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Detection of migratory herring in a shallow channel using 12- and 100-kHz sidescan sonars

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Abstract − A hydroacoustic monitoring program for migratory herring was conducted in Drogden Channel, near Copenhagen, Denmark, beginning in June, 1996. Using installations of 100-kHz sidescan sonar oriented across the channel, herring schools were observed at ranges up to 500 m in water depths of 10–14 m. In October 1997, this effort was supplemented with a 12-kHz sidescan mounted on a motorized tripod allowing azimuthal sector scanning. This 12-kHz sidescan was able to detect herring schools up to a 1 200-m range. Two examples are examined to assess the limits of herring school detectability and the feasibility of abundance estimation. In both cases, herring schools are detectable by their transience and up to 20 dB signal excess relative to the nominally stationary background reverberation, dominated by seabed backscattering. Attempts are made to extract quantitative abundance estimates using methods based on school size and density, and through quantitative echo-integration. Acoustic ray tracing was found to be useful in interpreting the results, and in particular modeling boundary-reflection focusing as a potential source of positive bias in herring abundance estimates. © 2000 Ifremer/CNRS/INRA/IRD/Cemagref/Éditions scientifiques et médicales Elsevier SAS

herring schools / sidescan sonar / acoustic ray-tracing

Résumé − Détection de harengs en migration dans un détroit peu profond au moyen de sonars latéraux de 12 et 100 kHz. À partir de juin 1996, un programme de surveillance hydroacoustique des harengs, lors de leur migration, a été effectué dans le détroit de Drogden, près de Copenhague au Danemark. À l'aide de sonars latéraux de 100 kHz, d'une portée de 500 m, au travers du détroit, des bancs de harengs ont été observés, à une profondeur comprise entre 10 et 14 m. En octobre 1997, ce travail a été complété avec un sonar latéral de 12 kHz monté sur un tripode motorisé permettant un balayage de section azimutale. Ce sonar de 12 kHz est capable de détecter des bancs de harengs dans un rayon de 1 200 m. Deux exemples ont été étudiés, pour évaluer les limites de détectabilité d'un banc de harengs et la faisabilité de l'estimation de l'abondance. Dans les deux cas, les bancs de harengs sont détectables par leur mouvement et jusqu'à un signal 20 dB au-dessus de la réverbération, dominé par l'énergie acoustique réfléchie par le fond de la mer. Des tentatives sont faites pour rechercher les estimations d'abondance quantitatives, en utilisant des méthodes basées sur la taille du banc et sa densité, et au moyen d'écho-intégration quantitative. Le traçage acoustique est utile pour interpréter les résultats, en particulier la modélisation de la réflexion au niveau des pourtours, réglée comme une source potentielle de biais positif dans les estimations d'abondance de harengs. © 2000 Ifremer/CNRS/INRA/IRD/Cemagref/Éditions scientifiques et médicales Elsevier SAS

bancs de harengs / sonar latéral / traçage acoustique

1. INTRODUCTION

The use of fixed-sonar installations for monitoring fish migration in shallow rivers and channels has been under development for many years. Generally, recent applications have focused on high-frequency (≥ 200 kHz) high-resolution sonar, operated at short range to avoid boundary interactions (Gaudet, 1990). However, lower-frequency side-looking sonars have a fish-detection potential at distances many times the

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water depth, in essence creating an acoustic net covering a significant fraction of the channel. With appropriate instrument maintenance and methods for handling the large quantities of data, continuous surveillance can be sustained. The penalty for extending the operating range in shallow waters is to invite interference from seabed and surface scattering, such that fish detection and abundance estimation becomes strongly dependent on environmental conditions. This study explores the longer-range capabilities of medium- and high-frequency side-looking sonars for detection and abundance estimation of herring in a shallow coastal channel.

Beginning in the 1960s, work reported by Weston and Revie (1971) and Revie et al. (1990) demonstrated long-range (up to 65 km) monitoring of fish populations using a large military sonar. More recently, vessel-based surveys have demonstrated quantitative herring detection at intermediate ranges (1–5 km, see Rusby et al., 1973; Misund et al., 1995). Recent work in rivers and coastal regions (Trevorrow, 1997; Trevorrow and Claytor, 1998; Pedersen and Trevorrow, 1999; Farmer et al., 1999) has shown that under some conditions fish echoes can be resolved relative to the background reverberation at horizontal ranges up to 100 times the water depth. All of these studies have shown the importance of boundary reflection and water column refraction on fish abundance measurements.

The purpose of this project was to evaluate the potential of long-range sonars for monitoring herring (*Clupea harengus*) migration through the Drogden channel. This project was pursued in the context of an environmental monitoring program during the construction of a bridge and tunnel connecting Copenhagen, Denmark and Malmö, Sweden. This channel lies at the southern end of the Øresund, connecting the Kattegat with the Baltic Sea. Herring are known to migrate into the Baltic for spawning during spring and autumn, returning to the Kattegat and North Sea for feeding and over-wintering. A hydroacoustic monitoring program using 100-kHz sonars was initiated in June 1996 and operated nearly continuously until May 1998 (Pedersen and Trevorrow, 1999). The 12-kHz sonar was installed in October 1997 and operated on a limited basis (Farmer et al., 1999). This work focuses on two example herring schools, investigating the detection characteristics and feasibility of extracting abundance estimates.

2. MATERIALS AND METHODS

The herring monitoring was conducted across the Drogden navigation channel between the islands of Amager and Saltholm (see *figure 1*), near Copenhagen, Denmark. The sonar were installed on the western edge of the Drogden channel near the narrowest part of the main channel, which was approximately 1 km wide, 10 to 14 m deep, with 2- to 5-m deep shallows on each side. Detailed seabed bathymetric surveys

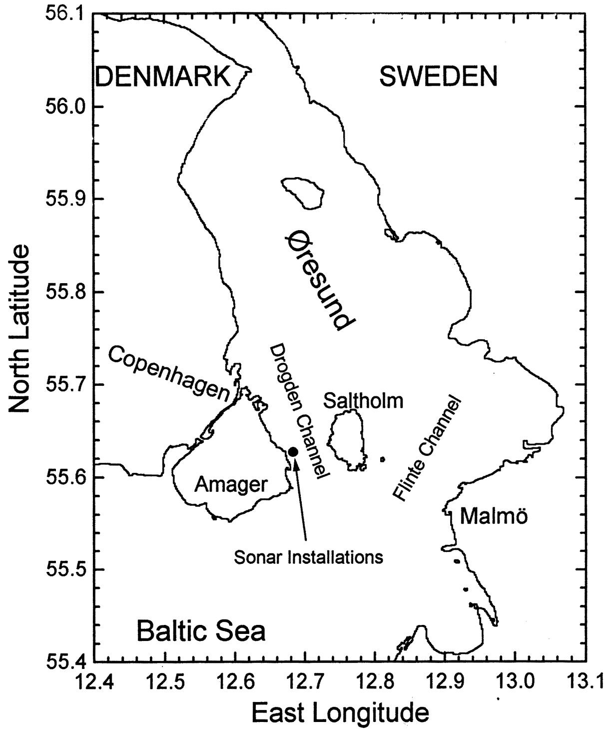

Figure 1. Map of northern Denmark and southern Sweden showing location of sonar installations in the Drogden Channel.

(example profile shown in *figure 5*) and continuous monitoring of water properties (e.g. temperature and salinity) and current profiles were conducted as part of the overall environmental program. The Drogden channel waters were characterized by either a northward flow of relatively fresh (10 practical salinity units, psu) Baltic Sea water or a southward flow of

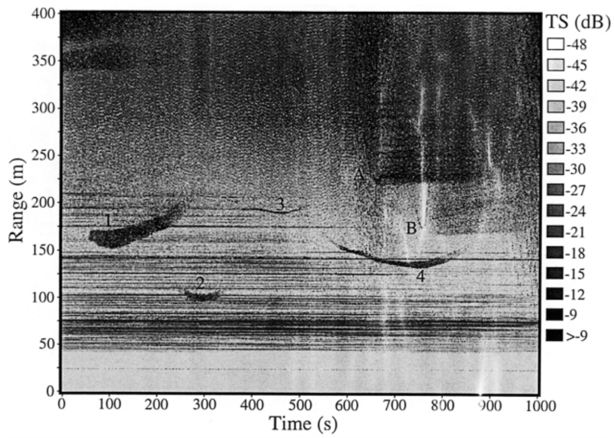

Figure 2. 100-kHz estimated target strength (*ETS*, dB:m^2) versus range and time image starting 8h53 UT April 5, 1997, showing probable fish schools (1–4) and vessel wakes (A, B) against background reverberation.

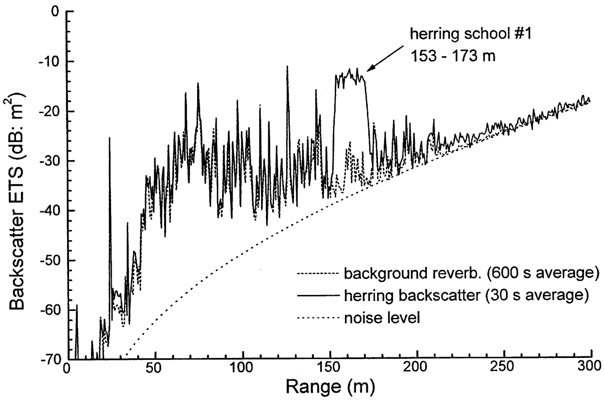

Figure 3. Profile of estimated target strength (*ETS*, dB:m^2) versus range through the widest part of herring school #1 in *figure 2*, compared with background reverberation and systemic noise level.

more saline (25 psu) water from the northern Øresund and the Kattegat. These flow regimes were not dominantly tidal, but driven by wind forcing and seasonal fluctuations. Both the 12- and 100-kHz sidescans were mounted on tripods 1.2 m above the seabed in water depth nominally 10 m. The sonar installations were focused on the deeper, main channel because the herring were assumed to avoid the 2- to 5-m shallows. The transducers were connected to sonar transceivers and computers inside the Nordre-Røse lighthouse via 200 m underwater cables.

The 100-kHz sidescan transducer (EDO/Western Corp. model 6400) had a fan-shaped beam 3° vertical by 60° horizontal (total angle to –3 dB). This sidescan was connected to a BioSonics model 101 sonar transceiver, which provided a nominal transmit power of 1 kW, a 20 log *R* time-varying gain, and an amplitude-detected output. The 100-kHz echo-amplitude was digitized at 1 kHz with 16-bit resolution in a data handling PC. The 100-kHz beam was directed perpendicular to the navigation channel, using a pulse length of 2 ms (1.5 m acoustic resolution) transmitted once every 2 s. The 100-kHz sonar was mounted with a wide beam axis horizontal and pointed eastward perpendicular to the channel. The 12-kHz sonar utilized a 40-element, 2.5-m aperture array custom-built by EDO/Western Corp. with measured beam widths of 2.8° (horizontal) by 120° (vertical). The 12-kHz sonar transmitted a 50-ms frequency modulated sweep (chirp) from 11.2 to 12.8 kHz with a nominal output power of 2 kW, with complex correlation of the received signal to yield 0.5 m acoustic resolution. The 12-kHz sonar did not use any time-varying gain. This sonar array was mounted on a motorized steering gear that could scan over a 50° sector oriented northwards across the channel. The 50° sector was scanned in 2° steps to a range of 2 200 m once every 150 s.

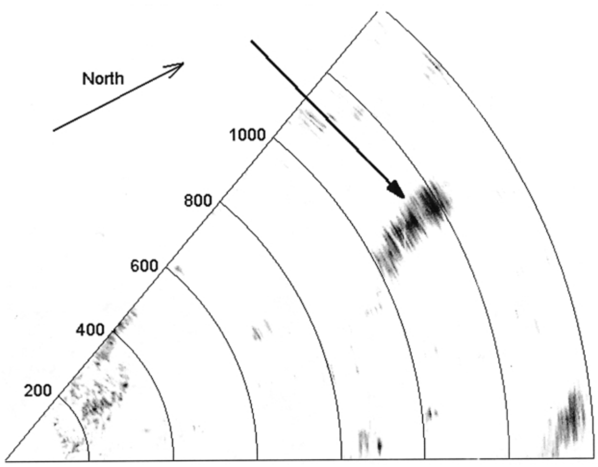

Figure 4. 12-kHz backscatter intensity sector scan at 1h00 UT October 30, 1997 composed of 25 successive transmissions spanning 150 s. Maximum range is 1 400 m with intensity scale 0 to 12 dB referenced to time-averaged reverberation. Arrow indicates herring school centered near 1 100 m.

Prior to deployment, system calibrations for both sonar were determined. This allowed the raw echo intensities at range *r*, to be converted to estimated target strength ($ETS = 10 \log_{10}$ [backscatter cross-section in m^2] in dB relative to 1 m^2) using the standard sonar equation, i.e. following Medwin and Clay (1998):

$$ETS = K + 20 \log_{10}[A(r)] - TVG(r) + 40 \log_{10}[r] + 2 \cdot \alpha \cdot r \quad (1)$$

where *K* is the calibration coefficient for each system (which includes transmit power, transducer sensitivity, pre-amplifier gains, waveform detection, and A/D conversion factors), $A(r)$ is the echo amplitude in digital counts, $TVG(r)$ is the receiver time-varying gain in dB, and α is the acoustic absorption in seawater (0.02 dB·m^{-1} at 100 kHz and 5.0×10^{-4} dB·m^{-1} at 12 kHz under these water conditions). Note that *ETS* as defined in this context includes all possible target contributions within the insonified volume, including echoes from multiple fish targets and seabed and surface scattering. The quantity *ETS* would only be equivalent to the true single fish target strength if that fish was located directly on the sonar axis in the absence of any confounding acoustic propagation effects. The interpretation of *ETS* in this context is complicated by the distributed nature of herring schools.

3. RESULTS

Figure 2 summarizes many of the important features observed with the 100-kHz system. The acoustic signatures of four fish schools and two vessels are shown, all of which can be recognized by their transient behavior relative to the background. The constant-range bands at 40–220 m are due to seabed backscatter, which is moderately time-invariant under typical flow conditions and generally independent of weather conditions. The gradual disappearance of seabed reverberation near the 220-m range marks the edge of a 100-m wide by 3-m deep gully in the channel bottom in combination with rising systemic noise levels. The thin lines at 25 and 145 m are due to temperature-salinity instrument moorings.

Gill net surveys conducted in this region throughout 1996 and 1997 (Stæhr, 1997) confirmed that schools of this size and migrating at this time of year were herring. In *figure 2* the largest school (#1) has a range dimension of roughly 20 m. If this school is assumed to be a circular target with a diameter of 20 m, the time interval from the point of closest approach to disappearance (150 s) in combination with the target range and sonar beam width suggests an advection speed of 60 $cm \cdot s^{-1}$. At this time the current was northwards at 30 $cm \cdot s^{-1}$, thus the fish were probably swimming northerly at 30 $cm \cdot s^{-1}$ relative to the water. Given the time of day and the presence of large ships it is reasonable to assume that the herring would be tightly schooled. With this horizontally wide beam it is impossible to extract the true school shape. Similar-sized herring schools were observed from the 50- to 500-m range, generally during daylight hours, throughout the spring and fall migration seasons.

Interference from ship wakes was regularly present in this busy shipping lane. Most vessels exhibited a direct echo from the hull, which appears as a hyperbolic trajectory on the range-time echograms. An intense noise event was often observed as a ship crossed the beam axis, which was assumed to be caused by propeller cavitation. Following the passage of the ship, an intense constant-range band was observed due to the injection of small air bubbles within the vessel wake. These wakes dissipated as the air bubbles either rose to the surface or dissolved, a process which typically required 6 to 10 min. All these features can be seen in *figure 2*.

The herring school signatures shown in *figure 2* had a *ETS* significantly higher than the seabed reverberation levels, as shown quantitatively in *figure 3*. Over most of the insonified range the short duration profile is essentially identical to the background reverberation. However, in the range interval of 153–173 m the herring school has a *ETS* to reverberation ratio (*ETSRR*) of up to 20 dB relative to the background reverberation. The peak *ETS* was near –13.8 $dB{:}m^2$. This background reverberation can be used to define a range-dependent threshold for echo-integration analysis, specifically where $ETSRR > 3.0$ dB (i.e. in this example from the 153 to 173-m range). Beyond the roughly 250-m range the background becomes dominated by systemic noise levels.

The 12-kHz sonar was able to detect herring schools at a much greater range, and in an azimuthally scanning operation it could map out the horizontal dimensions of a school. *Figure 4* shows an example herring school detected between the 1 000 and 1 250-m range. This image has the intensity scale referenced to the time-averaged reverberation vs. range and angle, thus enhancing the visibility of transient targets. As with the 100-kHz data, the background reverberation was approximately time-invariant. This school traversed the sonar sector heading northwards along the channel axis, with the centroid of the school moving from 550 to 1 200 m over a period of 12 min. This implies an average northward speed of 0.5 $m \cdot s^{-1}$, consistent with the measured northward current, suggesting that the school was (on average) drifting rather than actively swimming. Beyond roughly 1 200 m this herring school became lost in the reverberation. From quantitative analysis of this herring school the areal mean *ETS* was –22.4 $dB{:}m^2$ with an average *ETSRR* of 6.6 dB. Assuming the school to be stationary over the time it remained visible in the sonar beam, the total planar area of this school was 9 500 m^2.

4. DISCUSSION

4.1. Sonar results and abundance estimates

In addition to detecting the presence, timing, and morphological features of herring migration, the data from these sonar has the potential for quantitative abundance assessment. This can be pursued in two ways: through assumed areal or volumetric density relations based on school morphometry (i.e. following methods outlined in Misund et al., 1995), or through echo-integration analysis. In the first method, assumptions need to be made about the school density and shape. For example with herring school #1 (shown in *figures 2* and *3*), assuming a volumetric density of 5 $herring \cdot m^{-3}$ (Misund, 1993), a cylindrical school with a diameter of 20 m and a height of 6 m (half of the water depth), yields an estimated 9 400 fish. A similar estimate based on the observed school area from the 12-kHz sector image shown in *figure 4* yields an estimated 290 000 fish. Clearly, estimates of this kind are only as good as the assumed shapes and densities, and need in situ verification through simultaneous acoustic and net sampling. More generally such results could be utilized in an empirical relation postulated by Misund et al. (1995) of the form $\log_{10}(\text{biomass}) = a \log_{10}(\text{area}) + b$, where a and b are empirical constants.

To proceed with echo-integration analyses it is necessary to know the mean target strength, *TS*, for the fish under study and to assume an average orientation of the fish relative to the sonar beam. For individual herring the target strength at *dorsal* incidence is a well known function of length, i.e. using an empirical relation following Foote (1987) of the form $TS = 20 \log_{10}(L) - 71.9$ (in $dB{:}m^2$) for 38-kHz echosounders. Assuming a geometrical scattering regime (implicit in this empirical relation), the dorsal *TS* at 100 kHz is the same. Results from gill net surveys conducted in the Øresund during March and April 1997 found a mean herring length of 25.9 cm (Stæhr, 1997), which corresponds to a dorsal *TS* of

–43.6 dB:m^2. Assuming the herring to be swimming along the channel perpendicular to the 100-kHz sonar beam, they would be insonified at lateral incidence. Empirical results from a large number of fish species (including clupeoids) compiled by Love (1977) reveal that the lateral-incidence *TS* is 1.5 dB higher than at dorsal incidence. Thus the expected mean *TS* at 100 kHz for these Øresund herring at lateral incidence is –42.1 dB:m^2. Clearly, the overall accuracy is sensitive to this mean *TS* value, and ideally this should be based on specific, in situ measurements of herring lateral-incidence *TS* at 100 kHz.

Echo-integration approaches require an assumption that the entire school can be effectively sampled, either through the use of a horizontally wide beam or by azimuthally scanning over the area of the school. For the herring school observed with the 100-kHz sonar shown in *figures 2* and *3*, the profile was taken at the time of closest approach. Given the beam dimensions at this range (approximately 180 m wide by 8 m high) it can be assumed that the entire herring school lies within the sonar –3-dB beam width. Then the total number of herring in the school can be calculated as the range-integral of the ratio of estimated cross-section to fish cross-section (i.e. integration of the quantity 10 to the power 0.1·(*ETS* – *TS*)) over the school. In the example shown in *figure 3* the integrated number of herring is 13 600. This is slightly larger than the earlier morphological estimate, but is not corrected for acoustic propagation effects. This calculation also neglects acoustical multiple scattering and absorption within the herring school, which are small, second-order effects (Stanton, 1983) that should be included in later refinements of this technique.

Lacking any direct measurements of herring *TS* in the horizontal plane at 12 kHz, the 38-kHz dorsal value must again be used as a starting point. Given the northerly orientation of the 12-kHz sonar sector the herring shown in *figure 4* were insonified at roughly 10° to 30° off-tail incidence (assuming they were oriented along-channel), and thus the individual fish *TS* needs to be reduced. According to Love (1977), within a 0° to 30° sector near-tail incidence the average *TS* should be –11.5 dB relative to the dorsal value. Thus the expected *TS* for these herring should be –55.1 dB:m^2. Integrating over the school area (i.e. in range and successive pings where $ETSRR \geq 3$ dB) the estimated number of herring is 706 000 with an average volumetric density, assuming the school be 6 m high, of 9.25 herring·m^{-3}. These apparent abundance and density estimates are higher than expected, however these calculations have again neglected acoustic propagation effects, which should be more significant given the school range to depth ratio approaching 100.

4.2. Acoustic propagation issues

For target detection at longer range, the bottom and surface boundaries create a reflective acoustic waveguide which has the potential for increasing the backscattered amplitude and increasing the effective length of the echo relative to an unbounded medium. The fact that herring schools are composed of multiple closely-spaced targets implies that the direct and reflected multi-paths from each fish target are generally not separable. This complicates the use of integrated echo-intensity information for quantitatively estimating herring numbers. The above echo-integrated herring abundance estimates ignored seabed and surface reflections. At the relatively high sonar frequencies used in this study it is appropriate to model acoustic propagation using ray-tracing analysis (described in Medwin and Clay, 1998). A computer code due to Bowlin et al. (1992) was used to calculate the sound pressure level and other parameters along rays emanating from the source. The model needs environmental data such as the source depth, bathymetry versus range, sound speed profile, and boundary reflection losses. Predictions from this model can only be as accurate as these environmental inputs, and for this initial attempt at understanding propagation effects some realistic simplifying approximations were made. For both sonar the profile along the beam or sector center-line was taken from recent bathymetric surveys. The sound speed profile was based on measured water properties, with absorption appropriate to the sonar frequency, but was assumed range-independent. For both frequencies a 1 dB per bounce surface loss and a seabed loss versus angle given by classical two-layer reflection theory were assumed, using seabed properties appropriate for coarse sand. Corrections for vertical beam-deviation loss were applied modeling the transducers as rectangular sources of dimension either 242 mm for the 100-kHz and 62 mm for the 12-kHz sonar. The model was then used to generate the one-way sound pressure level (*SPL* in dB) over a range-depth cross-section along the beam axis. Clearly, it would have been valuable to verify and fine-tune these propagation model predictions with in situ acoustic measurements. This is an obvious area for further refinement.

Figure 5 shows the result of this model calculation for the 100-kHz sonar, using typical unstratified spring Baltic outflow conditions. This figure shows the one-way sound pressure level excess (*SPLE*) relative to spherical spreading, i.e. by adding $20 \log_{10}$ [range] and assuming the source level to be 0 dB. The figure shows the 3° sonar beam and its shadow zones, above the sonar at ranges up to 220 m and near the seabed beyond 520 m. Within the first 200 m the sonar beam impinges on the seabed but not on the sea-surface, thus seabed backscatter must be the dominant source of background reverberation shown in *figures 2* and *3*. Note that within the main beam there is a focusing effect due to reflections from the seabed. In particular, at the 165-m range the averaged *SPLE* from 5 to 11 m depth (following the example shown in *figure 3*) is –1.1 dB. This includes a one-way seawater absorption loss ($\alpha \cdot r$) of 1.9 dB, which was also included in the calculation of the apparent *ETS*. Therefore the effect of

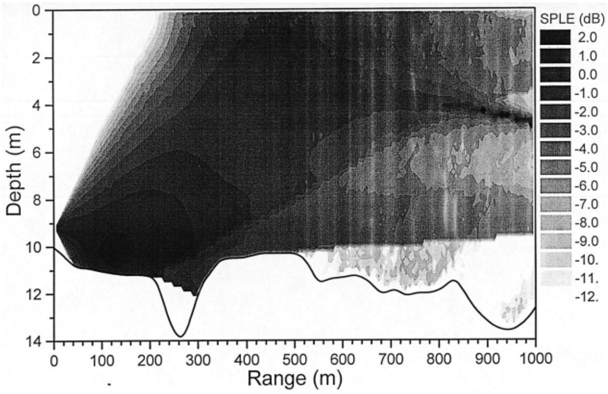

Figure 5. Cross-sectional distribution of modelled one-way sound pressure level excess (*SPLE*, dB) for the 100-kHz sonar in the Drogden Channel. Contours start at –12 dB and increase in 1-dB increments.

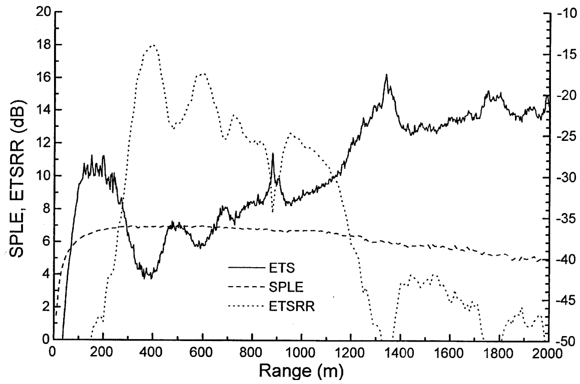

Figure 6. Sector-averaged estimated target strength (*ETS*, dB:m^2) versus range profile from the 12-kHz sonar at 1h00 UT on October 30, 1997 compared with depth-averaged sound pressure level excess (*SPLE*, dB) and a predicted target strength to reverberation ratio (*ETSRR*, dB) derived from ray-tracing model results assuming a herring school density of 1 herring·m^{-3}.

reflection focusing is to generate a 0.8-dB one-way signal excess over that found in an unbounded medium, leading to a 1.6-dB over-estimate of the school *ETS*. This positively biases the previous herring school size estimate by 46%. The corrected abundance for this school should be 9 400 fish, exactly the same as the assumed size-density estimate.

For the 12-kHz sonar with its vertically wide beam (±60°) the incident acoustic field is approximately homogeneous in depth, so that only depth-averaged quantities need to be considered. *Figure 6* compares the depth-averaged model predictions of sonar performance with the measured background *ETS*. The background reverberation generally increases with range due to the increasing surface area for boundary backscattering, with variations due to bathymetry and changes in seabed roughness. Due to the strong surface- and seabed-reflected propagation characteristics, the modeled *SPLE* builds up quickly with range to a value of 6.8 dB, diminishing mildly due absorption losses by 2 000 m. Following the example from *figure 4*, the one-way *SPLE* at 1 100-m range is 6.4 dB. Applying this to the previous calculation produces a corrected school *ETS* of –35.2 dB:m^2, an estimated 37 000 herring in the school, with a density of 0.49 herring·m^{-3}. Finally, for predictive purposes combining this modeled *SPLE* with an assumed herring school density of 1 herring·m^{-3}, we can calculate the expected *ETS* for a typical herring school. Dividing this by the measured reverberation vs. range yields the predicted *ETSRR* shown in *figure 6*. The *ETSRR* reaches a maximum of 18.0 dB at 390 m, decreasing mildly up to the 1 200-m range and then drastically dropping. This is in agreement with our observations of herring school detectability with this 12-kHz sonar.

5. CONCLUSION

Using fixed installations of 12 and 100-kHz sonars, herring school migration through Drogden Channel could be monitored continuously, subject to some environmental constraints. With both sonars herring schools were recognized by the combination of a greater echo-strength and transience relative to the nominally time-invariant background reverberation. The 100-kHz sonar was able to detect schools up to a 500-m range, limited by environmental reverberation and increasing levels of systemic noise with range. The 12-kHz sonar was able to detect herring schools up to 1 200 m, again limited by increasing levels of environmental reverberation. The difference in detection range between the two systems was due primarily to a higher transmit power and lower acoustic absorption at 12 kHz. Fish school echo to reverberation ratios up to 20 dB were observed with both systems. Because of its generally time-invariant nature, and ray-tracing model predictions which showed focusing of acoustic energy near the seabed, the background reverberation was dominated by backscatter from the seabed sediments. Wakes from vessels were also a consistent source of interference. Against these limitations must be balanced the capability for sampling at much greater range, covering significant fractions of the migration channel.

Two examples of herring school detection were examined to assess the feasibility of quantitative abundance estimation. This was attempted through two different approaches: the first based on the school width or area and an assumed volumetric density, and the second through quantitative echo-integration. There was agreement between the two approaches, particularly for the 100-kHz sonar example, however no specific fish capture data was collected to substantiate these estimates. The use of quantitative backscatter is sensitive to and requires a knowledge of both the fish orientation relative to the sonar and corrections for acoustic propagation conditions. Further, there is a need for better data on fish *TS* at horizontal incidence. Finally, the accuracy of these two methods can only be assessed through a combined acoustic and net capture survey.

The use of long-range side-looking sonar in shallow waters requires an understanding of boundary backscattering and reflection focusing effects. Acoustic ray-tracing analysis provides a method to quantify the sonar performance, specifically to model the estimation bias and fish detectability limits. For example, the predicted maximum detection range of 1 200 m for the 12-kHz sonar was in agreement with the observations. The ray-tracing model predicts a range-dependent positive bias in the echo strength from a herring school, based on the fact that boundary-reflected echoes from a single fish add to, and are indistinguishable from, the echoes from multiple fish in a school. Without correction for propagation effects, the echo-integrated density of the herring school observed with the 12-kHz sonar at the 1 100-m range was unrealistically high, and higher than the estimate based on school area. These ray-tracing model predictions are sensitive to the environmental conditions, such as bathymetry, water stratification, and seabed properties. Thus, it is necessary to measure these environmental conditions as part of the overall sonar survey. Clearly these ray-tracing model predictions, and hence the underlying measurements of environment conditions on which they are based, should be verified through independent acoustic measurements.

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