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Time-based signal characteristics as predictors of fish size and species for a side-looking hydroacoustic application in a river

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Side-looking, fixed-location sonar is used to estimate the abundance of migrating chinook salmon *Oncorhynchus tshawytscha* in the Kenai River, Alaska. For this application, echo-envelope length has previously been shown to predict fish size better than target strength. Using tethered-fish experiments we generalize these findings to other hydroacoustic descriptors based on time measurements, including range-measurement variability and fish lateral movement. These variables are all descriptors of the echo signal through time. Measurements of these attributes were correlated with daily indices of the species composition of unrestrained fish passing the sonar site. We hypothesize that time-based characteristics are superior predictors of fish size because they capitalize on, or are robust to, the factors which compromise amplitude-based measurements with side-looking sonar.

Keywords: classification, discrimination, echo length, hydroacoustic, pulse width, sonar.

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Introduction

Shallow-water applications of fisheries sonar present a unique set of challenges. Boundary effects may distort fish echoes and impede detection (Gerlotto *et al.*, 2000; Mulligan, 2000). Ranges are generally short, and beams narrow, leading to point-source violations because fish are large relative to the beam (Dawson *et al.*, 2000). Under these conditions, fish are complex scatterers that can return echoes which vary greatly in amplitude and duration. Furthermore, for side-looking applications, fish aspect relative to the transducer can be quite dynamic. Aspect can have profound effects on target-strength (TS) measurements at high frequencies (Love, 1969; Dahl and Mathisen, 1983; Kubecka, 1994; Horne and Clay, 1998). Finally, signal-to-noise ratios are generally low, leading to bias in the estimates of position (Kieser *et al.*, 2000) and TS (Fleischman and Burwen, 2000). As a result, TS measurements can be highly variable for shallow-water applications. Such variability makes it difficult, if not impossible, to discriminate among species using TS alone (e.g. Johnston and Hopelain, 1990; Lilja *et al.*, 2000).

Our particular application uses side-looking, fixed-location sonar to assess chinook salmon *Oncorhynchus tshawytscha* returns to the Kenai River in south-central Alaska. Sonar estimates of abundance provide the basis for estimating spawning escapement and regulating harvest in competing sport and commercial fisheries for these fish. Hydroacoustic assessment of chinook salmon in the Kenai River is complicated by the presence of sockeye salmon *Oncorhynchus nerka*, which migrate concurrently. Sockeye salmon are generally smaller than chinook salmon (Figure 1), but outnumber them by an order of magnitude in most years. The two species are spatially segregated to the extent that most sockeye salmon swim near shore and most chinook near mid-channel. Our acoustic beam coverage is focused on the bottom-middle section of the river where the relative abundance of chinook salmon is highest (Figure 2). However, netting studies have shown that both species are found, in varying proportions, in the ensonified zone (Burwen *et al.*, 1998).

Experiments with tethered and free-swimming fish in the mid-1990s uncovered echo-envelope length ("pulse width") as a potential species discriminator, far better than TS for our 200 kHz side-looking application (Burwen and Fleischman, 1998). These findings are now confirmed and expanded upon with results from additional tethered-fish experiments, and by comparison with gill-netted samples of

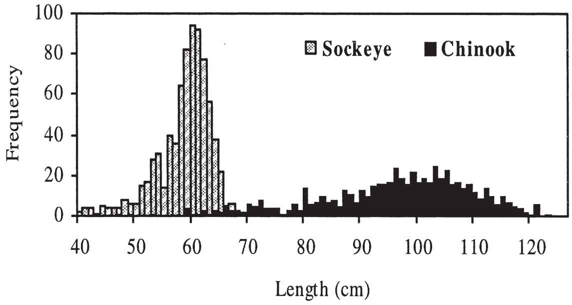

Figure 1. Typical length-frequency distributions for Kenai River chinook and sockeye salmon.

free-swimming fish. Two other hydroacoustic variables are identified, range-measurement variability and fish lateral movement (LM), which have potential as size/species discriminators. All of these variables rely primarily on characterization of the acoustic signal through time.

Methods

All experiments were conducted at river kilometer 14 of the Kenai River. The site is within tidal influence and water depth at mid-channel varies from 3 to 8 m (Figure 2). The river is approximately 100 m wide at this location and the bottom substrate varies from silty mud to medium gravel. Water temperatures ranged from 10 to 15°C during the study. Further details can be found in Miller and Burwen (2002).

Fish were tethered 19 June to 10 August 1995, 12–30 July 1998, and 4 June to 8 August 2001. Live chinook and sockeye salmon were captured with gillnets and held in live pens or totes until they could be deployed (Figure 3). A cable tie was inserted through a small hole punched in the lower jaw. The cable tie was then attached to approximately 10 m of dacron fishing line, which led to two 1.4-kg downrigger weights. Another section of dacron line (approximately 6 m in length) led from the weights to a buoy on the surface. The buoy, in turn, was attached with polypropylene line to an anchor upstream. Using this technique we were able to isolate the fish from other scattering surfaces, i.e., the lead weights, buoy, etc. The fish were tethered at approximately side aspect to the hydroacoustic beam 8–37 m from the transducer that was aimed perpendicularly to the river current. More than 90% of the salmon appeared to survive the tethering experience.

Hydroacoustic data were collected with a Hydroacoustics Technology (HTI), Inc. Model 244 split-beam echosounder operating at 200 kHz and a 2.9 by 10° elliptical-beam transducer with a near-field range of 3.1 m. The transmitted pulse length was 0.2 ms while the pulse repetition rate was $8\ s^{-1}$ in 1995, $1.5\ s^{-1}$ in 1998, and $3\ s^{-1}$ in 2001. The sound speed was assumed constant at $1500\ m\ s^{-1}$: any likely deviation would have negligible effect on the results. Data were recorded on 350–9319 echoes per fish, averaging 2397 in 1995, 702 in 1998, and 1419 in 2001. Background noise, as measured by the maximum detected peak amplitude at the range of the target, was equivalent to a −50 to −36 dB target on axis.

The system was calibrated before each field season. Reciprocity calibrations with a naval standard transducer were performed, and the calibration results verified using a 38.1 mm tungsten-carbide sphere (−39.5 dB in freshwater at 200 kHz; MacLennan and Simmonds, 1992). Further verification was obtained *in situ* by measuring the same standard sphere at the Kenai River study site.

Voltage thresholds were applied as follows. In 1995, echoes were rejected if they did not exceed a minimum voltage criterion that was equivalent to a −35 dB target on axis. In 1998 and 2001, data were acquired at voltage

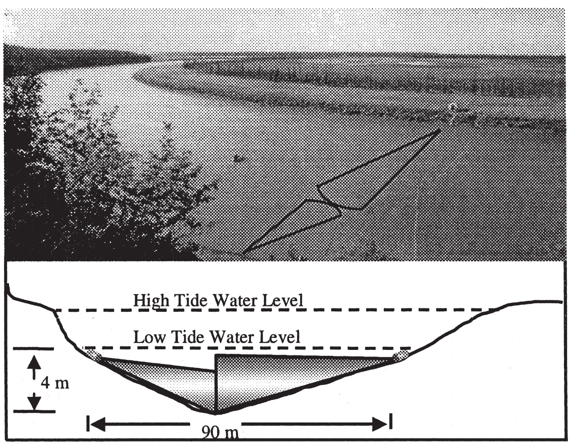

Figure 2. Aerial and cross-sectional views of the sonar site at river kilometer 14 on the Kenai River.

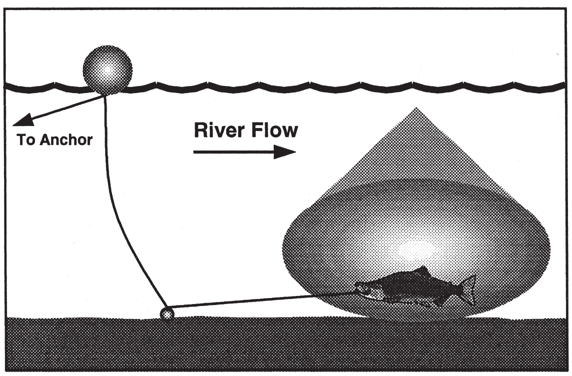

Figure 3. The configuration used to tether fish in the Kenai River, 1995, 1998, and 2001.

thresholds between −35 and −40 dB; echoes less than −35 dB were omitted during post-processing.

Potential echoes were also filtered for echo-length criteria, measured in digital samples (48 kHz) at the half-power (−6 dB) point or higher. The amplitude at which −6 dB echo length ($EL6_j$) was measured for echo j depended on the signal-to-threshold ratio, $STR_j = 20 \log(e_j/e_T)$, where e_j was the peak amplitude of echo j and e_T the minimum voltage threshold. If STR_j exceeded 6 dB, $EL6_j$ was measured at 6 dB below peak amplitude. If $STR_j <$ 6 dB, $EL6_j$ was measured at the threshold. In 1995, echoes with length between 7 and 14 sample units (0.15–0.29 ms), were retained for analysis. In 1998 and 2001, the acquisition criteria were liberalized to 5–19 sampling units (0.10–0.40 ms), or relaxed altogether. Echoes not meeting the 1995 criteria were omitted during post-processing. Echo data were logged and manually grouped into fish traces using HTI proprietary software. Post-processing was done with SAS®.

Hydroacoustic variables mean echo length (ELMN), echo-length standard deviation (ELSD), range jitter (RJ), LM, and TS were calculated for each fish as follows. ELMN was the average of $EL12_j$ across all echoes j, where $EL12_j$ was the length of echo j measured in 48 kHz sample units at −12 dB or higher. If STR_j exceeded 12 dB, $EL12_j$ was measured at 12 dB below peak amplitude. If 6 dB < STR_j < 12 db, $EL12_j$ was measured at the threshold. If STR_j < 6 dB, $EL12_j$ was not defined. ELSD was the standard deviation of $EL12_j$ across all echoes for which $EL12_j$ was defined. Range-measurement error and fish LM were indexed by first applying a local-regression (LOESS) smoother (Cleveland, 1993) to the range data over time. RJ was estimated as the standard deviation of the differences (m) between the observed range measurements and the fitted values from the LOESS smoother. LM was estimated as the median, absolute, echo-to-echo change ($m\,s^{-1}$) in the smoothed values of range. TS was calculated as $10 \log(\overline{\sigma}/4\pi)$, where $\overline{\sigma}$ is the average spherical-scattering cross-section over all echoes. ELMN and ELSD are equivalent to PW12 and SD12 of Burwen and Fleischman (1998).

Gillnets (7.5-in. stretched mesh) were drifted daily in mid-channel immediately downstream of the sonar site in 2001. The daily proportion of the netting catch comprising chinook salmon was used as an index—*not* an unbiased estimate—of relative chinook-salmon abundance, for comparison with the hydroacoustic data. We used Spearman's rank correlation coefficient (Conover, 1980) to quantify the association of sonar measurements with the species composition of the net catches.

Linear statistical models were used to estimate the relationships between individual hydroacoustic variables and fish length, controlling for species, and incorporating information from all three experiments (1995, 1998, and 2001) simultaneously. The full model was defined as follows (notation from Neter *et al.*, 1985):

$$y_{ijk} = \mu + \alpha_i + \gamma_j + \alpha\gamma_{ij} + \beta x_{ijk} + \alpha\beta_i x_{ijk} + \gamma\beta_j x_{ijk} + \alpha\gamma\beta_{ij} x_{ijk} + \varepsilon_{ijk} \quad (1)$$

where y_{ijk} and x_{ijk} are the values of the hydroacoustic variable and fish length, respectively, for experiment i, species j, and fish k; μ and β are the overall mean and slope; α_i is the effect of experiment i; γ_j is the effect of species j; $\alpha\gamma_{ij}$ is the interaction effect between experiment i and species j; $\alpha\beta_i$ is the effect of experiment i on the slope; $\gamma\beta_j$ is the effect of species j on the slope; $\alpha\gamma\beta_{ij}$ is the interactive effect of experiment i and species j on the slope; and ε_{ijk} is an independent and identical, normally distributed error term with mean 0 and variance σ^2. This is equivalent to estimating six unique intercepts $\{\beta_{0ij}\}$ and slopes $\{\beta_{1ij}\}$ for each combination of experiment (1995, 1998, and 2001) and species (chinook and sockeye):

$$y_{ijk} = \beta_{0ij} + \beta_{1ij} x_{ijk} + \varepsilon_{ijk} \quad (2)$$

where $\beta_{0ij} = \mu + \alpha_i + \gamma_j + \alpha\gamma_{ij}$ and $\beta_{1ij} = \beta + \alpha\beta_i + \gamma\beta_j + \alpha\gamma\beta_{ij}$.

Since there were unequal sample sizes among experiments and species, hypothesis tests were conducted using a multiple-regression approach, with indicator variables for experiment and species (Neter *et al.*, 1985: Section 10.2). Testing proceeded from high to low order, i.e. the first test was for the presence of any "three-way interactions" (H_0: all $\{\alpha\gamma\beta_{ij}\} = 0$), then for any two-way interactions (H_1: all $\{\gamma\beta\} = 0$, H_2: all $\{\alpha\beta\} = 0$, and H_3: all $\{\alpha\gamma\} = 0$). Finally, the main effects were tested (H_5: all $\{\alpha_i\} = 0$, H_6: both $\{\gamma_j\} = 0$, and H_7: $\beta = 0$). For each test, if the null hypothesis was not rejected (F-test, $p = 0.05$), then that factor was dropped from the model unless a higher order interaction involving that factor was present. The model was re-estimated each time an effect was dropped and the cascade of hypothesis tests begun again. All tests were conducted conditional on all equal- and lower-level effects being present in the model.

Results

The following hydroacoustic variables were considered as potential predictors of fish size and discriminators of species: ELMN, ELSD, RJ, LM, and TS. Note that 1995 measurements of ELMN and ELSD were reported previously as PW12 and SD12 by Burwen and Fleischman (1998). RJ and LM are new. RJ is related to how difficult it is to determine the exact range of a fish and LM to how rapidly a fish changes range. Because ELMN, ELSD, RJ, and LM are all measurements of time (or its surrogate "range"), they are referred to collectively as time-based measurements.

All five variables were related to tethered-fish size or species or both (Table 1 and Figure 4). Controlling for experiment or species or both, ELMN, ELSD, RJ, and TS were positively related to tethered-fish length

Table 1. The parameters of regression relationships between five hydroacoustic variables and fish mid-eye-to-fork length (cm) from chinook and sockeye salmon tethered in front of a 200 kHz side-looking sonar on the Kenai River, Alaska, 1995–2001. Standard errors in parentheses. Where intercepts (b_0) did not differ ($p > 0.05$) among experiments or species, a common intercept was estimated. Slopes (b_1) did not differ among experiments or species. The slope of LM versus fish length was not significantly different from zero within species, hence it was dropped from the model and the intercepts b_0 represent least-square means for LM by species. RMSE is the square root of the mean-squared error of the linear model (see text). The coefficient of determination r^2 applies to a simple linear regression of each variable on fish length, ignoring experiment and species.

Experiment	n	Parameter	ELMN (48 kHz su)	ELSD (48 kHz su)	RJ (m)	LM ($m\,s^{-1}$)	TS (dB)
1995	48	Chinook b_0	9.9 (0.21)	0.34 (0.25)	−0.018 (0.004)	0.099 (0.005)	−30.6 (1.2)
	38	Sockeye b_0	9.9 (0.21)	0.01 (0.17)	−0.018 (0.004)	0.057 (0.006)	−28.6 (0.8)
1998	21	Chinook b_0	10.7 (0.24)	0.68 (0.27)	−0.009 (0.004)	0.099 (0.005)	−28.9 (1.3)
	15	Sockeye b_0	10.7 (0.24)	0.35 (0.19)	−0.009 (0.004)	0.057 (0.006)	−26.9 (1.0)
2001	13	Chinook b_0	10.3 (0.26)	0.44 (0.27)	−0.020 (0.005)	0.099 (0.005)	−31.3 (1.3)
	6	Sockeye b_0	10.3 (0.26)	0.11 (0.20)	−0.020 (0.005)	0.057 (0.006)	−29.3 (1.0)
All	141	b_1	0.042 (0.003)	0.032 (0.003)	0.00071 (0.00005)	0	0.091 (0.014)
		RMSE	0.63	0.43	0.012	0.044	2.13
		r^2	0.61	0.75	0.59	0.12	0.21

($4.2 \le t \le 15.4$; $p < 0.0001$). Echoes from large salmon tended to be longer and more variable in length than echoes from small salmon, and large salmon tended to have greater variability in range measurements and greater TS. LM differed between species but was not related to fish length within species ($p = 0.79$). Chinook salmon had more extreme lateral swimming movements than sockeye salmon. Ignoring experiment and species, the relationship between the hydroacoustic measurement and tethered-fish length was far more precise for ELMN ($r^2 = 0.61$), ELSD ($r^2 = 0.75$), and RJ ($r^2 = 0.59$) than for LM ($r^2 = 0.12$) and TS ($r^2 = 0.21$).

Intercepts differed among experiments for all variables except LM. In all of these cases (ELMN, ELSD, RJ, and TS) the 1998 experiment produced the highest measurements. Slopes did not differ among experiments or species.

Intercepts differed between species for ELSD, LM, and TS. Chinook salmon had greater ELSD than sockeye salmon of the same size; i.e. ELSD was 0.33 (SE = 0.11) units higher. LM was 0.04 (SE = 0.01) $m\,s^{-1}$ faster for chinook than for sockeye. Conversely, chinook had 2.0 dB (SE = 0.6) lower TS than sockeye of the same size.

Measurements of all four time-based hydroacoustic variables were consistent with gill-net catches near the sonar site (Figure 5). When the catches were composed primarily of chinook salmon, time-based measurements of free-swimming fish passing the sonar site tended to be large. When sockeye salmon dominated, measurements tended to be small. Daily medians of time-based measurements were positively rank-correlated with the daily proportion of chinook salmon in the gill-net catch (Spearman's ρ 0.51–0.66, Figure 5).

Discussion

As a species discriminator for side-looking applications as described in this article, TS performs marginally at best. Among fish of the same size and species, TS varied as much as 10 dB (Figure 4). Though TS was significantly related to fish size within species, chinook salmon had 2 dB lower TS than sockeye salmon of the same size (Table 1). Thus the individual fish with the highest TS was a sockeye salmon (Figure 4). The relationship of TS with length was far weaker ($r^2 = 0.21$) than that of all the time-based variables ($0.59 < r^2 < 0.75$) except LM ($r^2 = 0.12$; Table 1). Finally, TS was a poor index of the species composition of unrestrained fish passing the sonar site (Spearman's $\rho = 0.12$, Figure 5).

Time-based measurements appear to be good indices of fish size or species or both for some of the same reasons that TS is not. For this side-looking application with narrow beams and short ranges, fish are large relative to the beam and present themselves at various oblique aspect angles to the transducer. The returned echo is a composite from multiple parts of the fish body. Consequently, measurements of peak amplitude and thus TS are highly variable. On the other hand, the duration of the echo from a large complex target is apparently quite sensitive to the size of that target, perhaps because the fish returns a signal provided the incident sound beam intersects any part of the swim bladder (Burwen and Fleischman, 1998: Figure 7). Under this model, echo length, like TS, would be sensitive to fish orientation. However, previous experiments have shown that the effect of aspect on ELMN is non-monotonic and therefore less severe than its effect on TS (Burwen and Fleischman, 1998: Figs. 4 and 5).

Large targets oriented at oblique angles return echoes with complex envelopes including occasional double peaks. The digital echo processor can interpret these as separate echoes, at least one of which may be quite short in duration. The combination of these occasional short echoes with the more common longer echoes is characteristic of large fish, thus ELSD is an especially good predictor of fish size. It is hypothesized that the utility of RJ as a size predictor may be

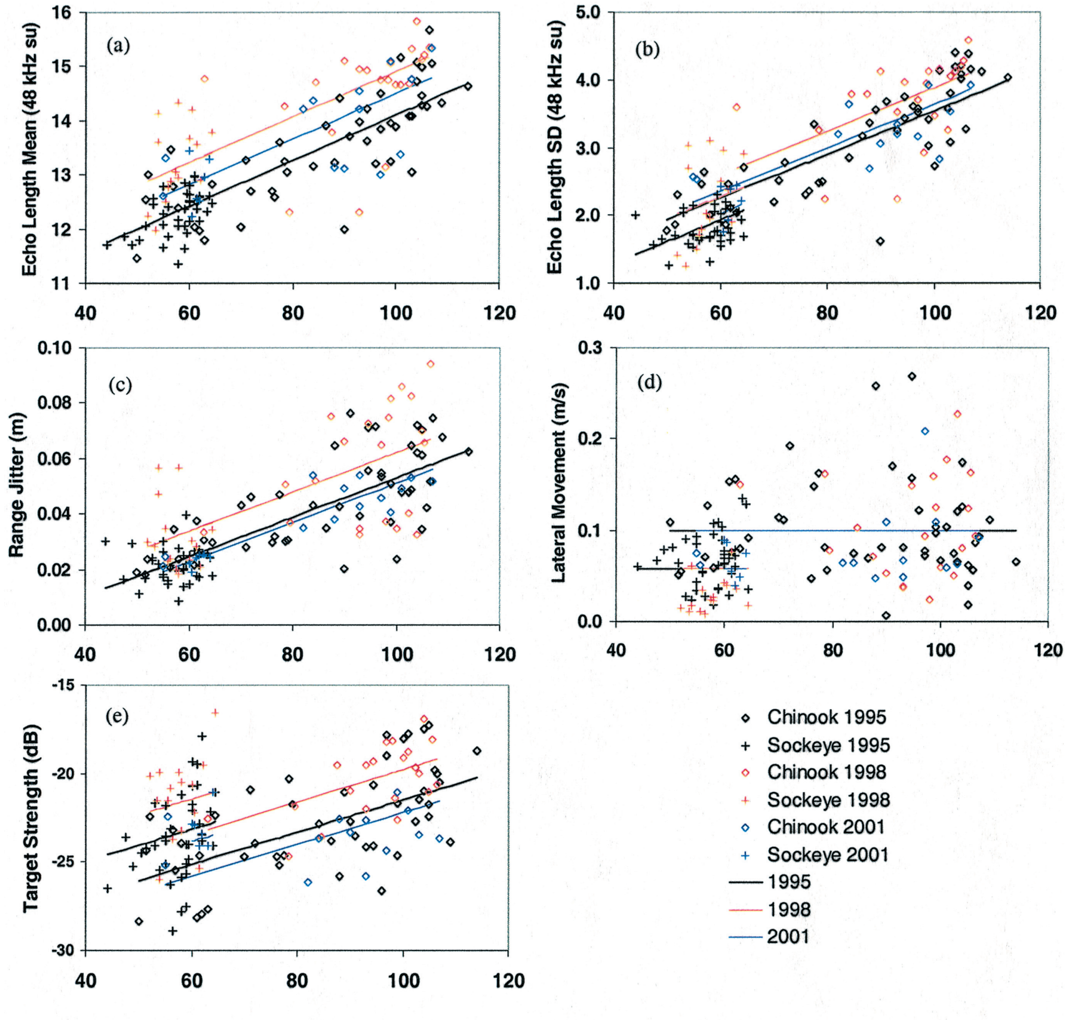

Figure 4. (a) ELMN, (b) ELSD, (c) RJ, (d) LM, and TS versus length of chinook (diamonds) and sockeye salmon (plus symbols) tethered in front of a 200 kHz sonar in the Kenai River, Alaska. Units for (a) and (b) are 48 kHz sample units. Black = 1995, red = 1998, blue = 2001 experiment. The parallel regression lines shown when intercepts differed by year or by species. There was no effect of length or experiment on LM, hence the separate flat lines for each species. See Table 1 for regression parameter estimates.

related to the same phenomenon, i.e. long and complex echo envelopes lead to variability in the location of the peak amplitude, which leads to more range "jitter" for large fish.

LM differed between species, which may reflect an underlying difference in behavior between chinook and sockeye salmon. LM was a good index of species composition of unrestrained fish (Figure 5), and was the only variable that did not appear subject to change between experiments (Figure 4). It was also expected that there would be an effect of fish size on LM as a result of simple allometry. That is, as the dimensions of a fish increase so should all the vectors of its movements. Tethered fish did not show this effect within species, possibly because the act of tethering affects behavior.

Thus, for this side-looking application, time-based characters are superior predictors of fish size because they capitalize on, or are robust to, some of the very factors that compromise amplitude-based measurements such as point-source violations and variable side aspects. They may also index important behavioral differences between species. It is worth noting that virtually all of the time-based information that was found useful is contained in a simple echogram, given sufficient resolution (Figure 6). Precise time measurement is a characteristic of echosounders in general. Thus, if one did not need the location information provided by split-beam sonar, single-beam sonar would provide almost equally useful information for species discrimination.

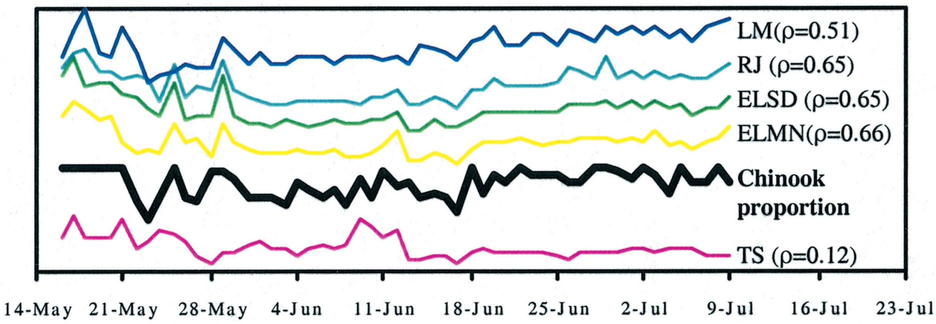

Figure 5. The time series of median hydroacoustic measurements from fish migrating past the chinook salmon sonar site on the Kenai River, 2001. ELMN (yellow), ELSD (green), RJ (light blue), and an index of fish LM (dark blue) all track closely the proportion of chinook salmon captured in gillnets nearby (heavy black). TS (magenta) tracks poorly. The vertical-axis scales are various. Spearman rank correlation coefficients (ρ) between each variable and chinook proportion are given in parentheses.

Note that none of the measurements presented here predict fish size precisely. In a companion paper, a statistical technique involving mixture models is demonstrated which extracts maximal information from the frequency distributions of imprecise discriminators such as these (Fleischman and Burwen, 2003).

It is somewhat disturbing that four of the five measures differed significantly among tethered-fish experiments (Table 1, separate intercepts). There is one possible explanation. The 1998 experiment produced the largest and most variable measurements for ELMN, ELSD, RJ, and TS, whereas the 1995 and 2001 data agreed fairly well (Table 1). The 1998 data were collected by an independent sonar system that often operated simultaneously with the regular 200 kHz system used for estimating upstream fish passage. We suspect that the two systems may have interfered with each other. Minimum voltage thresholds also differed among experiments and may have contributed to differences in the hydroacoustic measurements. Voltage thresholds affect how echo length is measured (see Methods). We are currently trying to quantify this effect.

Finally, some limitations of the data and possible directions for future research need to be noted. Most of these findings are derived from tethered-fish experiments. Hydroacoustic observations of unrestrained fish of known size and species are desirable for further confirmation of the results presented here. Also, it is recognized that the current measures of echo-envelope length used in this article may not be optimal. Additional metrics of echo-envelope shape may enhance size prediction and species discrimination.

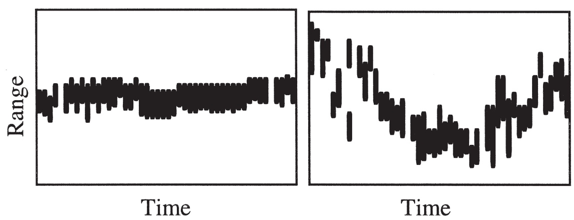

Figure 6. A high-resolution echogram of (left) a tethered 64 cm sockeye salmon, and (right) a tethered 101 cm chinook salmon. The horizontal axis is time, vertical is range from the transducer, each bar represents one echo, and bar length represents echo length. The chinook salmon exhibits longer and more variable echoes, greater RJ, and more LM than the sockeye salmon.

Acknowledgements

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References

Burwen, D. L., and Fleischman, S. J. 1998. Evaluation of side-aspect target strength and pulse width as hydroacoustic discriminators of fish species in rivers. Canadian Journal of Fisheries and Aquatic Sciences, 55: 2492–2502.

Burwen, D. L., Bosch, D. E., and Fleischman, S. J. 1998. Evaluation of Hydroacoustic Assessment Techniques for Chinook Salmon on the Kenai River, 1995. Fishery Data Series No. 98-3. Alaska Department of Fish and Game, Anchorage, AK, USA. http://www.sf.adfg.state.ak.us/statewide/divreports/html/intersearch.cfm

Cleveland, W. 1993. Visualizing Data. AT&T Bell Laboratories.

Conover, W. J. 1980. Practical Nonparametric Statistics. Wiley, New York. 493 pp.

Dahl, P. H., and Mathisen, O. A. 1983. Measurements of fish target strength and associated directivity at high frequencies. Journal of the Acoustical Society of America, 73: 1205–1211.

Dawson, J. J., Wiggins, D., Degan, D., Geiger, H., Hart, D., and Adams, B. 2000. Point-source violations: split-beam tracking of fish at close range. Aquatic Living Resources, 13: 291–295.

Fleischman, S. J., and Burwen, D. L. 2000. Correcting for position-related bias in estimates of the acoustic backscattering cross-section. Aquatic Living Resources, 13: 283–290.

Fleischman, S. J., and Burwen, D. L., 2003. Mixture models for species apportionment of hydroacoustic data, with echo envelope length as the discriminatory variable. ICES Journal of Marine Science, 60: 594–600.

Gerlotto, F., Georgakarakos, S., and Eriksen, P. 2000. The application of multibeam sonar technology for quantitative estimates of fish density in shallow water acoustic surveys. Aquatic Living Resources, 13: 385–393.

Horne, J. K., and Clay, C. S. 1998. Sonar systems and aquatic organisms: matching equipment and model parameters. Canadian Journal of Fisheries and Aquatic Sciences, 55: 1296–1306.

Johnston, S. V., and Hopelain, J. S. 1990. The application of dual-beam target tracking and Doppler-shifted echo processing to assess upstream salmonid migration in the Klamath River, California. Rapports et Proces-Verbaux Reunions du Conseil International pour l'Exploration de la Mer, 189: 210–222.

Kieser, R., Mulligan, T. J., and Ehrenberg, J. E. 2000. Observation and explanation of noise-induced split-beam angle measurement errors. Aquatic Living Resources, 13: 275–281.

Kubecka, J. 1994. Simple model on the relationship between fish acoustical target strength and aspect for high-frequency sonar in shallow waters. Journal of Applied Ichthyology, 10: 75–81.

Lilja, J., Marjomaki, T. J., Riikonen, R., and Jurvelius, J. 2000. Side-aspect target strength of Atlantic salmon (*Salmo salar*), brown trout (*S. trutta*), whitefish (*Coregonus lavaretus*), and pike (*Esox lucius*). Aquatic Living Resources, 13: 355–360.

Love, R. H. 1969. Maximum side-aspect target strength of an individual fish. Journal of the Acoustic Society of America, 46: 746–752.

MacLennan, D. N., and Simmonds, E. J. 1992. Fisheries Acoustics. Chapman & Hall, London. 325 pp.

Miller, J. D., and Burwen, D. L. (2002) Estimates of Chinook Salmon Abundance in the Kenai River Using Split-Beam Sonar, 2000 Fishery Data Series No. 02-09. Alaska Department of Fish and Game, Anchorage, AK, http://www.sf.adfg.state.ak.us/statewide/divreports/html/intersearch.cfm.

Mulligan, T. J. 2000. Shallow water fisheries sonar: a personal view. Aquatic Living Resources, 13: 269–273.

Neter, J., Wasserman, W., and Kutner, M. H. 1985. Applied Linear Statistical Models, 2nd edition. Richard D. Irwin, Homewood, IL. 1127 pp.