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Juha Lilja

Assessment of Fish Migration in Rivers by Horizontal Echo Sounding

Problems Concerning Side-aspect Target Strength

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UNIVERSITY OF JYVÄSKYLÄ

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ABSTRACT

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The main objective of this thesis was measurement of fish side-aspect target strength, which was determined with simulations and under experimental conditions with both immobilized and swimming fish. In addition, target strength was measured in the natural environment of the fish. Furthermore, horizontal hydroacoustics was utilized to establish the effects of environmental factors on fish migration.

Target-strength simulations with a swimbladder model demonstrated that the relationship between target strength and swimbladder length was not linear. Furthermore, with the concave bending of the swimbladder model, the interference between wavelets caused fluctuation in target strength, which could be over 15 dB. A single log-linear regression for target strength as a function of fish length was fitted. The *ex situ* measurements of immobilized Atlantic salmon (*Salmo salar* L.) and other species showed that the linear relationship between mean target strength and the logarithm length of fish increases with a slope larger than 20. In addition, whitefish (*Coregonus lavaretus* (L) *s.l.*) has a target strength that is about 5 dB higher than salmon of the same size. The variation in target strength with the side-aspect angle was very large. The best fit of the all-side-aspect models between mean target strength and side-aspect angle (α) was obtained using the $\cos^3(2\alpha)$ function.

A statistical approach was utilized to predict target-strength distributions of salmon as they ascended a river. With a large number of fish, the large value for standard error of the estimate (S.E.E) in a log-linear regression for target strength and fish length smoothed out these distributions. The probability of detection of salmon with threshold target strength (-29 dB) increased as length of the fish increased.

Few statistically significant correlations were observed between entry of salmon into the river and six environmental factors measured in the Tornionjoki River. In Äijälänsalmi Channel, migration of cyprinids and percids through the channel was triggered by the temperature difference between lakes, and migration occurred around dawn and dusk.

Key words: Atlantic salmon; echo sounder; environmental factors; migration; side-aspect; target strength; variation in target strength.

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CONTENTS

LIST OF ORIGINAL PUBLICATIONS

The thesis is based on the following papers, which are referred to in the text by their Roman numbers:

I Lilja, J., Marjomäki, T.J., Jurvelius, J., Rossi, T. & Heikkola, E. 2004. Simulation and experimental measurement of side-aspect target strength of Atlantic salmon (*Salmo salar*) at high frequency. Submitted manuscript to Can. J. Fish. Aquat. Sci.

II Lilja, J., Marjomäki, T.J., Riikonen, R. & Jurvelius, J. 2000. Side-aspect target strength of Atlantic salmon (*Salmo salar*), brown trout (*Salmo trutta*), whitefish (*Coregonus lavaretus*), and pike (*Esox lucius*). Aquat. Living Resour. 13: 355-360.

III Lilja, J., Keskinen, T., Marjomäki, T.J., Valkeajärvi, P. & Karjalainen, J. 2003. Upstream migration of cyprinids and percids in a channel, monitored by horizontal split-beam echosounder. Aquat. Living Resour. 16: 185-190.

IV Romakkaniemi, A., Lilja, J., Nykänen, M., Marjomäki, T.J. & Jurvelius, J. 2000. Spawning run of Atlantic salmon (*Salmo salar*) in the River Tornionjoki monitored by horizontal split-beam echosounding. Aquat. Living Resour. 13: 349-354.

V Lilja, J. & Romakkaniemi, A. 2003. Early-season river entry of adult Atlantic salmon: its dependency on environmental factors. J. Fish Biol. 62: 41-50.

Responsibilities of Juha Lilja in the articles of the thesis

Paper I. I was responsible in designing, setting up and collecting the *ex situ* target strength data. Erkki Heikkola and Tuomo Rossi made the target strength simulations. I wrote the draft of the manuscript.

Paper II. I, Timo Marjomäki and Juha Jurvelius planned the study. I conducted the target strength measurements with Raimo Riikonen, and I analyzed the data and wrote the draft of article.

Paper III. I, Tapio Keskinen and Timo Marjomäki set up the study. I analysed the acoustic data and wrote the article with other authors.

Paper IV. I collected and analysed the acoustic data from years 1998 and 1999. Atso Romakkaniemi conducted this large EU-project and Mari Nykänen collected the acoustic data from year 1997.

Paper V. I collected the acoustic data in years 1998 and 1999. I analysed the data and wrote the draft of the article.

1 INTRODUCTION

In fisheries research, one purpose of echo sounding is to estimate the density or number of aquatic organisms, especially fish (MacLennan & Simmonds 1992). The classification and identification of these organisms generally combines knowledge of the distribution and behavior patterns of constituent species with collection and analysis of acoustic and catch data (Horne 2000). In echo-sounding systems, acoustic energy is transmitted in pulses at a particular frequency (usually 38 – 420 kHz) by means of a transducer producing a directional sound beam. When a sound wave encounters a density difference, e.g. a fish, an echo propagates outward from this target back to the receiver. Echoes returning to the transducer are said to be backscattered sound (Midttun 1984). Accurate interpretation of the acoustic data from fisheries surveys requires an understanding of the scattering properties of fish.

Traditionally in fisheries acoustics, the acoustic beam has been aimed vertically. However, the echo sounder can also be used to transmit the sound beam horizontally across water. During the past decade, a side-looking (horizontal), fixed location split-beam or dual-beam echo sounder has been used for assessment of fish stock in rivers and shallow channels (Kubecka 1996, Ransom et al. 1998). Use of an acoustic system in a river offers the advantage that it is made up of noninvasive and nondestructive devices for counting number of fish and observing the behavior of fish. In a fixed location, horizontal echo sounding has basically four different sources of echoes. These are echoes (a) from passing fish, (b) from drifting debris, (c) from stationary targets like bottom and stones, and (d) from noise or reverberation. Echoes from fish are naturally the main objective in fisheries acoustics; the rest are usually unwanted sources of echoes (Balk 2001). In rivers, the downstream migration of fish may be passive or active, but upstream migration must be active. Therefore, it can be assumed that all targets that are moving upstream are fish. Selection of sampling site is the most important factor for successful hydroacoustic monitoring in rivers. The most important factors are bottom, noise level and water current. An ideal bottom is shaped like the lower edge of the sound beam, with the water depth increasing according to the opening angle of the transducer. The noise level (reverberation and noise) should be low and the current of water steady.

The split-beam echo-sounding system compares the echo from four receiver elements placed in a quadrant. The phase difference of the sound wave is used to calculate the real position of the target. In echo-counting studies with a fixed location split-beam echo sounder, fish are tracked in three dimensions as they pass through the acoustic beam. Moreover, this system enables direct measurement of the backscattering cross section (σ) or target strength (TS) of fish for each echo (Traynor & Ehrenberg 1990, MacLennan & Simmonds 1992). The target strength of the fish is a value that indicates the size of the echo. Target strength is a logarithmic measure of the proportion of the incident pressure or energy that is backscattered by the fish. To convert data collected during an acoustic survey to population estimates, it is essential to have precise estimates of fish target strength (Fig. 1). Therefore, studies of fish target strength have always been an important part of fisheries acoustics.

Basically three main methods have been used to study the target strength of fish: First, in *ex situ* methods, fish are removed from their natural environment before measurements, which have been performed on tethered or caged fish in order to gain an understanding of how the size of the fish affects target strength. Second, *in situ* measurements are made of fish in their natural environment. Third, theoretical backscattering models are based on measurements of fish morphology. The *ex situ* and *in situ* methods are reviewed by Love (1971a), Foote (1991) and MacLennan & Simmonds (1992). A number of different scattering models have been applied to different fish species and their swimbladders (e.g. Foote 1980a, Clay & Heist 1984, Foote 1985, Stanton 1988, 1989, Clay & Horne 1994, Foote & Francis 2002). Among fish, the swimbladder provides a high-density contrast to flesh or skeletal elements. Foote (1980b) concluded that about 90 % of the echo energy from fish was reflected from the swimbladder. For this reason, scattering models and measurements of the fish swimbladder have long been a crucial component in fisheries acoustics (e.g. Foote & Ona 1985, Blaxter & Batty 1990, Clay 1992, Ye & Farmer 1994, McClatchie et al. 1996b).

The target strength of a single fish generally increases with the size of the fish (e.g. Love 1971b, 1977, Dahl & Mathisen 1982, Kubecka 1994, McClatchie et al. 1996a, Kubecka & Duncan 1998, Burwen & Fleischman 1998, McClatchie & Ye 2000). In addition to fish size, several other factors, including orientation, behavior, and species-specific characteristics, affect the target strength (e.g. Midttun 1984). The species-specific target strength generally depends on the presence or absence of a swimbladder (Foote 1980b, Barr 2001), but differences can be also found between fish with swimbladders (Kubecka & Duncan 1998, McClatchie et al. 1996a). Many of the early target-strength studies were an attempt to establish the relationship between target strength and fish length, usually under controlled conditions (*ex situ*). The target strength versus length regressions derived from these experiments was used later in estimations of fish abundance and size (MacLennan & Simmonds 1992).

Fluctuation in the target strength of individual fish has been a challenging problem in fisheries acoustics (e.g. Dawson & Karp 1990). The main sources of this variation appear to be associated with behavior of the fish and the complexity of the backscattering process (random variation). Especially in horizontal acoustics, variation in target strength increases due to the behavior of the fish, i.e. a change in swimming angle in the acoustic beam and the bending of the fish due to swimming movements. When the target is parallel to incident wavefront, the reflected wavelets strengthen each other. When the target yaws, the wavelets originating at different part of the target become progressively out of phase and the summed amplitude is reduced (MacLennan & Simmonds 1992). Despite the importance of fish behavior for target strength, relatively few studies have been carried out to estimate these effects, especially for horizontal high frequency sounders.

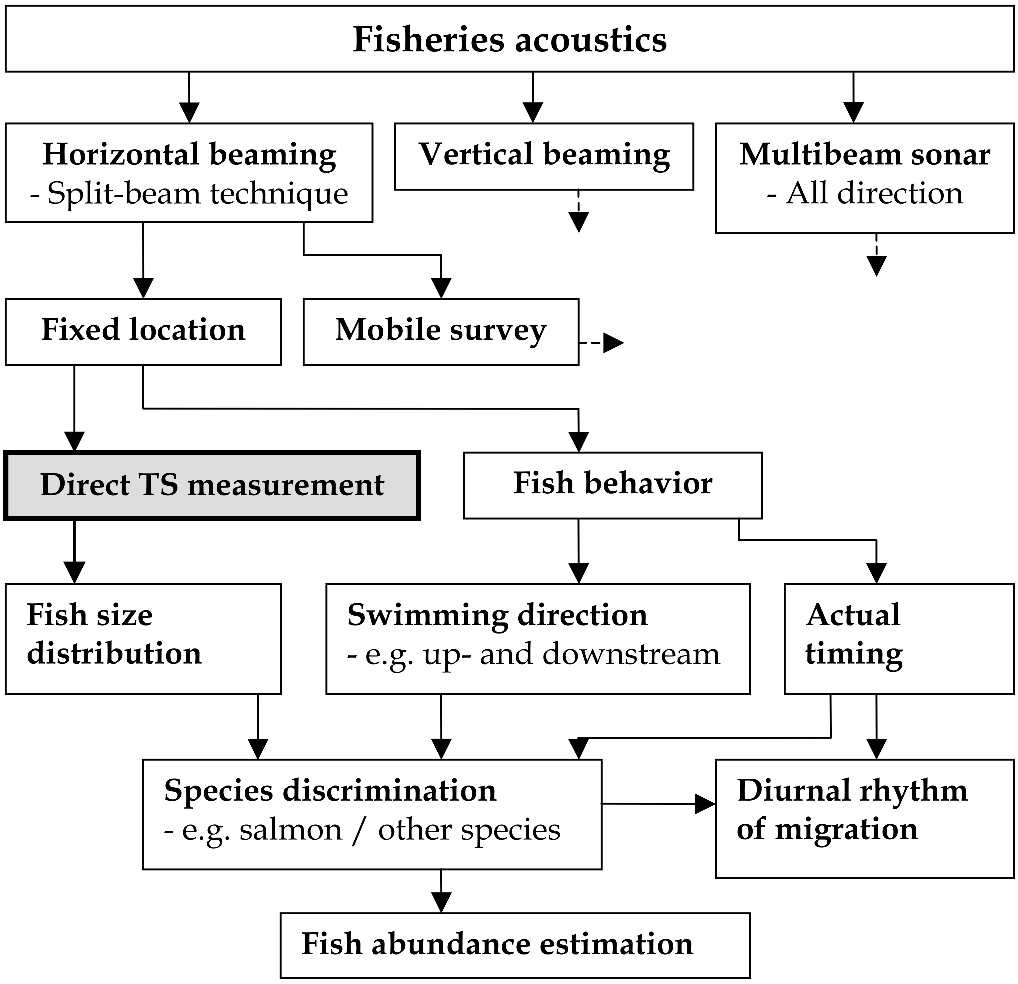

FIGURE 1 Schematic approach for estimation of population size in horizontal fisheries acoustics. TS = target strength. The gray box indicates the main subject of this thesis.

2 OBJECTIVES

The aim of this thesis was to determine the effect of fish size, species and orientation on the side-aspect target strength of fish, especially Atlantic salmon (*Salmo salar* L.). In addition, the effect of environmental factors on fish migration was determined. Although it is commonly accepted that in horizontal echo sounding fish target strength varies, the effects of this variation on data interpretation have not always been studied. Several series of experimental and field studies were made

(a) to predict the theoretical target strength of backscattering from the simple three-dimensional model of the swimbladder (I),
(b) to estimate the side-aspect target strength of immobilized fish (II) and of Atlantic salmon swimming in a large net cage (I),
(c) to estimate the side-aspect target strength of fish *in situ* compared with target-strength distributions and catches from the Tornionjoki River (IV) and Äijälänsalmi Channel (III),
(d) to determine the effect of variation in target strength on interpretation of acoustic data, and
(e) to study the effects of environmental factors on fish migration (III & V).

3 MATERIALS AND METHODS

All field measurements of fish target strength were carried out with an HTI (Hydroacoustic Technology Inc.) 200 kHz Model 243 split-beam echo-sounder (HTI 1997). In the HTI echo sounder system, an output echogram originates from a single echo detector (SED). Therefore, all observed echoes from fish have gone through the selected criteria (see Balk 2001). The echo-sounder system consisted of two elliptical transducers, dual-axis transducer rotators, a digital audio tape recorder, an oscilloscope, a printer and a computer. Acoustic data were analyzed with the analysis software HTI Trakman or EchoScape. General aspects of the materials and methods used in this study are presented here. Certain detailed components are given in the original papers.

3.1 Target-strength simulation (I)

Scattering of acoustic waves by the swimbladder was predicted according to the Helmholtz equation, which describes the linear propagation of time-harmonic acoustic waves. The finite element method (FEM) was used for numerical solution of the Helmholtz equation (eq. 1 in I). The linear system arising from the finite element discretization is solved by an efficient iterative solution procedure known as the algebraic fictitious domain method. E. Heikkola developed the software used in the simulations. A detailed presentation of the mathematical model and numerical method can be found in Heikkola et al. (2003a, 2003b)

In this study target strength was simulated in three groups. First, the effect of length of the swimbladder on target strength was studied. Second, the reflected target strength of the fish swimbladder from different directions of incident waves was simulated. And third, target strength was simulated with a bending swimbladder. In all simulations, the contribution of fish flesh and bones to backscattering was ignored, and scattering was assumed to be coherent. In addition, the relationship between the total length of Atlantic salmon and the length of the swimbladder was determined. The effect of the length of the swimbladder on the fish target strength was calculated with 11 different lengths of swimbladder (Table 1 in I).

3.2 Target strength of immobilized fish (II)

To study the side aspect target strength of immobilized fish, a total of 54 fish were used. Thin fishing lines held the fish so that the body did not move during the measurements. Study specimens included Atlantic salmon (*Salmo salar* L.), brown trout (*S. trutta* L.), whitefish (*Coreconus lavaretus* (L) *s.l.*), and pike (*Esox lucius* L.). The fish in this study were obtained from the Finnish Game and Fisheries Research Institute of Enonkoski (hatchery stocks), Lake Ylä-Enonvesi and the Simojoki River. Altogether 1644 target-strength measurements of fish were carried out during this experiment, one measurement taking about 50 s. The linear relationship between the side-aspect target strength and the logarithm of fish length was modeled (e.g. Love 1977, Foote 1980a, Kubecka & Duncan 1998).

$$\mathrm{TS} = \mathrm{A}\log_{10}(L) + \mathrm{B} \qquad (1)$$

where A is the slope of the line, B is the intercept and L is the length of the fish. In addition, the effect of side-aspect angle on target strength was modeled with the $\cos^3(2\alpha)$ function (Kubecka 1994). This function assumes the existence of average all-aspect target strength with a symmetrical distribution of the amplitude of target strength between maximal and minimal values.

$$\mathrm{TS} = \mathrm{C}\log_{10}(L) + \mathrm{D}\cos^3(2\alpha) + \mathrm{E} \qquad (2)$$

where L is the length of the fish (cm), α is the angle of the side aspect (°) and C, D and E are empirically determined constants.

3.3 Target strength of swimming Atlantic salmon (I)

Useful acoustic measurements of swimming fish can be carried out under experimental conditions only if the fish is in excellent condition and its behavior is as natural as possible. The *ex situ* target strength of swimming Atlantic salmon was measured in a large cage in the Tornionjoki River. Only one salmon was in the cage at a time during the target-strength measurement, and a total of 11 adult Atlantic salmon were used. The fish were caught with a seine in the River Kemijoki (about 20 km from the study site) immediately below the lowest hydroelectric dam. In order to estimate the movements and swimming angle of the salmon in the acoustic beam, the fish were filmed with a video camera (Osprey OE 1323 SIT).

Fish traces were accepted only when the fish swam upstream approximately perpendicularly through the acoustic beam. The mean target strength of each fish trace was calculated from the mean backscattering cross-section, according to equation 3 and also with the mean of the target strength observations (TS_{TS}, eq. 5).

3.4 *In situ* target strength and fish behavior studies

Fish migration was monitored in Äijälänsalmi Channel (III) and the Tornionjoki River (IV & V). Two sets of sounder system were used in the Tornionjoki River and one in Äijälänsalmi Channel. In both applications, the FM slide (chirp) signal was used (Ehrenberg & Torkelson 2000). The echo-sounder system was calibrated before and after studies under experimental conditions using the standard target method with a tungsten-carbide sphere (ø = 38.1 mm). In Äijälänsalmi Channel the test fishing was carried out in order to separate out the species. Atlantic salmon is the only numerous large species of fish in the Tornionjoki River (Kallio-Nyberg & Romakkaniemi 1998). Thus, Atlantic salmon were separated from non-target species using the following hypothetical target strength limit for fish species: target strength ≥ -29 dB for the Atlantic salmon; target strength < -29 dB for other species. The echo sounder was capable of tracking and counting individual migrating fish in real time. Therefore, the effect of the change in environmental factor on fish migration in the short term can be studied conveniently with echo sounder.

3.4.1 Äijälänsalmi Channel (III)

Fish migration through Äijälänsalmi Channel was monitored from 24 April to 28 June 2001. This channel connects eutrophic Lake Jyväsjärvi to mesotrophic Lake Päijänne. However, Lake Jyväsjärvi is currently an important location for development, growth and reproduction of many commercially unimportant fish species. The most common species in these lakes are roach (*Rutilus rutilus* (L.)), perch (*Perca fluviatilis* L.), bream (*Abramis brama* (L.)), white bream (*Blicca bjoerkna* (L.)) and ruffe (*Gymnocephalus cernuus* (L.)). The species and length distribution of migrating fish populations were estimated from trap-net catches. The trap net was placed 50 m towards Lake Jyväsjärvi from the echo sounding site, and was set to catch fish migrating upstream to Lake Jyväsjärvi.

Thus it was possible to estimate the relationship between side-aspect target strength and fish length *in situ* by comparing the distributions of the target strength and fish length in same period (n = 8). It was assumed that the relationship between target strength and the logarithm of fish length increases with the slope of 20 (A in equation 1).

3.4.2 The Tornionjoki River (IV & V)

Migration of Atlantic salmon into the Tornionjoki River was monitored at a site 4 km upstream from the mouth of the river during the summers of 1997, 1998, and 1999. Four elliptical transducers were mounted across the river and when properly mounted, were kept stationary. The river there is 280 m wide and its maximum depth is about 10 m. The river flow was relatively laminar, but the profile of the bottom was slightly irregular. Production of Atlantic salmon in the Tornionjoki River is now the highest of all Atlantic salmon rivers in the Baltic region (ICES 1999). The pattern of migration activity of Atlantic salmon was illustrated (IV) and the environmental factors affecting the river entry were identified (V). The relationship between daily mean target strength and mean total length of salmon per catch was described from data of the year 1998 (IV).

3.5 Prediction of target-strength distributions

A bootstrap method was used to predict the target-strength distribution of fish. Predictions were simulated with the length distribution of the salmon and a linear relationship between target strength and logarithmic length of the fish. The length distribution of Atlantic salmons was estimated from the trap-net catches in the estuary of the Simojoki River during the summer of 2003. To collect brood fish, returning spawners have been trapped annually at the mouth of the river. The length distribution of salmon was estimated in 2 cm intervals. In simulations, the number of salmon has been increased ten-fold and hundred-fold. The relationship between target strength and length, determined in the cage experiment with swimming salmon, was used (eq. 9). Target strength distributions were carried out with three different standard errors of estimates (S.E.E): 2, 3, and 4. The standard error of the estimate measures the dispersion of the observed values around the regression line when normal distribution is assumed.

In a study carried out during the summer of 2003, simulated distributions of target-strength were compared with the measured target strength distribution from the Simojoki River. The ascent of adult Atlantic salmon into the river was monitored at a site 4.5 km upstream from the river mouth. The Simojoki River, which is 175 km long with a mean discharge of 38 m^3s^{-1}, flows into the northern Gulf of Bothnia. Adult Atlantic salmon normally ascend the river up to 110 km from the mouth (Jutila et al. 2003). Two elliptical transducers were mounted across the river from opposite riverbanks. Due to the low level of reverberation, the sensitivity threshold value of the detected echoes was –43 dB (-37 dB at full beam). At the study site, the river was about 80 m wide with a maximum depth of 4 m. The two transducers collected data in turn for 30 min every hour. In all, 885 hourly files were analysed between 10 June and 17 July.

3.6 Calculation of mean target strength and statistical analysis

The mean target strength (TS_{σ}) of fish was calculated from the mean backscattering cross-section as recommended by MacLennan & Simmonds (1992):

$$TS_{\sigma} = 10 \log_{10}(\bar{\sigma} / 4\pi) \tag{3}$$

$$\bar{\sigma} = \frac{1}{n}\sum_{i=1}^{n}\sigma_i \tag{4}$$

where σ is the fish backscattering cross-section (m^2) and 4π is the cross-section of an idealized sphere with a radius of 2 m. In addition, the mean for the individual fish target strength (TS_{TS}) from the observed echoes was calculated as:

$$TS_{TS} = \frac{1}{n}\sum_{i=1}^{n} TS_i \tag{5}$$

$$TS_i = 10 \log_{10}(\sigma_i / 4\pi) \tag{6}$$

Using this mean for individual observations of target strength, integrated HTI fish-tracking software calculates the acoustic size of fish. In addition, this method was used during monitoring of the spawning run in the Tornionjoki River (IV & V). All mean target strengths mentioned below are calculated as in equation 1; if not, the method of calculation is mentioned.

Distribution of the individual values for target strength was more or less normally distributed, whereas distribution of the backscattering cross-section (σ) was skewed (e.g. Dahl & Mathisen 1982; Dawson & Karp 1990, Shankar 2003). Therefore, the standard deviation (SD) and variance (SD^2) of the individual values for target strength were used to describe the variation in target strength. It was assumed that the SD of individual values for target strength in relation to fish length is virtually constant; it follows that the coefficient of variation (CV) for the relation of σ to fish length should also be virtually constant. Mean standard deviation (SD_{mean}) was calculated as the square root of the mean variance:

$$SD_{mean} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} SD_i^2} \tag{7}$$

The variance (SD^2) of the individual target strength values was compared for the stationary and the continuously rotating (180°) Atlantic salmon. These data were collected in the Kemijoki River on October 20, 1998. The aspect-angles used during the target strength measurements of six Atlantic salmon were both continuous rotating (180°) and stationary. Differencing of the original series was used to eliminate the effect of the slowly varying (trend) from continuous rotating target strength series.

The probability of detecting a length L salmon [$d(L)$] was determined when the threshold target strength was -29 dB. If the mean target strength of the fish trace was larger than -29 dB, the trace was judged to be salmon. This was done with both methods of target-strength calculation (eq. 3 and 5). To describe the shape of the relationship between detection probability and fish length, symmetric and asymmetric logistic curves were fitted.

$$d(L) = \left(\frac{\exp(a + bL)}{1 + \exp(a + bL)} \right)^{1/c} \tag{8}$$

where a, b, and c are parameters to be estimated. As the value of parameter c is 1, the logistic curve is symmetrical. Logistic regression is commonly used in studies of the size selectivity of the fishing gear (Millar & Walsh 1992). The threshold target strength of -29 dB was assumed to correspond a salmon length of about 60 cm, and in our applications in the Tornionjoki River this threshold value was used to discriminate Atlantic salmon from other species (IV and V).

4 RESULTS AND DISCUSSION

4.1 Target strength of stationary fish (I & II)

The overall mean standard deviation (SD_{mean}) of the target-strength measurements in all-aspects was 2.5 dB. This value can be considered to be the random variation of the backscattering amplitude from stationary fish. However, the typical value of the standard deviation for the reference target (tungsten carbide sphere) was 0.5 dB, which can be considered to be the accuracy of the used equipment.

4.1.1 Fish length parallel to incident wavefront

When the longitudinal axis of the fish and the acoustic axis of the sound beam were perpendicular (±15°), the maximum target strengths of the reflected echoes were detected. Thus, the target strength versus the length relationship based on these measurements was higher than, for example, that of a swimming fish (Fig. 2). *Ex situ* measurements of immobilized Atlantic salmon and other species showed that, with a slightly larger slope than the theoretical value of 20, the linear relationship between mean target strength and logarithm length of the fish increases (Table III in I). It was assumed that the approximate relationship between fish length (L) and area being constant $\times L^2$ and for weight constant $\times L^3$, the slopes for area and weight should be about 1/2 and 1/3 of the slope for length, respectively. However, these estimated slopes did not differ statistically significantly from the theoretical value of 20. Moreover, the slopes for area and weight closely follow the above-mentioned ratios.

Many authors have established that there is a linear relationship between the target strength and the logarithm of fish length (e.g. Love 1977, Foote 1980a, Kubecka & Duncan 1998, McClatchie et al. 1996a, Benoit-Bird et al. 2003). It is generally accepted that target strength depends upon fish length according to equation 1, where A and B are constant for a given species and frequency

(MacLennan & Simmonds 1992). The variability of the data makes it difficult to make any definite statements about the slopes of the regression lines, which are merely the best fits to the available target strength measurements. Basically, the target strength versus length relationship is not necessarily linear.

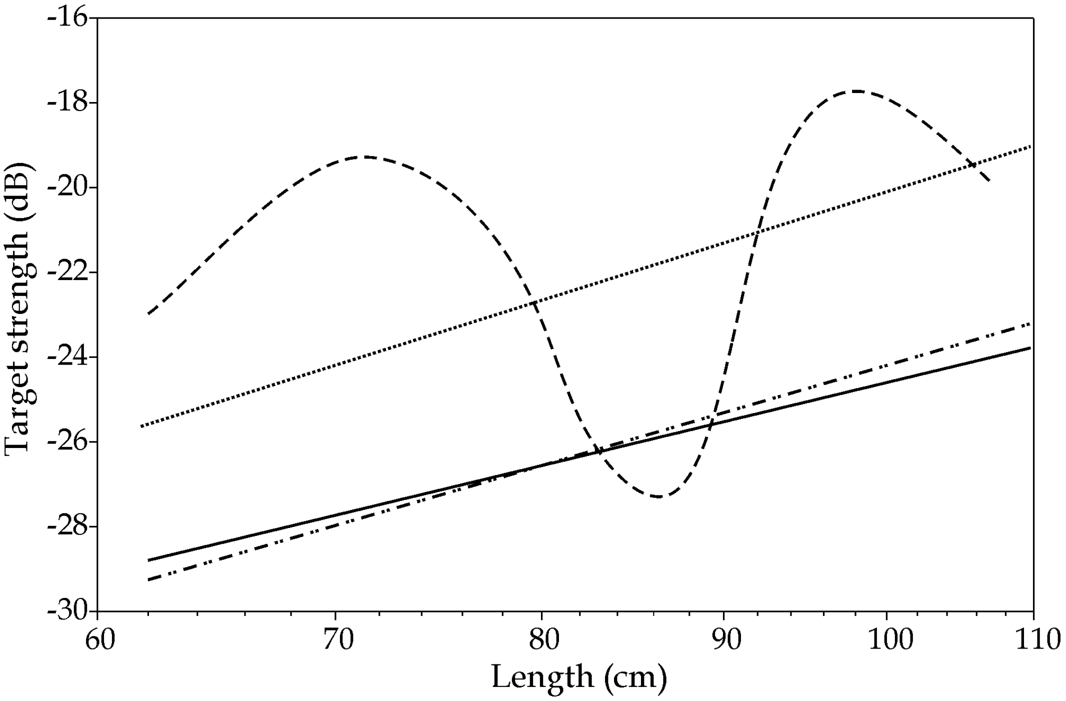

FIGURE 2 Relationship between side-aspect target strength and fish length for Atlantic salmon, estimated with immobilized fish (···) (II), swimming in cage*ex situ* (—··) (I), free swimming in the Torniojoki River *in situ* (——) (IV) and theoretical model (— —) (I). Note the log scale of x-axis.

Our target strength versus length-of-swimbladder relationship calculated with the theoretical model (FEM) differs from the regressions based on empirical measurements (Fig. 2). The periodicity of peaks and troughs, due to interference between the diffracted wave and front-face reflection, is typical of the target strength-length relationship based on theoretical backscattering models (Medwin & Clay 1998). Traditionally in fisheries acoustics, the target strength-length regression models are used for interpretation of acoustic data. These regressions are based on *ex situ* or *in situ* target-strength measurements of fish (MacLennan & Simmonds 1992). However, many authors have produced theoretical models and compared then with experimental data (e.g. Foote & Traynor 1988, Clay & Horne 1994, McClatchie et al. 1998, McClatchie & Ye 2000, Barr 2001). A comfortable model of acoustic scattering from the whole fish has not yet been produced. Therefore, acoustic models describe only the basic occurrence of scattering (Medwin & Clay 1998).

The simulation of acoustic scattering by fish is often based on various high frequency models such as the Kirchoff-approximation model (Foote 1985, Clay

1992, Clay & Horne 1994, Jech et al. 1995, Medwin & Clay 1998, Kang & Hwang 2003). Simulation of acoustic scattering by the boundary element method (BEM) can also be used to determine acoustic scattering (Hwang 1997, Foote & Francis 2002, Okumura et al. 2003). Our simulations were based on the finite element method (FEM) for numerical solution of the Helmholtz equation. Simulation models, which are based directly on the Helmholtz equation, lead to more accuracy results; but they often require huge amounts of computational work (Elman & O'Leary 1998). With a special discretization mesh and the algebraic fictitious-domain method, it is possible to obtain a very efficient solution procedure, which reduces the memory consumption of FEM to the level of BEM (Heikkola et al. 2003a). The theoretical backscatter models such as Kirchhoff-ray mode or FEM model are not typically used in acoustic assessments of fish abundance because these are only approximations from real backscattering process (Horne et al. 2000).

4.1.2 Change in aspect angle

The variation of target strength with the side-aspect angle was very large. The best fit of the all-side-aspect model between the mean target strength and the side-aspect angle was obtained using the $\cos^3(2\alpha)$ function. This model explained 75.3%, 77.6%, and 77.0% of the variance for salmon, pike, and whitefish, respectively (Table 5 in II). According to this model, the difference in the target strength between full side-aspect and head/tail aspect was almost 20 dB. The target-strength simulation from the swimbladder model for salmon also showed fluctuation due to change in aspect angle. The change in aspect angle of the swimbladder (length 26.7 cm) affected target strength dramatically, especially between angles 88° and 95° (Fig. 5 in I).

Earlier studies with anaesthetized fish showed that the target strength of fish decreases with increasing departures from the side-aspect (Love 1977, Dahl & Mathisen 1983, Kubecka 1994, Burwen & Fleischman 1998, Burwen et al. 2003). In addition, our results showed that, at the frequency used, the target strength of fish was very sensitive to change in aspect angle (Fig. 3). When an acoustic pulse is reflected by a long target ($L > \lambda$), the amplitude of the backscattering wave will change as the target yaws. This change can be split into two components: first, the smooth variation with fish position as expressed by $\cos^3$ function (eq. 2); and second, the backscattering amplitude may change more rapidly because of interference between wavelets reflected from different parts of the target.

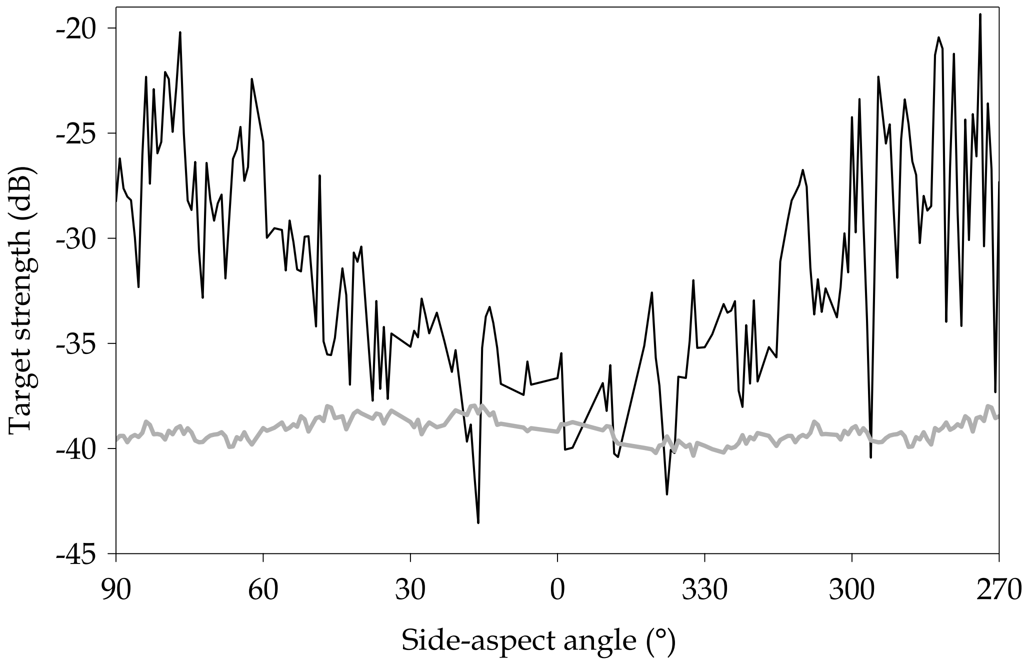

FIGURE 3 Example of variation in target strength (——) during the continuous rotating (180°) of Atlantic salmon (L = 59 cm) (0° = head forward), and target strength variation of the tungsten carbide sphere (ø = 38.1 mm) (——) at a frequency of 200 kHz.

After differencing the continuous rotating target-strength series, the variation of the residuals consisted only of the random variation, which did not change with fish length ($R^2 = 0.04$; $p = 0.7$). Nor did the variance of the target strength from stationary aspect angles change with fish length ($R^2 = 0.4$; $p = 0.2$). Instead, the total variance of continuous rotating target-strength series (without differencing) increased as the length of the salmon increased (Variance = 64 $\log_{10}(L)$ – 85; $R^2 = 0.75$; $p = 0.02$). This may be caused by the noise-threshold, which probably cut out the weakest echoes and reduced the variance in the smallest fish.

4.1.3 Between species variation in length-specific target strength

According to our measurements of immobilized fish, a whitefish has a target strength that is about 5 dB higher than that of a salmon of the same size (Fig. 3 in II). Given the resemblance of the two species in terms of scales, form and density of their flesh, this difference is very significant. In addition, both species have an open swimbladder (physostomous), and the length of the swimbladder did not differ between species of the same size (Lilja, unpubl.). This result is very interesting but quite challenging for the acoustic method in those rivers where both species are present.

Kubecka & Duncan (1998) reported that the length–specific target strength for salmons was lower than that for cyprinids. Target strength of fish may differ between individuals due to difference in behavior and physiology. Ona (1990) concluded that substantial differences in the target strength of individual fish of the same size might be explained by natural variation in the state of maturity and the condition factor within the population. In a multi-species fish community, the interpretation of the species of fish targets relies considerably on their size, as estimated from their target strength. Therefore, the use of hydroacoustics is often limited by the inability to discriminate among fish species. For instance, the appearance of sea-running whitefish spawners from mid-July onwards, together with decreasing mean size of ascending Atlantic salmon during the season, may cause a bias in the salmon count in the Tornionjoki River (IV).

4.2 Effects of swimbladder and *L*/λ ratio on target strength

4.2.1 Target strength and fish swimbladder

Our results showed that the swimbladder length (L_{sb}) of adult Atlantic salmon was about 43% of the total length of the fish (L_T), $L_{sb} = 0.433\ L_T$, ($R^2 = 0.98$, n = 22) (Fig. 4). This relationship was used to compare the length of the swimbladder model to the total length of salmon. In general, the target strength of a fish depends on the swimbladder volume, which increases with fish size and varies with depth and also with swimming behavior (Blaxter & Batty 1990, Ye & Farmer 1996). Anatomical and physiological factors also affect the size of the swimbladder (Ona 1990, Machias & Tsimenides 1996).

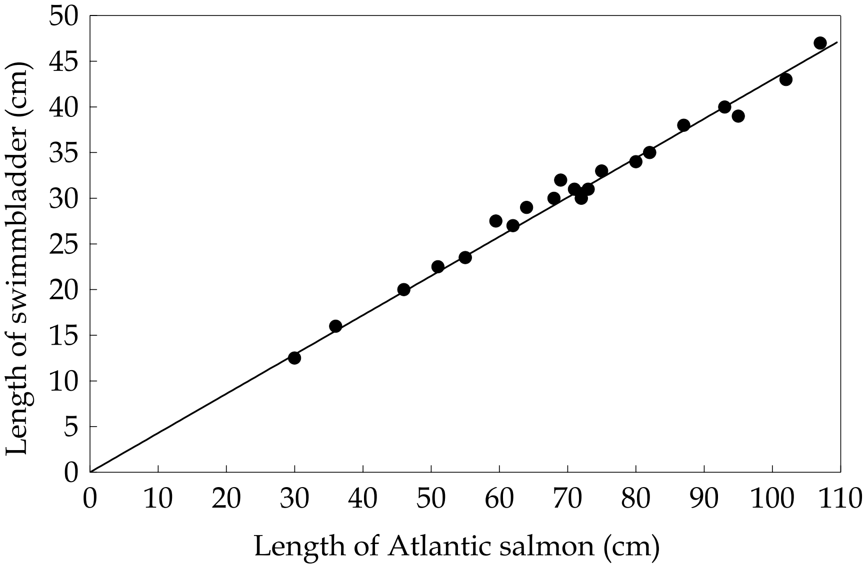

FIGURE 4 Linear relationship between total length of the Atlantic salmon (L_T) and length of the swimbladder (L_{sb}). Solid line represents $L_{sb} = 0.43\ L_T$ cm.

Many fish species usually have a swimbladder with an irregular shape that is difficult to model analytically (e.g. Foote & Ona 1985, McClatchie et al., 1996a). However, the swimbladder surface of the Atlantic salmon is quite smooth with a regular shape; therefore in this study an analytical model of the swimbaldder was justified (I).

4.2.2 Target strength and L/λ ratio

In this thesis, all target strength was measured and simulated with a frequency of 200 kHz. The ratio of L/λ varied between 40 and 148. Traditionally, acoustic estimations of fish biomass have been carried out with a single frequency. The normal operating frequencies of scientific echo sounders are between 38 kHz and 420 kHz. Furthermore, the backscattering amplitude from the fish depends on the applied frequency. This must be taken into account when data are analyzed. Benoit-Bird et al. (2003) found no consistent effects of frequency on the length versus the target-strength relationship. At low L/λ values the effect of aspect angle on echo amplitude is low. As fish length or acoustic frequency increases, the influence of fish orientation on echo amplitude increases (Dahl & Mathisen 1983, Medwin & Clay 1998, Au & Benoit-Bird 2003). The fish body becomes progressively a more important source of sound reflection, and at high frequencies it is the dominant source. At 200 kHz for a fish whose length is over 11 cm scattering by the fish body dominates (Ye & Farmer 1996). Furusawa (1991) recommended that a value of $L/\lambda \geq 2$ provides relatively robust measures of sound scatter by aquatic organisms; and Horne & Clay (1998) concluded that to avoid bias in acoustic backscatter measures or to aid in species identification of acoustic targets, the frequency should be chosen as a value of L/λ from a range of 2 to 10. The dependence of target strength on the ratio of L/λ has generally been estimated with scattering models (e.g. Ye & Farmer 1996, Horne & Clay 1998, Foote & Francis 2002).

4.3 Target strength of swimming fish (I, III & IV)

4.3.1 Measurements of swimming motion

The momentary position of swimming Atlantic salmon was detected from 440 freeze-frames, from which both swimming angle and deflection of the fish were measured (Fig. 5). The mean swimming angle was 89° (*SD* = 16.7), which was quite near the angle of the full side-aspect (90°) (Fig. 7b in I). Deflection from the straight position of the fish varied from -10 % to 16 %, with an average of 1.4 % (*SD* = 4.7). The back-calculated target-strength series from measured swimming angles with equation (2) demonstrated that variation in swimming angle caused an average variation of 3 dB (*SD*) in target strength.

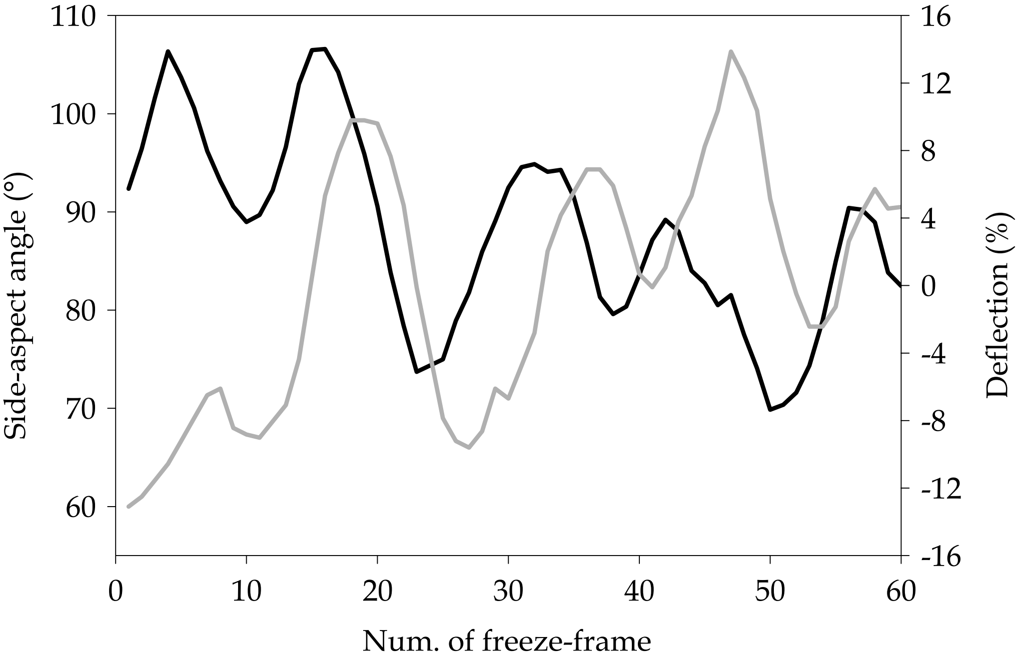

FIGURE 5 Example of variation in side-aspect angle (—) and bending (—) of Atlantic salmon during swimming motion for 6 sec.

4.3.2 Simulation of swimming motion

The results of the target-strength simulations based on the theoretical backscattering model showed that the variability in the side-aspect target strength increases due to the swimming motion of fish. The effect of the side-aspect angle on target strength was discussed above. In addition, the change in swimbladder shape also affected target strength (Fig. 6 in I). When the target bent, the interference between wavelets caused fluctuation in target strength, which could be over 15 dB. In particular, during the concave bends of the swimbladder model, the variation in target strength was predicted to be large. This variation increased with the increase in the proportion of concave bending.

4.3.3 *Ex situ* measurements

A total of 11 Atlantic salmon were used, and 6 to 28 traces were detected per measured fish. The number of echoes per trace varied from 10 to 128 (Table 1 in I). For swimming fish, the mean standard deviation (SD_{mean}) of individual target-strength values for all swimming salmon was 5.7 dB, which was clearly higher than for immobilized fish (*SD* = 2.5 dB). Comparison between the variance of immobilized and swimming salmon indicated that the swimming motion of the fish caused about 80 % of variance in target strength.

The linear regression between mean target strength ($TS_{\mathrm{Swim\ ex}\ situ}$) of the swimming salmon and the logarithm of the fish length (L) was,

$$TS_{\mathrm{Swim\ ex}\ situ} = 24.4 \log_{10}(L) - 72.9 \text{ dB} \qquad (9)$$

($R^2 = 0.79$, n = 11) (Fig. 2), and the relationship between the maximum target strength and fish length made a level that was about 10 dB higher than the relationship for mean target strength (Fig. 4 in I).

4.3.4 *In situ* measurements

4.3.4.1 Äijälänsalmi Channel (III)

Altogether, about 124 000 fish were detected moving from Lake Päijänne to Lake Jyväsjärvi, past the sampling site in Äijälänsalmi Channel. The most common species in the catch samples were roach (*Rutilus rutilus*), perch (*Perca fluviatilis*) and ruffe (*Gymnocephalus cernuus*) (Fig. 6 in III). It was not possible to separate the different species with an echo sounder. Hence, the *in situ* relationship between target strength ($TS_{\mathrm{Äijälä}}$) and fish length (L) was estimated for all of the species present:

$$TS_{\mathrm{Äijälä}} = 20 \log_{10}(L) - 63.7\ [\pm 1.2\ (SD)] \text{ dB}. \qquad (10)$$

When the mean variance (SD^2) for upstream migrating fish was 22.0, the mean standard deviation (SD_{mean}) was 4.7 dB.

4.3.4.2 The Tornionjoki River (IV)

The mean standard deviations (SD_{mean}) for upstream migrating fish in the Tornionjoki River were 2.8, 3.8, and 2.9 dB in years 1997, 1998 and 1999, respectively. These are rather low values for variability compared with *ex situ* measurements of immobilized or swimming salmon. In the Tornionjoki River in 1998, in order to inhibit storage of the noise and reverberation echoes onto the disk, the noise-threshold was at its highest, –38 dB (full-beam –32 db). This rather high noise threshold might have caused a bias in the measured standard deviation because the reverberation blocked out the weakest echoes from fish and decreased the variability in target strength.

During the migration season 1998, the target strength of upstream migrating fish decreased as did the mean length of Atlantic salmon in the test fishing catch from the estuary of the Tornionjoki River (Fig. 4 in IV). From this data, the relationship, estimated *in situ*, between target strength ($TS_{\mathrm{Salmon}\ in\ situ}$) and the total length ($L$) of Atlantic salmon is:

$$TS_{\mathrm{Salmon}\ in\ situ} = 20.2 \log_{10}(L) - 65 \text{ dB} \qquad (11)$$

($R^2 = 0.79$). This decrease in mean target strength during the migration season proved that large fish, which consisted primarily of Atlantic salmon, entered the Tornionjoki River first.

4.4 Prediction of target-strength distributions

During the summer of 2003, the salmon catch of the brood-fish fishery was 181 fish in the mouth of the Simojoki River. The range of the length of Atlantic salmon in the catch was broad. The total length of the salmon varied between 48 and 110 cm (Fig. 6a). Altogether, 782 and 465 targets were detected moving upstream through the sampling site with a mean target strength greater than –34 dB and –29dB, respectively (Fig. 6b).

The simulation of target-strength distribution with caught salmons showed large variation between simulations, which was caused by the small number of salmon in the catch. Simulations with 10 times the actual catch decreased this variation. Furthermore, when the number of fish was increased further (100*Catch), the simulated distribution of the target strength resembled normal distribution (Fig. 7). With a large number of migrants the multi-peaked length distribution of fish may result in a unimodal distribution of the target strengths. Comparison between observed and simulated target-strength distributions showed that these distributions had similar patterns, especially with an increase in the number of fish (10*Catch & 100*Catch). In most cases, the peak of the distribution occurred in a target-strength class of –26.5 dB (center of the class). This was also the peak of the target-strength distribution when the length distribution of the caught fish was converted directly to the distribution of target strength with equation 9 (S.E.E = 0). However, the mean target strength of fish detected from echoes (*in situ*) may be different from the mean target strength in measurements of cage-swimming fish (*ex situ*). This might cause reduction in both the calculated size distribution of fish and the total abundance of the population.

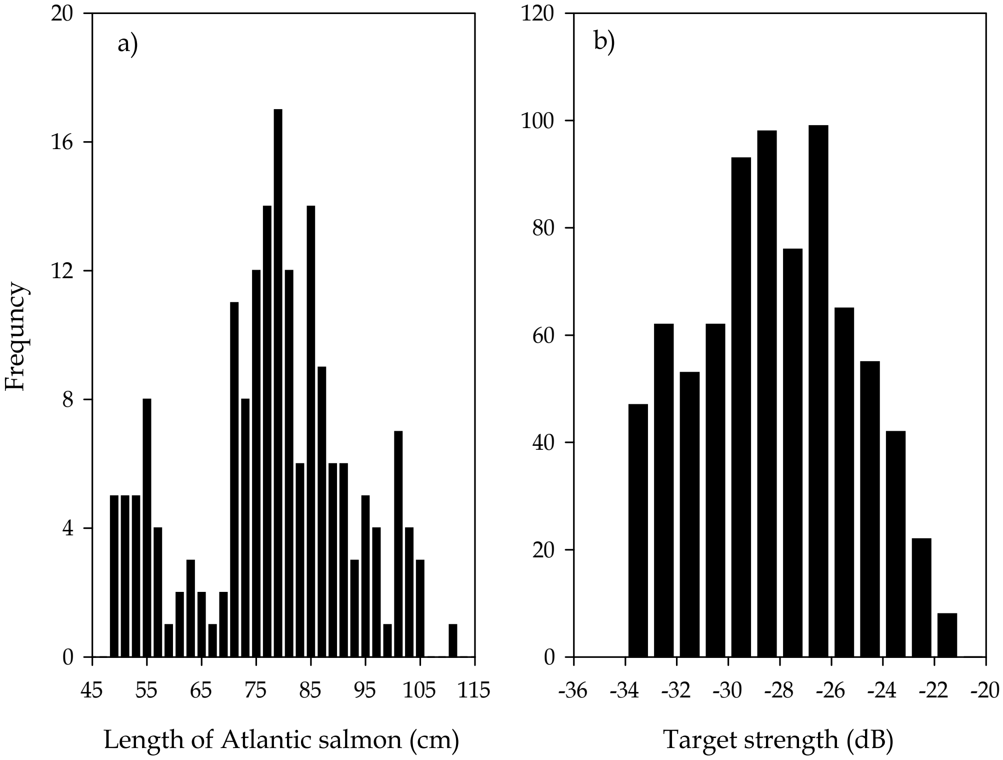

FIGURE 6 Observed a) length distribution of the Atlantic salmon in the brood fish catch (n = 181) in the mouth of the Simojoki River and b) target strength distribution from the hydroacoustic survey. Both sets of data were collected during the summer of 2003.

The target-strength distribution was naturally wider with the high standard error of the estimate (S.E.E) than with the lower one (Fig. 7). For the linear relationship between the target strength of immobilized salmon and the logarithm of fish length, the standard error of estimate was 2.4 (II). The swimming movements of fish increase the fluctuation in target strength, but the measurement conditions (e.g. signal-to-noise ratio) may decrease this fluctuation. Therefore, the target-strength distribution of fish from riverine applications is generally confined to measurement conditions, which can differ between rivers. Consequently, without supplementary catch samples the interpretation and comparison of the target strength data from horizontal hydroacoustic surveys is quite unreliable.

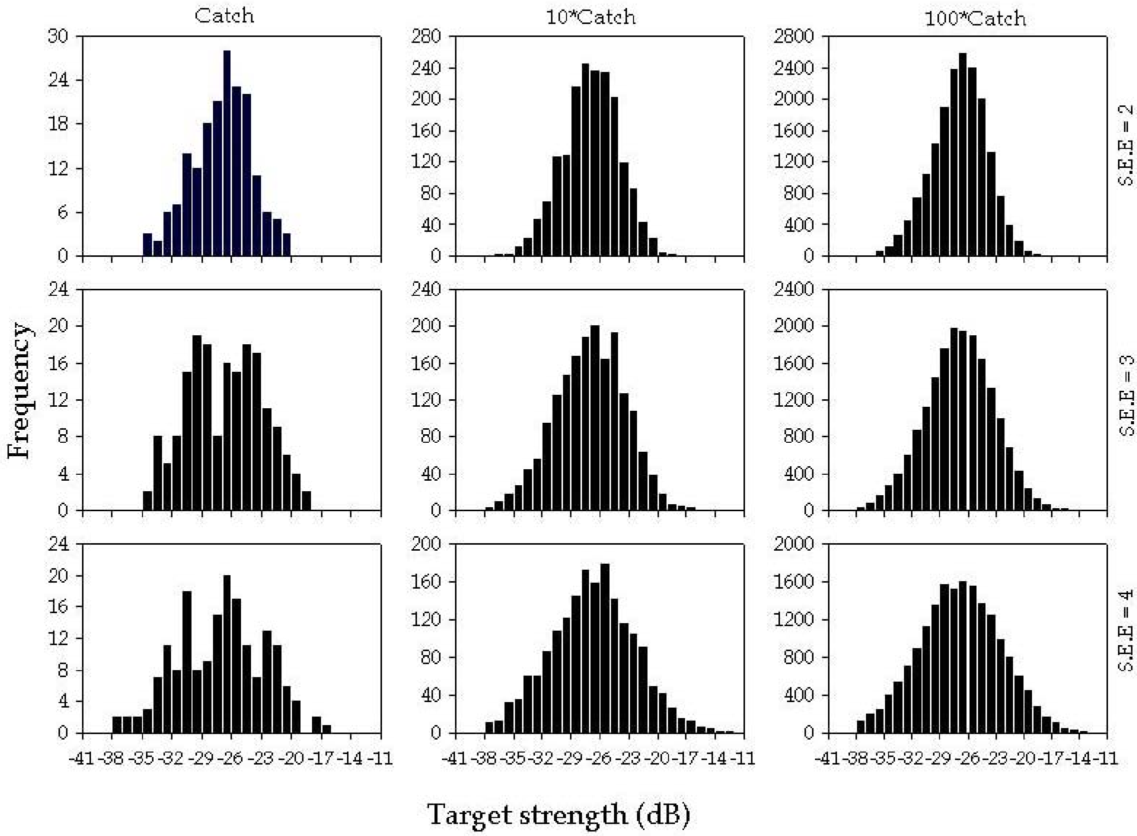

FIGURE 7 Simulated target strength distributions with three different numbers of fish (Catch, 10*Catch, and 100*Catch) and three different standard errors of estimates (S.E.E), which were 2, 3, and 4.

4.5 Detection of salmon with horizontal sounding

Experiments on size-selectivity of swimming salmon indicated that the probability of detection increases with the length of the fish. This probability is substantially higher with a mean target strength calculated from the mean backscattering cross-section (σ) (eq. 3) than from that calculated with equation 5 (Fig. 8). Fish seemed to be larger when calculated with mean σ. However, the slope of the curve with a detection probability of 0.5 was also steeper for mean backscattering cross-section than for the mean of the individual target-strength values. For the threshold target strength -29 dB, based on the mean of the individual target strength and mean σ, the estimated 75% detection lengths ($L_{75\%}$) for target strength calculations are 76 cm and 99 cm, respectively. In addition, in the length range 60 to 120 cm, with the mean target strength calculated from mean σ and the mean of the individual target-strength values, an average of 85% and 55%, respectively, of the passed salmon were detected. These proportions are based on symmetric logistic curves (Fig. 8), which also demonstrate that, with the method used in the Tornionjoki River slightly over 50% of the fish in the length range 60 – 120 cm will be detected.

As recommended by MacLennan & Simmonds (1992), the mean target strength of fish should be calculated from the average of the individual acoustic cross-section estimates (eq. 3), not from the average of the individual target-strength estimates (eq. 5). Despite this, the integrated HTI fish-tracking software calculates the mean target strength of fish from the mean of the individual target-strength observations (geometric mean of σ), and this method was used in our applications in the Tornionjoki River (IV and V). However, the geometric mean of σ is always less than the corresponding arithmetic mean, and this difference can be estimated with the standard deviation of the approximately normally distributed items (e.g. Ricker 1975). The difference between mean target strength determined from individual target-strength values and mean target strength determined from mean σ increases with an increase in the standard deviation of the individual target strength values. In retrospect, it can be said that the method used for calculation of mean target strength was not the best possible for detecting salmon, even though it could be proven that the detected fish were indeed salmon.

In horizontal hydroacoustic applications, the shape of the beam also affects fish detection. Enzenhofer et al. (1998) concluded that the efficiency of fish detection is substantially higher with an elliptical beam than with a circular one. In most riverine acoustic applications, transducers with elliptical beam are used. This is because salmon that are migrating upstream usually swim close to and parallel to the river bottom, and because an elliptical beam can be directed closer to the river bottom, the trajectory of salmon crossed the beam longer in an elliptical beam than in a circular beam. In addition, in order to optimize size estimation of fish from reflected echoes, the trajectories of fish through the beam should generally be parallel to the horizontal axis of the beam (Cronkite & Enzenhofer 2002). Also in our applications, salmon that were migrating upstream swam close to the river bottom. During migration seasons, in the Tornionjoki River and the Simojoki River, of the salmon-sized fish 94 % and 80 %, respectively, were moving upstream through the lower half of the acoustic beam.

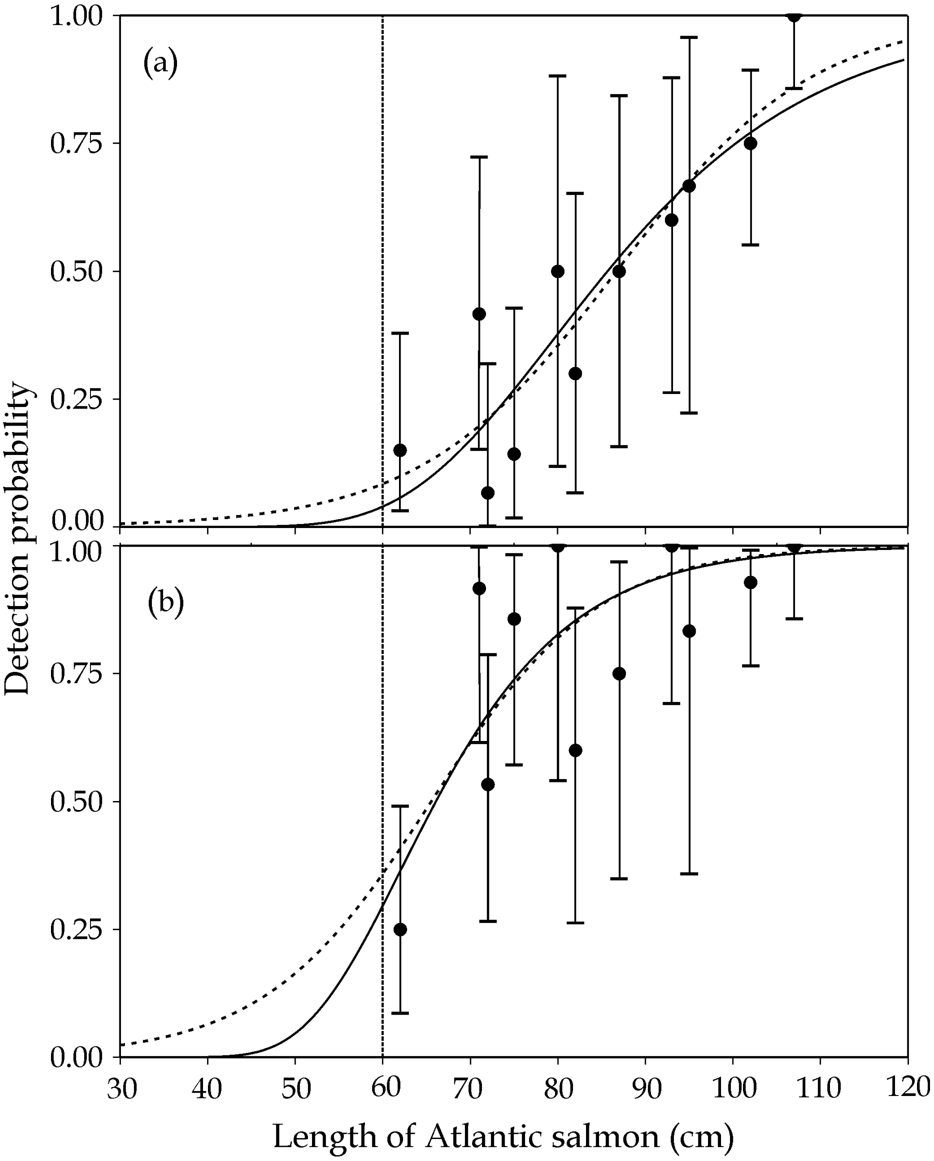

FIGURE 8 Probability of detection different lengths of Atlantic salmon when the threshold value of the mean target strength was –29 dB. Detection probability indicates the proportion of traces with mean target strength higher than this threshold value. Mean target strength calculated from individual target strength values (a), and from mean backscattering cross-section (b). Symmetric (broken line) and asymmetric (solid line) logistic curves and CL of 95 % for detection probability (whiskers).

Enzenhofer et al. (1998) concluded that the detection efficiency of horizontal hydroacoustics at 200 kHz was excellent up to 2 000 salmon h^{-1}. For most Atlantic salmon rivers, however, the rate of passage is considerably lower than that (Mills 1989). The importance of fish detection and unbiased target-strength measurements increase in rivers where fish density is low and migration occurs over a long period of time

4.6 Fish migration and environmental factors (III & V)

In Äijälänsalmi Channel, fish migration occurred mainly at dawn and dusk (Fig. 5 in III). The upstream migration of fish was triggered by a temperature difference between lakes (Fig. 3 and Fig. 4 in III). Thus, the warm water from Lake Jyväsjärvi attracted fish to enter the channel. These results show that, if there are supplementary catch samples, horizontal echo sounding is an efficient method for studying the behavior of fish.

In the Tornionjoki River, 7 700, 5 300, and 4 300 salmon-sized fish [mean target strength (eq. 3) $\geq$ -29 dB] were estimated to moving upstream past acoustic beams during 1997, 1998, and 1999, respectively (V). River entry started in early June when water temperature was about 9° C and the discharge varied between 1700 and 2000 m^3s^{-1}. In a large pristine river located at high latitude, environmental factors have little effect on entry of Atlantic salmon into the river. Statistically significant correlations are presented in Fig. 4 in V.

5 CONCLUSIONS

Basically, the side-aspect target strength of immobilized fish increased with fish size but unfortunately there was a large within and between species variation in this relationship. This variation makes it difficult to make any definite statements about the slopes or intercepts of the regression lines between the target strength and the logarithm of fish length. These regressions are merely the best fits to the available target strength measurements. All regressions increased with a slope larger than 20. In addition, whitefish has a target strength that is about 5 dB higher than salmon of the same size.

Both simulations and experiments with immobilized fish showed that the variation of target strength with the side-aspect angle was very large. The best fit of the all-side-aspect model between the mean target strength and the side-aspect angle was obtained using the $\cos^3(2\alpha)$ function. In addition, the fluctuation in target strength increases with the swimming motion of fish. Because of the large variation in side-aspect target strength, the interpretation of this data is quite difficult in a riverine environment, and the precision of the estimated fish lengths is not presentable. Despite this, the counting results are reliable.

Experiments on size-selectivity with fixed threshold target strength (-29 dB) demonstrated that, with the method used in the Tornionjoki River slightly over 50% of the fish in the length range 60 – 120 cm would have been detected during the years 1997, 1998 and 1999. Hence, the mean side-aspect target strength of fish should be calculated from the average of the individual acoustic cross-section estimates, not from the average of the individual target-strength estimates.

Using the echo sounder with frequency of 200 kHz, it is not possible to use target-strength alone for discriminate the species. The collection of supplementary catch samples used to document species occurrence and length frequency distributions should be therefore carried out as routine components of acoustic survey in multi-species environments. After supplementation, the hydroacoustics will be the most feasible way to estimate the spawning run of the fish into rivers.

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YHTEENVETO

Jokeen vaeltavien kalojen laskeminen sivuttaissuuntaisella kaikuluotauksella: sivuaspektikohdevoimakkuuteen liittyviä ongelmia

Kaikuluotaus soveltuu hyvin vedenalaisten eläinten kuvaamiseen ja tutkimiseen, sillä toisin kuin sähkömagneettinen säteily (esim. näkyvä valo), ääniaallot kulkeutuvat vedessä erittäin hyvin. Kaikuluotausta käytetään erityisesti pelagisten merikalojen ja –äyriäisten tiheys- ja kanta-arvioissa. Kaikuluotauslaitteistojen, etenkin lohkokeilakaikuluotaimen (split-beam), tekninen kehittyminen mahdollistaa jokeen nousevien emolohien lukumäärän laskemisen kiinteästi paikalleen asetetuilla sivuttaissuuntaisilla luotaimilla. Samanaikainen monien Tyynenmeren lohikantojen taantuminen loi tarpeen tämän kalastuksesta riippumattoman nousulohien laskentamenetelmän kehittämiselle.

Väitöskirjatyössäni olen tutkinut sivuttaissuuntaisella kaikuluotauksella kaloista heijastuvan äänen voimakkuutta (sivuaspektikohdevoimakkuus) ja sen vaihteluun vaikuttavia tekijöitä sekä niiden merkitystä sivuttaissuuntaisella kaikuluotauksella tehtävissä lohien (*Salmo salar* L.) kutukanta- ja käyttäytymistutkimuksissa. Kalan sivuaspektikohdevoimakkuudelle on tyypillistä sen suuri vaihtelu, mikä lisääntyy käytettävän äänitaajuuden kasvaessa. Tässä väitöskirjatyössä olen käyttänyt 200 kHz:n äänitaajuutta, mikä on suhteellisen korkea taajuus tarkasteltaessa kalan pituuden (L) ja äänen aallonpituuden (λ) välistä suhdetta ($L/\lambda > 40$). Tällöin sivuaspektikohdevoimakkuuden vaihtelua lisäsi erityisesti kalan uintiliike.

Väitöskirjatyössäni olen tutkinut ensinnäkin teoreettisesti simuloimalla äänen heijastumista 3-ulotteisen, lohen uimarakkoa muistuttavan kappaleen pinnasta. Seuraavaksi sivuaspektikohdevoimakkuutta tutkittiin koeolosuhteissa tainnutetulla kalalla kalan koon, asennon ja lajin funktiona. Koeolosuhteissa tutkittiin myös lohen uintiliikkeen vaikutusta kohdevoimakkuuteen ja sen hajontaan, sekä lisäksi määritettiin näiden lohien havaitsemistodennäköisyys tietyllä kohdevoimakkuusraja-arvolla (-29 dB) kalan pituuden funktiona. Lopuksi kalan pituuden ja sivuaspektikohdevoimakkuuden välinen riippuvuus määritettiin kalojen luonnollisessa elinympäristössä (*in situ*) Tornionjoessa ja Äijälänsalmessa.

Koeolosuhteissa tainnutetun kalan sivuaspektikohdevoimakkuuden keskihajonta oli tyypillisesti 2,5 dB, kun taas koeolosuhteissa uivan kalan kohdevoimakkuuden keskihajonta oli 5,7 dB. Toisaalta kohdevoimakkuuden keskihajonta Tornionjoessa vastavirtaan uivilla lohilla (kohdevoimakkuus-havaintojen keskiarvo ≥ -29 dB) oli tyypillisesti vain noin 3 dB. Syy tähän pieneen kohdevoimakkuuden hajontaan Tornionjoessa sekä yleensä jokiolosuhteissa että matalissa vesissä on suuri ”taustakohina” (noise) ja jälkikaiunta (reverbaration). Tällöin kaikusignaalin ja kohinan välinen suhde on pieni ja joudutaan käyttämään palaavalle kaiulle korkeaa kynnysarvoa (threshold) eli suodatetaan kohina pois. Tämä saattaa suodattaa myös kalasta heijastuneet heikoimmat kaikusignaalit, jolloin havaittu kohdevoimakkuuden hajonta on pienempi kuin samankokoisella kalalla on hyvissä koeolosuhteissa havaittu.

Kalan koon ja sivuaspektikohdevoimakkuuden välillä oli positiivinen korrelaatio eli kalan koon kasvaessa myös kohdevoimakkuus kasvoi. Toisaalta tämä riippuvuus sisältää paljon vaihtelua ja eri lajien regressiosuorat poikkesivat merkittävästi toisistaan. Simuloidun kohdevoimakkuuden ja uimarakon pituuden välinen riippuvuus ei ollut lineaarinen, mikä on tyypillistä simulaatiotuloksille, sillä niissä heijastuneen ääniaallon vuorovaikutuksia kalan ruodosta ja lihaksesta heijastuneiden ääniaaltojen kanssa ei ole vielä pystytty mallintamaan.

Kalan sivuaspektikohdevoimakkuus on yleensä suurin, kun kalan pituussuuntainen akseli on kohtisuorassa äänikeilan akustiseen akseliin nähden. Kulmapoikkeaman kasvaessa kohdevoimakkuus heikkenee ja se on pienimmillään kalan pyrstön tai kuonon osoittaessa kohti luotainta. Tämä kalan asennosta johtuva kohdevoimakkuuden vaihtelu on mallinnettu $\cos^3$-funktiolla, ja vaihtelun suuruus oli meri lohella (*Salmo salar* L.) ja taimenella (*S. trutta* L.) 17,4 dB, siialla (*Coregonus lavaretus* (L) *s.l.*) 19,0 dB ja hauella (*Esox lucius* L.) 19,7 dB. Myös simulaatiotulokset osoittivat kalan asennolla olevan merkittävä vaikutus kohdevoimakkuuteen, erityisesti sivuaspektikulmilla 88–95°, jolloin ääniaaltojen interferenssi aiheutti voimakkaan lisäyksen kohdevoimakkuuteen.

Kalan uintiliike vaikutti koeolosuhteissa merkittävästi sivuaspektikohdevoimakkuuden vaihteluun: uintiliike aiheutti noin 80 % kasvun varianssissa. Simuloitaessa uimarakon taipumisen vaikutusta kohdevoimakkuuteen havaittiin, että uimarakon koveran pinnan ollessa äänen tulosuuntaan päin, heijastunut kaiku heikkeni, ja heikkeneminen lisääntyi koveruuden lisääntyessä. Sitävastoin kuperuuden lisääntyminen ei vaikuttanut merkittävästi kohdevoimakkuuteen.

Kaikenkaikkiaan sivuttaissuuntaisella kaikuluotauksella pystytään hyvin havaitsemaan vastavirtaan uivat kalat, mutta kalan koon sekä monilajisessa kalayhteisössä lajien erottaminen toisistaan ei vielä toistaiseksi ole mahdollista tarkastelemalla pelkästään heijastunutta kaikua. Kaikuluotaustutkimuksiin onkin syytä yhdistää koekalastukset aina, kun tutkittavan lajin lisäksi läsnä on muita kalalajeja.

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