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Side-aspect target strength of Atlantic salmon (*Salmo salar*), brown trout (*Salmo trutta*), whitefish (*Coregonus lavaretus*), and pike (*Esox lucius*)

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Abstract − The side-aspect acoustic target strengths (*TS*) of 19 Atlantic salmons (*Salmo salar*), 16 brown trouts (*Salmo trutta*), 10 whitefish (*Coregonus lavaretus*) and 9 pikes (*Esox lucius*) were measured using a 200 kHz split-beam echosounder, in order to study the relationship between *TS* and fish size indices (length, weight and side area). The effect of side aspect angle on *TS* was also studied. Linear models between *TS* and the logarithm of the fish size indices were fitted with length being best for predicting *TS*. Typically, the standard error of estimate was 1.2–2.9 dB. The side-aspect *TS* measurements with specimens of known size showed that the linear relationship between full side-aspect *TS* and the logarithm of fish length for salmonid (*Salmo salar* + *Salmo trutta*) was on average 4.7 dB (*SE* = 0.7), lower than for whitefish and pike combined. The effect of side aspect angle on *TS* was modelled with $\cos^3(2\alpha)$ function. The differences in the *TS* between full side aspect and head/tail aspect were 17.4, 19.0 and 19.6 dB for salmonid, whitefish, and pike, respectively. © 2000 Ifremer/CNRS/INRA/IRD/Cemagref/Éditions scientifiques et médicales Elsevier SAS

target strength / split-beam / side-aspect angle / freshwater fish / Baltic sea

Résumé − Indice de réflexion latérale du saumon Atlantique (*Salmo salar*), de la truite de mer (*Salmo trutta*), du corégone (*Coregonus lavaretus*) et du brochet (*Esox lucius*). L'indice de réflexion acoustique latérale (*TS*) de 19 saumons Atlantique (*Salmo salar*), 16 truites de mer (*Salmo trutta*), 10 corégones (*Coregonus lavaretus*) et 7 brochets (*Esox lucius*) a été mesuré en utilisant un sondeur de 200 kHz, afin d'étudier la relation entre l'indice *TS* et la taille, le poids et la surface du poisson. Les effets de l'angle d'incidence sur l'indice *TS* ont aussi été étudiés. Des modèles linéaires entre *TS* et le logarithme de l'indice de taille du poisson ont été ajustés et ont montré que la meilleure prévision provient de l'indice de longueur. Classiquement, l'erreur standard de l'estimation était de 1,2 à 2,9 dB. Les résultats des mesures de *TS* sur des poissons de longueur connue montrent une relation linéaire entre l'indice *TS* latéral et le logarithme de la longueur pour les deux espèces confondues (*Salmo salar* + *Salmo trutta*), soit en moyenne 4,7 dB (*SE* = 0,7), inférieurs aux deux autres espèces confondues (corégone et brochet). L'effet de l'angle sur le *TS* a été modélisé par la fonction $\cos^3(2\alpha)$. Les différences de *TS* entre une insonification de profil ou de face sont respectivement de 17,4 ; 19,0 et 19,6 dB pour le saumon, le corégone et le brochet. © 2000 Ifremer/CNRS/INRA/IRD/Cemagref/Éditions scientifiques et médicales Elsevier SAS

indice de réflexion / double faisceau / angle d'incidence / poisson d'eau douce / mer Baltique

1. INTRODUCTION

During the last decade, hydroacoustic methods for estimating salmon escapement to rivers have attracted considerable attention (Ransom et al., 1998). An important concept, in the interpretation of hydroacoustic data, is the fact that the target strength (*TS*) from a single fish increases with fish size (MacLennan and Simmonds, 1992). In most riverine acoustic applications, fish are assumed to present approximately their side aspect to the transducer as they swim through the sonar beam. Side-aspect *TS* measurements, on immo-

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Table I. Fish species, number of fish, their length, weight, and side-aspect area range, and fish origin.

Species	*n*	Length* (cm)	Weight* (kg)	Side-aspect area* (cm^2)	Origin
Salmo salar	19	30.0 – 119.0	0.280 – 16.060	98 – 1 555	HS and River Simo
Salmo trutta	16	29.0 – 63.0	0.180 – 2.515	74 – 379	HS
Coregonus lavaretus	10	34.5 – 54.0	0.405 – 1.795	109 – 305	HS
Esox lucius	9	42.5 – 73.0	0.480 – 2.655	142 – 431	Lake Ylä-Enonvesi

* Values are minima and maxima. HS = Hatchery Stocks.

bilised fish, have been published by several authors (Love, 1977; Dahl and Mathisen, 1982; Kubecka, 1994; Burwen and Fleischman, 1998; Kubecka and Duncan, 1998). In a multispecies fish community, the interpretation of the species of fish targets relies much on their size estimated from their *TS*. In addition to size, however, several other factors, including orientation, activity, behaviour, and structural components of the body of different species affect *TS* (Midttun, 1984). Therefore, the use of hydroacoustics is often limited by the inability to discriminate among fish species.

On the River Tornionjoki, in the northern most part of the Baltic Sea, a split-beam side-looking hydroacoustic system has been used to monitor the upstream migration of adult multi-sea-winter salmons (*Salmo salar*) since 1997 (EU Study Project 96-069). According to catch statistics, the peak in their migration occurs in June (Romakkaniemi et al., 2000). However, several other migratory and resident non-target fishes e.g. whitefish (*Coregonus lavaretus*), pike (*Esox lucius*), brown trout (*Salmo trutta*) and 1-sea-winter salmon are present at the monitoring site, in much higher numbers than the endangered adult salmon. Peak migrations of non-target species are different from those of salmon, but overlap in run timing does occur. Thus, despite the fact that the adult salmons are usually larger (> 60 cm total length) than other fish, their separation from other acoustic targets based on the observed *TS* distribution is difficult and may be a source of severe bias in salmon stock estimates. In addition, some unrealistic fish sizes were estimated by Love's (1977) side-aspect equation.

The aim of this paper is to estimate the relationship between side aspect target strength and the size of Atlantic salmon, brown trout, whitefish, and pike. In addition, the largest possible size ranges of fish are used to test the differences between these species. The effect of side aspect angle on *TS* is also modelled, in order to determine how sensitive the *TS* measurements are to the side aspect angle.

2. MATERIAL AND METHODS

This study was carried out in the Saimaa Fisheries Research and Aquaculture facilities Enonkoski, during April 1997 and 1998. In addition, six salmon were measured in the River Kemijoki on October 20, 1998. The fish in this study came from the Finnish Game and Fisheries Research Institute of Enonkoski (hatchery stocks), Lake Ylä-Enonvesi, and the River Simo (*table I*). The fish were caught with gill nets in Lake Ylä-Enonvesi, and were held in net cages for about 2 weeks to adapt to the surrounding conditions as much as possible. Study specimens included salmon and brown trout, whitefish, and pike. The soundings took place in a large pool (length 30 m, width 5 m, and depth 1.5 m). Fish were mounted in a rotating hanger using 0.3 and 0.7 mm diameter fishing line and weight (*figure 1*) outside the near field (6.5–10 m) of the transducer and as close as possible to the acoustic axis of the transducer beam. The side-aspect *TS* of the fish were measured by rotating the fish in the horizontal plane at 10° intervals (*figure 2*). *TS* was measured at each aspect angle for at least 50 s (> 250 pings). In addition, total length (*L*), weight (*W*), and height (H_i) of fish at five points were measured. The side-aspect area (*A*) was estimated:

$$A = \frac{L}{7}\sum_{i=1}^{5} H_i \tag{1}$$

A Hydroacoustic Technology, Inc. (HTI; 1997) split-beam system was used throughout the study. The system consisted of a 200 kHz split-beam echo sounder, digital echo processor, elliptical-beam transducer, transducer cable, chart recorder, oscilloscope, digital audio tape recorder, and data analysis computer.

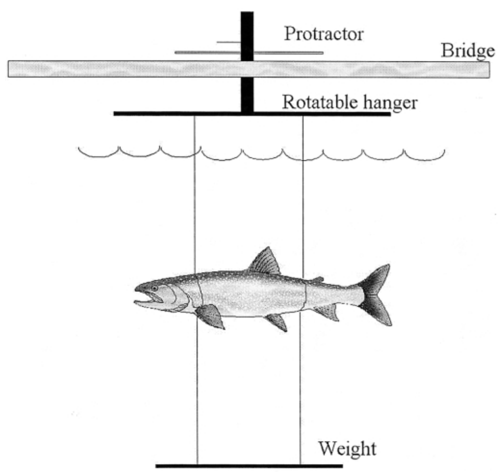

Figure 1. Hanger and fishing line were used to fix and rotate fish in the beam of the side-looking split-beam echo sounder.

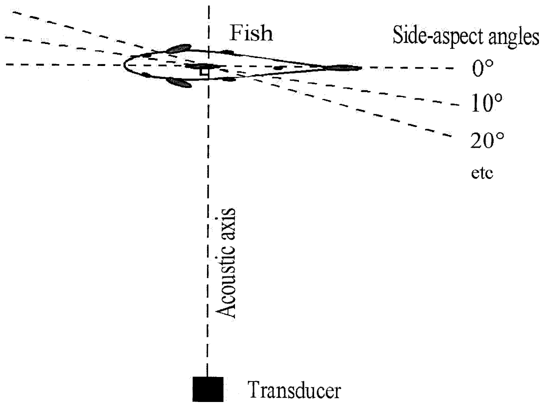

Figure 2. Fixed side-aspect angles during the *TS* measurements. Fish were located outside the near field (6.5–10 m) from the transducer.

The nominal beam width (measured at –3 dB down from the acoustic axis) was 4° × 10° (HTI, 1997). The echo sounder settings are illustrated in *table II*.

The acoustic target strength (*TS*, dB) of the fish is defined as the echo strength (dB) of the fish when it is located on the acoustic axis of the transducer beam. The acoustic axis is the position at which the transmitted energy is the greatest. The split-beam technique provides three-dimensional positioning for each returning echo. In addition, this technique calculates target strength for each returning echo from its echo strength (Traynor and Ehrenberg, 1990). The target strength (TS_i) for an individual echo *i* was estimated using the formula:

$$TS_i = -SL - G_0 - R_G + 20\log_{10}(U_i) - B_i(\phi, \theta) \quad (2)$$

where SL = Source level (dB), G_0 = Through-system gain (dB), R_G = Receiver gain (dB), U_i = peak amplitude of echo *i* (V), and $B_i(\phi, \theta)$ = beam pattern factor (dB). The arithmetic mean of the individual fish target strength (TS_{TS}) for each fish was calculated as:

$$TS_{TS} = \frac{1}{n}\sum_{i=1}^{n} TS_i \quad (3)$$

Mean target strength can also be estimated from the backscattering cross-section for individual echoes comprising a fish as follows:

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

$$\bar{\sigma} = \frac{1}{n}\sum_{i=1}^{n}\sigma_i \quad (5)$$

where σ is the fish backscattering cross section (m^2) and 4π is the cross section of an idealized sphere of 2-m radius. Integrated HTI fish-tracking software estimates the acoustic size of fish using the arithmetic mean of its *TS*-observations (eq. 3). The standard deviation of TS_{TS} values is approximately normally distributed, whereas distribution of backscattering cross-section (σ) is skewed (Dahl and Mathisen, 1982; Dawson and Karp, 1990). Therefore, instead of using the TS_σ (eq. 4) (as recommended by MacLennan and Simmonds, 1992), we used the former estimator equation. In our data, TS_{TS} was measured approximately 1 dB lower than TS_σ. *TS* measurements of each fish were recorded as a separate file on the PC and could be processed separately under its own filename.

Before and after the *TS* measurements of a fish the sonar system was in situ-calibrated using a standard target. A 38.1 mm (ϕ) tungsten-carbide standard target was suspended on monofilament line approximately between 6.5–10 m from the transducer. The nominal target strength of this sphere is –39.5 dB at the frequency of 200 kHz (MacLennan and Simmonds, 1992).

The linear relationship between *TS* and the logarithm of fish length has been applied by many authors because it is a simple way both for presentation and for later use in applied work (Love, 1977; Foote, 1980; Kubecka and Duncan, 1998).

$$TS = A\log_{10}(L) + B \quad (6)$$

where *A* is the slope of the line and *B* is the intercept, *L* is the length of the fish. The slope of 20 (A_{20}) implies the acoustic cross-section being proportional to the length squared (MacLennan and Simmonds, 1992). The parameters *A* and *B* were estimated using linear regression. The linear relationships between side-

Table II. The settings of the echo sounder during side-aspect target strength (*TS*) measurements in Enonkoski and Kemi.

	Enonkoski (1997)	Enonkoski (1998)	R. Kemijoki (1998)
Transmit power (dB)	20	20	20
Source level, *SL* (dB)	211.00	211.06	211.06
Through-system gain, G_0 (dB)	–174.97	–173.97	–173.97
Receiver gain, R_G (dB)	–12.0	–12.0	–12.0
TVG-function	$40\log_{10}R$	$40\log_{10}R$	$40\log_{10}R$
Pulse width (ms)	0.4	0.4	0.4
Ping rate ($ping \cdot s^{-1}$)	2	5	5
Echogram threshold (mV/dB)	80/–46	80/–47	80/–47

R = target range (m) and TVG = Time Varied Gain function.

Table III. Regression statistics between full side-aspect target strength (*TS*) and log total length (cm) for all fish*.

Model	*A*	*SE* of *A*	*B*	*SE* of *B*	*n*	R^2	*P*-level	*SE* of estimate
$TS_{S.\ salar}$	25.6	4.0	–72.6	7.2	19	0.71	< 0.001	2.6
$TS_{S.\ trutta}$	28.9	6.2	–77.8	10.15	16	0.61	< 0.001	2.9
TS_{Wh}	39.7	10.7	–90.3	17.7	10	0.63	0.006	2.2
TS_{Pike}	28.6	5.8	–73.7	10.0	9	0.77	0.002	1.2
$TS_{20-Salmo}$	20		–62.8	0.5	35	0.68		
TS_{Salmo}	26.2	2.9	–73.8	5.0	35	0.72	< 0.001	2.7
$TS_{Wh + Pike}$	28.0	6.0	–71.7	10.3	19	0.55	< 0.001	2.0
TS_{all}	24.2	3.3	–68.3	5.7	54	0.50	< 0.001	3.3

* salmon (*S. salar*), brown trout (*S. trutta*), salmon + brown trout (Salmo), whitefish (Wh), pike (Pike), and whitefish + pike. Equations are $TS = A \log_{10}(L) + B$, and n = number of fish. SE = standard error.

aspect *TS* and the logarithm of weight and side-aspect area were also estimated. Analysis of variance using log(size) as a covariate and a dummy variable regression were used in testing the differences in parameter B, assuming constant slope A for all groups (McCullagh and Nelder, 1989).

The relationship between *TS* (dB) and side-aspect angle (α) were modelled (all-aspect model) using a function $\cos^3(2\alpha)$, according to Kubecka (1994). The dependence of *TS* on length was also included in the model ($TS_{All\text{-}aspect}$):

$$TS_{All-aspect} = C \log_{10}(L) + D \cos^3(2\alpha) + E \quad (7)$$

where L = fish length (cm), α = side-aspect angle (°) and C, D, and E are the empirically determined constants which vary with fish species. The $\cos^3(2\alpha)$ function assumes the existence of an average all-aspect *TS* with a symmetrical distribution of the amplitude of *TS* between maximal and minimal values. In addition, the $\cos(2\alpha)$ and $\cos^5(2\alpha)$ function were also fitted. All-aspect models were fitted using the iterative least square method. No clear between-fish differences were observed between individuals of same size. Therefore, every mean *TS* measurement was used in parameter estimation as independent observation.

3. RESULTS

Significant linear regressions between side-aspect target strength and the logarithm of length, weight and side-aspect area of fishes were detected (*tables III*, *IV*), with the length of the fish explaining best the variation in *TS*. Even for the regression of *TS* on length, the standard errors of the estimate were large, from 1.2 to 2.9 dB, for different species. The model fitted the pike data best ($R^2 = 0.77$). In the linear model between fish mean full side-aspect ($\alpha = 0°$) *TS* and logarithm of fish length increasing slopes of 25.7, 28.6, 28.9, and 39.7, were estimated for salmon, pike, brown trout, and whitefish, respectively (*table III*, *figure 3*). However, the slopes of these individual species did not statisti-

Table IV. Regression statistics between full side-aspect target strength (*TS*) and weight or side-aspect area for all fish*.

	Model	*A*	*SE* of *A*	*B*	*SE* of *B*	*n*	R^2	*P*-level	*SE* of estimates
Weight	$TS_{S.\ salar}$	8.9	1.5	–56.3	4.9	19	0.68	< 0.001	2.7
	$TS_{S.\ trutta}$	8.2	2.1	–54.5	6.3	16	0.51	0.002	3.3
	TS_{Wh}	11.4	3.6	–58.4	10.6	10	0.56	0.013	2.4
	TS_{Pike}	8.9	2.0	–50.9	6.1	9	0.73	0.003	1.3
	TS_{Salmo}	8.8	1.1	–56.1	3.5	35	0.67	< 0.001	2.9
	$TS_{Wh + Pike}$	10.2	2.0	–55.0	6.1	19	0.60	< 0.001	1.9
	TS_{all}	7.3	1.2	–49.8	3.9	54	0.40	< 0.001	3.6
Area	$TS_{S.\ salar}$	12.5	2.0	–58.9	5.2	19	0.70	< 0.001	2.6
	$TS_{S.\ trutta}$	12.9	3.2	-60.0	7.4	16	0.53	0.001	3.2
	TS_{Wh}	17.3	5.5	–64.7	12.7	10	0.56	0.013	2.5
	TS_{Pike}	12.6	3.6	–54.0	8.6	9	0.63	0.01	1.5
	TS_{Salmo}	12.7	1.5	–59.5	3.7	35	0.68	< 0.001	2.8
	$TS_{Wh + Pike}$	15.0	3.2	–59.5	7.5	19	0.56	< 0.001	2.0
	TS_{all}	10.8	1.8	–53.0	4.3	54	0.41	< 0.001	3.6

* Atlantic salmon (*S. salar*), brown trout (*S. trutta*), Atlantic salmon + brown trout (Salmo), whitefish (Wh), pike, and whitefish + pike. Equations are $TS = A \log_{10}(weight \text{ or } area) + B$, and n = number of fish. *SE* = standard error.

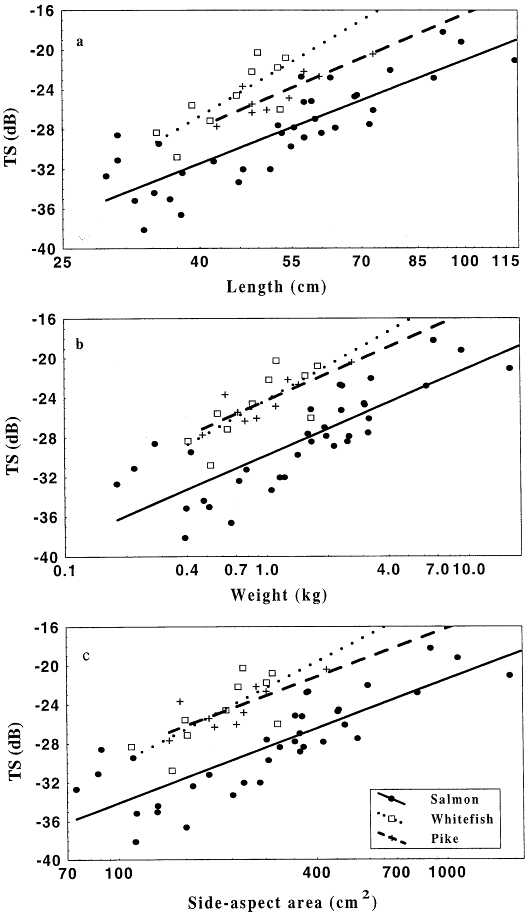

Figure 3. The linear relationships between full side-aspect *TS* (angle 0°) and a) total length, b) weight, and c) side-aspect area for salmon, whitefish, and pike. Note the log scale of X–axis.

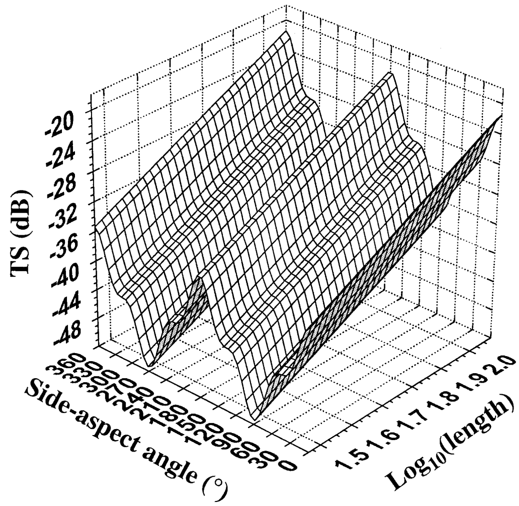

Figure 4. Three-dimensional model between side-aspect *TS* (dB), angle (°), and fish length (cm) for Salmon (*S. salar* and *S. trutta*).

cally differ among species ($F = 0.64$, $P > 0.05$), or from the theoretical value of 20.

Analysis of covariance revealed that *TS* standardised by logarithm of length, weight or side-aspect area of salmon and brown trout differed significantly from those of whitefish and pike ($P < 0.01$, Tukey's test), whereas significant difference was observed neither between salmon and brown trout ($P = 0.943$, $P = 0.988$, $P > 0.999$) nor between whitefish and pike ($P = 0.513$, $P > 0.999$, $P = 0.999$). For further analysis, data from salmon and brown trout species were pooled (variable Salmo), and whitefish and pike data were combined (variable W + P). If the slope is taken to be 20, then the intercept B_{20} is –62.8 for Salmo. The *TS* of whitefish and pike (W + P) was considerably greater than that of salmon and brown trout (Salmo) of the same size. The differences were 4.7 dB ($SE = 0.7$, $P < 0.001$), 5.5 dB ($SE = 0.7$, $P < 0.001$) and 5.4 dB ($SE = 0.7$, $P < 0.001$) for length, weight and side-aspect area, respectively.

The best fit of the all-aspect model between mean *TS* and side-aspect angle was obtained using the $\cos^3(2\alpha)$ function used by Kubecka (1994), 75.3%, 77.6%, and 77.0% of the variance being explained for Salmo, pike, and whitefish, respectively (*table V*). When comparing functions $\cos(2\alpha)$, $\cos^3(2\alpha)$ $\cos^5(2\alpha)$, $\cos^3(2\alpha)$ gave the best fit to the data. The side aspect angle had a significant effect on *TS* (*figures 4, 5*), the difference between full side aspect and head/tail aspect being 17.4, 19.0 and 19.6 dB (2 D in *table V*) for Salmo, pike and whitefish, respectively.

4. DISCUSSION

According to Kubecka and Duncan (1998), the slope of the regression between standard length and *TS* for

Table V. Estimated parameter values of all-aspect function for Atlantic salmon + brown trout (Salmo), pike, and whitefish*.

Species	*n*	*C*	*SE* of *C*	*D*	*SE* of *D*	*E*	*SE* of *E*	Variance explained
Salmo	949	22.2	0.8	8.7	0.2	–75.2	1.4	75.3%
Pike	451	26.1	1.9	9.5	0.3	–81.2	3.2	77.6%
Whitefish	244	35.0	3.3	9.8	0.4	–95.8	5.4	77.0%

* Equation is $TS_{\text{All-aspect}} = C \log_{10}(L) + D \cos^3(2\ \textit{side-aspect angle}) + E$, and n = number of target strength (*TS*) measurements

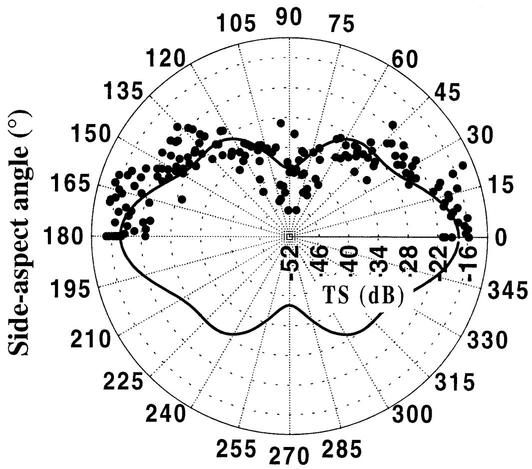

Figure 5. Polar plot of target strengths of a salmon (*Salmo salar*) (fish length = 119 cm). Side-aspect angle (°) on circle and *TS* (dB) on radius. Curve represents average *TS* vs. aspect angle relationship described by $\cos^3$-model.

freshwater fish insonified (420 kHz) in side-aspect fell between 27 and 30. According to Love (1977), the typical slope is 22.8. Our results for different species do not differ significantly from these, when standard errors of estimate are taken into account. Assuming 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. The estimated slopes are in good agreement with this.

The low *TS* of salmonids, in comparison to other species in our data, is in accordance with observations of Kubecka and Duncan (1998) who found that regressions for salmonids lay somewhat lower in elevation than those for some cyprinids and perch. The typical difference interpreted from their regression is of the same order of magnitude (about 5 dB) as in our results. The effect of side-aspect angle on *TS* was relatively insignificant when the angle was less than 15° from full side-aspect (*figure 5*). At greater angles, *TS* decreased more rapidly with an increase in angle. For an angle of 45°, the *TS* level is about 9 dB lower than that for full side aspect (7/8 decrease in sound intensity). The difference between full size-aspect *TS* and head/tail *TS*, in our results, is in accordance with observations of Love (1977) and Kubecka and Duncan (1998).

In practice, the relationships between *TS* and length are used for estimating fish length from their *TS*. Our data indicate low success in this operation. For example, some salmonids of about 30 cm in length had a mean *TS* comparable to a typical expected *TS* of about a 55 cm fish. Furthermore, the expected *TS* for a 40 cm whitefish (about – 25 dB) is equal to that of a 60 cm salmon and some of the less than 50 cm whitefish could have been misinterpreted to be over 1 m long salmon. Finally, taking into the consideration the variation in side-aspect, swimming movements and low number of echoes per observed fish, in the natural river conditions, it can be stated that observed mean *TS* per se is a poor measure of fish size, let alone its species. Other dimensions of returning echoes (e.g. Burwen and Fleischman, 1998), behavioural characteristics of the targets (e.g. distribution of targets in river cross section), comparison of *TS* distribution with catch data (e.g. Romakkaniemi et al., 2000), and direct observation by video camera are needed to prevent estimates of salmon run in rivers with multispecies community from being severely biased.

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