Identification and target strength of orange roughy (*Hoplostethus atlanticus*) measured *in situ*

Rudy J. Kloser[a)]
Wealth from Oceans Flagship, Marine and Atmospheric Research, Commonwealth Scientific and Industrial Research Organisation, GPO Box 1538, Hobart, Tasmania 7001, Australia

Gavin J. Macaulay
Institute of Marine Research, P.O. Box 1870, Nordnes, 5817 Bergen, Norway

Tim E. Ryan and Mark Lewis
Wealth from Oceans Flagship, Marine and Atmospheric Research, Commonwealth Scientific and Industrial Research Organisation, GPO Box 1538, Hobart, Tasmania 7001, Australia

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It is often assumed that *in situ* target strength (TS) measurements from dispersed fish are representative of the surveyed schooling fish. For *in situ* TS measurements of orange roughy in deep water, it has been difficult to validate the target species, individual lengths, and tilt angles and how representative these are of schooling fish. These problems have been addressed by attaching an acoustic optical system (AOS) to a trawl net. The AOS enables *in situ* measurements of TS and volume backscattering strength (*Sv*) at 38 and 120 kHz with optical verification of species and stereo camera measurements of fish length and tilt angle. TS estimates believed representative of the schooling population were derived by (1) weighting the frequency-dependent TS values by the *Sv* frequency difference distribution of orange roughy schools and (2) weighting the *in situ* TS measurements with an assumed tilt angle distribution. The 120-kHz TS estimates were less sensitive to variations in frequency difference and tilt angle, suggesting that this frequency may be better for biomass estimates than 38 kHz, the traditional survey frequency. Computations performed with an anatomically detailed scattering model agree with measurements of TS at both frequencies over a range of tilt angles.
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I. INTRODUCTION

Accurate estimates of biomass are needed to manage fish resources sustainably, and the acoustic echo integration method can be used to provide these estimates (Simmonds and MacLennan, 2005). In the case of the deep-water fish, orange roughy (*Hoplostethus atlanticus*), acoustic estimates at 38 kHz have been used to monitor stock status (Do and Coombs, 1989; Kloser *et al.*, 1996). In Australian waters, orange roughy were listed as conservation dependent in October 2006 (i.e., parts of the fishery were closed) as the biomass was reported to be well below the limit reference point set for the fishery (Tuck, 2007). A monitoring program was initiated to determine if the fish were recovering at the major spawning site at St Helens seamount and at what rate.

Orange roughy form large aggregations (with other species also present) around this seamount in July each year with peak spawning estimated to occur in mid July (Kloser *et al.*, 1996). The ability of the monitoring method to detect change requires biomass estimates of high precision and accuracy with uncertainty less than the expected stock recovery rate, which is very low (Tuck, 2007). A major challenge in applying the acoustic echo integration method to estimate orange roughy biomass is to accurately determine the proportion of orange roughy in multi-species aggregations and then to use appropriate target strength (TS) values for orange roughy and other acoustically significant species.

Orange roughy have a wax ester swim bladder and a very much lower TS at 38 kHz than other associated fish species (Kloser *et al.*, 1997). This makes echo-integration estimates sensitive to the presence of relatively low proportions of fish with higher target strengths (McClatchie and Coombs, 2005). It is possible to discriminate the dominant acoustic groups at depth by using multiple frequencies and hence reducing errors in species classification of backscatter (Kloser *et al.*, 2002). Multiple frequency methods of species identification are often supported both empirically (e.g., trawling) and by using species-specific scattering models (Korneliussen and Ona, 2002). For example, both empirical (trawl catch) and scattering model validation has been successfully applied to Antarctic krill (Madureira *et al.*, 1993; Demer, 2004).

Most modeling of orange roughy backscatter has been based on simple outlines of the body and the wax-ester-filled swim bladder using the Kirchhoff approximation (Phleger and Grigor, 1990; McClatchie and Ye, 2000; Barr, 2001; Kloser and Horne, 2003). These modeling methods have been unable to predict the differences in backscatter that have been observed empirically between the frequencies of

[a)]Author to whom correspondence should be addressed. Electronic mail: rudy.kloser@csiro.au

38 and 120 kHz (Kloser and Horne, 2003). A different approach is to use an anatomically detailed scattering model based on the solution of the wave equation in a heterogeneous fish using the finite element or finite difference methods with detailed anatomy of the fish being derived from an imaging system such as *x*-ray computed tomography (CT) or magnetic resonance imaging (MRI) (Macaulay, 2002; O'Driscoll *et al.*, 2011). Even with a detailed model of orange roughy at several frequencies, some assumptions or measurements about the behavior of the fish in schools are required to derive a tilt-averaged target strength (Foote, 1980). It may be possible to derive a tilt angle and hence target strength by matching modeled scattering at several frequencies to the scattering differences from schools (Demer and Conti, 2005), but an inherent problem with this method is the reliance on the model being representative of the population.

An alternative, complementary, and perhaps preferred method is to measure the TS of the species *in situ*. For orange roughy, this requires an acoustic instrument to be lowered close to the targets so as to resolve single fish within the pulse resolution volume (Soule *et al.*, 1995; Kloser *et al.*, 1997). This typically requires that fish be at low densities or on the periphery of schools. These fish, however, may not be representative of the population in terms of the species and their acoustically relevant characteristics such as school sex ratio, maturity stage, lipid content, length, weight, and tilt angle.

To help ensure that *in situ* measurements are of the desired species, both frequency difference and acoustic-phase methods have been used (Kloser and Horne, 2003; Coombs and Barr, 2007). Estimates from these two methods differ by 3.6 dB, which could be due to uncertainties in the species ensonified (Macaulay *et al.*, 2013) and, hence, how representative the measurements are of the population; this limits the use of acoustic surveys for absolute estimates of biomass and estimates of the rate of recovery for overfished stocks. Optical verification of the ensonified species would be a major advance for estimation of *in situ* target strength, but unfortunately orange roughy have shown a marked avoidance reaction to conventional lowered or towed gears (Koslow *et al.*, 1995). Better success has been achieved by mounting an acoustic optical system (AOS) on the head line of a trawl net and using the herding effect of the trawl to place orange roughy within the measurement volumes of the acoustic and optical sensors (Ryan *et al.*, 2009). The addition of calibrated stereo cameras to this AOS now allows for the measurement of fish length and orientation, giving a highly useful set of measurements (species, tilt angle, size, TS) (Kloser *et al.*, 2011). Such measurements, however, are from herded fish in an unnatural state and may not represent the tilt angle distribution and behavior of schooling fish (Kloser *et al.*, 2011). In contrast, the frequency response of an aggregation can be measured from large ranges without any apparent effect on behavior; it is therefore feasible to use this information to explore the frequency difference of single fish and how representative they are of the schooling population.

To investigate how representative our net-attached *in situ* target strength measurements are of the surveyed population, we present several ways of interpreting the optically measured fish with associated *in situ* TS data. These results are compared to an anatomically detailed scattering model and previously published results.

II. METHODS

Acoustic, optical, and biological measurements were obtained in July 2010 from a winter spawning site of orange roughy (St Helens Hill) off the east coast of Tasmania (Kloser *et al.*, 1996). St Helens Hill (41°14.0′S 148°45.5′E) is a conical seamount that rises from ~1100 to 600 m depth. A 34 m fishing vessel, *Saxon Onwards*, was used to deploy a modified Acoustic Optical System (AOS) attached to the headline of a standard orange roughy demersal trawl (Fig. 1) (Ryan *et al.*, 2009). The trawl had a headline length of 38.4 m and average height of 5 m. The wing and headline mesh size was 300 mm when stretched (150 mm bar length) grading down to 105 mm (52.5 mm bar length) in the cod end. The doors were 3.5 m^2 Super Vee doors weighing 750 kg each. The AOS was attached to the headline so that it was neutrally buoyant and trimmed to be horizontal when towed. The depth of the AOS in the water column and the height above the seabed were monitored with a Furuno CN24 net sounder mounted on the headline with data transmitted in real time to the ship via an acoustic link.

A. Acoustic optical system

Both school backscatter and *in situ* TS measurements were made using the net-attached AOS system. For these experiments, the AOS housed four Simrad EK60 echosounders of which only two were used in this analysis (38 and 120 kHz, connected to a Simrad 38 kHz ES38-DD 7° split-beam transducer and a Simrad 120 kHz ES120-7D 7° split-beam transducer) (Table I). The AOS also contained a Wildlife Computers MK9 depth-temperature logger, a

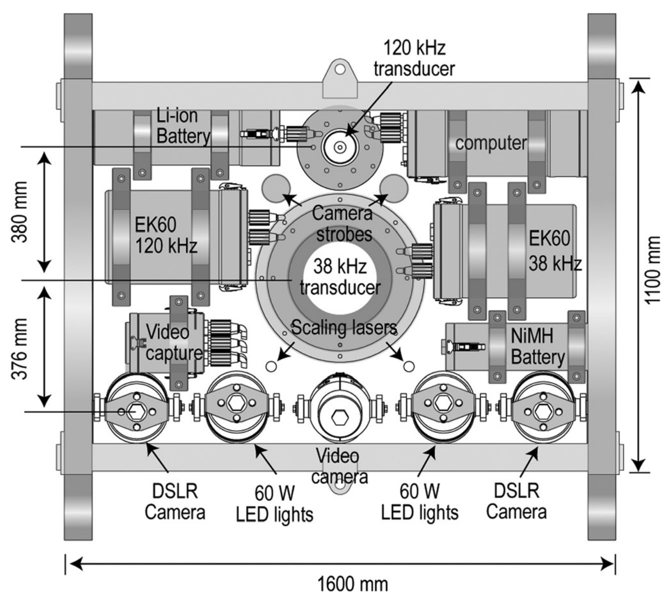

FIG. 1. Plan view of the acoustic optical system that was attached to the headline of the net. The main instruments are labeled. The distance in the along-track axis (upward direction in the figure) for the 120-kHz transducer and stereo cameras were 380 and −376 mm, respectively.

TABLE I. Echosounder parameters and settings and target strength analysis criteria.

Echosounder parameter	Value		Units
Frequency	38	120	kHz
Transducer model	Simrad ES38DD	Simrad ES120-7DD	
Transducer serial number	28332	27386	
Pulse length	0.512	0.256	ms
Power	2000	500	W
Bandwidth	3275	8710	kHz
Beamwidth -3 dB power	6.9/7.1 (along/athwart)	6.7/6.5	degrees
Nominal absorption	0.0099	0.0374	dB/m
Nominal sound speed	1493.9	1493.9	m/s
Angle sensitivity	21.9	21.0	
Single target detection criteria	**Value**		**Units**
TS threshold	−65	−65	dB
Pulse length determination level	6	6	dB
Min normalised pulse length	0.3	0.3	
Max. normalised pulse length	1.5	1.5	
Maximum beam compensation	12	12	dB
Maximum phase deviation minor axis	3	3	degrees
Maximum phase deviation major axis	3	3	degrees

MicroStrain 3DM-GX1 attitude sensor, and video and stereo optical sensors (see following text). The echosounders were calibrated at depth by lowering the AOS (when removed from the trawl net) down to 1000 m with a 38.1 mm tungsten carbide sphere (TS = −42.3 dB at 38 kHz and −40.0 dB at 120 kHz) suspended 11.6 m below the transducers to give a calibration that compensated for the variation in transducer performance with depth (Ryan *et al.*, 2009). This was done before and after the TS measurements. Sound speed and acoustic absorption were calculated using the MacKenzie (1981) and Francois and Garrison (1982) formulas, respectively, using data from the depth-temperature logger and salinity data from the WOCE 98 world ocean database. The transducer beam compensation was optimized to give a flat response over echo arrival angles of ±4° in both the alongship and athwartship axes. The echo integration calibration was derived when the sphere was on axis at each depth using the method of Foote *et al.* (1987).

The optical sensor system on the AOS was improved over that described in Kloser *et al.* (2011) by the addition of two Canon 500D digital SLR cameras. These were triggered when the 120 kHz acoustic system detected single target echoes with amplitudes greater than −60 dB and between 3 and 12 m range from the transducer. The trigger event initiated a sequence of four photographs at a rate of 3.4/s. Two Canon 580 EX II strobe units running at 1/8 power provided illumination. The timing of flash events (to millisecond resolution) was recorded using the same time source as the acoustic system, providing a means to synchronize the two data sets. Photographs were matched to the acoustic ping that was closest in time. The acoustic system ping rate was 9/s, giving a maximum error between acoustic and photo time synchronization of 55 ms or less.

The stereo camera system was calibrated from in-water images of a reference cube and fish metrics taken from field images made using the SEAGIS CAL and PHOTOMEASURE software packages respectively (Seager, 2008). Checks on the accuracy of measurements were obtained by measuring the separation of two slightly diverging lasers projected onto the seafloor during deployments. The PHOTOMEASURE estimates were typically within 3 mm of the laser separation (nominally 430 mm) for ranges of 3–12 m. User measures of the same fish (which included errors in estimating fish end points) were within 10 mm and 3° of the PHOTOMEASURE estimates for length and tilt angle, respectively.

B. School scattering measurements

Volume backscatter strength measurements (*Sv*, dB re 1 m^{-1}, MacLennan *et al.*, 2002) of orange roughy schools at 38 and 120 kHz were made by towing the net-attached AOS in north-south or south-north transects spaced 0.25 nautical miles apart above St Helens Hill. The height of the AOS above the seabed was maintained between 300 and 500 m with the distance being lowest at the summit and highest away from the summit. The acoustic data from the AOS was processed in ECHOVIEW 4.90 and corrected for the depth dependent calibration, acoustic absorption, and short duration acoustic impulse noise using an algorithm based on Anderson *et al.* (2005; Myriax, 2009). A composite echogram was obtained by combining the 38 and 120 kHz frequency data with orange roughy schools selected as described by Kloser *et al.* (2002) and verified with target trawling (Fig. 2). The mean *Sv* logarithmic frequency difference (*Sv* at 120 kHz subtracted from *Sv* at 38 kHz) for school j (ΔSv_j) and its standard deviation were calculated from the n values within the selected schools at 1 m cell height and per acoustic ping resolution using Eq. (1),

$$\overline{\Delta Sv_j} = \frac{\sum_{1}^{n}(Sv_{38_i} - Sv_{120i})}{n}, \tag{1}$$

where the numerical subscript to *Sv* indicates the acoustic frequency in kHz.

The confidence interval of the measurements was determined by bootstrapping the j school difference means, selected at random 2000 times, using the bias corrected and accelerated percentile method in the MATLAB Statistics toolbox v. 7.4.

C. *In situ* TS and biological measurements

The net-attached AOS was targeted on schools that were considered to be orange roughy. To minimize the catch (which can be large for orange roughy), the cod end of the net was left open unless biological specimens were required. The net was towed from the peak of the hill to a designated depth with the AOS at 5–15 m above the seabed. Standard length, weight, sex, and maturity stage were measured from 100 orange roughy in each catch and a representative sample of any bycatch. The acoustic TS data were analyzed in ECHOVIEW 4.90, after correcting for the depth-varying

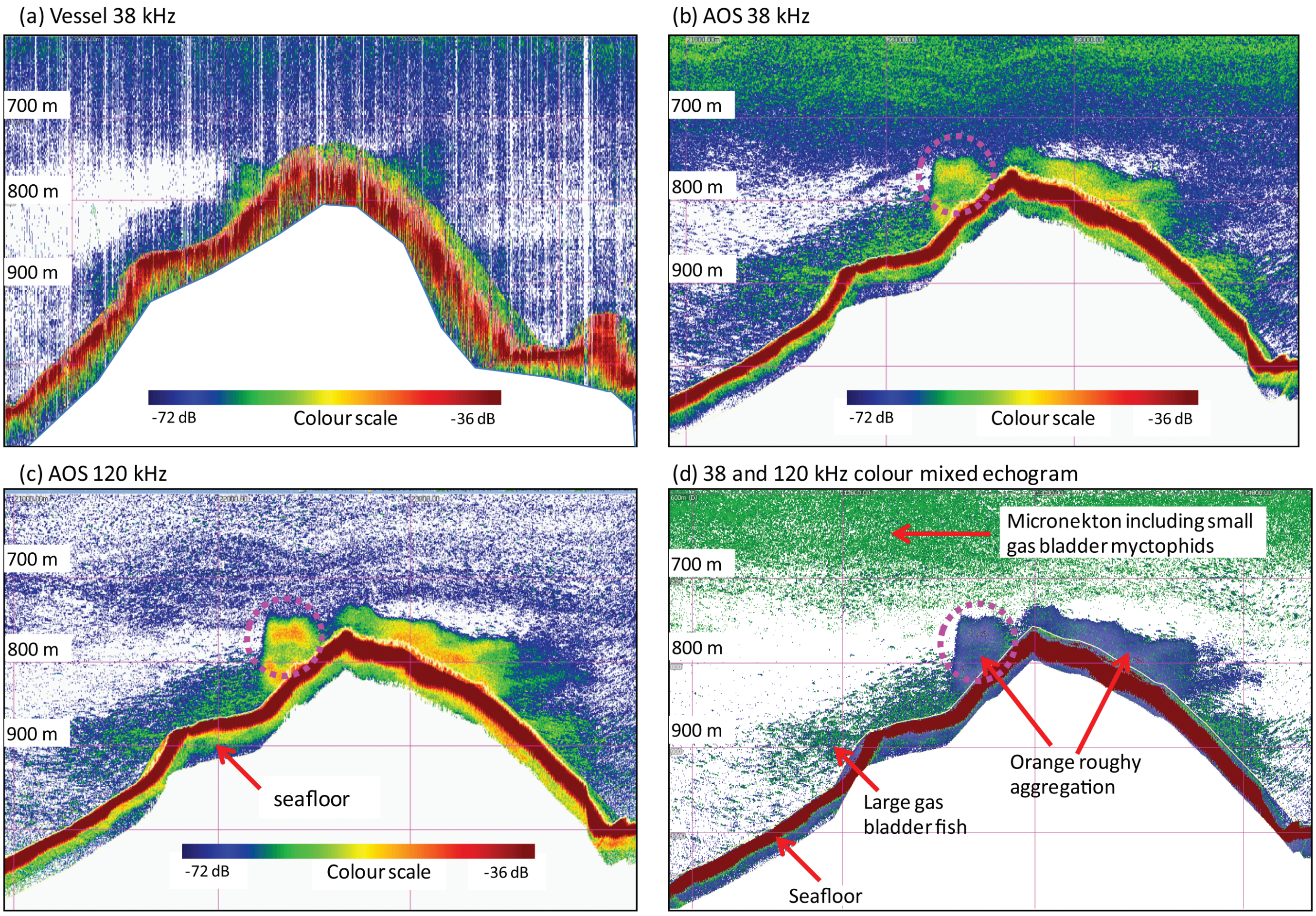

FIG. 2. Echogram of volume backscatter (Sv) from transects over St Helens Hill; (a) acoustic data at 38 kHz from the vessel-mounted acoustics in moderate weather conditions; the 38 kHz (b) and 120 kHz (c) echograms from the trawl mounted acoustic optical system towed at a nominal depth of 450 m; (d) the corresponding composite color mixed 38 and 120 kHz echogram with orange roughy schools indicated.

calibration. Target strengths of fish were derived from both the 38 and 120 kHz data using the single target selection criteria given in Table I. Tracked targets were derived from these single targets using ECHOVIEW's alpha-beta algorithm set to 0.7 and 0.5, respectively. Track acceptance required a minimum of three targets with a maximum gap within a track of one ping. Target strength threshold was set at −65 dB at 38 kHz to avoid spurious low value targets at the beginning and end of tracks due to an inferred noise limit. Tracked targets were merged by time, depth, and location in beam with optical measurements using the center of the 38 kHz transducer as the reference. The 120 kHz data were offset by −380 mm and the optical measurements by 376 mm in the along-track direction. No offset was required in the across-track direction as all instruments were aligned (Fig. 1). Species, range, length, tilt angle, and bearing were recorded from the stereo images of all fish and matched to tracked targets at 38 and 120 kHz for angles off axis of less than 4° and ranges between 3 and 12 m. For each tracked orange roughy, the mean of TS at 38 and 120 kHz and the logarithmic difference was calculated.

The minimum acceptance range of 3 m was estimated to be greater than the near field of the transducers and the targets. The transition regions from near to far field for the 38 and 120 kHz transducers are 2.2 m and 0.8 m, respectively (Clay and Medwin, 1977). The acoustic near-field of the scatter from a fish, such as an orange roughy, is not well understood (Dawson *et al.*, 2000; Gerlotto *et al.*, 2000; Moszynski and Hedgepeth, 2000), but an approximate estimate was obtained by calculating the near-field of an elliptical transducer with a size similar to the dorsal view of an orange roughy [viz., major axis set to the mean length of orange roughy and minor axis set to 20% of the mean length of the fish (McClatchie and Ye, 2000)]. The near-field of orange roughy was estimated to be 0.5 and 1.5 m at 38 and 120 kHz, respectively, using a mean length of 0.35 m and a sound speed of 1491 m s^{-1}.

D. *In situ* TS estimates

First, the mean TS at frequency, f, ($\overline{TS_f}$) of the tracked targets was assumed to be representative of the schooling population if their frequency difference was equal to the Sv frequency difference of the schooling population. The mean of the logarithmic frequency difference of orange roughy schools $\overline{\Delta Sv}$ and its Gaussian probability distribution $P(\Delta Sv_i)$ were used to weight the tracked single fish, TS_{f_i}, with a similar logarithmic frequency difference ($\Delta TS_i = TS_{38_i} - TS_{120_i}$). The mean TS was then derived by weighting the values around the mean logarithmic difference in Sv and the standard deviation of its Gaussian-distributed school logarithmic difference $P(\Delta Sv)$ via Eq. (2),

$$\overline{TS_f} = 10\log 10\left(\frac{\sum_{i=1}^{n} 10^{TS_{fi}/10} P(\Delta Sv_i)}{\sum_{i=1}^{n} P(\Delta Sv_i)}\right) \text{dB}. \quad (2)$$

Second, the mean TS was derived from the tracked targets assuming they are representative of the population in all respects excepting their tilt angle. To calculate the tilt angle averaged mean TS at frequency f, $\langle TS_f \rangle$, we follow Foote (1980) and McClatchie *et al.* (1999), simplified in this case as the tracked targets have the beam pattern function removed and the lengths are assumed to be representative of the population and not correlated with tilt angle. The TS from each tracked fish of measured tilt angle $TS_f(\theta_i)$ is weighted by the probability density function (P) of the tilt angle θ_i for varying pdf mean ($-30°$ to $0°$) and Gaussian distribution of 15° [Eq. (3)],

$$\langle TS_f \rangle = 10\log 10\left(\frac{\sum_i (10^{TS_f(\theta_i)/10} P(\theta_i))}{\sum_i P(\theta_i)}\right) \text{dB}. \quad (3)$$

E. FEM estimates

The reflection of acoustic waves from and through a fish and surrounding water was modeled using the time-harmonic inhomogeneous Helmholtz equation and solved using the finite element method (FEM) using the same technique and software as presented in O'Driscoll *et al.* (2011). The fish were represented as a volume of varying density and sound speed as obtained from computed tomography (CT) scans of fish. Note that this model does not simulate acoustic shear wave as one could expect to occur in some parts of a fish.

The accuracy of the FEM model was tested by simulating the backscattered target strength from a sphere of radius 10 mm immersed in water (density 1026.8 kg m^{-3} and sound speed 1477.3 m s^{-1}). Four sphere types were simulated: Rigid, pressure release, gas-filled (density 1.24 kg m^{-3} and sound speed 345 m s^{-1}), and fluid-filled (density 1028.9 kg m^{-3} and sound speed 1480.3 m s^{-1}). Simulations were conducted at frequencies of 12–120 kHz in 2 kHz steps and compared to theoretical solutions [rigid and pressure release spheres from equations 10.16 and 11.34, respectively, in Junger and Feit (1986); gas-filled and fluid-filled as per Anderson (1950)]. The model correctly simulated the scattering from spheres and the resonance of gas-filled spheres at certain frequencies and nulls for the fluid-filled sphere. Of particular note is that the model could accurately predict the very low backscatter from the fluid-filled sphere, the situation most similar to modeling the scatter from fish without gas-filled swim bladders.

F. Fish scan and analysis

CT scans were taken of two thawed orange roughy (OR2 and OR3; Table II) using a Siemens Sensation 16 CT scanner located at the Royal Hobart Hospital in Hobart, Australia. The fish were arranged in an expanded polystyrene foam box, separated by blocks of expanded polystyrene foam and the whole box scanned. A slice was taken every 2 mm with a thickness of 2 mm, with the fish scanned either head or tail first. Exposure was 0.75 s per slice, with a tube voltage of 120 kV and a current of 80 mA. The field of view was 177 mm for fish OR2 and 175 for fish OR3, giving a transverse and vertical image resolution of 0.346 and 0.341 mm, respectively (the 3rd dimension of the resolution volume was the slice thickness, 2 mm). A proprietary Siemens processing algorithm was used to produce the CT images from the raw *x*-ray data. The scanner produced one value for each resolution volume and these were converted to density using Eq. (4),

TABLE II. Details on the two fish that were CT scanned. Lengths are standard length.

Fish	Length (cm)	Sex	Stage	Weight (g)	Voxel size (mm)
OR2	33.4	F	Ovulated	1215	0.345,0.345,2.0
OR3	35.8	M	Fully spermiated	1429	0.342,0.342,2.0

$$\rho = (d - 1024) + 1000, \quad (4)$$

where ρ is the tissue density in kg m^{-3} and d the value from the scanner. No calibration samples were scanned, so the constants in the relationship are nominal values. The linear relationship between scanner output (Hounsfield Unit) and density is expected to be valid over a wide density range (Henson *et al.*, 1987). Sound speed was estimated using the density to sound speed relationship given by Aroyan (2001), where all points with a scanner value in the range 150–300 were given a constant sound speed of 1730 m s^{-1}, and all points above 300 were given a sound speed of 3450 m s^{-1} and taken to represent bone. In addition, all scanner output values less than -100 were taken to be air and the sound speed and density set to that of seawater. This scheme attempts to account for the effect of density blurring in the transition from bone to soft tissue, and soft-tissue to air, and also re-immerses the fish in seawater.

Several alterations were made to the CT scan data in an attempt to correct for differences between the living fish and their state during the CT scans (fish having been frozen and thawed). Changes were as follows: First, the CT scans from the two fish contained some voids in the fish flesh with a density similar to air. The mechanism for the formation of these voids is unknown and if left in the model, they would have generated strong acoustic reflections, degrading the accuracy of the simulations. To avoid this, each void was replaced with a material having the same density and sound speed as the surrounding fish tissue. Second, orange roughy have cavities in the skull that contain wax esters in life (Phleger and Grigor, 1990) but did not when the fish were scanned. Wax ester oil was reintroduced by identifying such cavities and replacing them with a CT scanner value for orange roughy oil of 1014, which converts to a density of 990 kg m^{-3} and a sound speed of 1522 m s^{-1}.

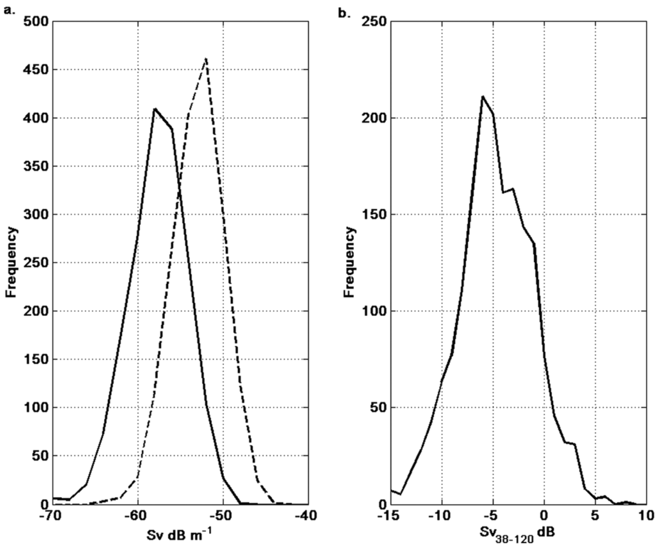

FIG. 3. (a) Distribution of volume backscatter, Sv (dB m^{-1}), for the region shown in Fig. 2 at 38 kHz (solid) and 120 kHz (dashed). (b) The distribution of the Sv difference, $\Delta Sv = Sv_{38} - Sv_{120}$.

Finally, areas of water were present in CT scan data, and these were replaced by a fluid with properties close to that of air (and consequently converted to seawater during the simulation).

For each fish, a simulation was carried out at pitch angles of $-40°$ to $+40°$ in steps of $2°$ at 38 and 120 kHz. The pitch angle of the incident acoustic wave was defined as $-90°$ for tail on, $0°$ for dorsal aspect, and $+90°$ for head on, the roll angle was always $0°$ for these simulations. Each model run produced the far-field backscattered pressure and an image of the scattered field immediately surrounding the fish for quality checking purposes. For all simulations, the sound speed and density of seawater in the model were set to 1491 m s^{-1} and 1032 kg m^{-3}, respectively, being representative of the waters that orange roughy inhabit.

The modeled TS was weighted with a range of tilt angle distributions [means ranging from $-15°$ to $+15°$ with a standard deviation of $15°$ (McClatchie *et al.*, 1996)] to yield a set of mean tilt-averaged TS estimates for each fish at 38 and 120 kHz. The logarithmic difference, $\Delta TS = TS_{38} - TS_{120}$, was also calculated for each incidence angle.

III. RESULTS

A. School scattering

Volume backscatter strength at 38 and 120 kHz from orange roughy schools was normally distributed and for a trawl-verified school gave a mean Sv_{38} of -57.5 dB, and logarithmic difference (ΔSv) of -4.7 dB as determined using 1 m cell sizes. This is similar to using the entire school backscatter for the logarithmic difference, indicating minimal bias due to cell size (Fig. 3). Based on the 17 observed schools, the mean Sv_{38} ranged from -56 to -68 dB, and the mean logarithmic difference ranged from -1 to -5.5 dB with associated standard deviation of 3.5–4.5 dB (Fig. 4). There was no significant correlation between the intensity of the school (mean Sv_{38}) and the logarithmic frequency difference (mean ΔSv), and there was no relationship with the mean pitch of the AOS over the school (which varied between $+2°$ and $-10°$) and ΔSv. The mean ΔSv of the 17 schools was -3.3 dB (SD of 3.9 dB) with bootstrapped confidence intervals for the mean of -2.8 to -3.9 dB.

B. Biological measurements

Ten trawls were targeted at schools and caught a total of 98 tonnes of orange roughy and small amounts (less than 1% by weight) of morids, whiptails, and sharks. The length distribution of orange roughy was unimodal with a mean length for males of 33.1 cm (SD = 2, $n = 355$) and for females 35.3 cm (SD = 2.4, $n = 704$). Mean orange roughy length varied between trawls (33.0–35.2 cm); this reflects the

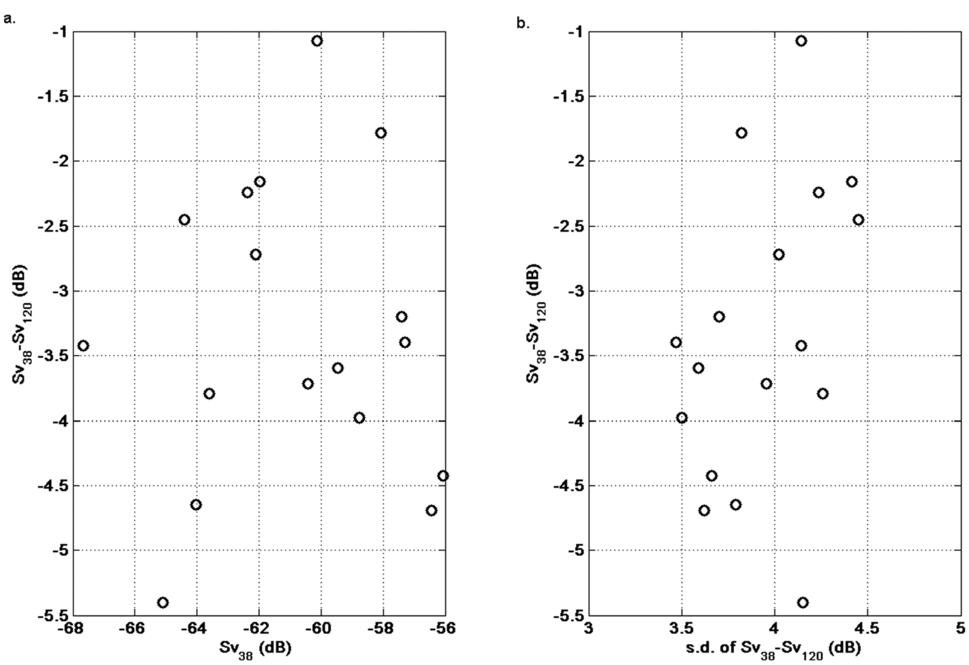

FIG. 4. Mean Sv difference, $\Delta Sv = Sv_{38} - Sv_{120}$, from the 17 schools; (a) mean Sv_{38} against ΔSv and (b) the standard deviation of ΔSv against mean ΔSv.

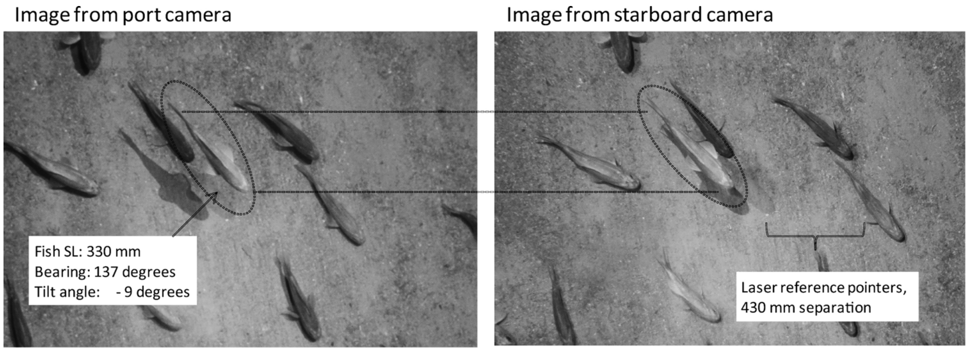

FIG. 5. An example of stereo optical images of an orange roughy with its associated length, bearing, and tilt angle as obtained from the photo measuring software.

variation in the ratio of males to females in the catch (0.32 to 7.25) with a mean ratio of 3.5 (SD = 3.1). The mean weight of individuals was 1.43 kg for females and 1.14 kg for males with a mean (over both sexes) weight per trawl of 1.32 kg.

C. Target strength

The net-attached AOS, towed over the depth range of 750 to 1000 m, collected 6022 single targets originating from 667 tracked fish, verified with 1074 stereo pair photographs (Fig. 5). Matching the acoustically tracked single targets from 3 to 12 m to fish within the stereo optical pairs produced 447 fish measures (from 123 tracked fish) of combined 38 and 120 kHz target strengths, species identification, length, range, and fishes tilt angle (Table III). The dominant species identified were orange roughy, *H. atlanticus* (110), the morid *Halargyreus johnsonii* (10), and the macrourid *Coryphaenoides subserrulatus* (3). *H. johnsonii* have a large gas bladder and associated high target strength that is lower at 120 kHz than 38 kHz. *C. subserrulatus* has a small gas bladder with a low target strength similar to orange roughy at 38 kHz and a pronounced (52.2°) head-down tilt angle for the three individuals measured. For the 110 visually verified orange roughy, representing 401 targets and used for the subsequent analyses, there was a negative correlation between TS_{38} and tilt angle and a positive correlation for TS_{120} [Table IV, Figs. 6(a) and 6(b)]. Hence, there was a negative correlation between the logarithmic difference ΔTS and tilt angle [Fig. 6(c)]. At 120 kHz, there was a positive correlation with length for the length range 26.5–46.5 cm, although the modal length distribution was narrow (mean = 35.9 cm; SD = 2.7 cm; Table III). The TS measurements were not significantly correlated with fish bearing, suggesting that there is minimal bias due to lateral tilt angle. Likewise there was no correlation between length and tilt angle. Target range was not significantly correlated with TS_{38} or TS_{120}, suggesting that there are no significant near-field effects with this data set [Fig. 6(d)]. For example there is less than a 0.1 dB change in the mean target strength at 38 and 120 kHz when selecting tracked fish from 3 m ($n = 110$) and 5 m ($n = 99$) range. The correlation of range and length suggest that larger fish were found at longer ranges, although the precision of fish length measurements decreases with range.

Predictions of mean orange roughy TS were calculated in two ways using Eqs. (2) and (3). First, predictions of $\overline{TS}_{38}$ and $\overline{TS}_{120}$ weighted by the school logarithmic difference, ΔSv with standard deviation of 3.9 dB were derived from the 110 tracked orange roughy measurements (Fig. 7). For a mean school logarithmic difference of −3.3 dB, the mean TS within the schools is −52.0 dB at 38 kHz and −48.7 dB at 120 kHz (Table V). Confidence intervals for TS based on the variation in school logarithmic difference were −52.5 to −51.5 dB at 38 kHz and −48.6 to −48.8 dB at 120 kHz. Second, predictions of mean orange roughy target strengths $\langle TS_{38}\rangle$ and $\langle TS_{120}\rangle$ were calculated by weighting the 110 tracked targets using a Gaussian tilt angle distribution with mean varying from −30° to 0° and SD of 15° (Fig. 8). For a mean tilt angle of 0° and SD of 15°, orange roughy target strength was −52.1 dB at 38 kHz and −48.8 dB at 120 kHz (Table V).

D. FEM predictions

The relative characteristic acoustic impedance throughout the two scanned orange roughy specimens was calculated from the density and sound speed derived from the CT scans, and provides insight into which parts of the fish are likely to scatter strongly (Fig. 9, shown as a transverse average). Regions where the impedance changes rapidly generate strong reflections, whereas areas with slow or small impedance change generate weak reflections. Regions of high reflection are the head and backbone, whereas regions of low reflection are the oil filled swim bladder and fish body. The complexity of the impedance changes highlights the need for

TABLE III. Summary of acoustic and optically measured fish that matched the search criteria within the acoustic and optical footprints, standard deviation in parentheses.

Number	Species	Mean TS_{38} (dB)		Mean TS_{120} (dB)		Standard length (cm)		Tilt (deg. head up positive)		Range (m)		Bearing (deg)	
110	*H. atlanticus* (Orange roughy)	−50.7	*(−2.9)*	−48.6	*(2.6)*	35.9	*(2.7)*	−16.3	*(11.1)*	6.9	*(1.4)*	228.7	*(104.3)*
10	*H. johnsoni* (Morid)	−35.3	*(5.1)*	−39	*(8)*	45.8	*(6.6)*	14.6	*(19.1)*	8.3	*(2.4)*	226.8	*(138.5)*
3	*C. subserrulatus* (Whiptail)	−52.7	(1.3)	−52.2	(1.8)	28.3	(1.4)	−52.2	(16)	5.6	(2.9)	151.1	(47.5)

TABLE IV. Correlations of variables with significant relationships in bold ($p \leq 0.05$). The bearing distribution failed the normality test.

	TS_{38}	TS_{120}	ΔTS	Tilt angle	Length	Bearing
TS_{120}	0.1					
Tilt angle	**−0.2**	**0.2**	**−0.3**			
Length	0.0	**0.3**	−0.2	0.0		
Bearing	0.1	0.0	0.0	0.0	−0.1	
Range	0.1	0.1	0.0	0.1	**0.3**	0.0

a detailed modeling approach. For the two scanned fish the TS distributions are very different with a strong angular dependence for the small female fish and minimal angular dependence for the larger male fish [Figs. 10(a) and 10(b)]. The model predicted 120 kHz TS values were usually greater than the 38 kHz values for all angles between −40° and 40° but does reverse at specific angles. When the model data are averaged over an assumed tilt angle distribution (mean = 0°, SD = 15°), the TS estimates for male fish OR2 are −55.0 and −50.2 dB and for female fish OR3 are −57.9 and −52.7 dB at 38 and 120 kHz, respectively [Fig. 10(c)]. Likewise $\langle \Delta TS \rangle$ for tilt distribution modes of −15° to +15° and standard deviation of 15° varies between −4.2 and −5.5 dB [Fig. 10(d)]. Of note is the agreement between the FEM predictions and *in situ* data where the logarithmic difference increases for head down tilt angles [Figs. 6(c) and 10(d)].

IV. DISCUSSION

Our stereo high-resolution optically verified *in situ* measurements provide an advance in the interpretation of orange roughy TS. Previous studies based on *ex situ* TS measurements have potential contamination due to bubbles or changes in material properties (McClatchie *et al.*, 1999), whereas *in situ* measurements without visual verification do not provide certainty about the species of the targets (Kloser and Horne, 2003; Coombs and Barr, 2007). Regardless of the source of previous *in situ* and *ex situ* measurements, they could be biased if they were not representative of the surveyed population, even if they have visual verification (Macaulay *et al.*, 2013). In this analysis, we match the frequency difference observed in schools to the *in situ* frequency difference at the time of an acoustic survey. In this way, we directly link the scattering response of schools to the scattering response of individual fish.

This method of deriving a target strength for use in survey analysis should be less subjective than previously applied methods that relied on inferred tilt angle or representative samples (McClatchie *et al.*, 1999; Kloser and Horne, 2003; Coombs and Barr, 2007). While it is not unusual to use frequency differences for species identification in acoustic surveys (Madureira *et al.*, 1993), the new aspect presented in this paper is a method of predicting the TS of a population based on their schooling *Sv* frequency difference. Using visually verified *in situ* target strengths with measured lengths and tilt angles, it has been possible to account for these two sources of potential bias. This application has been assisted by the observation that TS_{38} and TS_{120} have opposing positive and negative correlations with fish tilt angle and length. This means that the school logarithmic *Sv* frequency difference constrains the potential range of target strengths observed *in situ*.

It is not certain that the 110 optically and acoustically measured fish are fully representative of the tilt angle, length, sex, and stage of the schooling fish. The tilt angle of the measured fish was predominantly head down. The head down tilt angle of fish in orange roughy schools has also been estimated by moored video measurements to be approximately −5° with standard deviation 25° (Fig. 4, O'Driscoll *et al.*, 2012.); we therefore need more measurements of fish with positive tilt angles if moored video tilt angle measurements are representative of the population.

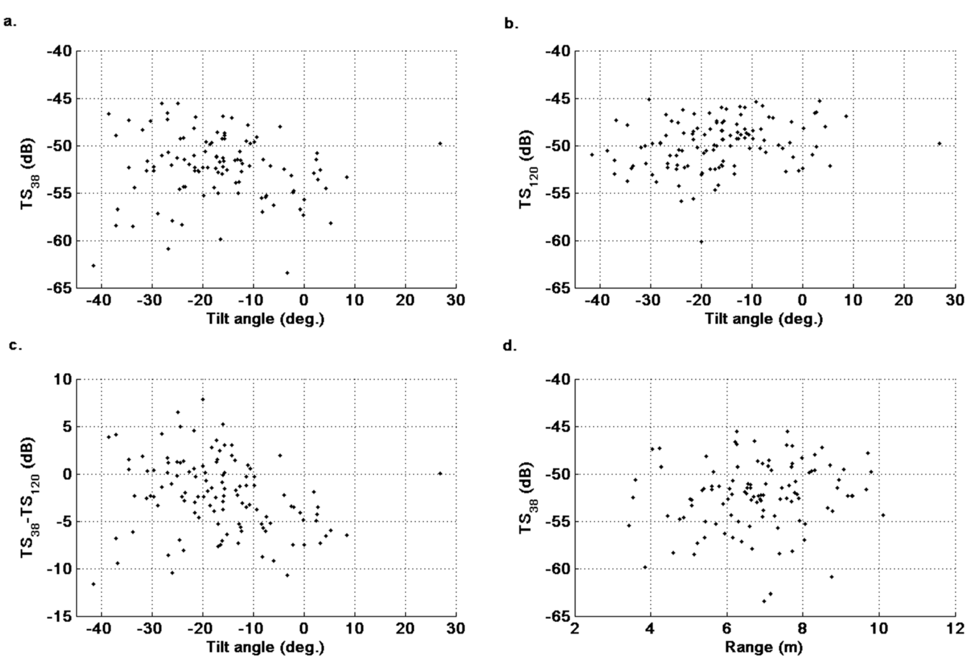

FIG. 6. Orange roughy tilt angle shown against mean tracked TS at 38 kHz (a), mean tracked TS at 120 kHz (b), and mean TS difference $\Delta TS = TS_{38} - TS_{120}$ (c). (d) The fish range against mean tracked *TS* at 38 kHz (see Table IV).

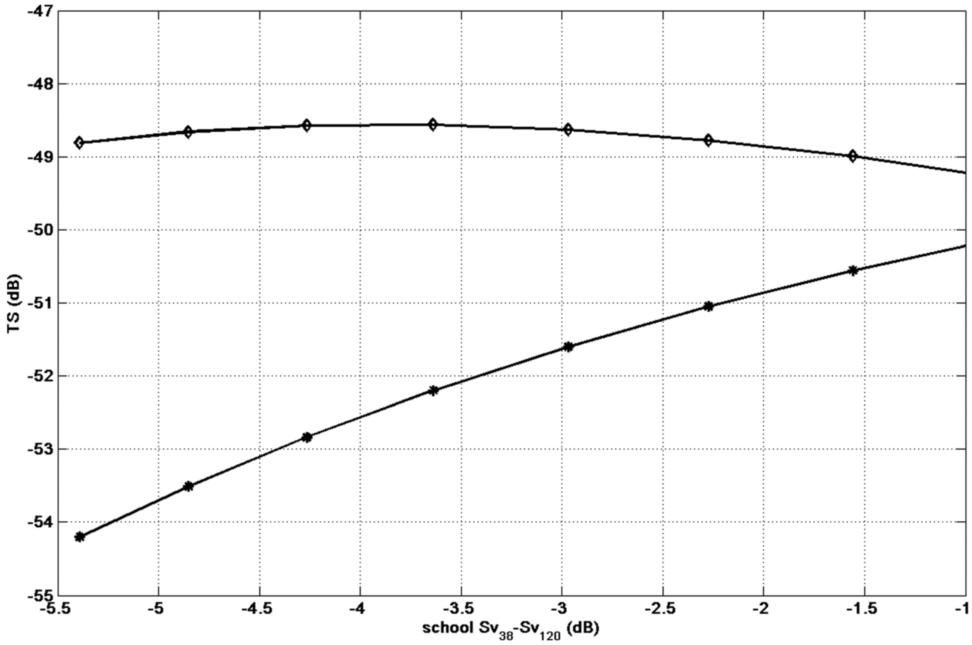

FIG. 7. Predictions of orange roughy TS at 38 kHz (asterisk) and 120 kHz (diamond) weighted by their frequency difference, $\Delta TS = TS_{38} - TS_{120}$, for a mean school Sv difference ($\Delta Sv = Sv_{38} - Sv_{120}$) of −5.5 to −1 dB and standard deviation of 3.9 dB.

Our tilt-angle-averaged target strength estimates were derived at a maximum tilt angle of 0° with SD of 15°, but extrapolation to larger tilt angles could be inferred using the trend in model TS data. Based on the two modeled fish, the responses were very different and more modeled fish would be required to establish a population trend in TS. In addition, we cannot derive the sex and stage of maturity from the optically measured fish—this is only possible using the retained catch. There is also some circularity in verifying this possibility with trawling. The retained catch from the trawl contains a mix of males and females of various lengths, but it is not certain if these are representative of the surveyed population. Orange roughy schools are large and extend 100 m into the water column while the trawling captures fish on or close to the seabed that have been herded by the trawl (Koslow *et al.*, 1995). However, we assume that our *in situ* and optical measurements and trawl data are comparable because the AOS measurements are taken at the headline of the trawl and it is likely that if a fish is observed on the AOS it will end up in the trawl. The attempt here is to weight our TS measurements by the Sv frequency difference observed from schooling fish. By doing this, we can better interpret acoustic data from the whole population. This is also done by weighting the TS measurements by an assumed population tilt-angle distribution as the tilt angle of fish measured at the net may not be representative of the schooling fish.

Complexity of scattering from orange roughy is demonstrated by the CT scans and FEM model. The two modeled fish gave quite different scattering behaviors but both had TS nulls (to −75 dB) at 38 kHz near horizontal to dorsal

TABLE V. Summary of methods used to weight the optically verified *in situ* orange roughy targets (bold preferred), FEM model and recently published *in situ* and *ex situ* target strength results at 38 and 120 kHz.

				Mean TS			Tilt Angle			
Method	**Species identification**	**Fish**	**Echos**	**38 kHz dB re 1m^2**	**120 kHz dB re 1m^2**	**ΔTS dB**	**Mean (deg.)**	**SD (deg.)**	**Mean length cm**	**Reference**
Net-attached *in situ*	Optical	110	401	−50.7	−48.6	−2.1	−16.3	11.1	35.9	this work
Net-attached *in situ* weighted to tilt angle pdf	Optical	110	401	−52.1	−48.8	−3.5	0.0	15.0	34.5	this work
Net-attached *in situ* weighted to frequency difference pdf	**Optical**	**110**	**401**	**−52.0**	**−48.7**	**−3.3**			**34.5**	**this work**
FEM model weighted to tilt angle pdf		2		−56.5	−51.5	−5.0	0.0	15.0	34.6	this work
Recently published results										
Net attached *in situ*	Optical	24	83	−52.0	−47.9	−4.1			33.9	Macaulay *et al.* (2013)
In situ	Phase		> 10 000	−49.3					35.0	Coombs and Barr (2007)
In situ	Frequency	13	201	−52.9		−2.5 to −7.5			34.9	Kloser and Horne (2003)
In situ	None	168	1604	−51.0					34.9	Kloser and Horne (2003)
Ex situ tethered/model		16		−48.3			−7.0	19.0	35.0	McClatchie *et al.* (1999)

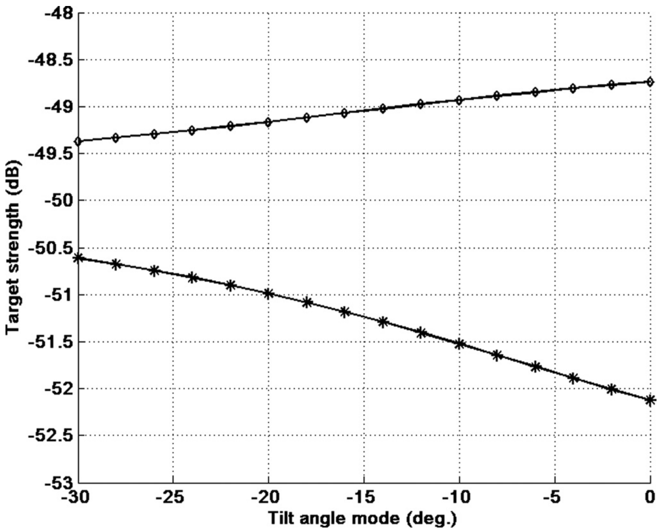

FIG. 8. Orange roughy target strength at 38 kHz (asterisk) and 120 kHz (diamonds) based on the *in situ* visually verified tracked targets, assuming a Gaussian tilt distribution with mean of −30° to 0° and standard deviation of 15°.

aspect. Nulls in orange roughy TS near horizontal dorsal aspect have been observed in our *in situ* data and in tank experiments on dead fish but only to −65 dB (McClatchie *et al.*, 1999). The stronger effect here may be due to a combined effect of transducer beam pattern and noise limits of experiments. Single targets were selected with a −65 dB threshold to avoid suspected spurious low values at the start and end of tracks. If a −75 dB threshold was used, the mean target strength was reduced by 0.5 dB. Our work questions the validity of previous models of orange roughy that have been based on scattering only from the fish shape and the oil filled swim bladder. The application of the Kirchhoff model by Kloser and Horne (2003) assumed the swim bladder was the dominant reflector within the body, but the CT scans show that the oil-filled swim bladder is not a dominant scattering region.

Our detailed FEM modeling work provides the first model-based support of the experimentally observed school *Sv* frequency difference. The mean expected TS based on the model is −56.5 dB at 38 kHz and a ΔTS of −5.0 dB. This is much lower than the mean estimated logarithmic difference but is consistent with some of our tracked fish and school logarithmic difference measurements. This contrasts with the KRM model predictions reported by Kloser and Horne (2003) for a 35 cm male and female orange roughy, where the logarithmic difference did not support the observed schooling logarithmic difference.

The general characteristics of the FEM model also support the new experimental data where the TS frequency difference increases for increasing head down tilt angles. Unfortunately it is also clear that given the large variation in scattering responses, more fish need to be modeled to gain further insights, and we recommend that a full range of fish lengths, sexes, and maturity stages be modeled in future studies. Other acoustic models of orange roughy have tried to predict the scattering response based on length and

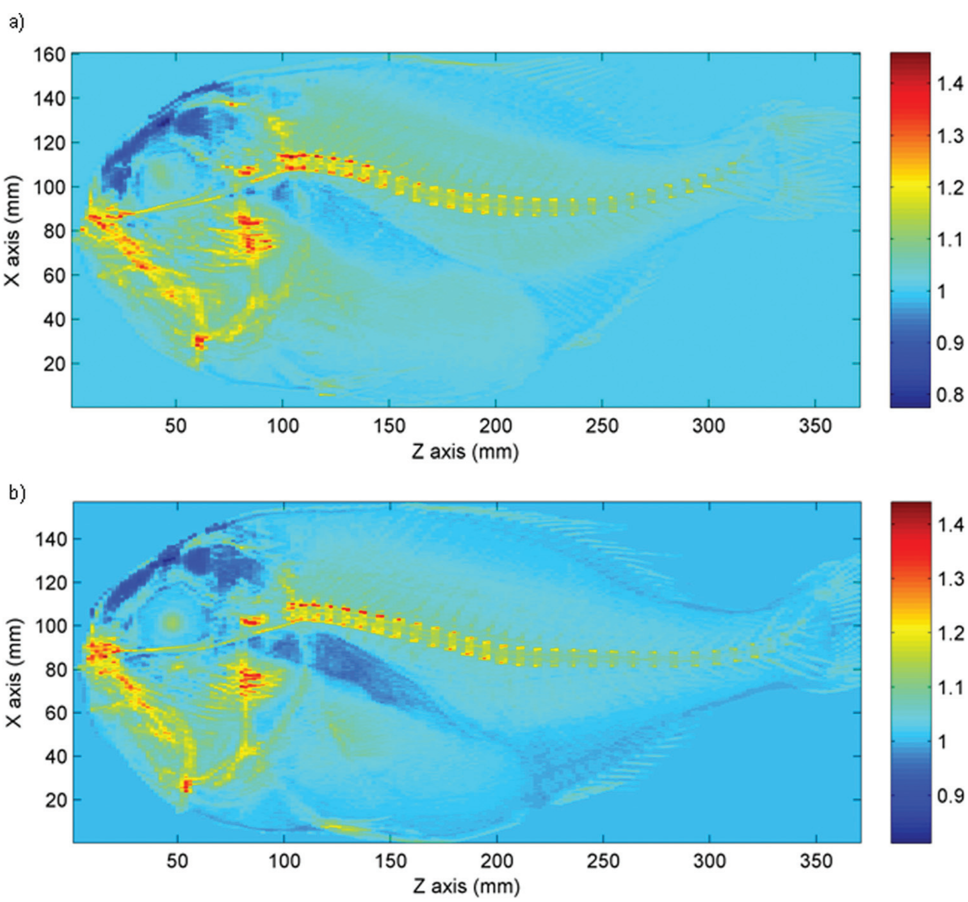

FIG. 9. Characteristic acoustic impedance of two orange roughy specimens relative to that of seawater, shown as a transverse average through the fish. Red and yellow areas are bone and the otoliths while the darker blue region below the spine is the swim bladder [(a) is fish OR2, a 33.4 cm female and (b) is a 35.8 cm male].

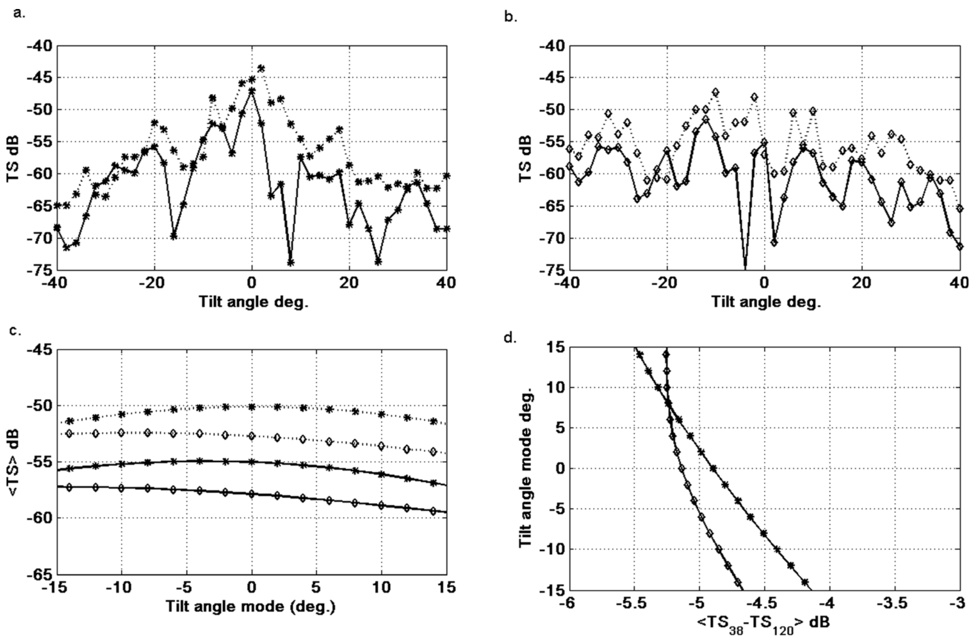

FIG. 10. Model predictions of orange roughy target strength at 38 kHz (solid) and 120 kHz (dashed) for a 33.4 cm female fish OR2 (a) and a 35.8 cm male fish OR3 (b) for tilt angles from $-40°$ to $40°$. (c) Ensemble tilt-angle-averaged target strength with mean tilt angle of $-15°$ to $15°$ and Gaussian distribution standard deviation of $15°$ for OR2 (asterisk) and OR3 (diamond) at 38 kHz (solid) and 120 kHz (dashed). (d) The predicted TS difference, $\Delta TS = TS_{38} - TS_{120}$, based on a Gaussian tilt distribution with modes of $-15°$ to $+15°$ and standard deviation of $15°$ for the OR2 (asterisk) and OR3 (diamond) orange roughy.

frequency (Barr, 2001; Kloser and Horne, 2003), but given the model predictions and *in situ* results presented here, we suggest that predictions based on simplified models be treated with caution.

One aspect of this work not addressed here is the issue of mixed species aggregations. We assumed that the *Sv* frequency difference in schools is dominated by within species scattering differences. However, it is also possible that the frequency response is sensitive to the presence of other species. Initial results suggest that the frequency response of gas-bladdered species will tend to decrease the *Sv* frequency difference observed in schools. In this situation, our method of matching school *Sv* frequency differences will increase the apparent orange roughy TS at 38 kHz and decrease the estimated orange roughy biomass. It would also be consistent with the school *Sv* frequency difference TS being higher than the tilt averaged TS. The effect of the presence of gas-bladdered species on the estimated biomass of orange roughy within schools could be partially compensated for using our school TS methodology.

The *Sv* logarithmic frequency difference and tilt angle weighted *in situ* derived TS results reported here at 38 kHz are lower than those reported by McClatchie and Ye (2000) and Coombs and Barr (2007) but within the range reported by Kloser and Horne (2003) and Macaulay *et al.* 2013 (Table V). Of note is the wide range of model and *in situ* estimates at 38 kHz (-50.7 to -56.5 dB) compared with 120 kHz (-48.6 to -51.5 dB). Commonly 38 kHz has been used to survey orange roughy and provide biomass estimates, but our results show that ensemble target strengths at 120 kHz are less sensitive to tilt angle than at 38 kHz. FEM results show that at 38 kHz, the target strength has nulls near horizontal to dorsal aspect; this could add to the variability and uncertainty in TS. Also, orange roughy target strength at 120 kHz is higher than at 38 kHz and much lower for the co-occurring small gas-bladdered mesopelagic fishes (Kloser *et al.*, 2002). Assuming other error factors such as calibration, absorption, and noise are similar, these observations suggest that acoustic biomass estimates would be more precise if done at 120 kHz than at 38 kHz. This is highlighted by the echograms in Fig. 2 where the improved discrimination of the orange roughy schools is observed at 120 kHz using a deep towed transducer compared to 38 kHz.

V. CONCLUSION

Our optically verified *in situ* measurements represent an advance in the understanding and application of TS for estimating orange roughy biomass. By matching both school scattering and *in situ* TS frequency differences, we have derived a TS that is representative of orange roughy schools of -52 dB at 38 kHz and -48.7 dB at 120 kHz for a mean school volume backscattering strength frequency difference of -3.3 dB and SD 4 dB. This method is proposed as an objective way of attributing an *in situ* TS measurement to a population at the same time as the survey. Acoustic biomass estimates at 120 kHz may be more precise than those at 38 kHz due to higher target strength and less sensitivity both to orange roughy tilt angle, and to the presence of gas-bladdered species.

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