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THE POTENTIAL OF THE SECTOR-SCANNING SONAR FOR IN SITU MEASUREMENT OF FISH TARGET STRENGTHS

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1. INTRODUCTION

In recent years, a great deal of effort has gone into studies to determine the target strength of individual acoustic scatterers. The scatterers of interest in nearly all these studies have been fish. This interest has been motivated by the extensive use of acoustical techniques to monitor and quantify fish stocks for management purposes. The two common acoustic assessment techniques, echo counting and echo integration, depend on the target-strength distribution of the fish being surveyed.[1]

One method of obtaining target-strength information for a particular population is to make in situ measurements of the individual fish during the acoustic survey. Various in situ target-strength measurement techniques have been proposed.[1-5] One of the main limitations of the systems used to date is that they do not have sufficient resolution for use in moderate or high scattering densities. It is possible to increase the resolution by decreasing the beamwidth of the acoustic transducer. However, this also reduces the volume being sampled and thereby reduces the number of targets processed. An alternative to the simple systems previously used for in situ measurements is the sector-scanning sonar. The sector scanner can provide both good resolution and good volume coverage. This paper deals with the potential uses of a sector-scanning sonar for target-strength measurements.

In the sector-scanning system, a whole sector is ensonified by a pulse transmitted from a widebeam transducer. A narrow receiving beam is electronically swept across the sector within the time required for a pulse to travel its own length in the water. The received signal is then envelope detected. In most applications, the detected signal is displayed on a CRT which presents received intensity as a function of bearing and range. However, for quantitative measurements, it is best to process the detected signal directly. The intensity of the detected output for a single scatterer with scattering cross section σ_i is

$$I_i = K \frac{e^{-2\alpha R_i}}{R_i^4} b_T(\theta_i, \phi_i)\, b_R(\theta_i, \phi_i)\, \sigma_i , \tag{1}$$

where K is a constant that depends on transmitted source level, receiving sensitivity, and system gains; $\exp(-2\alpha R_i)/R_i^4$ is the propagation loss due to spreading and absorption for the scatterer at range R_i; and $b_T(\theta_i, \phi_i)$ and $b_R(\theta_i, \phi_i)$ are the transmitting and receiving transducer beam patterns for the target at angular coordinates (θ_i, ϕ_i). The angular location of the target is specified by its angle in the scanned direction, θ_i, and its angle in the off-scanned direction, ϕ_i, rather than by the normally used spherical coordinates.

The propagation loss and the beam pattern terms must be removed from equation 1 to provide an intensity that is proportional only to the scattering cross section, σ_i. The propagation loss is a deterministic function of range (or equivalently time from transmission) and can be removed by a time-varied gain (TVG) amplifier. The beam pattern terms depend on the random angular locations of the individual scatterers and are not so easily removed. Various techniques for dealing with the beam-pattern factors will be considered in the following sections.

2. ECHO LEVEL MEASUREMENTS

The simplest way of dealing with the beam-pattern factors is to ignore their effect and assume that the measured levels of the received signals are directly proportional to the scattering cross section. This was the approach used by Cook and Rushworth in a paper presented in September 1978.[6] The error due to ignoring the beam-pattern effect will, in general, be less for a sector-scanning system than it will be for a conventional single-transducer system. The reason is that in an ideal sector scanner the peak output level for a detected single target is a function of the beam pattern in the off-scanned direction only. In other words, the scanner has a one-dimensional beam pattern whereas a single transducer has a two-dimensional pattern. The beam patterns for targets that occur at the beginning and end of the scan are a function of the angles in both the scanned and off-scanned directions. However, for most scanners, these targets can be excluded from processing without significantly affecting the sampling volume. In practice, there may be some variation in the response of the system in the scanned direction owing to the angular response of the transmitting and/or receiving transducer. In most cases, these variations are a deterministic effect which can be measured and removed from the overall response of the system.

The target-strength error due to the beam-pattern factor also depends on the dynamic range of the system. For a fixed scattering cross section, σ, the dynamic range determines the maximum and minimum echo levels that will be processed.

The following model is used to determine the errors in single-transducer and sector-scanning target-strength-measurement systems that do not remove the beam-pattern factors. The scattering cross section of the target is assumed to be constant. The transmitting and receiving arrays in the sector-scanning system are assumed to consist of rectangular elements and are assumed to have identical beam patterns in the off-scanned direction. These beam patterns are given by

$$b_T(\phi) = b_R(\phi) = \left[\frac{\sin\left(\frac{2\pi L}{\lambda}\sin\phi\right)}{\frac{2\pi L}{\lambda}\sin\phi} \right]^2 , \qquad (2)$$

where L is the length of the element in the off-scanned direction and γ is the acoustic wavelength. The single transducer is assumed to be a piston with diameter d and identical transmitting and receiving beam pattern given by

$$b_T(\psi) = b_R(\psi) = \left[\frac{2J_1\left(\frac{\pi d}{\lambda} \sin \psi\right)}{\frac{\pi d}{\lambda} \sin \psi} \right]^2 , \tag{3}$$

where $J_1(X)$ is a first-order Bessel function and ψ is the angle between the transducer axis and the target. The transducer dimensions, L and d, are chosen to provide a 3-dB beamwidth of approximately 6^o. The results of the analysis do not change significantly with changes in beamwidth. The minimum detected signal has a combined beam pattern factor of

$$b^2_{min} = 10^{-DR/10} , \tag{4}$$

where DR is the dynamic range of the system in decibels. The individual targets are assumed to be distributed uniformly in space. From this assumption, it follows that, for the single-transducer system, the density function for the angular locations of detected single targets is

$$p(\psi) = K \sin \psi \tag{5}$$

for all ψ such that $b^2(\psi) > b^2_{min}$, where K is a constant that ensure $p(\psi)$ integrates to 1. Similarly, for the sector-scanning system,

$$p(\phi) = K_2 \tag{6}$$

for all ϕ such that $b^2(\phi) > b^2_{min}$, where K_2 is a constant that ensures $p(\phi)$ integrates to 1.

The mean error in the target strength measured using the echo levels from the sector scanner is

$$E\left[b^2\right] = \int b^2(\phi)p(\phi)d\phi , \tag{7}$$

where b(o) is given in equation 2 and $p(\phi)$ is given in equation 6. Similarly, the mean error for the piston transducer is given by

$$E\left[b^2\right] = \int b^2(\psi)p(\psi)d\psi , \tag{8}$$

where $b(\psi)$ and $p(\psi)$ are given by equations 3 and 5, respectively. The integrals are evaluated numerically by first finding the angular ranges for which $b^2 > b^2_{min}$ to determine the limits of integration, and then using Simpson's rule. Figure 1 shows the magnitude of the target strength error (in decibels) as a function of the dynamic range of the system (in decibels). The large increase in the sector-scanning error at dynamic ranges greater than 26 dB is due to the detection of individual targets in the first side lobe of the off-scanned beam. A similar effect is observed for the piston transducer at dynamic ranges greater than 35 dB. It should be noted that the target-strength error for the individual scatterers can differ significantly from the mean error. Figure 2 shows the probability that the target-strength error for any individual scatterer will exceed a value of X dB for the sector-scanning system and a single-transducer system with a dynamic range of 30 dB. Although the mean error for a sector-scanning system with a 30-dB dynamic range is less than 6 dB, there is a 25% probability that the error for any individual scatterer will exceed 25 dB.

The errors introduced by ignoring the beam-pattern factors are usually too large to be acceptable for either the sector-scanning systems or the single-transducer systems. For this reason, in most applications of echo-sounding systems for target-strength measurement, an attempt is made to remove the beam-pattern effect from the echo levels. Techniques for removing the beam-pattern factor from the sector-scanner output are discussed in the next sections.

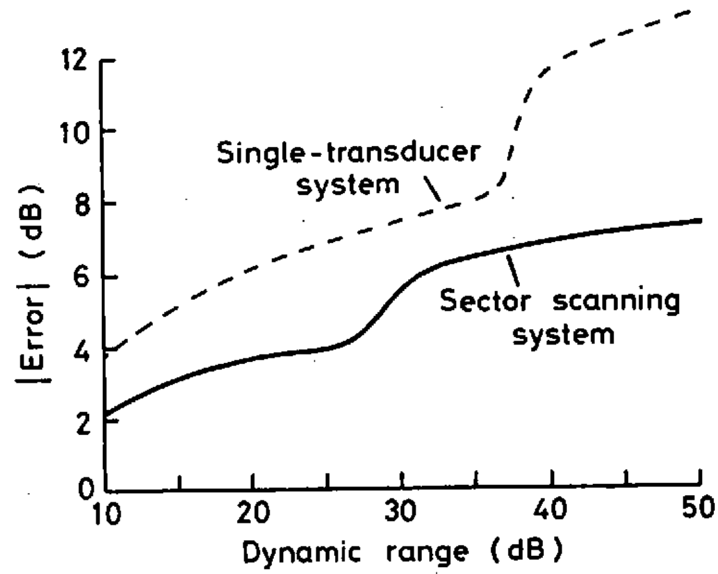

Figure 1. Mean target strength error as a function of system dynamic range.

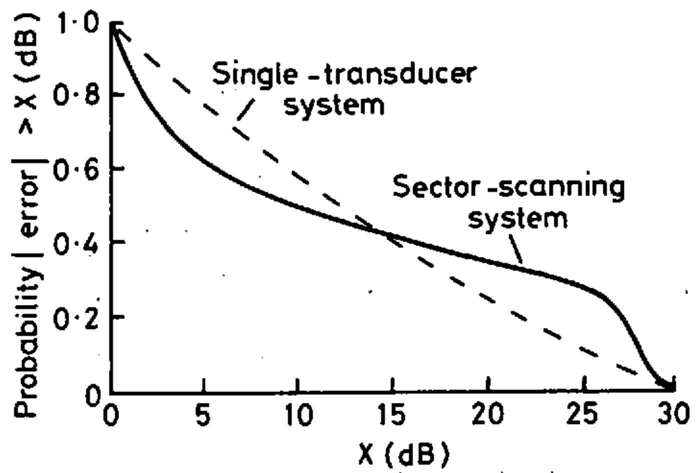

Figure 2. Probability that the target strength error exceeds X dB.

3. INDIRECT EXTRACTION OF THE BEAM PATTERN

Two different classes of techniques can be used to remove the beam-pattern factor from acoustic echoes, direct and indirect. This section considers indirect techniques in which the effect of the beam pattern is statistically removed from a collection of echo levels. The main attraction of the indirect techniques is that they do not require any modifications to the basic acoustic system. The commonly used indirect target-strength-estimation procedure was originally proposed in a paper by Craig and Forbes.[2] Alternate procedures were later proposed by Ehrenberg[3] and Robinson.[7] A derivation of the Craig and Forbes method for sector-scanning systems is discussed here.

The method starts with an expression for obtaining the echo intensity, E_i, in decibels.

$$E_i = T_i + D_i \,, \tag{9}$$

where

$$E_i = 10 \log_{10} I_i$$
$$T_i = 10 \log_{10} (K\sigma_i)$$
$$D_i = 10 \log_{10} \left[b_T(\theta_i, \phi_i) \; b_R(\theta_i, \phi_i) \right] \,.$$

The probability density function for the random variable E is the convolution of the densities for T and D.

$$p_E(e) = \int_{-\infty}^{\infty} p_T(x)\, p_D(x-e)\, dx \,. \tag{10}$$

Now, assume that the densities for E and I can be represented as a staircase function with stair width Δ; that is,

$$p_E(e) = \begin{cases} p_1 & E_{max} - \Delta < e < E_{max} \\ \bullet & \\ \bullet & \\ \bullet & \\ p_N & E_{max} - N\Delta < e < E_{max} - (N-1)\Delta \end{cases} \qquad (11)$$

and

$$p_T(t) = \begin{cases} q_1 & E_{max} - \Delta < t < E_{max} \\ \bullet & \\ \bullet & \\ \bullet & \\ q_N & E_{max} - N\Delta < t < E_{max} - (N-1)\Delta \end{cases}, \qquad (12)$$

where $E_{max} = 10 \log_{10} A_{max}$. With these approximations, equation 10 can be written as N linear equations where

$$p_i = q_1 \int_{E_{max}-\Delta}^{E_{max}} p_D (E_i - X)\, dx + \ldots + q_N \int_{E_{max}-N\Delta}^{E_{max}-(N-1)\Delta} p_D (E_i - X)\, dx \qquad (13)$$

and $i = 1, 2, \ldots, N$. The integrals in equation 13 can be simplified by making a suitable change of variables to yield

$$\int_{E_{max}-j\Delta}^{E_{max}-(j-1)\Delta} p_D (E_i - x)\, dx = \begin{cases} D_{i-j+1} & j \leq i \\ O & j > i \end{cases}, \qquad (14)$$

where

$$D_{i-j+1} = \int_{(j-i-1)\Delta}^{(j-i)\Delta} p_D(y)\, dy .$$

The resulting system of linear equations is

$$
\begin{aligned}
p_1 &= q_1 D_1 \\
p_2 &= q_1 D_2 + q_2 D_1 \\
&\cdot \\
&\cdot \\
&\cdot \\
p_N &= q_1 D_N + q_2 D_{N-1} + \dots + q_N D_N \ .
\end{aligned}
\tag{15}
$$

The log intensity histogram levels, $p_1, \dots, p_N$, can be easily calculated from the received echo levels. The beam-pattern terms, D_k, can be written as an integral of the density function for the random variable B. However, it is simpler to write D_k in terms of the density function for the off-scanned target angle, ϕ; i.e.,

$$
D_k = \int_{\phi_k}^{\phi_{k+1}} p(\phi)\, d\phi + \int_{\phi'_{k+1}}^{\phi'_k} p(\phi)\, d\phi + \dots , \tag{16}
$$

where ϕ_k, ϕ'_k, ... are angles for which

$$
b_T(\phi)\, b_R(\phi) = 10^{-k\Delta/10} .
$$

The off-scanned target angle, o, is a uniformly distributed random variable with density function given by equation 6. It follows that

$$
D_k = K \left(\phi_{k+1} - \phi_k\right) + k \left(\phi'_k - \phi'_{k+1}\right) + \dots . \tag{17}
$$

Once $p_i, \dots, p_N$ and $D_1, \dots, D_N$ have been calculated, the unknown target strength density levels, $q_i, \dots, q_N$, can be obtained by recursively solving the linear equations in equation 15.

The indirect methods for extracting the beam pattern factor from echoes received using a single-transducer system have been extensively studied using Monte Carlo simulations.[1] These studies have shown that the method works well only when the underlying target strength distribution is well behaved and narrow in extent. When the target strength distribution is too wide or has too much structure (such as being bimodal), the estimated target-strength density is not good. Some simulations of the indirect method described in this section have been carried out by the author for a sector-scanning system. These simulations have shown that the indirect target-strength-estimation technique has the same limitations for sector-scanning systems as it does for single-transducer systems.

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4. DIRECT EXTRACTION OF THE BEAM PATTERN

The alternative to the indirect beam-pattern-extraction procedures discussed in the previous section is to remove the off-scanned beam-pattern factor directly from each individual echo. There are a number of techniques that could be used to remove the beam-pattern effect. Unfortunately, all of these techniques require an increase in the complexity of the acoustic portion of the system. Some techniques for obtaining direct target-strength measurements with simple echo-sounding systems are discussed in References 1 and 5. This section will discuss the implementation of some of these techniques in a high-resolution sector-scanning system.

If it is assumed that performance is limited by the effects of noise, the optimum processor for estimating the beam-pattern factor would be one based on maximum-likelihood estimation theory. It has been shown[5] that, for an ideal one-dimensional line array, the maximum-likelihood estimator would steer the beam until the maximum output was obtained. The angle at which the maximum occurred would provide the estimate of the target angle from which the beam-pattern factor could be calculated. The theory can be easily generalized to apply to two-dimensional arrays. However, the implementation of an optimum estimator is considerably more complicated for the two-dimensional array than it is for a one-dimensional line array. A two-dimensional sector-scanning system would be one way to approximate the maximum-likelihood beam-pattern estimator. By using a two-dimensional scanner, it would be possible to determine the angular location of each target in two planes at right angles to one another. The effect of the transmitting beam pattern and any known variation in the sensitivity of the receiving beam as a function of its position in the scan could then be removed from the echo level. Such a system would also retain the high resolution and good volume coverage achieved with the sector scanner. Although the two-dimensional sector-scanning system appears to be the nearly ultimate solution to the direct target-strength measurement problem, it is unlikely to be built for some time owing to the technological problems in such a development.

An alternative to the full two-dimensional scanner would be two one-dimensional scanned arrays at right angles. The angular location measured with one array could be used to remove the off-scanned beam-pattern effect from the output of the other array. The angles at which the peak outputs occurred for the two scanners would specify the two-dimensional angular location of the target and could be used to remove any variation due to the transmitter beam pattern. A right-angle steered array would be considerably simpler to implement than a full two-dimensional scanned array. The price paid for this simplicity would be reduced performance in the presence of noise and a reduction in the range of target densities for which the system could be used. With the right-angle array, the correct angular location of a target could be determined only if it were the only target detected during the scan. If more than one target were detected during a scan, there would be ambiguities in the angular locations of the targets and all the data from that particular scan would have to be rejected. In other words, the right-angle array can only process echoes when they are separated in time by an amount equal to the length of the transmitted pulse. This requirement on target spacing is the same as that for most of the simpler echo-sounding systems used to measure target strength, and clearly does not exploit the high resolution available with the scanner. One advantage that the right-angle array would have over the simpler direct-extraction methods is that most target echoes not separated by one transmitter pulse length could easily be recognized. The problem of isolating single target echoes can be very difficult with the simpler systems.

Another possible technique, which again uses two sector-scanning line arrays, is based on the dual-beam target-strength-measurement system.[1] For this technique, the off-scanned beamwidth of one of the arrays must be considerably wider than that of the other. The two arrays are placed parallel to each other and are scanned simultaneously. The peak echo intensity for a target with scattering cross section σ_i, angular location θ_i, ϕ_i, and transmitting beam pattern factor $b_T(\theta_i, \phi_i)$ will be

$$I_{Ni} = K_N \, b_T(\theta_i, \phi_i) \, b_N(\phi_i) \, \sigma_i \qquad (18)$$

for the sector scanner with the narrow beam and

$$I_{Ni} = K_W \, b_T(\theta_i, \phi_i) \, b_W(\phi_i) \, \sigma_i \qquad (19)$$

for the sector scanner with the wide beam. If the gain factors K_N and K_W are adjusted to be equal, and if the off-scanned beamwidth of the widebeam scanner is chosen such that $b_W(\phi_i) = 1$ for all detected targets, the ratio of I_{Ni} to I_{Wi} is $b_N(\phi_i)$. The ratio therefor provides an estimate of one of the previously unknown beam pattern terms in equation 18. Once $b_N(\phi_i)$ is determined, the magnitude of the off-scanned angle can be found, and the transmitting beam pattern factor, $b_T(\theta_i, \phi_i)$, can therefore be determined and its effect removed from equation 18. This dual-scanner technique can process targets that are more closely spaced than one pulse length provided that only one target is received per scanner resolution cell.

5. DISCUSSION AND CONCLUSIONS

The various target-strength-measurement techniques discussed in this paper have been based on the assumption that each echo is from only one scatterer. Echo-sounder target-strength-measurement systems often incorporate some additional signal-processing hardware or software to isolate single-target echoes from multiple-target echoes. The isolation is usually accomplished by measuring pulse shape parameters such as the pulse width at various amplitudes relative to the peak amplitude. If the parameters measured are outside a predetermined range, the pulse is assumed to be from multiple targets and is not processed. Similar single-echo isolation techniques could be incorporated into the various sector-scanning target-strength-measurement systems discussed in this paper. However, in many cases, the high resolution of the sector-scanning system will be sufficient to ensure that all target echoes detected are from single scatterers.

The sector-scanning techniques that have been discussed have also assumed that targets are detected when they are in the main lobe of the scanned beam and not when they are in the side lobes. This assumption may not always be satisfied unless the receiving array contains some appropriate amplitude or phase shading. An unshaded linear array has first side lobes that are only 13 dB down from the main lobe. Using shading to reduce the side lobes results in an increase in the width of the main beam and a corresponding decrease in the resolution of the system.

For complex scatterers such as fish, the target strength can vary considerably with acoustic frequency and the orientation of the scatterer in the acoustic beam. One must be aware of this variability when making target-strength measurements. Ideally, the acoustic frequency and target orientation during the measurements should be the same as they are in the particular application in which the measurements are being used. One potential problem with using wide-scan sector-scanning systems for target-strength measurements is that the effective orientation of a target will vary depending on its location in the scan. For this reason, it may not be reasonable to use the results of target-strength measurements obtained using a wide-scan sector-scanning system to determine the target-strength parameters for a narrowbeam echo counter or echo integrator. Any variation in the mean target strength as a function of position in the beam will increase with increasing frequency. At present, there is insufficient data available to predict what the change in mean target strength as a function of position in the scan will be at a specific acoustic frequency.

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REFERENCES

1. J.E. Ehrenberg, "Two applications for a dual-beam transducer in hydroacoustic fish assessment systems," Proc. 1974 IEEE Conf. on Eng. Ocean Environ., 1: 152-155.

2. R.E. Craig and S.T. Forbes, "Design of a sonar for fish counting," Fisk. Dir. Skr. Ser. Havunders, 15: 210-219 (November 1969).

3. J.E. Ehrenberg, "A method for extracting the fish target strength from acoustic echoes," Proc. 1972 IEEE Conf. on Eng. Ocean Environ., pp. 61-64.

4. W.I. Dunn, "A controlled beam width echo sounder for fish counting," Rapp. P-V. Réun. Cons. int. Explor. Mer., 170: 162-166.

5. J.E. Ehrenberg, "A comparative analysis of in situ methods for directly measuring the acoustic target strength of individual fish," submitted for publication in IEEE J. Ocean. Eng.

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6. J.C. Cook and A. Rushworth, "Measuring fish target strength and shoaling density using a high resolution scanning sonar," Proc. Institute of Acoustics Conference on Acoustics in Fisheries, September 1978.

7. B.J. Robinson, "In situ measurement of fish target strength," Proc. Institute of Acoustics Conference on Acoustics in Fisheries, September 1978.