FISH DETECTION IN SHALLOW WATERS USING SIDE-LOOKING SONARS: THE IMPORTANCE OF ACOUSTIC PROPAGATION EFFECTS

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1. INTRODUCTION AND MOTIVATION

A fundamental challenge to fishery surveys is the acquisition of data over an area sufficient to allow accurate estimates of abundance. The use of vessel-based echo-sounders and echo-integration techniques is well-established, but the usefulness of such surveys is often compromised by limited spatial coverage and the consequent need for statistical compensation. Echo-sounder surveys of shallow-water or epi-pelagic stocks are further limited by the small sampling volume beneath the ship and vessel-avoidance behaviour by the fish. In contrast, side-looking sonars have the potential for fish detection at horizontal ranges of order several kilometres, even in shallow waters, providing spatial coverage and resolution significantly greater than that possible with conventional echo-sounders or net trawls. However, the use of side-looking sonars is greatly complicated by environmental influences such as a boundary back-scattering and propagation effects. These effects must be understood before fisheries surveys with side-looking sonars can be successful.

Pioneering work in the 1960's demonstrated long-range (up to 65 km) fish monitoring using a high-power, low-frequency military sonar installation near Perranporth, England (Weston & Revie 1971, 1989; Revie et al. 1990; Weston & Andrews 1990). Since then several vessel-based surveys have demonstrated fish detection and biomass estimation at intermediate ranges (Rusby et al. 1973; Hewitt et al. 1976; Misund et al. 1995; Farmer et al. 1999). It is clear in all of these intermediate and long range studies that acoustic propagation effects were of fundamental importance. More recently the use of high-frequency horizontally-oriented sonars for fish detection in rivers and lakes has been gaining acceptance (e.g. Gaudet 1990; Kubecka et al. 1994; Enzenhofer et al. 1998). However, in the majority of these riverine or lacustrine applications interactions with the surface and bottom boundaries were avoided by careful beam steering and restricting the measurement range (typically <20 m). Clearly, it is desirable to sample at greater range and probe close to the boundaries where fish are often found. Unfortunately, extending the survey range and probing close to the boundaries necessarily invites both back-scattered interference and acoustic biases created by reflection and refraction effects. Recent work (Trevorrow 1997; Trevorrow & Claytor 1998; Pedersen & Trevorrow 1999; Farmer et al. 1999) has shown that under typical shallow water conditions fish echoes can be resolved relative to the background reverberation. This paper addresses the acoustic biases generated by reflection and refraction effects in shallow waters.

2. EVIDENCE OF PROPAGATION EFFECTS

Over the past four years several field trials using sidescan sonars on salmon and herring have accumulated evidence of acoustic reflection and refraction effects. These studies have generally been conducted in shallow waters, defined herein as conditions where the horizontal ranging of the sonar is much greater than the water depth. Both fixed-location and towed systems were used. Acoustically these surveys may be divided into two categories: single targets where the acoustic multi-paths are potentially resolvable and distributed targets where the acoustic multi-paths are not separable from the multiple fish echoes. The fish enumeration approaches for these two categories are different: i.e. echo-counting techniques are used for single targets and echo-integration for distributed targets. In both cases there are significant positive biases in the fish abundance estimates created by reflection and refraction effects, although the effects are qualitatively different for the two cases.

For the high frequency sonars (12, 100, and 330 kHz) used in these studies it is appropriate to model acoustic propagation using ray-tracing analysis. Although more sophisticated models exist, for this first attempt at applying propagation modelling to fisheries problems a simple model is desired. A ray-tracing model due to Bowlin et al. (1992) is used to calculate sound pressure level and arrival times for the possible reflected and refracted *eigenrays* connecting the source and target. The model needs as input the source and target depth, bathymetry vs. range, sound speed profile, and boundary reflection losses. In all of the following analysis the water stratification is assumed range-independent, with a seawater absorption appropriate to the sonar operating frequency, a 1 dB surface loss is applied, and the bottom loss vs. angle is given by classical two-layer reflection theory, with a 1 dB loss at grazing angles below critical.

2.1 Single Fish Targets: Pacific Salmon

Migratory Pacific salmon were monitored in two different environments. In 1995 a fixed-location 100 kHz sidescan sonar was operated on the Fraser River near Mission, B.C. monitoring the upstream migration of adult salmon (described in Trevorrow 1997). In 1997 a 12 kHz towed sidescan was used to investigate salmon in the southern Strait of Georgia near Vancouver, B.C. (described in Farmer et al. 1999). In both situations the adult salmon, typically 55 cm in length with a maximum lateral-incidence target strength near -28 dB (re 1 m^2), were detected at horizontal ranges many times the water depth.

The Fraser River study utilised a pair of 1.8° x 60° 100 kHz sidescan sonars, one mounted vertically and the other horizontally. The sidescans were mounted on a tripod 4.7 m deep in 6 m water depth and aimed cross-river, perpendicular to the water flow. At this location the river cross-section was 320 m wide by 6 to 12 m deep. The turbulent river flow ensured non-stratified water conditions. The sonar was operated for 1 to 2 hour periods several times per day. The sonar used a pulse length of 0.5 ms, a pulse repetition interval of 0.6 s, and the received echo was digitised at 2500 samples per second, approximately matching the 37 cm range-resolution of the transmit pulse. This allowed salmon detection up to 250 m range with signal to reverberation ratios up to 30 dB. With the fixed sonar geometry, the moving salmon were readily detected relative to the time-invariant background reverberation from the river-bed. Salmon enumeration was accomplished by identifying and counting the fish tracks.

This echo-counting process was confounded by the presence of surface and bottom reflected multi-paths which both upwardly biased the estimated target strength and produced spurious or *ghost* images. In the crossed-transducer operating mode, the vertically narrow transmit beam insonified fish at mid-depth in the river, while the vertically wide receive beam accepted the surface and bottom reflected multi-paths. The time delay of these multi-paths was a sensitive function of fish depth, range, and bathymetry. The typically observed time delay was 1 to 2 ms, but generally decreased with range such that some of the multi-paths could not be distinguished from the direct arrival beyond roughly 50 m range. Figure 1(a) shows the river cross-section and an example of nine possible eigenrays connecting the sonar and a fish target near 63 m range. The bottom portion of this figure compares the instantaneous (1.2 s average) echo vs. range with the background reverberation averaged over 1 hour. There are distinct echo peaks in excess of 30 dB above the background reverberation that can be attributed to fish. From the ray-tracing analysis, the direct and multiply-reflected echoes are shown for two -28 dB fish targets, located at 62.7 and 68.2 m range. The target depth of 3.5 m was chosen to lie within the vertically narrow transmit beam. The ray-tracing result shows that the observed primary peaks are in fact a superposition of the first three (the direct, surface, and bottom-reflected) returns. This would account for the over-estimates of target strength (near -23 dB) for both fish. Clearly a shorter transmit pulse and higher digitisation rate should have been used to resolve these multi-paths. For the target at 62.7 m range the secondary *ghost* peak at 64 m range is due to the fourth and fifth (surface-bottom reflected) returns and is not in fact a separate fish target. Since these ghost images have amplitudes similar to the direct echo there is potential to include them as actual targets, upwardly biasing the target count by a factor of two or three. One solution is to ignore any targets occurring within a few milli-seconds after the direct (or first) arrival. However, this might erroneously remove a second real fish target swimming closely with the first. Clearly, acoustic propagation analysis is necessary to identify multi-paths.

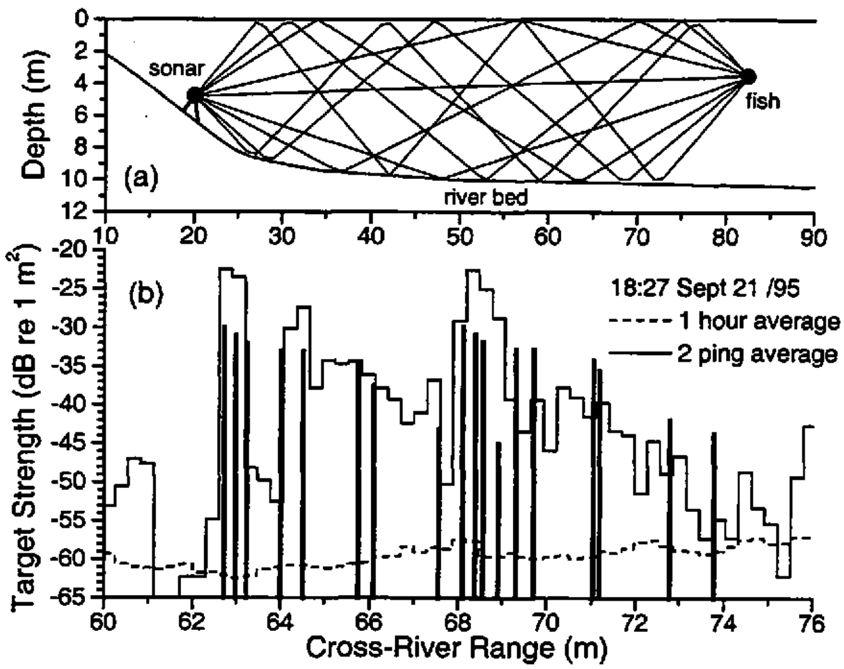

Figure 1: (a) Fraser river 100 kHz sonar geometry and nine possible eigenrays for target at 62.7 m range and 3.5 m depth. (b) comparison of measured acoustic target strength for two salmon targets with background reverberation and predicted multi-path intensities assuming a salmon TS = -28 dB.

The 1997 surveys in the Strait of Georgia detected adult salmon at horizontal ranges up to 7.2 km using a 2.5 m aperture, 12 kHz towed sonar array. The sonar was towed at approximately 35 m depth in waters depths from 100 to 250 m. A 200 ms by 1600 Hz chirp pulse was transmitted once every 10 s, with correlation processing of the received echo to achieve a 25 dB processing gain with a 47 cm range resolution. The long range propagation was aided by a sub-surface sound channel, centred near 35 m depth, formed beneath the warmer, fresher Fraser River outflow as it mixed with the more saline deep waters in the Strait. The resulting sound channel possessed strong downward refraction near the surface layer and weaker upward refraction below. Thus, in contrast to the Fraser River survey, internal refraction was now equally important to boundary reflection effects. Prior studies indicated that the salmon were generally restricted to the upper 40 m in this region.

One aspect of this Strait of Georgia survey was the propagation focusing effect and how this influenced the detectability and *apparent* target strength of the salmon. The salmon were observed as short linear streaks with duration from 5 to 50 transmissions (1 to 8 minutes). This duration in the beam increased with target range, and targets closer than 1 km were difficult to identify as their duration in the beam was less than 2 transmissions. Figure 2 compares the apparent target strength of the salmon streaks with the time-averaged background reverberation. This apparent target strength has been corrected only for spherical spreading and seawater absorption losses, ignoring reflection and refraction effects. The figure shows that the salmon targets can have signal-to-reverberation ratios of up to 25 dB and apparent target strengths up to -5 dB (re 1 m^2). This apparent target strength appears to increase with range. These values are greatly in excess of the expected -28 dB lateral incidence maximum, indicating that some kind of propagation focusing is taking place.

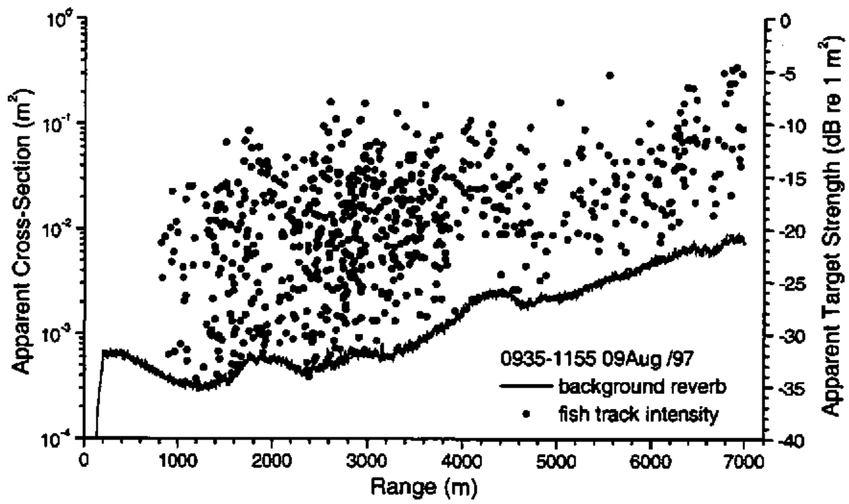

Figure 2: Comparison of salmon apparent target strengths with background reverberation from 12 kHz sonar operation in the Strait of Georgia.

The quantitative propagation effects can be seen by performing the eigenray-tracing computation over a matrix of possible range-depth fish target locations. The result of this one-way propagation calculation is shown in Figure 3. At each range-depth point (on a grid 1.5 m depth by 25 m range), the eigenray intensities, corrected for seawater absorption, were summed incoherently. Generally, there were from 2 to 25 contributing eigenrays, depending on depth and increasing in number with range. Eigenrays arriving more then 5 ms after the first were ignored as it was expected that these would be resolved as separate targets. The intensities in Figure 3 are referenced to a $20 \cdot \log_{10}$[range] dependence, and thus positive values can be interpreted as a one-way propagation enhancement relative to spherical spreading. The figure clearly shows the refractive sound channel from 20 to 60 m depth. These calculations predict a positive propagation enhancement over the whole water column at ranges up to approximately 3500 m, with peak enhancements in excess of 12 dB at some locations within the sound channel. This accounts for the up to 24 dB overestimates in the salmon back-scatter target strength shown in Figure 2. However, there are also regions with decreased insonification, especially shallower than 20 m and beyond 4000 m range, where fish target strengths will be reduced, perhaps to the point where they are lost in the background reverberation. Clearly, the use of propagation modelling enables both the correction of fish target strengths for propagation effects and identification of regions of detectability.

Similar to the Fraser River case, the acoustic multi-paths in the Strait of Georgia have the potential to create ghost targets. Clearly there are a multitude of reflected and refracted arrivals for each real target, but only a few of those will have sufficient amplitude to be observed above the background reverberation. This point is demonstrated in Figure 4, which shows the modelled target strength and arrival time (converted to apparent range) for all the possible two-way eigenray pairs connecting the source and a single fish target at 3000 m range. In this case there are 29 possible eigenrays connecting the source and receiver, thus there are $29^2 = 841$ possible two-way paths. The figure shows only a few (11) to be significant, with the last one apparently 60 m further out from the direct echo. The clustering of the multi-paths near the direct arrival would presumably not be resolvable, producing an increased target width and strength. The intensity and structure of these multi-paths is sensitive function of target depth and range, greatly complicating the ability to discriminate between real and ghost targets.

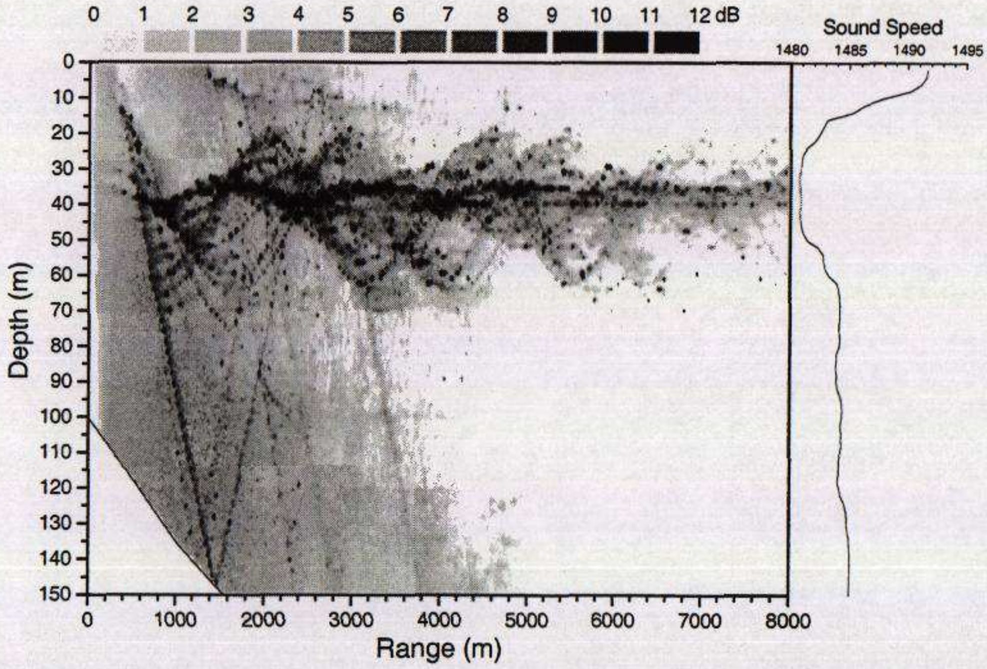

Figure 3: Sound pressure level enhancement at 12 kHz in Strait of Georgia. Measured sound speed profile is shown in right panel. Intensities are in deciBels referenced to 20log[r] spreading.

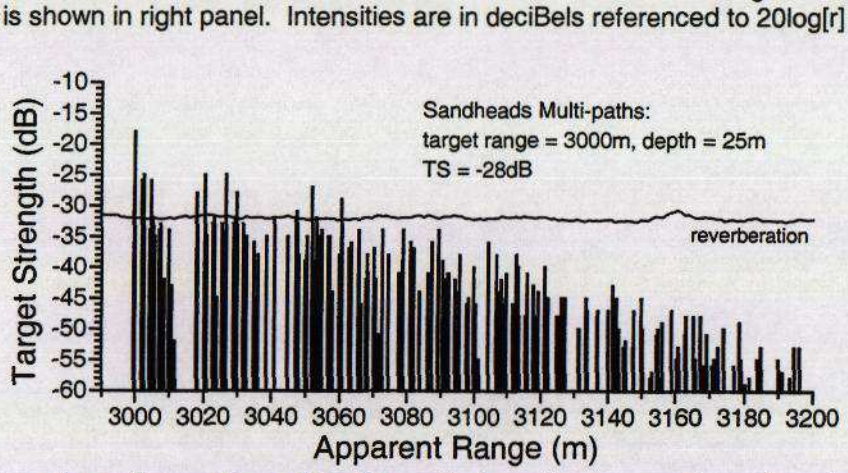

Figure 4: Comparison of acoustic multi-path amplitudes with measured reverberation for target at 3000 m range, 25 m depth in the Strait of Georgia.

2.2 Schooling Fish: Atlantic Herring

Atlantic herring were investigated in two shallow, coastal environments: a spawning ground survey near Escuminac, New Brunswick, Canada in 1996 (described in Trevorrow and Claytor 1998) and a migration monitoring project through Drogden Channel, between Copenhagen, Denmark and Malmo, Sweden (described in Pedersen and Trevorrow 1999 and Farmer et al. 1999). In their schooling mode, herring have a volume scattering strength sufficient to be detected above the seabed reverberation at ranges from 10 to 100 times the water depth. In fixed sonar installations this detection is further aided by observing the motion of the school relative to the fixed background.

However, accurate abundance estimates require that the horizontal propagation enhancement be included in the echo-integration calculations.

The Escuminac region has the largest and most consistent spring herring spawn and associated gillnet fishery in the southern Gulf of St. Lawrence. After the ice retreats in late April, the herring come close inshore for spawning along a 10-km strength of coastline in waters only 3 to 6 m deep. From the gillnet fisheries landings, the herring population had a mean length of 29 cm, corresponding to an average horizontal-incidence target strength of -47 dB per fish. A towed 330 kHz imaging sidescan was used, deployed nominally 2 m deep from the port side of a small fishing vessel. The sidescan utilised a 1.8° x 18° transducer oriented horizontally and perpendicular to the ship's track, transmitting a 0.1 ms pulse nominally once every 0.24 s. Owing to wave and tidal currents, the waters near Escuminac were relatively unstratified so refraction effects can be ignored.

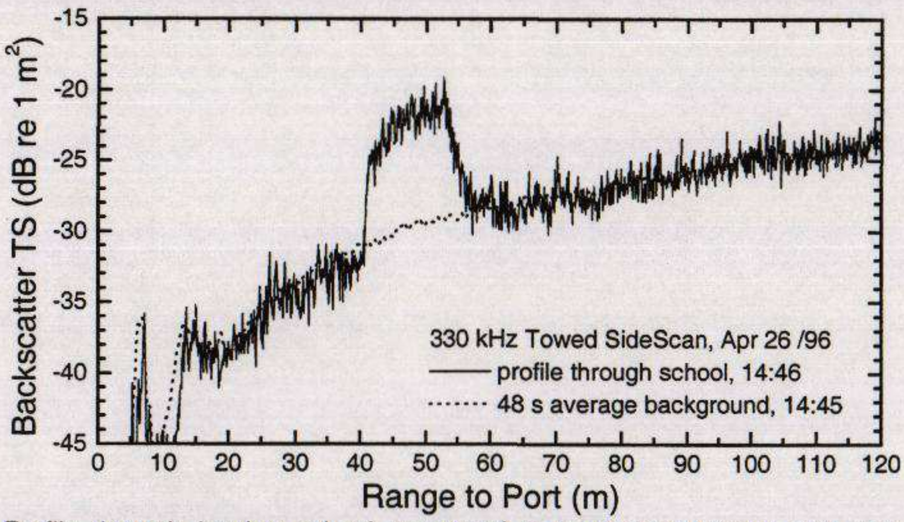

Figure 5: Profile through herring school compared to background taken with 330 kHz towed sidescan near Escuminac, New Brunswick on April 26th, 1996.

In this coastal environment the herring schools were widely dispersed and mobile, and only one large school was encountered during 2 days of towing operations. Figure 5 shows an echo intensity vs. range slice taken through the centre of this school. In this area the water depth was 6.2 m. Overall, the school was observed at ranges of 42 - 65 m and had a thickness of 4 - 15 m with length roughly 280 m. In particular, note the high acoustic contrast at the near edge of the herring school. The herring school displays a signal to reverberation ratio of approximately 10 dB and an apparent target strength (corrected only for spherical spreading and seawater absorption losses) near -20 dB (re 1 m^2). This background reverberation curve defines a range-dependent threshold for echo-integration analysis. By integrating over the area of the herring school echo (i.e. in both range and successive acoustic transmissions during towing) where it exceeds the threshold, the total biomass and number of herring can be estimated. For this school the apparent number of herring observed was 624,000 with an average density of 61 fish per m^3. This density is considerably above reasonable expectations of 1 to 10 per m^3, and presumably is a result of acoustic propagation enhancement effects.

In essence, this shallow environment acts as a reflective acoustic waveguide that both focuses more acoustic energy on the target and increases the effective length of the echo. Using the ray-tracing model the quantitative effect of the reflection focusing can be calculated. At each range-point, the herring school was modelled as a cluster of 16 targets spaced 20 cm vertically from 3 to 6 m depth. For each target the amplitude-corrected, time-shifted pulse replicas along each eigenray pair (outward and return propagation) were coherently added together. The transmitted and received eigenray amplitudes were corrected for the transducer beam pattern. Then, the synthetic waveforms for all 16 targets in the vertical cluster were coherently added together. The result of this synthetic waveform calculation at a range of 43 m (the near edge of the school in Fig. 5) is shown in Figure 6. At this range there were 3 significant eigenrays (direct, surface-, and bottom-reflected), creating 9 possible two-way paths. Both the amplitude and echo-length are increased by about a factor of 3 relative to the direct-path echo. To mimic the sidescan data acquisition process, the root-mean-square of the synthetic waveform was calculated and echo-integration used to estimate the number of targets. Echo-integration of the direct-path-only waveform yielded the correct answer of 16 targets, whereas for the full reverberation the estimated number of targets was 73. This gives a reflection enhancement ratio of 4.6. Repeating this simulation at 55 m range (the far edge of the school) finds four significant eigenrays and a reflection enhancement of 7.6. Using an average enhancement factor of 6.1 the corrected size of the school is then 102,000 herring with an average density of 10 per m^3. Note that in shallower waters and at greater range this reflection enhancement increases as a larger number of eigenrays become significant.

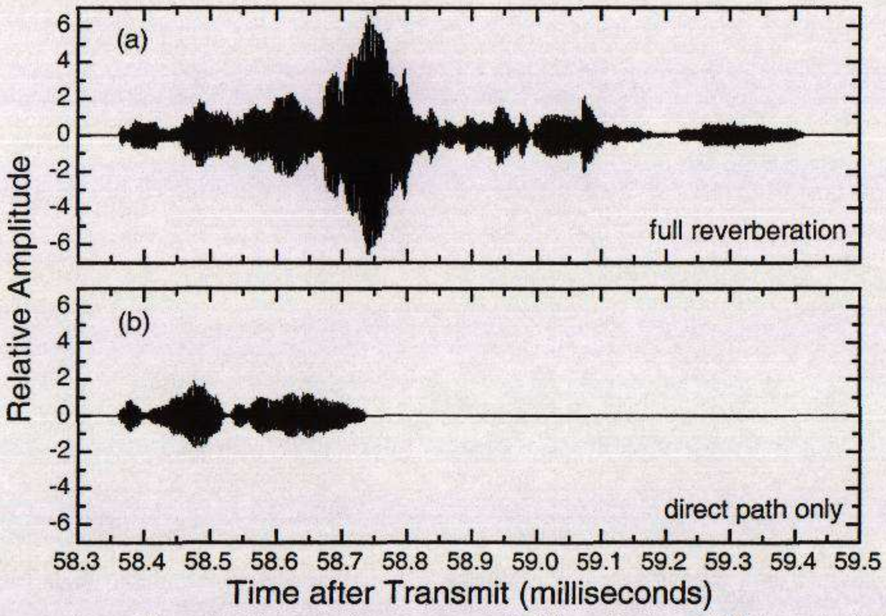

Figure 6: Comparison of synthetic waveforms generated for cluster of 16 targets in 6.2 m water depth simulating the herring school shown in Fig. 5.

Several sonar systems were installed in Drogden Channel, Denmark beginning in 1995 as part of a long-term herring monitoring project. This main channel is approximately 1 km wide, bracketed by 500 m wide shallows on each shore, with water depths of 10 to 14 m. It is a busy navigation channel connecting the Baltic Sea and the Kattegat. The Drogden Channel waters were normally vertically mixed and characterised by either a northward flow of relatively fresh (~10 psu) Baltic Sea water or a southward flow of more saline(~20 psu) water from the Kattegat. Both 12 and 100 kHz sidescan sonar arrays were installed on tripods fixed to the seabed. The results from the 100 kHz sonars were qualitatively similar to those from the Escuminac area (discussed above), with herring detected up to 500 m range. Of interest here is the long-range detection capability of the 12 kHz sonar. This sonar was the same as that used in a towed configuration in the Strait of Georgia, except here it was mounted on a tripod equipped with a motorised steering assembly that could scan a 50° sector oriented to the North across the channel. A 50 ms chirp pulse with correlation processing was used. This 50° sector was scanned in 2° steps to a range of 2.2 km, scanning a measurement area in excess of 2×10^6 m^2 once every 150 s.

In this sector-scanning mode, herring schools were identifiable as transient objects relative to the time-invariant reverberation vs. range and azimuthal angle. Figure 7 shows an example of herring school between 1000 and 1200 m range (indicated with an arrow). This school exhibits an echo strength that is on average 6.6 dB greater than the background reverberation. This school traversed the sector moving northwards with a speed of ~0.5 $m \cdot s^{-1}$ over a period of 22 minutes (9 scans), taking advantage of a northward flowing current. The school expanded in area as it moved northwards, such that Fig. 7 shows its largest areal extent and thus its minimum density. The total planar area of the school in Fig. 7 is 6500 m^2. Gillnet surveys of herring in this area yielded a mean length of 26 cm, corresponding to a horizontal near-tail-incidence target strength of -55.1 dB per fish. Without correction for propagation effects, the *apparent* target strength averaged over the school was -22.4 dB (re 1 m^2), which when integrated produced an estimated 706,000 fish with a mean density of 9.3 fish per m^3.

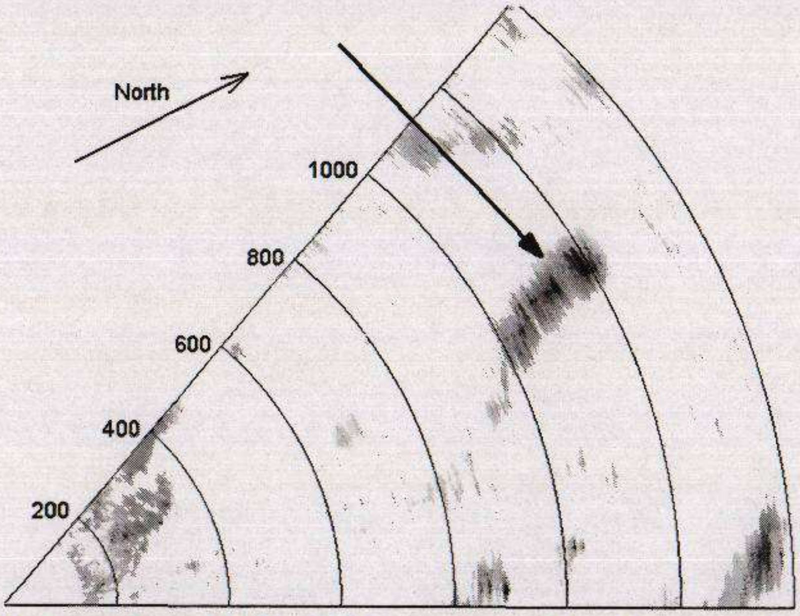

Figure 7: 12 kHz sector scan (50° by 1400 m) showing herring school in Drogden Channel, Denmark on Oct. 30th, 1997.

As before, the ray-tracing propagation model enables prediction of the reflection enhancement effects. The incoherent eigenray summation technique was applied to a grid of 5 m range by 0.2 m depth for the geometry, bathymetry, sediment, and sound speed conditions of Drogden Channel. For the wide vertical aperture of this 12 kHz sonar (±60°) and well-mixed water conditions, the insonification was essentially independent of depth. As shown in Figure 8, the reflection enhancement approaches 6.9 dB (one-way) in the first 1000 m, diminishing slightly with range after that due to seawater absorption and boundary reflection losses. In the first 200 m the reflection enhancement increases as the number of significant eigenrays (i.e. arriving within 5 ms of the direct) increases. By 1 km there are in excess of 25 significant eigenrays, however the intensities of the later arrivals are greatly attenuated relative to the direct path because of boundary reflection losses. If attention is limited to arrivals with intensities within -10 dB of the direct path (one-way), then at 1 km range the effective pulse lengthening will be roughly 4 ms. This increases the apparent size of the herring school by only a few metres, which is not significant. However, correction for the reflection enhancement (6.4 dB one-way at 1100 m range) is important. With this correction, the *true* average target strength of the school shown in Fig. 7 is -35.2 dB (re 1 m^2), corresponding to a school size of 37,000 fish with density of 0.49 per m^3. These estimates are more realistic.

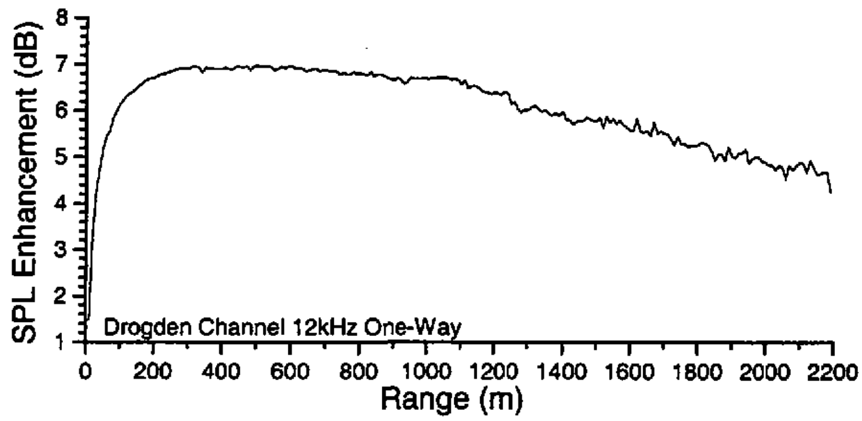

Figure 8: Depth averaged acoustic propagation enhancement from Drogden Channel, Denmark.

3. CONCLUSIONS

Side-looking sonars acquire data that is qualitatively and quantitatively different from vertically oriented echo-sounders. A general feature of this approach is that the insonified volume and echo amplitudes are influenced by the acoustic propagation environment. This paper has shown four examples of positive biases in echo strength and apparent number of targets created by acoustic reflection and refraction effects. Against such acoustic complications must be balanced the potential for surveying over much greater ranges and areas, close to the boundaries, and at distances where the fish behaviour is unaffected by the presence of the ship or sonar installation. Fortunately, the application of acoustic propagation modelling provides the means to understand, recognise, and correct for these biases in echo strength and apparent number of targets. This then requires that appropriate measurements of environmental variables, such as water temperature and salinity, be performed along with the fisheries acoustic survey.

For the case of detecting single fish targets such as salmon, the acoustic multi-pathing effects created both *ghost* targets and increased the apparent target strength. At ranges greater than roughly 5 times the river or sound-channel depth the time-delay between the direct and reflected/refracted arrivals decreased to the point where they were not separable given the range resolution of the sonars used. In the Fraser River this produced an upward bias in the apparent target strength by up to 6 dB at ranges up to 200 m. In the Strait of Georgia this target strength bias was observed up to 25 dB at ranges up to 7 km, in agreement with propagation modelling.

For the detection of schooling fish such as herring in shallow waters, significant positive biases in the integrated school sizes were observed. For spawning herring at Escuminac, acoustic models of the reflection enhancement effects predicted biases of a factor of 6 at a range of 50 m in water depth of 6 m. These biases were calculated using synthetic waveforms generated from the coherent summation of multi-path echoes from multi-fish clusters. Without correction for these biases the fish density within the school was impossibly high. In Denmark herring schools were detected up to 1200 m range in waters only 10 - 12 m deep. The ray-tracing calculations predicted reflection enhancement factors for two-way propagation up to 13.8 dB (a factor of 24). Clearly, these reflection enhancement predictions deserve further study and in situ verification, for example through measuring the incident sound pressure level at range and/or through a combined sonar and net trawl survey.

Acknowledgements:

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