Species identification in deep water using multiple acoustic frequencies

R.J. Kloser, T. Ryan, P. Sakov, A. Williams, and J.A. Koslow

Abstract: Multifrequency 12, 38, and 120 kHz acoustics were used to identify the dominant fish groups around a deepwater (>600 m) seamount (a known spawning site for orange roughy, *Hoplostethus atlanticus*) by amplitude mixing of the frequencies. This method showed three distinct acoustic groupings that corresponded to three groups of fishes based on size and swimbladder type: myctophids of total length less than 10 cm, morids and macrourids with lengths >30 cm, and orange roughy with a mean standard length of 36 cm. These three groups were the dominant groups caught in the demersal and pelagic trawls in the study area. A simple model of swimbladder resonance at depth of large and small gas-filled bladder fish groups is in agreement with our experimental observations. Traditionally, demersal and pelagic trawling is used to identify fish species in acoustic records. However, orange roughy are rarely caught in mid-water owing to net avoidance. Using three frequencies, these groups could be distinguished directly over their entire vertical extent from the acoustic records. This reduces a major source of positive bias uncertainty (factor range of 2.0–6.4) in the orange roughy biomass estimates.

Résumé : Une méthode acoustique à fréquences multiples de 12, 38 et 120 Hz a servi à identifier, par le mixage des amplitudes des fréquences, les groupes dominants de poissons sur un mont sous-marin en eau profonde (>600 m), un site de fraye connu de l'hoplostète orange, *Hoplostethus atlanticus*. La méthode révèle l'existence de trois regroupements acoustiques distincts qui correspondent à trois groupes de poissons caractérisés par leur taille et leur type de vessie natatoire: les myctophidés de longueur totale inférieure à 10 cm, les moridés et les macrouridés de longueur supérieure à 30 cm et les hoplostètes de longueur standard moyenne de 36 cm. Ces trois groupes sont ceux qui dominent dans les récoltes aux chaluts démersal et pélagique dans la région. Un modèle simple de la résonance en profondeur de la vessie natatoire chez les groupes de poissons à grande et à petite vessie remplie de gaz s'accorde bien avec nos observations expérimentales. Généralement, le chalutage démersal et pélagique sert à identifier les poissons repérés dans les inventaires acoustiques. Cependant, l'hoplostète orange est rarement récolté à mi-profondeur, car il peut éviter les chaluts. L'utilisation de trois fréquences a permis de reconnaître directement les trois groupes sur toute la colonne d'eau d'après les données acoustiques. Cela réduit une source importante d'erreur d'incertitude positive (facteur variant de 2,0 à 6,4) dans les estimations de la biomasse de l'hoplostète orange.

[Traduit par la Rédaction]

Introduction

Species identification remains a critical requirement in interpreting acoustic recordings for fisheries management (Horne 2000). This is especially true in the deepwater orange roughy (*Hoplostethus atlanticus*) fisheries of Australia, New Zealand, Namibia, Chile, and the High Seas (Kloser et al. 1996 Clark 1999; Boyer and Hampton 2001). Orange roughy are a long-lived fish that have low recruitment and form large schools when spawning, making them vulnerable to over fishing. In Australian waters, the major spawning aggregation was reduced by a quarter based on acoustic snapshot surveys between 1990 and 1993 (Kloser et al. 1996). This decline in biomass combined with catch and age data led to a fishery management strategy of reduced catches to rebuild the population in future years (Bax 1999). To establish whether the orange roughy stocks are rebuilding, the acoustic echo integration method has been proposed to monitor the spawning aggregation. Orange roughy have a wax ester swimbladder and a very low target strength (TS) compared with the other dominant gas-bladdered species of deepwater communities, hence the ability to accurately monitor the spawning population becomes very sensitive to the proportion of gas-bladdered species (Kloser et al. 1997).

Trawl sampling is traditionally used to allocate species compositions to the acoustic records in mixed-species situations. Net sampling has potential biases such as variable catchability between species and spatial and temporal extrapolation of patchy demersal and pelagic trawls. Orange roughy are typically captured with demersal trawls using headline heights of 5–10 m and are not generally caught in mid-water with pelagic trawls, presumably because of their marked avoidance reaction (Koslow et al. 1995). However, acoustic measurements indicate that orange roughy schools range from the sea bed to as high as 150 m into the water column. Pelagic trawls on these acoustic marks only capture a variety of mid-water fishes, many of which have gas-filled swimbladders (Kloser et al. 1997). This avoidance of trawl

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sampling by orange roughy could bias the assessment of species composition allocated to the acoustic records. A method is required that uses the acoustic data to distinguish the major species groups throughout the water column.

Species identification at a single acoustic frequency was developed and used in shallow water (<200 m) using echo statistics and environmental factors (e.g., Rose and Leggett 1988; Scalabrin et al. 1996). These classification methods require a reference set of acoustic and biological data on schools that have been accurately captured and for which there have been metrics obtained. In deep water (>750 m), the resolution of the vessel-mounted surface acoustics is poor and the time required to accurately capture fishes leads to small reference data sets. The avoidance response of orange roughy to mid-water sampling gears compounds the problem, as not all fishes can be sampled equally. Fishers' observations of orange roughy schools show they aggregate and disperse over very short time frames when in a spawning aggregation, or that the observation tool is too coarse to accurately determine their true dynamics or school shapes. This makes using vessel-mounted single frequency acoustic methods for species identification difficult in deep water.

Multiple frequency acoustic methods have been used to distinguish species or groups of zooplankton and discriminate between fish and zooplankton (e.g., Holliday 1977; Greenlaw and Johnson 1983; Cochrane et al. 1991). Fish species have been discriminated or sized using broadband frequencies or a number of discrete frequencies (e.g., Holliday 1971; Trevorrow 1996). In past acoustic surveys, we observed that particular deep scattering layers at >600 m depth were sometimes more prominent on either the 12- or 38-kHz hull-mounted echosounders on our research vessel. This observation is consistent with the change in resonance of small mid-water fishes with depth (Andreeva 1964). However, we found that these echosounders and a further 12-kHz hull-mounted echosounder available on the vessel were unable to distinguish between orange roughy and other scatterers, because of either the large sampling volume or insufficient range in frequencies. We therefore placed three frequencies (12, 38, and 120 kHz) on a deep towed multifrequency towed instrument (MUFTI) and trialed the system in 1996 during our routine acoustic survey of orange roughy. The multifrequency methodology was further refined with a specific orange roughy survey in 1999. The aim of our study was to improve methods for understanding the distribution and abundance of deepwater species, and in particular, the abundance of spawning orange roughy.

Material and methods

Biological sampling

Biological samples were obtained from pelagic and demersal trawls that targeted fish concentrations that had been located acoustically. The demersal trawl net was a commercial orange roughy trawl with a 40-mm codend liner, headline length of ~35 m, and height ~4 m. Demersal trawl time (actual fishing time) varied between 5 and 15 min for target shots on marks. During target shots the gear can be almost in free-fall (moving downwards at a steep angle). A large pelagic trawl was fitted with an opening–closing, five-net cod-end system based on the multiple plankton sampler of Pearcy et al. (1977). The cross-sectional area of the net mouth when fishing, as measured by acoustic sensors, was about 105 m^2. Mesh sizes in the trawl were 100 mm in the wings, reducing to 20 mm in the body and 10 mm in the extension; cod-ends were 7 mm. Pelagic tow duration was 10–15 min in the target shots. Trawling was at a speed of 2.5–3 knots. The system could take four samples from known depths per deployment. Target trawling of fish concentrations was possible with Scanmar acoustic sensors (Åsgårdstrand, Norway) to monitor the geometry and position of the fishing gear in the water column (Williams and Koslow 1997).

The composition of each demersal catch was identified to acoustic species groups based on body size and swimbladder type (Kloser et al. 1997) and numbers, lengths, and weights obtained. Seven dominant acoustic groups were eels (2 species), morid cod (3 species), oreos (5 species), orange roughy, sharks (10 species), macrourids (14 species), and 18 species of fish and crustacea that occurred in low abundance. Macrourids have large gas-filled swimbladders, except for the dominant species, *Coryphaenoides subserrulatus*, which has a large gas-filled bladder containing a spongy matrix. Further analysis was only carried out for species groups that represented >1% of the total catch. Pelagic trawl catches were treated in the same way. Myctophids of similar size (6–10 cm) and morphology and all having gas-filled swimbladders made up the vast majority of catches; therefore, they made the greatest contribution to acoustic scattering in the water column. Small numbers of morids and macrourids were also captured in mid-water.

Acoustic equipment

The acoustic equipment consisted of a purpose-built MUFTI that housed the single-beam 12-kHz and split-beam 38- and 120-kHz transducers (Table 1). The towed body was a deadweight type (450 kg in air) that was 2.4 m long and 0.5 m in diameter with a flat base to avoid the use of acoustic windows. The MUFTI towed body housed the transducers, transmitters, pre-amplifiers, Falmouth Scientific conductivity, temperature, and depth logger (FSI Micro CTD #1332, Cataumet, Mass.), and a monitoring pressure case. The monitoring pressure case contained equipment to measure physical parameters such as towed body pitch, roll, depth, and operating voltage, all displayed and logged continuously aboard the research vessel. The towed body was connected to the vessel by 2500 m of electromechanical cable and is further described by Kloser (1996).

Acoustic calibration

The acoustic system was calibrated at the surface and at depth with a 38.1-mm tungsten carbide sphere for all the transducers to obtain the on-axis echo integration constant (Foote et al. 1987; SIMRAD EK500 version 5.3, 1993). The TS of the sphere at a given frequency was calculated following MacLennan (1981) and checked for stability following Miyanohana et al. (1993). The equivalent beam angle is not calibrated using this method and was measured by the manufacturer of the transducer with tests on these values confirmed with a special calibration rig that rotated the transducers at the surface. The deep-tow transducers were also calibrated from 100 to 700 m to correct for changes with depth in transducer sensitivity and to test for changes in beam pattern (Kloser 1996). The seawater propagation pa-

Table 1. Specification of the transducers for the MUFTI deep-towed body and relevant calibration and instrument settings.

Transducer	12 kHz	38 kHz	120 kHz	Units
Manufacturer	MASA (single beam)	EDO Western (split beam)	SIMRAD (split beam)	
Equivalent beam width	–10	–21.1	–20.6	dB re 1 steradian
Beam width ± 3 dB	40	6.5	7	degrees
Band width	1	3.3	3.3	kHz
Pulse length	1.0	1.0	1.0	ms
Target sphere TC 38.1 mm	–42	–42.4	–39.5	dB re 1 m^2
Integrated absorption at 850-m towed body at 700 m	1.3	9.4	31.9	dB·km^{-1}

rameters of absorption and sound velocity were calculated from the formulae of Francois and Garrison (1982) and MacKenzie (1981), respectively, based upon temperature and salinity profiles obtained during the surveys with a CTD (calibration results for the relevant depths are presented in Table 1).

Acoustic sampling

Field samples were obtained from a spawning aggregation of orange roughy on St. Helens Hill (eastern Tasmania 41°14.0′S, 148°45.4′E) in July 1996 and 1999 as part of an ongoing acoustic survey for the management of the stock in the region (Kloser et al. 1996; Bax 1999). St. Helens Hill rises from 1100 to 600 m and is conical in shape (Fig. 1). The repeat surveys have used a system of straight line north–south transects at preset locations with the MUFTI towed body at a fixed depth of between 450 and 550 m (Kloser et al. 1996). To efficiently sample the fish species occurring around the hill, the MUFTI system was towed in a circle "loop" with 1800–2100 m of wire in the water at 2–5 knots, keeping the towed system a fixed 100–200 m above the seabed. For example, the ship would follow the 900-m depth contour, but owing to the long cable and vessel speed, the MUFTI towed body would be sampling in the 800- to 850-m depth contour. The vessel circled the hill in this fashion covering the 750- to 1100-m depth contours at 100-m intervals. This deployment method enabled optimal sampling of the fish species around the hill and minimized fish avoidance and down time due to turning of the vessel with long lengths of wire in the water when using traditional straight line transects.

Acoustic visualization

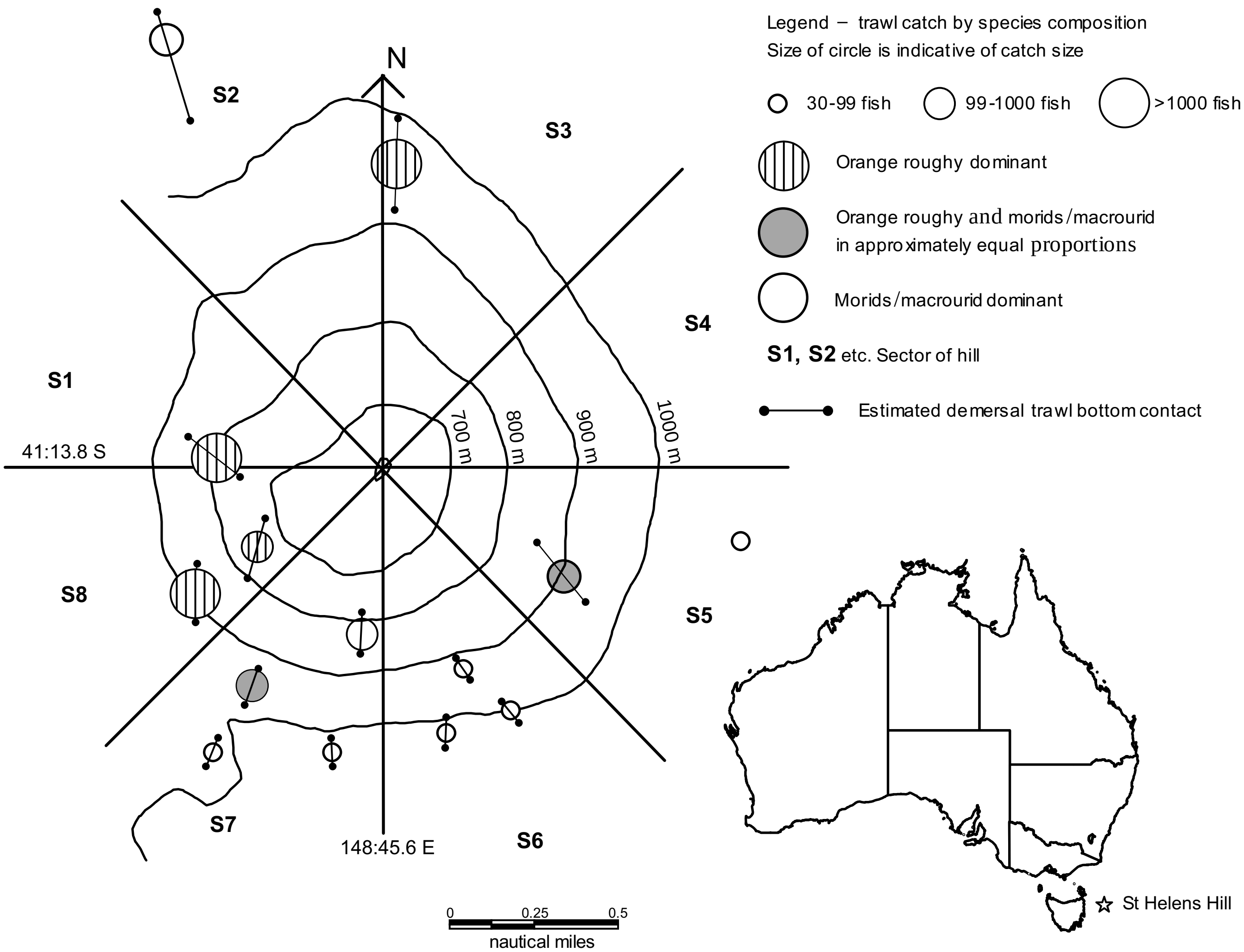
To manage, edit, and visualize the acoustic data, a specialized software program (ECHO) was written in C and C++ on a Sun Microsystems workstation (now Linux) using X-Windows and an Oracle database (Waring et al. 1994). This software program was upgraded to include methods for visualizing multifrequency echograms (Kloser et al. 1998). The philosophy of the program operation involved scrutinizing the individual acoustic frequencies and correcting the data by applying data modifiers and spatial restrictors. In this application, data modifiers included algorithms for noise thresholding or subtraction and applying compensation for known calibration offsets. The spatial restrictors (referenced from the surface, transducer, or sea bed) were applied to limit further computations on the particular data. Specifically, spatial restrictors were required on this data when affected by excessive platform movement and (or) electrical noise, and in redefining the start of the seabed echo. The resultant spatial offsets and data modifiers were displayed in a WYSIWYG (what you see is what you get) environment to ensure quality assurance and good user feedback for changes made. In mixing the frequencies, each frequency was allocated a separate colour palette with independent intensity start and dynamic ranges. The user could then dynamically adjust the frequencies to highlight specific differences in the echograms. Once a given presentation system was finalized, it was stored and all subsequent multifrequency echograms were viewed in the same way. The mixing algorithm used in this analysis involved displaying a particular frequency colour if it was higher in amplitude than the associated frequencies. The ability of the user to adjust the individual gains and dynamic ranges for each frequency in a dynamic fashion created an environment that greatly assisted in highlighting visual features in the frequency amplitude differences.

In total, 13 loops were carried out around St. Helens Hill in 1996 with the MUFTI deep-towed system and these were processed using the ECHO software. Each frequency was assigned a separate colour palette (12 kHz red, 38 kHz green, and 120 kHz blue) and the volume reverberation (S_v) signals adjusted for background noise, absorption, and calibration. The calibrated volume reverberation frequencies were then combined with separate colour palettes and mixed using amplitude dominance (Fig. 2). Each individual frequency and the frequency mixing highlight differences over an orange roughy aggregation (Fig. 2). This was used to train the visual classification system and to show up relative differences. The figure shows how the user adjusted the individual frequency gains to ensure that the orange roughy was an even mix of all the frequencies amplitudes seen as an even mixture of red, green, and blue pixels on the computer screen. The remaining multifrequency echogram separated into two regions of colour dominance of red (high 12-kHz signal) and green (high 38-kHz signal) (Fig. 2).

Target strength

In situ TS as derived from the SIMRAD EK500 version 5.3 were extracted from low-density regions associated with an acoustic group between frequencies at constant depth. The relevant TS selection criteria used were target threshold, –65 dB; normalized pulse length, 0.7–1.5; maximum gain compensation, 6 dB; and phase deviation, 0.5. Regions were selected where the depth was 20–30 m from the transducer face and acoustic intensity was low, targeted by pelagic trawling, and showed distinct differences in the frequency amplitudes (Fig. 3). Selection of regions based on these criteria was expected to reduce the known biases in in situ TS data

Fig. 1. Demersal trawl catch positions and the relative proportions of dominant species combined by swimbladder type of orange roughy (*Hoplostethus atlanticus*) and large gas bladder (macrourids and morids) associated with the sector of the St. Helens seamount (Australia) in July 1996.



due to depth and target density (Sawada et al. 1993; Soule et al. 1995; Koslow et al. 1997). For each region the mean linear TS was calculated for the 38- and 120-kHz split beam transducers and compared to previous TS measurements following Kloser et al. (1997) (Table 2).

Simple gas bladder resonance model

To investigate the normal incident TS of gas-filled swimbladders with depth and frequency, the simple model developed for spherical spheres by Andreeva (1964), adapted for prolate spheroids by Weston (1967), and applied by Holliday (1971) was used in the following equations with minor changes in notation based on Ye (1997):

$$\text{(1)} \qquad \mathrm{TS} = 10\log_{10}(\sigma_{\mathrm{bs}})$$

$$\text{(2)} \qquad \sigma_{\mathrm{bs}} = {a_{\mathrm{es}}}^2\left(\left(\left(\frac{f_{\mathrm{p}}}{f}\right)^2 - 1\right)^2 + \frac{1}{Q^2}\right)^{-1}$$

$$\text{(3)} \qquad f_{\mathrm{p}} = f_{\mathrm{o}}2^{\frac{1}{2}}e^{-\frac{1}{3}}(1-e^2)^{\frac{1}{4}}\left\{\ln\left[\frac{1+(1-e^2)^{\frac{1}{2}}}{1-(1-e^2)^{\frac{1}{2}}}\right]\right\}^{-\frac{1}{2}}$$

$$\text{(4)} \qquad f_{\mathrm{o}} = \frac{1}{2\pi a_{\mathrm{es}}}\left(\frac{3\gamma P + 4\mu_1}{\rho}\right)^{\frac{1}{2}}$$

$$\text{(5)} \qquad P = (1 + 0.103D)10^5$$

Here, σ_{bs} is the acoustic backscattering cross section at the incident acoustic frequency (f) of the equivalent spherical swimbladder volume of radius a_{es} with a prolate resonant frequency (f_{p}), and resonance quality factor of Q. The prolate resonant frequency is a function of the prolate spheroid roundness (e) and the spherical resonant frequency (f_{o}) at a hydrostatic pressure (P) for fish depth (D) and fish tissue density (ρ), with a ratio of specific heats for the swimbladder gas (γ) and the real part of the complex shear modulus of the

Fig. 2. Example of mixing three frequencies showing the individual calibrated volume reverberation compensated frequencies that are first quality assured removing known artefacts (*a*) red (12 kHz), (*b*) green (38 kHz), and (*c*) blue (120 kHz). A composite image (*d*) is produced where the frequencies have been optimized dynamically to highlight the amplitude differences in the echogram when there is an even mix on the region interpreted to be originating from orange roughy (*Hoplostethus atlanticus*). The dominant red (12 kHz) is interpreted to be originating from regions of species with large gas bladders (morids and macrourids), green (38 kHz) highlights the species with small gas bladders, and blue (120 kHz) highlights the orange roughy.

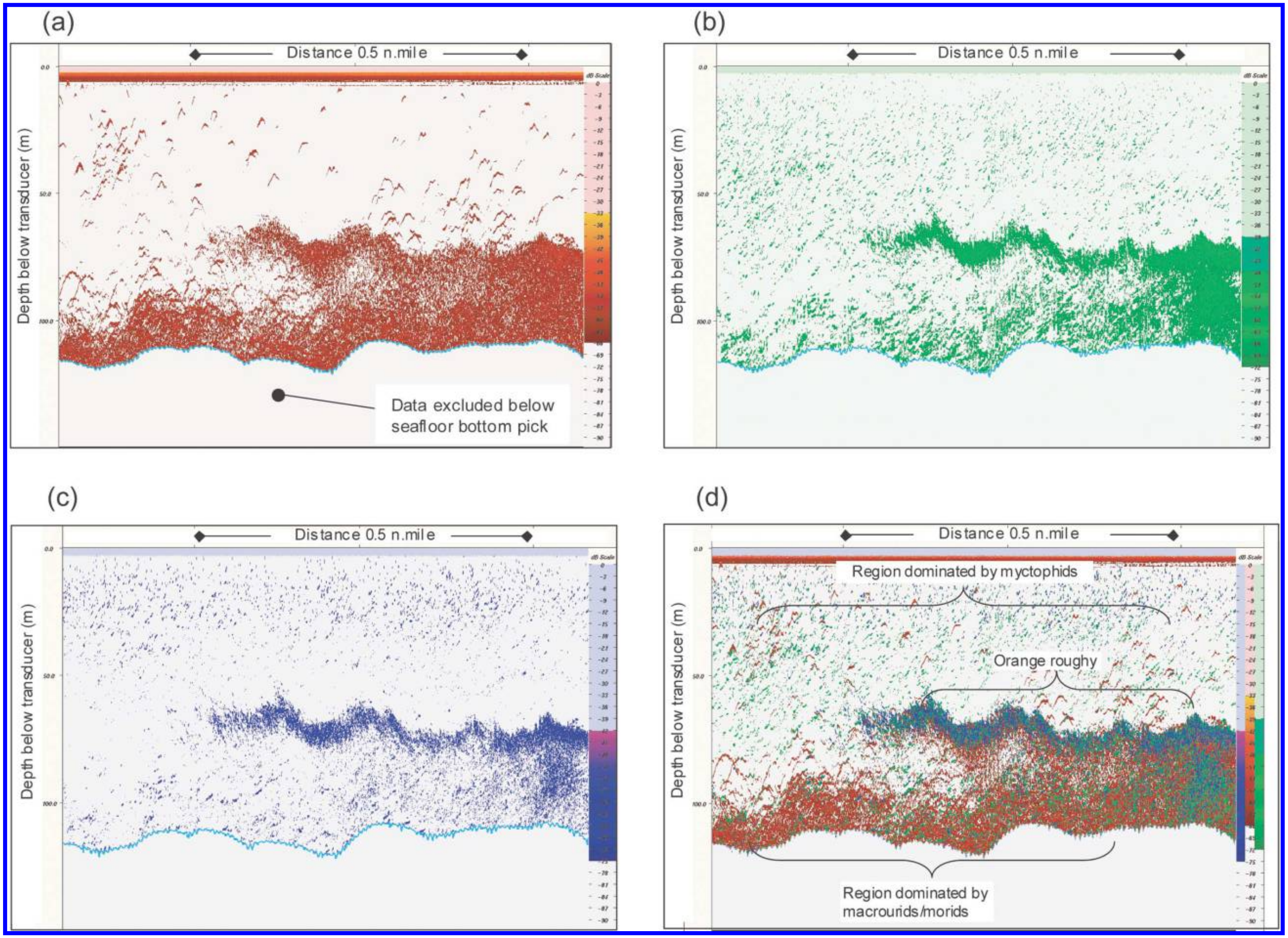
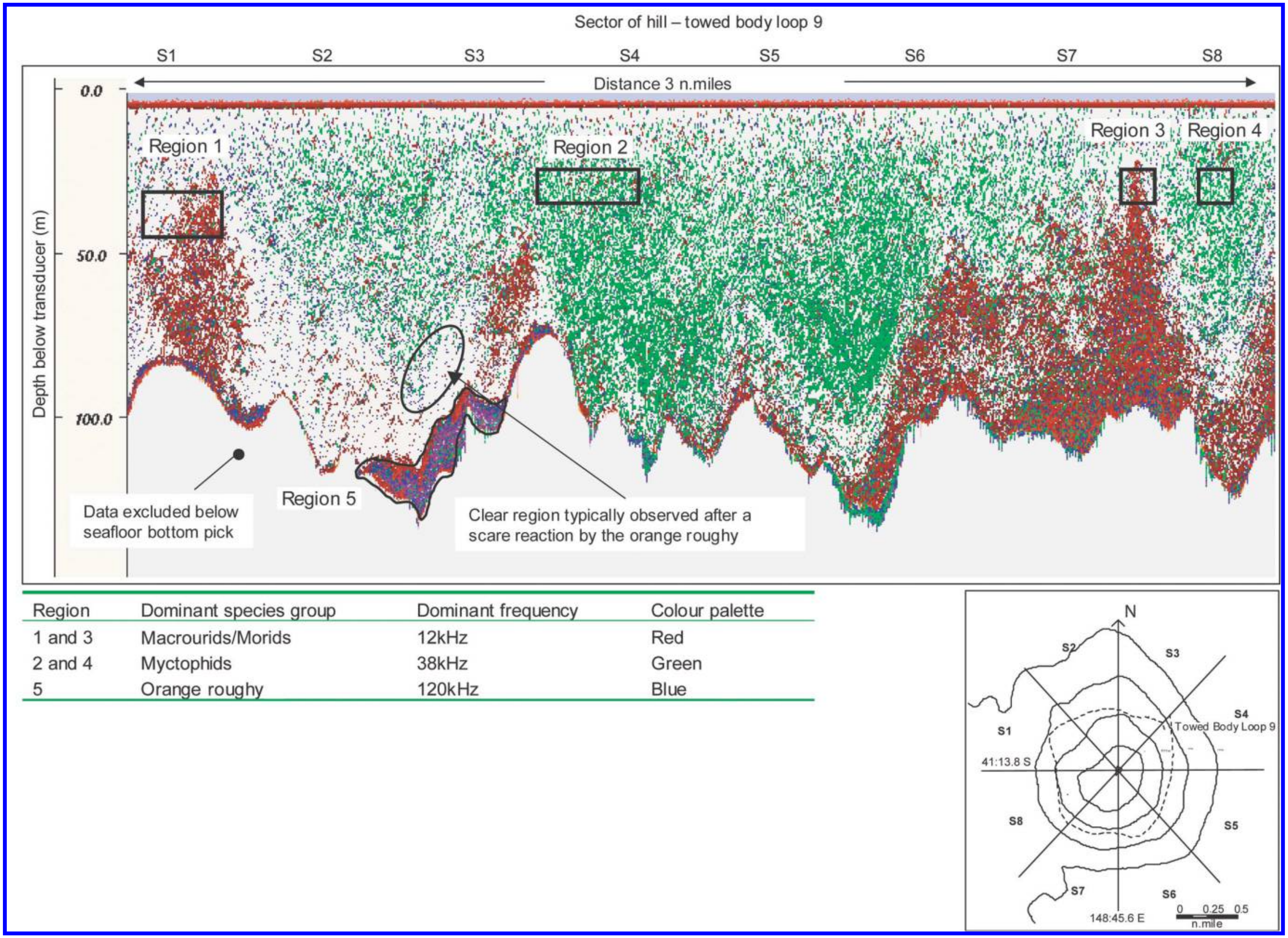


Fig. 3. Multifrequency acoustic data from a “loop” transect around St. Helens Hill, Australia, showing the dominant acoustic species group distribution as a function of sector around the hill according to the frequency mixing of Fig. 2. The towed body (MUFTI) is at a depth of ~700 m and is being towed clockwise with the vessel following the ~850-m depth contour. The five regions extracted for volume reverberation and target strength measurements are shown by enclosed polygons.



Region	Dominant species group	Dominant frequency	Colour palette
1 and 3	Macrourids/Morids	12kHz	Red
2 and 4	Myctophids	38kHz	Green
5	Orange roughy	120kHz	Blue

Table 2. Dominant species and species groups at St. Helens Hill, Tasmania, Australia.

Species	Swimbladder type	Length (mean, SD) (cm)	TS (dB re 1 m^2)	Acoustic category
Orange roughy	Wax ester filled	36 (4) SL	–48 to –52	Orange roughy
Myctophids (9 species with two dominant length modes)	Gas filled	5.8 (1)	–48 to –55	Small gas bladder
		9 (1)		
Macrourids (8 species)	Spongy tissue gas matrix or gas filled	34 (3)	–42	Large gas bladder
Morids (2 species)	Gas filled	50(8)	–32	Large gas bladder

Note: Swimbladder description and estimated target strength (TS at 38 kHz) from in situ measurements (Kloser et al. 1997). Fish length is total length unless shown otherwise as standard length (SL). SD, standard deviation.

fish tissue defined by μ_1. e is defined by the ratio of the minor semi-axis to the major semi-axis and is assumed to be 0.2.

To explore the indicative form of the model for the species encountered in this study, literature values were used from previous studies on shallower water species (Holliday 1971). Specifically, the following values were assumed: $\mu_1 = 10^5$ Pa, $\gamma = 1.4$, $\rho = 1.075$ kg·m^{-3}, and $\delta = 5$. No measurements at depth were available for a_{es} of the gas bladders, but to best fit the experimental data, these were set to 1.4 mm for myctophids, with small gas bladders, and 5.1 mm for macrourids–morids, which have larger gas bladders. These values represent the lower end of the range of values calculated by Brooks (1977) for mid-water species, and they are consistent with the high lipid content observed in the fishes.

School size and biomass comparison

The size of orange roughy schools and associated biomass was calculated separately for both the single frequency straight line and multifrequency loop surveys. Using ECHO software, the single 38-kHz frequency north–south transect data (MUFTI towed transducer at depth 450 m) were evaluated for echo structures that originate from orange roughy based on the accumulated knowledge of trawl catches and temporal school behaviour in the region. These echo features were circled by hand using a mouse and the acoustic returns echo integrated by linearly summing the volume reverberation values vertically, automatically compensating for near-seabed shadow-zone, and averaging horizontally according to Kloser et al. (1996).

The MUFTI multifrequency loop transects circled the hill at 100-m depth contour intervals (from 750 to 1150 m depth) with the transducer 150–200 m above the seabed. The multifrequency data were used to highlight the orange roughy based on the mixing of the three frequencies and regions on the echograms were circled by hand using a mouse. The highlighted regions, on the 38-kHz frequency, were echo integrated on a per transect basis to produce an area backscatter, S_{a_l}, value for each loop representing a 100-m contour interval area, A_l, (Fig. 1). The biomass, B, of orange roughy was calculated assuming a mean weight, W, of 1.5 kg and mean TS of –50 dB re 1 m^2, where

$$B = \frac{\left(\sum_{l=1}^{n} \overline{S_{a_l}} A_l\right) W}{4\pi 10^{\frac{TS}{10}}} \text{ kg}$$

Further details of the biomass calculations are outlined in Kloser et al. (2001).

Results

Biological sampling

Twenty-two demersal tows were carried out on St. Helens Hill (Fig. 1), of which 15 contained >20 fish; the total catch was 35.1 tonnes (t). The 45 species obtained were grouped into the seven acoustic categories, with four groups only contributing to <1% of the total. The three remaining groups were analysed further; orange roughy, macrourids, and morids represented 96, 2, and 1% of the total numbers, respectively. Orange roughy dominated catches on St. Helens Hill in sectors 1, 3, and 8, whereas sectors 5, 6, and 7 were dominated by macrourids and morids (Fig. 1). The difficulty of sampling all sectors and depth ranges of the hill equally resulted from seabed roughness, and lack of time availability left sectors 2, 3, 4, and 5 poorly sampled.

Three depth-stratified pelagic tows were targeted around the hill, 50–100 m above the seabed. These caught 35 species of pelagic fish, squid, and crustaceans, of which myctophids (possessing a gas-filled swimbladder) accounted for 95.5% (by numbers) of the catch. The total length of the dominant myctophids formed strong total length modes at 5.8 and 9 cm (Kloser et al. 1997). Morids and macrourids with relatively large gas bladders were also caught, but they represented less than 0.3% (by numbers) of the catch.

Acoustics

The acoustic loop survey data from the MUFTI towed system, deployed at a depth of ~150 m above the seabed, were analyzed as outlined in Materials and methods (Fig. 2) and are referenced to sectors of the hill (Fig. 3). Both the acoustics and demersal trawl distributions indicate that orange roughy were located in sectors 1, 2, and 3 and morids and macrourids are concentrated in sectors 6 and 7, as well as sectors 1 and 3, along with orange roughy (Figs. 1 and 3). It should be noted that the demersal trawling was undertaken over several days, whereas the acoustic loop transect was carried out in 1.5 h. Complete congruence between the two data sets is therefore not expected.

To directly compare volume reverberation (S_v) and in situ TS metrics between frequencies, five regions (Fig. 3) were extracted based on depth, frequency dominance, and sector on the hill associated with a particular species group (Table 3). Regions 1 and 3 are associated with species with large gas bladders dominated by the 12-kHz frequency, 4–8 dB higher

Table 3. Summary of the frequency differences in volume reverberation (S_v) and target strength (TS) for the selected regions identified in Fig. 3 with classification of dominant acoustic groups.

Region	Frequency (Hz)	Mean volume reverberation Sv (dB re 1 m)	S_v relative to dominant frequency in each region (dB re 1 m)	Mean TS (dB re 1 m^2)	No. targets	Relative TS to 38 kHz per region (dB)	Classification of dominant acoustic groups based on trawling
1	12	–63.3	0	na	na	na	Large gas bladder
1	38	–70.0	–6.7	–44.1	190	0	Large gas bladder
1	120	–71.3	–8	–42.6	48	1.5	Large gas bladder
2	12	–69.9	–5.3	na	na	na	Small gas bladder
2	38	–64.6	0	–49.3	240	0	Small gas bladder
2	120	–74.1	–9.5	–56.3	81	–7.0	Small gas bladder
3	12	–59.3	0	na	na	na	Large gas bladder
3	38	–63.4	–4.1	–39.7	206	0	Large gas bladder
3	120	–66.4	–7.1	–37.6	48	2.1	Large gas bladder
4	12	–77.1	–11.6	na	na	na	Small gas bladder
4	38	–65.5	0	–48.9	147	0	Small gas bladder
4	120	–75.5	–10	–57.6	24	–8.7	Small gas bladder
5	12	–50.6	–2.9	na	na	na	Orange roughy
5	38	–52.3	–4.6	na	na	na	Orange roughy
5	120	–47.7	0	na	na	na	Orange roughy

Note: na, not applicable.

than the S_v backscatter at 38 and 120 kHz (Fig. 4). The mean in situ TS in these regions range from –44.1 to –39.7 dB at 38 kHz and 1.5–2.1 dB higher at 120 kHz (Table 3). The higher TS at 120 kHz in these regions is unexplained and may indicate a problem with bias in the TS selection process due to the low number of targets selected at this frequency. In regions 2 and 4, which were associated with species with small gas bladders, the 38-kHz frequency was dominant with 9.5–10 dB higher S_v backscatter than the 120-kHz frequency (Fig. 4). Region 2 has a higher S_v (5.3 dB) at 12-kHz frequency owing to its larger sampling volume also including some fishes with large gas bladders, indicated in red (high 12-kHz S_v backscatter) (Fig. 3). The mean in situ TS in this region ranges from –48.9 to –49.3 dB at 38 kHz and 7–8.7 dB lower at 120 kHz (Table 3). Region 5, which we ascribe to orange roughy because of the characteristic avoidance response and trawl catch is characterized by high S_v backscatter at 120 kHz, 2.9–4.6 dB higher than at 12 or 38 kHz, respectively (Table 3). The lowest S_v backscatter for the orange roughy region 5 was from the 38-kHz frequency. No in situ TS data were obtained from region 5 because of the range from the transducer and high density of fishes.

The resonance model of small (a_{es} = 1.4 mm) and large (a_{es} = 5.1 mm) gas bladders shows the potential change in TS as a function of depth assuming constant swimbladder volume (Fig. 5). At the mean MUFTI operating depth of 750 m, the experimental TS measurements are compared to the simple model (Fig. 6). The TS values for the 12-kHz frequency have been extrapolated using the 38-kHz in situ TS values and the difference in volume backscattering strength for region 4, associated with myctophids, and region 1, associated with macrourids–morids. The simple normal incident resonance gas bladder model supports the general trend in the TS measurements with frequency; hence, our interpretation that of the three frequencies, the 38-kHz frequency has the highest S_v backscatter for small gas-filled swimbladders and the 12-kHz frequency has the highest backscatter for large gas-filled swimbladders in this example (Fig. 6).

The biomass of orange roughy on the St. Helens Hill seamount during surveys in 1999 ranged from null to 7000 t for the north–south grid surveys and 1100–2600 t for the MUFTI loop surveys (Table 4). The null value obtained from the grid survey indicates that no schooling features were observed that could be attributed to orange roughy. The lower biomass loop survey may have been due to avoidance of fish to the MUFTI towed system being closer than 100 m at times, as observed on echograms (Fig. 3). Error in the biomass calculation due to improperly assigning species composition using the north–south grid surveys could be a positive bias as high as a factor of 6.4. This error in the biomass calculation can be observed in the school areas of the echograms where they pass over the same school feature 2 h apart (Fig. 7). The estimated size of the orange roughy school defined from the grid survey based on trawl sampling and single frequency echo structure has a mean school height of 82 m, whereas the loop survey crossing the same school shows the mean school height to be 13 m. More importantly, the region allocated as orange roughy using a single frequency is shown to also contain a high mixture of fishes with large and small gas bladders using the MUFTI system (Fig. 7). No avoidance of orange roughy resulting

Fig. 4. Mean volume reverberation difference at 12 kHz (shaded) and 120 kHz (solid) frequencies relative to 38 kHz for each of the five selected regions based on Table 3. Region 5 associated with orange roughy (*Hoplostethus atlanticus*) has the lowest volume reverberation at 38 kHz.

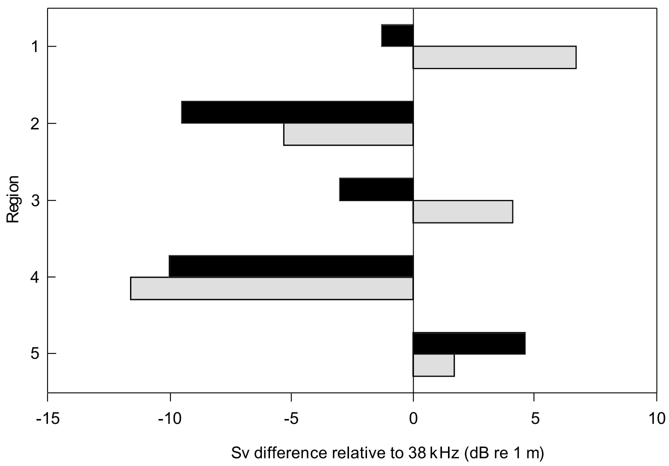
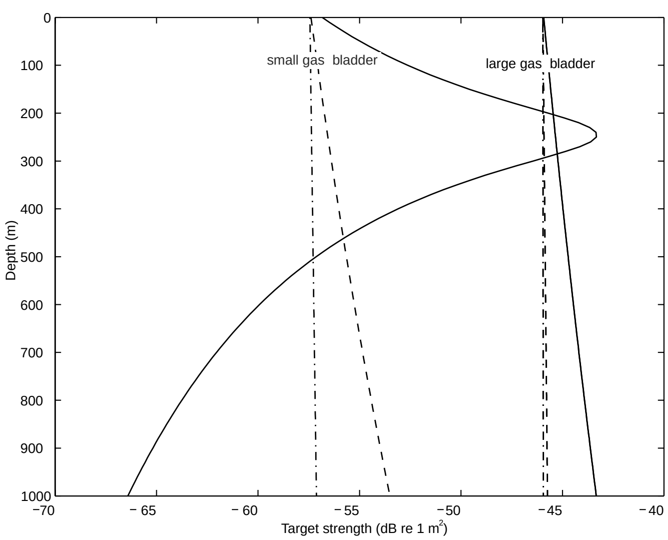


Fig. 5. Simple resonance target strength model of a spherical gas bladder for small (radius 1.4 mm) and large (radius 5.1 mm) fishes at 12 (solid line), 38 (broken line), and 120 (dotted broken line) kHz as a function of depth, assuming constant swimbladder volume.

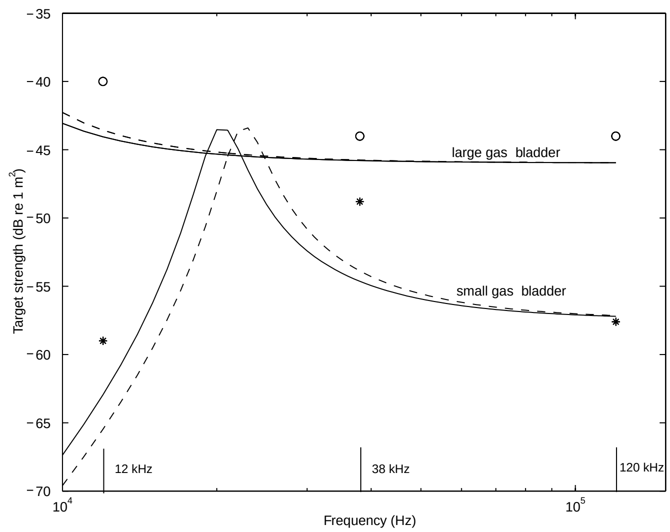


from the MUFTI transducer being 150 m above the school is evident in the echograms.

Discussion

Our acoustic system identified three acoustic groups based on the amplitude differences in the frequencies. ECHO software enabled these differences to be highlighted in a dynamic fashion that extracts the features of interest (Kloser et al. 1998). In this case, we have attributed the frequency differences to three acoustic groups of fishes as determined by their swimbladder type, size, and relative abundance. The three groups are myctophids of total length <10 cm, morids and macrourids with total lengths >30 cm, and orange

Fig. 6. Simple resonance target strength model at 750 m depth for a normal incident prolate spheroid (broken line, $e = 0.2$) and spheroid (solid line) swimbladder for small and large fishes (equivalent spherical radius of 1.4 and 5.1 mm, respectively) with experimental data for region 1 (○, macrourids–morids) and region 4 (*, myctophids) at the three frequencies 12, 38, and 120 kHz. The 12-kHz target strength values have been extrapolated from the ratio of S_v differences between the 38-kHz frequency in region 4 (Table 3).



roughy with a mean standard length of 36 cm. Our ability to differentiate orange roughy from other species in schools has been a major advance in interpreting single-frequency echograms and has been used in several biomass surveys of orange roughy both in Australia and New Zealand with consistent observations of species mixes in schools at orange roughy spawning sites (Kloser et al. 2000, 2001).

Our knowledge of orange roughy avoidance behaviour and the location of orange roughy schools on St. Helens Hill enabled us to tune the ECHO software (Koslow et al. 1995; Kloser et al. 1997). The avoidance reaction of orange roughy is evident in our echograms characterized by a low reverberation region remaining when the orange roughy school moves. The implication of this avoidance is that any remote sensing species identification system needs to be far enough away from the fish (ranges from 100 to 150 m are typical), so as not to influence their behaviour. Our use of the 120-kHz frequency is not ideal because of its high absorption in sea water for these surveys (31.9 $dB \cdot km^{-1}$ re 1 μPa at 1 m) reducing the effective usable range to 200 m. Other frequencies and (or) pulse transmission methods should be explored to improve this method.

Simple frequency models of the resonance from small gas bladders show a marked sensitivity to gas bladder size, eccentricity, and depth (Johnson 1977; Babailov and Kanevskii 1988). Our experimental results show that for regions dominated by fishes with small gas bladders, the backscatter measured at 38 kHz is 5 and 12 dB higher than for the 12- and 120-kHz frequencies, respectively. In this region, the mean in situ TS at 38 kHz is –49 dB and at 120 kHz is –57 dB. Based on a simple model (Weston 1967) we propose that swimbladder resonance is responsible for the high 38-kHz backscatter in this region. Conversely, the absence of a gas-

Fig. 7. Example of the difference in school size and acoustic species recognition using acoustic data from the same location in July 1999 from (*a*) the single-frequency 38-kHz north–south transects at 450 m depth and (*b*) an associated multifrequency loop transects at 750-m depth and height above bottom of 150–200 m approximately 2 h later.

Table 4. Biomass estimates of orange roughy at St. Helens Hill at 38 kHz based on north–south grid surveys with MUFTI at 450-m depth and trawl species identification, MUFTI loop surveys at 150–200 m above seabed (1999 only) using frequency mixing to highlight orange roughy (*Hoplostethus atlanticus*) schools.

Date	Survey type	Biomass estimate (tonnes)	Dominant species identification method
July 1996	North–south rid	9300*	Trawl
19 July 1999	North–south grid	Null	Trawl
31 July 1999	North–south grid	3500–7000^{+} mean 5200	Trawl
20 July 1999	Loop	2600	Multifrequency
31 July 1999	Loop	1100	Multifrequency

Note: $^{+}$Lower value indicates stricter classification of orange roughy schools using multifrequency classifications; *indicates the mean of two surveys.

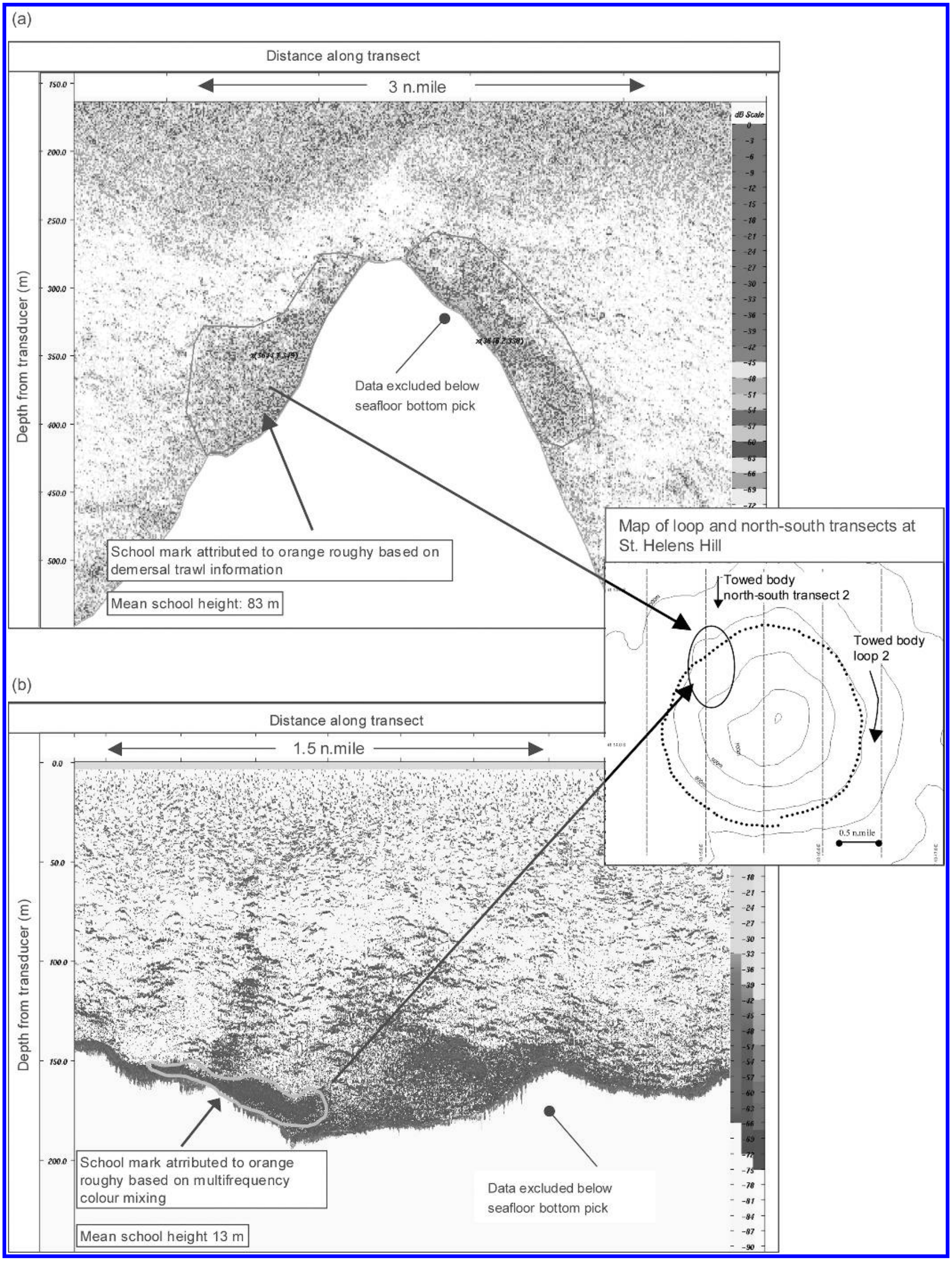
filled swimbladder in orange roughy results in a relatively lower reflectance at 38 kHz, which demonstrates that this frequency is not optimal for detection of orange roughy. For regions dominated by fish with large gas bladders, the results show a high backscatter at 12 kHz, 4–7 dB higher than 38 kHz, and 7–8 dB higher than 120 kHz. For the region of aggregated orange roughy, the backscatter at 120 kHz is 2.9 and 4.6 dB higher than for 12 and 38 kHz, respectively. Thus the 120-kHz frequency has the best discrimination for orange roughy because of its lower relative response to small- and medium-sized gas bladdered fishes. The 12-kHz wide beam width is best for the fishes with large gas bladders and the 38 kHz is best for the species with small gas bladders featured in this study.

We have used a simple resonance model to explain general trends in experimental observations. Our choice of gas bladder size, and to a lesser degree, elongation, greatly alters the form of the model output. We have not measured directly the expected swimbladder size at depth or parameters such as the ratio of specific heats of the swimbladder gas and the fish tissue density and complex shear modulus over the frequency range. Measurements of swimbladder size would ideally be based on the required fish buoyancy at depth based on the fishes' lipid content. Also, we have not considered the effect of swimbladder orientation (Babailov and Kanevskii 1988). We conclude from our spherical resonance target that the general trend that we observe with the experimental data will also hold for Gaussian changes in tilt orientations. Feuillade and Nero (1998) and Ye (1997) have developed more complex gas bladder resonance scattering models. These models may be useful to explore more quantitative assessments of the multifrequency method. In this work, we have used a simple model to explore the dominant relationships in the experimental observations of fishes with gas-filled swimbladders: that excludes orange roughy.

Orange roughy represent complex scatterers with a relatively large, ossified, and cavernous head, dense backbone, and high lipid content (including a wax ester filled swimbladder) that makes accurate modelling challenging. Existing models based on overall shape and composition parameters are necessarily simplistic and there is a large disagreement between model results for this species (McClatchie and Ye 2000; Barr 2001). Our in situ TS data appears to support the model results of Barr (2001) where a 33.6-cm orange roughy has a model TS of approximately –51 dB and in situ measurements of –51 to –52.1 dB (Kloser et al. 2000). No sensitivity analysis of the model to variations in radius of curvature and (or) sound speed and density measurements of fish flesh and wax ester were performed, so the comparison may be fortuitous. The frequency response model of orange roughy proposed by Barr (2001) has many peaks for an individual fish, but we suggest that these peaks would smooth out for a range of fish sizes with more complicated composition and tilt angles, as is encountered in the ocean. The model of Barr (2001) does not explain the higher backscatter at 12 and 120 kHz experienced in this study.

A limitation of the equipment used in this trial was the wide 40-degree beam of the 12-kHz system. Unfortunately, to have a narrow beam at this low frequency, similar to the 7-degree beam width of the 38- and 120-kHz systems, would require a transducer 1.2 m in diameter. The sampling width and volume at the half power points of the 12-kHz, 1-ms pulse-length system at 100-m depth is 73 m and 3121 m^3, compared with 12 m and 112 m^3 for the 7-degree 38- and 120-kHz frequencies; the 12-kHz frequency effectively samples 28 times the water volume compared with the 38- and 120-kHz frequencies at 100-m depth. As the 12 kHz shows higher reflectance for the fishes with large gas bladders, they appear even more dominant on a multifrequency S_v compensated echogram owing to the greater sampling volume. Multifrequency echograms derived from differing beam widths complicates and limits quantitative assessment. To reduce the impact of differing sample volumes, the species mixtures need to be homogeneous over dimensions larger than the largest sampling volume, in this case 3121 m^3 at 100-m depth. Small, apparent orange roughy schools were sometimes completely absent from the 12-kHz records, making unsupervised classification based on multiple frequencies problematic. Also, the ability to ground truth our acoustic records with precisely located trawling in time and space is not possible given current technology. This limits our ability to perform rigorous statistical analyses of the data.

An obvious advantage of the multifrequency technique we have developed is the speed at which the dominant acoustic species groups can be obtained during a survey. The single-


(a)
Distance along transect
3 n.mile
Depth from transducer (m)
dB Scale
Data excluded below seafloor bottom pick
School mark attributed to orange roughy based on demersal trawl information
Mean school height: 83 m
Map of loop and north-south transects at St. Helens Hill
Towed body north-south transect 2
Towed body loop 2
0.5 n.mile
(b)
Distance along transect
1.5 n.mile
Depth from transducer (m)
School mark atrributed to orange roughy based on multifrequency colour mixing
Mean school height 13 m
Data excluded below seafloor bottom pick

loop survey of the hill was undertaken in 1.5 h, whereas the trawl sampling was undertaken over several days (with possible movement of fishes); also, many parts of St. Helens Hill could not be trawled. Additionally, the method of frequency mixing is relatively insensitive to calibration errors. The user can isolate a characteristic in the echo space by adjusting the colour amplitude mixing to be equal at all frequencies. Frequency amplitude differences can then be observed in other parts of the image. We have supplemented our interpretation here by both physical sampling and using a simple resonance model to explain the gross differences observed. Using this species identification technique, the snapshot biomass of orange roughy at St. Helens Hill is a factor of 2–6.4 lower than the traditional north–south grid surveys. We assume that the loop survey method is a robust relative snapshot measure of the spawning population not biased by avoidance or survey design. The 1996 and 1999 north–south grid surveys shows that the estimated biomass on the grounds has continued to decline and our new method reinforced the observed decline. This decline in biomass is occurring at a time when the assessment model is expecting an increase and has major implications for the management of the fishery (Bax 1999).

This application of multifrequency species identification has highlighted the problem of the 38-kHz frequency that is commonly used to survey orange roughy stocks. It appears that this frequency produces higher reflectance for myctophid fishes with small gas bladders at our operating depth than the 12- and 120-kHz frequencies. The 120-kHz frequency is the best of the three frequencies used for orange roughy discrimination, but has a very limited range because of its high absorption. The method of frequency mixing developed here can be used more generally to explore echo features in a wide range of multifrequency acoustic data sets. To extend this work to find optimal frequencies for particular species groups will require more refined acoustic scattering models with associated field testing. We postulate that the use of lower frequencies like commercially available 70-kHz would increase the usable range of our method and still provide the required discrimination between fishes with small gas bladders and orange roughy at 700-m depth.

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