Fisheries Research 261 (2023) 106611

Contents lists available at ScienceDirect

Fisheries Research

journal homepage: www.elsevier.com/locate/fishres

A new *in-situ* method to estimate fish target strength reveals high variability in broadband measurements

James Dunning[a,b,*], Teunis Jansen[b,c], Alan J. Fenwick[a], Paul G. Fernandes[a,1]

[a] University of Aberdeen, School of Biological Sciences, Zoology Building, Tillydrone Avenue, Aberdeen AB24 2TZ, UK
[b] GINR (Greenland Institute of Natural Resources), Kivioq 2, PO Box 570, 3900 Nuuk, Greenland
[c] DTU AQUA (National Institute of Aquatic Resources), Kemitorvet, 2800 Kgs. Lyngby, Denmark

ARTICLE INFO

Handled by Dr Niels Madsen

Keywords:
Atlantic cod
Broadband acoustics
in-situ
Single target
Target strength

ABSTRACT

Fish Target Strength (TS) is a requirement for estimating abundance from surveys of pelagic fish using echosounders. This paper describes a novel *in-situ* method to estimate TS as a function of fish body length (L), according to the standard equation TS = 20 log (L) +b_{20}, where b_{20} is the species-specific factor to be estimated. We made measurements of TS with a broadband scientific echosounder, which is becoming the new tool of choice in fisheries acoustics due to its enhanced signal-to-noise ratio, and higher range resolution and the ability to measure the frequency response. A split-beam 38 kHz broadband transducer was pole-mounted on a small boat in the fjords of Nuuk, Greenland. With the boat stationary, individual Atlantic cod *Gadus morhua* were detected as echotraces, caught with a fishing line, measured in length and then released. Video footage, from a camera attached to the line, was inspected to verify a single individual was attracted to the lure and caught. Fish echotrace tracking techniques were applied to estimate the tilt of the fish from each acoustic sample and the measured TS was adjusted accordingly with the use of a Kirchhoff-Approximation scattering model. The b_{20} parameter was estimated by linear regression. This method combines the benefits of associating TS from single fish of known length, which is typical of *ex-situ* methods, with the *in-situ* advantages of measuring TS of an undisturbed fish in its natural environment. Results yielded a b_{20} of − 65.6 dB (± 0.83 dB C.I.), which is within the range of previously published values for Atlantic cod measured with narrowband systems. Large variability of TS was observed within fish tracks (average s.d. of 5.55 dB). This is the first description of TS for Atlantic cod with broadband equipment. The high variability could not be attributed to variation in fish length nor tilt angle. Other physiological and behavioural aspects were also discarded. It is possible that this may be an intrinsic property of broadband acoustics, which indicates a need for re-evaluating TS to length relationships as fisheries science moves towards the wider application of broadband acoustics.

1. Introduction

Fish target strength (TS) is an essential requirement for estimating abundance from surveys of pelagic fish using echosounders, typically referred to as fisheries acoustics surveys. TS is a measure of the proportion of acoustic energy backscattered by a single fish in the form of an echo. In general, given similar material properties, the larger a fish, the stronger its echo and thus its TS. Therefore, knowledge of TS allows for the estimation of the number of individuals in echoes from a school (assuming the lengths are known, e.g. by obtaining information from an alternative sampling tool such as a trawl); or for the estimation of the length of an individual fish from its echo. The standard TS to length relationship (Foote, 1979, 1987) is described as the linear function:

$$TS = 20\log L + b_{20} \tag{1}$$

Where TS = target strength (dB re 1 m^2); 20 = a fixed slope, L = fish length (cm), b_{20} = intercept and empirical parameter specific to species and frequency. All dB units hereafter refer to dB re 1 m^2.

The b_{20} parameter has typically been estimated by linear regression of measurements of TS of fish of known species and length. TS has been published for many narrowband frequencies and species (Simmonds and MacLennan, 2005), including Atlantic cod *Gadus morhua* (Table 1). The

* Corresponding author at: University of Aberdeen, School of Biological Sciences, Zoology Building, Tillydrone Avenue, Aberdeen AB24 2TZ, UK.
E-mail address: j.dunning.18@abdn.ac.uk (J. Dunning).
[1] Present address: Lyell Centre, Heriot-Watt University, Edinburgh EH14 4AP, UK

https://doi.org/10.1016/j.fishres.2023.106611
Received 9 March 2022; Received in revised form 19 September 2022; Accepted 5 January 2023
Available online 17 January 2023
0165-7836/

TS measurements required to estimate b_{20} are usually carried out either: *ex-situ,* in controlled systems such as cages (Gauthier and Rose, 2001), pens (Brooking and Rudstam, 2009; Edwards et al., 1984) or with tethered fish (Chen et al., 2012; Gurshin, 2012; Manik, 2015); or *in-situ*, by acoustically recording and subsequently sampling those of fish (e.g. with a pelagic trawl) to then apply a probabilistic approach (MacLennan and Menz, 1996; Rose and Porter, 1996).

Active acoustic systems, such as echosounders, are non-invasive, cost-effective tools used to survey large areas at high spatial resolution to estimate the abundance and distribution of a variety of aquatic animal populations (Dunlop et al., 2018; Horne and Jech, 1999; J. E. Purcell et al., 2000; Warren and Demer, 2010). Acoustic surveys of commercial fish stocks have become common practice in many countries (Eriksen et al., 2018; ICES, 2014; Ormseth, 2019; Roberts et al., 2019). One of two methods is usually applied: echo-integration or echo-counting. The former is the most common and used in conditions where fish form aggregations so that individuals cannot be resolved by the acoustic system, such as schooling fish. Echo-integration estimates the density of fish from the ensemble (school) echo intensity (Scherbino and Truskanov, 1966). However, the length distribution of the fish within the ensemble needs to be known to estimate the density, as the same echo could come from a small number of large fish (with a high TS) or a large number of small fish (with a low TS). The TS to length relationship then needs to be known to convert the length to an acoustic quantity that can be divided into the backscatter from the ensemble to estimate density. The second method, echo-counting, is used when single fish can be resolved. It works by detecting and counting single targets (a.k.a. single echo detections or SED). Fish density is then estimated by accounting for the [known] volume of water sampled. TS can then be used to estimate the length of fish (Eq. 1) which is essential for estimates of population dynamics. Fish length distribution is usually estimated by some alternative sampling method, such as pelagic trawling, often referred to as groundtruthing (McClatchie et al., 2000), however, Fernandes et al. (2016), prefer the term "alternative evidence" as most types of underwater sampling tools have inherent biases.

To date, both echo-integration and echo-counting have relied on single or multi-frequency narrowband systems. However, thanks to advancements in technology, broadband systems are becoming more widely available. Broadband systems have several advantages over traditional narrowband systems, including: spectral analysis of targets to estimate their frequency response (Bassett et al., 2018; Benoit-Bird and Waluk, 2020); higher range resolution thanks to pulse compression (Demer et al., 2017; Kubilius et al., 2020; Stanton and Chu, 2008); and better signal-to-noise ratio (SNR) (Lavery et al., 2017). Disadvantages of these systems include the output requiring an order of magnitude greater data storage; more complex signal processing (Demer et al., 2017); and, due to its infancy, fewer examples of applications and standard protocols.

The improved SNR and range resolution of broadband are desirable traits for echo-counting, a technique that has been limited, largely, to freshwater ecosystems due to their shallower depths (Simmonds and MacLennan, 2005). However, echo-counting has also been applied in marine systems: for example, Atlantic bluefin tuna *Thunnus thynnus* in Nova Scotia (Melvin, 2016), black rockfish (*Sebastes melanops*) in Alaska (Tschersich, 2018; Tschersich and Gaeuman, 2019), and mesopelagic organisms in New England (Cotter et al., 2021). Another application of echo-counting is the detection of single targets at the periphery of fish schools (Gastauer et al., 2017; Scoulding et al., 2017). The fjords of Greenland are an ideal site to test this technique because the upper approx. 200 m of this species-poor marine ecosystem is dominated by Atlantic cod, and single individuals are well distributed across the water column especially during the dark hours (Fig. 1).

With the prospect of conducting an echo-counting survey for Atlantic cod in Greenland, this study produced an estimate of b20 from a broadband pulse. Results were compared with previously published narrowband data on the same species. We achieved this by adopting a novel method that allowed the *in-situ* direct measurement of TS and length of individual fish, along with estimates of its tilt angle. The length was measured after catching the ensonified individual using rod, line, camera and a precisely positioned lure that was viewed 'live' on the same echosounder.

2. Materials and methods

TS of numerous Atlantic cod were measured as SED in the wild. Attempts were made to catch each clearly resolved individual SED, to measure their length, after which they were released back into the wild.

2.1. Equipment

Data was collected within Nuup Kangerlua, the fjord system around Nuuk in south west Greenland, between 08th-13th October 2019. A Simrad WBT (Wide Band Transceiver) mini EK80 wideband scientific echosounder was deployed on a 5.5 m long motor-powered dinghy. The echosounder was connected to a dual frequency pole mounted transducer (Simrad ES38–18/200–18 C), consisting of a split-beam unit with a nominal frequency of 38 kHz (34–45 kHz band) and a single beam unit with central frequency of 200 kHz (190–230 kHz band), both with an 18° beam opening angle. Only the data from the split-beam 38 kHz transducer was considered. The transmitted signal was set to slow ramping and a pulse duration of 1.024 ms. Due to the size of the boat and exposure to the elements, data was collected during the day (from 08:00–20:00) and in good weather conditions (no precipitation, minimal wind and flat sea). Calibration of the echosounder was performed

Table 1
Previous studies on TS and length of Atlantic cod *Gadus morhua* and other gadoids using narrowband data at given frequency (f). Parameters m and b refer to the general equation { $TS = m \log(L) + b$} whereas the parameter b_{20} refers to the standard equation { $TS = 20 \log(L) + b_{20}$}. To translate m and b into a b_{20} value the following formula was used { $(m - 20) \log(L_{ref}) + b$}, where L_{ref} is the midpoint of the length range. Methods key: DB= *in-situ* observations with dual-beam echosounder; SB= *in-situ* observations with split-beam echosounder; M= metadata from multiple studies; CF= *ex-situ* measurements on captive fish; DF= *ex-situ* on dead fish. References: 1 = Nakken and Olsen (1977); 2 = McClatchie et al. (1996); 3 = McQuinn and Winger (2003); 4 = Rose and Porter (1996); 5 = Ermolchev and Zaferman (2003); 6 = Foote (1987); 7 = Foote et al. (1986).

Species	Location	Fish length (cm)	Time of day	f (kHz)	m (dB)	b (dB)	b_{20} (dB)	Method	Ref.
Atlantic cod	Bergen (NO)	6–95	Any	38	24.6	-66.6	-58.8	DF, CF	1
Atlantic cod	Bergen (NO)	6–95	Any	120	24.6	-67.6	-59.8	DF, CF	1
Atlantic cod	(Various)	?	Any	30, 38			-61	M	2
Atlantic cod	Newfoundland (CA)	40–53	Night	38			-63.4	SB	3
Atlantic cod	Newfoundland (CA)	18–60	Night	38			-66	CF, DB	4
Atlantic cod	Kola Bay (RU)	15–21	Any	120	31.6	-80.7	-66.1	SB	5
Gadoids	(Various)	9–105	Any	38			-67.4	M	6
Atlantic cod	Lofoten (NO)	50–105	Any	38			-68.9*	SB	7

* average from 3 samples

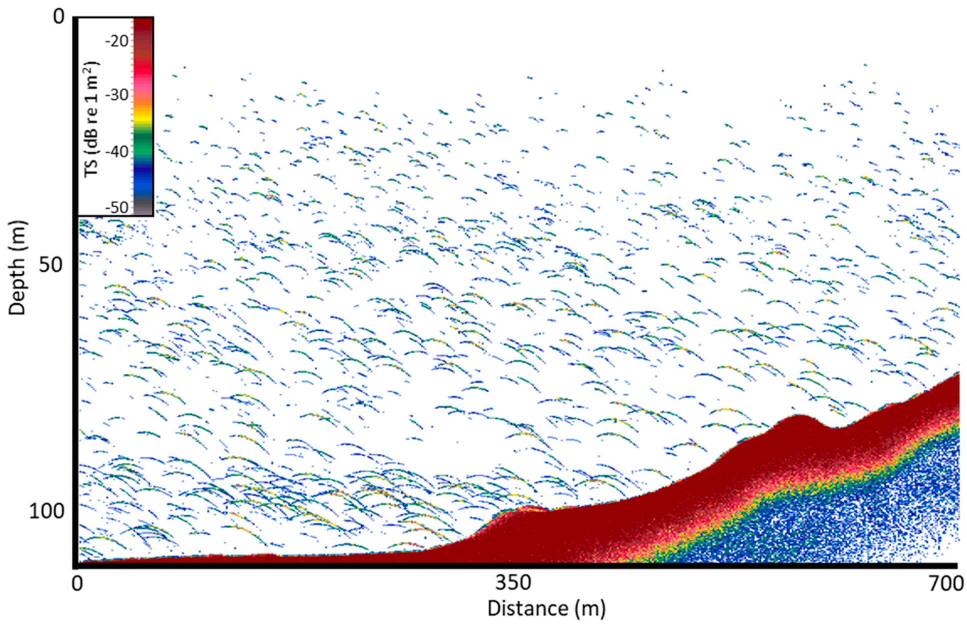

Fig. 1. A 35–45 kHz pulse compressed echogram (40 log range compensation) from the Nuuk fjord system taken during cruising from a research vessel at 6 knots (3.1 m s^{-1}) and a transmission rate of 2 Hz, on 10th October 2019. Colour scale refers to uncompensated TS (no beam compensation). The thick red line is the seabed, sloping from 110 m to 71 m; each thin blue-green curved line (a.k.a. fingernails) are the consecutive echoes from a single individual (target) of Atlantic cod *Gadus morhua.*

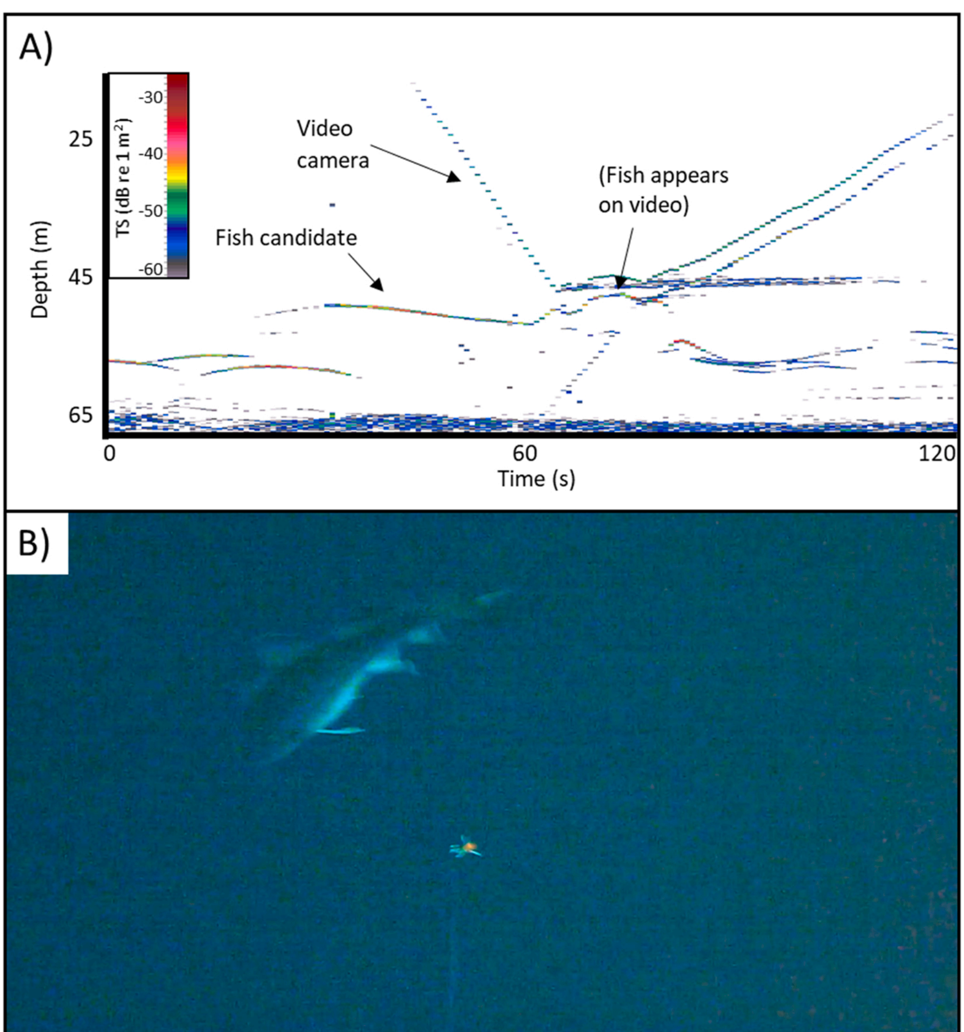

Fig. 2. Visual representation of the catch method. (A) 35–45 kHz pulse compressed echogram (40 log range compensation) as viewed on the echosounder display to monitor the catch of single target Atlantic cod *Gadus morhua*. Colour scale refers to uncompensated TS (TS_u). A second fish can be seen approaching the lure, coming from ~60 s, 65 m depth. However, video footage confirmed that only the fish candidate attempted and caught the lure. (B) Screenshot of video footage 4 s before catch.

off site in a 4 m deep tank, using a 38.1 mm tungsten carbide sphere according to standard methods (Demer et al., 2015).

The fishing gear consisted of a rod and line with a 500 g metal jig as lure. A specialised underwater camera (Water wolf) was mounted 1 m above the hook, to record the catch. However, due to the long hours and the availability of only one video camera battery, only about half of the catches were recorded.

2.2. Procedure

The boat was kept stationary on the water while live-viewing the echogram generated by the echosounder. This was achieved with none or little use of the boat motor given the very calm wind and sea conditions. When a single target fish candidate was identified and sufficient amount of acoustic data had been collected, then the hook and line were deployed to catch it. The descent of the hook was visible on the echogram so it could be stopped at the same depth as the fish of interest (Fig. 2A). A video description of the procedure is available at https://drive.google.com/file/d/1EraUy2HDSeECHSp4lPuwdTsrGFRgJuOj/view?usp=sharing.

To increase the chances of getting acoustic data from a single fish which could be caught, a fish candidate was defined as: (i) being isolated from other fish in the water column; (ii) with no other fish above it which may otherwise take the lure; (iii) positioned well within the beam so that it would not be lost by the acoustic system during the descent of the lure; and (iv) at less than 60 m depth to allow enough ambient light for the video camera to operate. Once the candidate fish was caught, it was reeled onto the boat and its length was measured as total length without pinching the tail (Hansen et al., 2018). It was then, immediately after, released back alive into the water. The video footage, when available, was examined back in the laboratory to ensure that the echotrace was generated from a single fish (Fig. 2B).

2.3. TS measurement

Acoustic data were first processed using Echoview® 11.0.255 (Echoview Software Pty Ltd, Hobart, Australia). Echotraces from a 35–45 kHz pulse compressed, uncompensated TS (TS_u) echogram were processed through the wideband single detection algorithm to yield beam compensated TS (TS_c) for each of the measured fish. Beam compensation corrected the TS_u of targets for transducer directivity by taking into account the target location in the beam pattern. Single echo detection parameters were set as follows: TS threshold = −50 dB; pulse length determination = 6 dB; normalised pulse length range: 0.5–1.5; minimum target separation = 0 m; maximum beam compensation = 19 dB; maximum standard deviation of minor- and major-axis angles = 0.6 deg. Each echotrace of interest was visually scrutinised for evidence of noise or other bad data which were excluded from analysis. For instance, all detections where fish altered their swimming behaviour to chase the fishing lure were excluded. Echoview's built-in tracking algorithm (based on Blackman, 1986) was adopted to confirm that echotraces were generated by the same fish. Settings included a minimum track length of 3 targets, maximum gap between single targets of 3 pings, and the weights for detection were set to 30% for both major and minor axes, and 40% for range. SEDs and associated statistics were then exported and processed in the statistical programming language R (R Core Team, 2020) as tracks of detections of the same individual. The TS exported from broadband SEDs should not be mistaken as a narrowband value. Both narrowband and broadband TS are representative of the proportion of transmitted acoustic energy that is received by the transducer. In the case of broadband data, energy transmitted/received includes contributions from a wider range of frequencies. Therefore, TS exports from broadband SEDs represent the full frequency band (35–45 kHz in this case), not just 38 kHz (Haley Viehman, Echoview, pers. comm., 2022).

The tilt angle of the fish was also estimated for each ping across the fish track. This was achieved by determining the xyz coordinates of the fish from the alongship (θ) and athwartship (ϕ) angles of the target detected within the echosounder beam, and the range (r), as measured by the split beam echosounder (Eq. 2). The X and Y axes (alongship and athwartship respectively) characterise the horizontal plane, and the Z axis runs concurrent to the depth dimension.

$$\left\{ \begin{array}{c} x = z\tan(\theta) \\ y = z\tan(\varphi) \\ z = \sqrt{r^2 - (x^2 + y^2)} \end{array} \right\} \tag{2}$$

Where z was:

$$z = \sqrt{\frac{r^2}{\tan^2(\theta) + \tan^2(\varphi) + 1}} \tag{3}$$

xyz coordinates were then smoothed on each axis with a cubic smoothing spline function (smoothing parameter 0.75) to reduce noise in spatial localisation. To calculate tilt, the movement of fish from ping to ping was assumed to be the result of their active motion in a straight line, assuming minimal movement of the boat. The tilt between two points (pings) was identified as the angle (α) between their distance on the XY plane and their distance in the 3D system (Fig. 3). The tilt of the fish at a given ping was calculated as the average between the two tilts associated with the previous and following pings. For the first ping of an acoustic track, which has no previous ping, no average was taken but estimated simply as the angle (α) between it and the next acoustic sample. Similarly, for the last ping of a track. Positive tilt angles described fish swimming towards the surface, negative tilt angles to the seabed, and a value of zero described a horizontal fish.

To estimate the effect of tilt on TS, a Kirchhoff-Approximation model (hereafter referred to as KA model) was constructed (Clay and Horne, 1994) but modified to work in a broadband framework. This model is accurate for fish tilts between − 25° and 25°, therefore, any data exceeding these limits was discarded. To determine the theoretical broadband TS of Atlantic cod, narrowband TS_{cw} were calculated with the KA model for an array of frequencies equal to the bandwidth of the echosounder used in this study (34 – 45 kHz, sampled every 100 Hz), and then applied to the following equations:

$$\sigma_{bs(f)} = 10^{TS_{CW(f)}/10} \tag{4}$$

$$\overline{\sigma_{bs}} = \left(\sum_{f=1}^{n} \sigma_{bs(f)}\right) \Big/ n \tag{5}$$

$$TS_{FM} = 10Log(\overline{\sigma_{bs}}) \tag{6}$$

Where $\sigma_{bs(f)}$ was the backscattering cross-section at a given narrowband frequency, $TS_{CW(f)}$ was the theoretical narrowband (continuous wave) TS estimate from the KA model, n was the number of narrowband frequencies sampled to simulate the bandwidth of broadband (in this case

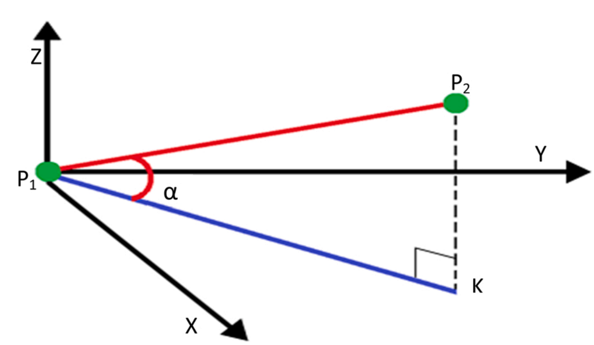

Fig. 3. Graphic representation of the tilt angle (α) estimation method for a single target moving between two points (P_1,P_2) in successive pings. K is the projection of P_2 on the XY plane.

n = 111), and TS_{FM} was the theoretical broadband (Frequency Modulated) TS.

Along with fish length, tilt angle, and pulse frequencies, the KA model required other acoustic parameters, and a geometric construction of the fish body and swimbladder (Fig. 4), all described by Clay and Horne (1994). The geometric model was set to maintain the same shape and proportions relative to the fish length.

With all parameters assumed to be constant, the theoretical TS_{FM} was then estimated according to fish length and tilt. From this, the measured broadband TS_u of wild Atlantic cod at a given length was compensated for tilt at every acoustic sample as:

$$TS_t = TS_c + \Delta \tag{7}$$

$$where \Delta = TS_{FM(0)} - TS_{FM(\alpha)} \tag{8}$$

Where TS_c is the beam compensated target strength, TS_t is the beam and tilt compensated target strength, Δ is the tilt compensation factor, $TS_{FM(0)}$ is the theoretical target strength at tilt zero, $TS_{FM(\alpha)}$ is the theoretical target strength at tilt α (angle estimated from fish tracking).

The TS to length relationship was then fitted by linear regression to estimate b_{20} from Eq. 1. Multiple b_{20} values were estimated (from TS_c and TS_t, and including/excluding echotraces with no video verification). To test for significance between these, their 95% confidence intervals (CI) was assessed for overlap. Finally, to check whether it was correct to assume a slope of 20, a modified version of Eq. 1 was fitted:

$$TS = (20 + m) * \log L + b \tag{9}$$

Where (20 + m) is the slope and b is an unknown intercept different than b_{20}. If m was not found to be a significant parameter of the linear regression ($p < 0.05$), this model was discarded and the standard form (b_{20}) was used instead.

3. Results

A total of 27 fish were successfully caught and measured in length with suitable SEDs. Of these, 12 had clear single target tracks, of which 2 were discarded after video analysis. Of the remaining ten sets of data, two were discarded, the first because only one single target acoustic data point was available, the other because all of its 10 acoustic samples were associated with tilts outside the KA model limits of ± 25° (−67.7° to −34.5°). Therefore, 8 single targets, of lengths ranging from 46.1 to 58.5 cm were analysed. These 8 targets were associated with 261 acoustic SEDs, of which 222 of them (85%) were with tilts within the KA model boundaries, yielding the equivalent number (222) of valid acoustic samples. The mean tilt angle was + 3.7° (head up) with a standard deviation of 21.6° (Fig. 5).

Of the fish analysed, 4 were successfully filmed with the underwater camera attached to the fishing line. Depth and time of the day played a significant role in the clarity of the footage, yet fish could be distinguished at depths of around 50 m in the middle of the day, and 25 m in the late afternoon without the need of external light sources. The remaining 4 fish were not recorded on camera due to power exhaustion.

For any given fish, there was large variability in TS measurements from ping to ping. The average standard deviation of TS_u (no beam and tilt compensations) per fish track of 5.9 dB, and the largest range of TS_u spanned 34 dB (−58.9 to −25.1 dB). After beam compensation the standard deviation of TS_c was 4.76 dB, and greatest range was 22 dB (−45.6 to −23.6 dB). After beam and tilt compensation the standard deviation of TS_t was 5.55 dB, and greatest range was 30 dB (−49.8 to −20.3 dB). Therefore, accounting for fish tilt did not reduce the high variation in TS.

The TS_c/length standard relationship produced an estimated b_{20} = −66.2 dB (95% CI = −66.40 to −64.74 dB) (Fig. 6A). With compensation for tilt, the TS_t/length standard relationship yielded an estimate of b_{20} = −65.6 dB (95% CI = −67.07 to −65.30 dB). This was equal to a 0.6 dB increase in b_{20} compared to the one estimated without tilt compensation, although it was not statistically different (95% CIs overlap). Further, compensating for tilt resulted in a better fit to the linear model (Fig. 6B) (Akaike Information Criterion: with tilt compensation: AICc = 1447.89, weight = 1, LL = −721.92; without tilt compensation AICc = 1477.67, Δ AICc = 29.78, weight = 0, LL = −736.81). Further, when fitting the data with a model where the slope was estimated (Eq. 9), the slope did not significantly deviate from the standard value of 20 (m = −11.03, p = 0.42). Therefore, the use of the standard (b_{20}) relationship was accepted. To check for sensitivity to the video verification, analysis was also performed excluding data from fish without video footage. This resulted in a b_{20} = −66.6 dB (95% CI = ± 1.48 dB), which was not significantly different from the previous estimate of − 65.6 dB (95% CIs overlap).

4. Discussion

The present study is the first description of a standard TS to length relationship for Atlantic cod with a broadband pulse using an *in-situ* method. The method for *in-situ* studies that does not require a broadband system, provided the targets are resolvable, and has the advantage of linking the acoustic trace of an individual wild fish to their measured length with observations of the inferred tilt behaviour. The estimated b_{20} of − 65.6 dB is well within the range of previously published values obtained with narrowband data (Table 1). This lends support to the validity of the method in spite of the observed high TS variability. There have been few published methods that share the quality of measuring both TS and length from individually identified wild fish. Ermolchev and Zaferman (2003) describe a system that integrated a video camera and a laser on the same platform as the echosounder. At the passage of a single fish in the field of view, the acoustic data were recorded for TS and the footage combined with the laser was used for estimating the fish length.

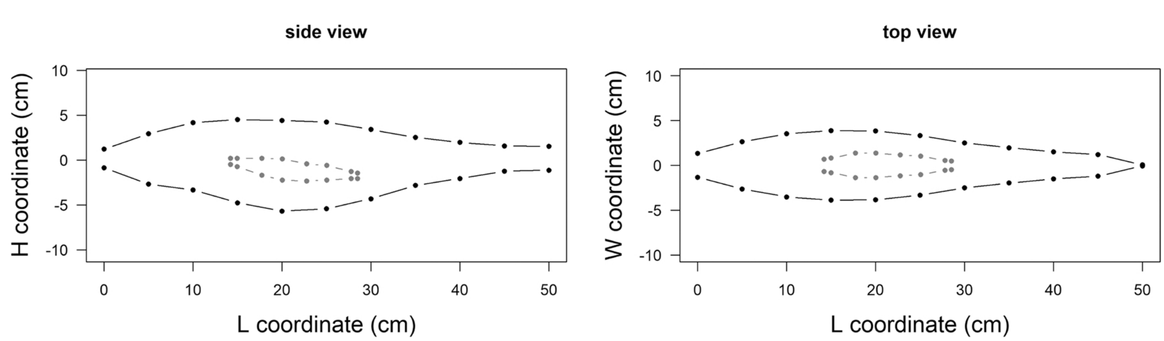

Fig. 4. Shape and proportions of the cod-like object used in the KA model to estimate theoretical TS of Atlantic cod *Gadus morhua* (Clay and Horne, 1994). L, H, W coordinates were length, height, and width respectively. In this example the fish length was 50 cm. The left side of each plot represents the head, whereas the tail is on the right. The inner shape represents the swimbladder. The dots show all the coordinates input in the KA model.

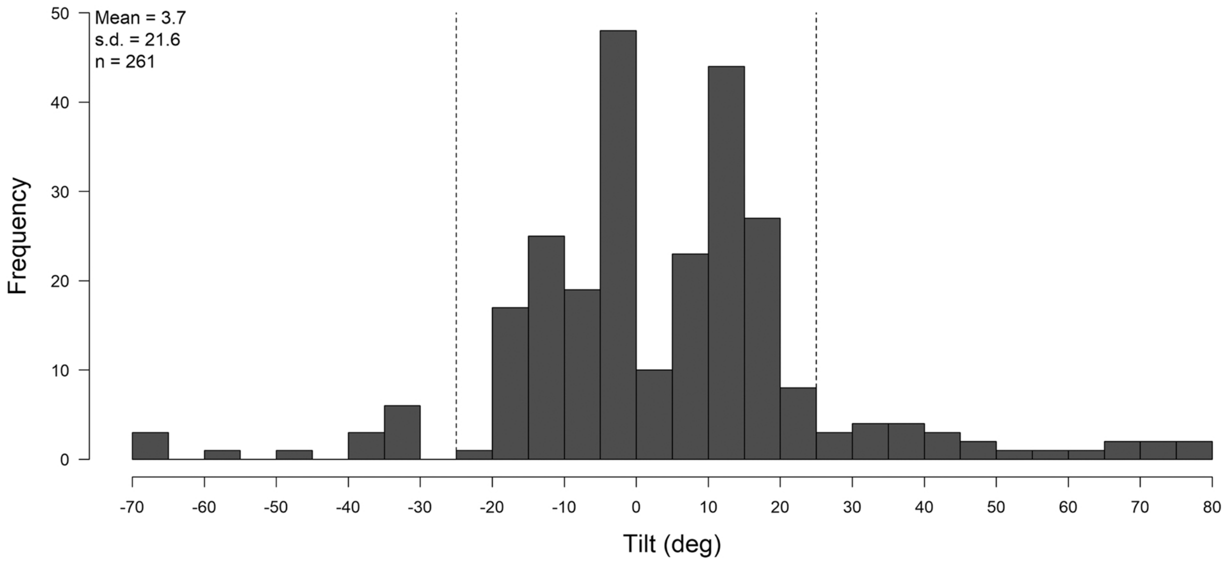

Fig. 5. Frequency distribution of tilt angles estimated from 261 Single Echo Detections from 8 single target tracks of Atlantic cod *Gadus morhua*. Vertical dashed lines represent the range within which the KA model (Kirchhoff-Approximation model) is applicable.

Similarly, Scoulding and Kloser (2021) describe an acoustic-optical system (AOS) attached to a trawl net able to measure the length of acoustically detected single fish with a stereo camera. In contrast to Ermolchev and Zaferman (2003) and Scoulding and Kloser (2021), the method described here provides a direct measurement of fish length and uses standard acoustic equipment coupled with an inexpensive, low tech fishing rod. The capture of specimens allows a one-to-one connection between *in-situ* measured TS and other fish properties such as stomach contents, gonad development, and fat storage which could be beneficial for future studies. The direct connection between TS and length measurements from individual wild fish allowed to measure and account for fish tilt as a source of TS variability. Large variations in TS are often attributed to unknown fish tilts and lengths. Enabled by the novel method presented, this study provides evidence that there may be other sources at play.

Thanks to the single target detection and tracking algorithms, the method here described could also be applied without a video camera to greater depths and/or at night. This is further supported by the fact that, in this study, the estimated b_{20} excluding non-video verified data was not significantly different from the full data value. This method can be further applied to any aquatic environment where fish are well distributed to produce SEDs and can be caught easily; some modification on the fishing gear may be necessary to best suit the species of interest. For instance, in Lake Champlain (New York, Vermont, Quebec) and Eastern Lake Erie (New York, Ontario), rainbow smelt *Osmerus mordax* is the dominant pelagic species, contributing to 99% of trawl catches (Einhouse et al., 1997), and yields a large number of single targets (Rudstam et al., 2003). This method could also be deployed in proximity of fish aggregating devices (FADs) for tuna species. Over 50% of commercial tuna, such as Bigeye *Thunnus obesus*, skipjack *Katsuwonus pelamis*, and yellowfin *Thunnus albacares*, are caught using FADs (Fonteneau et al., 2013). There has also been interest to acoustically discriminate between different species of tropical tuna in order to target those with healthy populations (Moreno et al., 2019). The method presented here can be used for collecting data both on TS and frequency response of single target tuna found in association with FADs (Boyra et al., 2019). Finally, this method needs not to be limited to fish species. In recent years, attention has been given to jellyfish (scyphozoans, cubozoans, hydrozoans, ctenophores, and salps) and their acoustic properties to monitor the increasing abundance in worldwide ecosystems (Brotz et al., 2012; Kogovšek et al., 2018; Mills, 2001). For example, single target TS was measured for jellyfish (*Chrysaora hysoscella* and *Aequorea Aequorea*) that were caught, tethered, and re-suspended in water for acoustic measurement (Brierley et al., 2004). Although great care was reported, each step could have damaged the jellyfish or introduced air bubbles. Although jellyfish would not be caught with a fishing rod, a dipnet would prove effective (Brierley et al., 2004). Therefore, the method described in the current study could have been more advantageous. The adoption by the scientific community of the method presented here in different environments and with different species would help in determining the observed sources of TS variability from broadband SED targets.

Despite its importance, there is no single preferred method of estimating TS of fish. Each method has its strengths and weaknesses. *Ex-situ* methods typically involve tethered or encaged fish. Tethered fish are either dead or stunned (Chen et al., 2012; Gurshin, 2012; Manik, 2015), and, therefore, fish lose physiological control of their swimbladder which is the main source for sound reflection, contributing up to 95% of the total backscatter (Foote, 1980). McClatchie et al. (1996) found a significant difference in measured TS between dead and live fish. Another approach is to confine living fish in monofilament cages (Edwards et al., 1984; Gauthier and Rose, 2001) or pens (Brooking and Rudstam, 2009; Gurshin, 2012). This allows for direct association of the TS to the known length of fish. However, fish depth is often shallow (Gauthier and Rose, 2001; He and Wardle, 1986) and fish may display different behaviours than in the wild (e.g. altered swimming pattern and tilt in a confined space) which can alter the observed TS. On the other hand, classic *in-situ* methods typically record the acoustic traces of wild fish schools before sampling them to acquire their length distribution, typically with a trawl net. This allows for the collection of a large amount of acoustic and biological data, however there are issues about catching the same school of fish as seen on the echogram. It is technically challenging to target a trawl at the correct depth and location, fish may move by chance or active avoidance, and bycatch can be caught in the process (Fernandes et al., 2016). All of these issues ultimately weaken the connection between the acoustically observed and caught fish, and lead to biases (MacLennan and Menz, 1996). The method described here combines the benefit of direct measurement of TS and length of single fish (typical of *ex-situ* studies) with the advantage of observing wild fish in their natural environment (typical of *in-situ* studies).

As might be expected, there are disadvantages to the method being presented and scope for improvement. First of all, this was a time-consuming process. There is an element of chance in finding a single

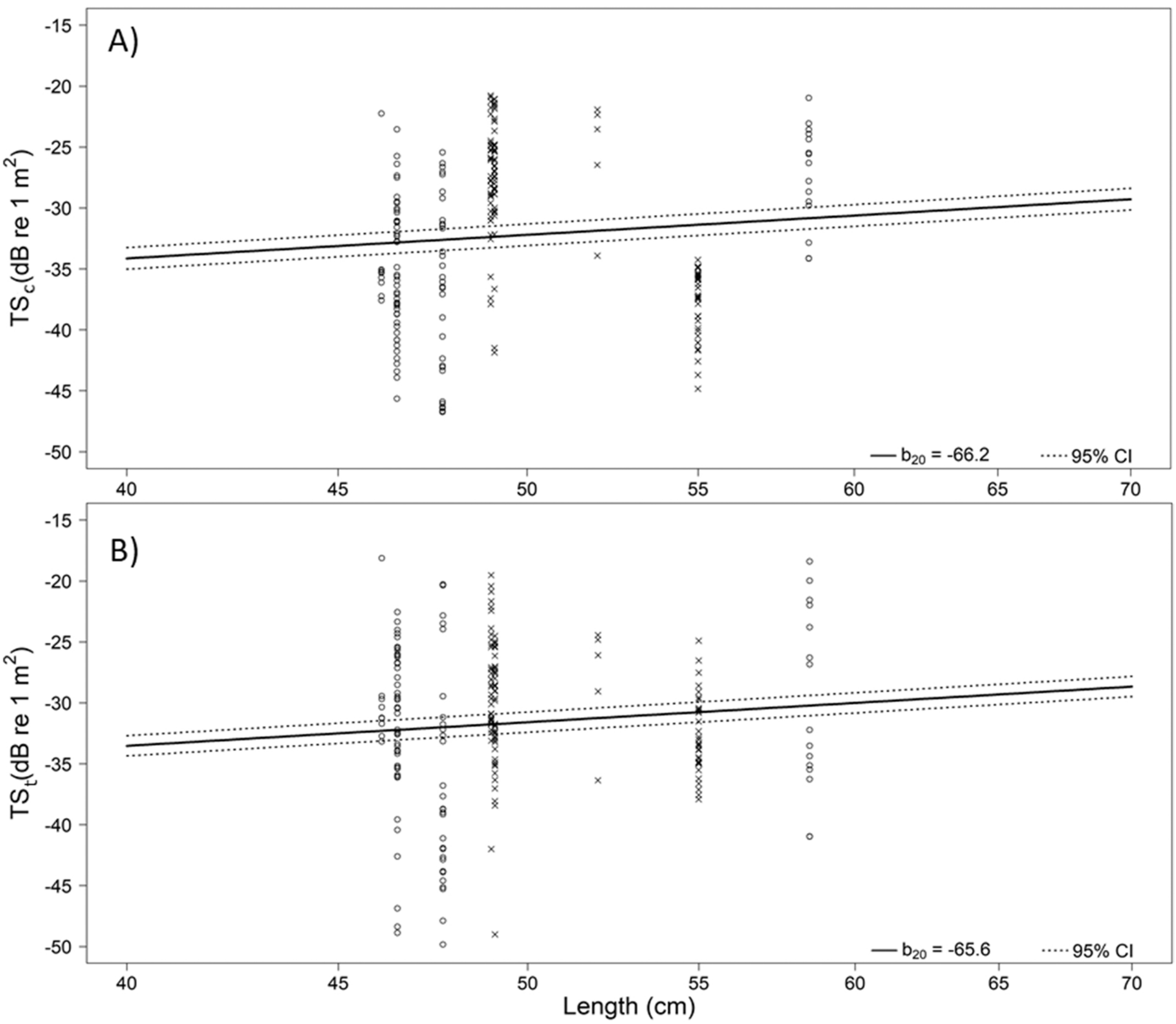

Fig. 6. TS (target strength) (dB re 1 m^2) against Length (cm) of 8 individual Atlantic cod *Gadus morhua*. (A) TS_c = beam compensated TS; (B) TS_t = tilt and beam compensated TS. Acoustic measurements were taken with a 38 kHz broadband echosounder (35–45 kHz bandwidth). Each fish, of a particular length, had multiple broadband acoustic single echo detections along a detected fish track. Dots represent data from single targets that were video verified, opposed to crosses that were not video verified. The continuous black line was fitted by least square regression of the standard form TS = 20 log L + b_{20}. Dotted lines represent the 95% confidence intervals.

fish that meets all the requirements, in particular, one that is well isolated from other fish and remains in the acoustic beam for enough time to sample data and subsequently to position the lure. In our case, the sampling of 8 individuals (222 measurements of TS) took 22 h across 3 days with ideal weather conditions. However, there was a learning curve in optimising the efficiency of this method (e.g. development of the fish candidate criteria and best locations for fishing). Therefore, future studies will be more time effective. To increase the accuracy of b_{20} estimation, improvements could be applied on the calculation of fish tilt. In this study the boat was assumed to be stationary on the water given the pristine environmental conditions. However, the method could be adopted in less favourable conditions with the adoption of a motion reference unit (MRU) mounted on the transducer to account for vessel movements such as roll and pitch.

The model to base the tilt compensation factor Δ (Eq. 8) may also have an effect on the estimated b_{20}. The KA model is frequently used in fisheries acoustics (Foote and Francis, 2002; Gauthier and Horne, 2004; Macaulay et al., 2013) and was chosen as the best model for this study. However, a simpler approach that did not require modelling was considered in early stages by applying the empirical relationship described by McQuinn and Winger (2003). Yet, this relationship lacks a theoretical support and is tested only on tilt angles between − 0.6 and 10.4° (McQuinn and Winger, 2003) which only applied to 24% of data in this study. The range of tilts observed (Fig. 5) is consistent with previous measurements of swimming Atlantic cod, e.g. Olsen (1971), which ranged between − 40 and + 40°, and Rose and Porter (1996), between − 30° and + 10°. Tilt is an important variable in the estimation of TS (Nakken and Olsen, 1977), and has been recognised for a number of species other than cod such as mackerel (Fernandes et al., 2016), herring (Huse and Ona, 1996), anchovy (Aoki and Inagaki, 1988; Sawada et al., 2009), sandeel (Kubilius and Ona, 2012; Safruddin et al., 2013), and orange roughy (O'Driscoll et al., 2012).

In each fish track, the high variability in TS (all TS_u, TS_c, TS_t) was not explained by the fish tilt nor by variation in length. Therefore, other sources of variability need to be considered. The standard TS/length relationship is widely used within fisheries science; however, it is a simplistic model. TS is also dependent on a variety of biological and behavioural factors that influence size and/or shape of the swimbladder. For example, under Boyle's law, a swimbladder is compressed (decrease in TS) when fish swim to deeper waters and expands (increase in TS) when they rise towards the surface (Mukai and Iida, 1996; Ona, 1990). However, gadoids such as Atlantic cod, are physoclistous and, therefore, are thought to be neutrally buoyant in midwater by maintaining a constant swimbladder volume (Arnold and Greer Walker, 1992). Further, in this study, fish were not selected if they had been observed to significantly change depth, and being fished from mid-water, they were not likely to have been diving before sampling. Stomach contents, gonad development, and fat storage may also compress the swimbladder (Ona, 1990). In particular, full stomachs and ripe gonads may lead to a 2–5 dB reduction in TS (Ona, 1990). However, these factors would not influence TS at a rate of seconds from one ping to the next. Therefore, it is not expected that the measured TS was affected by behavioural nor physiological factors.

The transducer used for this study was found to have an 11% error in transducer angle sensitivity (compared to the one reported by the manufacturer), and a 16.9° beamwidth (compared to the nominal 18°) (Renfree et al., 2019). Suspicion was raised regarding the accuracy of angular measurements due to these errors, and the manufacturer was reported to agree with the assessment (Renfree et al., 2019). With faulty angular positions of targets, the beam compensation for TS of SEDs would also result inaccurate and could thus introduce a source of variability. However, Renfree et al. (2019) also reported accurate measurements of uncompensated TS of a calibration sphere at different off-axis angles. We also did not see large variations in TS variability during calibration activities with our ES38–18. At the same time, we did see high variability in uncompensated TS. Therefore, the inaccurate angular measurements may have played a role in stochasticity but they do not resolve the issue. Other studies which have used this (ES38–18) transducer did not mention TS variability (Levine et al., 2021; Malin et al., 2021; Puckeridge et al., 2021; Scoulding et al., 2020; Villalobos et al., 2021).

The high variability of TS for each fish track remains, therefore, unexplained. In traditional studies, variability in TS is often attributed to differing tilt and size of fish despite the inability to measure them directly (e.g. McQuinn and Winger, 2003; Zhang et al., 2021). Further, under normal survey conditions, at cruising speed, each single target trace may only composed by one or a handful of SEDs (e.g. Linløkken et al., 2019; Zeng et al., 2018). On the contrary, here, the length of each fish is known, tilt is accounted for, and many acoustic samples were taken (around 30 per fish). This may suggest that broadband acoustics could have an unknown source of TS variability previously confounded by tilt and size of fish, and scarce acoustic samples. Jaya et al. (2019), measured TS of a single, tethered mackerel tuna E*uthynnus affinis* with a 160–240 kHz EK80, and reported a range of approximately 24 dB (−72 to −48 dB), not far from the 30 dB range found in this study. Similarly, Hasegawa et al. (2021) reported a high variability (in the order of 20–40 dB) in TS spectra from single targets of walleye pollock *Gadus chalcogrammus* and pointhead flounder *Cleisthenes pinetorum*, although the variation of mean TS was only a few dB within each frequency band.

Another hypothesis is the high variability we measured in TS of individual fish may be an intrinsic effect of the use of broadband systems. First, the measurement of TS with a broadband pulse is influenced by nulls determined by frequency and tilt (Lavia et al., 2020; Lee, 2015). Small variations in tilt, smaller than fish tracking can estimate, could therefore lead to large variations in TS. Second, the high range resolution of broadband, smaller than the height of Atlantic cod, in the order of 1–10 cm, may be recording the acoustic trace of sections of fish rather than the whole individual, therefore introducing an element of stochasticity. The higher variability may be dependent on which section of the fish is being recognised as a single target from ping to ping. Testing this hypothesis will need further studies. Understanding and solving this phenomenon is important as the use of broadband systems is becoming more common in the scientific community and their TS measurements are thought to be compatible with those from narrowband (Demer et al., 2017). Therefore, there may be a need to re-evaluate the acoustic properties of fish in a broadband acoustic context.

5. Conclusion

This study describes a novel method to acquire the TS/length relationship of wild fish by exploiting split-beam broadband acoustics and single target detection algorithms in situations where single fish are dispersed and easily sampled by hook and line. The estimated b_{20} of − 65.6 dB for Atlantic cod is in line with previously published data with narrowband systems but was associated with high TS variability. This study paves the way for the estimation of abundance and biomass of Atlantic cod in Greenland based on echo-counting.

CRediT authorship contribution statement

P.G.F and T.J conceived the idea; P.G.F, T.J and J.D. developed and performed the methodology; A.J.F. provided theoretical support for analysis and interpretation of data; J.D. analysed the data and wrote R scripts for the KA model, fish tilt estimation, and TS tilt compensation; J. D led the writing of the manuscript. All the authors contributed critically to the drafts and gave final approval for this submission.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

Acknowledgements

The authors thank the Greenland Institute of Natural Resources (GINR), the University of Aberdeen, and Marine Alliance for Science and Technology for Scotland (MASTS) for funding this study. MASTS is funded by the Scottish Funding Council (grant no. HR09011) and contributing institutions. Further, they thank GINR for providing access to their facilities.

References

Aoki, I., Inagaki, T., 1988. Photographic observations on the behaviour of Japanese anchovy Engraulis japonica at night in the sea. Mar. Ecol. Prog. Ser. 43, 213–221. https://doi.org/10.3354/meps043213.

Arnold, G.P., Greer Walker, M., 1992. Vertical movements of cod (Gadus morhua L.) in the open sea and the hydrostatic function of the swimbladder. ICES J. Mar. Sci. 49 (3), 357–372. https://doi.org/10.1093/icesjms/49.3.357.

Bassett, C., De Robertis, A., Wilson, C.D., 2018. Broadband echosounder measurements of the frequency response of fishes and euphausiids in the Gulf of Alaska. ICES J. Mar. Sci. 75 (3), 1131–1142. https://doi.org/10.1093/icesjms/fsx204.

Benoit-Bird, K.J., Waluk, C.M., 2020. Exploring the promise of broadband fisheries echosounders for species discrimination with quantitative assessment of data processing effects. J. Acoust. Soc. Am. 147 (1), 411–427. https://doi.org/10.1121/10.0000594.

Blackman, S.S., 1986. Multiple-Target Tracking with Radar Applications. Artech House, Inc.

Boyra, G., Moreno, G., Orue, B., Sobradillo, B., Sancristobal, I., 2019. In situ target strength of bigeye tuna (Thunnus obesus) associated with fish aggregating devices. ICES J. Mar. Sci. 76 (7), 2446–2458. https://doi.org/10.1093/icesjms/fsz131.

Brierley, A.S., Axelsen, B.E., Boyer, D.C., Lynam, C.P., Didcock, C.A., Boyer, H.J., Sparks, C.A.J., Purcell, J.E., Gibbons, M.J., 2004. Single-target echo detections of jellyfish. ICES J. Mar. Sci. 61 (3), 383–393. https://doi.org/10.1016/j.icesjms.2003.12.008.

Brooking, T.E., Rudstam, L.G., 2009. Hydroacoustic target strength distributions of alewives in a net-cage compared with field surveys: deciphering target strength distributions and effect on density estimates. Trans. Am. Fish. Soc. 138 (3), 471–486. https://doi.org/10.1577/T07-215.1.

Brotz, L., Cheung, W.W.L., Kleisner, K., Pakhomov, E., Pauly, D., 2012. Increasing jellyfish populations: Trends in Large Marine Ecosystems. In: Purcell, J., Mianzan, H., Frost, J.R. (Eds.), Jellyfish Blooms IV: Interactions with humans and fisheries. Springer, Netherlands, pp. 3–20. https://doi.org/10.1007/978-94-007-5316-7_2.

Chen, G., Li, Y., Chen, P., Zhang, J., Fang, L., Li, N., 2012. Measurement of single-fish target strength in the South China Sea. Chin. J. Oceanol. Limnol. 30 (4), 554–562. https://doi.org/10.1007/s00343-012-1218-4.

Clay, C.S., Horne, J.K., 1994. Acoustic models of fish: The Atlantic cod (*Gadus morhua*). J. Acoust. Soc. Am. 96 (3), 1661–1668. https://doi.org/10.1121/1.410245.

Cotter, E., Bassett, C., Lavery, A., 2021. Comparison of mesopelagic organism abundance estimates using in situ target strength measurements and echo-counting techniques. JASA Express Lett. 1 (4), 040801 https://doi.org/10.1121/10.0003940.

Demer, D.A., Berger, L., Bernasconi, M., Bethke, E., Boswell, K., Chu, D., Domokos, R., Dunford, A., Fassler, S., Gauthier, S., Hufnagle, L., Jech, J., Le Bouffant, N., Lebourges-Dhaussy, A., Lurton, X., Macaulay, G., Perrot, Y., Ryan, T., Parker-Stetter, S., Williamson, N., 2015. Calibration of acoustic instruments. ICES Coop. Res. Rep. 326. https://doi.org/10.17895/ices.pub.5494.

Demer, D.A., Andersen, L.N., Bassett, C., Berger, L., Chu, D., Condiotty, J., Cutter, G.R., Hutton, B., Korneliussen, R., Bouffant, N.L., Macaulay, G., Michaels, W.L., Murfin, D., Pobitzer, A., Renfree, J.S., Sessions, T.S., Stierhoff, K.L., Thompson, C.H., 2017. 2016 USA-Norway EK80 Workshop Report: Evaluation of a wideband echosounder for fisheries and marine ecosystem science. ICES Coop. Res. Re-Port. No. 336, 69. https://doi.org/10.17895/ICES.PUB.2318.

Dunlop, K.M., Jarvis, T., Benoit-Bird, K.J., Waluk, C.M., Caress, D.W., Thomas, H., Smith, K.L., 2018. Detection and characterisation of deep-sea benthopelagic animals from an autonomous underwater vehicle with a multibeam echosounder: A proof of concept and description of data-processing methods. Deep Sea Res. Part I: Oceanogr. Res. Pap. 134, 64–79. https://doi.org/10.1016/j.dsr.2018.01.006.

Edwards, J.I., Armstrong, F., Magurran, A.E., & Pitcher, T.J. (1984). HERRING MACKEREL AND SPRAT TARGET STRENGTH EXPERIMENTS WITH BEHAVIOURAL OBSERVATIONS. 23.

Einhouse, D., Tyson, J., Bur, M., Deller, J., Haas, R., Murray, C., Nepszy, S., Sztramko, L., Thomas, M., Trometer, E., Rudstam, L., & Witzel, L. (1997). Report of the Forage Task Group to the Lake Erie Committee and the Great Lakes Fishery Commission. Ann Arbor, MI, USA.

Eriksen, E., Gjøsæter, H., Prozorkevich, D., Shamray, E., Dolgov, A., Skern-Mauritzen, M., Stiansen, J.E., Kovalev, Yu, Sunnanå, K., 2018. From single species surveys towards monitoring of the Barents Sea ecosystem. Prog. Oceanogr. 166, 4–14. https://doi.org/10.1016/j.pocean.2017.09.007.

Ermolchev, V.A., Zaferman, M.L., 2003. Results of experiments on the video-acoustic estimation of fish target strength in situ. ICES J. Mar. Sci. 60 (3), 544–547. https://doi.org/10.1016/S1054-3139(03)00049-3.

Fernandes, P.G., Copland, P., Garcia, R., Nicosevici, T., Scoulding, B., 2016. Additional evidence for fisheries acoustics: Small cameras and angling gear provide tilt angle distributions and other relevant data for mackerel surveys. ICES J. Mar. Sci. 73 (8), 2009–2019. https://doi.org/10.1093/icesjms/fsw091.

Fonteneau, A., Chassot, E., Bodin, N., 2013. Global spatio-temporal patterns in tropical tuna purse seine fisheries on drifting fish aggregating devices (DFADs): Taking a historical perspective to inform current challenges. Aquat. Living Resour. 26 (1), 37–48. https://doi.org/10.1051/alr/2013046.

Foote, K.G., 1979. Fish target-strength-to-length regressions for application in fisheries research. Proc. Ultrason. Int. 19Graz, Austria 327–333.

Foote, K.G., 1980. Importance of the swimbladder in acoustic scattering by fish: A comparison of gadoid and mackerel target strengths. J. Acoust. Soc. Am. 67 (6), 2084–2089. https://doi.org/10.1121/1.384452.

Foote, K.G., 1987. Fish target strengths for use in echo integrator surveys. J. Acoust. Soc. Am. 82 (3), 981–987. https://doi.org/10.1121/1.395298.

Foote, K.G., Francis, D.T.I., 2002. Comparing Kirchhoff-approximation and boundary-element models for computing gadoid target strengths. J. Acoust. Soc. Am. 111 (4), 1644–1654. https://doi.org/10.1121/1.1458939.

Foote, K.G., Aglen, A., Nakken, O., 1986. Measurement of fish target strength with a split-beam echo sounder. J. Acoust. Soc. Am. 80 (2), 612–621. https://doi.org/10.1121/1.394056.

Gastauer, S., Scoulding, B., Parsons, M., 2017. Estimates of variability of goldband snapper target strength and biomass in three fishing regions within the Northern Demersal Scalefish Fishery (Western Australia). Fish. Res. 193, 250–262. https://doi.org/10.1016/j.fishres.2017.05.001.

Gauthier, S., Horne, J.K., 2004. Acoustic characteristics of forage fish species in the Gulf of Alaska and Bering Sea based on Kirchhoff-approximation models. Can. J. Fish. Aquat. Sci. https://doi.org/10.1139/f04-117.

Gauthier, S., Rose, G.A., 2001. Target strength of encaged atlantic redfish (Sebastes spp.). ICES J. Mar. Sci. 58 (3), 562–568. https://doi.org/10.1006/jmsc.2001.1066.

Gurshin, C.W.D., 2012. Target strength measurements of juvenile blueback herring from the Mohawk River, New York. North Am. J. Fish. Manag. 32 (2), 381–386. https://doi.org/10.1080/02755947.2012.678562.

Hansen, F.T., Burns, F., Post, S., Thygesen, U.H., Jansen, T., 2018. Length measurement methods of Atlantic mackerel (Scomber scombrus) and Atlantic horse mackerel (Trachurus trachurus) – current practice, conversion keys and recommendations. Fish. Res. 205, 57–64. https://doi.org/10.1016/j.fishres.2018.04.002.

Hasegawa, K., Yan, N., Mukai, T., 2021. In situ broadband acoustic measurements of age-0 walleye pollock and pointhead flounder in Funka Bay, Hokkaido, Japan. J. Mar. Sci. Technol. 29 (2) https://doi.org/10.51400/2709-6998.1076.

He, P., Wardle, C.S., 1986. Tilting behaviour of the Atlantic mackerel, Scomber scombrus, at low swimming speeds. J. Fish. Biol. 29 (sA), 223–232. https://doi.org/10.1111/j.1095-8649.1986.tb05013.x.

Horne, J.K., Jech, J.M., 1999. Multi-frequency estimates of fish abundance: Constraints of rather high frequencies. ICES J. Mar. Sci. 56 (2), 184–199. https://doi.org/10.1006/jmsc.1998.0432.

Huse, I., Ona, E., 1996. Tilt angle distribution and swimming speed of overwintering Norwegian spring spawning herring. ICES J. Mar. Sci. 53 (5), 863–873. https://doi.org/10.1006/jmsc.1996.9999.

ICES. (2014). Report of the ICES Advisory Committee 2014 (6 North Sea; p. 414). ⟨http://www.ices.dk/sites/pub/Publication%20Reports/ICES%20Advice/2014/Book%206%20-%20Greater%20North%20Sea.pdf⟩.

Jaya, I., Aulya, R., Fauziyah, 2019. Measurement and analysis of TS-Frequency relationship on mackerel tuna (*Euthynnus affinis*) using bandwidth frequency. J. Phys.: Conf. Ser. 1282, 012096 https://doi.org/10.1088/1742-6596/1282/1/012096.

Kogovšek, T., Vodopivec, M., Raicich, F., Uye, S., Malej, A., 2018. Comparative analysis of the ecosystems in the northern Adriatic Sea and the Inland Sea of Japan: Can anthropogenic pressures disclose jellyfish outbreaks? Sci. Total Environ. 626, 982–994. https://doi.org/10.1016/j.scitotenv.2018.01.011.

Kubilius, R., Ona, E., 2012. Target strength and tilt-angle distribution of the lesser sandeel (Ammodytes marinus). ICES J. Mar. Sci. 69 (6), 1099–1107. https://doi.org/10.1093/icesjms/fss093.

Kubilius, R., Macaulay, G.J., Ona, E., 2020. Remote sizing of fish-like targets using broadband acoustics. Fish. Res. 228, 105568 https://doi.org/10.1016/j.fishres.2020.105568.

Lavery, A.C., Bassett, C., Lawson, G.L., Jech, J.M., 2017. Exploiting signal processing approaches for broadband echosounders. ICES J. Mar. Sci. 74 (8), 2262–2275. https://doi.org/10.1093/icesjms/fsx155.

Lavia, E.F., González, J.D., Menna, B.V., Prario, I., Cascallares, G., Cabreira, A.G., Madirolas, A., & Blanc, S. (2020). Numerical modelling of broadband acoustic signatures for two Argentinian swimbladdered fish species. 2020 IEEE Congreso Bienal de Argentina (ARGENCON), 1–7. https://doi.org/10.1109/ARGENCON49523.2020.9505349.

Lee, D.-J., 2015. Changes in the orientation and frequency dependence of target strength due to morphological differences in the fish swim bladder. Korean J. Fish. Aquat. Sci. 48 (2), 233–243. https://doi.org/10.5657/KFAS.2015.0233.

Levine, R.M., De Robertis, A., Grünbaum, D., Woodgate, R., Mordy, C.W., Mueter, F., Cokelet, E., Lawrence-Slavas, N., Tabisola, H., 2021. Autonomous vehicle surveys indicate that flow reversals retain juvenile fishes in a highly advective high-latitude ecosystem. Limnol. Oceanogr. 66 (4), 1139–1154. https://doi.org/10.1002/lno.11671.

Linløkken, A.N., Næstad, F., Langdal, K., Østbye, K., 2019. Comparing fish density and echo strength distribution recorded by two generations of single beam echo sounders. Appl. Sci. 9 (10), 2041. https://doi.org/10.3390/app9102041.

Macaulay, G.J., Peña, H., Fässler, S.M.M., Pedersen, G., Ona, E., 2013. Accuracy of the Kirchhoff-approximation and Kirchhoff-ray-mode fish swimbladder acoustic scattering models. PLoS One 8 (5), e64055. https://doi.org/10.1371/journal.pone.0064055.

MacLennan, D.N., Menz, A., 1996. Interpretation of in situ target-strength data. ICES J. Mar. Sci. 53 (2), 233–236. https://doi.org/10.1006/jmsc.1996.0027.

Malin, M.I., Zhdanova, S.M., Kosolapov, D.B., Malina, I.P., Kosolapova, N.G., Sabitova, R. Z., Krylov, V., 2021. Unusual vertical distribution of zooplankton and fish in the pelagic zone of Lake Sevan during summer stratification. Ecosyst. Transform. 4 (3), 27–41. https://doi.org/10.23859/estr-210312.

Manik, H.M. (2015). Measurement and numerical model of fish target strength for quantitative echo sounder. 8(5), 9.

McClatchie, S., Alsop, J., Coombs, R.F., 1996. A re-evaluation of relationships between fish size, acoustic frequency, and target strength. ICES J. Mar. Sci. 53 (5), 780–791. https://doi.org/10.1006/jmsc.1996.0099.

McClatchie, S., Thorne, R.E., Grimes, P., Hanchet, S., 2000. Ground truth and target identification for fisheries acoustics. Fish. Res. 47 (2), 173–191. https://doi.org/10.1016/S0165-7836(00)00168-5.

McQuinn, I.H., Winger, P.D., 2003. Tilt angle and target strength: target tracking of Atlantic cod (Gadus morhua) during trawling. ICES J. Mar. Sci. 60 (3), 575–583. https://doi.org/10.1016/S1054-3139(03)000390.

Melvin, G.D., 2016. Observations of in situ Atlantic bluefin tuna (Thunnus thynnus) with 500-kHz multibeam sonar. ICES J. Mar. Sci. 73 (8), 1975–1986. https://doi.org/10.1093/icesjms/fsw077.

Mills, C.E., 2001. Jellyfish blooms: are populations increasing globally in response to changing ocean conditions? Hydrobiologia 451 (1), 55–68. https://doi.org/10.1023/A:1011888006302.

Moreno, G., Boyra, G., Sancristobal, I., Itano, D., Restrepo, V., 2019. Towards acoustic discrimination of tropical tuna associated with fish aggregating devices. PLoS One 14 (6), e0216353. https://doi.org/10.1371/journal.pone.0216353.

Mukai, T., Iida, K., 1996. Depth dependence of target strength of live kokanee salmon in accordance with Boyle's law. ICES J. Mar. Sci. 53 (2), 245–248. https://doi.org/10.1006/jmsc.1996.0029.

Nakken, O., & Olsen, K. (1977). Target strength measurements of fish. 52–69. ⟨https://imr.brage.unit.no/imr-xmlui/handle/11250/107967⟩.

O'Driscoll, R.L., de Joux, P., Nelson, R., Macaulay, G.J., Dunford, A.J., Marriott, P.M., Stewart, C., Miller, B.S., 2012. Species identification in seamount fish aggregations using moored underwater video. ICES J. Mar. Sci. 69 (4), 648–659. https://doi.org/10.1093/icesjms/fss010.

Olsen, K. (1971). Orientation measurements of cod in Lofoten obtained from underwater photographs and their relation to target strength. 8.

Ona, E. (1990). Physiological factors causing natural variations in acoustic target strength of fish. 21.

Ormseth, O.A. (2019). Status of forage species in the Bering Sea and Aleutian Islands region. 46.

Puckeridge, A., Becker, A., Taylor, M., Lowry, M., McLeod, J., Schilling, H., Suthers, I., 2021. Foraging behaviour and movements of an ambush predator reveal

benthopelagic coupling on artificial reefs. Mar. Ecol. Prog. Ser. 666, 171–182. https://doi.org/10.3354/meps13691.
Purcell, J.E., Brown, E.D., Stokesbury, K.D.E., Haldorson, L.H., Shirley, T.C., 2000. Aggregations of the jellyfish Aurelia labiata: Abundance, distribution, association with age-0 walleye pollock, and behaviors promoting aggregation in Prince William Sound, Alaska, USA. Mar. Ecol. Prog. Ser. 195, 145–158. https://doi.org/10.3354/meps195145.
R Core Team. (2020). R: A language and environment for statistical computing. R Foundation for Statistical Computing; Vienna, Austria. ⟨https://www.R-project.org/⟩.
Renfree, J.S., Sessions, T.S., Murfin, D., Palance, D.G., & Demer, D.A. (2019). Calibrations of Wide-Bandwidth Transceivers (WBT Mini) with Dualfrequency Transducers (ES38–18/200–18C) for Saildrong Surveys of the California Current Ecosystem During Summer 2018. Department of Commerce, NOAA Technical Memorandum NMFS-SWFSC-608. https://doi.org/10.25923/W57K-7G54.
Roberts, J., Hanchet, S.M., & Fisheries New Zealand (Government agency). (2019). Southern blue whiting (Micromesistius australis) stock assessment for the Campbell Island Rise for 2017. Fisheries New Zealand (Government agency). ⟨https://fs.fish.govt.nz/Doc/24742/FAR-2019–44-SBW-Stock-Assessment-Campbell-Island-Rise.pdf.ashx⟩.
Rose, G., Porter, D.R., 1996. Target-strength studies on Atlantic cod (Gadus morhua) in Newfoundland waters. ICES J. Mar. Sci. 53 (2), 259–265. https://doi.org/10.1006/jmsc.1996.0032.
Rudstam, L.G., Parker, S.L., Einhouse, D.W., Witzel, L.D., Warner, D.M., Stritzel, J.L., Parrish, D.L., Sullivan, P.J., 2003. Application of in situ target-strength estimations in lakes: examples from rainbow-smelt surveys in Lakes Erie and Champlain. ICES J. Mar. Sci. 60 (3), 500–507. https://doi.org/10.1016/S1054-3139(03)00046-8.
Safruddin, Kawauchi, Y., Ito, Y., Minami, K., Itaya, K., Maeda, K., Matsukura, R., Abe, K., Yasuma, H., & Miyashita, K. (2013). Tilt Angle and Theoretical Target Strength of the Japanese Sandeel, Ammodytes personatus, Captured on the Northern Coast of Hokkaido. 海洋音響学会誌, *40*(4), 329–338. https://doi.org/10.3135/jmasj.40.329.
Sawada, K., Takahashi, H., Abe, K., Ichii, T., Watanabe, K., Takao, Y., 2009. Target-strength, length, and tilt-angle measurements of Pacific saury (Cololabis saira) and Japanese anchovy (Engraulis japonicus) using an acoustic-optical system. ICES J. Mar. Sci. 66 (6), 1212–1218. https://doi.org/10.1093/icesjms/fsp079.
Scherbino, M., & Truskanov, M.D. (1966). Determination of fish concentration by means of acoustic apparatus. ICES CM 1966/F:3, 6 Pp.
Scoulding, B., Kloser, R., 2021. Industry-collected target strength of high seas orange roughy in the Indian Ocean. ICES J. Mar. Sci. 78 (6), 2120–2131. https://doi.org/10.1093/icesjms/fsaa101.
Scoulding, B., Gastauer, S., MacLennan, D.N., Fässler, S.M.M., Copland, P., Fernandes, P. G., 2017. Effects of variable mean target strength on estimates of abundance: the case of Atlantic mackerel (Scomber scombrus). ICES J. Mar. Sci. 74 (3), 822–831. https://doi.org/10.1093/icesjms/fsw212.
Scoulding, B., Kloser, R., Gastauer, S., 2020. Evaluation of unmanned surface vehicle acoustics for gas seep detection in shallow coastal waters. Int. J. Greenh. Gas Control 102, 103158. https://doi.org/10.1016/j.ijggc.2020.103158.
Simmonds, E.J., MacLennan, D.N., 2005. Fisheries Acoustics: Theory and Practice, second ed. Blackwell Science.
Stanton, T.K., Chu, D., 2008. Calibration of broadband active acoustic systems using a single standard spherical target. J. Acoust. Soc. Am. 124 (1), 10.
Tschersich, P. (2018). Hydroacoustic survey of black rockfish abundance and distribution operational plan for the Kodiak Management Area, 2017–2019. Alaska Department of Fish and Game, Division of Commercial Fisheries.
Tschersich, P., & Gaeuman, W. (2019). Hydroacoustic survey of black rockfish abundance and distribution operational plan for the Kodiak Management Area, 2020–2022. Alaska Department of Fish and Game, Division of Commercial Fisheries.
Villalobos, H., Zwolinski, J.P., Godínez-Pérez, C.A., González-Máynez, V.E., Manini-Ramos, F., Mayorga-Martínez, M., Michaels, W.L., Palacios-Higuera, M.S., Rubio-Rodríguez, U., Sarmiento-Lezcano, A.N., Demer, D.A., 2021. A practical approach to monitoring marine protected areas: an application to El Bajo Espíritu Santo Seamount Near La Paz, Mexico. Oceanography 34 (3), 32–43.
Warren, J.D.W.D., Demer, D.A.D.A., 2010. Abundance and distribution of Antarctic krill (Euphausia superba) nearshore of Cape Shirreff, Livingston Island, Antarctica, during six austral summers between 2000 and 2007. Can. J. Fish. Aquat. Sci. https://doi.org/10.1139/F10-042.
Zeng, L., Tang, Z., Chen, P., Hou, C., Chen, G., 2018. Bioacoustic application on fisheries management in an artificial reefs' ecological reserve of Bohai Gulf China. Environ. Earth Sci. 77 (21), 728. https://doi.org/10.1007/s12665-018-7912-6.
Zhang, J., Zhang, K., Chen, Z., Dong, J., Qiu, Y., 2021. Hydroacoustic studies on Katsuwonus pelamis and juvenile Thunnus albacares associated with light fish-aggregating devices in the South China Sea. Fish. Res. 233, 105765 https://doi.org/10.1016/j.fishres.2020.105765.