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# THE DUAL-BEAM SYSTEM -- A TECHNIQUE FOR MAKING *IN SITU* MEASUREMENTS OF THE TARGET STRENGTH OF FISH

by

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## INTRODUCTION

In recent years, many studies have been conducted to determine the acoustic target strength of fish. These efforts have been motivated by the extensive use of acoustic techniques to obtain fish abundance estimates. The two common acoustic techniques, echo integration and echo counting, depend on the target strength distribution of the fish being surveyed. The output of an echo integrator is proportional to the average scattering cross section (per fish or per unit biomass).* The sampling volume for an echo counting system is a function of the acoustic transducer's beam pattern and the target strength distribution of the fish.

A number of researchers have measured the target strength of fish whose size is known.[1-3] The results from these controlled experiments are then used to obtain regression relationships relating target strength, fish length and acoustic frequency. The use of these regression relationships requires a knowledge of the length distribution of the fish being surveyed and some assumptions about the vertical tilt of the fish. Nakken and Olsen[2] have shown that the target strength of a fish can change significantly with small changes in the tilt of the fish. For example, they have shown that the target strength of herring averaged over a 6° angle of illumination is 6 dB less than the target strength for the maximum dorsal-aspect.

An alternate method for obtaining target strength information for a particular population is to make *in situ* measurements of individual fish during the acoustic survey. Craig and Forbes[4] and Ehrenberg[5] proposed procedures for extracting the beam pattern effect from the single fish echo level distribution to obtain the target strength distribution. These techniques can be applied to the data collected with the basic acoustic system used for either echo counting or echo integration.

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*The scattering cross section, $\sigma$, and target strength, TS, are related by $TS = 10 \log_{10} (\sigma/4\pi)$.

However, the methods are subject to statistical errors and do not work well for many distributions of interest. Dunn[6] and Ehrenberg[7,8] later proposed methods for directly measuring the target strength by extracting the beam pattern effect from single fish echoes. The disadvantage of these methods is that they require a more complex system of acoustic assessment. The University of Washington, in conjunction with the Northwest Center of the National Marine Fisheries Service (NMFS), implemented the dual-beam target strength measurement system originally proposed by Ehrenberg. Dual-beam systems operating at 38 kHz, 105 kHz, and 120 kHz have been built and tested. Mr. J. Traynor of NMFS has reported on some of the field applications of their 38-kHz dual-beam system.[9] Most of the work at 105 kHz has been done by Mr. A. Drew, a Ph.D. student in the College of Fisheries at the University of Washington.

In addition to the field tests of the dual-beam system, there have been extensive simulation studies and analyses of the system to evaluate and optimize its performance. This paper primarily deals with the results of some of these studies. In particular, the effect of noise on the performance of the system is considered. Some previously unpublished target strength field data obtained with the system are also presented.

## The Dual-Beam System

A brief description of the dual-beam target strength measurement system is given before the effects of noise on the system are discussed. The main element in the dual-beam system is a transducer that has both a narrow and a wide beam. The actual beam patterns for the 105-kHz dual-beam transducer are shown in Figure 1. The acoustic pulse is transmitted using the narrow beam and the scattered signal is received simultaneously on the narrow and wide beams. The first step in obtaining an estimate of the acoustic scattering cross section of individual fish is to isolate echoes from individual fish. The method developed for isolating individual fish echoes is discussed in Appendix A. If a single fish with a scattering cross section $\sigma_i$ is located at angular coordinates of

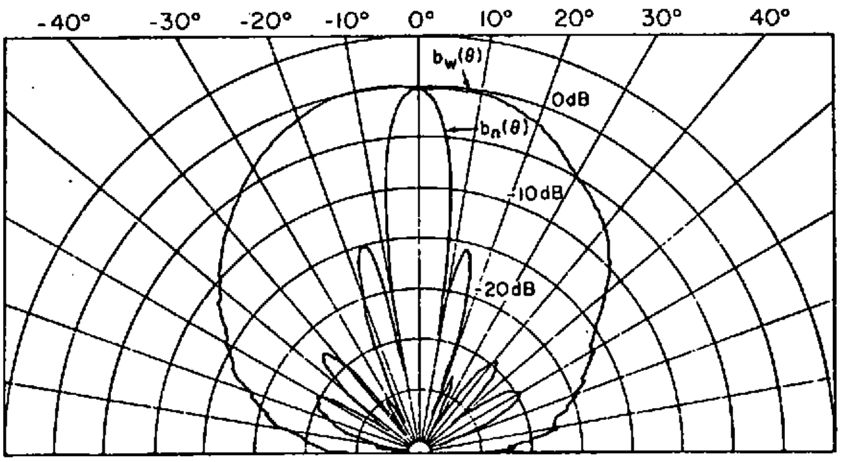


*Figure 1. Beam patterns for the 105-kHz dual-beam transducer*

$\theta_i$ and $\phi_i$ with respect to the transducer axis, and if noise is disregarded, the squared signal levels from the narrow and wide beam receivers are

$$E_N^2 = k_1 \frac{10^{-2\alpha R}}{R^4} b_N^2(\theta_i,\phi_i)\, \sigma_i$$

and

$$E_W^2 = k_2 \frac{10^{-2\alpha R}}{R^4} b_W(\theta_i,\phi_i)\; b_N(\theta_i,\phi_i)\, \sigma_i \ ,$$

where $b_N(\theta_i,\phi_i)$ and $b_W(\theta_i,\phi_i)$ are the narrow and wide beam pattern factors, respectively, $k_1$ and $k_2$ are constants, and $10^{-2\alpha R}/R^4$ is the loss due to spreading and absorption. The gains in the narrow and wide beam channels are adjusted during system calibration so that $k_1 = k_2$. The propagation losses are removed by a time-varied gain (TVG) amplifier. Only fish that are located within the main lobe of the narrow beam have sufficiently high echo intensities to be detected as single fish targets. The wide beam pattern factor, $b_W(\theta,\phi)$ is designed to be approximately unity over the main lobe of the narrow beam. Therefore the squared detected signals from the narrow and wide beam receiving channels for a detected single fish are

$$E_N^2 = k\, b_N^2(\theta_i,\phi_i)\, \sigma_i$$

and

$$E_W^2 = k\, b_N(\theta_i,\phi_i)\, \sigma_i \ .$$

The beam pattern factor and scattering cross section for the detected single fish echo can be determined as follows:

$$\hat{b}_N(\theta_i,\phi_i) = \frac{E_N^2}{E_W^2}$$

and

$$\sigma_i = \frac{E_W^2}{k\,\hat{b}_N(\theta_i,\phi_i)} = \frac{E_W^4}{k\,E_N^2} .$$

The average scattering cross section, $\overline{\sigma_N}$, is obtained by averaging $\sigma_i$ for N individual fish targets. That is

$$\overline{\sigma_N} = \frac{1}{N}\sum_{i=1}^{N} \sigma_i .$$

The above analysis assumes that the signal from the transducer contains no noise.

In reality, the received signal does contain noise, which places a limit on the minimum signal that can be reasonably processed. To avoid processing very noisy echoes and to minimize the probability of accepting noise as a valid echo signal, all signals below a given threshold are set equal to zero. For the dual-beam systems developed at the University of Washington and the Northwest Center of the National Marine Fisheries Service, the threshold is implemented in the computer portion of the processing. The threshold level for both the narrow and wide beam channel is usually set at about twice the detected rms noise level. While these thresholds remove some of the adverse effects of the noise, they also introduce a bias against small fish targets since the echoes from small targets are less likely to exceed the thresholds than are echoes from larger targets. The discrimination against small targets is greatest when the targets are near the edge of the beam where the beam pattern factor is the smallest. It follows that the bias can be reduced by processing only those echoes that originate from fish near the acoustic axis of the transducers. This is done by comparing the beam pattern estimate of each detected single target with a beam pattern threshold, $t_b$. If the beam pattern estimate exceeds the threshold, the target is used. The price one pays for this beam pattern threshold is a reduction in the number of fish echoes processed and a subsequent increase in the variance of the average scattering cross section estimate $\overline{\sigma_N}$.

An extensive analysis and simulation study of the effects of noise on the dual-beam method has been conducted. The details of the analysis are contained in a master's thesis and a report.[10,11] The discussion here deals mostly with some of the results of the study.

One of the effects of noise on the dual-beam system is that noise introduces variability into the target strength estimates. This effect was studied using a Monto Carlo simulation. The simulation was done by generating the narrow and wide beam detector outputs for a received signal plus Gaussian noise. The levels of the squared signals for the narrow and wide beam, respectively, were

$$A_N^2 = b_N^2(\theta,\phi)\,\sigma$$

and

$$A_W^2 = b_N(\theta,\phi)\,\sigma \ ,$$

where $\sigma$ was a fixed scattering cross section variable, and $b_N(\theta,\phi)$ was a random beam pattern factor variable. The distribution of $b_N(\theta,\phi)$ was chosen to correspond to a circular transducer and uniformly distributed fish within the beam. The simulations were done for various ratios of signal level (for an on-axis target) to noise level into the detector. The results of some of these simulations are shown in Figure 2. The figure shows that there is considerable spread in the target strength distribution when the signal-to-noise ratio of an on-axis target is 15 dB or less.

Some experimental measurements of the effects of noise on the estimated target strength of a ping-pong ball were made using the National Marine Fisheries Service's 38-kHz dual-beam system. A detailed description of the system used and the measurement procedure is given in a

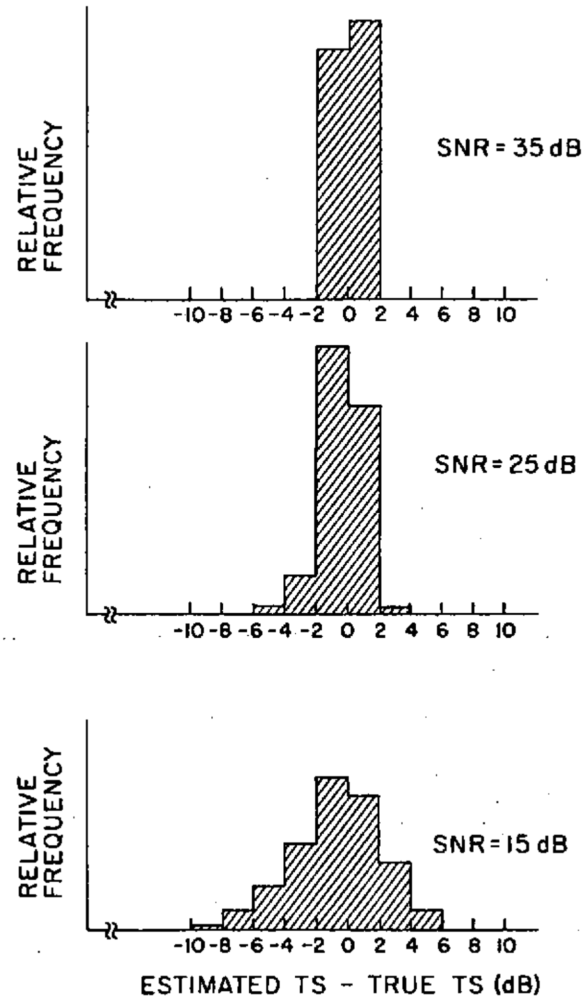


*Figure 2. Results of the simulation of the effects of noise on the dual-beam system. The results shown are for a fixed scattering cross section and equal on-axis signal-to-noise ratios (SNR) for the narrow and wide beam. The beam pattern threshold was set at -2 dB.*

recent paper by Traynor and Ehrenberg.[12] The measured and predicted normalized standard deviation in the scattering cross section of the ping-pong ball as a function of beam pattern threshold are shown in Figure 3. The slightly higher values for the measured normalized standard deviation are probably due to some variations in ping-pong ball target strength with aspect angle.

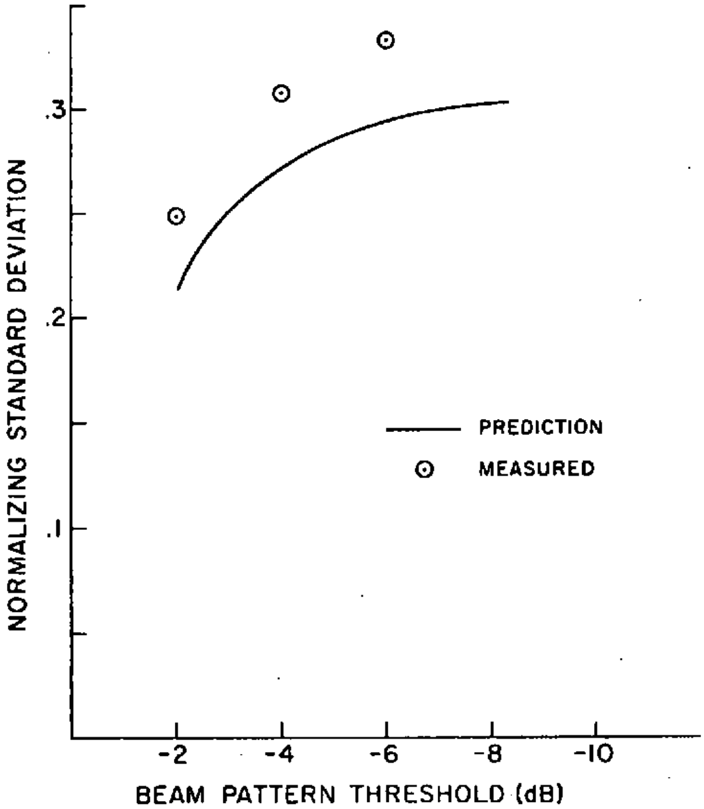


*Figure 3. Comparison of the predicted and measured normalized standard deviation of the target strength of a ping-pong ball. Measured values were obtained from 4000 individual measurements. The on-axis signal-to-noise ratio was 24 dB.*

The beam pattern threshold, $t_b$, affects both the bias and the variance in the scattering cross section estimate. Therefore, one part of the analysis and simulation study was to determine the value of beam pattern threshold which produced the minimum mean squared error (bias squared plus variance) in $\overline{\sigma_N}$. For this portion of the study, it was assumed that the fish had target strengths that were Gaussian-distributed (in decibels). A typical plot of the normalized rms error as a function of beam pattern threshold is shown in Figure 4. The assumed target strength standard deviation was 4.5 dB and the on-axis signal-to-noise ratio was 27 dB. These simulation parameters matched the measurement conditions of some field data reported later in this paper.

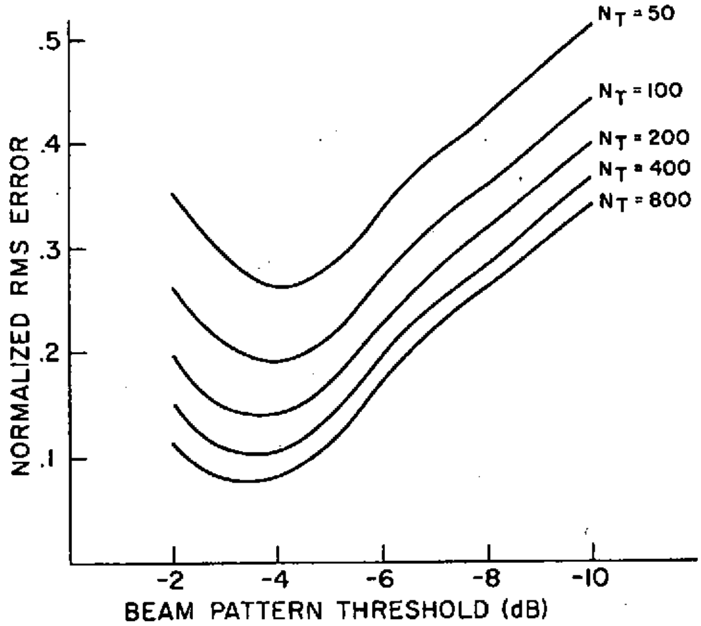


*Figure 4. Normalized rms error in the estimated mean scattering cross section as a function of beam pattern threshold. $N_T$ is the number of targets with a beam pattern factor estimate greater than -15 dB.*

The simulation studies showed that a beam pattern threshold between -2 dB and -4 dB was optimum in most cases. It was also found that, while noise can introduce considerable spread in the estimated target strength histogram (Figure 2), the total rms error in the estimated mean scattering cross section, $\overline{\sigma_N}$, can be made small by the proper choice of $t_b$.

## Field Measurements

The dual-beam system's hardware and software have undergone a number of modifications in the past few years, and consequently field data are not as plentiful as we would like. We believe the system is now in its final form, and a large amount of good field data should be collected in the next few years. The two sets of field results now described represent that potential.

The target strength histograms shown in Figure 5 were obtained using the dual-beam system at the south end of Lake Washington (near Seattle) during two days in July 1976.* During this time, the adult salmon in the lake were migrating to the southern end of the lake, preparing to return up the Cedar River and spawn. Juvenile salmon were also present in the lake. The increase in the relative population of the larger adult salmon toward the end of July is clearly demonstrated in the figure.

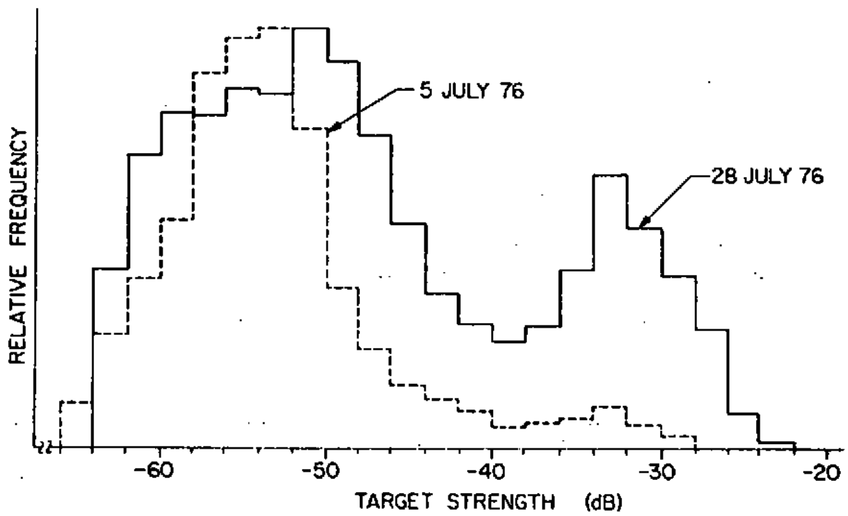


*Figure 5. Target strength histogram obtained with dual-beam system for Lake Washington salmon.*

The second example is some field data collected by Mr. J. Traynor of the National Marine Fisheries Service.[12] These data were collected in the Bering Sea in February 1978. Target strength measurements of 637 individual fish targets were made with the dual-beam system. Using a pelagic trawl, the fish were identified as walleye pollock (*Theragra chalchogramma*) with a mean length of 33.6 cm and a mean weight of 0.27 kg. The results of the target strength measurements for various beam pattern thresholds are shown in Figure 6. The predicted target strength as a function of beam pattern threshold was obtained assuming that the target strength of the fish was Gaussian distributed. The mean

*This data was collected by Mr. A. Drew, a Ph.D student in the College of Fisheries at the University of Washington.

of the target strength distribution was set at -38.5 dB/fish (the value corresponding to the minimum rms error $t_b$ setting) and the standard deviation was 4.5 dB. This choice for target strength standard deviation produced the best agreement between the measured and simulated estimated target strength standard deviation. The estimated mean target strength (for $t_b$ = -4 dB) of -38.5 dB/fish or -32.8 dB/kg agrees well with the "best estimate" for 30-cm cod and 30-cm saithe of -33.5 dB/kg and -33.0 dB/kg, respectively, suggested in a recent meeting of an FAO working party on fish target strength.[13]

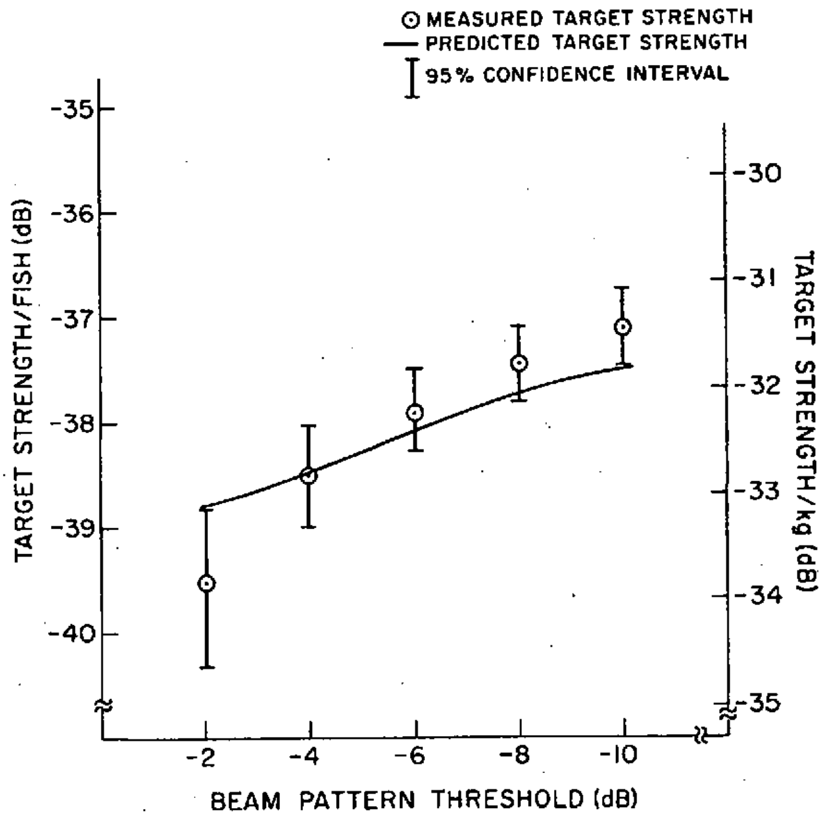


*Figure 6. Dual-beam target strength values for walleye pollock. The predicted curve is based on a signal-to-noise ratio of 27 dB.*

## CONCLUSIONS

The experience we have obtained with the dual-beam system has shown that it is a very useful technique for making *in situ* measurements of the acoustic target strength of individual free-swimming fish. Simulations, analysis and field tests have shown that the noise present at the output of the echo sounder introduces additional variability in the estimated target strength distribution. However, with the proper choice of system parameters, the technique provides a good estimate of the mean scattering cross section, or mean target strength.

The pulse width criterion presently used for isolating single fish echoes works well for low and moderate fish densities. A more complex method for isolating single fish echoes should probably be employed when the technique is to be used in high fish densities.

## ACKNOWLEDGMENTS

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