AN APPRAISAL OF ECHO INTEGRATION METHODS

by

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1. ABSTRACT

This paper presents a review of the principles and practical problems associated with acoustic surveys of fish stocks using the echo integrator. Sources of error experienced in current estimates of abundance are examined and those areas are indicated where further research is required to increase confidence in the technique.

2. INTRODUCTION

Fisheries management is highly dependent upon the availability of detailed information on fish populations. Consequently a need has arisen for rapid survey techniques capable of providing reliable estimates of the abundance of numerous, widely differing fish stocks. It has been recognised that acoustic techniques are well suited to this role and consequently two echo processing systems have evolved, the echo counter and the echo integrator. Both systems employ high power echo sounders to detect fish aggregations and TVG (Time Varied Gain) receivers to compensate for the effects of spreading and absorption losses upon return echoes from different depths. However, subsequent signal processing and the resulting accuracy of the two systems under varying acoustic conditions differ considerably.

The echo counter simply counts those signals which originate within a selected depth interval and whose amplitude exceeds a preset noise dependent threshold. If it is known that these signals are single fish returns, then echo amplitude is relatively unimportant and detailed target strength measurements are not necessarily required.

However, the probability of error is critically dependent upon the fish density, since if more than one target occurs within a pulse volume, the echoes overlap and only a single count is recorded. A bias is therefore introduced into the estimate and it cannot be reduced by processing a large number of echoes.

The echo integrator is also subject to errors due to echo overlap but the principles of the system are such that these errors are of a completely different nature from those experienced by the echo counter. The return signals are initially squared to provide a voltage which is proportional to the received echo intensity and which is then integrated over a time interval corresponding to the selected depth range. The output voltage, M, may then be shown (1) to be related to the fish density, N, within the sonar beam, by:

$$M = CN + d$$

where C is a calibration constant proportional to the fish target strength and the sonar equipment parameters:

d is the threshold voltage below which return signals are masked by noise.

Potential errors in the system arise from the effects of destructive interference between overlapping pulses whose phase differences range from 0° to 180°. By squaring the echo signals the effects of phase interference are progressively reduced when large numbers of return echoes are processed.

3. THEORETICAL LIMITATIONS OF THE SIGNAL PROCESSING TECHNIQUES IN CASES OF HIGH FISH DENSITY

In order to assess the overall performance of acoustic survey techniques it is initially necessary to calculate the errors introduced by the adopted signal processing system under varying acoustic conditions.

The errors created by echo overlap have been briefly described in the previous section. By making certain simplifying assumptions about the statistics of fish aggregations (principally that the fish act as independent scatterers, uniformly distributed within the insonified volume), these errors have been evaluated as a function of fish density by Ehrenberg (2) and are of the general form illustrated in Figure 1.

At low densities both processors exhibit errors due to variance in the fish density distribution. As the density increases both processors produce fewer errors until echo overlap begins to bias significantly the output of the echo counter at densities greater than 0.1 fish per pulse volume, ie when Vp = 0.1. This bias becomes unacceptably large at densities where Vp > 1 (at which density, the count is approximately 20% low, assuming a Poisson density distribution), and it is therefore necessary either to decrease the sonar sampling volume or to resort to the echo integrator. However, since densities of up to 100 fish per cubic metre are frequently encountered in certain species, even a sonar system employing 100 µS pulses and 1^{o} beam would be incapable of adequately resolving single fish at depths greater than 20 metres below the sonar transducer. Hence for all such situations echo integration is the only suitable technique.

The variance in the integrated output, σ_m^2, continues to fall with increasing density until a limiting value is reached (at approximately 30 fish per pulse volume in the example of Figure 1), given by:-

$$\sigma_m^2 \approx \frac{T}{4Dn}$$

where T is the pulse length in metres

D is the depth interval

n is the number of independent return echoes processed by the system

eg for a shoal of mackerel of density 100 fish per cubic metre within a depth interval of 40 metres, the variance in the integrated output after 400 1mS pulses had been transmitted would be 0.23 10^{-4}, corresponding to a standard deviation of less than 0.5% which, as will be demonstrated later, is an insignificant error compared with the other sources of error in the system.

4. PRACTICAL CONSTRAINTS ON THE ACCURACY OF THE INTEGRATION SYSTEM

It has been demonstrated that the signal processing technique does not contribute significant variance to the final estimate of abundance. However, in order to relate the integrated output voltage to biomass density it is necessary to apply a calibration constant for each fish population. These constants are subject to considerable uncertainty and are dependent upon three major factors:

a. Measurement of the target strengths of fish present within the surveyed population;

b. Evaluation of any acoustic propagation limitations;

c. Limitations in the sonar equipment.

Since all three factors can introduce significant variance into the biomass estimate, they are each examined in detail in the following sections.

4.1 TARGET STRENGTH DETERMINATION

An accurate knowledge of fish target strength is fundamental to the integration process since it has been demonstrated that it is not possible to derive a biomass estimate whose precision exceeds that of the target strength estimate. However, in practice it has proved extremely difficult to establish a representative target strength for a particular fish population, since the backscattered echo varies with acoustic frequency, fish species, physiology and also with aspect, movement and possibly depth.

In an effort to quantify some of these effects several research workers have derived empirical formulae relating the mean target strength of certain commercially important fish to their body length and the acoustic wavelength. The application of these formulae requires knowledge of the characteristics of fish present within the surveyed areas. At present this can only be established by trawl samples which are often difficult to obtain and are subject to bias due to the indeterminate nature of the sampling process. However, target strength experiments have only been performed on a limited number of species and consequently no consistent results are available for several currently important fish (eg mackerel, *Scomber scombrus* and blue whiting, *Micromesistiscus poutassou* (Risso). Whilst further measurements could be made on caged fish, the use of such results is questionable when considering fish with swimbladders, since it is possible that their target strength varies with depth. A further and probably more important source of error can be attributed to uncertainty over the particular attitude adopted by free swimming fish, whose target strength has been found to vary by up to 6 dB with a small change of pitch angle (3). Information on the behaviour of free swimming fish is not sufficient to allow this source of variance to be eliminated from the final biomass estimate and it is not expected that this situation will improve.

In order to reduce these uncertainties the possibilities of *in situ* target strength measurement have been considered. This technique would eliminate many of the difficulties and biases introduced by measurements upon caged fish and may also allow length distributions to be determined directly without the necessity of trawling. However, the feasibility of such measurements is dependent upon the isolation of echoes from single fish and it would therefore be necessary to use very high resolution sonar equipment in conjunction with a processing system capable of distinguishing echoes from single and multiple targets.

Currently available 30 kHz equipment is typically only capable of resolving single fish when their density does not exceed 1 per 5 cubic metres, and then only if the sonar transducer is maintained within 20 metres of the fish aggregation. This close proximity could introduce several biases into the target strength estimate since it would only be possible to sample echoes from fish in the top layers of the shoal. In certain species these fish are usually the younger and hence smaller fish which could cause an under-estimate of the mean back scattering strength, and there could also be a behavioural problem due to the possibility of an indeterminate fright reaction.

Whilst the system resolution could be improved considerably, in order to keep the transducer size within practical limits it would be necessary to employ higher sonar frequencies with the attendant range limitation problems. It is also known that the variance in the back scattered signal amplitudes increases with frequency. Hence the adoption of a higher frequency would result in an increase in the number of single fish echoes which would have to be processed in order to reduce the error in the measured mean target strength to an acceptable level. The development of high resolution, non-linear sonar systems could alleviate this problem by allowing measurements to be made at low frequencies. (In these systems the acoustic fields from two high frequency sources can be made to interact to produce a different frequency "source" which possesses essentially the same beamwidth as the originating high frequency sources.) However, if *in situ* measurements are to be feasible, the equally important problem of removing the effects of the transducer directivity pattern from the individual fish echoes must be solved.

Attempts to treat statistically the received echo level distribution have not met with success and require a large number of single echoes to be isolated. The solution to the problem would therefore seem to lie in the use of a narrow beam transducer whose beamshape was approximated to a "flat-topped" response. However, the integration process requires a large sampling volume and hence a more appropriate transducer design could be similar to the dual beam system proposed by Ehrenberg (4). In principle, such a system would enable the echo intensity and the mean single fish target strength to be measured in parallel, thereby allowing the biomass to be computed automatically as the survey proceeds.

4.2 ACOUSTIC PROPAGATION WITHIN FISH SCATTERING LAYERS

In order to relate integrated echo intensity to the fish biomass within an insonified volume it has been assumed that individual fish act as independent acoustic scatterers. The validity of this assumption must however be reconsidered when the fish density is such that the spacing between individuals is not large compared with the acoustic wavelength (eg as in the case of a mackerel shoal of density 100 per cubic metre when using a 30 kHz sonar). Under these conditions the incident acoustic energy could experience specular reflection and appreciable diffraction and multi-scattering within the fish aggregation. Since the fish would also display highly directional forward scattering, deeper fish would be in the acoustic shadow of those nearer the surface. The overall effect of all these factors would be to cause acoustic attenuation through the shoal leading to an underestimate of fish numbers. Whilst it should be possible to quantify this effect, in order to apply a compensation factor to the calculated biomass it would still be necessary to know the density of the fish of interest. This measurement has proved difficult to perform using conventional techniques such as trawling and photography, due to uncertainties over fish behaviour in the presence of nets and intense lights etc. However the solution may lie in the use of high resolution sonar systems provided that their limited range and finite near field problems can be overcome (5).

In certain deep water circumstances (eg blue whiting surveys (6)) the attenuation within the fish aggregation may not be as significant as that within shallower scattering layers of smaller fish (myctophids), the effect being aggravated by the possibility of swimbladder resonance in juveniles at certain sonar frequencies. No experimental investigations have been performed on this phenomenon and consequently its effect on the accuracy of an acoustic survey is at present unknown.

In some situations it is not normally possible to isolate physically the fish of interest and it is necessary to consider the effects of other organisms within the surveyed population. Sonar systems are only capable of discriminating against a minimum signal level which could correspond to that from a small single fish or could, in fact, be due to a group of much smaller fish or even a dense patch of jellyfish. In order to quantify this effect it will be necessary to measure the target strength of such organisms and to establish their relative abundance in the surveyed area. The latter requirement is, however, especially difficult to fulfil due to the practical problems associated with fine mesh trawls and the grossly uncertain sampling process.

4.3 LIMITATIONS IN THE SONAR EQUIPMENT

If the accuracy of the integration process is not to be further degraded, the design of the sonar system must be such that errors introduced by the chosen signal processing equipment do not significantly affect the final biomass estimate. At present, echo integration systems may be divided into two major parts, the TVG receiver and the integrator.

Current receivers are essentially analogue devices and consequently it has proved extremely difficult to achieve the required dynamic range and accuracy of the gain laws. The adoption of digital techniques would result in a considerable improvement and facilitate the introduction of several refinements (eg the addition of a variable acoustic attenuation coefficient). The integrator would also lend itself to digital techniques, thereby introducing the possibility of automatic signal processing with a mini-computer. (7)

However, the whole sonar system must be critically appraised and the effects of such things as bandwidth limitations in the transducer and-TVG receiver and the accuracy of the calibration procedure must be examined in detail.

5. SUMMARY

It has been demonstrated that the integration technique is theoretically capable of producing accurate estimates of abundance. However, in practice, due to fundamental uncertainties over fish behaviour and acoustic propagation it has proved difficult to derive an accurate calibration constant relating integrated echo voltages to fish biomass. After consideration of all the sources of variance, it is thought likely that current acoustic estimates are only accurate to within an order of magnitude. However, acoustic data on a particular fish stock are not considered in isolation and by evaluation of all the available biological information the uncertainty in the final biomass estimate can be reduced.

By adopting more sophisticated survey techniques, notably *in situ* target strength measurements, these errors could be further reduced, but any such improvement is limited by the natural target strength distribution within the shoal due to length differences between individual fish. For those species with a large size diversity this fact alone would imply that the biomass estimate could only be accurate to within approximately ± 50%. However, this figure compares very favourably with that obtained from other types of non-acoustic surveys and hence the research effort involved in refining the integration process can be justified.

6. REFERENCES

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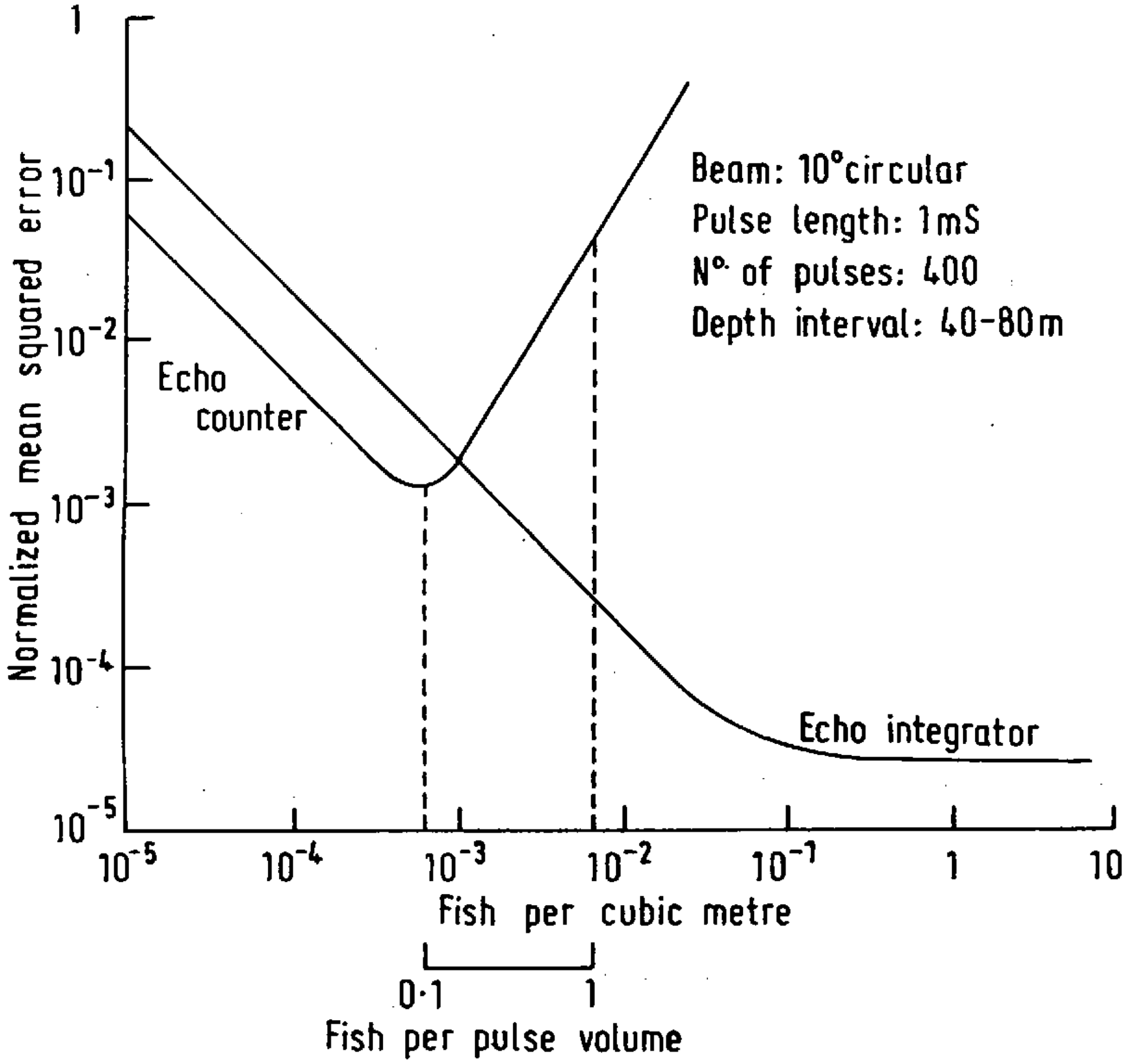

Figure 1. Normalized mean squared error of the echo counter and integrator as a function of fish density.

DISCUSSION FOLLOWING THE PAPER BY MR.B.J.ROBINSON : AN APPRAISAL OF THE ECHO INTEGRATION METHOD.

DR.CUSHING: I would like to point out that the mackerel shoal with densities of greater than 100 fish per m^3 is probably not typical. The experience I have gained from measurements made using a sector scanning sonar on herring, horse mackerel and sprats indicates a more likely range of densities between 1 and 10 per m^3. There is a relation between shoal size and density; the bigger the shoal, the more dense it is. There is a suggestion from some recently reported work that fish in shoals are no closer than 0.6 length to one another.

MR.O.NAKKEN: It is important to find out at what level the echo signal to shoal density becomes non-linear. We have carried out some research which will soon be published in English. It gives some figures for the saturation density in a cage, for smaller fish it is evident that the saturation will occur at densities which do occur in nature.

DR.F.R.HARDEN JONES: If Dr.Cushing said 0.6 length apart it means approximately 4000 sprats in a metre cube.

DR.P.O.JOHNSON: There are about 120-130 mackerel per m^3 in the underwater photograph. From the analysis made and bearing in mind the distortion the fish are roughly 0.6 length apart. At the time that the photograph was taken the range was about $3\frac{1}{2}$ m to resolve an image.

MR.J.J.TRAYNOR: I would like to comment that you bring out the fact that the variance in trawl haul catches can be an important factor in the error of the estimate. The identification and separation of echo intensities to different fishes is a difficult problem.