A multifrequency method to classify and evaluate fisheries acoustics data

J. Michael Jech and William L. Michaels

Abstract: Acoustic surveys have been conducted on Georges Bank from 1998 to present to estimate Atlantic herring (*Clupea harengus*) population abundance. Acoustic data were collected with a 12 or 18, 38, and 120 kHz Simrad EK500 scientific echo sounder. A pelagic trawl and underwater video images were used to collect biological information and to verify the species composition of acoustic backscatter. A multifrequency classification method was developed to improve the efficiency and accuracy of classifying species from acoustic echograms. In this method, a volume backscatter (S_v) threshold was applied equivalently to all echograms, and then a composite echogram was created based on which frequencies had S_v greater than or less than the S_v threshold. The results of this method were compared with the standard method of visually scrutinizing regions, and metrics were developed to evaluate the accuracy of classification algorithms relative to current methods, as well as to assess the effects of classification methods on population abundance estimates. In general, this method matched visually scrutinized Atlantic herring regions, but with consistent biases in classifying 38 kHz backscatter. The metrics highlighted spatial and temporal changes in the acoustic landscape, which may be indicative of intra- and inter-annual biological changes.

Résumé : Des inventaires acoustiques sur le banc Georges de 1998 à aujourd'hui cherchent à estimer l'abondance de la population de harengs de l'Atlantique (*Clupea harengus*). Les données acoustiques ont été recueillies à l'aide d'une écho-sonde scientifique Simrad EK500 de 12 ou 18, 38 et 120 kHz. Un chalut pélagique et des images vidéo sous-marines ont servi à amasser des renseignements biologiques et à vérifier la composition spécifique de la rétrodiffusion acoustique. Nous avons mis au point une méthode de classification à fréquences multiples pour améliorer l'efficacité et la précision de la classification des espèces à partir des échogrammes acoustiques. Dans cette méthode, un seuil de volume de rétrodiffusion (S_v) est appliqué de façon équivalente à tous les échogrammes et un échogramme composite est créé à partir des fréquences qui ont des S_v plus grands ou plus faibles que le seuil de S_v. Nous avons comparé les résultats de cette méthode à la méthode standard qui consiste à scruter visuellement les régions et nous avons mis au point des métriques pour évaluer la précision des algorithmes de classification par rapport aux méthodes courantes ainsi que pour déterminer les effets des méthodes de classification sur les estimations d'abondance de la population. En général, notre méthode se compare à celle de l'examen visuel des régions contenant des harengs, mais avec des déformations uniformes dans la classification des rétrodiffusions de 38 kHz. Les métriques mettent en lumière les changements spatiaux et temporels du paysage acoustique, qui peuvent peut-être représenter des changements biologiques intra- et inter-annuels.

[Traduit par la Rédaction]

Introduction

Identification of acoustic backscatter to taxa is one of the grand challenges of fisheries acoustics (MacLennan and Holliday 1996). In this paper, identification is defined as the objective determination of acoustic backscatter to genus or species, whereas classification is defined as the less rigorous product of objectively categorizing acoustic backscatter to some anatomical feature or lower-level taxon. For example, acoustic backscatter may be classified or categorized as fish with a gas-filled swimbladder or as non-gas-bearing zooplankton, but the species comprising either group may only be broadly known. Interpretation of acoustic data currently involves verification of backscatter in conjunction with visual scrutiny of echograms (Reid et al. 1998). Scrutinization is the process of visually interpreting an echogram and selecting and allocating backscatter to a species. Verification of acoustic backscatter primarily involves physical capture with nets and, to a lesser extent, optical imaging. Visual interpretation of echograms is highly dependent on the experience of the person scrutinizing the data, and consequently, biases are difficult to quantify. Objective identification or classification methods are preferable to subjective methods because objective classification can be applied as data are collected; biases due to personal experience are minimized or eliminated; objective methods can be transferred among

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surveys without transferring "experienced" specialists; data analyses are more efficient, timely, less sensitive to subjective interpretation, and potentially more accurate; error and bias are more amenable to quantification; and spatial and temporal distributions and changes in these distributions can be efficiently characterized.

The dependence of backscatter by zooplankton and fish on acoustic frequency and size of the animal has long been recognized (e.g., Anderson 1950; Haslett 1965) and has been used to separate size classes (McNaught 1969; Holliday 1977) or classify or identify organisms (Zakharia and Sessarego 1982). Utilizing this frequency dependence for remotely estimating organism size or identifying species requires a wide acoustic bandwidth. Widening the frequency bandwidth can be achieved with broadband signals and (or) multiple, narrowband echo sounders (multifrequency). Broadband signals transmit and receive continuous energy over a broad (greater than 10% of the center frequency) frequency range. Broadband methods have been used to measure spectral responses from individuals (Kjærgaard et al. 1990; Reeder et al. 2004), compare spectra among different species (Simmonds and Armstrong 1990), and differentiate species using neural networks (Simmonds et al. 1996). These methods have had some success in the laboratory but have had limited application to fisheries surveys (Zakharia et al. 1996). A drawback to broadband technology is that the energy per frequency is lower than with narrowband systems, so that the detection of targets at the ranges required for most fisheries assessments is limited.

Alternatively, multiple narrowband frequencies (multifrequency) can be used to widen the acoustic bandwidth. The two common methods of analyzing multifrequency data are an inverse approach (Holliday 1977) and the difference in mean volume backscattering strength (ΔMVBS) (Madureira et al. 1993) or "dB differencing" (Higgenbottom et al. 2000). These techniques have been used to separate fish with gas-filled swimbladders from fish with no swimbladder (Kirkegaard and Lassen 1990) and swimbladder-bearing fish from zooplankton (Sætersdal et al. 1982; Cochrane et al. 1991; Kang et al. 2002), to generate size-based estimates of zooplankton (Greenlaw and Johnson 1983; Holliday and Pieper 1995; Mitson et al. 1996), to estimate swimbladder sizes (Holliday 1972; Kalish et al. 1986), and to discriminate squid from other targets (Goss et al. 1998). The nearly ubiquitous availability of two or three narrowband echo sounders on fisheries research vessels has driven the use of the ΔMVBS method, and it is becoming a standard technique for separating gas-bearing organisms from those without a gas-bearing organ (e.g., Korneliussen and Ona 2002, 2003) and in ecological studies (Simard and Lavoie 1999; Swartzman et al. 1999).

The ΔMVBS method uses ratios of volume backscatter ($s_v(f)$ ($m^2 \cdot m^{-3}$)) or, in the logarithmic domain, the difference between $S_v(f)$ (dB) values, where f denotes the frequency dependence. The general success of this method to discriminate zooplankton and fish is apparent when the frequency-dependent backscatter for gas-bearing organisms versus those organisms without a gas-bearing feature is compared. However, the ΔMVBS method uses the ratio of two frequencies regardless of how many frequencies are available. When three or more frequencies are available, ratios of two frequencies are compared with other ratios of two frequencies. Comparing ratios of ratios is a cumbersome method to analyze data from three or more frequencies. In this paper, a method is presented that incorporates information from multiple frequencies to investigate the potential for classifying Atlantic herring (*Clupea harengus*) in the Northwest Atlantic. This method is evaluated by comparison with visually scrutinized data, and the benefits and limitations of this method for surveys are discussed.

Materials and methods

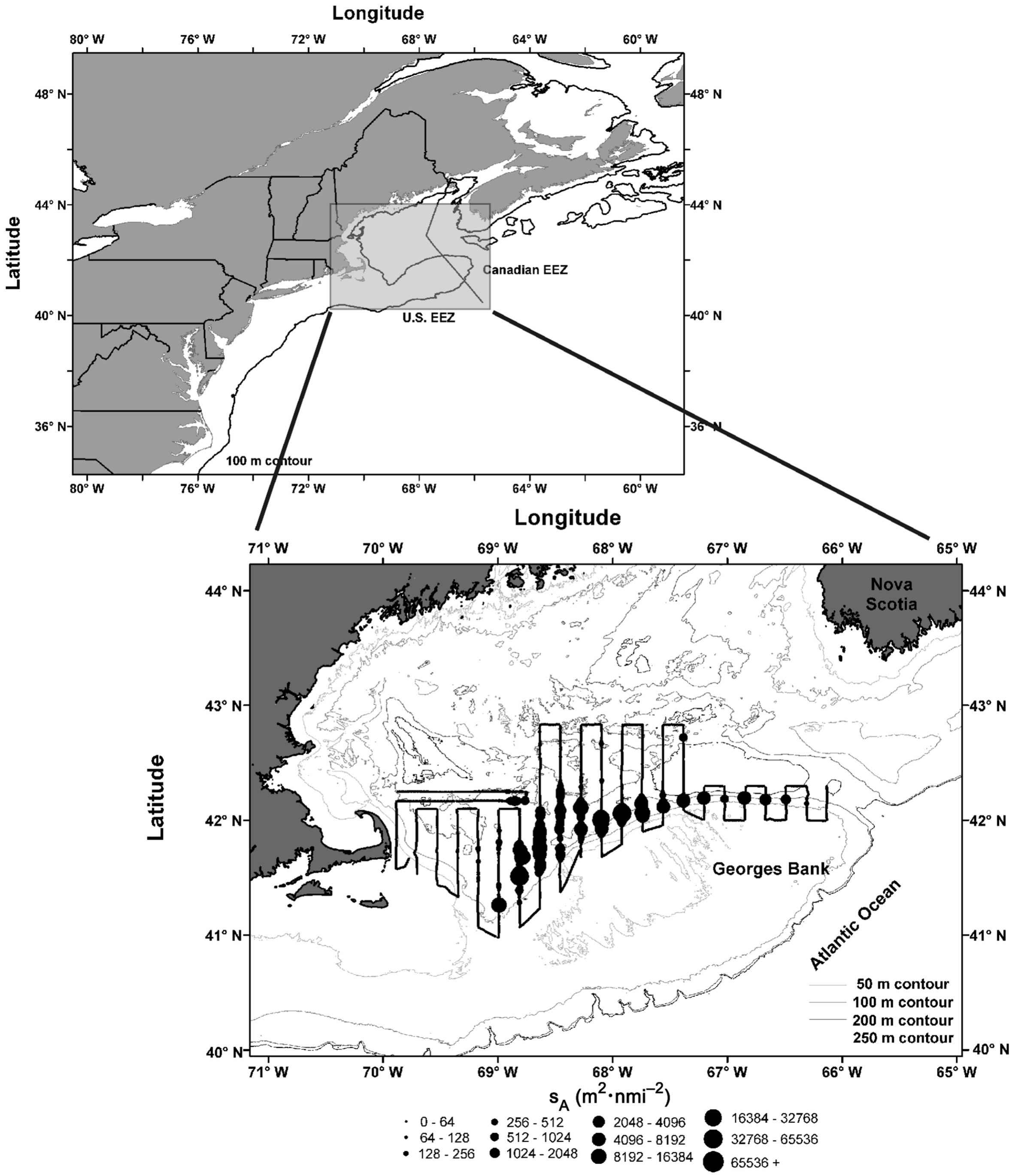
Data were collected during the Northeast Fisheries Science Center's (NEFSC) annual Atlantic herring acoustical survey. These surveys consisted of systematic parallel or zigzag transects conducted during September and October in the Gulf of Maine and Georges Bank regions (Fig. 1). The primary survey is designed to survey the offshore component of the Atlantic herring population, which migrates to Georges Bank in the fall to spawn.

Acoustic data

Acoustic data were collected from 1995 to 2004 on the NOAA R/V *Delaware II* with a Simrad EK500 scientific echo sounder (Simrad, Horton, Norway). Before 1999, acoustic data were collected as part of pilot projects to investigate the potential for using acoustic methods to estimate abundance and biomass of pelagic species. During 1999–2001, the EK500 operated a hull-mounted, single-beam, 12 kHz transducer (model 12-16) and hull-mounted 38 kHz (ES38-12) and 120 kHz (ES120-7) split-beam transducers. From 2002 to present, the 12 kHz transducer was replaced with an 18 kHz (ES18) split-beam transducer. Beam widths, as measured by the manufacturer at the half-power points, were 16°, 12°, 12°, and 7° for the 12, 18, 38, and 120 kHz transducers, respectively. The 38 and 120 kHz transducers were located on the keel, with the 120 kHz transducer 1.24 m aft of the 38 kHz transducer. The 12 and 18 kHz transducers were located 2.97 m forward and 0.66 m to the port of the 38 kHz transducer. Each frequency was transmitted simultaneously at a rate of 1 ping per 2 s. Pulse durations were 1 ms for the 38 and 120 kHz echo sounders, 3 ms for the 12 kHz echo sounder, and 2 ms for the 18 kHz echo sounder. Although it may be advantageous to maintain consistent pulse durations among all frequencies, the signal to noise ratio for the 12 and 18 kHz systems was unacceptable at shorter pulse durations. The 18, 38, and 120 kHz systems were calibrated before each survey and often were calibrated during and (or) immediately after the survey period using the standard target method (Foote et al. 1987). The 12 kHz system was successfully calibrated in 1999 and 2001. Target strength and volume backscatter calibration gains varied less than 0.5 dB for the 12 and 18 kHz systems, 0.3 dB for the 38 kHz system, and 0.8 dB for the 120 kHz system over the period from 1999 to 2004.

Acoustic signals were processed by the EK500 by applying $20\log R$ time-varying gain, frequency-dependent absorption coefficients, and calibration gains. A –90 dB S_v threshold was set during data collection. These data were vertically inte-

Fig. 1. Systematic parallel acoustic survey conducted on Georges Bank during 18–26 September 2002. Areal backscatter (s_A) values at 38 kHz are based on volume backscatter allocated to Atlantic herring (*Clupea harengus*).



grated at 0.5 m intervals (1999 and 2000) or 1 m intervals (2001–2004) for volume backscatter (S_v (dB·m^{-3})). Volume backscatter data collected in 1999 and 2000 were transferred via Ethernet to a UNIX workstation in Simrad's BI500 data format. Volume backscatter data collected from 2001 to 2004 were transferred via Ethernet to a personal computer (PC) and logged with SonarData's Echolog software (SonarData Pty Ltd., Hobart, Tasmania).

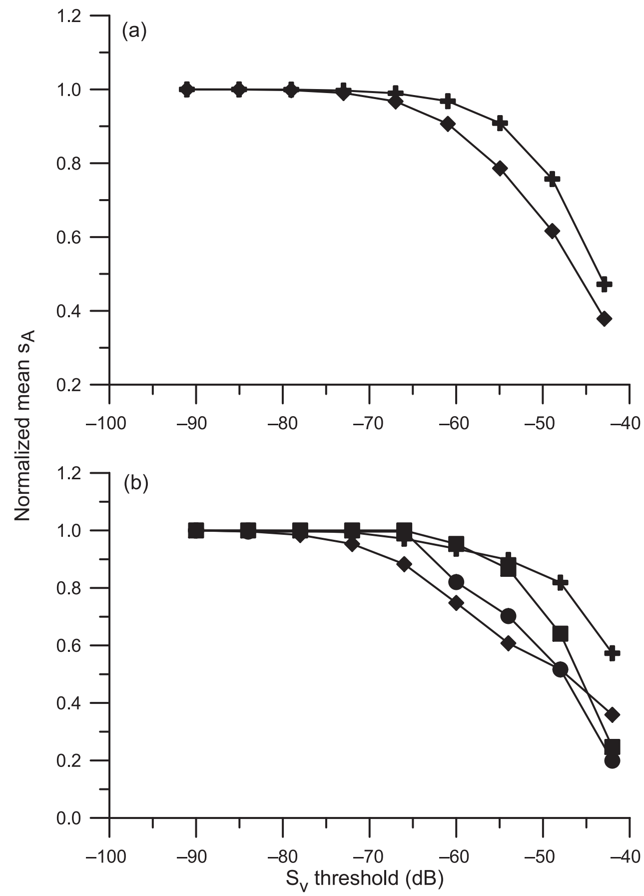
Volume backscatter data were postprocessed using SonarData's Echoview software. Data shallower than 10 m were removed from analyses to eliminate the transmit pulse and reduce backscatter by surface bubbles. Data deeper than 0.5 m above the seafloor echo were removed from analyses. The seafloor echo was selected using Echoview's "Maximum Sv with backstep" algorithm, where the backstep was set at 0.5 m. The bottom detection was then visually inspected and corrected if necessary.

Volume backscatter data were horizontally averaged over 0.5 nautical miles (nmi) for measures of areal backscatter (s_A (m^2·nmi^{-2})). This equivalent sampling distance unit (ESDU) was based on analyses of Atlantic herring abundance and biomass estimates using traditional statistics and geostatistical methods and was determined to be optimal for deriving abundance and biomass estimates of Atlantic herring during the annual surveys (William Overholtz, NEFSC, 166 Water Street, Woods Hole, MA 02543, USA, personal communication).

During postprocessing, an S_v threshold of –66 dB was applied equivalently to all echograms and all frequencies. This threshold was determined by analyzing a subset of data collected in 1999. Data were selected from transects where the greatest concentrations of Atlantic herring were observed. Total water-column s_A and s_A apportioned to herring were calculated at 0.5 nmi intervals for S_v thresholds ranging from –91 to –43 dB in 6 dB steps. The mean s_A was calculated at each S_v threshold and then normalized to the maximum mean value (Fig. 2*a*). Mean water-column s_A and herring s_A decreased slightly for S_v thresholds from –91 to –70 dB. For thresholds above –70 dB, mean water-column s_A deviated from the maximum at a greater rate than did the mean herring s_A. The mean water-column s_A was reduced to 91% of the maximum at an S_v threshold of –61 dB, whereas mean herring s_A was only reduced to 97% of the maximum. The final choice of –66 dB as the postprocessing S_v threshold was based on these results and the qualitative ability to visually select Atlantic herring.

Acoustic backscatter attributed to Atlantic herring was visually selected (i.e., “scrutinized”) in near-real time during the surveys. Selection of Atlantic herring was accomplished through experience and examination of trawl catches. Two sets of areal backscatter values were exported from Echoview and imported into an Oracle® database: s_A for the entire water column and s_A apportioned to Atlantic herring.

Fig. 2. Mean 38 kHz areal backscatter (s_A) integrated throughout the entire water column (s_A(WC), +), in visually selected herring regions (s_A(AH$_V$), ◆), in cells where all three frequencies were present throughout the water column (s_A(WC$_{123}$), ●), and in cells where all three frequencies were present within visually selected herring regions (s_A(AH$_{123}$), ■) as a function of 38 kHz volume backscatter (S_v) threshold. Data presented in (*a*) were collected in September 1999 and data presented in (*b*) were collected in September 2003 along the transect shown in Fig. 8.



Biological data

A high-speed midwater rope trawl (HSMRT) was used to collect biological samples and verify species composition of acoustic backscatter. This trawl was designed for fishing at relatively high speeds (4–5 knots) with minimal drag. Its symmetrical four-seam box design had 53.1 m footrope, headrope, and breast lines, providing a mouth opening of roughly 300–350 m^2 when fishing. The trawl was rigged with four 54.8 m bridles and 1.8 m^2 US Jet double-foiled suberkrub-type doors with double door weights. Optimal tow configuration was set to a total (forward and aft sections) setback of 2.5 m with 275 kg tom weights for each side. A Simrad FS903 third-wire trawl monitoring system was used to determine net configuration while towing and to estimate the catch amount to collect a representative sample of the organisms comprising acoustic backscatter.

Trawl locations, tow depths, and tow durations were chosen on an ad hoc basis to sample Atlantic herring aggregations, as well as unknown backscatter. Because tow duration was not standardized, trawl catches were not used for abundance estimates. Trawl catch data were recorded, audited, and archived using the Fisheries Scientific Computer System (FSCS). FSCS has been developed within NOAA Fisheries as an electronic on-board data entry system. Catch data are imported to an Oracle® database for data auditing and archiving. The trawl catch was separated by species, and the total weight of each species was recorded. Fork lengths to the nearest centimetre were recorded for a sample of 100–150 fish for all species, except Atlantic herring. A sample of 100–150 Atlantic herring was randomly selected and individual fork lengths to the nearest millimetre and individual weights to the nearest gram were recorded. A subsample of one herring per centimetre interval was selected for measurements of sex, maturity, stomach contents, and otolith extraction for age estimation.

Other data

Conductivity–temperature–depth (CTD) profiles were obtained at the beginning and end of each transect and before each trawl haul. The on-board data recording and entry system, Scientific Computer System (SCS), was used to record time series of time (GMT), geographic position, and the EK500 vessel log, as well as electronically enter events such as the beginning and end of transects and deployments. This event log was audited and imported to an Oracle® database. The event log, biological data, and acoustic data are all linked within Oracle®.

Table 1. Year, beginning and end dates, number of transects in each survey, and the survey design for Atlantic herring (*Clupea harengus*) acoustic surveys in the Georges Bank region.

Survey year	Begin date	End date	No. of transects	Survey design
1999*a*	25 September	27 September	13	Systematic zigzag
1999*b*	27 September	28 September	13	Systematic zigzag
2000*a*	11 September	16 September	17	Systematic parallel
2000*b*	04 October	06 October	7	Systematic parallel
2000*c*	06 October	08 October	7	Systematic parallel
2001	18 September	23 September	18	Systematic parallel
2002	18 September	26 September	22	Systematic parallel
2003*a*	04 September	10 September	18	Systematic parallel
2003*b*	18 September	24 September	18	Systematic parallel
2003*c*	03 October	10 October	18	Systematic parallel
2004	21 September	27 September	17	Systematic parallel

Classification method

A method is introduced that records whether the S_v in an echogram "cell" (1 m or 0.5 m vertical by 1 ping horizontal) is greater than the S_v threshold and then codes each cell depending on which frequencies are greater than the S_v threshold ("present") or less than the S_v threshold ("absent"). The number of present or absent combinations can be calculated from Pascal's triangle. For three frequencies, there are eight possible outcomes: - - -, 1- -, 12-, 123, 1-3, -2-, -23, and - -3, where "1" denotes the presence of 12 or 18 kHz S_v, "2" denotes the presence of 38 kHz S_v, "3" denotes the presence of 120 kHz S_v, and "-" denotes the absence of a frequency. A series of virtual echograms was created in Echoview (Higgenbottom et al. 2000) and the final result of the classification was applied to the 38 kHz S_v data.

Through experience with visually scrutinizing echograms and examining trawl catches, backscatter by Atlantic herring appeared to correspond closely with S_v that was present in all three frequencies (code value "123"). Overall, Atlantic herring dominated (>90% by number or weight) pelagic trawl catches within 10–15 nmi of Georges Bank. For the entire survey area on Georges Bank (Fig. 1), Atlantic herring, silver hake (*Merluccius bilinearis*), and Acadian redfish (*Sebastes fasciatus*) typically comprised 95% or greater of the trawl catches. Therefore, those cells where all three frequencies are present were hypothesized to be Atlantic herring.

Thirty-eight kHz s_A values were exported from Echoview and imported to an Oracle® database for analysis. The following data categories were used for analysis: s_A values for the entire water column (s_A(WC)); s_A values for visually selected Atlantic herring regions ($s_A(AH_V)$); s_A values for the entire water column where S_v was present in all three frequencies ($s_A(WC_{123})$); and s_A values within visually selected Atlantic herring regions where S_v was present in all three frequencies ($s_A(AH_{123})$). Only s_A values along systematic zigzag (1999) or parallel (2000–2004) transects were selected for analysis and s_A values during deployments, transits, and crossover transects were excluded (Table 1).

Analysis and comparisons

Objective classification methods require evaluation of the accuracy and precision of the method and consideration of how the method affects long-term time series of population estimates. Evaluating the accuracy of classification methods in situ is often very difficult because of the limited ability at sea to accurately verify all acoustic backscatter. For these analyses, the classification method is compared with the de facto standard of visually scrutinizing echograms.

To assess whether the frequency combination where all three frequencies were present corresponded to the visually selected Atlantic herring regions (AH_V), the number of visually selected Atlantic herring regions was compared with the number of these regions containing S_v where all three frequencies were present (AH_{123}).

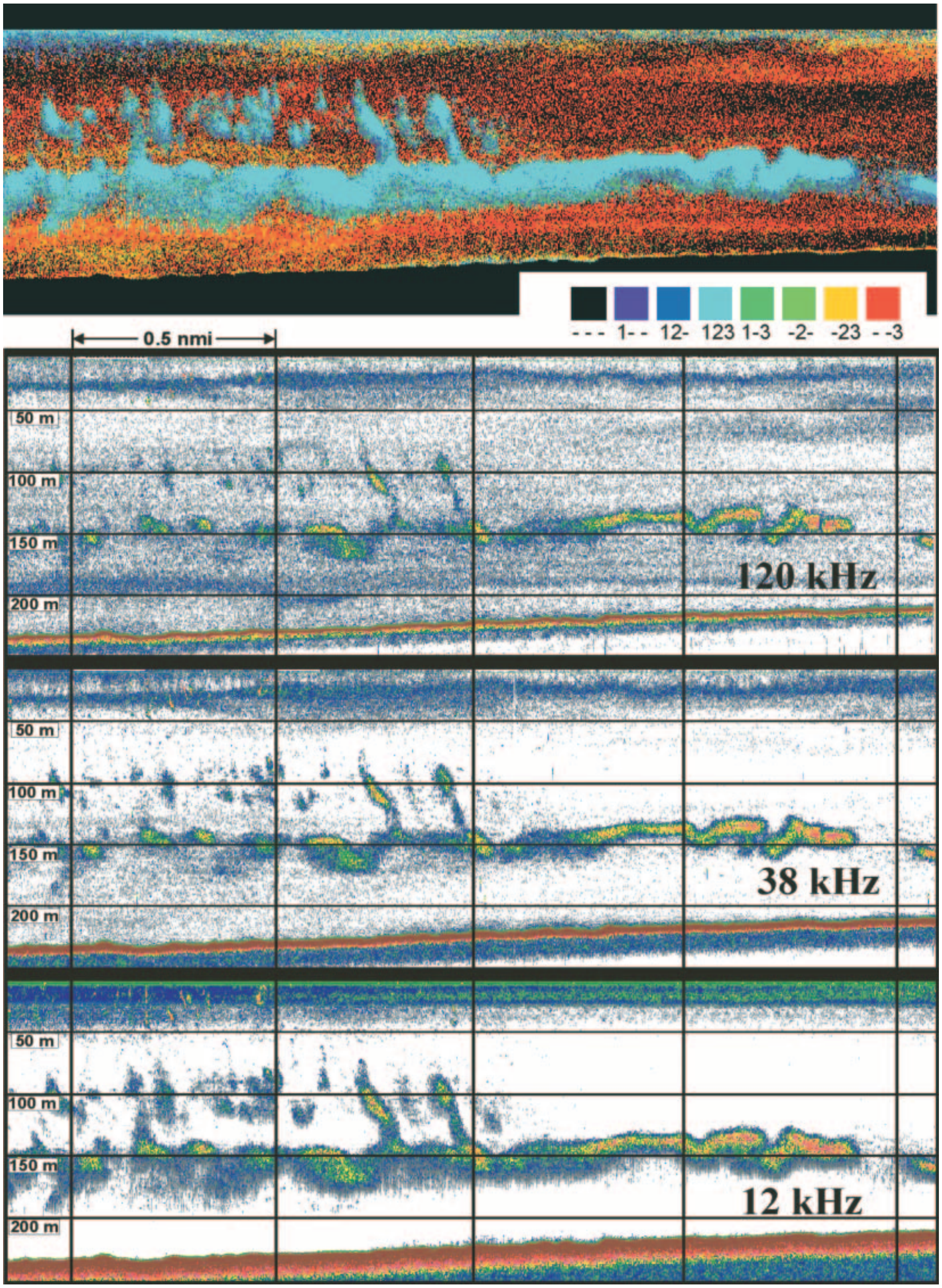
To evaluate which frequency combinations, if any, were more prevalent in visually selected Atlantic herring regions (AH_V) relative to the water column, the proportion of cells for each frequency combination (FC) within Atlantic herring regions (p_{AH_V}(FC)) was compared with the proportion in the water column (p_{WC}(FC)):

$$(1) \qquad P(\mathrm{FC}) = \frac{p_{\mathrm{AH_V}}(\mathrm{FC})}{p_{\mathrm{WC}}(\mathrm{FC})}$$

where p_{AH_V}(FC) was the number of cells for each frequency combination within visually selected Atlantic herring regions divided by the total number of cells within those regions, and p_{WC}(FC) was the number of cells for each frequency combination in the water column divided by the total number of cells. Water-column cells comprised all cells except those within Atlantic herring regions along the entire survey. Values of P(FC) greater than one indicate a greater proportion of that frequency combination within visually selected regions, values less than one indicate a greater proportion of that frequency combination in the water column, and values of one indicate equivalent proportions.

This classification method is dependent on the S_v threshold used to postprocess the echograms. If the S_v threshold is set such that all cells have volume backscatter greater than the threshold, then the entire water column will be classified homogeneously. Conversely, setting a high S_v threshold will eliminate all volume backscatter. Similar to the S_v-threshold analysis in 1999, data collected along a transect during 21 September 2003 were analyzed to examine the effects of S_v threshold on the classification method; s_A(WC), $s_A(AH_V)$,

Fig. 3. Echograms of three frequency (12, 38, and 120 kHz) data (lower three panels) and corresponding composite echogram (top panel) from the classification method. In the composite echogram, volume backscatter cells are color-coded based on the frequency combinations, where “1”, “2”, or “3” denotes the presence of 12, 38, or 120 kHz S_v values, respectively, and “–” denotes the absence of a frequency. The cyan color represents all three frequencies greater than the S_v threshold, and these cells are hypothesized to represent Atlantic herring (*Clupea harengus*). Note that color in the composite echogram does not represent magnitude. nmi, nautical mile.



$s_A(WC_{123})$, and $s_A(AH_{123})$ were averaged over 0.5 nmi intervals for S_v thresholds ranging from –90 to –42 dB in 6 dB steps. The mean s_A was calculated at each S_v threshold and then normalized to the maximum mean value.

Areal backscatter values are used for abundance estimates. Three comparisons of s_A values were done. For these comparisons, water-column cells comprised all echogram cells, including those within Atlantic herring regions. The first comparison was the ratio of $s_A(AH_{123})$ to ($s_A(AH_V)$). This ratio provides a metric of the proportion of backscatter objectively classified as Atlantic herring relative to the backscatter visually allocated to herring:

Table 2. Number of regions visually selected and the number of visually selected regions with cells where all three frequencies were present.

Survey	No. of visually selected regions	No. of regions with all three frequencies present
1999*a*	14	14
1999*b*	14	14
2000*a*	25	25
2000*b*	19	19
2000*c*	16	16
2001	29	29
2002	25	25
2003*a*	28	27*
2003*b*	57	57
2003*c*	39	39
2004	30	30

Note: With the exception of one region in survey 2003*a* (indicated by *), all visually selected regions had S_v values that had all three frequencies present. The s_A for the single region in survey 2003*a* was 27 $m^2 \cdot nmi^{-2}$.

$$(2) \qquad R(s_A(AH_{123}){:}s_A(AH_V)) = \frac{\sum s_A(AH_{123})}{\sum s_A(AH_V)}$$

where the summation is over the entire survey. This ratio can be used to quantify a change in abundance indices when using the objective method.

The second comparison was the ratio of $s_A(WC_{123})$ to $s_A(WC)$. This ratio provides a metric of the total water-column backscatter relative to the backscatter objectively classified as Atlantic herring:

$$(3) \qquad R(s_A(WC_{123}){:}s_A(WC)) = \frac{\sum s_A(WC_{123})}{\sum s_A(WC)}$$

where the summation is over the entire survey. This ratio measures the proportion of backscatter within the water column that can be potentially classified as Atlantic herring.

The third comparison provides a metric of $s_A(AH_V)$ relative to $s_A(WC_{123})$:

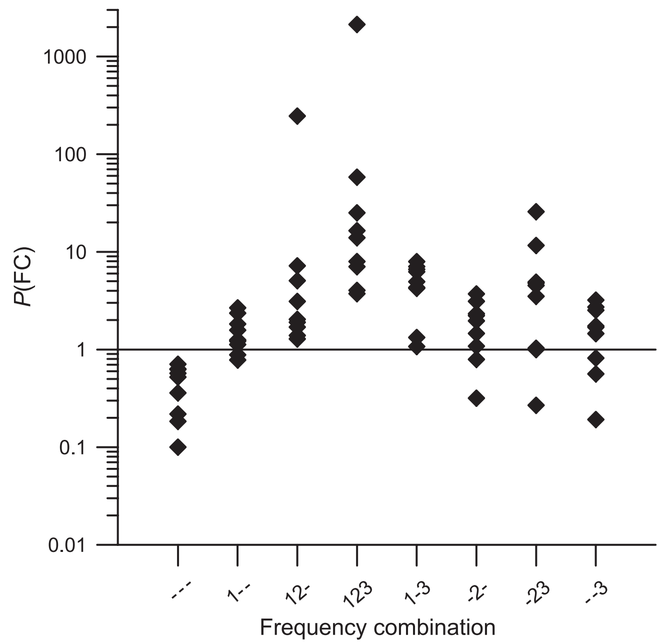
$$(4) \qquad R(s_A(AH_V){:}s_A(WC_{123})) = \frac{\sum s_A(AH_V)}{\sum s_A(WC_{123})}$$

where the summation is over the entire survey. This ratio measures the proportion of backscatter in the water column that could be objectively classified as Atlantic herring to that backscatter visually allocated.

Results

Mean water-column s_A ($s_A(WC)$) and visually apportioned herring s_A ($s_A(AH_V)$) decreased slightly for S_v thresholds less than –72 dB for data collected in 2003 (Fig. 2*b*). For thresholds above –70 dB, mean $s_A(WC)$ deviated from the maximum at a greater rate than did the mean $s_A(AH_V)$ and at a greater rate than in 1999 (Fig. 2*a*). The mean $s_A(WC)$ was reduced to 75% of the maximum at an S_v threshold of –60 dB, whereas mean $s_A(AH_V)$ was only reduced to 94% of the maximum. For backscatter where all three frequencies were above the S_v threshold, mean $s_A(WC_{123})$ and $s_A(AH_{123})$ were insensitive to S_v threshold at thresholds less than –66 dB. At thresholds greater than –66 dB, similar to results in 1999, the mean $s_A(WC_{123})$ deviated from the maximum at a greater rate than did the mean $s_A(AH_{123})$. At thresholds less than –60 dB, mean $s_A(AH_{123})$ was less sensitive to the S_v threshold than was the mean $s_A(AH_V)$, whereas for thresholds above –60 dB, the opposite trend occurred.

Fig. 4. The proportion of each frequency combination within visually selected Atlantic herring (*Clupea harengus*) regions relative to the proportion of frequency combinations in the water column. Each point represents the cumulative proportion for each survey. Frequency combinations are coded as “1”, “2”, or “3” where each value denotes the presence of 12 or 18, 38, or 120 kHz S_v, respectively, and “–” denotes the absence of a frequency. Values greater than 1 represent a greater proportion of a frequency combination within regions relative to the water column. Values less than 1 represent a smaller proportion of a frequency combination within regions relative to the water column, and a value of 1 represents equivalent proportions between regions and the water column.



Conventional echograms commonly display S_v in color, where color is used to represent backscattering intensity. For this method $S_v(f)$ frequency combinations are visualized by color coding each frequency combination and displaying the results as an echogram (Fig. 3). The use of color is a powerful tool to display data, to highlight features, and to interpret the data (Swartzman et al. 1999; Kloser et al. 2002; Towler et al. 2003). For these data, cyan represents S_v data where all three frequencies were greater than the S_v threshold. This frequency combination is hypothesized to be representative of Atlantic herring.

To evaluate whether visually selected Atlantic herring regions were objectively categorized as Atlantic herring, the number of visually selected regions were compared with the number of regions that contained S_v where all three frequencies were present. Every visually selected Atlantic herring region, with the exception of one region selected in 2003, contained cells with S_v where all frequencies were greater

Fig. 5. Ratio of 38 kHz areal backscatter based on 38 kHz volume backscatter where all three frequencies were present within visually selected herring regions ($s_A(AH_{123})$) to the 38 kHz areal backscatter based on volume backscatter within visually selected regions ($s_A(AH_V)$) for each survey.

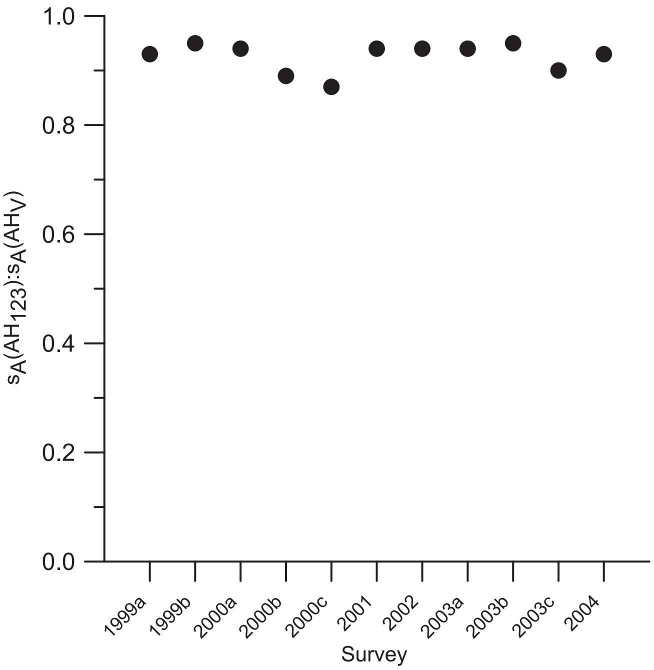
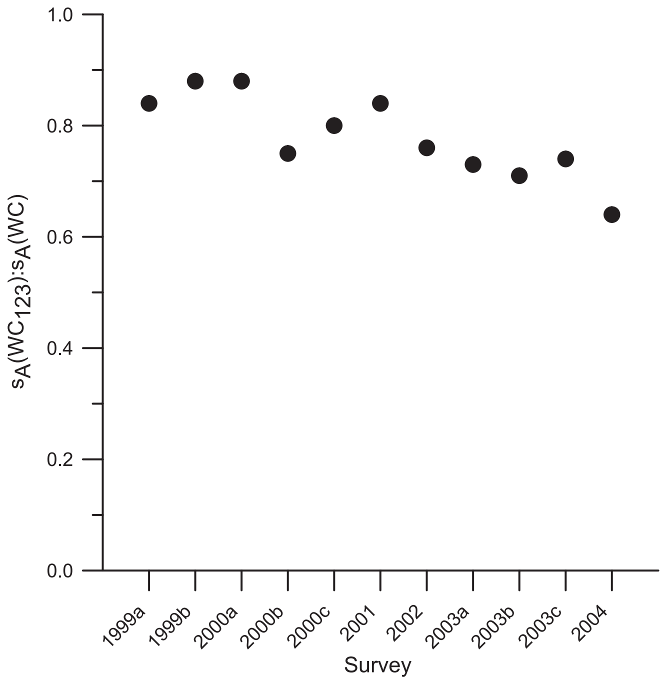


Fig. 6. Ratio of 38 kHz areal backscatter based on volume backscatter where all three frequencies were present throughout the water column ($s_A(WC_{123})$) to 38 kHz areal backscatter throughout the water column ($s_A(WC)$) for each survey.



than the S_v threshold (Table 2). The single region in 2003 was a small aggregation, horizontal dimension less than 0.5 nmi, with an s_A of 27 $m^2 \cdot nmi^{-2}$.

In general, the proportion of each frequency combination relative to the other combinations within Atlantic herring regions was greater than the proportion of each corresponding frequency combination in the water column (Fig. 4). For the frequency combination where all frequencies were less than the S_v threshold, the proportion of empty cells was greater in the water column than in scrutinized regions. However, this comparison is biased because scrutinized regions were created to minimize the number of empty cells. Three frequency combinations (12 or 18 and 38 kHz (frequency combination code "12-"), 12 or 18, 38, and 120 kHz ("123"), and 12 or 18 and 120 kHz ("1-3")) had greater proportions within scrutinized Atlantic herring regions for all surveys, whereas the other frequency combinations were not consistently greater or less than the proportion of those combinations in the water column.

Within regions scrutinized for Atlantic herring, 38 kHz s_A derived from S_v cells with all three frequencies greater than the S_v threshold was 5%–13% lower than the 38 kHz s_A from corresponding visually selected regions (Fig. 5). The ratio $s_A(AH_{123})$ to $s_A(AH_V)$ varied between 93% and 95% for surveys conducted in September, whereas the three surveys conducted in October had the lowest ratios (2000*b*, 89%; 2000*c*, 87%; 2003*c*, 90%).

Water-column 38 kHz s_A values derived from S_v cells with all three frequencies greater than the S_v threshold ($s_A(WC_{123})$) were 88% to 64% of the 38 kHz water-column s_A ($s_A(WC)$) (Fig. 6). The ratio of $s_A(WC_{123})$ to $s_A(WC)$ showed a decreasing trend from 1999 to 2004.

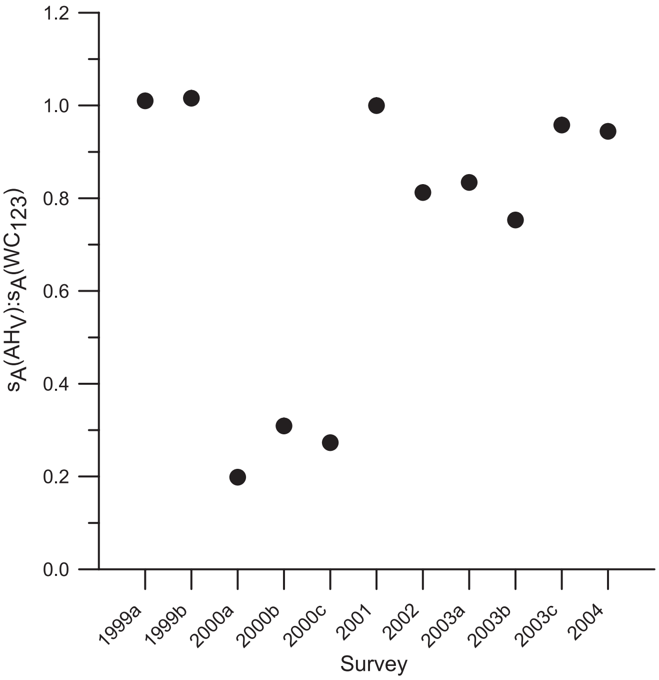
The s_A values from scrutinized Atlantic herring regions relative to water-column cells where all three frequencies were greater than the S_v threshold ($s_A(AH_V)$ to $s_A(WC_{123})$) ranged from 100% to 20% (Fig. 7). Ratios of $s_A(AH_V)$ to $s_A(WC_{123})$ were considerably lower during 2000, ranging from 20% to 31% in 2000 versus 75% to 100% during the other years. There appears to be a disjunct in these ratio values between 2001 and 2002, where $s_A(AH_V)$:$s_A(WC_{123})$ values were near 100% during 1999 and 2001 and in the 70%–90% range during 2002–2004.

Discussion

The S_v threshold used in this analysis is that used for estimating Atlantic herring abundance at the Northeast Fisheries Science Center and was chosen as a compromise between the ability to visually scrutinize echograms for Atlantic herring and minimizing the effect of S_v threshold on areal backscatter and the resulting abundance estimates. The classification method was less sensitive to S_v threshold at lower thresholds than was visually scrutinizing the data. This suggests that echogram cells where all three frequencies are above the threshold dominate the total backscatter. Interestingly, at higher thresholds, the classification method was more sensitive to S_v threshold. The overall response (a flat response and then a relatively sharp drop) of the classification method to S_v threshold suggests that an objective classification method could be used to select an optimal S_v threshold.

The acoustic data were neither spatially smoothed (e.g., Korneliussen and Ona 2003) nor corrected for beam-width or pulse-duration effects (e.g., Diner 2001). During these surveys, the herring are queuing to spawn on Georges Bank

Fig. 7. Ratio of 38 kHz areal backscatter based on volume backscatter within visually selected herring regions ($s_A(AH_V)$) to 38 kHz areal backscatter based on volume backscatter where all three frequencies were present throughout the water column ($s_A(WC_{123})$) for each survey.



and are observed in fairly large and continuous aggregations. The spatial extent of the aggregations along the transects tends to be on the order of miles, which is much larger than the beam-width dimensions. Corrections described by Diner (2001) were applied to a subset of the data to determine whether these corrections should be applied to the data before applying the classification method. Corrections ranged from 0.1 to 0.4 dB and thus were deemed negligible for these data. During other surveys at other times and locations, Atlantic herring are observed in smaller aggregations and smoothing and other corrections may be required.

Through experience in scrutinizing multifrequency data collected during the Atlantic herring surveys, it was hypothesized that echogram cells that had S_v greater than the threshold for all three frequencies could be classified as Atlantic herring. In support of this hypothesis, essentially every scrutinized region contained cells that met this criterion. In addition, the proportion of cells with all three frequencies greater than the S_v threshold was consistently greater in scrutinized regions than in the water column. However, all frequency combinations occurred in scrutinized regions and the frequency combination of all three frequencies greater than the S_v threshold did occur, sometimes in significant magnitude, outside of scrutinized regions. Examination of trawl catches showed that the backscatter outside of scrutinized regions was not attributable to Atlantic herring, thus demonstrating that this method is not sufficient for identification of Atlantic herring alone. However, it does appear that this method may be used to discriminate between gas-bearing organisms, such as swimbladder-bearing fish, and non-gas-bearing organisms, such as euphausiids or shrimp.

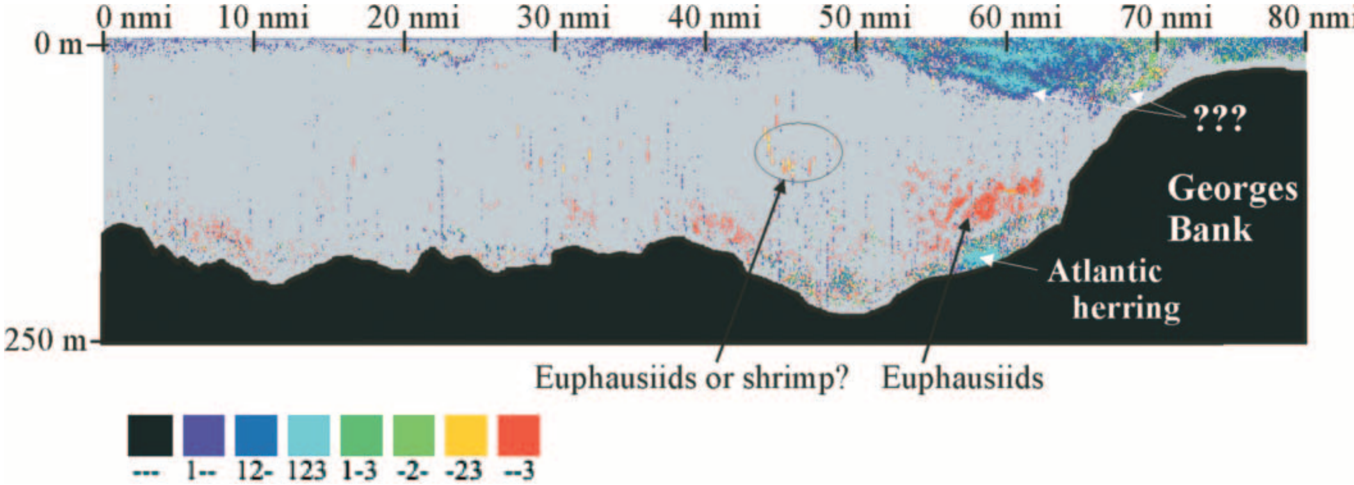
At present, this method must be used in a supervised mode where the classification is applied to the echograms and then the data are scrutinized. This two-step process changes the scrutinize paradigm from asking “what is?” to “what is not?” For our Atlantic herring surveys, the objective method effectively classifies a subset of the total backscatter as potentially herring, and then the scrutinizer selects from only that subset. This allows the scrutinizer to focus on a smaller set of data and may enhance the efficiency of scrutinizing echograms.

When utilizing multiple frequencies, the choice of frequencies is potentially more important than the number of frequencies (Horne and Jech 1999). Our results suggest that incorporating 12 or 18 kHz data is valuable for classifying swimbladder-bearing fish. There were consistently higher proportions of the frequency combinations that included the lower frequency within visually scrutinized regions than in the water column. This result is consistent with acoustic scattering theory where zooplankton are in the Rayleigh scattering region at the lower frequencies and thus are less sensitive to detection by the 12 or 18 kHz echo sounders.

When new classification schemes, whether they are subjective or objective, are applied to acoustic data that are used for long-term abundance indices, the effects of that method must be quantified relative to the index. Evaluating the accuracy in situ of acoustic classification or identification algorithms is difficult because of size-selectivity and catchability biases of physical capture gear, spatial and temporal displacement between acoustic sampling and verification sampling, and other limitations in verification methods. For these analyses, the classification method was compared with the standard method of visually scrutinizing echograms. Although this does not directly address the accuracy of the objective method, it does provide a means to quantify the effects of a new classification scheme on a long-term index. For these Atlantic herring surveys, areal backscatter was consistently 5%–10% lower using the multifrequency algorithm presented here than when the data were scrutinized. The cause of this reduction is not known, but it is most likely due to eliminating S_v from scatterers other than swimbladder-bearing fish. It is interesting to note that at the scale of a survey, the cumulative effect of this scattering is small relative to the scattering by swimbladder-bearing fish. The ultimate issue of whether to adjust estimates from prior surveys (in this case decreasing estimates by 5%–10%) or adjust future estimates (increasing estimates by 5%–10%) remains. This choice will be dictated by the confidence in the classification method and the long-term effects on the population assessments and must be made in cooperation with the fisheries managers.

An advantage to objective classification or identification methods is that real-time interpretation can be used to direct sampling. Although the method presented did not entirely succeed at identifying Atlantic herring, it did provide insights to the acoustic landscape. When viewing composite echograms for these surveys, spatial patterns (i.e., color-coded frequency combinations) emerged that were attributable to Atlantic herring, but other patterns were observed, the origins of which can only be speculated on at this time. These patterns could be used to select times, locations, and types of gear to optimally sample the backscatter, which

Fig. 8. Composite echogram of 18, 38, and 120 kHz data collected along a transect conducted during 21 September 2003 (0950–2010 GMT). The transect is oriented north to south (left to right). In the composite echogram, volume backscatter cells are color-coded based on the frequency combinations, where "1", "2", or "3" denotes the presence of 18, 38, or 120 kHz S_v values, and "–" denotes the absence of a frequency. The grey band at the surface designates the upper 10 m of the water column, which was not used in the analyses. The image is vertically distorted to highlight details of the backscattering patterns. The purple "streaks" throughout the water column are 18 kHz noise, most likely caused by cavitation at the transducer. nmi, nautical miles.



would reduce the uncertainty in acoustic classification and ultimately improve abundance estimates.

Metrics developed to evaluate classification methods may also have utility for monitoring interannual changes in backscatter patterns, which may be indicative of biological or ecosystem changes. A dramatic change in the ratio of 38 kHz backscatter within scrutinized regions to backscatter in the water column was observed in surveys conducted in 2000. During the three surveys conducted in 2000, the level of 38 kHz backscatter was considerably greater in the water column relative to the level of backscatter in scrutinized regions than in the other years. The cause of this change is unknown, but inspection of the echograms during this year showed high backscatter within the top 20 m of the surface, and it is thought that this backscatter may be due to siphonophores or possibly other small gas-bearing fish or organisms. Only a few trawls were directed at this layer and the trawl was not optimized for towing near the surface. However, no Atlantic herring were captured in these tows, and during these surveys, siphonophores were observed on the trawls, as well as on other instrumentation, such as the CTD and video towbody, when they were brought on board. Other interannual changes in backscatter patterns were a decreasing trend in the ratio of water-column 38 kHz s_A from cells where all three frequencies were greater than the S_v threshold to all other s_A and, between 2001 and 2002, a drop in the ratios of 38 kHz s_A within scrutinized regions to s_A in the water column. Again the causes of these changes are unknown but may be indicative of biological changes in this area.

This classification method highlighted spatial distributions of backscatter patterns and changes in these patterns may be indicative of biological changes. For example, a composite echogram using the classification method for a transect conducted during daylight on 21 September 2003 is illustrated in Fig. 8. This transect was oriented north to south and different backscatter patterns are observed along the transect. The primary concentration of Atlantic herring is located at the base of the slope (near the 60 nmi mark). Backscatter represented by red (backscatter dominated by 120 kHz) is believed to be euphausiids (*Euphausia* sp.), and the small yellow (backscatter dominated by 38 and 120 kHz) aggregations (between 40 and 50 nmi marks) are believed to be either shrimp (*Pandalus* sp. or *Penaeus* sp.) or euphausiids. Backscatter patterns observed near the surface were especially interesting where 18 kHz backscatter dominated north of Georges Bank (between 0 and 50 nmi) then changed to backscatter dominated by all three frequencies (between 50 and 65 nmi) and then to backscatter dominated by 38 kHz (between 65 and 80 nmi) over Georges Bank. The organisms or mix of organisms causing these patterns can only be speculated on at this time, but this emphasizes the need for multiple types of sampling gear during acoustic surveys.

This paper presents a classification method and metrics to evaluate the performance of an objective method relative to prior methods. These metrics have the additional benefit of being able to monitor changes in the acoustic landscape, which may be indicative of changes in the ecosystem. As fisheries management moves toward ecosystem-based assessments (e.g., NOAA 2004), the need to measure and monitor multiple species and trophic levels will require objective and timely data processing. Multifrequency acoustics address several data needs for ecosystem-based management such as quantifying the spatial and temporal distributions of living marine resources and measuring multiple size and trophic levels. Objective methods to classify or remotely identify living marine resources and metrics to evaluate these methods, such as those presented here, are needed for producing timely abundance estimates and will lead to an improved understanding of the aquatic environment.

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