and Simmonds, 1992). In the case of adult tuna, experiments in tanks would be difficult to set up because of beam-angle problems. Tuna grown in fish farming cages could provide a suitable opportunity but at present this is only possible for two species: the bluefin (*Thunnus thynnus* Linnaeus) and south bluefin tuna (*Thunnus maccoyii* Castelnau). For *in situ* measurements on fish swimming free in their environment the main difficulty is knowing precisely which fish (species, size) has been observed. This problem can be avoided by coupling a split-beam TS measurement with the sonic tracking of tagged fish as described by Bertrand *et al.* (unpubl.). The aim of this paper is to analyse the first results of such experiments with yellowfin tuna (*Thunnus albacares* Bonnaterre) and bigeye tuna (*Thunnus obesus* Lowe) observed up to 500 m depth to improve the knowledge about TS variability and the possible influence of depth and fish behaviour on this variability.

The experiments were conducted in French Polynesia within the framework of the ECOTAP programme (Etude du Comportement des Thonidés par

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l'Acoustique et la Pêche/Studies of tuna behaviour using acoustics and fishing experiments). This programme is a joint action between ORSTOM (L'institut Français de recherche scientifique pour le développement en coopération), IFREMER (Institut Français de Recherche pour l'Exploitation de la MER), and SMA (Service de la Mer et de l'Aquaculture). The aim of this programme is to study the distribution and behaviour of sub-surface tunas, *T. albacares*, *T. obesus*, and *T. alalunga* (Bonnaterre), exploited by local longline and drop-stone fisheries (Moarii and Leproux, 1996).

Materials and methods

The observations were made during ECOTAP surveys on board the ORSTOM Research Vessel "ALIS" (28 m long). Experiments were carried out in the Society and Tuamotu Archipelagos from October 1995 to August 1997.

Acoustic TS measurements

Acoustic data were collected with a SIMRAD EK500 (version 4.01) echosounder connected to a 38 kHz split-beam vessel mounted transducer, SIMRAD ES38B (beam angle 6.9°) used with a pulse duration of 1.0 ms. The maximum phase deviation was set at two phase steps and the noise margin between 10 and 13 dB due to a strong vessel noise. The water column extended to 500 m in depth. Acoustic and navigation data were stored via Ethernet on a PC through SIMRAD EP500 software. The on-axis and off-axis calibration was done using the standard procedure described in the EK500 manual (SIMRAD Subsea, 1993).

Individual target echoes (all species mixed) were selected afterward using EP500 trace tracking procedure. A drift in TS according to depth was systematically observed. Detection of small targets decreases with depth probably due to background noise integration.

Fish sonic tracking measurements

The tracking equipment used during these surveys was a VEMCO system (Shad Bay, Nova Scotia, Canada) V16P, 50 kHz, 500 and 1000 PSI equipped with pressure sensor. A VEMCO V10 directional hydrophone (50 kHz) fitted to a V-Fin towed depressor was used with a VEMCO VR60 receiver on board the RV "ALIS" during the first experiments. Later the directional hydrophone was replaced by a VEMCO V41 bearing hydrophone. This V41 four-elements hydrophone has acceptance angles in the four horizontal directions. The four hydrophone signals are wired to a four channel VR28 receiver, then sent to a PC running the software "TRACK" which displays the signal strength and the bearing of the acoustic transmitter. Depth data are stored every second and navigation data, through a Global Positioning System (GPS) every 5 s.

Some fish were caught on board RV "ALIS" by traditional drop-stone fishing technique (Moarii and Leproux, 1996) or longline. Others were caught on board longline fishing units; in this particular case the RV "ALIS" was only used for the tracking operation. According to the fish size, two different methods were applied to attach the transmitters. If the fish was small enough it was hauled aboard without causing injury, the fork length was measured and the transmitter attached using two nylon tie-wraps through the muscle of its back just behind the second dorsal fin. When the fish was too large it was not removed from the water but only drawn alongside the ship. The fork length was only estimated and the sonic tag fixed to the anterior dorsal musculature of the fish using a tagging pole.

TS of acoustic tag

The TS of the connected acoustic tag was measured after calibration of the echosounder in order to exclude its possible contribution to total fish TS. The values obtained were closed to -50 dB. The tag TS can be considered too low to modify the fish TS (the addition of a -50 dB target to a -30 dB target increase the latter by only 1%) and the acoustic effect of the tag has therefore been neglected in the present study.

TS of PVC target

To observe the possible effect of swimbladder changes with depth, a special experiment was carried out with a PVC cylinder 11 cm long and 5.4 cm of diameter (inner dimensions) containing 0.25 l of air sealed by two caps. This target is not a standard calibration sphere but may be acceptable for this type of experiment where the change in TS can only be due to the tilt angle and not volume change. Therefore this artificial target may be likened to a constant volume gas-filled swimbladder since it was sufficiently strong not to implode at depth. This target was immersed successively at 100, 200, 300, 410 and 460 m depth using a cable. It was maintained long enough at each depth to collect data throughout the range of tilt angle variation caused by vessel movements although the actual tilt angle at any one time could not be monitored.

Coupling fish sonic tracking and TS measurement

Target-strength measurements of tuna were carried out by coupling split-beam acoustic measurements with

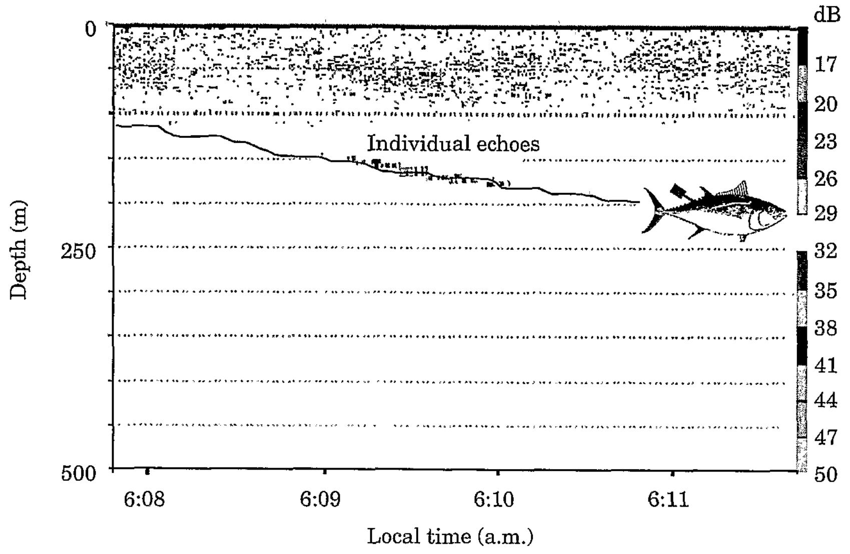

Figure 1. Echoes (points) and depth (solid line) of a tracked fish.

Table 1. Characteristics of the tagged fish used in target strength analysis.

Fish no.	Survey	Species	Fishing gear	Fork length (cm)	Estimated weight (kg)	Duration of track (h)	Date of track
YF10	ECOTAP03	Yellowfin	Drop-stone	60	4	22	27–28 October 1995
YF13	ECOTAP06	Yellowfin	Drop-stone	90	14	80	2–5 March 1996
YF14	ECOTAP07	Yellowfin	Drop-stone	108	25	91	20–24 April 1996
YF19	ECOTAP15	Yellowfin	Longline	120*	30	28	16–18 April 1997
BE21	ECOTAP15	Bigeye	Longline	110*	30	12	20–21 April 1997
BE22	ECOTAP18	Bigeye	Longline	130*	50	33	1–3 August 1997

*Estimated length.

sonic tracking of tagged fish. Depths of both TS and tagged fish were compared at equal times (Fig. 1) in order to select the precise tagged fish echoes. Coupling acoustic survey and fish sonic tracking was particularly difficult for several reasons: (1) it is difficult to catch, tag, and release a large fish without causing harm (Carey, 1990), for instance it was impossible to tag any albacore tuna as their swimbladder would often burst; (2) in the area of the study, TS data of tagged fish could only be recorded during daytime. At night the tagged fish moved too close to the surface to be easily detected; for instance at 50 m depth the beam radius is only 3 m. Furthermore, a dense scattering layer, which is almost always present close to the surface at night, prevents individual TS measurement; (3) comparison between tagged fish depth and TS depth is more difficult when the fish is inside a school. Despite these restrictions it was possible to record six series of TS measurements corresponding to four yellowfin tuna (YF10, YF13, YF17, and YF19) and two bigeye tuna (BE21 and BE22) (Table 1).

Data processing

Obtaining TS values for the fish was a three-stage process; (1) the TS data were extracted with EP500 trace tracking procedure (SIMRAD, 1994); (2) the depth of both TS and tagged fish were compared at equal times in order to select the precise tagged fish echoes; (3) a final control was made looking at the paper records and monitoring the EP500.

In accordance with convention, TS in this paper are expressed in dB. However, data were transformed to the equivalent acoustic cross-section for use in statistical analysis.

In order to distinguish vertical and horizontal movements, vertical fish direction and speed were calculated from changes in depth as provided by the echoes since they are less erratic than those provided by tagging. The movement was considered as vertical when the vertical movement reached 0.18 m s^{-1} over more than three pings. A visual check was made on the paper records.

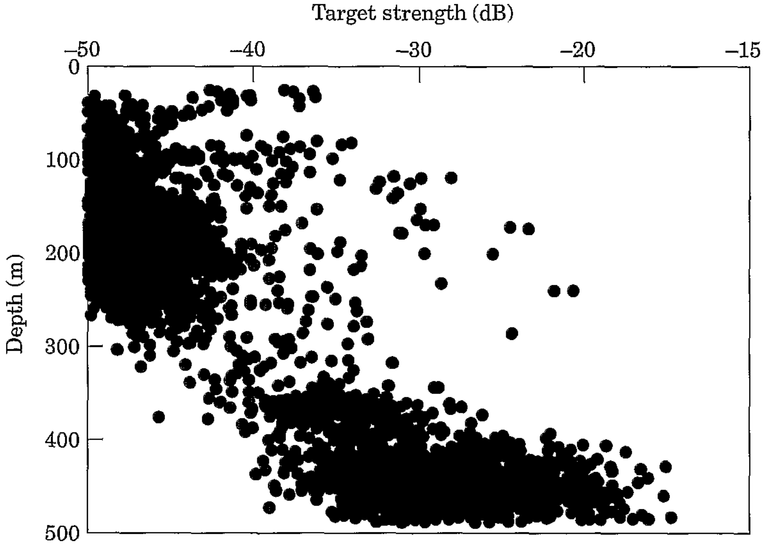

Figure 2. Distribution of target strength (TS) related to depth, all species mixed while no tuna was tracked.

Vertical movements were classified in upward and downward directions. For each fish an average TS was calculated: (1) for the whole data; (2) during a stable horizontal position; (3) during ascent; and (4) during descent. Target-strength values were then calculated in relation to depth. For each fish, when the number of echoes was sufficient for statistical analysis, average TS during an ascending vs. descending direction and an average TS by depth strata were compared using Student's t-test.

Results

Single fish echoes distribution

All the single target energies selected by EP500 during echosounding while no tuna was tracked are shown in Figure 2. It shows that small echoes disappear with depth (lower than − 50 dB beyond 270 m depth and − 34 dB at 500 m depth), probably due to background noise effect. This is consistent with the calculations obtained using the sonar equation at the observed level of noise. Under experimental conditions, the transducer performance gives 245 m for the maximum detection depth of − 50 dB targets and 465 m for targets higher than − 34 dB. The figure shows both an increase of the TS threshold and of the maximum values detected with depth. The second effect is compounded by the acceptance of multiple targets when the diameter of the beam increase with depth.

The PVC target

The average TS value obtained for the PVC target (Table 2) varies significantly according to depth strata (Table 3, Fig. 3a). There is a decrease from 100 m (− 29 dB) to 200 m depth (− 32.2 dB) then an increase to 460 m (− 24 dB) where the maximum value is observed. It should be noted that average TS is not dependent on position in the beam. All the average TS by depth strata are highly significantly different ($p<0.01$) except for the strata between 200 and 300 m where no significant difference occurs.

Tagged fish TS

The average TS of tagged fish varies from − 34.8 to − 21.4 dB (Table 2). Target- strength linearly increases with the size of fish for the same species and with the theoretical swimbladder volume for both species. Histograms of TS are widely distributed (Fig. 4) with a coefficient of variation from 51.1 to 92.8% (Table 2). In the case of the two bigeye tuna (Fig. 4e and 4f), TS were measured up to more than 300 m of depth. Histograms are thus probably biased because of a bias against weaker target at depth. Typically, TS do not significantly differ between horizontal and vertical movements. However, in the vertical plane TS are higher when the fish is moving downwards rather than upwards (Table 4). A Student's t-test on TS comparison between ascending and descending movements is highly significant for YF14 ($p<0.01$) and significant ($p<0.05$) for BE21.

Depth effect on TS measurements was observed for both bigeye tuna (Fig. 3d and 3e, Table 3) but not for yellowfin tuna (Fig. 3b and 3c). It must be noted that yellowfin were observed over a narrower depth range than bigeye tuna.

For BE21, TS data are classified among three depth strata ($100 \leq d < 150$ m, $200 \leq d < 250$ m, and

Table 2. Characteristics and mean target strength (TS) of PVC target and tagged tuna. The swimbladder volume was estimated from ECOTAP, unpubl. data. Data in parentheses are the number of observations.

Target or fish no.	Length (cm)	Estimated swimbladder volume (ml)	Mean TS	Coefficient of variation (%)
PVC	—	250**	−29.3 (554)	123.9
YF10	60	80	−34.8 (18)	51.1
YF13	90	130	−33.0 (102)	86.4
YF14	108	215	−30.4 (189)	92.8
YF19	120*	270	−26.1 (26)	52.2
BE21	110*	1000	−24.4 (141)	85.1
BE22	130*	2500	−21.4 (70)	60.1

*Estimated length; **exact volume.

Table 3. Average target strength (TS) (in dB) by depth (d) strata for the PVC target, BE21 and BE22.

Target	$100 \leq d < 150$	$150 \leq d < 200$	$200 \leq d < 250$	$250 \leq d < 300$	$300 \leq d < 350$	$350 \leq d < 400$	$400 \leq d < 450$	$450 \leq d < 500$
PVC	−29.0		−32.2		−31.1		−27.0	−24.0
BE21	−23.0		−26.1		−24.0			
BE22		−20.9			−26.6	−24.1		−19.3

$300 \leq d < 350$ m) (Fig. 3d); all the average TS by depth strata are significantly or highly significantly different except between strata 100–150 m and 300–350 m. For BE22, TS data are classified among four depth strata ($150 \leq d < 200$ m, $300 \leq d < 350$ m, $400 \leq d < 450$ m, and $450 \leq d < 500$ m) (Fig. 3e); all the average TS by depth strata are significantly or highly significantly different. For both bigeye tuna, a decrease was first observed followed by an increase in TS values with depth. It can be seen that for bigeye tuna, TS behave in the same manner with depth as the PVC target. Avoiding TS measured deeper than 310 m does not noticeably change the average TS for BE21 and BE22 (identical for BE21 and average TS is −21.8 instead of −21.4 for BE22) with the whole data.

Discussion

This method seems to be valid for *in situ* TS measurements of well-identified large pelagic fish swimming free in the open sea, independent of behaviour, vertical position in the water column, and the time period (up to several days).

The present study results show a great variability of TS (more than 15 dB for the same fish) even though fish are at a constant depth. This large amplitude is common in TS measurements (Dawson and Karp, 1990; Ona, 1990; MacLennan and Simmonds, 1992; Rose and Porter, 1996) and may correspond with changes in swimming aspect (Rose and Porter, 1996). The tilt angle and the swimbladder state are the main parameters determining TS (Nakken and Olsen, 1977; Foote, 1980a; Foote, 1980b; Blaxter and Batty, 1990; Dawson and Karp, 1990; Ona, 1990; MacLennan and Simmonds, 1992; Koslow *et al.*, 1997; Misund, 1997) and are closely linked to behaviour. The present TS values seem to be consistent as TS values are seen to increase with the size of the fish body and the estimated swimbladder volume. Comparison between these results and TS measurements of other species is difficult because TS depends not only on swimbladder volume but also on swimbladder shape (Foote and Ona, 1985; McClatchie *et al.*, 1996a; McClatchie *et al.*, 1996b). Nevertheless, recent TS measurements were carried out on caged south bluefin tuna using a split-beam 70 kHz EY500. TS of 25.7 kg, 106 cm length fish were recorded at 9 m depth; the mean TS measured was −29.2 dB (Kloser, pers. comm.). This result is in agreement with the observations made on YF14 which was very similar in size and weight.

The swimbladder is supposed to be responsible for 90–95% of the backscattering energy (Foote, 1980b). Yellowfin and bigeye tuna are physoclists (as the gadoids). Physoclistous fish have a closed swimbladder with a gas gland and resorption area (oval) for gas secretion/resorption from the blood to and from the swimbladder (Blaxter and Batty, 1990; Misund, 1997). Yellowfin tuna develop a gas-filled swimbladder as soon as their weight exceeds nearly 2 kg. The swimbladder volume then increases with a slight positive allometry as the fish increase in mass (Magnuson, 1973). The

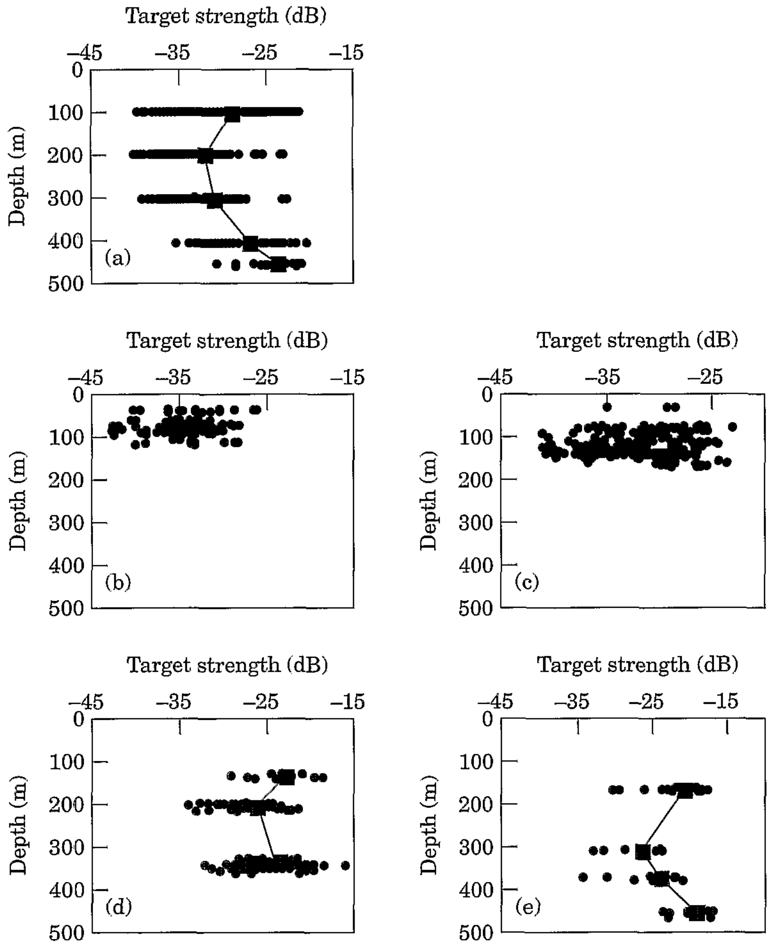

Figure 3. Target-strength (TS) measurement in relation to depth. (a) PVC target; (b) YF13; (c) YF14; (d) BE21; (e) BE22. The solid line joins the average TS by depth strata.

Table 4. Average target strength (TS) of tagged tuna for all the data, during horizontal movements, during ascending and descending movements. Data in parentheses are the number of observations.

	TS (dB)			
Fish no.	Total	Vertical stability	Ascending movements	Descending movements
YF10	−34.8 (18)	—	—	—
YF13	−33.0 (102)	−33.2 (36)	−33.7 (23)	−32.4 (43)
YF14	−30.4 (189)	−30.2 (107)	−33.2 (21)	−29.9 (61)
YF19	−26.1 (26)	—	—	—
BE21	−24.4 (141)	−24.9 (55)	−25.6 (17)	−23.8 (62)
BE22	−21.4 (70)	−20.8 (31)	−22.2 (10)	−21.9 (29)

—, Insufficient number of data.

swimbladder volume of yellowfin tuna is approximately 1–1.7% of the fish's volume (Fig. 5). The swimbladder volume of bigeye tuna has a positive allometry, increasing slowly at small size then rapidly becoming positive. The maximum swimbladder volume by weight is approximately 3% for a 20 kg fish, 5% for a 45 kg fish, and 8% for a 90 kg (Fig. 5). The volume of the swimbladder is highly labile and depends not only on the recent depth "history" of the fish (Blaxter and Batty, 1990) but also on the stomach content, gonad stage, fat

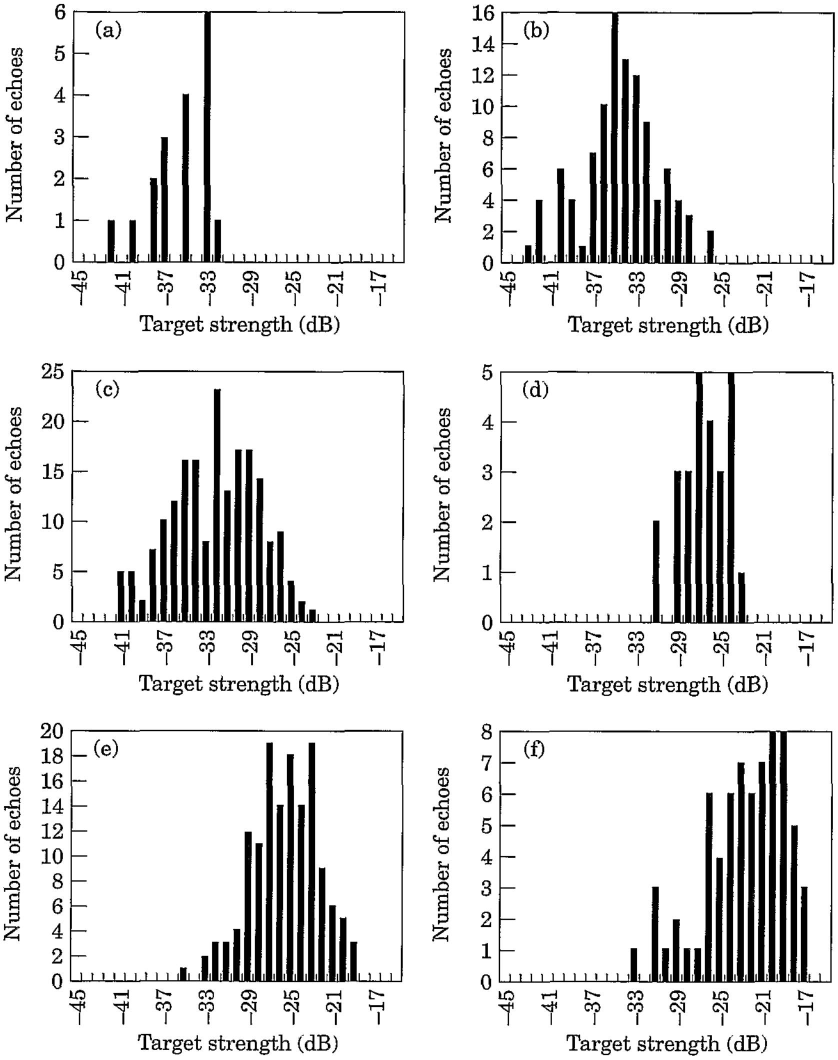

Figure 4. Target-strength histograms of the tagged fish. (a) YF10; (b) YF13; (c) YF14; (d) YF19; (e) BE21; (f) BE22.

content, and pressure (Ona, 1990). All these factors lead Ona (1990) to state that: "The idea of a 'standard', fixed target strength relation with a precision level of 0.1 dB for each species has no biological foundation, and should be used only as a reference or guideline". For physoclistous fish, a descending movement will decrease the swimbladder volume and an ascending movement will increase it. To prevent the swimbladder bursting, resorption is generally faster than secretion (Blaxter and Batty, 1990). Gas resorption would appear efficient for bigeye tuna as the swimbladders rarely burst after a rapid ascent from up to 500 m during longline hauling. Nevertheless the swimbladder may not be fully inflated at 500 m if secretion rates are insufficient to compensate for fast descents. Such "lagging" may mean that tuna swimbladder volumes are rarely adapted to any particular depth (Blaxter, pers. comm.). Target strengths are significantly higher when the fish is descending than when it is ascending for YF14 and BE21. This could be explained by the tilt angle change. The tilt angle is predominant in determining the TS by changing the acoustic cross-section of the fish (Nakken and Olsen, 1977; Foote, 1980a; Blaxter and Batty, 1990; MacLennan and Simmonds, 1992; Misund, 1997). Observations from X-ray (Fig. 6) revealed that the swimbladder angle is 20° to the horizontal for bigeye tuna. Therefore when the fish is ascending with a 20° angle, the swimbladder tilt angle becomes 40°. When the fish is descending with a 20° angle the tilt angle becomes 0° (Fig. 7). As TS is maximal when the swimbladder axis is near horizontal (Blaxter and Batty, 1990; MacLennan and Simmonds, 1992), the highest TS measurement will

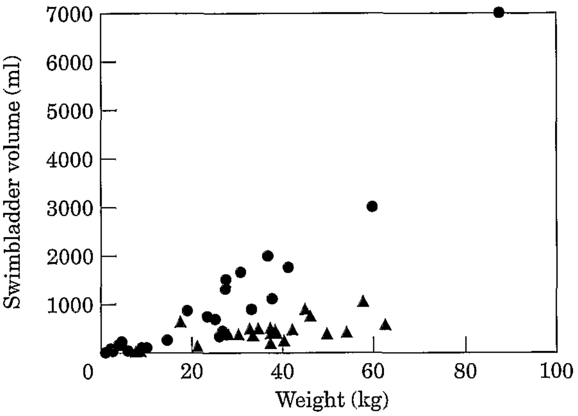

Figure 5. Relations between fish weight and swimbladder volume for Yellowfin (▲) and Bigeye (●) tuna (redrawn from Bard *et al.*, 1998a).

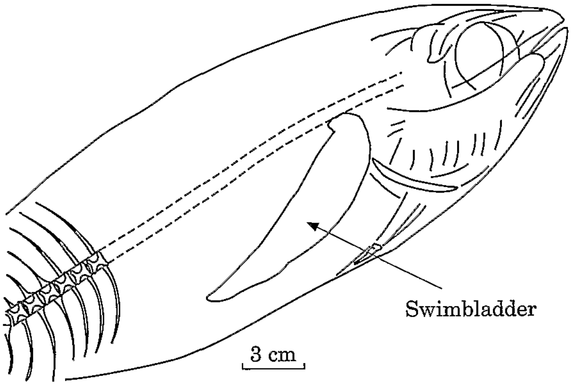

Figure 6. Diagram of a longitudinal section of a 43 cm Bigeye (redrawn from an X-ray in Bard *et al.*, 1998b).

be produced by tuna descending at an angle of 20°. A similar interpretation has already been made for TS measurement of saithe (*Pollachius virens*) where maximum values are obtained at a 7° tilt angle (head down) in accordance with the swimbladder axis (Blaxter, 1981 in Blaxter and Batty, 1990).

From the collected TS data (Fig. 3), a trend in TS can be observed according to depth. Values first decrease then increase with depth for the two tagged bigeye and the PVC target. This depth-TS dependent change is not observed with the tagged yellowfin tuna as they have a lower depth range. Several hypotheses can be proposed.

The relationship between depth and TS follows the Boyle-Mariotte's law and has been described by Mukai and Iida (1996) with kokanee salmon (*Oncorhynchus nerka*). Salmon are physostomatous fish (as are the clupeoids) meaning that they lack a gas-secreting mechanism and are unable to compensate for changes in swimbladder volume with depth. They observed a continuous TS decreasing with increasing depth (from 5 to 40 m).

Boyle-Mariotte's law could explain the TS decreasing with depth up to nearly 250 m. In this case, a continuously decreasing TS with depth for the bigeye tuna and no variation for the PVC target should be observed. Furthermore, it is important to note that the lowest BE21 TS measured between 200 and 250 m depth were observed after a diving movement whereas the lowest BE22 TS measured between 300 and 350 m depth were observed after an ascending movement. Finally, between nearly 250–460 m depth, Boyle-Mariotte's law effect should have led to a decreasing of TS with depth or at least a stability if the swimbladder volume compensation by gas secretion was very efficient. This is in opposition to what was observed, suggesting that this depth-dependent TS variation has a non-biological bias.

Soule *et al.* (1995), expressed TS overestimation bias with the possible acceptance of multiple echoes. This particular problem may not really be applicable to the present study as the bias was mainly observed on lower TS and with higher maximum allowable phase deviations than here.

These authors also expressed a second bias due to the effect of the maximum allowable phase deviation of the transducer according to target size. However, they observed no bias with a target of − 33.6 dB and a maximum phase deviation of two-phase steps, the settings used in the present study.

Bias due to the depth was studied by Koslow *et al.* (1997) with a towed 38 kHz split-beam transducer. They observed a reduction of single target echoes at a distance of the transducer up to 60 m for small targets (< − 40 dB). Unfortunately they did not study larger targets and distances beyond 60 m from the transducer. On the contrary, with a SIMRAD ES400-38 kHz split beam transducer, Barange *et al.* (1993) observed a bias against weaker targets (− 60 to − 55 dB) when targets were detected less than 3° off-axis. Such a bias was not observed for higher targets (− 40 to − 45 dB) but their depth range was only 120 m. For PVC target and tracked tuna, the use of targets located less than 3° off-axis does not change the results.

The maximum detection depth for a specified target depends on the ambient noise. The signal-to-noise ratio decreases with depth so at greater depths only larger targets can be detected. This effect may be compounded by the noise margin used. In addition small objects at the periphery of the transducer beam will be much weaker than the same objects in the beam axis. In this way, the beam width will effectively be smaller the deeper the objects are. Both effects reduce the number of weak echoes at greater depth.

Furthermore, the probability of multiple target acceptance increases with depth and may explain a part of the nearly 15 dB drift toward high TS beyond 250 m depth for all targets (Fig. 2). However, a large target, even observed at small depth, such as tuna or PVC

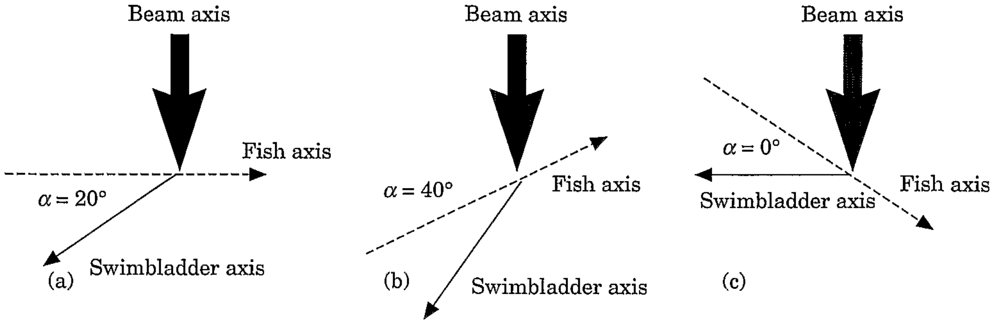

Figure 7. Tilt angle of tuna in: (a) horizontal movement; (b) ascent movement; (c) descent movement. α: swimbladder angle with horizontal.

target should not show a large TS variation with depth. In the case of the PVC target and the two bigeye tuna, the problem of multiple target acceptance may be excluded as they were individually tracked by sequences up to 10 pings.

So the diminution of the number of small targets could be explained by a combination of the signal-to-noise ratio and the periphery effect but the drift toward stronger targets cannot be fully explained by these factors. It can be supposed that a part of the 15 dB drift is due to multiple target acceptance in the case of all targets mixed but the rest of the drift and the nearly 10 dB drift observed with both tuna and the PVC target certainly have a multiple origin. We have no actual answer to this problem although a bias in the TVG calculation could exist.

Conclusion

Simultaneous fish sonic tracking operation and split-beam echosounder survey is an appropriate method for TS measurements of large pelagic fish. The TS variability can be observed according to the behaviour of a well-identified fish, swimming free in its environment.

The large range of observed TS may be due more to tilt angle changes than swimbladder volume changes. Nevertheless, an average TS calculated from all the values collected in the present study independently of the depth must be used with care. Otherwise a depth-linked bias which can lead to an overestimation of the TS will result. Consequently, for behavioural or stock estimation studies, TS obtained with the split-beam echosounder used here must be considered according to depth, especially where large depths are concerned. It is particularly the case for bigeye tuna which can move across a large depth range. The average TS measured for the two bigeye tuna considered in this experiment are therefore probably overestimates.

Further experiments following the same method must be carried out to confirm these preliminary results and to extend the range of results. This method is nevertheless promising and could be used for other large pelagic fish for which data are particularly sparse, billfish for example.

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