Target strength of skipjack tuna (Katsuwanus pelamis) associated with fish aggregating devices (FADs)

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This paper presents measures of target strength (TS: dB re 1 m²) and models of TS vs. fork length (L; cm), i.e. $TS = 20 \log(L) + b_{20}$, for skipjack tuna associated with fish aggregating devices (FADs) in the Central Pacific Ocean. Measurements were made using 38-, 120-, and 200-kHz split-beam echosounders on a purse-seine workboat during fishing operations. To mitigate potential bias due to unresolved targets, TS measurements were rejected if they were not simultaneously detected with multiple echosounder frequencies in approximately the same location. The filtered TS and concomitantly sampled $L$ data were used to estimate $b_{20} = \gamma_{76}, \gamma_{71},$ and $\gamma_{70.5}$ dB for 38, 120, and 200 kHz, respectively, using the method of least squares. For comparison, quasi-independent estimates of TS and $b_{20}$ were calculated from acoustic echo-integration and catch data representing entire aggregations around the FADs. The results differed by $\gamma_{20}$ dB for all three frequencies. The sensitivities of these results to variations in fish morphology and behaviour were explored using a simulation of TS for fish without swimbladders. The utility of the results on acoustic properties of skipjack tuna and next research steps to achieve selective fishing at FADs are discussed.

Keywords: acoustics, echosounder, FAD, frequency response, multiple targets, selectivity, sonar, split beam, tropical tuna, tuna

Introduction

Fish aggregating devices (FADs) are used to catch tropical tunas, skipjack (Katsuwanus pelamis) comprising more than half of the global tuna catch. Almost invariably, skipjack are found with bigeye (Thunnus obesus) and yellowfin tuna (Thunnus albacares) at FADs (Fonteneau et al., 2013). Although the stocks of skipjack are reported to be in healthy condition, recent stock assessments for bigeye and yellowfin tuna indicate that these tuna stocks are fully exploited or subject to overfishing in different regions (ISSF, 2017).

In recent years, the widespread use of FADs to catch skipjack has motivated increased efforts to minimize catches of bigeye, yellowfin, and other non-target species (bycatch). One approach is to use the fishers’ echosounders, sonars, and echosounder buoys (Lopez et al., 2014; Moreno et al., 2016) to not only locate and fish on target species, but also to identify the presence and distribution of non-target species near FADs before nets are set. Data from these instruments could also be used to estimate tuna distributions and abundances to inform stock assessments (Moreno et al., 2016). To quantitatively interpret acoustic data collected around FADs, it is necessary to know the sound scattering characteristics of the target species. In particular, echo-integration estimates of fish abundance requires knowledge of mean target strength [$TS = 10 \log(\sigma_{0b})$, dB re 1 m²], where $\sigma_{0b}$ (m²) is the backscattering cross-section (MacLennan et al., 2002), vs. acoustic frequency ($f$; kHz) and fish length ($L$; cm) (Simmonds and MacLennan, 2005). Models of $TS(f)$ can be used to allocate
and open source software (R, R Core Team, 2014). The TS and \( S_f \) data were analysed from \( \sim 5 \) min before the set until echoes from the net were visible at the bottom of the echogram (i.e. before the tuna changed their behaviour in response to the closing net).

**Target selection**

A routine was then applied to assure that the subsequent TS measurements were of pure skipjack targets. To avoid echoes from bycatch fish species, \( S_f \) and TS data were excluded if shallower than 25 m (Muir et al., 2012; Forget et al., 2015), deeper than 200m, or below echoes from the net. In addition, a school detection algorithm (Lawson et al., 2001) was then used to retain the main aggregation (assumed to be skipjack, given the high proportion of the catch). The rejected echoes from outside the aggregation were considered non-fish echoes (putative plankton or small nekton) that tend not to aggregate, or large bigeye and yellowfin, which tend to locate below the main aggregation (as described by Moreno et al., 2008; Govinden et al., 2010; Muir et al., 2012; Lopez et al., 2016) (Figure 2). After smoothing by an unweighted, normalized to unity, 5 × 5 convolution, ”schools” (i.e. the main aggregations around the FAD) were selected using: minimum total school length and height = 0.2 m; minimum candidate length and height = 0.1 m; and maximum vertical and horizontal linking distances = 5 and 20 m, respectively. The school detection was applied on both \( S_f \) and TS echograms, and data from within the schools were attributed to skipjack (Figure 2).

**TS estimation based on single targets**

The TS echograms at each frequency were processed using a single-target detection algorithm (SIMRAD, 1996; Soule et al., 1997) configured with the following settings: minimum threshold = -80 dB; normalized pulse durations = 0.9–1.5; maximum off-axis angles = \( 3^\circ \); and maximum standard deviations of phase = 0.6°.

**Multiple-target rejection**

To mitigate bias in TS measurements due to unresolved targets (Demer et al., 1999), the single-target detections were filtered further using the following methods:

1. Standard deviation (SD): Alongships and athwartships phase was thresholded (Soule et al., 1997) with values ranging from 0.9°–0.1°.
2. Fish tracking (FT): TS measurement sequences were ascribed to individual fish using a method (Blackman, 1986) applied in commercial software (Echoview; Hobart, Tasmania) and configured with the following parameters (Moreno et al., 2008): \( \geq 3 \) consecutive detections; \( \leq 5 \) missing pings; missed ping expansion = 0%; sensitivity to unpredicted change in position, alpha = 0.7; sensitivity to velocity, beta = 0.5; exclusion distances along major and minor axes = \( 4 \) m; target-to-track assignment weights = 30 (major axis), 30 (minor axis), and 40 (vertical axis); and \( \leq 1 \) inter-ping depth variation. The latter corresponds to the maximum vertical velocities recorded for tuna during ultrasonic tracking experiments around moored FADs (Cayré and Chabanne, 1986; Marsac and Cayré, 1998).

**Methods**

**Data collection**

**Acoustic data**

Sonar (Furuno FSV84), and purse-seine catch data were collected in the Central Pacific Ocean, aboard FV *Albatross* 3, between 3 and 31 May 2014. During this period, data were also collected from 38-, 120-, and 200-kHz echosounders (Simrad EK60) mounted on the vessel’s 8-m workboat, with the transducers (Simrad ES38-12, ES120-7C, and ES200-7C, respectively) projecting vertically downward (Figure 1). The echosounders were calibrated using a 38.1-mm diameter sphere made from tungsten carbide with 6% cobalt binder (Demer et al., 2015; Foote, 1987), and configured with the calibrated parameters (Table 1) prior to data collections.

Ten minutes before and throughout each of 20 purse-seine sets, the workboat was attached to the drifting FAD, and TS and volume backscattering strength (\( S_v; \text{dB re } 1 \text{ m}^{-1} \)) data were collected from 5- to 200-m depth. During the \( \sim 60 \)-min sets, the workboat slowly towed the FAD to maintain separations from the net and the vessel.

**Purse-seine catch data**

Skipjack schools were captured using an 1800-m long \( \times 310- \) m deep purse-seine net. During the second half of each set, two divers visually observed the species in the shallowest 25 m of the aggregation. While the catch was lifted aboard, 1–2 tons of fish was visually observed the species in the shallowest 25 m of the aggregation. While the catch was lifted aboard, 1–2 tons of fish was sampled, generally from every sixth or seventh brail, into a fiberglass box (110 \( \times \) 70 \( \times \) 100 cm). Fish species were identified and sampled, generally from every sixth or seventh brail, into a fiberglass box (110 \( \times \) 70 \( \times \) 100 cm). Fish species were identified and fork lengths, \( L \), were measured (1-cm precision) using flat measuring boards. For each species, fish weights (w; g) were estimated from the measured \( L \) and a model of \( L(w) \) (Cayré and Laloe, 1986). The catch weight for each species was estimated by multiplying the weight proportion for each species and the fishing master’s estimate of total-catch tonnage for the set.

**Data analysis**

Echosounder, sonar, and catch data from three purse-seine sets with \( \geq 96\% \) skipjack by number (\( \geq 94\% \) by weight) (Table 2) were processed using commercial (Echoview; Hobart, Tasmania) and open source software (R, R Core Team, 2014). The TS and \( S_f \) data were analysed from \( \sim 5 \) min before the set until echoes from the net were visible at the bottom of the echogram (i.e. before the tuna changed their behaviour in response to the closing net).
(3) Multiple frequencies simultaneously (MFS): TS measurements were accepted if concomitantly detected by multiple frequencies (Demer et al., 1999). First, the relative transducer positions were determined (Conti et al., 2005) using sphere echoes recorded simultaneously at multiple frequencies, and a non-linear optimization (Powell, 1994) implemented in the R (R Core Team, 2014) package “NLOptr” (Johnson, n.d.). Then, the target coordinates were transformed into a common coordinate system (Conti et al., 2005). The minimum distance between detections by different frequencies was varied sequentially from 5 to 0.01 m.

(4) High fish density (HFD): TS measurements were accepted if they were from areas with low fish densities (Sawada et al., 1993). The threshold fish density was determined by plotting the number of single targets per cell ($TV$) against the total number of fish per cell ($NV$) and choosing (Gauthier and Rose, 2001) the $NV$ that produced a peak in $TV$. This procedure assures that the threshold density is independent of the TS value used to calculate it. The threshold was evaluated for grid-cell dimensions ranging from 1500 ($10 \text{ m} \times 100 \text{ pings}$; 1 ping $= 0.15 \text{ m}$) to 3.0 m$^2$ ($10 \text{ m} \times 2 \text{ pings}$).

**Figure 1.** For each of 20 purse-seine sets, echosounders on a workboat were used to measure target strength (TS; dB re 1 m$^2$), volume backscattering strength ($SV$; dB re 1 m$^2$), and school height ($2R_z$; m) for skipjack beneath the FAD; and a scanning sonar on a purse-seine vessel was used to estimate the school width ($2R_{cw}$; m) and length ($2R_{lw}$; m).

**Table 1.** Calibrated echosounder (Simrad EK60) settings used to measure target strength (TS; dB re 1 m$^2$), volume backscattering strength ($SV$; dB re 1 m$^2$), and school height ($2R_z$; m).

| Frequency (kHz) | 38 | 120 | 200 |
|----------------|----|-----|-----|
| Pulse duration (μs) | 512 | 512 | 512 |
| Power (W) | 2000 | 250 | 150 |
| Gain (dB) | 26.16 | 25.96 | 27.09 |
| $Sa$ correction (dB) | −0.86 | −0.39 | −0.34 |
| Ath. beam angle (deg) | 6.92 | 6.38 | 6.43 |
| Along beam angle (deg) | 6.94 | 6.39 | 6.37 |
| Sphere TS (dB) | 42.3 | 40 | 39.9 |
| TS deviation (dB) | 5 | 5 | 5 |
| RMS beam model | 0.19 | 0.18 | 0.20 |
| RMS polynomial model | 0.16 | 0.16 | 0.15 |

**TS(L) and TS(f) relationships**

After filtering echoes from multiple targets, $TS(L)$ was modelled as

$$TS = 20\log(L) + b_{20},$$

(1)

where $b_{20}$ (Simmonds and MacLennan, 2005) of skipjack was estimated for each frequency using the in situ TS distributions, measurements of $L$ distribution from the purse-seine catches (Fernandes et al., 2006), and the method of least squares (MacLennan and Menz, 1996). The slope in (1) was assumed to be 20 (Simmonds and MacLennan, 2005) because the inter-set differences in mean $L$ (< 3 cm) were too small to estimate its
value from the data. Standard deviations, calculated with the R package “Seewave” (Sueur et al., 2013), confidence intervals of the TS distributions, and coefficient of determination values of the TS(L) models were calculated.

**TS estimation based on volume backscatter**

Mean TS was independently estimated for each of the three frequencies and purse-seine catches by inverting the volume backscatter equation (Misund and Beltestad, 1996),

$$TS \text{ [dB re } 1 \text{ m}^2] = 10\log(S_VwV/B),$$

(2)

where $S_V$ is the volume backscattering coefficient ($\text{m}^2/\text{m}^3$), $w$ is the mean weight of skipjack in the spill sample (g), $B$ is the skipjack biomass in the catch (g), and $V$ is the ellipsoidal volume of the skipjack aggregation ($\text{m}^3$),

$$V = (4/3)\pi R_{cw}R_wR_z,$$

(3)

where the average school height ($R_z$; m) is estimated from the $S_V$ echogram (Figure 1), and the school width ($R_{cw}$; m) and length ($R_w$; m), assumed to be equal, are estimated from horizontal range in a sonar image (e.g. Figure 3) recorded at the beginning of the set, scaled and corrected for distortion according to the procedure of Misund (1993). The school width was made equal to the length one instead of calculating it from the screen because the crosswise dimensions of the schools obtained from the sonar screenshots were slightly but consistently higher than the lengthwise ones, thus indicating a likely poorer effectiveness of the distortion correction (and thus slightly biased estimation) in this direction.

**TS sensitivity**

TS of a bladderless fish is not only a function of acoustic frequency and fish size, but also shape, material properties (flesh, bone, and other organs) and behaviour (Gorska et al., 2005; Korneliussen, 2010). To have a better understanding of the factors that contribute to the TS of bladderless species in general and skipjack tuna in particular, finite element models (FEM) (Jech et al., 2015) were run to predict in situ TS measurements of skipjack tuna. However, due to the paucity of published material properties for this species, the simulations were run in comparison with Atlantic mackerel, a more studied bladderless fish (Gorska et al., 2005) that was taken as a reference. The simulations were run by pairs, one for Atlantic mackerel, considered as a baseline, and a second one obtained by changing only one of the model parameters of Atlantic mackerel to suitable values for skipjack. The resulting change in $b_{20}$ in each pair informed on

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**Table 2.** Proportions and mean lengths of skipjack (SKJ), bigeye (BET), and yellowfin tuna (YFT) in three catches that included ≥ 96% SKJ by number (≥ 94% by weight).

| Set ID | Catch (tons) | Weight proportion (%) | Number proportion (%) | Mean Fork Length (cm) |
|-------|-------------|-----------------------|-----------------------|-----------------------|
|       |             | SKJ | BET | YFT | SKJ | BET | YFT | SKJ | BET | YFT |
| 24    | 170         | 100 | 0   | 0   | 99  | 1   | 0   | 48  | 32  | 49  |
| 26    | 125         | 94  | 4   | 2   | 97  | 2   | 1   | 52  | 58  | 62  |
| 27    | 170         | 94  | 4   | 2   | 96  | 2   | 2   | 49  | 55  | 47  |

**Figure 2.** The procedure to attribute echoes to skipjack, illustrated by data from set ID 24. The original $S_V$ and TS echograms (columns 1 and 2) were filtered using a school detection algorithm, converted to a mask (column 3, row 2) applied to the $S_V$ (column 4) and TS (column 5) echograms, resulting in data for putative skipjack tuna. Minimum display thresholds = 70 dB.
which individual properties could theoretically contribute more to the TS differences between the two species. The goal of the simulations, rather than obtaining the best match with the experimental results, was to understand which parameters can contribute more to the TS of fish species when the swimbladder is absent.

For Atlantic mackerel, published density and sound speed values of flesh and backbone were used (Gorska et al., 2007; Sigfusson et al., 2001a) (Table 3). For skipjack, we used albacore tuna (Thunnus alalunga) values (Table 3) for flesh sound speed (Sigfusson et al., 2001b) and density (Alexander, 2013). Arbitrary values were used for the backbone, assumed more rigid and dense than for Atlantic mackerel, to match the qualitative impression obtained cutting slices of specimens of both species. The FEM models were solved using \( L = 20 \text{ cm} \), and \( f = 18, 38, 70, \text{ and } 80 \text{ kHz} \) for both species.

Shape was modelled as an ellipsoid (flesh only, model code A, Table 3), an ellipsoid with an internal cylinder (flesh and bone, model code B), and outlines of X-ray images of one specimen of each species (model code C). For computational efficiency, only longitudinal waves were considered along the backbone (Forland et al., 2014a, b). Convergence was assessed with \( \geq 20 \) nodes per wavelength. Evaluations at higher frequencies required more computer memory than was available (Jech et al., 2015).

Model sensitivities were evaluated for: equivalent shape and different flesh properties (model code A.1, Table 3); equivalent shape and bone but different flesh properties (B.1); equivalent shape and flesh but different backbone properties (B.2); equivalent shape but different flesh and bone properties (B.3); equivalent shape, flesh and bone properties, but different incidence angle distributions (B.4); equivalent flesh and bone properties but different shapes (from X-ray images) and incidence angle distributions (C.2) (Table 3).
the mean TS and the SE (Figure 6). This indicated an optimal distance threshold for filtering multiple targets.

(4) Decreasing the grid size for determining the high-density threshold (HDF) decreased the mean TS until the minimum usable grid size was reached (10 m × 2 pings) (Figure 6). Because mean TS did not stabilize prior to reaching this smallest usable grid size, HDF was not considered further.

Table 3. Model parameters and average b_{20} values.

| Models          | Body (flesh) parameters | Bone parameters | b_{20} @ f (kHz) |
|-----------------|-------------------------|-----------------|------------------|
|                 | Length (cm) | Height (cm) | Width (cm) | ρ (kg/l) | c (m/s) | Length (cm) | Diameter (cm) | ρ (kg/l) | c (m/s) | 18 (dB) | 38 (dB) | 70 (dB) | 80 (dB) |
| A.1 F Ellipsoid Flesh | 20          | 3.6        | 3          | 1.06      | 1537    | —          | —            | —         | —         | —       | —       | —       | —       |
| A.1 F Ellipsoid Flesh “SKJ” | 20          | 3.6        | 3          | 1.06      | 1537    | 18         | 0.36         | 1.13      | 2600      | 77.12   | 78.12   | 78.12   | 78.12   |
| B.1 F&B Ellipsoid Flesh | 20          | 3.6        | 3          | 1.06      | 1537    | 18         | 0.36         | 1.13      | 2600      | 77.12   | 78.12   | 78.12   | 78.12   |
| B.1 F&B Ellipsoid Bone | 20          | 3.6        | 3          | 1.06      | 1537    | 18         | 0.36         | 1.13      | 3200      | 71.92   | 76.72   | 66.62   | 71.12   |
| B.3 F&B Ellipsoid Flesh and bone | 20          | 3.6        | 3          | 1.06      | 1537    | 18         | 0.36         | 1.13      | 2600      | 77.12   | 78.12   | 78.12   | 78.12   |
| B.3 F&B Ellipsoid “SKJ” | 20          | 3.6        | 3          | 1.06      | 1537    | 18         | 0.36         | 1.13      | 3200      | 72.22   | 78.12   | 66.62   | 71.12   |
| B.4 F&B Ellipsoid Incidence angle | 20          | 3.6        | 3          | 1.06      | 1537    | 18         | 0.36         | 1.13      | 2600      | 77.72   | 78.12   | 78.12   | 78.12   |
| B.4 F&B Ellipsoid Incidence “SKJ” | 20          | 3.6        | 3          | 1.06      | 1537    | 18         | 0.36         | 1.13      | 2600      | 77.72   | 78.12   | 78.12   | 78.12   |
| C.1 F&B X-ray Shape MAC | 20          | 4.2        | 2.8        | 1.06      | 1537    | 14.9       | 0.35         | 1.13      | 2600      | 79.32   | 83.32   | 77.62   | 73.62   |
| C.1 F&B X-ray Shape “SKJ” | 20          | 5          | 4.8        | 1.06      | 1537    | 17.17      | 0.38         | 1.13      | 2600      | 78.52   | 86.52   | 76.12   | 73.42   |
| C.2 F&B X-ray Incidence angle MAC | 20          | 4.2        | 2.8        | 1.06      | 1537    | 14.9       | 0.35         | 1.13      | 2600      | 79.42   | 83.32   | 77.52   | 73.62   |
| C.2 F&B X-ray Incidence “SKJ” | 20          | 5          | 4.8        | 1.06      | 1537    | 17.17      | 0.38         | 1.13      | 2600      | 78.92   | 85.72   | 76.22   | 74.12   |

For all models, the values assumed for seawater density and sound speed were ρ = 1.030 kg/l and c = 1490 m/s. For each Code (defined in the text), the Type is either F (only flesh) or F&B (flesh and bone). The FAO code is either MAC (Atlantic mackerel) or “SKJ” (skipjack tuna; the quotations marks are a note to the reader that the parameters are not necessarily appropriate for skipjack tuna).

Figure 4. Dorsal (top row) and lateral (bottom row) X-ray images of Atlantic mackerel (left column) and skipjack tuna (right column) specimens with length, height, and width dimensions: 26.94, 5.26, and 3.86 cm (MAC1); and 41.8, 10.26, and 7.23 cm (SKJ2). (Note: X-rays for both species were taken using different settings, and are thus not directly comparable).
Among the methods tested to filter multiple targets, only MFS reduced bias in mean TS using an objectively defined threshold. Therefore, the results of the MFS filtering were used to fit TS(L) models for each frequency. The mean TS values did not change along the set duration (results not shown).

**TS(L) and TS(f) models**

The TS(L) relationships based on data passing the single target discrimination filters, have \( b_{20} \) values equal to \(-76, -71, \) and \(-70.5 \) dB for the 38, 120, and 200 kHz, respectively. Adjustment between observed TS distributions and those derived from (1) with measurements of \( L \) (Figure 7) with the least squares method have coefficients of determination \( (R^2) \approx 80\% \) (Table 4 and Figure 8). Values of \( b_{20} \) derived by echo-integration using (2) and (3) were \(-1 \) dB higher at all frequencies (Table 4). From measurements of single targets, TS of *in situ* skipjack tuna at 38 kHz is \(-5 \) and \(-5.5 \) dB lower than at 120 and 200 kHz, respectively (Figure 9); whereas from echo-integration, the TS at 38 kHz is \(-5 \) and \(-6 \) dB lower than at 120 and 200 kHz, respectively (Table 4). The uncertainties were lower for TS measurements of single targets \( (SD = 7, 6, \) and \( 6 \) dB at 38, 120, and 200 kHz, respectively) than for TS measurements derived from echo-integrations \( (SD = 15, 8, \) and \( 7 \) dB, respectively).

**TS sensitivities**

In the FEM models, in general, TS decreased from 18 to 38 kHz, then increased with higher frequencies, the frequency response showing generally larger values at high (70–80 kHz) compared to low (18–38 kHz) frequencies for both species (Table 3). This increase at higher frequencies was not accentuated by the inclusion of a backbone.

Considering the comparison between skipjack and Atlantic mackerel at 38 kHz (the only simulated frequency that was directly comparable with the experimental results), larger values for flesh density and sound speed increased TS by 5–10 dB (Table 3). These models (A.1, B.2, and B.3) predicted \( b_{20} \) values within \(-1 \) dB of the observed ones (Tables 3 and 4). Larger values for bone density and sound speed also increased TS, but by less than 2 dB. In contrast, TS did not increase with differences in shape nor a wider distribution of incidence angles (Table 3).
Discussion

Experimental measurements

TS measurements of in situ fish may be biased due to inclusion of non-target species or multiple targets (Soule et al., 1997; Demer et al., 1999). Here, we use vertical stratification and a school detection algorithm to filter echoes from plankton, micro-necton and bycatch species and, after evaluating several methods, apply a multiple-frequency TS-detection method to filter multiple targets (Demer et al., 1999; Conti et al., 2005). The school detection algorithm filtered non-target echoes from above the skipjack school, likely from small tunas and other species (Forget et al., 2015; Muir et al., 2012; diver observations), and below the school, potentially larger bigeye and yellowfin tuna (Moreno et al., 2008; Govinden et al., 2010; Muir et al., 2012). The sensitivity analyses for each of the filtering steps served to evaluate their effectiveness and optimize their parameters. For the MFS filter, we refined earlier works (Demer et al., 1999; Conti et al., 2005) by optimizing a threshold on the distance between simultaneous detections of candidate single targets. The school and MFS filters reduced the TS-measurement biases by ~2–4 dB and, although they also reduced the number of targets by two orders of magnitude, the adjustment between predicted and observed TS values with the method of least squares provided high (~80%) coefficients of determination (Figure 8).

The echo-integration estimates of skipjack tuna TS were based on various important assumptions: (1) that the skipper’s biomass estimates were accurate and precise, (2) that the schools had equivalent horizontal dimensions (i.e. $R_{cw} = R_{lw}$) and (3) that the measurement of a single sonar screenshot gives a reliable measurement of the horizontal aggregation size. The accuracy of the tonnage estimates for each set is unknown because multiple catches are stored in the same hold, but their combined tonnage typically differs by ~5% from the total discharge weight (pers. comm., fishing company representative). Perhaps the measurement accuracy obtained with this approach could be improved by weighting entire catches ashore. It could also be improved by correcting bias in the measurements made perpendicular to the sonar beams, thereby allowing estimates of both horizontal dimensions of the school. And, finally, by averaging the measurements of horizontal school dimensions throughout the sets instead of using measures taken at the beginning of each set.

Despite the aforementioned uncertainties, the quasi-independent single-target-detection and echo-integration methods for estimating TS produced $b_{90}$ values for skipjack tuna that were within ~1 dB (33%) of each other at all frequencies (Table 4). However, because of the assumptions of the echo-integration approach and their higher uncertainty (Table 4), the results from the single-target approach should be used to identify echoes from skipjack tuna and estimate their number densities.

This work compares the results of TS(L) models estimated using the single target discrimination and echo-integration methods, which are quasi-independent and have different sources of uncertainty. Therefore, similar results corroborate each other. Besides, the capability of the TS values to obtain accurate biomass estimations is implicitly tested in the echo-integration method. Therefore, the results of this study should facilitate unbiased acoustic estimates skipjack biomass.

Theoretical interpretation of skipjack TS

Our 38-kHz TS measurements of in situ skipjack tuna are ~2.5 dB lower than the mean TS measured for one skipjack tuna...
The FEM model sensitivity analysis showed that this difference could be due to differences in material properties or incidence angle distributions for skipjack tuna aggregated near FADs vs. those for one captive specimen.

Our 38-kHz estimate of mean $b_{20}$ for in situ skipjack tuna ($-76$ dB) is higher than values reported for Atlantic mackerel ($Scomber scombrus$), i.e. $-90$ dB (Scoulding et al., 2016), $-88$ dB (Clay and Castonguay, 1996), $-86$ dB (Fernandes et al., 2006), $-84.9$ or $-82$ dB (ICES, 2006). The FEM model results (Table 3) predict $b_{20}$ for skipjack higher than that of Atlantic mackerel. According to the simulations, the material properties can account for difference in $b_{20}$ of up to $-10$ dB at 38 kHz (model B.1). From those, acoustic properties of flesh accounted for the main $b_{20}$ difference between both species, followed by backbone properties. In contrast, variations in shape and incidence angle distribution may have relatively little effect on the difference in TS of skipjack tuna vs. Atlantic mackerel (Table 3). It is possible, however, that a $5^\circ$ change in the standard deviation of the incidence angle distribution in the model does not reflect the true range of natural behaviour for skipjack.

Some of the tested models matched the experimental results rather well (within $<1$ dB), whereas other models yielded very different results (up to $10$ dB). However, as mentioned earlier, the goal of the simulations was not to match the experimental results in absolute terms, but rather to help interpreting them in terms of the relative contribution of different parameters to the TS of bladderless fish. In this regard, the $10$ dB difference predicted for different flesh properties (density and sound speed) alone can justify the differences between our results and TS of Atlantic mackerel found in bibliography.

However, these simulation results should be taken with caution due to the mentioned scarcity of information on material properties of skipjack. Overall, skipjack is known to be denser than Atlantic mackerel based on their respective length–weight relationships (Cayré & Laloë, 1986; Coull et al., 1989) but it is not clear how much of this density difference is attributable to the bone and the flesh. Consequently, the values chosen for flesh properties (i.e. the parameters with the highest contribution to the TS) were taken from another tuna species, albacore tuna, of similar size. The rigidity of the backbone appears to be considerably higher for skipjack, but it has not been measured. Consequently, future studies should include direct measurements of skipjack flesh and bone properties for a range of fish lengths (e.g. Forland et al., 2014b) and measurements of their orientation distributions.

Although the magnitude of skipjack TS differs from that of Atlantic mackerel, its $TS(f)$ resembles that of many species without swimbladders (Mosteiro et al., 2004; Fernandes et al., 2006; Korneliussen, 2010; Forland et al., 2014a). However, because skipjack tuna are larger than Atlantic mackerel, the 5 and 5.5 dB increases in skipjack tuna TS at 120 and 200 kHz relative to 38 kHz (Figure 9) may be larger than for Atlantic mackerel (Gorska et al., 2005, 2007). This $TS(f)$ for skipjack tuna is also different from that of fish species with swimbladders (Fernandes et al., 2006).
et al., 2006; Horne et al., 2009). As skipjack is the main tuna species without swimbladder associated with FADs, this could be used to acoustically discriminate it from the other tuna species.

Use of acoustic data to support the sustainable fishing of tropical tunas

Bigeye and yellowfin tuna, the most abundant tuna species found at FADs, together with skipjack, are subject to overfishing in different regions. Informing fishers about the relative abundance of skipjack compared with that of yellowfin and bigeye could allow fishers to avoid setting nets on large abundances of species of concern.

The TS(f) and TS(L) relationships obtained for skipjack in this study are useful to improve the interpretation of the acoustic data collected by purse seiners fishing at FADs. However, the knowledge acquired is not enough: to provide acoustic estimations of abundance per tuna species, TS(f) and TS(L) of the other main tuna species found at FADs are also needed. TS(L) relationships at 38 kHz are available for bigeye and yellowfin tuna from previous works (Bertrand et al., 1999; Josse and Bertrand, 2000), but their TS(f) are absent from bibliography and should be studied.

Given that our measurements were made in situ under real commercial fishery conditions, the obtained TS(L) relationships reflect the true values of skipjack and be directly usable to

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Figure 8. TS distributions of in situ skipjack tuna measured at 38, 120, and 200 kHz. To mitigate bias due to measurements of multiple targets, the split-beam detections (top row) were filtered to retain those (N = number remaining) that were simultaneously detected at multiple frequencies (bottom row). As in MacLennan and Menz (1996), each dataset was fit with a normal distribution (black lines) to evaluate the mean (dashed vertical line), standard deviation (SD) and b20 of the best fit, given by coefficient of determination (R2), of observed vs. modelled TS distributions.

Figure 9. Measured b20 for skipjack tuna associated with FADs. The error bars (CI for b20 measurements) at 38 kHz don’t overlap with those at 120 or 200 kHz, indicating significantly different (Cumming et al., 2007) response between low and high frequencies. This pattern could be potentially useful for discriminating this species acoustically.
estimate skipjack abundance. The acoustic abundance estimation is obtained by isolating the biomass in (2), which leaves $C_{b}$ (i.e. the linearized TS) at the denominator. The standard error of the measured $C_{b}$ is $\sim 5\%$ at the three frequencies. As the variance of a quotient equals the sum of the variances of numerator and denominator plus their covariance in relative terms (Seber, 1982), assuming independence between the variances of the factors in (2), the uncertainty of the measured $C_{b}$ alone would cause confidence intervals for the biomass $\sim 10\%$ around the mean (Cumming et al., 2007).

To estimate the abundances of multiple species typically aggregated beneath FADs, it is necessary to first estimate the proportions of each species present. To do this, the frequency response of the aggregation may be compared with a mixed TS(f) model derived from a proportion (x) of the skipjack TS(f) model and proportion (1 – x) of a swimbladder fish TS(f) model, where the difference is minimized by optimizing x (e.g. Korneliussen, 2010). To increase the precision of the species proportion estimations, the mixed TS(f) model could include proportions of models for the other tuna species (e.g. Korneliussen et al., 2016). The estimated proportions can then be used, analogous to species proportions in catches, to estimate abundances for each of the species following standard procedure (Simmonds and MacLennan, 2005).

### Conclusion

The application of fish school and MFS filters on single-target detections at 38, 120, and 200 kHz served to mitigate measurement bias of TS distributions of skipjack tuna associated with FADs. The combination of echosounder, sonar, and net-sample measurements allowed inversion of the echo-integration equation to provide quasi-independent TS estimates. Values of $b_{10}$ derived from these two methods differed by $< 1$ dB at all three frequencies. The TS(f) measured in this study is useful to estimate abundance of this species at FADs and to distinguish the echoes from skipjack tuna from tuna species with swimbladders, e.g. bigeye and yellowfin tunas, before purse-seine fishing at FADs. This manuscript represents the first of a series of studies on the acoustic properties of tropical tunas, with the final goal of providing estimates of tuna abundance at FADs by species, suitable for selective fishing and fisheries independent estimates of tropical tuna abundance.

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