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Report of Fishing Industry Science Alliance (FISA) project 13/15

Scottish Marine and Freshwater Science Vol 7 No 15

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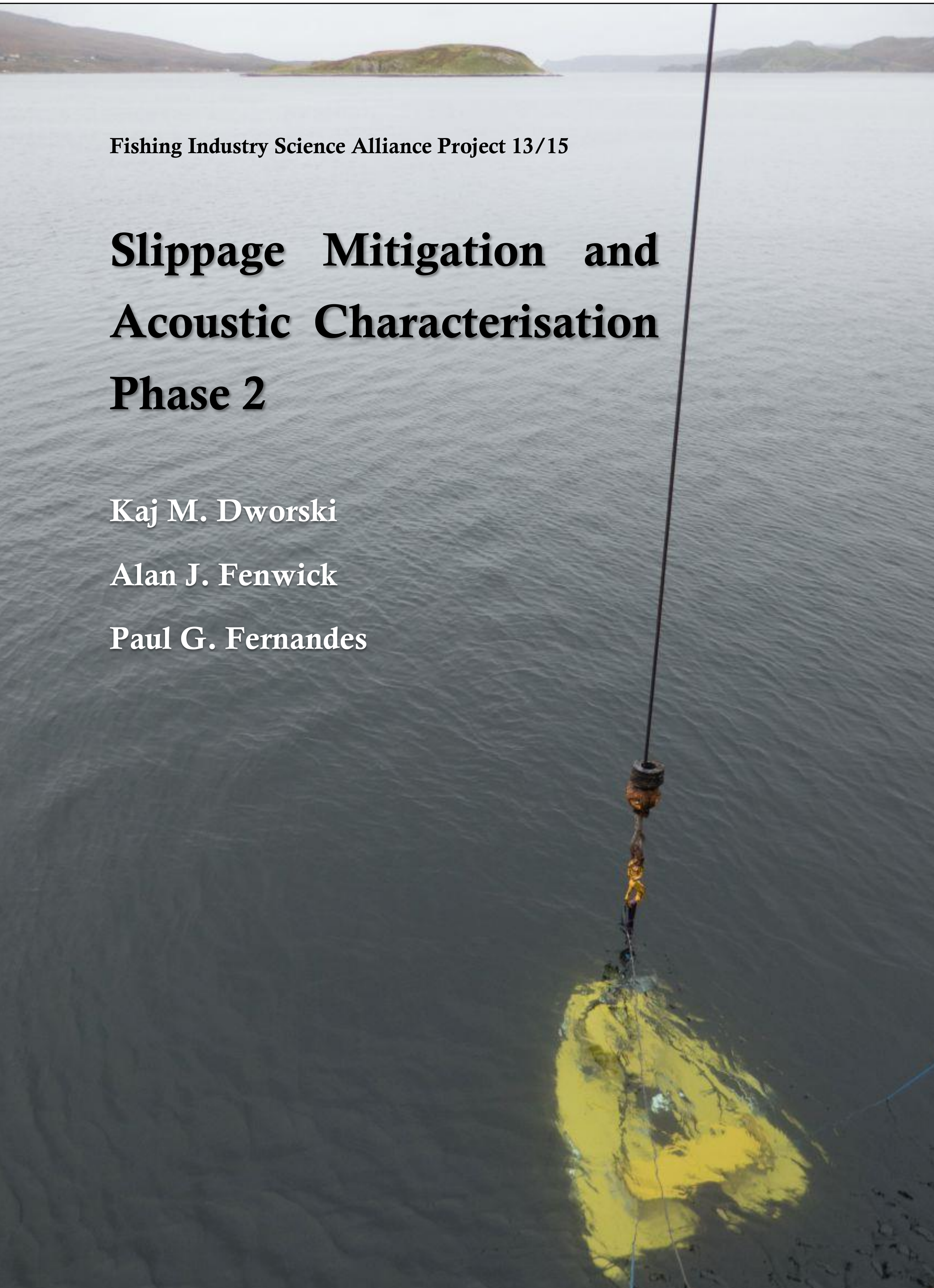

Fishing Industry Science Alliance Project 13/15

Slippage Mitigation and Acoustic Characterisation Phase 2

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Front cover. Deployment of the Edgetech broadband sonar in Loch Erribol, Scotland on 6th October 2015.

Executive Summary

The work reported here is the second phase of what is envisaged as a four phase project to develop a facility for the fishing fleet to estimate the size of mackerel using sonar. In the first phase a new sonar system was tested at Woods Hole Oceanographic Institution, analysis software was acquired and adapted, and a fish sizing algorithm was developed. The algorithm was initially tested on model data. In this second phase, the sonar system was deployed at sea during the mackerel fishing season and data was collected to refine the sizing algorithm.

The sonar was a modified EdgeTech 3200 sub-bottom profiler comprising a towed body with four broadband sonar channels and on-board processing. It was deployed from MRV Scotia in the North Sea from 5-15 October 2015, during the annual mackerel survey carried out by Marine Scotland Science. The first activity was to calibrate the system in Loch Eriboll and St Magnus Bay. During the cruise, records were taken of schools of herring, pearlsides (*Maurolicus muelleri*) and mackerel.

Analysis of these data included enhancement of the processing software to improve the estimation of volume backscattering strength spectra. Unfortunately, the mackerel were not present in the expected areas of the survey and only after searching extensively to the extreme north east of the North Sea were mackerel schools found. Only one school was sampled with the fishing trawl: the average fish size in this catch was 33 cm. The equivalent estimates of mackerel size as calculated from the sonar data was 21.5 cm. Although this is close to what was observed in the catch, it is not as close as is required. Clearly more data is required to tune the sizing algorithm using more catch data of various sizes. Enhancements to the algorithm and scattering model on which it is based are also required.

The sonar's towed body could be towed at speeds up to ten knots, though data quality was poor above five knots. Data were collected on all four channels but there were problems with data quality from the two lower frequency channels. The acquisition software developed in the first phase was modified to improve utility.

The system was also successfully calibrated and methods to perform the calibration and analyse the data were established. There is one outstanding issue with the varying levels of scattering between transducers: this will require further investigation and a solution based on using the seabed for calibration has been identified.

Overall, the results were very promising: the distinctive theoretical broadband scattering spectra (a rise in scattering at low frequencies), was captured in the field data. This is all the more evident when comparing the broadband spectra of other species encountered: herring and pearlsides, as expected from theory, did not exhibit such a rise. In order to collect more biological samples, it is recommended that the project proceed to the next phase which will involve deploying the sonar from a trawler during fishing operations.

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1. Introduction

Mackerel is the most important pelagic species in the Scottish fishing fleet and the most valuable single species fishery in Scotland, accounting for 29% (£126 million) of the total value of Scottish landings in 2013. The species consists of one stock, known as the North East Atlantic mackerel stock, and is managed under the European Union's (EUs) Common Fisheries Policy (CFP), normally in agreement with other coastal states (Norway & the Faroe Islands). ICES stock assessments in 2015 indicate that the stock is being overexploited (Fishing mortality F >Fmsy) although the spawning biomass remains above the reference points. The total catch taken from this stock in 2014 was 1,393,000 t, which at an approximate/average value of over £1000 per tonne makes this a fishery worth in excess of a billion pounds. The fishery is important to many other northern European nations such as Norway, Netherlands, Ireland, the Faroe Islands, and more recently, Iceland.

The landings obligation of the European Commission's current Common Fisheries Policy (CFP) requires all pelagic fishing vessels to land all of their catch (i.e. not to discard or "slip" any of the catch). This has potential impacts on the profitability of the European mackerel fishery, because small fish are less valuable than large fish: this in turn could lead to [illegal] discarding - or "slippage" as it is known in the pelagic industry - of small fish. In the light of the control regulations of the landing obligation, there are reputational issues associated with continued activity of this type and there may also be detrimental effects on the population. The problem of slippage is also relevant to the industry's continued certification of its produce: in 2011 the Marine Stewardship Council certified the Mackerel Industry Northern Sustainability Alliance (MINSA, which Scotland's mackerel fishing industry is a part of) as sustainable; this has been suspended since 2012 due to the disputes with Iceland and the Faroese (Hannesson 2013). With a resolution to the latter dispute in sight, the focus will return to other aspects important to accreditation which include slippage and its mitigation. There is, therefore, a need for the industry to be able to determine the size of individual mackerel within a fishable school. Ideally this should take place before fishing operations take place, to avoid catching fish of an inappropriate [small] size. Some of the measures currently available to fishers to determine the size of fish prior to fishing (e.g. jigging, which is an automated form of multiplehook fishing) are ineffective. This project, called Slippage Mitigation and Acoustic Characterisation (SMAC), aims to provide acoustic tools to determine the size of mackerel prior to capture and so avoid slippage.

Fisheries acoustics (Simmonds and MacLennan 2005) is a branch of applied biological oceanography aimed at developing and using active hydroacoustic systems for the detection, quantification & qualification of aquatic life. The techniques have widespread applications, most notably in the use of surveys of marine resources such as sardine (Zwolinski *et al.* 2009), herring (Simmonds 2003), anchovy (Boyra *et al.* 2013), as well as cod (Rose *et al.* 2000) and krill (Brierley *et al.* 1997); but also in the study of marine ecology (Rose 1995; Brierley *et al.* 2002). Acoustic surveys currently provide fisheries-independent abundance indices for the assessment of many pelagic species in the Northeast Atlantic, including North Sea herring and blue whiting. Thus far, the techniques have been based largely on the use of single beam, narrowband echosounders, although in the last decade or so, the combined use of many narrowband frequencies (typically numbering 3 to 6 individual frequencies of e.g. 18, 38, 50, 120, 200 and 333 kHz) has allowed for better identification of the backscattered signal (Lavery *et al.* 2007).

The use of multi-frequency techniques has certainly improved echogram scrutiny, and therefore, assessment quality: however, uncertainties remain surrounding species identification, particularly in mixed-species aggregations in some areas. These issues can now be further improved by the use of broadband systems which sweep throughout the frequency range, thereby exploiting size specific scattering spectra. Broadband echosounder systems have been developed as bespoke systems (Simmonds *et al.* 1996; Zakharia *et al.* 1996), but until recently, have not been available as commercial products.

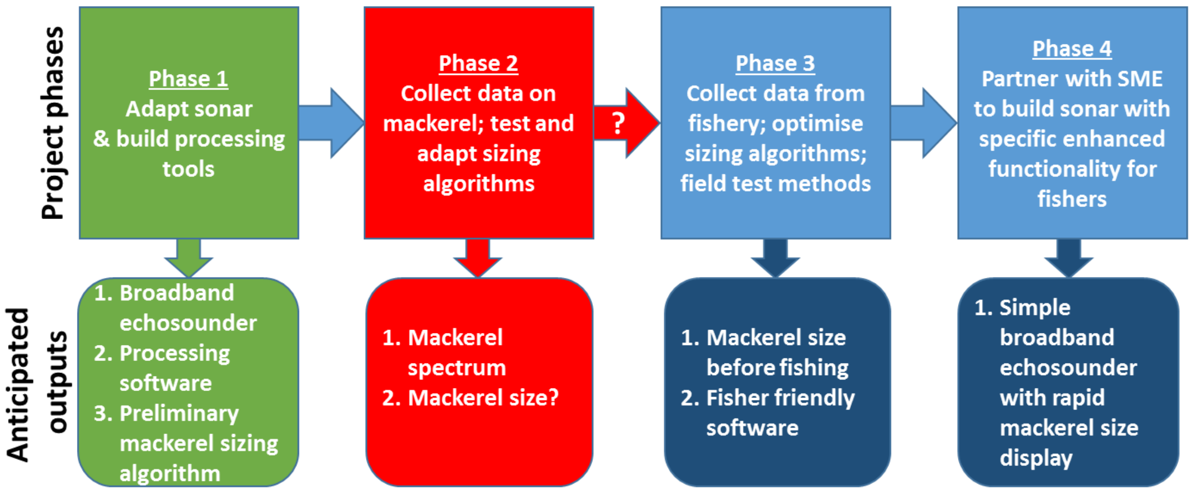

Figure 1. Phased sequence of projects to deliver a system for the remote determination of mackerel size. Green boxes represent the current completed project. Red arrows and boxes indicate the critical phase: whether the broadband spectra (acoustic characteristics), collected from mackerel schools in the wild, conform to theory and allow for size to be estimated. Blue boxes represent further phases proposed to achieve the ultimate goal of developing an acoustic system for sizing mackerel for use by the fishing fleet.

The next generation of Simrad echosounder, long the industry standard in fisheries acoustics, will be a broadband device: the Simrad EK80. However, this will be limited to the higher frequencies (greater than ~20 kHz). An alternative commercial system, supplied by Edgetech as a sub-bottom profiler, has been adapted for use as a broadband sonar (Stanton *et al.* 2010). This has the advantage of operating to low frequencies (greater than ~1 kHz) which allows for resonance peaks of fish with swim bladders to be captured and the turning point between Rayleigh and geometric scattering to be pinpointed (see Lavery et al. 2007, their Figure 1). These features of the broadband scattering spectrum may allow for sizing of fish (Holliday 1972) and are the features which we aim to investigate in this project as being potentially indicative of mackerel (fish) size.

The project has four phases (Fig. 1). Phase one of the project (SMAC.1) funded by Fisheries Innovation Scotland (FIS) was completed in the summer of 2015. Following publication of collected data by Woods Hole Oceanographic Institution (WHOI) demonstrating that the commercially available EdgeTech sub-bottom profiler could be modified and operated as a broadband echo sounder, a similar system was specified and procured by Marine Scotland Science (MSS). During a previous cruise some of the practicalities of deploying, towing and calibrating the system had been addressed. However, it had not been possible to successfully collect acoustic data across the entire frequency spectrum. The unit was returned to the manufacturer and was subsequently successfully tested at WHOI. Staff from the University of Aberdeen (AU) and MSS were trained in the use of the EdgeTech propriety data acquisition software and the analysis and modelling software developed by WHOI. Modifications necessary for the use of the analysis software with the MSS system were also undertaken. Sizing algorithms were developed at AU and successfully tested against data simulating the acoustic returns from a school of mackerel, generated using acoustic scattering models.

The aim of the second phase (SMAC.2) was to field test the sizing algorithms and refine them using data collected during the MSS mackerel acoustic survey from 5 October to 16 October 2015. The survey was carried by MRV Scotia. A narrative of the cruise is contained in the next section. The theory of estimating size from broadband acoustic data is presented in Section 3. Results of the analysis of size estimation and comparison with sizes measured from the catch are presented in Section 4. These results are then discussed in Section 5 along with conclusions and suggestions for further work.

2. Cruise Report

2.1 Aims

The aims of the cruise in respect of the EdgeTech broadband sonar were to:

1. Calibrate the sonar
2. Determine the towing characteristics of the sonar's towed body
3. Collect broadband acoustic data on mackerel and other fish targets
4. Process and analyse the acquired data to validate the proposed mackerel sizing algorithm

The sonar was deployed when schools were found during transects in the mackerel survey and towed over the school. The ship then trawled on the school to collect samples for measurement. The area covered by the survey was chosen according to where pelagic trawlers were fishing.

2.2 Narrative

MRV Scotia left Aberdeen on the 5 October and sailed to Loch Eriboll where the EK60 multi-frequency survey sonar was calibrated. An attempt was also made to calibrate the EdgeTech sonar system. The towed body was deployed with the ship stationary - see front cover. An aluminium sphere was hung beneath the body, and readings taken. The results were not as clear as hoped which may be due to two factors. One is that the water may have been too shallow at 50 m deep. Another may be the large quantity of fish present throughout the water column. The calibration was attempted again in St Magnus Bay, with MRV Scotia drifting in water depths of 150 m. The results were much improved and the calibration curves were similar to those which had been obtained previously during testing at WHOI.

After transit to the survey area a series of transects was begun and continued for four days, during which the sonar was deployed from the starboard side. Towing trails were carried out at various speeds. Herring schools were detected and data collected. No mackerel were found. As could have been predicted there was interference from the low frequencies of the EK 60 (18 and 38 kHz) so these were switched off when the EdgeTech was deployed. The survey was abandoned on the 12th while on zig-zag legs up the east of Shetland mainland, due to the lack of mackerel encountered. MRV Scotia then transited NNE to the area north of Viking bank where Norwegian and two Scottish trawlers had been fishing for mackerel.

After arrival and unsuccessful searches with the EK60, the EdgeTech sonar was deployed and towed at 5 knots on the 13th and 14th. There was interference from search sonars when trawlers were nearby. A large body of pearlsides was detected, and eventually a school of mackerel was detected shortly before the body had to be recovered for the return journey to Aberdeen.

2.3 Outcome

Almost 40 hours of broadband acoustic data were recorded over 6 days. This includes calibration, various noise and tow tests. Fish school data was only a small proportion of this due to the low numbers of mackerel schools encountered.

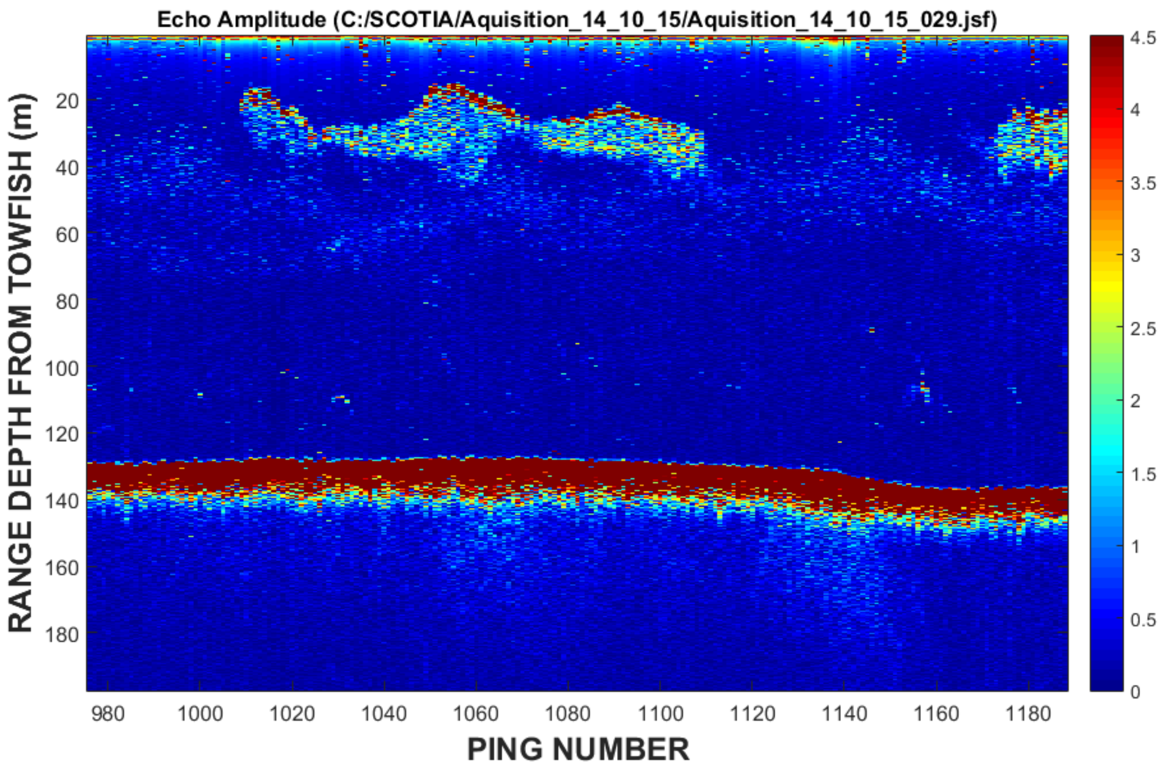

Figure 2. Echogram of a mackerel school from the EdgeTech broadband sonar. Depth on the y axis displayed as the range from the towfish (which was at a depth of 6 m). The ping number scale on the x axis, given a ping rate of 0.5 Hz and speed of 5 knots, equates to a total distance of approximately 1050 m. The colour scale is relative echo intensity: red is high, indicating strong echoes (fish schools and the seabed), blue is low (empty water).

Acquisition ranged from short runs, under 10 minutes, to a single continuous over-night run lasting 14 hours. Sets of data were obtained from three types of fish – herring, mackerel and pearlsides. Species were confirmed by sampling with a pelagic trawl. An example EdgeTech echogram taken from a mackerel school is given in Figure 2.

The sonar was operated with a variety of pulses of different lengths and bandwidths on the four transducers. The quality of the data was affected by noise which included internal electrical noise, ship noise, and noise associated with towing.

Shorter pulse widths proved more effective and at the depths encountered, there was no range penalty normally expected due to the smaller amount of energy in each pulse.

The towed body was deployed and successfully towed at speeds of up to 10 knots. Data quality was highly dependent on towing speed, with 5 knots established as the best compromise. Higher speeds introduced unacceptable amounts of noise in the system. It was found that there were noise artefacts on the two low frequency channels during towing. Their behaviour depended on the pulse length, the sea condition and the towing speed. When trawlers were nearby, there was interference from their search sonars which made one of the channels unusable.

Table 1. Specifications of the transducers contained in the MSS EdgeTech 3200 system.

Manufacturer	**EdgeTech**	**EdgeTech**	**Airmar**	**Airmar**
Model Designation	KT-0504 (Shamu)	KT-424	M1192 Custom housed unit	M159 Custom housed unit
Centre frequency (nom)	3.5 kHz	10 kHz	35 kHz	50 kHz
Bandwidth (nom)	1 - 5 kHz	4 - 24 kHz	25 - 45 kHz	42 - 65 kHz
Circular Beamwidth (nom)	25 deg.	15 deg.	19 deg.	20 deg.
Transmitting response (dB re 1uPa/V) at 1m	158	160	170	166
RMS power	2 kW	2 kW	1 kW	1 kW

Calibration of the system produced good results, with frequency characteristics similar to the ones obtained by the WHOI system. The lower frequency transducers require the bandwidth to be shortened compared to their declared nominal range to obtain optimal performance. Pulses were selected to allow frequency coverage from 1 to 65 kHz. The pulse lengths and bandwidths were chosen to ensure best sonar performance for data collection, but due to transducer limitations it was necessary to allow gaps between the bands of the individual transducers.

Experience was gained in handling and deploying the towed body and setting up the transmission and data collection parameters of the system. It was found during the cruise that the manufacturer supplied standard pulse characteristics were unsuited to collecting data on the species observed and as noted the pulse parameters were altered. Protocols were developed for collecting data with the multi-channel acquisition software, over extended periods. In terms of sonar performance, the data from the low-frequency, 1-5 kHz, Shamu transducer were disappointing. In addition there were as yet unexplained artefacts on both the Shamu and 424 channels (the low frequency channels). Overall, however, it was possible to collect good quality data.

During the cruise the opportunity was taken to streamline the operation of the processing software and the accompanying system manual was updated. Data collection during the calibration process has been simplified and automated where possible. In addition the selection of data for processing from the echogram is now more effective and easier.

When possible, detected schools were fished on, but as there were a number of schools in the area it was uncertain if the school that was sampled acoustically was actually the one sampled by the trawl.

2.4 Conclusion

Significant steps forward were taken in the successful operation of the sonar and establishing that the body can be towed at speeds up to ten knots. No particular difficulty was encountered in the deployment and recovery of the body and in the setting up and operation of the sonar and data recording software. However, data quality was affected by towing speed and thus, when deploying the towed body, the speed should be no more than 5 knots. This would have implications for commercial fishing operations.

3. Methods

This section contains an overview of the theory and the broad band data analysis procedures. Detailed descriptions of the software and procedures including a flow chart for the data collection and data collection process may also be found in the report on the first phase of the project (Daworski *et al.* 2015).

3.1 Theory: Mackerel Scattering Properties

A Distorted Wave Born Approximation (DWBA) acoustic scattering model was used to investigate the effect of size on acoustic scattering (Chu., D. pers. comm., NWFSC, NOAA Fisheries, USA). The model assumes that acoustic scattering from

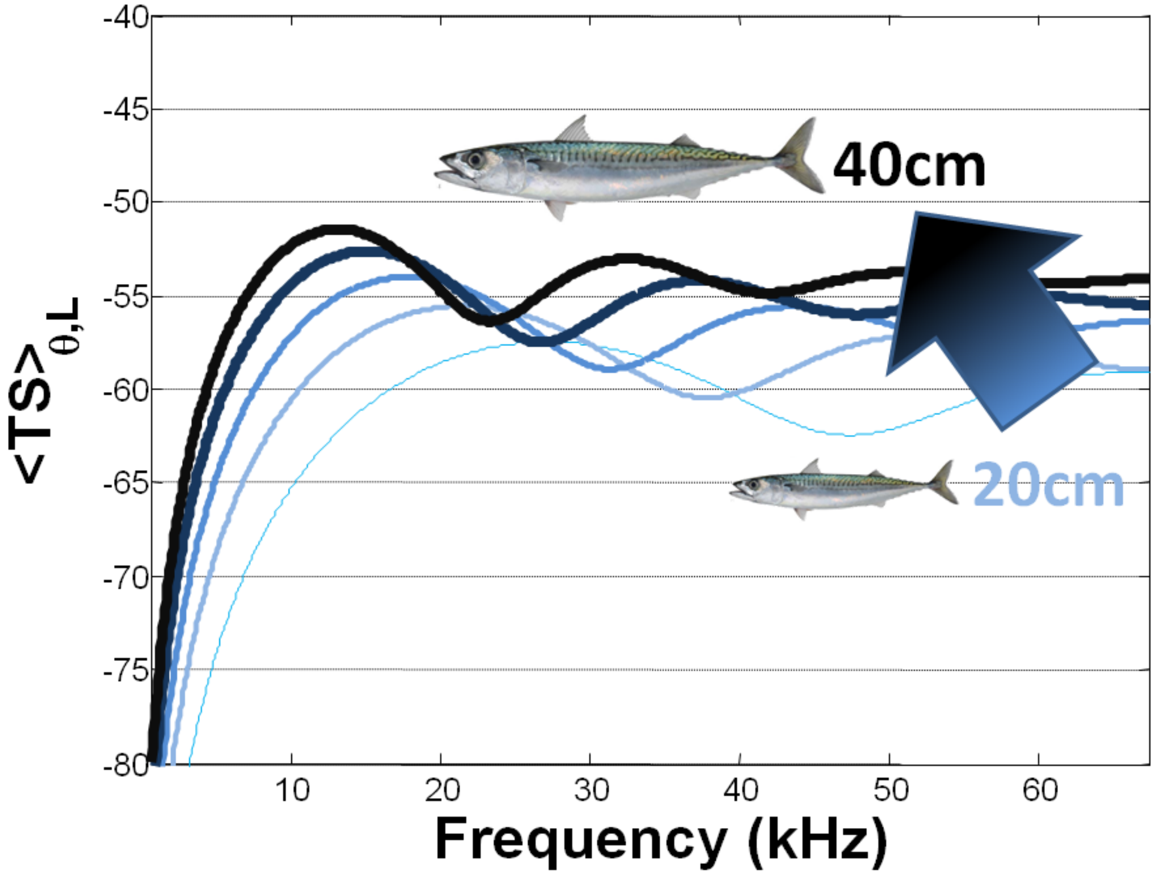

Figure 3. Backscattering (mean Target Strength, <TS> dB) at 1-70 kHz, by mackerel shaped spheroids as determined by an acoustic scattering model (DWBA). Curves represent scattering from a spheroid of average length 20, 25, 30, 35 and 40 cm (larger sizes represented by progressively darker and thicker lines), each with a coefficient of variation of length of 10%, and averaged over a 20° standard deviation in tilt angle. The feature of interest is the initial turning point on the curve which occurs gently (shallow slope) and peaks at 30 kHz for small fish, but rapidly (steep slope) and peaks at 15 kHz for large fish. Model code supplied by Dr Dezhang Chu, NWFSC, NOAA Fisheries, USA.

a school of fish aggregates contributions from individual fish with random orientations. The fish are represented by spheroids with shape and physical properties approximating those of mackerel. Over the range of a few kHz to about 100 kHz, the sound scattering processes change (Fig. 3). Initially, the scattering (as represented by the target strength in Fig. 3), rises in accordance with Rayleigh scattering where the wavelength is larger than the object. Scattering from the fish body reaches a maximum and is then followed by a decaying oscillation as the scattering becomes geometric where the wavelength is smaller than the object. The frequency at which this transition point occurs, between Rayleigh and geometric scattering (effectively the maximum scattering point), changes according to the size of the object, as the nature of the scattering is dependent on the ratio between the wavelength and the object size. It is this key feature, the transition point, which we aimed to capture and exploit in this project as it is potentially indicative of the size of mackerel (Fig. 3). The height and frequency of the peak depends on the average size and also the statistical distribution of the fish swim directions and the density and speed of sound of the fish relative to those of water.

3.2 Data Collection

There are four channels which nominally occupy the full bandwidth of the Edgetech system (Table 1). There are however, limitations on the usable bandwidth, particularly in the Shamu channel (Table 2). A chirp pulse is transmitted on each channel. The bandwidth determines the linear resolution. Longer pulses are used for long range detection, but in the water depths encountered during this cruise short pulses were found to be adequate. The raw data is processed in the towed body by correlating it with a replica of the pulse.

3.3 Pre-Processing

Raw sonar data is processed ping by ping in the sonar processing unit and combined with attitude, sensor and system status information into messages contained in *.jsf files. These are sent to the surface unit. The signals from the transducers are digitised, then correlated with the transmitted pulse and converted into analytical signals. Correlation improves the signal to noise ratio and range resolution by concentrating the energy in a long signal into a sharp correlation peak when there is a signal present. The analytical signal is a complex valued function whose real part is the raw data and imaginary part is its Hilbert transform. It has no negative frequency components and its use improves efficiency of later processing. In the surface unit, the messages are decoded using proprietary software. Raw trace data is converted from 16-bit integer form to floating point using a scaling factor. A depth window is selected and a Hann shading is applied to smooth the data at the edges of the window. There is a correction for propagation loss by the application of a time varying gain. The final result is stored in an array which is imported into Matlab and saved as a *.mat file and transferred to the analysis computer. The data in this file can then be used to display an echogram using WHOI software.

Table 2. Frequency (*f*) bandwidths that were actually calibrated for each transducer

Transducer	*Nominal f (kHz)*	*Calibrated f (kHz)*
Shamu	1 – 10	1.5 – 6
424	4 – 24	8 – 20
AirMar Low	25 – 45	26 – 42
AirMar High	42 – 65	45 – 60

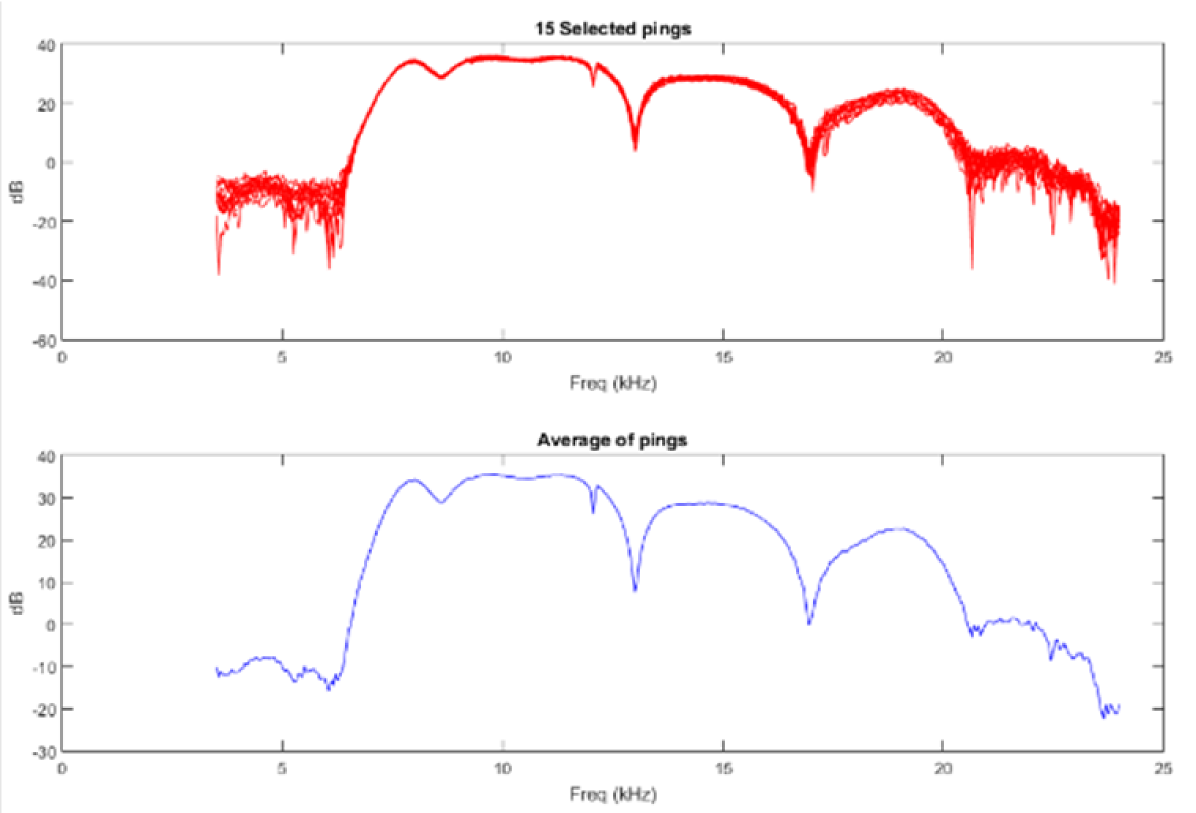

Figure 4. Volume backscattering spectrum of the calibration sphere from the 424 transducer. Top (red): Spectrum from 15 selected pings. Bottom (blue): average spectrum.

3.4 Calibration

With the ship stationary, a standard target sphere was hung beneath the towed body at a range of at least ten metres. Recordings were made of the echoes from the sphere for each pulse type in each channel to be used later in collection of data. At the lowest frequencies the echo from the sphere was too weak for use, and recordings were made of echoes from a flat section of the sea floor. The echo levels were corrected for distance and the position of the target in the sonar beam and compared with the theoretical value to find a correction factor at each frequency.

Some good quality calibration data were collected with clear echoes from the sphere for a good portion of the bandwidth of each corresponding transducer (Fig. 4). For Shamu and 424 these have proven smaller than then nominal bandwidths declared by the manufacturers (Table 2). This caused unexpected gaps in frequency coverage of the broadband spectrum.

3.5 Selection of Data for Analysis

An echogram is produced by adjusting the recorded data for pitch and roll and range from the tow body. From the display, two regions are selected: fish data and noise data (from a region with no fish). The noise data is for the purpose of calculating the signal to noise ratio (SNR) to ensure it is sufficiently high for confidence to be placed in the results. The most convenient method of selection is to outline a rectangular box including the region of the echogram containing fish data. This means, however, either a loss of fish data if the region is completely within the school or contaminating the selection with echoes not belonging to the school. To avoid this, an image processing step was introduced. The user selects a rectangular window from the echogram which is then fed through a thresholding algorithm. The user selects the desired amplitude threshold to apply and image analysis routines are employed to produce a mask (Fig. 5). The mask is then applied within the selected window on the echogram, reducing all the non-desired data to zeros, so that they do not contribute to further calculations.

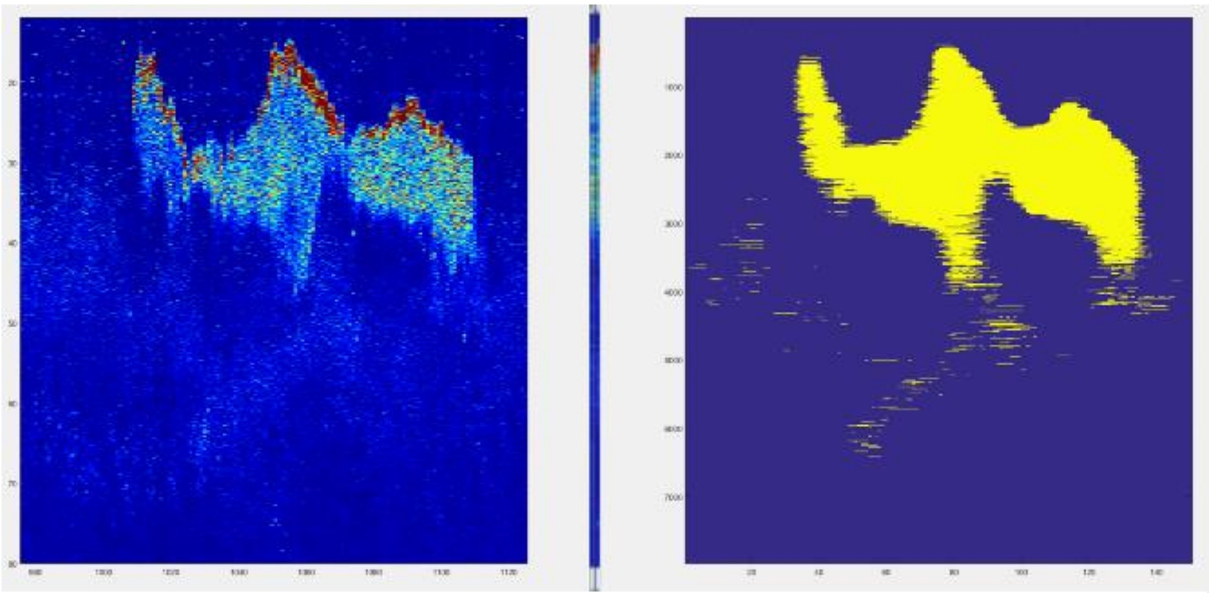

Figure 5. Echogram of a fish school (left) and the subsequent thresholded mask (right) used to isolate data from the fish school (only those points in yellow proceed to the image analysis for selection).

3.6 Volume Backscattering Strength (VBS) Calculation

The selected data is then processed further as a set of time domain voltages $v(t_n)$. A Fourier transform is calculated using an n-point FFT and the power spectrum (*Ps*) is calculated (Eqn. 1).

$$Ps = \left| FFT(v) \right|^2 \tag{1}$$

This is converted to dB (Eqn. 2).

$$PS_{fish} = 10\log(Ps) \tag{2}$$

This is an incoherent average over the volume defined by the transducer beamwidth, the distance travelled during data collection - defined by the ping range - and the user-selected depth window. The volume backscatter calculation is then calculated according to Equation 3.

$$VBS = PS_{fish} - CAL - BP + PL \tag{3}$$

Where:

CAL is a calibration factor

BP is stored beam pattern data

PL is a propagation loss factor

For the 424 and AirMar transducers CAL is based on the average of calibration pings which are selected by the user (Fig. 4). After correction for propagation and beam pattern losses, the echo level is compared with the theoretical target strength of the sphere to determine the correction. For the Shamu transducer, due to difficulties in using sphere data, a clear and clean echo from the seabed is required for calibration.

$$CAL = SF(i_{cutoff}) + ADJ(j_{cutoff}) \quad (4)$$

Where. SF is an array of averaged sea floor data, and i_{cutoff} is the [depth] index of the chosen cut-off point and $ADJ = fac.DIFF$ where $DIFF$ is the difference between averaged sphere calibration data and theoretical target strength and fac is an arbitrary factor aligning the seafloor data with the sphere calibration and j_{cutoff} is the index of the chosen cut-off point.

The beam pattern (*BP*) factor is pre-calculated as the product of the receive and transmit beam pattern levels. For the AirMar systems, the same transducer is used for both transmit and receive. Both are discs with beam pattern given by Equation 5:

$$BP(\theta) = 2J_1(\pi d \sin\theta/\lambda) / (\pi d \sin\theta/\lambda) \quad (5)$$

where d is the diameter of the disc, λ is the wavelength and θ is the angle to the acoustic axis of the transducer (vertical at the centre of the face). For the Shamu and 424 transducers, the transmitter is a disc, but the receiver is a square array. The beam pattern is calculated, accounting for element positioning errors, by summing the contributions from individual elements. For an element at position (x, y), if θ_x and θ_y are the angles with the X and Y directions, the phase angle is given by Equation 6.

$$\phi_{xy} = \pi(x/\lambda)\sin(\theta_x) + \pi(y/\lambda)\sin(\theta_y) \quad (6)$$

The propagation loss is calculated according to Equation 7

$$PL = 10\log\left(r_{av}^2 / \left(r^4 D\right)\right) \quad (7)$$

Where r_{av} is the average distance from echo sounder of data selected for analysis, r is the distance from echo sounder of the middle of the calibration sphere and D is the distance from echo sounder of the data currently being processed.

The average VBS across the transducer bandwidth is taken from data collected from the selected school. In order to make the sample size as large as possible, the boundary of the school is detected using image processing methods. Each point on the echogram is the result of pulse compression involving the cross-correlation of the data with the transmitted signal. Corrections are made for target range and also beam pattern loss due to the target being off the beam axis due to ship motion. The correction factor determined during calibration is also applied.

3.7 Size Estimation

The size estimation process consists of fitting the scattering model (Fig. 3) to the VBS spectrum by varying the fish length in the model holding other parameters constant, until the positions of the peaks in the model match those in the data. Variations in the tilt distribution parameters, and the physical parameters of the model fish do not change the location of the peak (only its magnitude).

4. Results

4.1 Data Available

Four channels of broadband data were collected. The lowest (Shamu) did not yield useful data and only the upper three channels were analysed. There was a noise artefact on both the Shamu and 424 channels that reduced the usable data available. Records were collected on three schools of mackerel and several schools of herring and pearlsides.

4.2 Mackerel

The best results were obtained on the largest school of mackerel which is school on the left in Figure 2. A feature of the echogram is the higher scattering levels in the upper portions of the school. The VBS spectrum was calculated for the whole school, and for the upper region. It was found, however, that in the region below the high readings, the levels are approximately equal to noise. Consequently, the analysis concentrated on the regions near the top of the school.

The three VBS spectra for the fish in the upper section of the school are shown in Figure 6. The spectra for fish in the upper right section have similar shapes, but are a few dB lower (Fig.7). There is a currently unexplained shift between the levels of the spectra. Some progress has been made in resolving this using sea floor echoes, but more work is required. There is a rise in scattering with frequency on the 424 channel (8-20 kHz) which is in keeping with the expected, theoretical spectrum (Fig. 3). The peak does not seem to have been reached and because of: (a) the gaps in

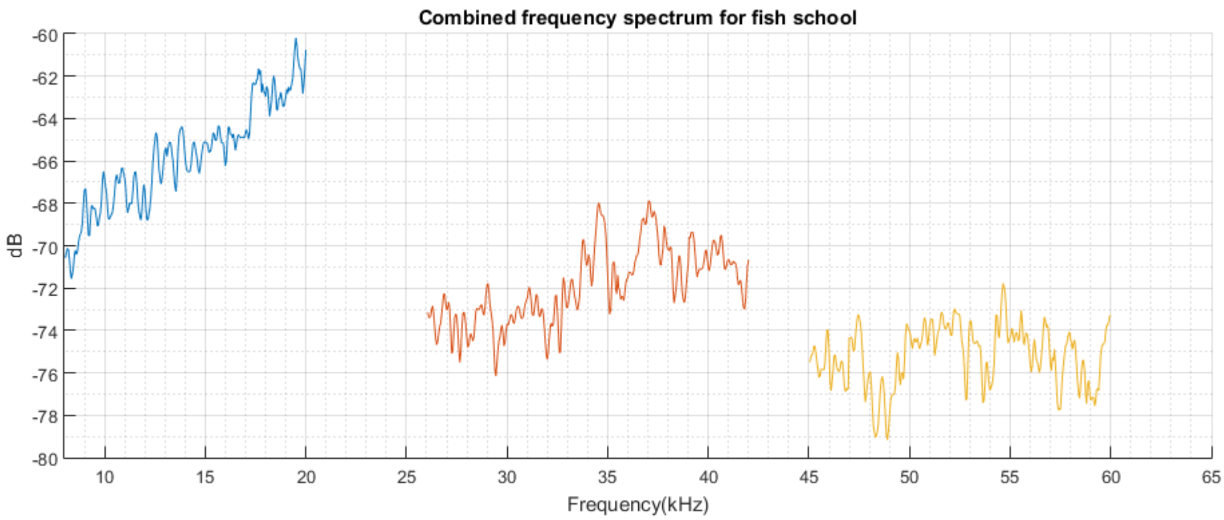

Figure 6. Broadband spectra of mackerel from upper middle section of the fish school in Figure 2.

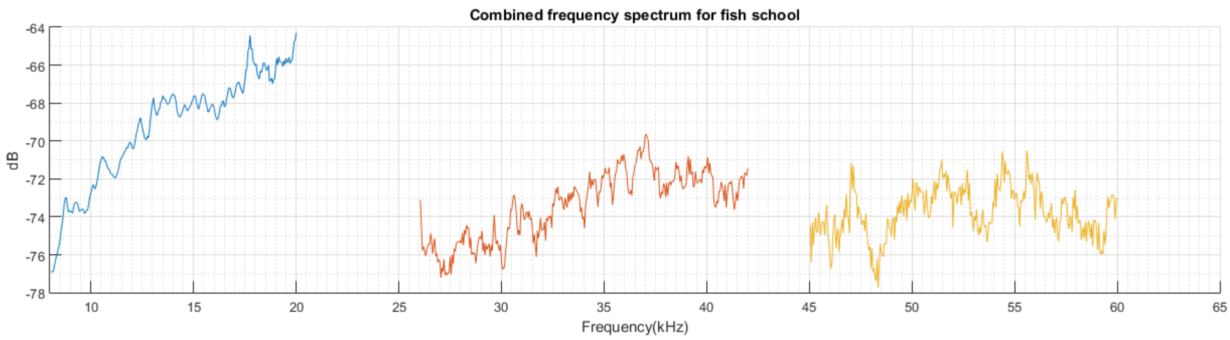

Figure 7. Broadband spectra of mackerel in the upper right section of the fish school in Figure 2.

the spectrum due to calibration; and (b) the level differences in the subsequent channels; it is difficult to infer how the spectrum continues beyond 20 kHz. The rise from 8-20 kHz was enough however, to fit the model and estimate size (see below).

4.3 Other Species

The corresponding spectrum for scattering from pearlsides is shown in Figure 8, and that for herring is shown in Figure 9. It can be seen that the shape of the spectra are different from those of mackerel, giving confidence in that the rise shown in Figures 7 and 8 is a real effect.

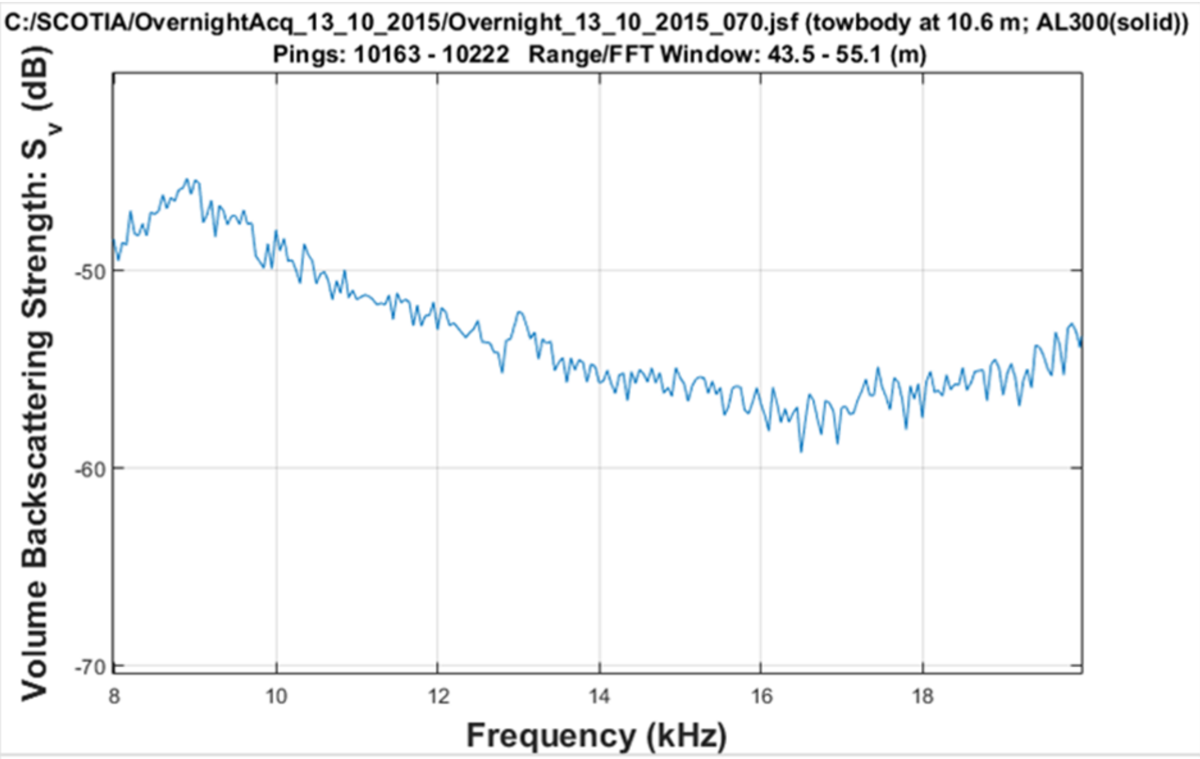

Figure 8. Volume backscattering spectrum from a school of myctophids using the 424 channel.

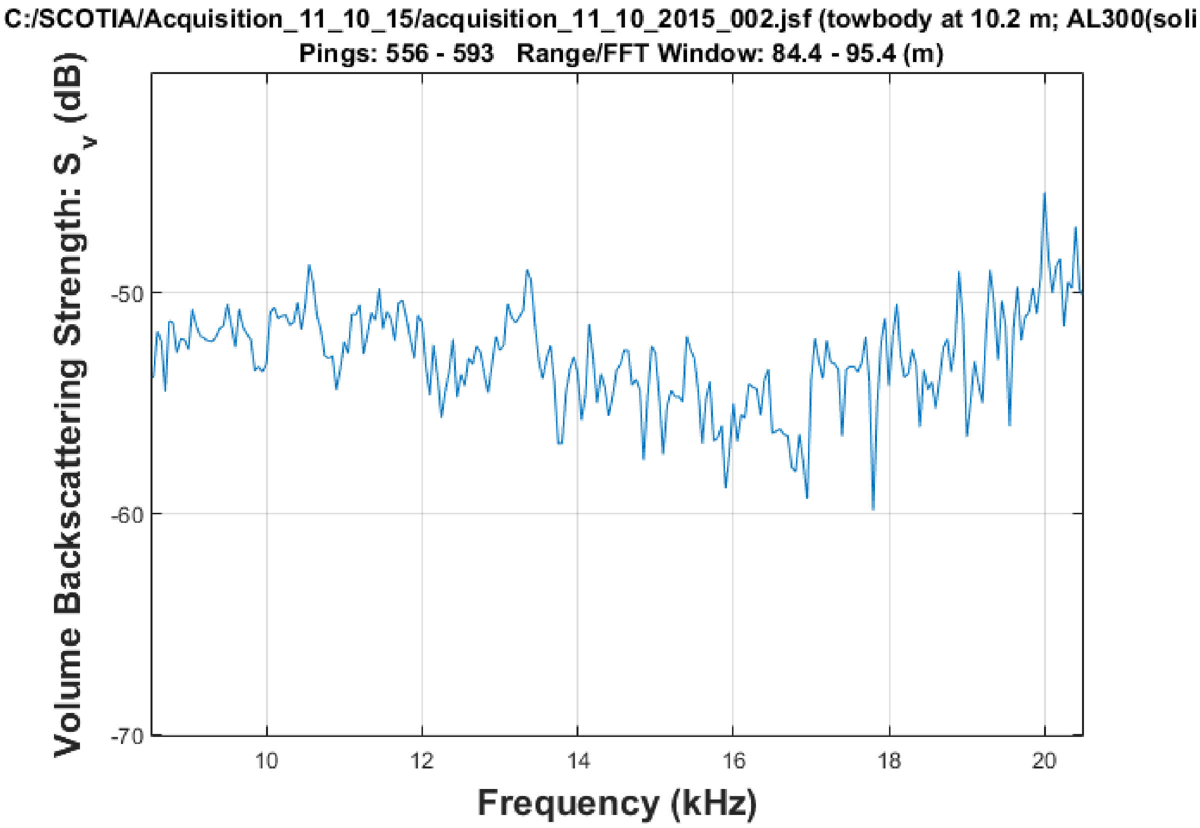

Figure 9. Volume backscattering spectrum from a school of herring using the 424 channel.

4.4 Size Estimation

The size estimation algorithm (Daworski *et al.* 2015) was run on the data from the upper middle of the school. Due to the current uncertainty in the absolute levels of the spectra, the algorithm was modified to allow the level to be estimated also.

Some results are shown in Table 3. A plot showing a fit of the theoretical curve to measured data is shown in Figure 10. This indicated that the mackerel were 21.5 cm long. Fishing samples indicated that the fish were an average length of 33 cm.

Table 3. Estimated lengths of mackerel for different transducers.

	424	AirMar Low	AirMar High
Length (mm)	214.9	95.3	63.2

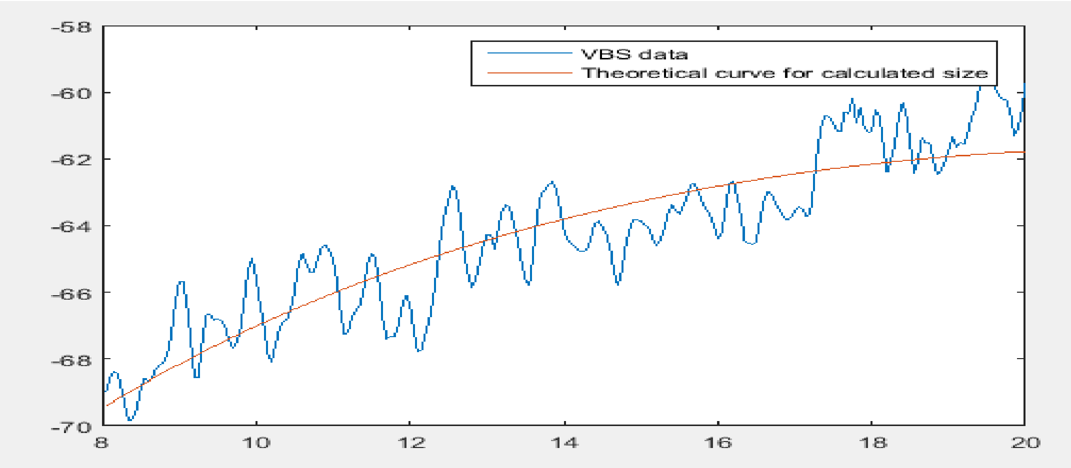

Figure 10. Volume backscattering spectrum (blue) from the upper middle section of the mackerel school in Fig.2 from the 424 channel and the fitted model (red) corresponding to a fish of length of 21.5 cm.

5. Discussion

Broadband echosounders are now routinely used in fisheries acoustics, particularly with the discontinuation of the Simrad EK60 scientific [narrowband multiple frequency] echosounder, which until recently was the most popular scientific device used throughout the marine community. The latter device has been superseded by the Simrad EK80 which has broadband capability and significant efforts are now underway to enable use of this device (see, for example, the latest ICES training course at http://bit.ly/1UXQkTQ). However, the lowest central frequency the EK80 operates to is 38 kHz. This has a likely bandwidth of approximately half the centre frequency (so approx. 29-47 kHz). This is clearly too high to capture much of the theoretical characteristic frequency response of the mackerel (notably the rise associated with Rayleigh scattering).

The Edgetech system used here has advantages, therefore, over these systems. It has a much lower frequency bandwidth that is capable of capturing the rise (Figure 6 and 7). However, as can be seen from Figures 6 and 7 there is clearly an issue between the relative levels of the three channels in the current system. These require some investigation, but a potential solution lies in examining seabed data to inter-calibrate the individual channels rather than using the sphere technique.

The accurate quantification of the broadband signal does, therefore, present some additional challenges. Calibration is also cumbersome, because the spheres required are large, although a satisfactory procedure was developed in the course of this project.

Nonetheless, the rise did allow for estimates of length to be made in accordance with the expected theory. These estimates were close in terms of magnitude, but not close enough to enable them to be useful. Clearly some offset is apparent, due most likely to the model being an oversimplification of the scattering process. Further work would involve making a series of measurements from several schools, ideally of fish of different sizes, to investigate if patterns that are consistent with the theory emerge. These might then be calibrated to determine the exact deviation from this particular theoretical model. It was very unfortunate that during the cruise, virtually no mackerel were detected. The pelagic fishing fleet, which are good indicators of fish presence, were largely not on the fishing grounds. By the time mackerel had been found, far to the north of the area where they were expected, the vessel had to make its return and so only one verified trawl could be carried out to determine the fish size.

Nonetheless, the rise detected and the estimate (within 12 cm of the actual value) give some confidence that the technique may work. With the successful completion of phase 2, the next step is to collect data from the fishery and attempt to estimate many more sizes acoustically. The correspondence between the measured and predicted sizes, may be improved by changes to the model. A review of the assumptions has found three areas for investigation. The first is to assess the effect of using a more general shape to model the fish in the calculation of acoustic scattering. The second is to use measured probability distributions for the tilt angle to estimate the scattering from a school of fish with the expected tilt angle distributions. The third is to improve the relative levels discrepancy between the individual channels.

An exact fit to the current model is unlikely because of the number of aspects to be approximated to the required degree of accuracy, and uncertainty in the values of parameters. It is likely that an empirical correction will need to be applied and this will be constructed from a number of measurements at sea.

6. Conclusions

The EdgeTech 3200 sonar was successfully deployed in the towed body from the MRV Scotia at various speeds up to 10 knots. However, noise was present on the system at speeds greater than 5 knots which made the data unusable at higher speeds. This may be due to the towed body configuration rather than the sonar itself and alterations to the towed body might mitigate the problem. A calibration procedure was developed which worked well and analytical methods were devised to establish calibration correction factors for the sonar. Broadband acoustic data on a variety of fish schools was collected from 1.5 to 60 kHz with gaps at 6-8 kHz; 20-26 kHz and 42-45 kHz. This is still in a range that is far lower than other more popular systems such as the Simrad EK80 and crucially, the lower range is the most interesting because it encompasses the Rayleigh and resonant scattering regions of a number of fish species. The rise in scattering at low frequencies (Rayleigh scattering), which was expected from theory for mackerel, was detected. This enabled the size of mackerel to be estimated by fitting the scattering spectrum to a scattering model. The “sonar size” was estimated as 21.5 cm c.f. the average size of fish in the vicinity trawled of 33 cm. This is close but not close enough to be of utility. The market value of fish changes with size at the scale of cm so the device needs to be accurate to within 1 or 2 cm if possible.

The survey suffered from a distinct lack of mackerel due to the very late arrival of fish in the area. When mackerel were eventually found, the vessel only had time to fish on one occasion before departing. Clearly more schools need to be detected and fished on to modify the fish sizing algorithm.

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