Improved estimates of Orange roughy biomass using an acoustic-optical system in commercial trawl nets

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Introduction

Acoustic echo integration methods to estimate fish biomass are widely used in fisheries management (Simmonds and MacLennan, 2005). These methods have been applied to a commercially important deep-water fish species orange roughy (Hoplostethus atlanticus) in Australia and New Zealand for over 25 years (Kloser et al., 2015). Acoustic surveying on aggregations of orange roughy that can extend up to 200 m into the water column are usually carried out during their winter spawning period over flat, conical, or ridge seabed features, at seabed depths of 600–1200 m (Clark, 2001; Tracey et al., 2004). This aggregative behaviour of orange roughy when spawning makes estimating biomass more suited to acoustic methods than trawl catch methods (Kloser et al., 2015).

Acoustic methods have been refined in response to technology advances and the need for improved precision and accuracy. Vessel-based acoustics initially provided data for biomass estimation, but have significant limitations (Kloser, 1996). These include influence of weather on data quality, low resolution due to the long range to target, large acoustic dead zone on sloping seabed, and inability to identify and exclude co-occurring species. Single- then multifrequency towed bodies were used to reduce the range to target, improve precision, measure target strength (TS), and enable species discrimination through the use of multifrequency techniques (Kloser et al., 2002). Accurate species discrimination is important because orange roughy can co-occur with myctophid species (small gas bladder, similar TS at 38 kHz) and large gas bladder species (10- to 100-fold higher reflectivity) that can lead to large errors in biomass estimates, e.g. 6.4-fold in Kloser et al. (2002).

Uncertainty in estimates of orange roughy TS (3.1-fold; Kloser and Horne, 2003) had limited the use of echo integration biomass estimates as being relative indicators of population size (Kloser and Horne, 2003). The preferred in situ TS estimates were confounded by the long-range avoidance reaction to lowered instruments (Koslow et al., 1995; Macaulay et al., 2013). Development of a net-attached acoustic-optical system simultaneously records acoustic data at multiple frequencies (38 and 120 kHz), species composition in video and stereo imagery, and environmental data as the net collects biological samples and/or commercial catch. All data streams were considered in a multiple-lines-of-evidence approach to give improved estimates of orange roughy biomass with low error due to species uncertainty. AOS-based biomass estimates, made over a 5-year period from 11 key spawning locations in Australia and New Zealand, showed a strong correlation (r² = 0.97, n = 39) between frequencies (38 and 120 kHz); the 38 kHz estimates were, on average, 8% higher than 120 kHz, with a standard deviation of 20%. This similarity in estimates across frequencies improves confidence in results compared with single-frequency surveys that are potentially prone to large errors resulting from unknown (mixed) species composition and target strengths, calibration, and sound absorption uncertainties.

Keywords: acoustics, biomass, deepwater, multifrequency, optics, orange roughy.
system (AOS) (Ryan et al., 2009) overcame avoidance by forcing orange roughy beneath the headline-attached instrument to measure TS with concurrent optical images. This method enabled species-verified TS measures for the first time, importantly at two frequencies (38 and 120 kHz), to provide TS estimates with a high degree of confidence (Kloser et al., 2013; Macaulay et al., 2013). These visually verified TS estimates at 38 and 120 kHz have allowed echo-integration-based estimates of orange roughy biomass at both frequencies for the first time. Combining estimates of orange roughy at multiple frequencies should improve the confidence and precision in the measurement variance (Demer, 2004).

A logical extension of the net-attached AOS beyond TS measurement was to also conduct echo integration transect surveys for estimating biomass (Kloser et al., 2011a). This would integrate several observation methods; optical (Koslow et al., 1995), deep-towed multifrequency towed bodies (Kloser et al., 2002), and net capture systems. Trials of the net attached AOS method demonstrated that both TS and echo integration surveys could be done from a single industry vessel (Kloser et al., 2011a). This method has the advantage of using the industry infrastructure and skill to deploy and retrieve the AOS as well as utilizing their local knowledge of the fishing grounds. The AOS system can be seamlessly integrated into the operations of a commercial fishing vessel (Kloser et al., 2011a). In doing so, it is possible to survey orange roughy spawning aggregations cost-effectively for ongoing monitoring.

This study reviews the orange roughy biomass results obtained from using the net-attached AOS from fishing vessels in 11 locations in Australian and New Zealand over a 5-year period. We outline how data streams from the AOS (multifrequency acoustics, optics, and trawl catch) provides a “multiple-lines-of-evidence approach” in a single instrumentation and deployment system previously done by multiple devices. This deployment and integrated approach improves species identification to minimize bias in biomass estimates and maximize precision. Correlation of biomass estimates at two frequencies is used as an indicator of error in key biomass estimation parameters of species identification, TS, calibration, and sound absorption. Potential avoidance issues to the noise and vibration of the trawl net and its effect on school structure are investigated.

**Methods**

**System description**

Ryan et al. (2009) described the concept of a trawlnet-attached AOS. It involves a suite of acoustic and optical instruments housed in a sled-style platform. The platform attaches to the headline of the commercial fishing vessel’s demersal trawlnet (Figure 1). Two AOS’s have now been built, referred to as C-AOS (CSIRO-AOS) and S-AOS (Sealord New Zealand-AOS; Figure 1), respectively. These sleds are ca. 1.6 m wide, 1.2 m long, and 0.5 m high, with weight 400–700 kg in air depending on configuration. AOS instrumentation is outlined briefly here. Detailed technical descriptions of the systems can be found in Sherlock et al. (2010) and Underwood et al. (2015).

![Figure 1](http://icesjms.oxfordjournals.org/content/2/3/1385/F1.large.jpg)

**Figure 1.** (a) Demersal trawlnet with AOS attached. (b) Sealord AOS system. This figure is available in black and white in print and in colour at ICES Journal of Marine Science online.
**Mechanical arrangement**

Eight commercial fishing vessels have conducted AOS echo-integration surveys between 2010 and 2014. These ranged from 24 m fresh-fish trawlers to 70 m factory freezer trawlers. Their demersal trawl nets varied, but all were optimized for catching orange roughy for the particular vessel design. A typical arrangement (FV “Saxon Onward”, winter 2010) is as follows. A set of plastic floats rated to 1500 m was attached to the top of the AOS to reduce in-water weight. The demersal trawl net was 90 m long, with a headline length and height of 38.4 and 5 m, respectively. The wing and headline mesh size was 300 mm stretched mesh (150 mm bar length) grading down to 105 mm (52.5 mm bar length) at the codend. The doors were 3.5 m square Super Vee doors each weighing 750 kg.

**Acoustic instrumentation**

The different iterations of AOS platforms have housed between two and four echosounder systems. Simrad ES60 or EK60 38 and 120 kHz split-beam echosounders with 7° Simrad transducers were the key quantitative echosounders. Other echosounders (Simrad 18 and 70 kHz) provided redundancy and extra information to aid multifrequency discrimination. The fishing vessels had calibrated Simrad ES60 or ES70 38 kHz hull-mounted echosounders in all except one instance. These provided continuous echogram recordings and, in calm conditions, acoustic data suitable for biomass estimation of orange roughy if species uncertainty was low and/or supported by AOS data-streams obtained on other occasions.

**Optical instrumentation**

Phase alternating line (PAL) video was recorded during Mode 2 deployments (Table 1) after reaching a user-defined platform depth. Both platforms had stereo digital stills. The C-AOS had paired Canon EOS500D 15.1 megapixel DSLR cameras with Canon EF 35 mm lens and Canon 430EX Strobe. The S-AOS had paired Prosilica GX3300C eight megapixel Gig-E cameras with 25 mm Distagon T* ZF-I lens. A Quantum QF8 strobe provided light. The stereo still-cameras allowed observation of fish species and metrics of fish length and tilt-angle to be measured using stereo-photogrammetric techniques (Harvey and Shortis, 1995; Shortis and Harvey, 1998). The stereo systems were calibrated as per Shortis and Harvey (1998) and processed using SeaGIS calibration software (Seager, 2008).

**Survey methods**

Two AOS measurement modes and a calibration mode are summarized in Table 1. Net deployment and retrieval used the procedures of a routine commercial demersal trawl shot.

The vessel’s net monitoring system (Furuno CN22, CN24, or Marport) relayed depth of headline (i.e. AOS depth) and range from headline to seabed, both critical to keeping the AOS at a suitable height. Impulse noise (IN) interference from the Furuno net monitors was routinely observed in the AOS 38 kHz echograms.

IN was either removed through manual editing or more recently using a filter described by Ryan et al. (2015).

**Mode 1: echo integration surveys**

AOS acoustics Mode 1 operations conducted a set of transects across the survey region to obtain AOS acoustic volume backscatter ($S_V$, dB re 1 m$^{-2}$; MacLennan et al., 2002) data suitable for echo integration biomass estimates. The net-attached AOS was towed 250–350 m above the top of potential orange roughy aggregations (as observed on the vessel’s echosounder). This kept the system within the 120 kHz working range, but sufficiently distant to prevent avoidance. The 38 and 120 kHz pulse durations were 2048 and 1024 μs, respectively, to optimize resolution and signal-to-noise. At transect completion, the net was hauled from survey depths (600–800 m) to the surface to reduce trawl warp length, greatly speeding up time to turn to the next transect. A transect tow speed of ca. 4 knots was typically achieved. Larger flat regions used a grid design. In recent years, these applied an interlaced pattern to avoid potential bias due to fish movement (Simmonds et al., 1992). Star-pattern surveys were efficient for small, high-relief features (Doonan et al., 2003a), where depth range and distance from the feature constrained orange roughy within a defined area. A key objective of both star and grid design was that they bound the extent of the aggregations. For the grid survey, this means transects at the farthest extents should observe no aggregations.

**Vessel acoustics**

Despite limitations, the 38 kHz vessel acoustics were important. They provided continuous monitoring of aggregations to help understand temporal and spatial dynamics and to optimize AOS surveys to periods when orange roughy were at maximum availability to the acoustics. In calm seas and in low-relief terrain where dead-zone was not large, vessel acoustic transect surveys could obtain data suitable for echo integration biomass estimation if orange roughy aggregations were not significantly contaminated by other species. AOS data streams obtained at other times during the survey could support interpretation of vessel-based echograms. Vessel-based biomass estimates were presumed to have greater errors due to absorption, dead zone, platform motion, and undetected species mixing (Kloser, 1996).

**Analysis**

Echograms were analysed with Echoview 4.70 or higher to apply calibration corrections and quality control through manual editing of bad data regions. Manually drawn polygons marked regions as orange roughy (with interpretation of species guided by the “multiple-lines-of-evidence” approach described below), which were echo integrated at intervals of 0.1 nautical mile producing nautical area scattering coefficient (NASC) values (MacLennan et al., 2002). These were employed to estimate biomass using standard methods (Simmonds et al., 2002).
and MacLennan, 2005) using the biomass equation:

\[
B = \frac{NASC \times (W/1000) \times A}{4 \times \pi \times 10^{TS_f/10}}
\]

where \(W\) is the average weight of orange roughy in kg, \(A\) the survey area bounded by the acoustic transects (nautical miles\(^2\)), and \(TS_f\) the estimated \(TS\) (dB re 1 m\(^2\)) at frequency \(f\) kHz.

Biomass was estimated from both 38 and 120 kHz data, applying \(TS\) estimates established from other studies (Kloser et al., 2013; Macaulay et al., 2013). Intrinsic geostatistical methods (Rivoirard et al., 2000) using EVA2 software (Petitgas and Lafont, 1997) or RGeostats toolbox (Renard et al., 2014) provided survey sampling coefficient of variation (CV) for parallel transect surveys. Star-pattern survey data were weighted using the polar method (Doonan et al., 2003a) to account for the variation in sampling intensity as a function of distance from the survey centre. The variability in echo integration data binned into 20 m contour annuli around the survey centre provided estimates of survey sampling CV.

Mode 2: demersal trawls for TS, species identification, biological samples, and commercial catch

Mode 2 deployments involved a conventional demersal trawl with the acoustics optimized for TS measurement: short range (0–50 m), fast ping rate (~9 Hz), and 512 and 256 \(\mu s\) pulse duration for 38 and 120 kHz, respectively. Video and stereo still-cameras provided concurrent images of acoustically detected targets. A typical objective was to optimize a portion of the deployment for TS measurement (AOS held 10–20 m above seabed and at far-field range from fish). The remainder of the trawl moved closer to the seabed catching fish for biological samples and research and/or commercial quota. Mode 2 deployments are described in detail in Ryan et al. (2009), with case studies of AOS-based TS estimates supported by optical images and Table 2.

**Table 2.** Echogram interpretation based on decibel difference between 120 and 38 kHz volume backscatter (Kloser et al., 2002).

<table>
<thead>
<tr>
<th>(\Delta MVBS)</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>+2 to +4</td>
<td>Non-gas-bladder species. Orange roughy if supported by other evidence. Other possibilities are deepwater shark (Kloser and Ryan, 2014) or fluid filled crustaceans (Madureira et al., 1993)</td>
</tr>
<tr>
<td>−1 to +1</td>
<td>Large gas-bladder fish (20–100 cm) including morid cod, Johnston’s cod, whiptails, and oreos</td>
</tr>
<tr>
<td>−10</td>
<td>Small gas-bladder species (2–10 cm) including myctophids</td>
</tr>
</tbody>
</table>

**Table 3.** TS values at 38 and 120 kHz for key species groups.

<table>
<thead>
<tr>
<th>TS 38 kHz (dB re 1 m(^2))</th>
<th>TS 120 kHz (dB re 1 m(^2))</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>−52</td>
<td>−48.2</td>
<td>TS values based on 34.5-cm orange roughy, 120 kHz value adjusted from Kloser et al. (2013) for reference sphere TS of −39.5 dB (Kloser et al., 2013; Macaulay et al., 2013)</td>
</tr>
<tr>
<td>−25 to −45</td>
<td>−25 to −45</td>
<td>Large gas-bladder fish (Kloser et al., 2002)</td>
</tr>
<tr>
<td>−52</td>
<td>−62</td>
<td>Myctophids (Kloser et al., 2002)</td>
</tr>
</tbody>
</table>

**Figure 2.** Survey locations in Australia and New Zealand indicated by the grey circle with black dot. Management zones are labelled with white font on black background.
modelling presented in Kloser et al. (2011b) and Macaulay et al. (2013). TS estimates for biomass estimation were based on −52 dB re 1 m² and −48.19 dB re 1 m² (Kloser et al., 2013) for 38 and 120 kHz, respectively, for an orange roughy of 34.5 cm standard length. TS was adjusted using TS = 16.16 log₁₀(L) − 76.83 (McClatchie et al., 1999; Kloser et al., 2013) based on trawl catch length measurements and assuming 1:1 population sex ratio.

**Mode 3: acoustic calibration**

AOS echosounders were calibrated with a 38.1 mm tungsten carbide sphere suspended 20 m beneath the transducers and lowered to operating depths (800 m), pausing at intervals (100 m) to collect on-axis sphere data. On-axis gain Ga (dB re 1) and Sa correction, Sa cor (dB re 1) values (Demer et al., 2013) were calculated as a function of depth and characterized by a polynomial model. Values for Ga, and Sa cor, at a nominal operating depth (typically 600 m for Mode 1) were used when echo integrating survey results. The polynomial model provided a secondary correction to the data when the platform depth deviated above or below the nominal working depth.

**Platform stability**

A Microstrain 3DM-GX1 sensor sampled platform motion at 10 Hz. If necessary, adjustments were made to trawl warp and/or placement of floats with the aim of trimming the platform to 0° pitch and roll. Corrections to signal loss due to platform motion (Stanton, 1982) were made in Echoview using the Dunford (2005) algorithm.

**Platform geolocation**

AOS location was estimated by applying an offset to the vessel’s GPS position by measuring the time-lag between the vessel passing over a feature (either biological or seabed) and the AOS later arriving at the same location. We assumed no significant across-track difference between vessel and AOS.

**Species discrimination through multiple lines of evidence**

Accurate species discrimination is basic to providing robust and unbiased acoustic-based biomass estimates. Our conventional deep-towed body systems used the multifrequency approach as the primary method to discriminate orange roughy (Kloser et al., 2002). The trawlnet with attached AOS operating in either Mode 1 or 2 provides additional sources of information that can be used to as evidence of a particular species (or species group). We adopt a “weight of evidence” approach (Flood et al., 2012; Smith et al., 2013) where both empirical and qualitative “multiple-lines-of-evidence” (detailed below) from the trawlnet and AOS are systematically assessed to determine what they may infer about species. In this paper, we present only biomass estimates where the evidence of species is compelling in the light of all available information. A primary requirement is that the multifrequency information indicates orange roughy, with the secondary evidence consistently supporting that inference. Biomass estimates are not included when the secondary evidence provides additional sources of information that can be used to as evidence of a particular species (or species group). Before making ΔMVBS calculations, raw resolution Sa data at both frequencies were resampled to 1 m vertical resolution and passed through a $5 \times 5$ convolution matrix to smooth

**AOS multifrequency differences in mean volume backscatter**

Differences in mean volume backscatter strength (MVBS) in Mode 1 data \(\Delta \text{MVBS} = \text{MVBS} (120 \text{ kHz}) - \text{MVBS} (38 \text{ kHz})\) were used as the primary indicator of species (or species group). Before making ΔMVBS calculations, raw resolution Sa data at both frequencies were resampled to 1 m vertical resolution and passed through a $5 \times 5$ convolution matrix to smooth
sample–sample variability. ΔMVBS of +2 to +4 dB was a primary indicator of regions dominated by non-gas-bladder fish such as orange roughy (Kloser et al., 2002, 2013). ΔMVBS data were visualized as a synthetic echogram, with the colour palette tuned to contrast non-gas-bladder regions from those occupied by larger or smaller gas-bladder species, with interpretation guided as per Table 2.

AOS TS data
Mode 2 close-range acoustic data provided TS measures through the water column and close to the seabed (Table 3). In addition to providing orange roughy TS measures, TS data can indicate the presence of small and large gas-bladder fish species (Table 3).

AOS acoustically observed behaviour
Species-specific behaviour may be observed in the echogram images. For example, as has been well reported in the literature, evidence of an avoidance reaction would suggest orange roughy (Koslow et al., 1995; Kloser et al., 1997, 2002; O’Driscoll et al., 2012). We have made acoustic observations of orange roughy behaviour using deep-towed acoustic systems for over 20 years in Australia and New Zealand finding that orange roughy react strongly at platform ranges

![Figure 3](http://icesjms.oxfordjournals.org/)

**Figure 3.** Echograms from vessel and two AOS frequencies (a–c) at St Helens Hill spawning location on 18 June 2010. (d) Virtual echogram of ΔMVBS. Regions are identified as orange roughy, small and large gas-bladder species. (e) AOS platform motion during transect over this steep-sided feature. This figure is available in black and white in print and in colour at ICES Journal of Marine Science online.

**Table 5.** Metrics of platform pitch and roll as net-AOS platform approaches and departs sloping grounds along a transect line.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Start time</th>
<th>End time</th>
<th>Mean angle (°)</th>
<th>RMS angle (°)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roll</td>
<td>3:59</td>
<td>4:05</td>
<td>-0.22</td>
<td>1.27</td>
<td>Approaching slope</td>
</tr>
<tr>
<td>Pitch</td>
<td>3:59</td>
<td>4:05</td>
<td>0.7</td>
<td>1.21</td>
<td>Approaching slope</td>
</tr>
<tr>
<td>Roll</td>
<td>4:07</td>
<td>4:15</td>
<td>-0.7</td>
<td>1.74</td>
<td>Departing slope</td>
</tr>
<tr>
<td>Pitch</td>
<td>4:07</td>
<td>4:15</td>
<td>-5.56</td>
<td>5.77</td>
<td>Departing slope</td>
</tr>
</tbody>
</table>
of 200 m or less. Conversely, we have not observed (by video or inferred from multifrequency acoustics) avoidance reactions by other species at such ranges including oreos (smooth oreo—Pseudocyttus maculatus, black oreo—Allocyttus niger, spiky oreo—Neocyttus rhomboidalis), Johnson’s cod (Halargyrensis johnsonii) and deepwater sharks such as southern lantern shark (Etmopterus granulosus). On occasions, the AOS was deliberately moved close (100–150 m) to the aggregations to provoke an avoidance reaction (or not). This provided an extra line of enquiry to assist resolving species in instances where multifrequency information was ambiguous.

**Optics**

Digital still and/or video images provided information on species into the water column as well their along-track distribution providing a spatial component to species composition that is not possible from the trawl catch. Additionally, the video images provide information on fish behaviour (reactive, non-reactive) which can help interpret echograms from Mode 1 surveys.

**Trawl catch composition**

Mode 2 operations provided trawl catch. A random sample of 200 orange roughy per catch was measured for weight, standard length, sex, and macroscopic gonad stage for both male and females (Pankhurst, 1988). Between 20 and 60 otoliths (2 from each fish) per trawl were extracted from orange roughy for ageing purposes. Where practical, bycatch was identified to species level, with numeric and by-weight proportions of the total catch estimated. The total catch, level of bycatch, and trawl duration in combination provided evidence that assisted interpretation of the acoustic data.

**Does the AOS cause avoidance or herding of fish?**

Fisheries managers in New Zealand were concerned that the large and presumably noisy trawlnet could bias biomass estimates high if the trawl corralled fish beneath the AOS or low if there was avoidance. Experiments in New Zealand in 2013 towed the AOS above and below a nominal range of 200 m above the top of known orange roughy aggregations. Vessel acoustics provided reference data that captured the extent and structure of the aggregation before the arrival of the AOS ca. 10 min later. Visual comparison of AOS and vessel echograms and metrics of school dimensions assessed whether there was gross movement of orange roughy due to the trawlnet.

**Results**

**Surveys**

AOS survey programmes were completed at 11 orange roughy spawning grounds in Australia and New Zealand between 2010 and 2014 (Figure 2, Table 4). At additional locations, the AOS was used to determine species composition where previous vessel acoustics and trawl catch surveys had been inconclusive (e.g. Dork, Table 4).

**Multiple lines of evidence**

**Multifrequency acoustics and Mode 2 data products**

Consideration of AOS 38 and 120 kHz echograms from Mode 1 surveys was a first step in understanding species composition (Figure 3). A virtual echogram of ΔMVBS (Figure 3d) complemented these echograms. In the example shown, regions of species with small and large gas bladders and large species lacking gas bladders (most likely orange roughy) discretely partitioned according to our multifrequency criteria (Table 2). This interpretation was supported by trawl catch data that targeted likely orange roughy regions where that species accounted for 97.7% of the catch (by weight).

Figure 3a highlights some of the issues with 38 kHz vessel acoustics data where bubble-layer attenuation and vessel motion greatly affects data quality. At 800 m seabed depth and AOS at 250 m above the seabed, vessel acoustics has a range-to-target and sampling volume that is, respectively, ca. three- and tenfold greater than the AOS. The vessel acoustics consequently has reduced fine-scale detail and has a higher probability of inclusion of co-occurring species.

Figure 3e shows the pitch and roll angles of the AOS platform as it was towed across the steep-sided feature, with metrics given in Table 5. The trawlnet height-above-seabed was adjusted to keep...
the AOS within the specified 250–350 m height range while endeavou-ring to keep the platform level.

Our multiple-lines-of-evidence approach to echogram interpretation has produced encouragingly consistent results in Australia and New Zealand across a diverse range of survey locations (Table 4). Figure 4 shows box plots of AOS 120 kHz minus AOS 38 kHz NASC values from regions interpreted as orange roughy, echo integrated in intervals of 0.1 nautical mile (ΔNASC = NASC 120 kHz – NASC 38 kHz from hereon). The ΔNASC distribution for the Dork (Table 4) is included as a point of contrast as this location was dominated by ca. 300 mm length gas-bladdered spikey oreos (*N. rhomboidalis*) (Ryan and Kloser, 2012). The mean of all ΔNASC intervals (excluding the Dork) was 3.4 dB (dashed horizontal black line). The ΔNASC distribution of most of the surveys encompassed this mean value. The notable exceptions were Kaipara (median ΔNASC, 5.8 dB) and Rekohu (median ΔNASC, 2.2 dB). It is not clear why the Kaipara ΔNASC values are higher than the mean of all ΔNASC intervals. The lower ΔNASC values at Rekohu could be due to tilt-angle distribution (Kloser et al., 2013) or the influence of non-excluded fish with large gas bladders. The latter could be plausible as individual fish with very high TS (−25 to −30 dB) were observed at that location (Ryan and Kloser, 2014) and, if so, would suggest that present biomass estimates have an unaccounted-for positive bias.

**Mode 2 data: TS and optical information**

In addition to biological catch, Mode 2 operations provided concurrent close-range acoustics and optical images that supported interpretations (Figure 5). Treatment of AOS Mode 2 data specific to estimating fish TS has been described elsewhere for orange roughy and other species (Kloser et al., 2011b, 2013; Macaulay et al., 2013). The AOS acoustics provided TS distributions across two frequencies with visual confirmation of species. This enabled validation of decibel differences observed in the echo integration survey data (Kloser et al., 2013). Observing the expected decibel difference in the TS data gave comfort that AOS echosounders were working correctly and that calibration parameters were within acceptable limits. The optics allowed observation of fish behaviour (avoidance, non-avoidance) and provided along-track spatial information on species that is not available from trawl sampling that integrates catch into a single metric. Key features of this were observations of orange roughy well away from the seabed, along-track changes in densities, and, in some instances, transition from orange roughy to other species such as deepwater sharks.

**Acoustically observed behaviour**

Figure 6 shows examples of orange roughy avoidance and non-avoidance to the trawlnet. In both examples, these large aggregations were chosen because they had been well established as predominately orange roughy through sustained multifrequency acoustic observations at 38 and 120 kHz plus optical and catch data obtained when trawling. Figure 6a and b shows vessel 38 kHz and AOS 120 kHz echograms, respectively, during transect across a large aggregation of orange roughy at Rekohu (note, AOS 38 kHz was not working during this transect). The AOS was at least 230 m from the top of the aggregation. The polygon lines indicate orange roughy regions (solid black line AOS 120 kHz, dashed black line vessel 38 kHz). Visual inspection shows that the shape of the two polygon lines and the structure of the underlying echograms are similar. The height, length, and mean depth of the defined regions were within 15% of each other (Table 6). The mean $S_v$ of the AOS 120 kHz within the defined school region was 4.8 dB higher than the vessel’s 38 kHz, indicating that the aggregation consisted of a fish species without a gas bladder. Some differences are expected due to the vessel’s 38 kHz echosounder that has a greater range and sampling volume than the AOS 120 kHz (three- and tenfold, respectively). Along-track offset between vessel and AOS as well as the ca. 10 min lag of the towed system may explain fine-scale differences. We conclude that there has been no significant avoidance reaction to the presence of the AOS in this example.

Figure 6c and d shows an example when the AOS was towed within 130 m of the top of an aggregation. Again, solid black and black dashed lines indicate orange roughy regions for AOS 120 and vessel 38 kHz, respectively. The white dashed line polygon in Figure 6d indicates a “void” region, which had presumably been occupied by orange roughy before the arrival of the AOS system. The same polygon overlaid on the vessel 38 kHz echogram in Figure 6c indicates that this region was occupied at the time of vessel transit. The height and length of the AOS 120 kHz region is, respectively, 50 and 25% less

**Figure 5.** Concurrent AOS 120 kHz acoustics and frame grab from standard definition video from demersal trawl at the Morgue in July 2013. This figure is available in black and white in print and in colour at ICES Journal of Marine Science online.
than that of the vessel 38 kHz region (Table 6). The mean $S_v$ within the non-avoidance region (red dashed line) was $-58.7$ and $-62.1$ dB for AOS 120 and 38 kHz, respectively, a $\Delta$MVBS 3.4 dB that indicates large non-gas bladdered species, most likely orange roughy. Three regions (rectangles with solid black lines) in the “void” zone of the vessel echogram which were less affected by bubble-layer attenuation were echo integrated to obtain a mean backscatter value at 38 kHz of $-67.2$ dB (s.d. = 0.4) before the arrival of the AOS. The approximately corresponding regions in the AOS 38 kHz data were also echo integrated, giving a mean backscatter value of $-77.5$ (s.d. = 1.4), indicating 38 kHz backscatter reduced tenfold when the AOS arrived. All indications are that the net system provoked a strong avoidance reaction by orange roughy.

From these experiments and our observations over 5 years at 11 spawning grounds, we conclude that avoidance or herding reactions are unlikely if the AOS is within the recommended working range of 250–350 m. A strong reaction from orange roughy is increasingly likely if the range decreases below this.

**Biomass estimation of orange roughy**

Between 2010 and 2014, 100 biomass estimates have been made using AOS 38 kHz (41 estimates), AOS 120 kHz (45 estimates), and vessel 38 kHz acoustics (14 estimates) at 11 orange roughy spawning grounds in Australian and New Zealand (Figure 7). Biomass estimates ranged from 700 to 40,150 t. These estimates have used a multiple-lines-of-evidence approach to interpreting and partitioning echograms to define regions of orange roughy with low species composition uncertainty. Previous work estimated TS of orange roughy at 38 and 120 kHz using AOS acoustic measures supported by concurrent optical images (Kloser et al., 2013). This has enabled biomass estimates at both AOS frequencies that should produce the same biomass if all parameters are correct; key parameters include seawater absorption, TS, and echosounder calibration. Regression analysis of 39 biomass estimates at 38 and 120 kHz shows a strong correlation ($r^2 = 0.97$, Figure 8), while a slope of 0.92 indicates that the 38 kHz biomass estimates are, in

![Figure 6.](http://icesjms.oxfordjournals.org/)

Figure 6. Examples of non-avoidance (a) and (b) and avoidance (c) and (d) in response to the presence of the AOS. In the non-avoidance example, the AOS was at least 230 m from the top of the aggregations. In the avoidance example, the AOS was towed within 130 m of the top of the aggregation. Solid black-line polygons relate to the AOS 120 kHz data, black dashed-line polygons relate to the vessel 38 kHz data. These polygons indicate regions dominated by orange roughy. The white dashed-line polygon in (d) indicates a region of “empty water” where avoidance to the AOS has occurred. This same polygon in (c) indicates that the region was occupied at the time of the vessel transit. Three regions (rectangles with solid black lines) were echo integrated for both 38 kHz vessel and AOS data to compare backscatter in the “empty water” region before and after the arrival of the AOS. This figure is available in black and white in print and in colour at *ICES Journal of Marine Science* online.
general, marginally higher than 120 kHz (8%). The mean percentage difference of all 120 and 38 kHz biomass estimates shows a similarly close match, where on average the 120 kHz biomass estimates are only slightly lower (−0.4%). The percentage difference of 120 compared with 38 kHz biomass estimates is normally distributed (Kolmogorov–Smirnov test at 5% significance level) with a standard deviation of 20%.

Discussion

Improved biomass estimates using the AOS approach

When compared with vessel-based acoustic surveys of orange roughy, conventional deep-towed bodies used before 2010 were able to provide improved precision (Kloser, 1996) and improved species identification through the use of multifrequency acoustics (Kloster et al., 2002). These acoustic methods were used in conjunction with separate trawl hauls and optical devices (Koslow et al., 1995; Kloser et al., 1997). The net-attached AOS method integrates the net, optical, and acoustic devices by integrating visually verified TS at multiple frequencies, video, and stereo still images of species and trawl catch for biological sampling in one sampling device. It is an example on how multidisciplinary measurements can combine to improve outcomes (Demer et al., 2009; Ryan et al., 2009; Churnside et al., 2012). Through a combination of qualitative and empirically established criteria, these additional datasets enable a “multiple-lines-of-evidence” approach to provide greatly improved understanding of species composition, multifrequency response, and behaviour, therefore improving the robustness of the biomass estimates and consequently their acceptance for use in the stock assessment process.

Overview of survey programme

The extension of the AOS from TS measuring system (Ryan et al., 2009) to biomass estimation has been successful. The biomass

| Table 6. Metrics for vessel and AOS echogram regions for examples of non-avoidance and avoidance of the AOS platform (Figure 6). |
|-----------------|-----------------|-----------------|-----------------|-----------------|
|                 | Non-avoidance   | Avoidance       | Non-avoidance   | Avoidance       |
| Vessel 38 kHz   | AOS 120 kHz     | Vessel 38 kHz   | AOS 120 kHz     |
| Height (m)      | 53.9            | 62.14           | 96              | 44              |
| Mean depth (m)  | 764             | 768             | 763             | 823             |
| Length (m)      | 3200            | 3420            | 1695            | 1217            |
| Mean $S_0$ (dB) | −66.1           | −61.2           | −71.3           | −58.7           |
estimates of orange roughy were based on compelling evidence of species, with the results reviewed by stock assessment groups in Australia and New Zealand and incorporated into the stock assessment process. Conversely, the multiple-lines-of-evidence approach enabled us to determine that some locations were dominated by other species (Johnston’s cod, deepwater lantern shark; Kloser and Ryan, 2014) where prior vessel and trawl surveying had been unable to unequivocally determine species. In Australia, the methodology was developed and applied on the St Helens Hill and St Patricks Head spawning grounds between 2009 and 2013 (Kloser et al., 2011a, 2015). These results were incorporated in the stock assessment (Upston et al., 2015) and formed part of the evidence to support that the stock had rebuilt from its previous low levels. In New Zealand, the AOS estimates have been incorporated in the orange roughy stock assessment for a number of management zones.

Review of the 5 years of surveys has demonstrated the repeatability of the method within and between regions. We had no experience at many of the survey sites, some of which had complex terrain and unknown species composition. By utilizing all available information, we were able to rapidly gain an understanding of the survey locations, modify survey effort to focus on the most important regions, and conduct specific deployments to further clarify species if required. By selecting the appropriate survey design (star or grid), biomass estimates were possible for small (0.6 nautical mile$^2$) to large (35 nautical mile$^2$) areas, quantifying biomass from 720 to 40 150 t on flat, conical, or seabed features. The estimated biomass between areas can be used as an independent check on stock assessment methodology that may vary between regions and national borders. The consistency of the frequency difference between areas is evident (Figure 4), but significant variation in this parameter is a sign of possible bias for individual surveys (Figure 4). The cause of this bias could be due to remaining species-identification issues, TS variations due to length and orientation, and calibration or changes in sound absorption due to operating depth and temperature discussed below.

A potential source of bias due to changes in fish behaviour from the noise and vibrations of the net-attached AOS survey platform was explored. It was expected that orange roughy would sense and react to the net-attached AOS system based on previous studies (Koslow et al., 1995). Our comparison of the vessel and the AOS data showed that when operating at a distance of 130 m, there is strong active avoidance to the system. When surveying at a range greater than the recommended survey sounding distance (>250 m), no active avoidance was observed between the vessel and AOS recordings. What is not established is whether active avoidance actually biases biomass estimates. For example, the density per unit volume near the seabed may increase when avoiding, but the height of the aggregation can reduce therefore, and the effects could cancel each other such that biomass is unchanged. To understand this requires multiple transects at different ranges from the fish under similar undisturbed conditions, with both good quality vessel and AOS data recorded. These measures have been difficult to obtain in field campaigns to date.

**Role of 120 kHz**

The strong correlation between AOS 120 and 38 kHz biomass estimates ($r^2 = 0.97$) suggests that TS estimates at 38 and 120 kHz
and other potential sources of mean error (e.g. calibration, sound absorption) are low (unless errors are correlated). Significant differences, however, can occur between the individual 38 and 120 kHz biomass estimates (s.d. = 20%) and suggests that there can be between-survey variation in one or all of the TS, calibration, or sound-absorption parameters. Variation in TS of orange roughy (with consequent effects on biomass) is possible due to changes in the fish mean tilt angle (Kloser et al., 2013). Deepwater transducer sensitivity can alter as a function of depth (Kloser, 1996; Ryan et al., 2009). As a separate exercise, we characterize this by vertically lowering the AOS system through working depths with a calibration sphere suspended beneath. Possible hysteresis in transducer-depth sensitivity (Kloser, 1996) could affect the calibration stability of the system between deployments contributing to survey–survey variation. Seawater absorption is estimated at each site based on either direct measurement (CTD, TD) or oceanographic model-based values of salinity and temperature. We use the equations of Francois and Garrison (1982), but differences in the various equations are noted as being potentially significant (Doonan et al., 2003b) and may be the source of differences in biomass between frequencies.

The 120 kHz frequency has some advantages over the lower 38 kHz frequency. The echo integration results show that orange roughy provide on average 3.3 dB more signal at 120 than at 38 kHz (Figure 4), improving signal-to-noise by greater than twofold. Further, 120 kHz is about tenfold less sensitive to the presence of small gas-bladder fish (Table 3; Kloser et al., 2002). Orange roughy backscatter at 120 kHz appears less sensitive to fish tilt angle (Kloser et al., 2013), improving robustness, and repeatability should the surveyed population change mean tilt angle between survey locations and/or survey years. A disadvantage with 120 kHz is that seawater absorption at 120 kHz is about fourfold higher than at 38 kHz, limiting the working range and resulting in a greater source of error if not correctly estimated. Averaging of AOS 38 and 120 kHz biomass estimates for each survey is recommended until the variability between frequencies is better understood.

Limitations

The speed to tow and (more so) time to turn the AOS system to the next transect can be a significant overhead, although this is a challenge for any deeply towed system. A transect towing speed of ca. 4 knots was typical in good weather. If the area is large, surveys can take >12 h to complete. Fish movement, dispersion, or aggregation may bias results if these occur at shorter time-scales. In calm weather, vessel-acoustic surveys may provide a pragmatic alternative, particularly if prior or subsequent AOS surveys have established species composition of the main aggregations. These can be particularly effective on large flat grounds if the location of orange roughy is dynamic such that a rapid survey execution is needed. The advantage of rapid execution needs to be weighed against the benefit of accurately discriminating species using multiple lines of evidence from the AOS and improved robustness through estimating biomass at both 38 and 120 kHz.

We note that AOS in situ TS measurements are of herded fish that likely have a different tilt orientation distribution (and, therefore, TS distribution) than that of an undisturbed population. This needs consideration if using AOS data to provide estimates of mean population TS. Previous work specifically looked at how representative the net-attached measurements were of schooling fish by comparing the echo integrated school backscatter at multiple frequencies with that of AOS in situ measurements at multiple frequencies with fish tilt angle measurements (Kloser et al., 2013).

Future directions

The 5-year survey programme produced quantitative biomass estimates that were accepted as inputs for stock assessment. By readily integrating with the operations of a commercial fishing vessel, this method can be used for sustained monitoring that, in some cases, for reasons of cost or necessity (e.g. high seas), could be implemented by skippers without researchers on board. The AOS may be well suited to estimating biomass of other deepwater fish species (oresos, alfonsonino, hoki) where it could provide new in situ species–verified TS measurements and echo integration-based biomass estimates by applying the methods described in this paper. We envisage simplification of operation and a significantly smaller size as compact acoustic and optical technologies become available. An optic-fibre connection was trialled successfully in July 2015, providing video and acoustics at 1000 m depth to the surface. This capability opens up possibilities of real-time observations to minimize benthic impacts and enable selective harvesting of species.

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References


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