**IN SITU TARGET STRENGTH OF BIGEYE TUNA (THUNNUS OBESUS) AT FADS**

**PACS:** 43.30.Vh Sistemas de sonar activo

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Palabras Clave: Target strength, bigeye, biomass, tropical tuna, FAD, acoustics, selectivity, frequency response.

**ABSTRACT**

This paper measures in situ target-strength (TS) values and explores the frequency response of bigeye tuna at fish aggregating devices (FADs) in the Central Pacific Ocean, to discriminate it from other tuna species using three different frequencies. TS-length relationships were obtained at each frequency by a curve fitting method comparing observed in situ TS distributions and predicted ones based on length distributions caught in each set. For the mean body length caught of ~71 cm, the obtained mean TS values were -27, -28.5 and -35 dB for 38, 120 and 200 kHz respectively, yielding corresponding b20 values of -64, -65.5 and -72 dB.

**RESUMEN**

Este trabajo mide valores de fuerza del blanco (target strength o TS) y respuesta acústica en frecuencia de atún patudo en dispositivos concentradores de peces (FADs por su acrónimo en inglés) en el Oceano Pacífico Central usando tres frecuencias distintas. Las relaciones TS-talla se obtuvieron para cada especie usando un método de ajuste de curvas comparando distribuciones observadas (TS in situ) y esperadas, basadas en las distribuciones de tallas de los atunes capturados. Para la talla media de los atunes de 71 cm aproximadamente, los TS obtenidos fueron -27, -28.5 y -35 dB para 38, 120 y 200 kHz respectivamente, proporcionando valores b20 de -64, -65.5 y -72 dB.
**Introduction**

Bigeye tuna (*Thunnus obesus*) is a high value commercial species present in the subtropical and tropical areas of the Atlantic, Indian and Pacific Oceans. Bigeye can be observed either in free schools or associated with floating objects. Juvenile bigeye tuna schools are found with juvenile yellowfin and skipjack tuna schools. Smaller bigeye is also caught on the surface by a range of gears including handline, ringnet and purse seine and are used mainly for canning, while most of larger/older fish are caught by longline fisheries for the sashimi market.

Juveniles of bigeye tuna are normally caught associated with fish aggregating devices (FADs) which are artificial floating objects built by fishers to aggregate tuna (Kingsford, 1993; Parin and Fedoryako, 1999). Nowadays FADs are geolocated with a buoy equipped with an echo-sounder to provide remote estimates of the amount of tuna aggregated around the FAD (Moreno *et al.*, 2008; Lopez *et al.*, 2014). Currently, catches around FADs represent around 65% of the tuna catches of purse seiners (average for the 3 tropical oceans) (Scott and Lopez, 2014).

The most recent estimate from the assessment of the bigeye stock in the Eastern Pacific Ocean (EPO) indicates that the bigeye stock is not overfished, but that overfishing is taking place (Xu *et al.*, 2018). In the Western and Central Pacific Fisheries Commission (WCPFC), a change in the latest assessment, using a revised growth curve and a new regional structure in the model, has yielded in a more optimistic bigeye tuna stock status, relative to previous stock assessments, indicating that the Western Pacific bigeye tuna stock is not overfished (ISSF, 2017). In the Atlantic Ocean, the latest stock assessment indicated that overfishing is occurring and that the stock is in an overfished state. Only in the Indian Ocean the stock of bigeye tuna is estimated to be in good condition. Stock assessment requires a substantial amount of information. Data on retained catch, discards, catch per unit of effort (CPUE), and size compositions of the catches from several different fisheries are typically used. Several assumptions regarding processes such as growth, recruitment, movement, natural mortality (M), and fishing mortality (F), are also done. The interpretations of stock status are strongly dependent on those assumptions.

Due to the uncertainty derived from tropical tuna stock assessments, an important effort towards the use of direct acoustic tuna biomass estimates to complement traditional stock assessment is being conducted (Capello *et al.*, 2016; Moreno *et al.*, 2016; Boyra *et al.*, 2018). Direct estimates of abundance are already undertaken in other fisheries and have been proven to be effective for scientific advising the management. It is the case, for example, of anchovy and sardine in the SW Europe, where a series of acoustic and Daily Egg Production Method surveys (Massé and Uriarte, 2016) provide assessment information on the state of the stocks in different regions to the managers (Ibaibarriaga *et al.*, 2008). In the case of tropical tuna, biomass provided by echo-sounder buoys in quasi-real time could also be used to develop management measures (e.g. Santiago *et al.*, 2017), as dynamic time area closures.

FADs do not only aggregate bigeye tuna: they aggregate other tuna species, as skipjack (*Katsuwonus pelamis*), which is the main target species of purse seiners working with FADs, and yellowfin (*Thunnus albacares*), so that the three species can regularly be found together in a single FAD. Over-exploitation of bigeye tuna is in part due to the by-catch of small individuals by purse seiners at FADs that also target the other two tuna species (Pons *et al.*, 2016). Given that the majority of purse seine catches are conducted around FADs (that simultaneously aggregate the 3 species) one of the challenges that fishers, scientists and managers are facing
is how to continue fishing at FADs, target species in good stock condition while avoiding the catch of species that are subject to conservation measures.

Acoustics used by fishers may represent one of the key tools not only to obtain direct indices of tropical tuna abundance, independent from catch data, but also to discriminate tuna species found at FADs before the net is set. One of the prerequisites to discriminate tuna species and assess their biomass is knowing the target strength (TS; dB re 1 m), TS-length (L; cm) and TS-frequency (f; kHz) for the 3 species found at FADs. From the three species, the frequency response of skipjack tuna, a bladderless species, has been recently published (Boyra et al., 2018), whereas bigeye and yellowfin tuna, swimbladder bearing species, have been less studied. For these species, while there are published TS(L) relations, those are preliminary due to the small number of observations (Bertrand and Josse, 2000) and TS(f) relations are absent from bibliography.

Recent efforts by International Seafood Sustainability Foundation (ISSF) with the aim of developing acoustic methodologies to help discrimination of tropical tuna species around FADs have comprised research cruises to measure in situ TS of tropical tunas at FADs. As a result, methodologies for analyzing TS at FADs have recently been set up and skipjack tuna measurements of TS(L) and TS(f) have been provided (Boyra et al., 2018). The objective of this study is the application of some of those methodologies to obtain in situ TS measurements, TS-length relationship and frequency response of bigeye tuna found associated with FADs. The acoustic characteristics of bigeye tuna will represent another step beyond in the objective of achieving discrimination and abundance estimation of the main tuna species caught at FADs.

Figure 1. Sample echogram of set number 6 for the three frequencies, 38, 120 and 200 kHz from left to right. The upper panels show the raw echograms and the lower panels the echograms after the plankton / micronekton filtering.
Methods

Data collection

The cruise took place in May 2014 in the Central Pacific Ocean aboard the Albatun 3, a 115 m and 4,406 GT Spanish-flagged purse seiner. The cruise started in Christmas Is. (Kiribati) on May 3rd and ended in Tarawa Is. (Kiribati) on May 31st. Meteorological and oceanographic information was obtained from the CLS (Collecte Location Satellites, France, https://www.cls.fr). During the selected sets the conditions were 7-10 knot of wind (beaufort 3) and 1-1.5 m of swell. Acoustic data was registered during the purse-seine sets at 20 different FADs, followed by intensive spill sampling (Lawson, 2009) to compare acoustic data and species composition caught. The strategy to collect the data from the purse seiner are thoroughly detailed in Boyra et al. (2018).

Acoustic data

About ten minutes before the start of each of the purse-seine sets, a workboat was attached to the drifting FAD and slowly towed it to maintain it separated from the net and the vessel. The workboat was equipped with acoustic sensors and, during the ~60 min duration of the sets, it registered $S_v$ and volume backscattering strength ($S_v$; dB re 1 m$^{-1}$) data from 5 to 200 m depth. Acoustic data were collected with a Simrad EK60 echo-sounder with 38 kHz, 120 kHz and 200 kHz split-beam transducers (Simmonds and Maclennan, 2005), focused vertically (Figure 1) and working with a pulse duration of 0.512 ms (Table 1). The calibration was done at the beginning of the survey, following the standard target procedure (Foote, 1987a; Demer et al., 2015) with a tungsten carbide sphere of 38.1 mm.

Table 1:

<table>
<thead>
<tr>
<th>Configuration of the acoustic equipment and calibration parameters.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Frequency (kHz)</strong></td>
</tr>
<tr>
<td><strong>Pulse duration (μs)</strong></td>
</tr>
<tr>
<td><strong>Power (W)</strong></td>
</tr>
<tr>
<td><strong>Gain (dB)</strong></td>
</tr>
<tr>
<td><strong>SaCorrection (dB)</strong></td>
</tr>
<tr>
<td><strong>Ath. Beam Angle (deg)</strong></td>
</tr>
<tr>
<td><strong>Along Beam Angle (deg)</strong></td>
</tr>
<tr>
<td><strong>Ref. target TS (dB)</strong></td>
</tr>
<tr>
<td><strong>TS deviation (dB)</strong></td>
</tr>
<tr>
<td><strong>RMS beam model</strong></td>
</tr>
<tr>
<td><strong>RMS polynomial model</strong></td>
</tr>
</tbody>
</table>
Purse-seine catch data

Purse-seine sets, performed with a 1800 m length x 310 m height gear, were followed by intensive sampling of the catch (between 1 and 2 tons per set) once the aggregation was lifted onboard. Fish samples for sorting were selected randomly to avoid bias. Species were identified and each fish in the sample measured to the nearest centimeter on flat measuring boards. The weights of sampled individuals were estimated using length-weight relations available for each species (Caverivière, 1975; Parks et al., 1982). These proportions by weight were then extrapolated to the total tonnage of each set, as estimated by the fishing master. The sets with more than 90% of bigeye (Table 2) were selected for acoustic analysis to extract its TS-length relationship and acoustic frequency response.

Table 2:

Summary of the main tuna species composition in weight (w) and in numbers (n) of the two used fishing sets. FAO codes used for the species: SKJ for skipjack, BET for bigeye and YFT for yellowfin tuna.

<table>
<thead>
<tr>
<th>Set</th>
<th>Catch (tones)</th>
<th>Sample_w (kg)</th>
<th>Sample_n (%)</th>
<th>SKJ_w (%)</th>
<th>BET_w (%)</th>
<th>YFT_w (%)</th>
<th>SKJ_n (%)</th>
<th>BET_n (%)</th>
<th>YFT_n (%)</th>
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<td>6</td>
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<td>1</td>
</tr>
<tr>
<td>7</td>
<td>95</td>
<td>3102</td>
<td>499</td>
<td>7</td>
<td>91</td>
<td>2</td>
<td>21</td>
<td>75</td>
<td>5</td>
</tr>
</tbody>
</table>

Data analysis

Acoustic data were processed from the beginning of the set until the moment in which the net was visible in the echogram. To avoid echoes from bycatch fish species, $S_p$ and $TS$ data were excluded if shallower than 25-m (Forget et al., 2016; Muir et al., 2012). Then, the $TS$ echograms at each frequency were processed using a single-target detection algorithm (Simrad, 1996; Soule et al., 1997) with the following settings: minimum threshold = -80 dB; normalized pulse durations = 0.9 to 1.5; maximum off-axis angles = 3º; and maximum standard deviations of phase = 0.6º.

The application of a series of target selection filters followed to try to remove everything except single targets of bigeye tuna:

1. School masking: A school detection algorithm (Lawson et al., 2001) was used to retain the main aggregation. The rejected echoes from outside the aggregation were considered echoes of plankton and/or micronekton. After smoothing by a 5x5 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 $TS$ echograms, and data from within the schools were attributed to tuna (Fig. 2).
2. **Multifrequency simultaneity (MFS):** To remove potential unresolved multiple targets, we applied a methodology developed by Demer *et al.* (1999) and Conti *et al.* (2005) that requires the TS values to pass the single target criteria in at least two frequencies simultaneously to be considered valid. After setting the targets at all frequencies in the same reference system, for each target detected at one frequency, the method identifies the closest target in the other two. Then it defines a minimum distance between two detections at two different frequencies to consider them the same simultaneously detected target, discarding those targets whose closest detections are above the threshold. The method was applied as in Boyra *et al.* (2018), including a sensitivity analysis that tested the impact on the mean filtered TS of this distance threshold and hence help establishing it with objective criteria (Fig. 3).
The single target detection algorithm and the school processing were applied using Echoview (Myriax inc.) software. The remaining data processing was carried out on the exported csv files using R (R Core Team, 2014).

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

The relation between TS and fork length (L; cm) is normally assumed to be (Simmonds and MacLennan, 2005):

\[ TS = a \cdot \log(L) + b, \tag{1} \]

In our case, it was modelled as:

\[ TS = 20 \cdot \log(L) + b_{20} + \epsilon \tag{2} \]

i.e., considering a fixed slope of 20 due to the small number of sets (two) and adding an error term \( \epsilon \) to account for the natural variability of TS. For each frequency, \( b_{20} \) was estimated by fitting the observed TS distributions of *in situ* bigeye and the predicted TS distributions based on...
the measured L from the purse-seine catches, using a curve fitting method similar to that of MacLennan and Menz (1996) or Gastauer et al. (2017).

Figure 4. Illustration of the curve fitting procedure used to estimate $b_{20}$ from the observed length and TS distributions. The example corresponds to the 200 kHz frequency at set number 7. Top panel: predicted TS distributions as directly converted from the bigeye tuna length distribution (Fig. 2) using Eq. (1) and a slope of 20. Central panel: predicted TS distributions (grey curves) using Eq. (2), i.e., allowing a variability around the predicted TS value of each bin (black vertical lines). The thick black curve is the proposed predicted TS distribution, built as the sum of the individual bin curves. Bottom panel: observed TS distributions. Model parameters ($b_{20}$, standard deviation and skewness) are obtained by adjustment between the observed TS distribution and the predicted TS distribution in the central panel.
The bigeye tuna body length distributions were converted to predicted TS distributions using Eq. (2) (Figure 4). For the error term, two alternative curve types were used: a simple normal function, $\varepsilon = N(\mu=0, \sigma)$, and a two-folded (skewed) normal, $\varepsilon = N_s(\mu=0, \sigma, s)$, included to increase the accuracy of the estimated $b_{20}$ values in cases of asymmetric observed TS distributions. An optimization process was run for the parameters of Eq. (2) using sequences of $b_{20}$, (from -80 to 0 in intervals of 0.1 dB), standard deviation, $\sigma$, (from 0 to 20 in intervals of 0.1 dB) and, in the case of the two-folded normal, percentage of skewness, $s$, (from -100% -left sided- to 100% -right sided- in intervals of 5%), being the resulting functions fitted to the observed TS distributions. For each curve type, all the combinations of parameters were computed and the one with the highest coefficient of determination was chosen. Then, the choice of curve type was done based on AIC (Akaike Information Criterion, Akaike, 1973) to allow penalization for the extra parameter of the two-folded gaussian. The curves obtained with this optimization procedure were the proposed predicted TS distributions. 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 fit between observed and predicted TS distributions were calculated to evaluate the goodness of the obtained TS(L) relationships.

The TS(f) relationship was calculated as the succession of $b_{20}$ values at the three available frequencies. The TS(f) relationship was calculated for the two sets together as well as per individual set to try to assess the incidence of the relatively low predominance of bigeye tuna in set 7 (91%) with respect to set 6 (99%).

Table 3:
Summary of the results of the least square adjustment procedure. “Freq” stands for acoustic frequency, “L” for fork length, “sd” for standard deviation, “CI” for 95% confidence interval and “R$^2$” for adjusted coefficient of determination.

<table>
<thead>
<tr>
<th>Set</th>
<th>Freq</th>
<th>L</th>
<th>sd_L</th>
<th>N</th>
<th>TS</th>
<th>$b_{20}$</th>
<th>sd</th>
<th>CI</th>
<th>R$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(kHz)</td>
<td>(cm)</td>
<td>(cm)</td>
<td></td>
<td>(dB)</td>
<td>(dB)</td>
<td>(dB)</td>
<td>(dB)</td>
<td>(%)</td>
</tr>
<tr>
<td>6</td>
<td>38</td>
<td>75</td>
<td>8</td>
<td>7307</td>
<td>-26</td>
<td>-65</td>
<td>9</td>
<td>88</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>38</td>
<td>68</td>
<td>6</td>
<td>8555</td>
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<td>-63</td>
<td>9</td>
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<td></td>
</tr>
<tr>
<td>All</td>
<td>38</td>
<td>71</td>
<td>7</td>
<td>15862</td>
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<td>-64</td>
<td>9</td>
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<tr>
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<td>90</td>
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<td>19383</td>
<td>-35</td>
<td>-72</td>
<td>7</td>
<td>-72.1</td>
<td>-71.9</td>
</tr>
</tbody>
</table>
Results

Size distribution

From the 20 sets done in the survey, only two (sets 6 and 7) had more than 90% in mass of bigeye tuna (Table 2) and were hence used for this study. The average bigeye tuna sizes were 75 and 68 cm with 8 and 6 cm standard deviation respectively (Table 3). The length distributions were bimodal in both cases with modes centred in ~60 and ~90 cm respectively (Figure 2).

Figure 5. Histograms of TS values at the three frequencies for the incremental layers of filtering: (0) raw TS distribution without filtering; (1) filtered with the school masking; and (2) school masking plus multifrequency simultaneity requirement. Vertical dashed lines represent the median TS value and N is the remaining number of single targets in each step.
Figure 6. Observed (grey bars) against predicted (continuous line) TS distribution of the curve fitting procedure used to estimate $b_{20}$ for each set and acoustic frequency.

**TS filtering steps**

The initial TS distributions had multiple modes at all frequencies but after the school masking, the lower TS modes (presumably plankton and/or micronekton) were removed, increasing the mean value in more than 5 dB and changing the TS distributions into monomodal ones (Figure 5). The MFS sensitivity analysis showed a reduction of TS with the distance threshold until reaching stabilization at the three frequencies (Figure 3; only the 38 kHz case is shown), based on which, a distance threshold of 0.09 m was applied at all frequencies. The simultaneous detection requirement caused small change on the mean TS. Overall, the TS filtering steps reduced the number of single targets in one order of magnitude at all frequencies. The mean TS
values observed after all the filtering procedures were -27, -28.5 and -35 dB at 38, 120 and 200 kHz respectively (Table 3).

![Figure 7. TS frequency response of bigeye tuna (black), triangles representing set 6 and circles set 7. In grey squares, TS frequency response of skipjack tuna, redrawn from Boyra et al. (2018). Error bars represent standard deviation.](image)

**TS-L and TS-f relationships**

The fit between modelled and observed TS distributions had coefficients of determination well over 80% (Table 3; Figure 6). The fitted TS-length relationship in Eq. (1) had intercepts of -64, -65.5 and -72 dB respectively at 38, 120 and 200 kHz, with uncertainties of ~7.5, 6 and 5 dB. The frequency response was monotonously decreasing with the increasing frequency, the 38 kHz being ~1.5 dB higher than 120 kHz and ~8 dB higher than 200 kHz (Figure 7).

**Funding**

This work was supported by the International Seafood Sustainability Foundation (ISSF) and conducted independently by the authors. The report and its results, professional opinions and conclusions are solely the work of the authors.
Aknowledgements

We thank the following organizations and people for their support of this work: the governments of Kiribati, Tuvalu, and Tokelau which permitted this research in their EEZs; Albacora for allowing this work aboard F/V ALBATUN TRES; Fishing Master Ekena Mujika; the captain and crew; the divers and scientist J. Filmalter and F. Forget are thanked for invaluable insight about fish behaviour, vertical stratification and non-target species composition at FADs.

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