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Canadian Atlantic Fisheries Scientific Advisory Committee

CAFSAC Research Document 85/25

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Comité scientifique consultatif des pêches canadiennes dans l'Atlantique

CSCPCA Document de recherche 85/25

Acoustic Estimates of Fish Abundance

by

L.M. Dickie and P.R. Boudreau
Department of Fisheries and Oceans
Marine Ecology Laboratory
Bedford Institute of Oceanography
P.O. Box 1006
Dartmouth, Nova Scotia
B2Y 4A2

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ABSTRACT

Recent work with the ECOLOG dual-beam system shows that it can be used in the field to correct for errors that up to now have introduced a significant degree of uncertainty into abundance estimation by acoustic methods. Using ECOLOG in counting mode we show that our system of processing acoustic signals allows us to use acoustic transect data to accurately reconstruct the size-compositions and densities obtained from simultaneous fish catches with standard survey nets. It appears that ECOLOG is ready for trial use in abundance surveys for demersal fish and could be an important adjunct to acoustic integration systems to provide data on field target strength and effective system calibration levels.

RESUME

Les travaux effectués récemment avec le système à deux faisceaux ECOLOG montrent qu'on peut utiliser ce système sur le terrain pour corriger les erreurs qui jusqu'à maintenant ont produit un degré d'incertitude appréciable dans l'estimation de l'abondance par les méthodes acoustiques. En utilisant le système ECOLOG en mode de dénombrement, nous montrons que notre système de traitement des signaux sonores nous permet d'utiliser les données acoustiques de transects pour reconstruire avec précision les diagrammes de densité et de répartition des tailles établis à partir de prises simultanées de poisson à l'aide de filets de rélevé ordinaires. Il semble que le système ECOLOG soit prêt à être mis à l'essai dans des études sur l'abondance des poissons démersaux et qu'il pourrait constituer un ajout important aux systèmes d'intégration acoustiques servant à obtenir des données sur l'intensité des échos sur le terrain et des niveaux effectifs pour l'étalonnage des systèmes.

In estimating fish abundance by acoustic methods, it is useful to distinguish 4 stages of the estimation process. Each stage represents a source of variance and a place where bias may arise. They are:

1. The measurement of echo intensity
2. Calibration of echo levels to a standard target
3. Processing and interpretation of echo-intensity data
4. The process of population sampling (survey design).

Measures of error at each stage, hence their relation to the total, may be rather different for the two methods of acoustic sampling, echo-integration and echo-counting, that we are trying to assess at the workshop. They may also differ between demersal and pelagic species groups, or even among the species in a group.

We are thus undertaking review of a complex matrix of variations, and will not be helped by the fact that we don't have real measurements for some of the compartments or boxes of this matrix. However, we do now have sufficiently repeatable data for some of them which allows reasonable inferences about our likely progress in others. We therefore seem to be in a position to make worthwhile judgements about the value of acoustic survey.

In what follows we outline some of the differences and similarities between counting and integration approaches to abundance estimates. Our main purpose is to describe what we have learned from our use of the dual-beam echo-counting technique we call ECOLOG. The results have implications for judging the precision of integration methods.

1. MEASUREMENT OF ECHO INTENSITY

Sonar is used in fisheries to measure the voltage equivalents of sound energy reflected from objects in the water. All sonar systems measure the voltage echoed from successive transmissions, (often called "pings"). The reflecting cross-section of the detected object is proportional to the square of the voltage measurements. All acoustic systems therefore are designed to measure and to square the voltage. The resulting value is called the echo-intensity and our aim is to relate this to fish abundance.

Integration and counting systems use two different physical models for the process of generating an echo-intensity, and these models are responsible for choices made about the characteristics of the sound generated and received. It is necessary to appreciate how well these models approximate the realities encountered in nature, if we are to assess the relative merits and trustworthiness of the methods which are based on them.

In counting systems, the basic assumption is that there is a single object being seen at a given moment in the propagating front of the sound wave. That is, sound is generated from the directional transducer and travels in a sound cone. When an object is encountered, it is presumed to radiate an echo back through the cone. The energy or intensity of the echo at the transducer has been reduced by distance travelled, due to both absorption and to the spreading of sound over a larger and larger area. The electronic system has a built-in TVG system to correct for the reduced echo intensity due to these absorption and spreading losses. In the counting system, the spreading losses are considered to be two-way losses (i.e. spreading on the way out and the way back) and the TVG is used accordingly.

The integration model is different. In this case the assumption is made that targets are uniformly distributed in the water, so that the spreading loss with distance from the transducer is balanced by the increase in the number of targets encountered. The only spreading losses are then those of the reflected or returning wave, and the TVG is required to correct the received voltages for spreading losses in one direction only.

In fact, conversion of signals from one-way to two-way spreading losses is a relatively simple operation, so that acoustics practitioners pay very little attention to it, except to ensure that they make the right calculations and that amplification of returned echoes is optimal for the dynamic range and density of fish. However, the underlying physical model determines the parameters of the sonar system, and needs to be taken into account in comparing systems and understanding possible differences in the variances and biases which arise in measuring, calibrating and interpreting them.

It should be clear, for example, that the counting model has in mind situations of relatively low density. By contrast the integration model thinks in terms of swarms of plankton or of schools of fish. Real distributions of animals range from one extreme to the other, and part of our job is to decide the practical range of application of the methods. What we would all like to find is that there is an overlapping intermediate range of fish distributions in which the two methods of estimation could be used equally well, affording a chance to calibrate the echo-intensity measures to a common value of density or biomass.

The two models suggest different specifications for the ideal sampling system. For example, for our ECOLOG counting system, we have chosen a sound frequency of 50 Khz because it is sensitive to the fish sizes we expect in demersal populations (10 to 100 cms length) and because it gives us a good transmission range in salt water (a reliable 120 metre working range). We use a fairly short pulse length and a narrow beam width (3.5° half power angle from axis) in order to make our individual sample volumes as small as is consistent with seeing single fish, but we use a high frequency of sampling the pulse envelope (10 Khz or 100 microsecond intervals) and a transmission rate of 125 per min. in order to make repeated observations of a single fish.

The ideal integration system may make different choices of system. The best sound frequency might be the same but especially at low densities one might wish to use a wider beam angle or longer pulse to better meet the criterion of echos throughout the sound cone, but ideally each "ping" should be an independent population sample. The variation in both sizes and numbers of targets within a sample volume is an important consideration for how large the unit sample volume should be. In both systems the choice of sound characteristics is intended to minimize problems of overlap (coincidences) of targets or of bias and variance of echo-intensity which may arise in measurement. Given the best electronic system, integration and counting represent alternative methods of dealing with the remaining variations.

One particular aspect of variance and bias in acoustic estimation is appropriately treated as part of the measurement problem. This is the so-called "directivity", by which is meant the influence of the fall-off in echo strength with distance from the axis of the sonified cone. Echoes from a given target show a maximum value when the target is on axis, but in our narrow beam, for example, have fallen off to ¼ their maximum at 3.5° off axis. If we use a sounder for integration, and the targets are uniformly distributed in the unit sample volume it is a relatively simple matter to correct the received echo to the equivalent average echo per unit area. This "beam factor" depends on the diameter of the cone, and appropriate values are assigned in the calculations. The remaining variation in the echo-intensity is thus considered to be a function of the fish population itself, and should be amenable to study in relation to biological variables.

The chief difficulty is that of deciding on an appropriate measure of target strength to use in single-beam calculations. Several methods have been proposed for removing the effect of the beam directivity on the signals received by the single beam transducer. The most commonly used is the Craig-Forbes (1969) method which provides a weighting for the average echo-intensity value from the observed distribution of intensities. A number of workers have, however, regarded this correction as too imprecise and requiring an unrealistically large number of data points, (Traynor and Ehrenberg 1979). More mathematically sophisticated methods have been suggested by Ehrenberg (1972), Peterson _et al._ (1976) and Clay (1983). None of these indirect methods has been extensively tested. In fact, the methods for deciding just how good a job they are doing is a major source of doubt about them. For present purposes, what is interesting about them is that all such refinements are based on mathematical models which call for an echo-distribution in which single fish echoes of uniform size can be resolved. That is, solutions to the problem of error in measurement in echo-integration systems has depended upon making the method meet the basic conditions of the echo-counting technique. That is, the difference between echo-counting and echo-integrating becomes merely a difference in calculation methods. Arguments about the merits of the two approaches therefore seem to be counter-productive so long as both of the calculations are dependent on single-beam acoustic systems.

The only alternative to this dilemma that has yet reached the stage of practical application is the dual-beam sounding system which we have incorporated in ECOLOG. The method is based on the counting model, although with this system it is, of course, possible to use either beam to study echo-integration as well. The principle is simple. If we have two nested transducers with different beam widths, a target on the common axis will give an identical echo on both transducers. At any point off the axis, the ratio of the two signals will reflect the distance from the axis, so that each echo-intensity can be corrected for distance off axis, hence the echoes can be standardized to on-axis levels. The remaining variations in echo intensity can be studied in relation to biological factors.

We have undertaken this dual-beam correction with ECOLOG, a system which also incorporates other features that enable us to use it as a scientific instrument to study problems of acoustical estimation procedures. Of particular value has been the digitization of the data, permitting the recording and processing of the very large amounts of data obtained on a cruise. (Systems of analogue recording are still in use, but produce such voluminous records that only selected data can be studied practically.)

We report the most recent results of our study, in relation to problems of calibration, and signal interpretation. Our earlier results have been published in two papers (Dickie *et al.* 1983 and 1984) and indicate a generally satisfactory stage of interpretation. Since then, however, we have carried out another tank experiment in the Dalhousie aquatron and obtained field records from several additional cruises. These most recent data have indicated a problem in calibrations and interpretation which we had not anticipated. It appears, however, to represent a significant factor in directivity errors in echo-sounding, and appears to explain much of the remaining error we reported in 1984. Its removal gives results which underline the readiness of the system for incorporation in practical survey.

2. CALIBRATION OF ECHO LEVELS TO A STANDARD TARGET

Two different aspects of calibration are involved in acoustic abundance estimation. First, the strength and characteristics of the "ping" generated at the transducer, the conditions of transmission and the sensitivity of the transducers for receiving echo signals must be standardized. Second, there is the need to ensure that the criterion of the reflectivity of targets has not changed. In integration, for example, the integrated echo intensity is divided by average target strength to estimate density. Both echo-intensity and target strength require calibration.

Calibration of the echo-intensity is a function of the electronic system alone, and there have been many meetings and publications and much effort devoted to ensuring that not only do the adjustments made on a particular system standardize it in time, but make it possible to compare results from one system to another. The methodology of adjusting to a "standard target" is particularly popular in Europe though there is disagreement about what makes the best standard. In North America acoustically calibrated hydrophones are more commonly used. With ECOLOG we are particularly fortunate to have access to the Defence Research Establishment-Atlantic acoustics barge. It should be remarked however, that with the best electronics checks available, there is little likelihood that any *a priori*, shore-based calibration system can guarantee an electronic calibration to less than ±1 dB. That is, the calibrated received echo-intensity level, when measured in decibels might, in an extreme case, differ from the "true" level by as much as 2 dB. Since dB is a logarithmic function of $(\text{voltage})^2$, we note for comparison that 3 dB would represent a factor of 2 in the actual average echo-intensity. Even with the best of calibration facilities, it should be clear that it is highly desirable to verify electronic calibration by field measurements.

Electronic calibration errors affect the estimation procedures in 2 ways. The first is the relation of the average echo-intensity to some aspect of a standard target within the range of sizes of objects detected. For example, it is known that diameter of the scattering cross-section affects echo-intensity. We therefore require that a standard size of target give a specified voltage. In addition, however, it is necessary to recognize a threshold effect. At a given frequency a lower size limit of target detectable is determined by the system variance in sound energy which is described as "noise". Detection of an echo depends on a predetermined minimal signal to noise ratio. In the ECOLOG system we set the echo strength on a cruise to a threshold level which should detect a 10 cm codfish, and we do not record "signals" below this level. Should the calibration setting be as much as 2 dB in error, the actual threshold size may be as low as 5 cms or as high as 20 cms. The threshold effect thus has an additional influence on interpretation in relation to calculating the size of an average target.

These two effects of calibration uncertainties affect integration and counting systems in the same way, but their importance may be very different for different species groups. For example, if integration were used for herring schools in which the fish have an average size of 30 cms and a standard deviation of 5 cm the bias due to uncertainty around a threshold of 10 cms should be minimal. In demersal populations on the Scotian Shelf, our experience suggests that the peak abundance occurs at between 20 and 25 cms for some species and threshold would be of considerable significance in relation to the estimation of average size.

The problem is again, one of measurement, and in this connection, studies with ECOLOG are relevant to identification of the sources of error and standardization of the system.

The dual-beam process of echo counting may be represented as follows: We transmit a pulse on the narrow beam, so the incident echo intensity at the narrow receiver is $I_n = k_n(10^{-2\alpha R}/R^4)\ b_n^2(\theta,\phi)\,\sigma$. Where

k_n is the signal calibration, the term in brackets represents signal absorption and spreading losses, $b_n^2\ (\theta,\phi)$ is the two-way directivity of the narrow beam and σ is the acoustic back-scattering cross-section of the target. We receive the echo on the wide beam as well and the incident echo intensity for it is $I_w = k_w(10^{-2\alpha R}/R^4)\ b_n(\theta,\phi)\ b_w(\theta,\phi)\sigma$ which takes into account both the narrow (n) and wide (w) beam directivity characteristics.

We have developed a dual time varied gain (TVG) for the absorption and spreading losses in the system, and during calibration set $k_n = k_w = k$. The system is also designed so that $b_w\ (\theta,\phi) = 1$ over the narrow beam width. So we may rewrite the corrected echo-intensity as:

$$E_n^2 = k\ b_n^2\ (\theta,\phi)\ \sigma_i$$

$$E_w^2 = k\ b_n\ (\theta,\phi)\ \sigma_i$$

whence their ratio

$$\frac{E_n^2}{E_w^2} = b_n\ (\theta,\phi) \qquad (1)$$

Solving for

$$\sigma_i = \frac{E_w^2}{k\, b_n\,(\theta,\phi)} = \frac{1}{k}\ \frac{E_w^4}{E_n^2} \qquad (2)$$

which is the equation used in processing data for our 1984 paper.

In this equation system, we could, however, continue to write

$$E_n^2 = k_n\, b_n^2\ (\theta,\phi)\ \sigma_i$$

$$E_w^2 = k_w\, b_n\ (\theta,\phi)\ b_w\ (\theta,\phi)\ \sigma_i$$

whence

$$\frac{E_n^2}{E_w^2} = \frac{k_n}{k_w} \times \frac{b_n(\theta,\phi)}{b_w\ (\theta,\phi)} \qquad (3)$$

or solving for

$$\sigma = \frac{E_w^2}{k_w b_n(\theta,\phi)\ b_w\ (\theta,\phi)}$$

$$= \frac{k_n}{k_w^2} \times \frac{1}{b_w^2\ (\theta,\phi)} \times \frac{E_w^4}{E_n^2} \qquad (4)$$

That is, if for some reason $b_w\ (\theta,\phi) \neq 1$ or $k_n \neq k_w$ we have to recognize that the solution for σ could become quite complex.

In our study of the data most recently obtained in the tank experiments at Dalhousie, it appeared that for a given target, σ was not constant with E_n^2/E_w^2, hence the assumptions made in equations 1 and 2 may not have been sufficiently fulfilled. Noting, however, that the relationship between them was linear, it is a simple matter to use the dual-beam multiple observations of single fish to estimate the value of $_\sigma$ when $E_n^2/E_w^2 = 1$. From equation (3) and (4) it is apparent that this system of calculation effectively removes the joint effects of the directivity and the calibration ratios on the scattering cross section estimates. This system of calculation has been applied to the acoustic data from both the tank and from field experiments. The results show that there is a very considerable improvement in the acoustic estimate of the size-composition for demersal fish which is illustrated in Fig 1. It appears that much of the upper tail in the distribution of sizes in 1984, was introduced by our failure to apply a sufficiently strong directivity correction to the data. Our recent analysis (Fig. 1C) suggests that the acoustic data corrected in this manner provide satisfactory estimates of size-composition hence average size, for individual hauls of a trawl.

This system of calculation suggests that it should be possible to use the results of field calibrations to correct the data on a given cruise. Accordingly, for the Needler #10 cruise, from which the data of Fig. 1 are derived, we have calculated a revised average acoustic size for each transect with the average size determined by net tows made at the same time. The results are shown in Fig. 2, which indicates that within this cruise, despite a considerable difference in average size from tow to tow, there is a strong relation between the net estimate and the acoustical calculation (given in units of back-scattering cross-section). The scatter about this relationship is evidently amenable to study in relation to time of day, season, and other biological parameters.

With single beam systems, this method of field calibration is not available. In these systems it is customary to divide the integrated (voltage)^2 by an estimate of average target strength derived in various laboratory-type experiments. The best-known values are those which derive from the original experiments by Nakken and Olsen (1977). In our 1984 paper we used the version of their data which has been statistically analyzed by Foote (1979), which we refer to as the "Foote nomogram". In the 1984 paper it appeared that this nomogram, when applied to fish of known size gave an estimate of fish size which was roughly 10 cms too large, but given the variance in the data the nomogram performed well as a correction for the field data. That is, the data derived from a shore-based experiment was applied to field conditions.

Modification of the calibration for size by field measurements, permits us to make a more detailed study of the Foote nomogram as a means for calibrating the target strength. Foote used the Nakken and Olsen data for various species and verified that the average target strength measurement was significantly affected by fish size. In his fittings there was also variation in the slope of this relation among species, although in the majority of cases the slope of the relationship was not significantly different from the expectations of dimensionality relations between length and area (i.e. length^2 α area). If we assume that the theoretical value should be met, we can use the data we have derived from various cruises to check the values derived from Foote's calculation. From a preliminary study we show in Fig. 3 the relation of the Foote nomogram to the relations between σ and ℓ in two Needler cruises and one cruise of the E.E. Prince. While there is considerable variation among points derived from particular net-haul transect pairs, there is no significant differences in the average among the cruises, and the resulting composite relationship is not different from the Foote nomogram at an average body size of about 30 cm.

We have not yet been able to study these relationships in any detail. According to equations 3 and 4 the apparent cross section may vary as a result of the combined influence of calibration and beam directivity. Our ratio correction appears to remove their combined effect. However, in electronic calibration the constant for each transducer is accurate within only ±1 dB, so their ratio may take different values, depending on the levels of signals dealt with. At average calibration levels of about -40.0 dB the theoretical deviations of the ratio should be less than the observed variance. It is our tentative conclusion that the field calibration technique may well be reflecting real variations in target strength, for example, within a spawning population in May, and a post-spawning population in September, although with the limited number of samples used in Fig. 3 we cannot yet eliminate sampling errors. The observed variations suggest, however, that in single beam acoustic systems where there is no method of _in situ_ calibration, there are dangers of significant bias in the average target strength estimated used in calculations of integrated biomass.

3. PROCESSING AND INTERPRETATION OF ECHO INTENSITY DATA

The appeal of echo integration stems from its apparent simplicity. If successive squared voltages are summed and divided by an appropriate value of target strength (i.e. voltage^2 per fish or per kilo) the answer should be number or biomass per area sampled. Provided that calibration levels are satisfactory, and targets are uniform and sufficiently stable, the method should be as reliable as is afforded by the process of population sampling.

Unfortunately, in addition to the calibration effects noted above, there have been many reports of single-beam acoustic surveys which indicate that the authors are dissatisfied with the results. Sometimes the problem seems to be primarily with "finding the fish" (Jakobsson 1983), but differences in average echo-intensity between survey boats, between cruises, or between day and night transects (Olsen *et al.* 1983, Williamson and Traynor 1984, Kieser, pers. comm.) are reported. Problems may arise from many aspects of interpretation and a major difficulty has been the lack of a means of identifying the source of the problem and measuring its impact. The ECOLOG results offer information on various aspects of the errors of acoustic estimation.

In our research on demersal fish, we have aimed at the outset, to identify echoes from single fish and to measure their target strength. The process of selecting single fish was illustrated in our 1983 paper. (The paper deals with the details.) In summary, after studying several alternatives we chose to define an echo envelope for a single fish by finding the peak directivity-corrected echo-intensity within a given transmission or "ping" and averaging it with the corresponding peak in each succeeding overlapping ping. With our equipment used in deep water, we may often see a large fish in as many as five successive pings.

In our earlier data processing we chose from the defined single-fish envelope the peak value of echo-intensity, which was then studied for its characteristics in relation to the fish. Results, using this technique were reported in the 1983 paper as an aggregate size-distribution compared with net catches. The results in Fig. 4 show that the variance in the signals for a given sized fish must have been very high and the resulting distribution was quite flat. Much of the initial improvement reflected in Fig 1B from the 1984 paper was the result of the improved interpretation of the average within the single-fish envelope. The further correction resulting from the October 1984 tank experiment in Fig. 1C appears to us to verify that directivity effects have now been adequately accounted for, and that field calibration using ECOLOG permits proper setting of the calibration constants.

One further problem of interpretation must be considered. In some studies of fish populations, particularly demersal fish, the handling of the bottom echo is of importance. The advancing wave front of the transmitted sound is spherical and so the centre of the vertical sound beam hits bottom before its margin. That is, intensity of the bottom echo apparently rises with "distance" from the transducer. We set an upper threshold for the bottom signal, but the aim must be to trigger the bottom threshold so any fish present are seen as close to bottom as possible. Fish echoes are occasionally seen in the bottom rise. In the improved analysis of fish sizes reported here, it has appeared that echoes of fish close to bottom are added to the bottom signal. While it may eventually be possible to correct for this effect, we have concluded that for the present it is better to set an arbitrary bottom threshold 7 cm above the bottom rise. This correction is incorporated in our present processing.

Given the calibration settings, definitions of fish size, and bottom threshold we are in a position to re-examine the estimates of fish density reported in the 1984 paper. Results for the Needler 10 cruise are shown in Fig. 5A and B, which indicates that with the revised size-estimates there is corresponding improvement in the relation between density estimated from acoustics and trawl hauls.

In the previous section it was noted that the field calibration suggests little difference in average echo-level for the fish encountered on the N-15 cruise in September 1983 and those of the May cruise of the same year. The corresponding correlation between acoustic and net densities is given in Fig. 5C. The range in densities encountered is less than in the spring cruise and the estimated slope of the relationship appears somewhat low. The most important feature of the comparison, however, is the grand mean of the distributions which does not appear to be substantially different from that given in Needler 10.

We are not yet in a position to provide comparative analysis on other cruises that have been undertaken. Analyzed in the same manner as for the 1984 paper, data on one other Needler cruise and an E.E. Prince cruise, appeared from the field calibration to give results very close to that of Needler 10 in both slope and position of the density relationships. That is, our data do not give any indication of a difference among ships when the field data are used for calibration.

The remaining question is the extension of this study of density derived from dual-beam counting to single beam integration. The data of Fig. 2 indicating a strong correlation between average sizes in net and acoustic transects, also indicates a significant range in the values of average size among different transects. From such data it is apparent that the field calibrated average target strength would need to be used in order to arrive at the best estimates of biomass. Use of an *a priori* fixed, target strength would introduce needless variance. Furthermore, the deviation of the field nomograms for a cruise from the corresponding Foote nomogram would be an index of bias which might be expected in integration. From our limited experience this range of variation in Fig. 3 may represent the extremes for the Scotian Shelf with our equipment. However, if by chance the extremes had been chosen the result would represent a possible 4 fold error in the estimate of biomass. Such possibilities emphasize the need for careful field calibrations which are needed in acoustic survey.

4. THE INFLUENCE OF SURVEY DESIGN

By far the most important component of bias or variance in abundance estimation derives from the survey design (c.f. Jakobson 1983). In the extreme case, a survey transect run in an area when fish are absent from it, gives a wrong answer. An efficient design will stratify the potential area according to pre-established criteria, and will spread the sampling effort over strata in relation to the survey aim. We confine consideration here to the problem of sampling within one such stratum.

The principal advantage claimed for acoustic sampling, compared with any other form of sampling, is that for a given amount of ship time and data processing effort the intensity of coverage is several orders of magnitude higher than for any other known system. Existing acoustic systems can sample the whole water column below the transducer, and high pulse rates permit a high degree of replication. The usefulness of the acoustic estimates therefore depend on their precision, degree of detail and timeliness.

From the simplest possible point of view, the acoustic system could be regarded as one which defines presence or absence of fish within a unit sample volume of a sampling stratum. If the threshold value for detection is known, this method of utilizing acoustical data would eliminate all problems associated with the foregoing sections of this paper. Treated in this way, abundance can be gauged simply by the summation of unit areas containing fish, together with an estimate of density. The precision of the estimate therefore would depend entirely on the sampling intensity, the degree of aggregation of sample volumes and the estimate of density. For example, it is well known from groundfish sampling and verified on our Needler #10 cruise, that the fish density distribution is log-normal. The unit sample size and method of averaging would need to take this into account.

The problems discussed in preceeding sections become important when the acoustical system is used to estimate density within the sample volumes or to detect changes within these volumes over space and time.

From this point of view, the integrator system offers the opportunity to study the variance between sampling volumes. In practice this power of the system seems to have been all too rarely utilized. A notable recent exception is the work of Shotton to examine small-scale variations in echo-intensity within and between herring schools which he will report on separately. Also important have been observations that apparent average target strength per unit volume may vary between day and night or area to area. Substratification of survey data on this basis, would provide a means of greatly improving the precision and have the potentiality of giving relevant biological information about populations.

The present ultimate in this direction is the dual-beam echo counter, which we claim here will not only give information on changes in density, but will also provide information of fish sizes. It is still early for us to put statistical limits on our size determinations, but it is our present aim to give estimates of average size $\bar{m} \pm 5$ cms for most species of demersal fish, at the densities encountered in over 95% of randomly spaced trawl hauls. The level of information provided in the 1984 report of the combination of size-composition and abundance calculations from the field trials with the Needler is close to this level already, and we have not yet analyzed data from transects other than those accompanying the trawling. The data from our 1983 paper show a high variance in density with size and the ECOLOG data offer an opportunity to study this further (c.f. Fig. 6). It appears quite likely that the data can be used to estimate the mortality rates used in assessments. The data on biomass distribution with size also offer the prospect of developing new dynamical systems arising from the theory of the biomass spectrum (Borgmann 1982, Dickie and Kerr in press).

A further important point arises here. Traynor (personal communication) in the Seattle laboratory of the National Marine Fisheries Service, who uses a dual-beam sounder, has indicated to us that he sees evidence of significant changes in average target strengths in his field observations (Williamson and Traynor 1984). This verifies the heterogeneity of distributions which we discuss in our 1983 paper. If these changes have a certain coherency, they indicate that precision of the estimation of the average target strength in integrator studies may be markedly influenced by the integration intervals and may also require frequent modification. That is, the variance arising from the survey may have ~~significant~~ interactions with variance in the calibration and signal interpretation areas, and underlines the importance of systems which would permit field calibration.

With respect to the criterion of timeliness in acoustic analysis, we point out that with ECOLOG it is now possible for a trained computer operator to provide routine estimates of abundance and size-compositions by specified strata from acoustic data on a groundfish cruise in less than one working week. Requirements for provision of integration data appear to be roughly the same. The ideal use of any sea-going sampling system is, however, to be able to control the sampling program itself. A crude example is, of course, the use of a sounder by a fisherman to decide where and when to fish, which requires one level of real-time on board output. Control of sampling effort would need to be at a level of sophistication above this. Our own efforts have included programming on

HP-86 personal computer to give running estimates of density and size-composition. Our preliminary work shows that with existing processing and recording equipment it is possible to output data at about 1/3 to 1/4 of the present rate of acquisition in areas of high groundfish density. We consider this to be close to the minimum acceptable, and further development work is being undertaken.

5. SUMMARY AND CONCLUSIONS

Results of laboratory experiments and field analyses with the dual-beam counting system indicate that repeated observations of single fish may be used to reduce the variance usually associated with measurement of acoustic target strength. Corrections applied to field data permit in situ calibrations which appear to give unbiassed estimates of body-size and population density, as determined from net hauls. The remaining variance between acoustic transects and net hauls within a sample area and cruise appears consistent with the biological variance in population distribution. It remains to be established whether changes in calibration parameters between cruises are related to biological variables such as seasonal changes in condition factor.

REFERENCES

Borgmann, U. 1982. Particle-size conversion efficiency and total animal production in pelagic ecosystems. Can. J. Fish. Aquat. Sci. 39: 668-674.

Clay, C.S. 1983. Deconvolution of the fish scattering PDF from the echo PDF for a single transducer sonar. J. Acoust. Soc. Am. 73: 1989-1994.

Craig, R.W., and S.T. Forbes. 1969. Design of a sonar for fish counting. Fish. Dir. Skr. Ser. HavUnders. 15: 210-219.

Dickie, L.M., R.G. Dowd, and P.R. Boudreau. 1983. An echo counting and logging system (ECOLOG) for demersal fish size distributions and densities. Can. J. Fish. Aquat. Sci. 40: 487-498.

Dickie, L.M., R.G. Dowd, and P.R. Boudreau. 1984. Acoustic estimates of demersal fish using a dual-beam transducer in laboratory and field. J. Acoust. Soc. Am. 76: 1175-1183.

Dickie, L.M., and S.R. Kerr. In prep. Ecological processes affecting size-dependent regularities in aquatic ecosystem structure.

Ehrenberg, J.E. MS. 1972. A method for extracting the fish target strength distribution from acoustic echoes. Proceedings IEEE Conf. on Engineering in the Ocean Environment pp 61-64 (unpublished).

Foote, K.G. 1979. On representing the length dependance of acoustic target strengths of fish. J. Fish. Res. Bd. Canada 36: 1490-1496.

Jakobsson, Jakob. 1983. Echo surveying of the Icelandic summer spawning herring 1973-1982, pp. 240-248 in Symposium of Fisheries Acoustics (Nakken, O and S.C. Venema, Eds.) FAO Fisheries Report No. 300.

Nakken, D., and K. Olsen. 1977. Target strength measurements of fish. Rapp. P. -v. Reun. Cons. Int. Explor. Mer. 170: 52-69.

Olsen, Kjell, J. Angell and A. Løvik. 1983. Quantitative estimations of the influence of fish behaviour on acoustically determined fish abundance, pp 139-149 _In_ Symposium of Fisheries Acoustics (O. Nakken and S.C. Venema, Eds.) FAO Fisheries Report No. 300.

Peterson, M.L., C.S. Clay and S.B. Brandt. 1976. Acoustic estimates of fish density and scattering function. J. Acoust. Soc. Am. 60: 618-622.

Traynor, J.J., and J.E. Ehrenberg. 1979. Evoluation of the dual beam acoustic fish target strength measurement method. J. Fish. Res. Bd. Can. 36: 1065-1071.

Williamson, N.J., and J.J. Traynor. 1984. _In situ_ target strength estimation of Pacific whiting, _(Merlucius productus)_ using a dual-beam transducer. J. Cons. int. Expl. Mer. 41: 285-292.

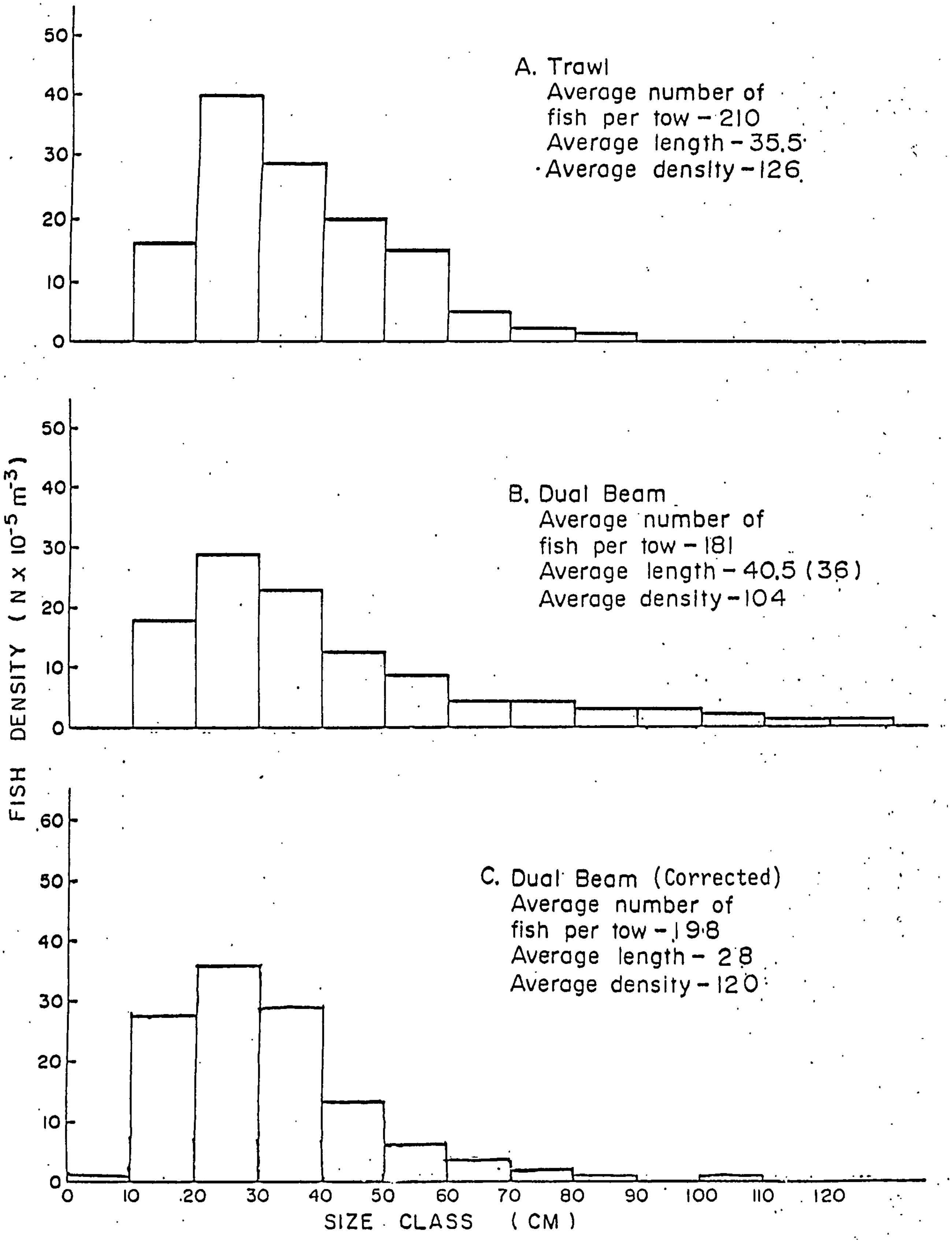

Figure 1. The average density of sizes of demersal fish in 7 transects in the Roseway Bank area. Sizes and densities are derived from

A. 7 30-min hauls of the Western IIA trawl.

B. 7 simultaneous acoustic transects as published in Dickie *et al.* (1984).

C. The same data corrected using the *in situ* calibration.

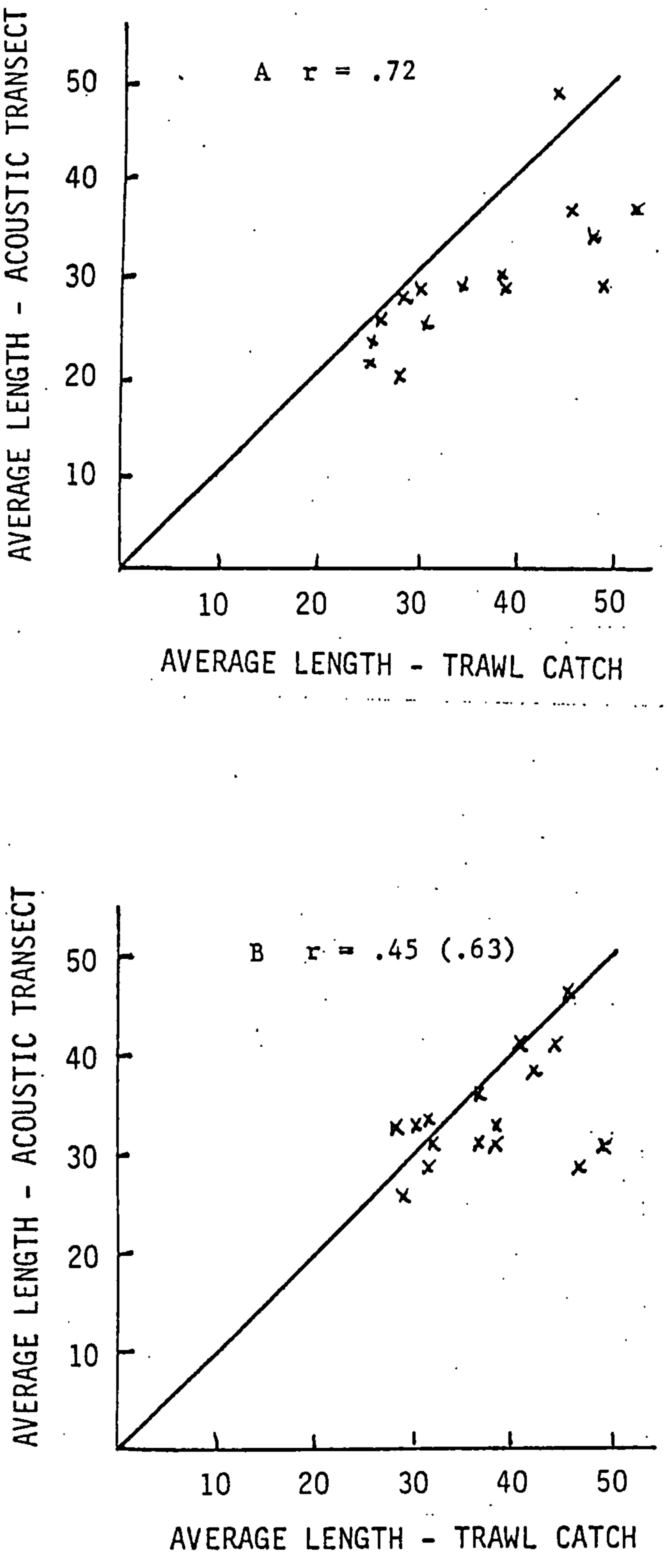

Fig.2. Average Lengths of demersal fish in "haddock" catches of more than 50 fish per haul, calculated from the trawl catch and from the dual-beam acoustic calculations using in situ calibration. A. Needler 10 cruise, May 1983. B. Needler 15 cruise, Sept. 1983.

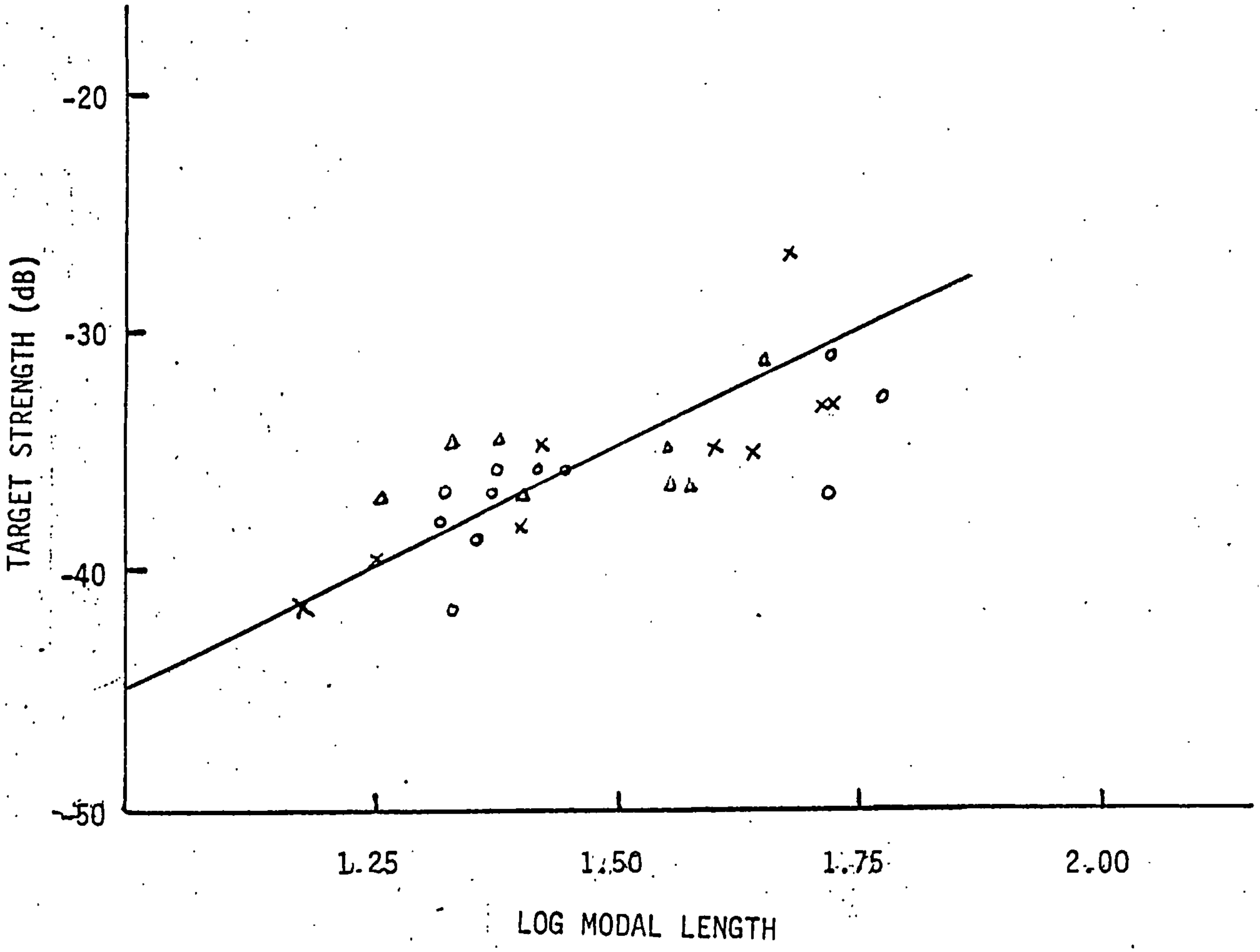

Figure 3. The <u>in situ</u> relationship between target strength and fish length (mainly haddock) in selected transects of three demersal fish cruises. Individual points represent modal values of corrected acoustic transect data plotted against modes in the length distributions of simultaneous tows. Data are from 3 cruises:

X - Needler 10, May 1983
o - Needler 15, September 1983
△ - E.E. Prince 287, October 1983

The line represents the nomogram: $TS = 65.6 + 20 \log L$

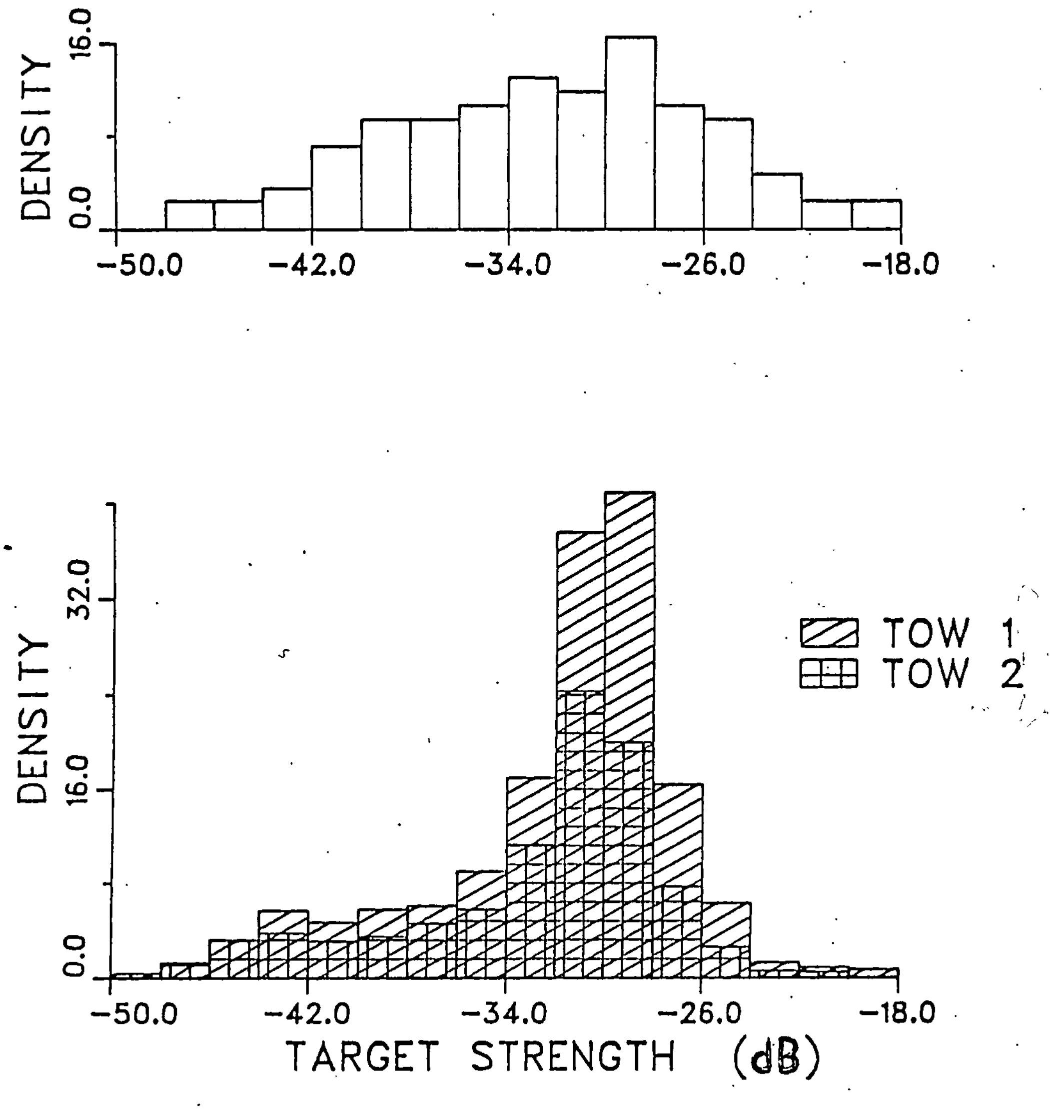

Figure 4. Size frequency distribution of two net hauls, converted to Target Strength (dB) for comparison with acoustic size distribution in the same vicinity, derived from peak dB in each single fish acoustic envelope (from Dickie et al. (1983)).

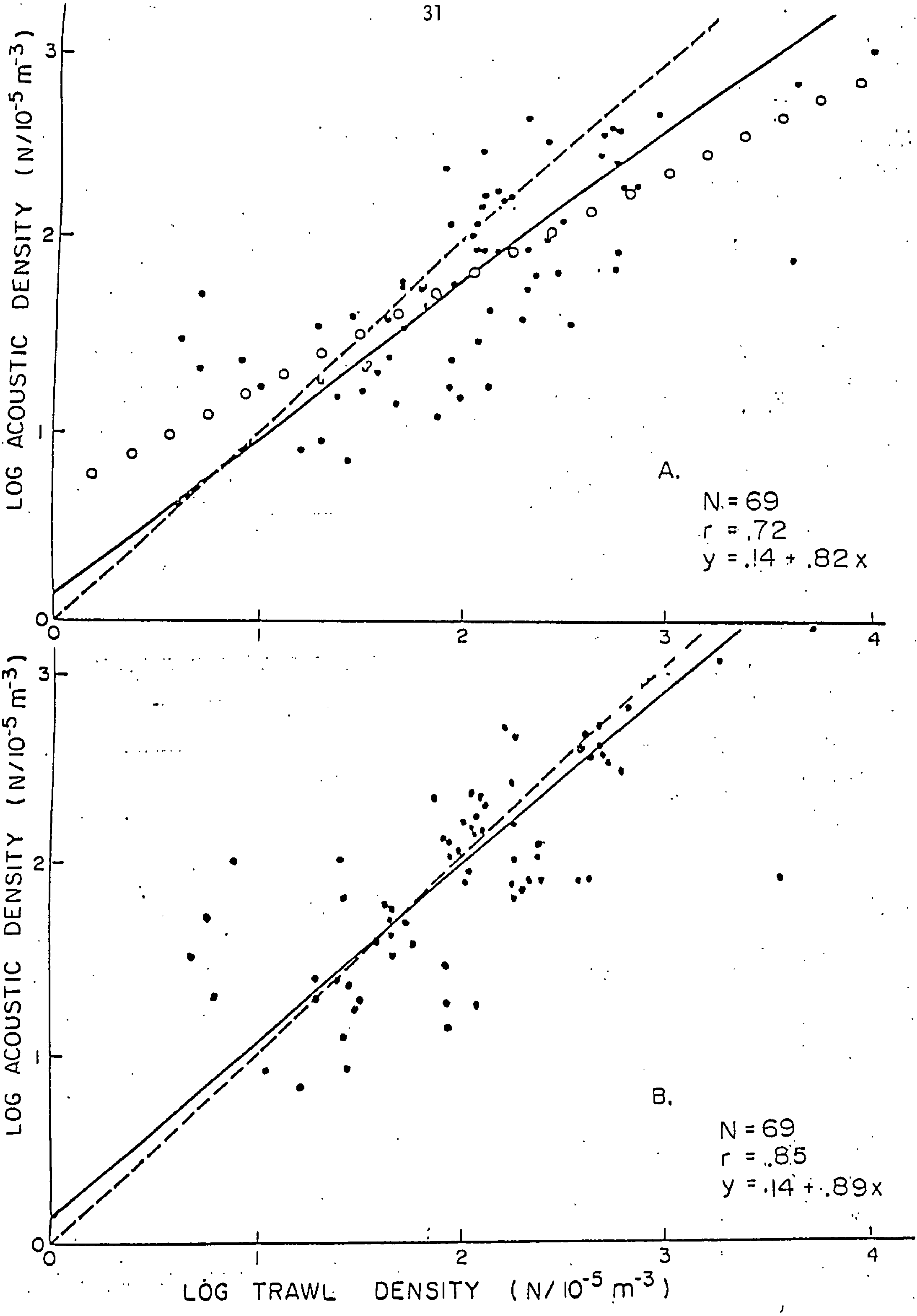

Figure 5. Average fish density per transect derived from trawl hauls and dual-beam counting and sizing techniques.
A. N-10 data, as published in Dickie _et al._ 1984
B. N-10 data, using _in situ_ calibration

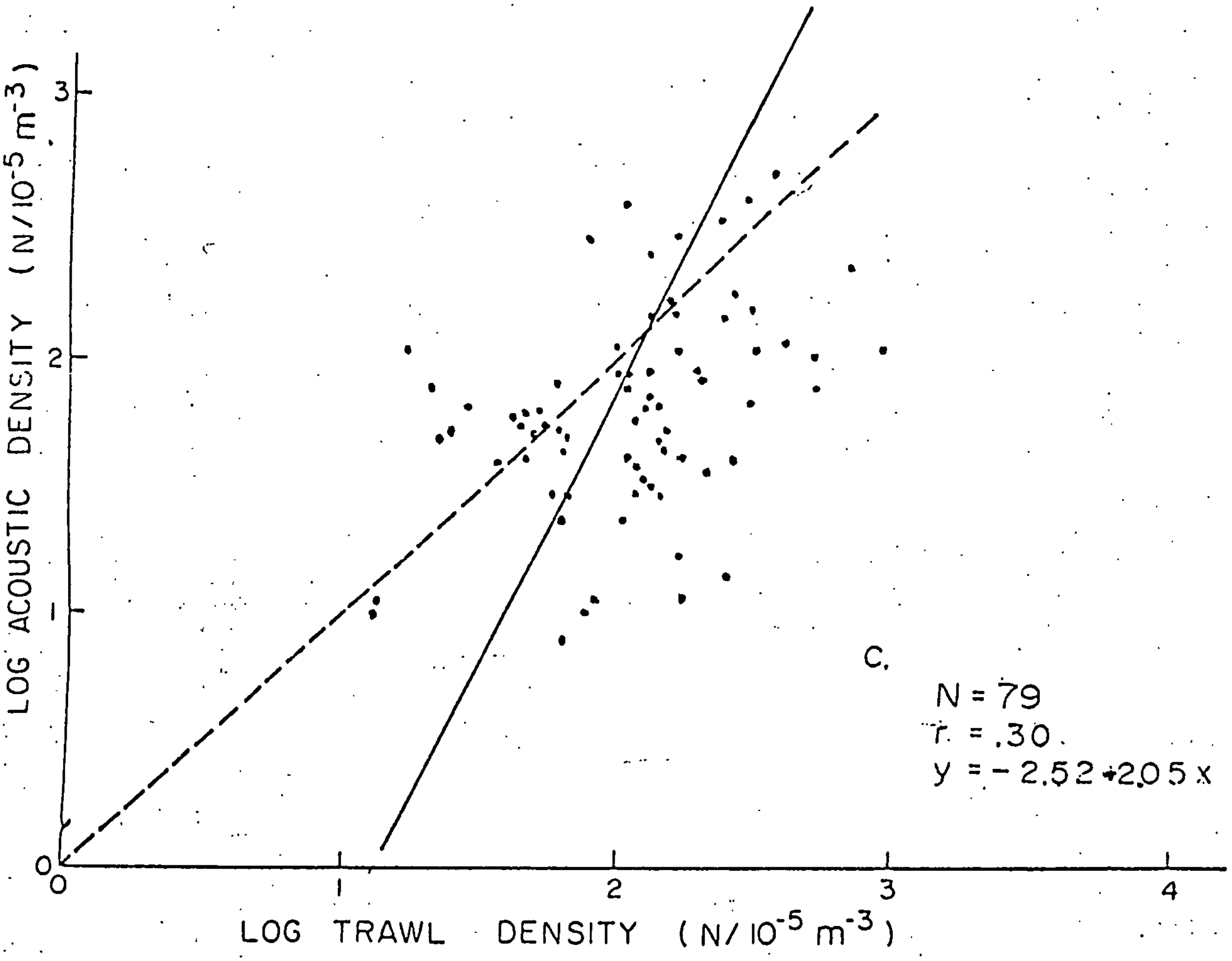

Figure 5. Average fish density per transect derived from trawl hauls and dual-beam counting and sizing techniques.

C. N-15 data, using in situ calibration

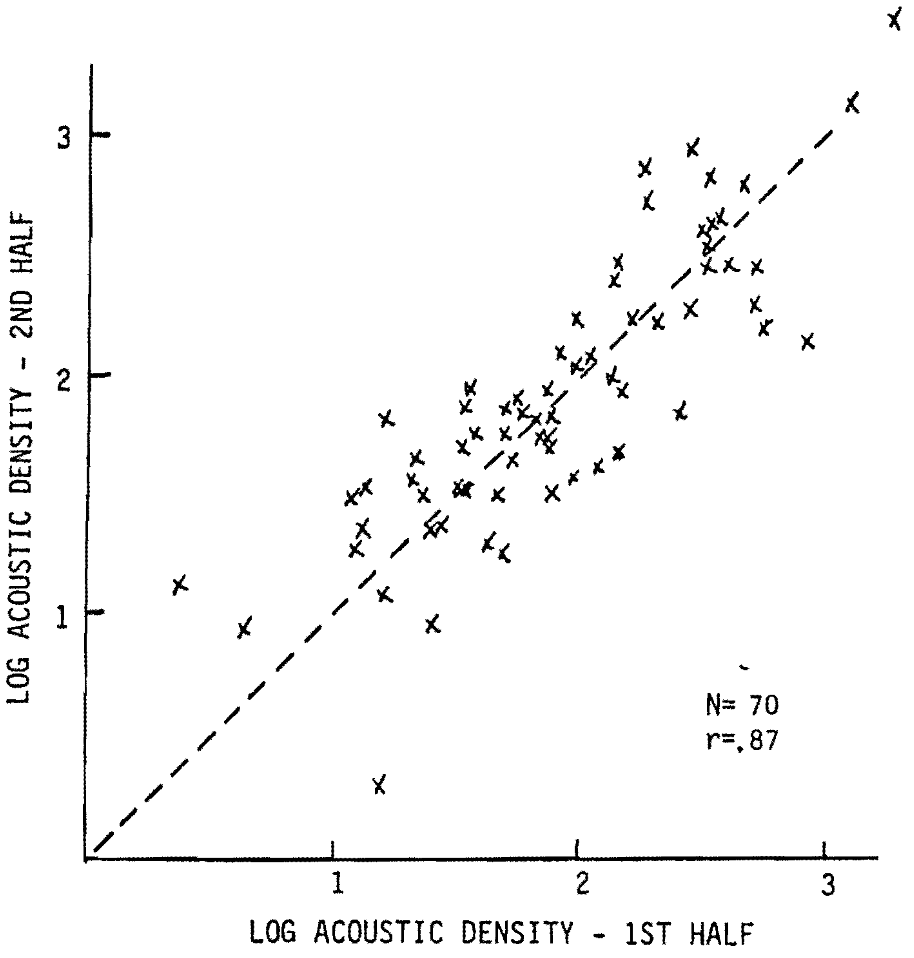

Fig. 6. An index of population variance within transects of cruise N-10: the correlation between densities of the first and second halves, calculated from acoustic counts and body-size data.