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In situ target strength studies on Atlantic redfish (*Sebastes* spp.)

Stéphane Gauthier and George A. Rose

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In situ acoustic target strength (TS) experiments were conducted on Atlantic redfish (*Sebastes* spp.) in Newfoundland waters (1996–1998) using deep-tow dual beam and hull-mounted split beam echosounders (38 kHz). The dual and split beam mean TSs did not differ. The deep-tow system was deployed at various depths over several aggregations. Calibration corrections were made for depths from 5–70 m (<1 dB). The TS declined at ranges <50 m from the top of the fish shoal suggesting avoidance behaviour. It was biased upward at ranges >200 m and a number of fish per sampled volume >0.04. After being controlled for variations related to range, reverberation volume and fish density the TS did not differ with respect to depth, distance from bottom, fish sex ratio, condition factor or weight. The mean length was the dominant influence on the mean TS. Pooled *ex situ* experimental data and controlled *in situ* data – which did not differ – indicated a length-based regression (weighted by s.e.$^{-1}$) in standard format: TS=20 log [length (cm)] − 68.7 (r^2=0.49).

Keywords: redfish, Newfoundland, target strengh, *in* and *ex situ*, dual and split beam, model.

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S. Gauthier and G. A. Rose: Fisheries Conservation Chair, Fisheries and Marine Institute of Memorial University of Newfoundland, PO Box 4920, St John's, NF, Canada A1C 5R3. New address for S. Gauthier: University of Washington, School of Aquatic and Fishery Sciences, Box 355020, Seattle, WA 98195-5020, USA; tel.: (206) 221-5459; fax: (206) 221-6939; e-mail: sgau@u.washington.edu.

Introduction

Accurate target strength (TS) information is an essential element of acoustic surveys of fish populations (Foote, 1987). Methods of TS estimation using dual-beam and split-beam techniques enable direct measurements of fish *in situ* (Ehrenberg, 1983; Foote, 1991a), and theoretically provide the best estimate of TS to scale integrator outputs (MacLennan and Simmonds, 1992; Rose, 1992). However, several potential biases limit the use of *in situ* TS. Bias can be attributed to the acoustic measurements themselves, in particular the resolution of single targets (Sawada *et al.*, 1993; Soule *et al.*, 1995), or as a result of transducer motion (Furosawa and Sawada, 1991). The complex nature of fish behaviour can lead to variations in tilt-angle distribution and TS (Foote, 1980) as a consequence of vertical migration and the avoidance to a boat or towed body (Olsen, 1990; Kloser *et al.*, 1997). The physiological state of the fish (Ona, 1990) can also affect the TS. Furthermore, interpretation of the species and size composition necessary for unbiased TS estimation depends on representative biological sampling (MacLennan and Menz, 1996). However, fishing gears are selective (MacLennan, 1992) and it is often difficult to sample fish at the exact time and location at which they were ensonified. The most realistic solution to these problems has been to conduct *in situ* TS experiments under optimal or well-measured conditions (e.g. Traynor, 1996; Rose and Porter, 1998).

Atlantic redfish (*Sebastes* spp.) are an important commercial species and have been surveyed acoustically in many areas including Newfoundland waters (Atkinson, 1989), the Irminger Sea (Reynisson and Sigurdson, 1996) and the Flemish Cap Bank (Vaskov *et al.*, 1998). The three species of redfish: *Sebastes mentella*, *S. fasciatus* and *S. marinus* (Scott and Scott, 1988) are difficult to identify from external features alone. Composite groups of *Sebastes* are typically managed as single stocks. Only very limited work has been conducted on redfish TS. Foote *et al.* (1986), Reynisson (1992), and Gauthier and Rose (1998) reported limited *in situ* estimates, while Gauthier and Rose (2001a) recently presented *ex situ* results for TS of redfish kept in sea cages.

In this paper we describe a series of *in situ* TS experiments on Northwest Atlantic redfish using dual-beam and split-beam methods. Measurements were made under a wide range of conditions and over several years. We address potential biases in TS attributable to acoustic technique (split and dual beam), time of day, range of measurements, density of fish, and avoidance behaviour. We also compare TS over seasons and years. Our objective is to provide a useful model of redfish TS to scale integrator outputs from acoustic surveys.

Materials and methods

All measurements were made from the Canadian Coast Guard Ship "Teleost", a 63 m stern trawler equipped for acoustic survey with both hull-mounted and deep-tow acoustic systems. The TS experiments were performed in June 1996 and January 1997 using an EK500 echosounder with a hull-mounted 38 kHz transducer (6 m from the surface) and a custom-built, dual-beam system (also at 38 kHz) with the transducer towed behind the vessel. Further experiments were conducted in March and June 1998 using only the EK500 system.

System configuration

The TS measurements were made using standard dual-beam and split-beam techniques (Ehrenberg, 1979; 1983). The custom-built, dual-beam system used in this study was designed and tested by the hydro-acoustic division of the Northwest Atlantic Fisheries Centre (C. Stevens and C. Lang, Department of Fisheries and Oceans, personal communication). The deep-tow transducer was a 38 kHz EDO SP303LT-38 dual-beam composed of 113 elements distributed in 5 rings with active electronic beamforming. The transducer diameter was 39 cm and the half-power angles in degrees for the narrow and wide beam were 7° and 14° respectively. Power was transmitted *via* an Instrument Inc. S14-4 class SS amplifier of 6 kVA and received by a Biosonic Inc. ES2000 with a 146 dB dynamic range (at 1 kHz bandwidth). The transducer was installed in a heavy stainless-steel towed body (500 kg, Indal Techno Inc.) deployed with a Fathom model 6-935 handling system designed for stern towing from the CCGS Teleost. A multichannel 400 m armored tow cable connected the towed transducer to the transmitter-receiver system. The cable was fitted with hydrodynamic fairings to reduce drag and vibration.

The split-beam ES38B transducer (Kongsberg, Simrad) had a beamwidth of 7.1° between half-power points. The maximum gain compensation was set to 3 dB to correct for directional attenuation as sound radiates away from the beam axis. In addition, strict positional restrictions were implemented between consecutive echoes. In a split-beam system different arrival times of acoustic wavefronts to the quadrants causes differences in the phase angle of the electrical output signal (MacLennan and Simmonds, 1992). The average electrical phase "jitter" between samples inside an echo pulse (phase deviation between the beam quadrants) was set to two phase steps, where 1 phase step is equal to a 2.8125 electrical degree difference in the carrier frequency (64 phase steps = 180 electrical degree). For the dual-beam system the signals were filtered to reject pulses narrower than the transmission pulse and wider than 1.2, 1.5, and 1.8 times the pulse width at the half, quarter and eighth pulse heights. Data were also rejected if the ratio of the width at the half to quarter heights and quarter to eighth heights was below 0.75. Only targets <3 dB of the acoustic axis were included in the analyses. A transmit pulse duration of 0.8 ms and a ping rate of 1 s^{-1} were used for both systems.

Calibration

Standard calibration procedures for scientific echosounders are based on the measurement of a copper or tungsten-carbide sphere having known acoustic properties (Foote and MacLennan, 1984). Temperature and sound speed can influence the echo measurements. Hence, calibrations are best performed under survey conditions (Demer and Hewitt, 1992). The two acoustic systems used in this study were calibrated on site before each *in situ* TS experiment using the procedures described by Foote *et al.* (1987). A calibration with the dual-beam transducer at deeper operating depths was performed after the research at sea had been completed.

Placement of the acoustic transducer well beneath the ocean surface and closer to the fish can greatly reduce the bias in TS measurements attributable to spreading and absorption signal loss (Kloser, 1996). We used the dual-beam transducer at depths to 300 m. Although repeatedly calibrated close to the surface (<10 m), this is the first report of its calibration at various depths. We calibrated the system at incremental depths from 4.5 to 72 m to test the effect of ambient pressure (depth) and change in temperature on the sensitivity of the instrument.

The calibrations were performed in Bull Arm, Trinity Bay, Newfoundland in September 1998. The CCGS Teleost was anchored in a sheltered and deep channel (total depth 85 m). An adjustable frame was installed on the towed body to provide three attachment points for a 38.1 mm tungsten-carbide calibration sphere. The sphere was centred on the beam at a range of 6.2 m from the transducer and a weight was attached at 8 m to minimize swing and drag induced by currents. The calibrations were conducted with the transducer at depths of 4.5, 9.4, 21.9, 32, 42, 51.7, 61.8, and 71.9 m. At each depth station acoustic pulses of 0.8 ms were transmitted at a rate of 1 ping s^{-1} for approximately 5 min. Stations were occupied during lowering and raising of the system.

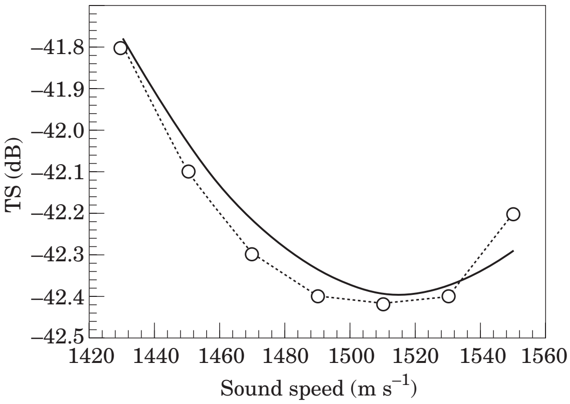

Figure 1. The target strength (dB) of the 38.1 mm tungsten-carbide calibration sphere as a function of sound speed in water. The solid line represents values calculated using equation (1) and the circles with the dotted line represent values given by MacLennan and Simmonds (1992).

This procedure was repeated seven times within 3 days. Following each experiment a complete depth profile of temperature and salinity was taken using a Seabird CTD probe. The TS of the tungsten-carbide sphere was calculated employing standard dual-beam techniques (Traynor and Ehrenberg, 1979) using the parameters obtained in surface calibration (source level of 225.8 dB, narrow- and wide-beam receiver sensitivity of −186.5 and −185.7 dB respectively, and a wide-beam roll-off of 0.66). The wide-beam roll-off is a factor applied to the narrow- and wide-beam peak amplitude ratio to calculate the off-axis position of a single target. Means and standard errors were arithmetically averaged from the backscattering cross-section of the target prior to logarithmic transformation (Foote, 1987).

The expected TS of the tungsten-carbide standard target at a particular depth was calculated from a polynomial equation derived from the sound speed – TS curve provided by the manufacturer. The equation had the form:

$$TS_i = 9.9424 \cdot 10^{-5} + (4.8692 \cdot 10^{-2} \cdot c_i) - (1.1962 \cdot 10^{-4} \cdot c_i^2) + (4.5551 \cdot 10^{-8} \cdot c_i^3) \quad (1)$$

where TS_i is the target strength of the sphere and c_i is the sound speed in water at depth i (Figure 1). Sound speed was calculated according to MacKenzie (1981) using the depth profiles of temperature and salinity obtained after each experiment.

Echosounders typically implement a range compensation (Time-Varied-Gain) on all measured targets:

$$TVG = 40 \log R + 2\alpha R \quad (2)$$

where R is the range from the transducer in m and α is the absorption coefficient in $db \cdot m^{-1}$. The custom-built system used in this study calculated gain and TVG in a combined form, using fixed sound speed:

$$TVG = G_0 + (40 \log + 2\alpha_0)\left(\frac{c_0}{2} t\right) \quad (3)$$

where G_0, c_0, and α_0 are, respectively, gain in dB, sound speed in $m \cdot s^{-1}$, and absorption coefficent in $db \cdot m^{-1}$. The propagation time (t) is the total time (in s) for the acoustic wave to travel from the transducer to the target and back to the transducer. Propagation time depends on the range (R_i) to the target and the average sound speed between the transducer and target (C_{avg}):

$$t_i = \frac{2R_i}{C_{avg}} \quad (4)$$

For the target at fixed range the difference in average sound speed as the transducer moved deeper introduced a bias in the TVG correction. If we consider the average sound speed between the target and the transducer at the surface as a reference, the bias in dB at any given transducer depth will be proportional to the error expressed in the range reported by the echosounder:

$$Bias_i = 40 \log\left(\frac{R_i}{R_{ref}}\right) + 2\alpha_0(R_i - R_{ref}) \quad (5)$$

where R_{ref} is the actual distance of the target to the transducer and R_i is the new reported range to the target at transducer depth i. To simplify the equation, α_0 was set to $0.01\ dB \cdot m^{-1}$ (a typical value for the absorption coefficient at a frequency of 38 kHz in sea water).

In situ TS measurements

Large aggregations of redfish were studied on the edge of the Green and Grand Banks of Newfoundland (NAFO Divisions 3Ps-3O) between depths of 100 to 800 m (Figure 2). In this area both species of beaked redfish are present (*Sebastes mentella* and *S. fasciatus*), while *S. marinus* is relatively uncommon (Power, 1998). Anal fin-ray counts indicated that *S. mentella* was the predominant species at our studied sites. However, hybridization is frequent in this area (Roque *et al.*, 2001). During each experiment (1996–1998), shoals of redfish were monitored acoustically for a period of at least 24 h (Table 1). At each site transects of 1.5 to 5 nautical miles were ran at five knots at randomly determined positions along and across the Continental slope. Species and size composition were assessed using an instrumented Campelen 1800 bottom trawl fished at depths and locations as close as possible to the acoustic transect using GPS (Global Positioning System) information. For transects across the continental slope

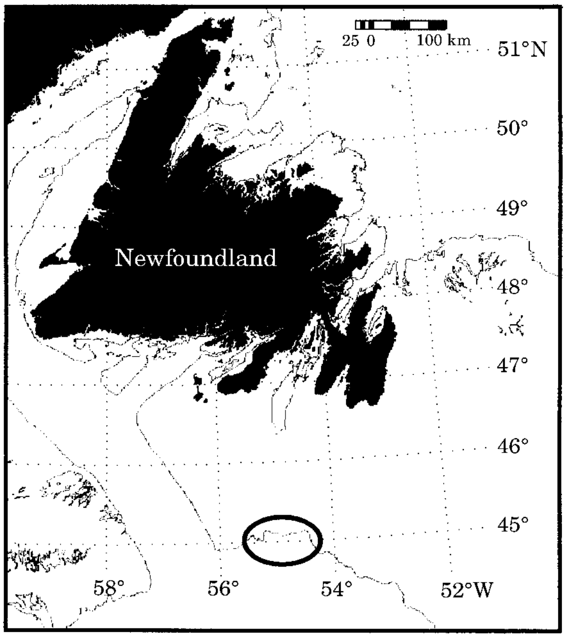

Figure 2. Map of Newfoundland with the 200 m depth contour (in grey). The outlined area indicates the location of our *in situ* experiments.

fishing was performed at depth intervals of approximately 100 m. Only sites where 90% or more of the catch, by weight, was redfish were used for TS analysis. A sub-sample of 200 to 500 fish was used to measure individual length, weight, and gender. Condition factors were calculated as:

$$K = 100\ wl^{-3} \quad (6)$$

with whole wet weight (w) measured in grams and length (l) in cm. Diamond IX or IYGPT midwater trawls were used to identify pelagic traces when necessary. In 1996 and 1997 the deep-tow, dual-beam system was deployed in multiple passes over the same transects at increments of 20 to 50 m from the surface to 300 m depth. The dual-beam system was used simultaneously with the EK500 system (pulse synchronized).

To determine the mean TS, backscattering cross-sections were averaged arithmetically prior to logarithmic transformation (Foote, 1987). TS-length regression models were generated as $TS = a\log L + b$ and $TS = 20\log L + b_{20}$ where L is the length in cm and b is given in dB (Love, 1977). The number of fish relative to one effective reverberation volume was calculated according to Sawada *et al.* (1993) as:

$$N_v = \frac{c\tau\psi R^2 n_{EI}}{2} \quad (7)$$

where c is the speed of sound in water in $m \cdot s^{-1}$, τ is the transmit-pulse duration in s, ψ is the equivalent beam angle in steradians, R is the target range in m and n_{EI} is the volumetric fish density in fish $\cdot\ m^{-3}$. The volumetric fish density was calculated for bins of 10 m depth by 300 to 500 pings (800–1400 m) using volume-scattering coefficients (s_V) and TS estimated from catch data and previous TS-length models for redfish (Gauthier and Rose, 2001a).

At sea several additional variables that could influence TS were measured. These included time of day, distance of fish from the transducer (avoidance behaviour and threshold effect), density of fish (N_v), and distance of fish above the bottom (buoyancy effect). Stepwise regression and a general linear modeling approach were used in an attempt to explain variations in TS according to fish characteristics (mean length, mean weight, condition factor K and sex ratio), estimation method (split vs dual beam), time of year (mission date), and depth of the fish aggregation.

Results

Calibration

Representative depth profiles of sound speed, expected TS of the tungsten-carbide sphere and TVG correction factor for the calibration experiments on the deep tow system are shown in Figure 3. Profiles from the seven experiments were relatively similar in trend, although absolute values differed because the tides affected temperature and salinity. At 4.5 m from the surface water temperature varied from 5.4 to 12.2°C throughout the experiment, which was carried out over 3 days. Temperature change did not affect the dual-beam transducer sensitivity (calibration error within 0.1 dB).

The observed TS of the tungsten carbide sphere (TS_o) decreased significantly ($p<0.001$, $r^2=0.92$) with depth due to transducer hysteresis (Figure 4). The depth corrected TS (TS_c) was:

$$TS_c = TS_o + 0.003\ (d_T - 4.5) \quad (8)$$

where d_T is the absolute transducer depth in m. An offset of 4.5 m represents the reference depth for calibration. The pressure correction factor was independent of the correction for sound speed. This correction factor was extrapolated for the entire deployment range of the transducer. At the maximum range used in this study ($\sim$300 m) the correction was less than 1 dB.

In situ TS measurements

Redfish exhibited diel patterns of shoaling behaviour in all surveys. During the day, fish were distributed in aggregations close to the bottom, packing densities were high and single targets were seldom recorded. At dusk, redfish migrated into the water column and individuals

Table 1. Summary of *in situ* TS (dB) experiments on redfish. Mean backscattering cross-sections ($\times\sigma_{bs}$ in m^2) are shown with standard error (s.e.). N is the number of accepted targets. K is the condition factor ($100\ wl^{-3}$). Length, weight, gender and K were individually measured from a sub-sample of 200–500 fish at each site. Sex ratio represents males to females. Depth is the average depth of targets in the water column. N_v is the mean number of fish in a sample volume.

Date	$[\times\sigma_{bs}$ (s.e.)] $\cdot 10^{-5}$	TS (dB)	N	L (cm)	W (g)	K	Sex ratio	Depth (m)	N_v	Method
Jul 96	5.50 (0.16)	−42.6	525	21	139	1.55	1.11	169	0.016	Split
Jul 96	6.92 (0.27)	−41.6	327	23	155	1.48	0.80	198	0.062	Split
Jul 96	6.03 (0.12)	−42.2	1106	22	143	1.38	0.79	218	0.015	Split
Jul 96	6.61 (0.17)	−41.8	1023	22	143	1.38	0.79	267	0.012	Dual
Jul 96	7.24 (0.21)	−41.4	602	23	160	1.32	1.12	239	0.025	Split
Jul 96	8.71 (0.22)	−40.6	1508	23	160	1.32	1.12	319	0.020	Dual
Jul 96	5.01 (0.10)	−43.0	1949	21.2	139	1.42	0.97	216	0.020	Split
Jul 96	4.79 (0.08)	−43.2	3697	21.2	139	1.42	0.97	246	0.015	Dual
Jul 96	5.75 (0.14)	−42.4	1015	21.8	142	1.44	0.53	239	0.023	Split
Jul 96	7.59 (0.27)	−41.2	1432	21.8	142	1.44	0.88	288	0.018	Dual
Jan 97	7.59 (0.16)	−41.2	1051	21.8	141	1.35	0.07	241	0.013	Split
Jan 97	6.61 (0.12)	−41.8	2057	22.5	157	1.32	0.46	224	0.012	Split
Jan 97	7.76 (0.20)	−41.1	3318	22.5	157	1.32	0.46	253	0.007	Dual
Jan 97	7.76 (0.16)	−41.1	2200	22.5	157	1.32	0.46	284	0.017	Dual
Jan 97	8.13 (0.33)	−40.9	516	21	127	1.29	0.80	165	0.002	Split
Jan 97	7.76 (0.36)	−41.1	1043	21	127	1.29	0.80	167	0.003	Dual
Jan 97	7.24 (0.26)	−41.4	686	21	127	1.29	0.80	209	0.021	Split
Jan 97	7.76 (0.26)	−41.1	1460	21	127	1.29	0.80	210	0.007	Dual
Jan 97	13.80 (0.81)	−38.6	131	32.3	463	1.35	1.21	338	0.071	Split
Jan 97	13.18 (0.42)	−38.8	833	32.3	463	1.35	1.21	387	0.025	Dual
Jan 97	15.14 (0.39)	−38.2	556	28.8	362	1.46	0.31	320	0.078	Split
Mar 98	5.25 (0.14)	−42.8	648	22.2	153	1.32	0.47	146	0.009	Split
Mar 98	5.89 (0.45)	−42.3	128	16.9	73	1.35	—	152	0.024	Split
Mar 98	6.76 (0.35)	−41.7	132	20.8	125	1.24	0.43	179	0.035	Split
Mar 98	5.89 (0.20)	−42.3	330	23.6	168	1.25	0.65	196	0.020	Split
Mar 98	6.61 (0.42)	−41.8	151	23.5	175	1.31	0.72	234	0.022	Split
Mar 98	3.72 (0.49)	−44.3	170	14.8	74	1.83	—	143	0.019	Split
Mar 98	5.62 (0.19)	−42.5	357	18.4	94	1.20	—	151	0.023	Split
Mar 98	6.31 (0.22)	−42.0	339	22.4	153	1.31	0.48	169	0.012	Split
Jun 98	6.17 (0.28)	−42.1	393	22	—	—	—	134	0.023	Split
Jun 98	12.88 (0.55)	−38.9	404	29	—	—	—	256	0.029	Split

became more widely dispersed. Fish returned to the bottom at dawn or shortly thereafter. The number of targets recorded per hour sharply increased at dusk and decreased at dawn (Figure 5). Few targets were recorded during the day (<50).

To test simultaneously for the effect of transducer depth and range to the fish, the mean TS of three large aggregations of redfish was measured with the transducer at various depths using the deep-tow, dual-beam system (Figure 6). In each case, the TS of redfish decreased as the transducer depth increased. However, the density of fish was often high at shallow transducer depths, as a result of the larger reverberation volumes at the depths of the fish (double circles in Figure 6). For measurements made at similar horizontal scales, Sawada *et al.* (1993) showed that significant bias in fish TS occurred at N_v values above 0.04. To assess such an effect of density on the TS of redfish, the TS in each aggregation was standardized by subtracting the mean TS which was estimated at $N_v<0.04$ (Figure 7). It was biased upward above a density threshold of 0.04 fish.

The TS of redfish was also measured at various ranges from the transducer, in layers of 10 m depth, at different locations and depths within each aggregation where $N_v \leq 0.04$ (Figure 8). At ranges <50 m from the transducer, mean TS was lower by 2–4 dB than at range from 50–200 m. At ranges between 50 and 200 m the TS did not differ. At ranges >200 m, the TS increased to levels greater than at 50–200 m (Figure 8). It did not differ with respect to distance of the fish from the bottom at ranges between 50 and 200 m (Figure 9A). However, when the transducer was closer than 50 m from the top of the redfish aggregation, the entire shoal showed a decrease in Target Strengh (Figure 9B).

Eight redfish aggregations were measured simultaneously with dual- and split-beam echosounders (Figure 10). TS measurements with the dual beam were limited to ranges between 50–200 m from the transducer. A threshold of 0.04 N_v was applied to all data. Univariate analysis of variance indicated that there was no significant difference between the mean TS obtained

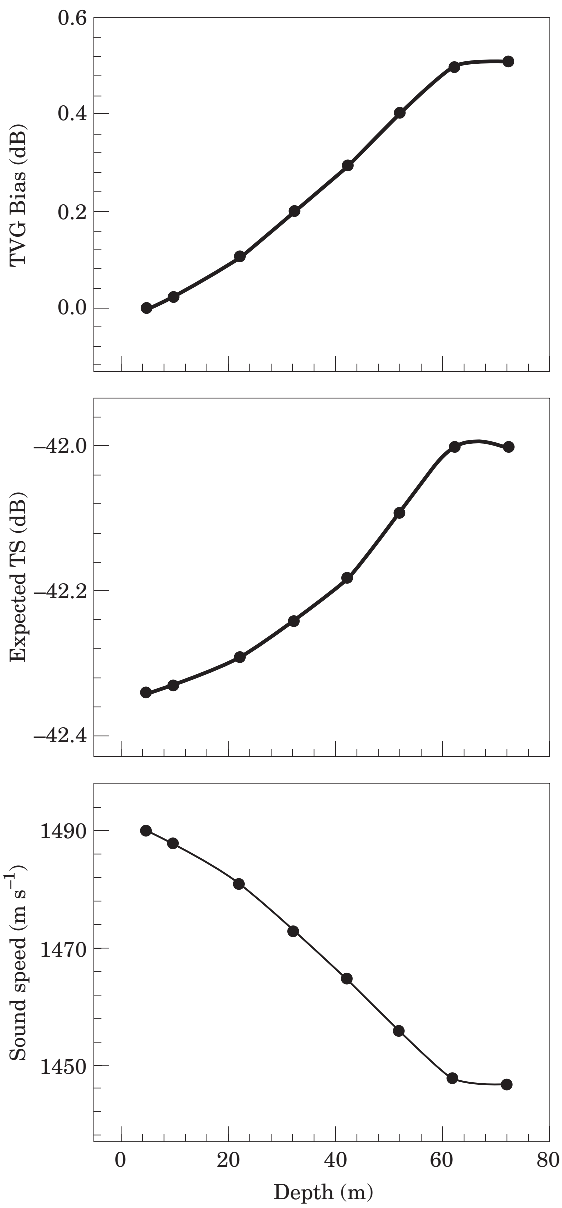

Figure 3. Depth profiles of TVG bias correction, expected TS and sound speed for a representative calibration cast with the 38.1 mm tungsten carbide standard target.

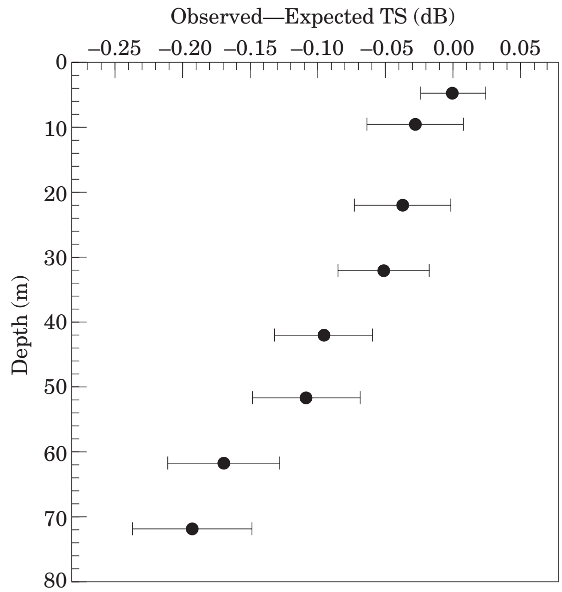

Figure 4. The effect of depth on the tungsten carbide sphere TS (dB). Horizontal bars represents ± 1 standard deviation.

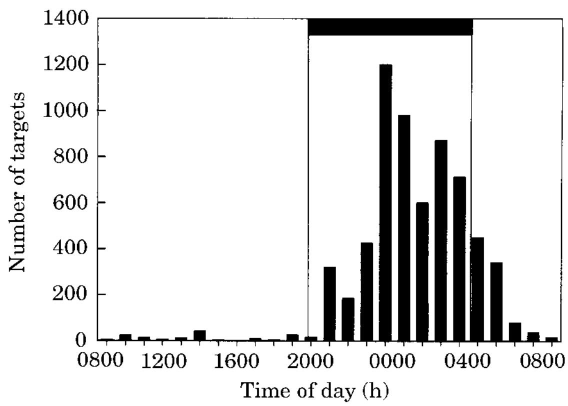

Figure 5. The number of targets recorded per hour for a transect line monitored for 24 h. The black horizontal bar delimits sunset and sunrise.

with the two methods ($p>0.1$; d.f.=1,16; $F=0.33$). The number of accepted targets was generally lower for the split-beam system, since measurements were made at much greater transducer range and reverberation volume. TS frequency distributions from split beam were in many cases narrower than from dual beam (up to eight dB difference in spread). However, at half peak height, the width of the histograms for the split-beam method was, on average, larger than for the dual-beam approach.

The results of the *in situ* redfish experiments are summarized in Table 1. For each site, redfish comprise >90% of the catch (by weight) and length distributions were monotonic. The mean number of fish per volume (N_v) was below 0.04 in all but 3 cases. Those 3 cases represented small groups of fish, in which sampling intervals were 200–300 pings less than at other sites. A general linear model approach and stepwise selection of variables were used to identify factors that influenced TS. Length and weight were logarithmically transformed prior to computations. Of all factors considered, only the length of redfish sampled and the mission date (time of year) had a significant effect on TS (Table 2). The interaction term (length × date) was also significant

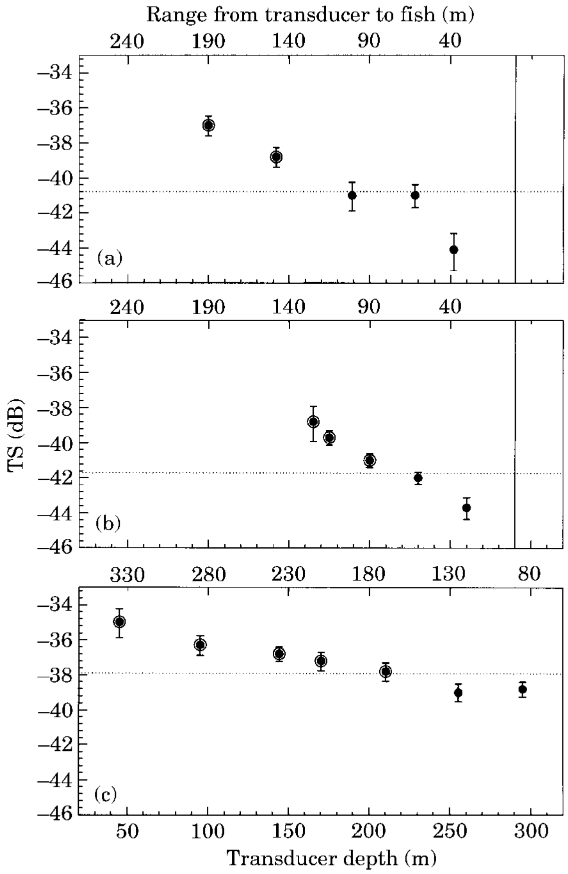

Figure 6. The TS in dB (±2 s.e.) of three aggregations of redfish measured with the transducer at several depths. Double circles indicate that the mean number of fish in a sample volume (N_v) exceeded 0.04. The horizontal dashed line represents the TS predicted by the model TS=[20logL (cm)]−68.1 (Gauthier and Rose, 2001a).

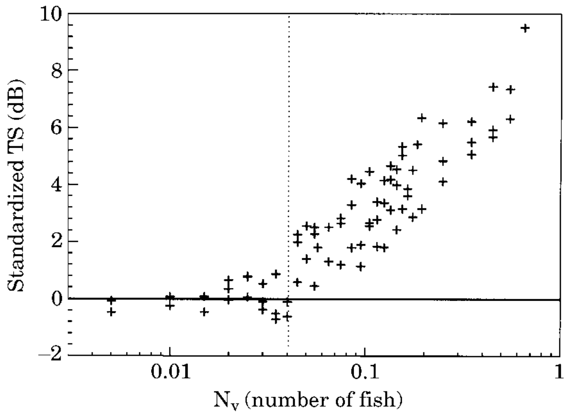

Figure 7. Relationship between the standardized TS (dB) and the number of fish in a sample volume (N_v). The standardized TS was measured by substracting the mean TS at which N_v was lower than 0.04 fish.

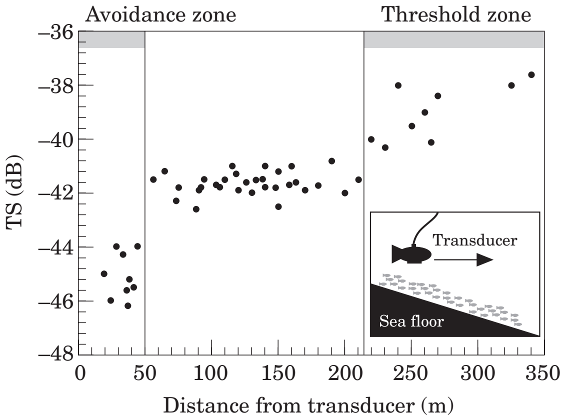

Figure 8. The TS (dB) of redfish measured at different ranges from the transducer within the same large aggregation. Each point represents the mean of 100 to 500 targets at densities <0.04. The inset diagram illustrates the sampling strategy. The grey zone on the left indicates a potential avoidance reaction, while the grey zone on the right indicates the range at which threshold biases become significant.

indicating that the slope of the regression between TS and length differed among dates.

For all *in situ* experiments (n=31), mean fish length ranged from 14.8 to 32.3 cm and TS ranged from −44.3 to −38.2 dB (Figure 11). The best-fit regression of TS on length was TS=16.8logL−64.2 (95% CI −64.4 to −63.9; r^2=0.69) and in the standard form TS=20logL−68.5 (95% CI −68.8 to −67.2; r^2=0.67). *Ex situ* data from encaged redfish are also plotted in Figure 11 (Gauthier and Rose, 2001a). A TS–length model based on the *ex situ* data does not differ either in slope, when not forced to 20, or intercept from the *in situ* model. A model based on a pooling of all *in situ* and *ex situ* experiments indicates TS=20logL−68.3 (95% CI −68.6 to −68; r^2=0.70).

In an attempt to account for differing precision in the various data (Table 1) a weighed regression was calculated using the inverse of the standard error of the mean backscattering cross-section as a weighing factor (s.e.$^{-1}$). The resulting model had the form TS=17.1logL−64.9 (95% CI −65.1 to −64.6; r^2=0.52) and in the standard form TS=20logL−68.7 (95% CI −69.0 to −68.4; r^2=0.50). A weighted model (with s.e.$^{-1}$) based on a pooling of all *in situ* and *ex situ* experiments (Table 1 and 3) indicates TS (dB)=17.5logL−65.2 (95% CI −65.5 to −64.9; r^2=0.49) and in the standard form TS=20logL−68.7 (95% CI −69 to −68.3; r^2=0.48). The unpooled, pooled, unweighted and weighted standard regression intercepts did not differ (ps<0.05).

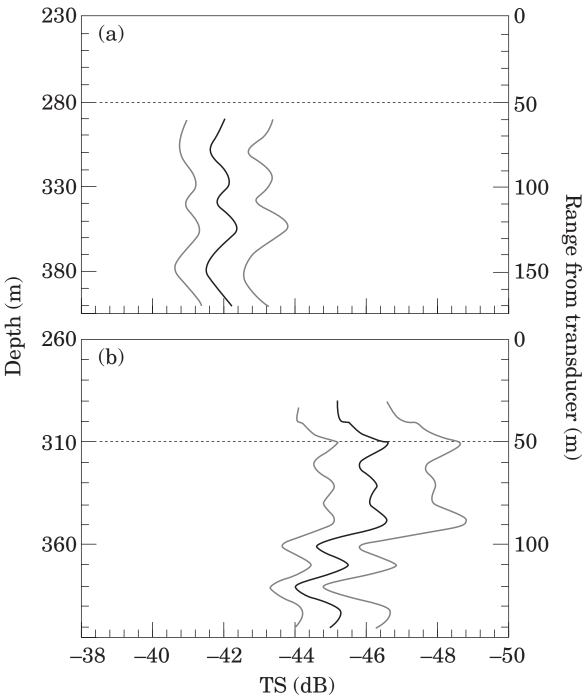

Figure 9. The TS in dB (bounded by the sd) for the same redfish aggregation measured at two transducer depths (a) 230 m and (b) 260 m. The horizontal dotted line represent the 50 m range from transducer

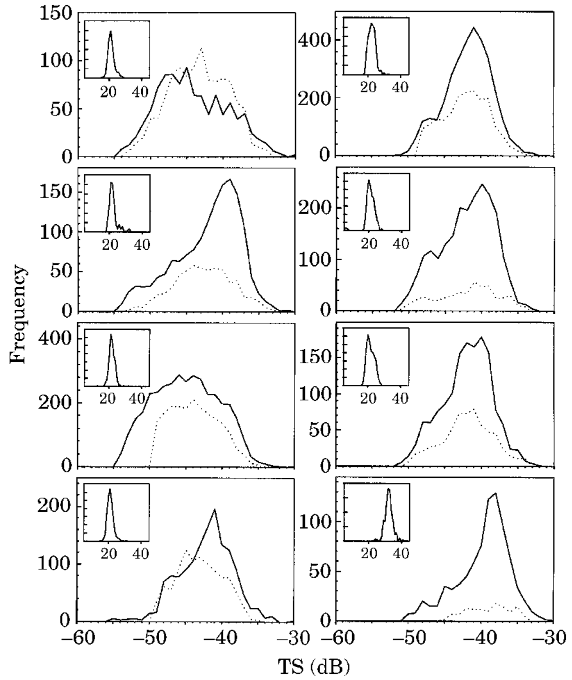

Figure 10. The TS (dB) frequency distribution for eight redfish aggregations measured using the dual-beam (plain line) and split-beam (dotted line) techniques. The inset windows represent the length-frequency distribution (cm) at each site.

Table 2. Statistics of univariate analysis of variance to account for effect on TS (dB).

Source	Sum of squares	d.f.	Mean square	F	p
Mission date	4.241	3	1.414	4.7	<0.05
Log (length)	13.495	1	13.495	44.9	<0.001
Interaction term	4.414	3	1.471	4.9	<0.01

Discussion

The calibration of acoustic instruments is essential to the precision and reliability of TS measurements (Foote *et al.*, 1987). It presented several challenges for the deep-tow, dual-beam system. To measure the tungsten-carbide sphere with the transducer at different depths we had to position the sphere at a distance that represented a trade-off between stability (on-axis position) and range from the transducer. Because of potential change in the relative sensitivity of the narrow to wide beam, the sphere had to be as steady as possible on the axis of the beams. At a distance of 6.2 m, the sphere was stable and located just outside the near-field of the transducer. The experiment was repeated under different environmental conditions over several tidal cycles, with different current velocities and directions, to ensure that movement of the sphere did not cause the observed differences. The results obtained in this study are of the same order as observed by Kloser (1996) in the calibration of an EDO Western 38 kHz split-beam echosounder mounted on a deep-towed body. He found that the TS of a 60 mm copper sphere measured at 1000 m depth was almost 3 dB lower than at 100 m. If extrapolated to a depth of 1000 m, which is well beyond the maximum range of the system used for this study, the correction factor we determined would be of approximately 3 dB.

No reliable measurements of *in situ* TS of redfish were possible during daylight hours as a consequence of the demersal behaviour and dense shoaling activity of these species. Hence, time of day had a strong influence on TS measurements. Our observation of vertical migration in redfish was consistent with previous studies (Beamish, 1966; Atkinson, 1989). Ambient pressure changes experienced during diel vertical migration did not seem to affect redfish TS significantly (Gauthier and Rose, in press). Variations in TS due to predicted swimbladder compression or expansion were not perceptible either because of compensation mechanisms – rapid gas secretion and excretion – or the presence of confounding effects. Diel vertical migration in redfish may have a significant impact on the catchability and efficiency of fishing gear (Michalsen *et al.*, 1996; Casey and Myers,

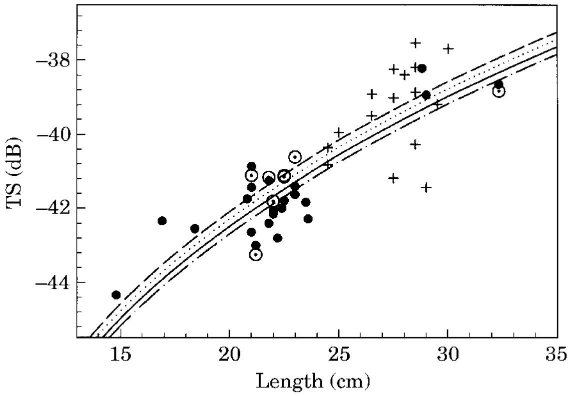

Figure 11. Mean TS (dB) and mean length (cm) for redfish measured *in situ* using the split-beam (closed circles) and dual-beam (dotted circles) techniques. Each point represents an experiment in which $N_v<0.04$. The sample size for each point is given in Table 1. Crosses represent mean values for individual encaged fish measured with a split-beam system (Gauthier and Rose, 2001a). Unbroken line: TS=20logL − 68.5 (*In situ* data only). Broken Line: TS=20logL − 68.1 (*Ex situ* data only). Dotted line: TS=20logL − 68.3 (*In situ* and *Ex situ* data). Broken and dotted line: TS=20logL − 68.7 (Weighted *In situ** and *Ex situ* data). *The weighted *in situ* data only has the same intercept.

Table 3. Summary of *ex situ* TS (dB) experiments on individual redfish (Gauthier and Rose, 2001a). Mean backscattering cross-sections ($\times \sigma_{bs}$ in m^2) are shown with standard error (s.e.). N is the number of accepted pings.

Length (cm)	$[\times \sigma_{bs}$ (s.e.)$] \cdot 10^{-5}$	TS (dB)	N
24.5	9.23 (0.16)	− 40.35	1 477
24.5	8.30 (0.11)	− 40.81	1 334
25	10.14 (0.03)	− 39.94	5 559
26.5	11.25 (0.17)	− 39.49	1 922
26.5	12.88 (0.17)	− 38.9	708
27.5	7.64 (0.12)	− 41.17	1 362
27.5	12.59 (0.13)	− 39	1 950
27.5	15.03 (0.82)	− 38.23	171
28	14.52 (0.13)	− 38.38	486
28.5	17.70 (0.51)	− 37.52	272
28.5	9.42 (0.15)	− 40.26	670
28.5	15.21 (0.06)	− 38.18	18 533
28.5	13.03 (0.39)	− 38.85	262
29	7.21 (0.03)	− 41.42	17 140
29.5	12.08 (0.17)	− 39.18	2 993
30	17.10 (0.19)	− 37.67	2 429

1998), which in turn could bias measurements of fish size distribution.

In this study high signal-to-noise ratio conditions were encountered predominantly. Sumbeam signal thresholding was therefore set at low levels with little effect on the TS distribution of fish, except at far ranges where spreading and attenuation losses were important. Beam angle thresholding was kept narrow throughout the experiments (within − 3 dB) to ensure accurate TS estimates and to minimize errors due to multiple scattering. Other factors influenced TS, including the presence of other species (multiple targets of euphausiids) and the fish density (Sawada *et al.*, 1993). These factors depend in part on the reverberation volume and are thus affected by the range of observation. Such biases were minimized by the use of low N_v threshold (Gauthier and Rose, 2001b). Sound absorption and beam thresholding are also range dependent (Weimer and Ehrenberg, 1975; Foote, 1991b). For redfish measured with the deep-tow, dual-beam system a significant bias towards smaller targets was observed at ranges above ∼200 m thus emphasizing the advantage of using this approach. Measurements of the same aggregation of fish made at ranges up to 350 m with the hull-mounted, split-beam transducer were comparable to the dual-beam measurements made within 200 m range, suggesting that the split-beam system was more robust at greater ranges. Backscattering cross-sections measured with the split beam were slightly less variable than those obtained with dual beam but the means were not significantly different. Previous studies indicated that bias and errors in TS associated with beam patterns are more important in dual-beam systems and that this technique is more sensitive to the presence of noise (Ehrenberg, 1979, 1983; Traynor and Ehrenberg, 1990; Ehrenberg and Torkelson, 1996). However, the dual-beam system was mounted in a deep towed body that enabled measurements at close range to the fish. Use of this system allowed a decrease in the acoustic range to the ocean floor, which greatly reduced the acoustic dead (or shadow) zone (Kloser, 1996; Ona and Mitson, 1996), thus enabling the measurement of targets closer to the bottom.

The data indicated a significant change in TS when the deep-towed body approach to within 50 m range from the redfish aggregation. Several studies (Olsen, 1979, 1981; Halldorsson, 1983; Olsen *et al.*, 1983) have suggested that reductions in acoustic backscattering can occur if fish adopt a downward swimming position while avoiding a vessel. Barange and Hampton (1994) showed that during trawling the TS of Horse mackerel (*Trachurus trachurus capensis*) was up to 12 dB lower than prior to and after trawling. The declines of approximately three dB observed in TS when the towed body was at ranges of <50 m from redfish are consistent with a significant change in aspect to a downward orientation, because directivity, i.e. the effect of tilt angle, is relatively weak in these species (Gauthier and Rose, 2001a). Such behaviour was observed at ocean depths of 200 to 500 m during the night, which suggests that fish were reacting to noise and pressure waves (e.g. cable strum) or both factors rather than visual stimuli. Fish lower in the aggregation may have reacted by following or "imitating" their closest neighbours. Kloser *et al.* (1997) observed that Orange roughy (*Hyplostethus atlanticus*) in deep water (>700 m) responded by moving away and schooling tightly when the towed transducer was less than 150 m from the aggregation.

Fish length was the sole fish characteristic that explained a significant amount of the variation in TS. However, there was a difference attributable to sampling dates. Sampling effort and size distribution of fish differed among dates, making interpretation of this result somewhat problematic. Nevertheless, it is possible that seasonal trends in TS exist as a consequence of unmeasured physiological differences. For example, Ona (1990) showed that stomach fullness and gonad maturation could significantly alter TS. Furthermore, seasonal change in feeding and swimming behaviour could also explain the discrepancy as these factors could lead to significant change in orientation distribution (Foote, 1980). We also considered the possibility that weather may have influenced the results. However, sea conditions were relatively fair throughout (winds <20 knots) for all the data presented and it is unlikely that observed differences are due to ship motion or sea turbulence.

The TS-length regression model proposed is in fair agreement with published data on physoclists (MacLennan and Simmonds, 1992). There have been few measures on *Sebastes* sp. The data from this study indicate an intercept of −68.7 (weighted standard 20logL form) that is approximately 1.5 dB lower than reported in previous studies, i.e. −67.1 for *in situ* measurement of redfish in the Norwegian sea (Foote *et al.*, 1986) and −67.5 for a general model on physoclists proposed by Foote (1997). Reynisson (1992) reported an average TS of −40 dB for redfish of 32.9 cm mean length measured with a split-beam system which is equivalent to a 20log intercept of −71.3. Using a single-beam technique, Orlowsky (1987) obtained an intercept of −69.4 for redfish of similar size to those measured by Reynisson (1992). Our TS model on encaged redfish collected in coastal Newfoundland waters indicated an intercept of −68.1, a difference of only 0.6 dB from the *in situ* data (Gauthier and Rose, 2001a). When pooled together and weighted by the s.e.$^{-1}$ of the mean backscattering cross-section of each data point, *in situ* and *ex situ* data indicated an intercept of −68.7: identical to the weighted model for *in situ* data alone. The consistency of TS data between *ex situ* and *in situ* experiments is encouraging and we believe this TS model can be useful in the acoustic assessment of redfish in the North Atlantic. It is also likely to have applicability in the Pacific Ocean where the diversity of *Sebastes* is much greater.

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