J. Cons. int. Explor. Mer, 38(1): 28–32.

The present state of acoustic survey

D. H. Cushing

Fisheries Laboratory, Lowestoft, Suffolk NR33 OHT, England

A distinction is drawn between methods for counting single fish and estimating biomass. Biases in both systems are indicated, and the most important of these is the capacity of the biomass method to record signals from animals smaller than desired. The best system would count individual fishes and record integrated signals from shoals and in this way the biases in either system are minimized.

Introduction

Since the mid-fifties there have been four stages in the development of acoustic survey in fisheries science. The first step was the recognition by Midttun and Saetersdal (1957) that single fishes could be detected on a paper recorder and hence could be counted in absolute numbers. Secondly, Craig and Forbes (1969) advocated the use of high frequency (400 kHz) so that shoals could be reduced to single fish so far as possible and then counted, perhaps automatically. The third step (Cushing, 1968) was to count single fishes and to calculate the volume sampled so that estimates of fish density were made. The final step made by Bodholt (1969) was to use volume reverberation theory (Raitt, 1948) to express the quantity of fish as biomass beneath unit surface.

The theoretical basis was derived from the sonar equations developed in studies of undersea warfare. Two forms of the sonar equation are relevant, that for single targets and that for a scattering layer. The first describes the signal from a point source, a single target, whereas the second describes that from the volume of a range shell.

Theory

The two sonar equations are as follows:

(a) Single targets

$$I = I_0\,(\sigma/4\pi)\,\{[\exp(-2\alpha R)]/R^4\}\,b^2(\theta, \varphi), \qquad (1)$$

where I_0 (or S) is the source level (in dB rel 1 μb), or intensity, in W m^{-2}; I (or E) is the signal, or echo level, in dB rel 1 μb, from a target at range R in m; $\sigma/4\pi$ (or T) is the scattering cross section (cm^2) (or target strength, dB rel 2 m radius sphere) α is the attenuation coefficient; and b is the directivity function in two dimensions, θ and φ.

This equation may also be written as

$$E = S + T - (40 \log R + 2\alpha R) + 20 \log b\,(\theta, \varphi).$$

(b) Scattering layer

$$I = I_0\,(\sigma/4\pi)\,\{[\exp(-2\alpha R)]/R^4\} \int_0^{\Omega} N R^2\,(c\tau/2)\,b^2(\theta, \varphi)\,\mathrm{d}\Omega$$

$$= I_0\,(\sigma N/4\pi)\,\{[\exp(-2\alpha R)]/R^2\}\,c\tau/2 \int_0^{\Omega} b^2(\theta, \varphi)\,\mathrm{d}\Omega.$$

Let $\int_0^{\Omega} b^2(\theta, \varphi)\,\mathrm{d}\Omega$ be constant $= \Omega_0$, a solid angle, then $I = I_0\,(\sigma N/4\pi)\,\{[\exp(-2\alpha R)]/R^2\}\,(c\tau/2)\Omega_0$, (2)

where N is the number of fish; c is the speed of sound in water in m s^{-1}; and τ is one pulse length in m. Again,

$$E = S + T + 10 \log N(c\tau/2) + 10 \log \Omega_0 - (20 \log R + 2\alpha R).$$

In recent years amplifiers with Time Varied Gains (TVG) have been introduced, with the result that effects due to spreading and attenuation are compensated; the terms $\{[\exp(-2\alpha R)]/R^4\}$ in Equation (1) and $\{[\exp(-2\alpha R)]/R^2\}$ in Equation (2) may then be left out. So Equations (1) and (2) become respectively

$$I = I_0\,(\sigma/4\pi)\,b^2(\theta, \varphi)$$

and

$$I = I_0\,(\sigma N/4\pi)\,(c\tau/2)\Omega_0.$$

The difference between the two expressions lies in the treatment of sampling volume. For a given signal-to-noise ratio, in Equation (1), target strength and sampling volume are distinct and may be estimated independently. In Equation (2) the sampling volume is predetermined. Hence the volume increases with range as R^2 and, as the signal from the scatterers *in that volume* decreases with $1/R^2$, the two effects cancel at any particular range. The essential expression is $\sigma N/4\pi$; as $\sigma/4\pi$ $(= T) = aW^{0\cdot72}$, where W is the weight of a target animal, we have effectively biomass from a fixed volume at any given range.

The single fish method (or 40 log R) was developed for counting single fishes and the scattering layer one (or 20 log R) for integrating signals from scattering layers or shoals although signals from single fishes are integrated perfectly well. For convenience I shall refer to the two methods as the single fish and the biomass methods respectively.

Integration and counting

Although we know little of how sound is propagated within a fish shoal, numbers are proportional to intensity. Signals received from fish shoals or from scattering layers as voltage are squared and integrated in time. Then the integrator output includes shoals and single fishes within the volume sampled.

Within small shoals, numbers are probably proportional to intensity quite properly. As packing density increases, which may occur as shoals increase in size (Cushing, 1977), one would expect sound to be absorbed, scattered or reverberated between fish. The evidence for this is that some dense shoals cast shadows on the bottom (as shown by reduced bottom signal beneath them) and others of aggregated pattern extend in range with constant signal as if reverberation continued in time. There are two potential sources of bias, that numbers are under-estimated by the shadowing effects and over-estimated due to reverberation. However, very recent work by Røttingen (1976) on the integrated signal received from known numbers of fish (sprat and coalfish) suggests that signal is proportional to numbers up to relatively high densities of about 2/3 lengths apart. Weihs (1973) has suggested on hydrodynamic grounds that fish should not usually shoal at greater densities than one length apart. Hence it is possible that numbers are proportional to intensity on nearly all occasions. If this generalization is true, then the problem becomes a purely biological one of determining the circumstances under which fish shoal more closely than 2/3 lengths apart.

A counting system depends on the description of a single fish signal as being of one pulse length (within the limits of a bandwidth limited system) and of more than a given amplitude above a threshold. A discriminator can separate single fish signals from shoals with longer pulse lengths with a cycle counter and the single fishes can be counted. Then such shoal signals are squared and integrated in time on an integrator.

There are three ideas necessary to the concept of signal discrimination. *Resolution* is the separation of signals from single fish at the threshold of a fixed number of cycles, e.g. 2. *Discrimination* is the establishment of a single fish signal to within the resolution of the equipment, e.g. 2. *Range coincidence* is the appearance of two single fish signals at the same range to within that fixed number of cycles, e.g. 2. Although signals can be discriminated to 2 cycles, that number or more is needed for resolution because signals that overlap in range may interfere with each other.

If fish are randomly distributed within a range gate, the chance of range coincidence may be calculated. At 30 kHz, 2 cycles = 0·1 m and 1 ms = 30 cycles. Within a range gate of X metres, the chance of the range coincidence of two fish is $0\cdot1/X$. The maximum number that can be resolved within that range gate is $X[(c\tau/2) + 0\cdot1] = X/0\cdot85$. The chance of range coincidence of the maximum number to be resolved is $(0\cdot1/X)\,(X/0\cdot85) = 0\cdot118$, irrespective of the length of the range gate; in cycles, it is effectively $2/(15 + 2)$ within one pulse as my colleague Dr M. G. Pawson pointed out to me. The chance of range coincidence of two fish decreases with increasing length of range gate; for range gates of from 10 to 100 m, the chance of range coincidence decreases from 12% to 0·1%. This approach is invalid if the fish are not randomly distributed with respect to the gate, e.g. if they were layered within a large gate.

The question arises whether such errors are tolerable. First, to estimate target strength *in situ*, the error in range coincidence is equally a bias in amplitude, which at the maximum density for resolution might bias the mean signal; it might be minimized by restricting the counts to one in each transmission, i.e. an error of about 1% in a range gate of 10 m. It would be desirable to restrict the range gate to limit the spread in size of the fish sampled. Secondly, in fish counting within specified size ranges, the error in numbers may be less important; if 12% is the maximum and the rest are arranged in the appropriate Poisson distribution down to very low levels, the average bias in numbers would be less than 5%. The important point is that the under-estimate in numbers is low and calculable (being a function of density in numbers), but that the under-estimate in mean amplitude cannot be easily calculated and should be eliminated so far as possible.

There are two further difficulties about such a counting system:

(a) That a signal of one pulse length at low amplitude just above a threshold may have few cycles; however, a relationship between threshold and the discriminating number of cycles can be established which secures the discriminatory character.

(b) Discrimination between single fish and shoal has to be made conventionally at a fixed number of cycles, and information may be lost between single fish and shoal, leading to some small under-estimates; e.g. a single fish is classified at $< n$ cycles, but a shoal may be classified at $> 2n$ cycles.

The counting technique works well when the signals are strong and the number of cycles is not reduced, i.e. on big fish at not too great a range, such as cod at 200 m. The system failed on blue whiting, a much smaller fish that lives between 300 and 500 m; the reason for failure was that signals were too close to the threshold and discrimination broke down because the signal-to-noise ratio was too low.

There is an important difference between counting and integration that has not yet been pointed out. When single fish are counted, the signals are defined in amplitude and in pulse length. The pulse length defines it as a single fish and the amplitude therefore sets a lower limit in size which could correspond, for example, to an age of first capture. The equipment may be set up to count all single fishes larger than, for example, 20 cm and it will never count smaller fish unless they are shoaled and the signals passed to an integrator.

On the integrator, using the biomass system, there is no pulse length restriction and only biomass is recorded. A threshold might be set on the integrator in $(\text{voltage})^2$ to represent the single 20 cm fish, but the system is open to a biomass of smaller animals yielding the same signal. Thus, even with a threshold, the integrator is open to signals from the biomass of smaller animals and absurdly from very small animals indeed.

The point has been partly realized by Nakken (1975). The Norwegian method of setting up an integrator is to integrate signals from single fish and to relate numbers to integrated voltage. In this system, there is an intercept to the regression of numbers on integrated voltage which is sometimes high. But the intercept only records the added biomass noticed by the integrator during the calibration and quite different added quantities may be integrated during the survey. Hence the integrator may estimate biomass beyond the intention of the survey. Johanneson (1975) recorded 5 million tons of biomass in Lake Tanganyika, whereas biological estimates based on water clarity or lake physiography are limited to 0·1–0·2 M tons; indeed, Fryer and Iles (1972) suggest 13 kg/ha/year (= 45000 tons). It is possible that an over-estimate was made in the way suggested.

Summarizing, an integrator will tend to bias the estimated biomass overall in that small animals are included. A counting system linked to an integrator counts the right number of single fish, but its integrator is open to exactly the same biases. The advantage is that the biases are limited in space to where shoals occur; to the extent that they are true shoals, the chance of finding inadvertent small animals amongst them is very much reduced. As fish nearly always disperse at night, the counter-cum-integrator will reduce the bias in biomass even when shoals predominate in daytime – provided, of course, that the survey is conducted both night and day.

Noise and sampling volume

Any acoustic measurement at sea is limited in range by the received noise, primarily from the sea state and the ship's propeller, although there are other components from the water itself and from the reverberation of the transmitted signal. The critical point is that noise increases sharply with worsening weather. The limit in range is treated differently in the two systems, single fish counting and biomass estimation.

In the counting system, the smallest fish required is detected to a maximum range on the axis defined by the signal-to-noise ratio. Larger fish are detected to greater ranges on the axis in accordance with their greater target strength but are limited in range by the same signal-to-noise ratio. The sampling volume is defined by that signal-to-noise ratio at path lengths off the axis. Typically, such a sampling volume is shaped somewhat like a peardrop in range, with maximum volume at middle ranges, small volumes at short range and zero volume at maximum range. There is a different sampling volume for each size of fish and each density of biomass and methods for calculating them were given in Cushing (1973)[1]. Expected echo levels can be calculated for each size of fish together with the sampling volumes; provided that the echo level can be properly estimated (as, for example, on a storage oscilloscope) and so sizes of individual fishes can be calculated. Maximum ranges and sampling volumes for each size of fish are determined by the signal-to-noise ratio.

---

[1] That system, however, was designed for deep-water work and the side lobes in directivity were ignored.

In the biomass system one step can make the sampling volume constant; the directivity pattern is integrated through the side lobes and may be taken to be constant to infinite range. It is convenient to calculate in decibels in Equation (2) and the problem of noise is ignored except in determining the maximum range, as a threshold. Whatever system is used, a maximum range must be defined at which the signal from biomass is greater than noise by a factor. Then the integration must be performed in angle to one less than the maximum. If the threshold on the integrator is set as a factor of the signal-to-noise ratio, then the integration in angle is performed to that threshold.

On any path length, the TVG compensates for range and attenuation. The signal from a single fish is the same at all ranges on that path length because the TVG increases the signal with increasing range, so the signal-to-noise ratio decreases with range. Then if noise is ignored for the convenience of calculation it is necessarily included in the integration at long ranges. If however the threshold is some factor of the signal-to-noise ratio, noise is excluded from the integration. It follows that the sampling volume is noise limited. Because noise varies with depth of water and with sea state, it should be monitored frequently in case the sampling volume has become reduced.

Sometimes a solid angle equivalent in volume to the total sampled in range is used. Figure 1 (from Urick, 1967) shows the equivalent ideal beam pattern (dotted line) which approximates the true pattern (full line); Urick tabulates values of the ideal solid angle ψ for different transducer arrays. It is calculated effectively to a noise limited threshold in range, but not in angle, but the slight over-estimate in angle at short ranges need not matter. If a gate from short range to maximum range is used, the procedure is entirely satisfactory and was used initially for estimating volume reverberation in the deep ocean (Raitt, 1948). If, however, a short and intermediate gate is used, the sampling volume may become biased as shown in Figure 1. With a cone of equivalent angle, a gate at short range may sample less volume than the insonified one and that at maximum range will sample a greater volume. At intermediate ranges, the volumes may be about the same, but the definition of "intermediate" depends on the noise level and the threshold.

Noise may be treated in the following way. A threshold in biomass may be entered on the integrator, a minimum recordable biomass which is not attributable to any range. A maximum range can be defined with the signal-to-noise ratio, which sets the extreme sampling volume. In principle a threshold need not be used if range were unlimited and noise were expressed in tons/km^2 of "biomass", to be subtracted from the observations. In practice, the dynamic range of an integrator is limited and so a threshold is conveniently set at a high signal-to-noise ratio.

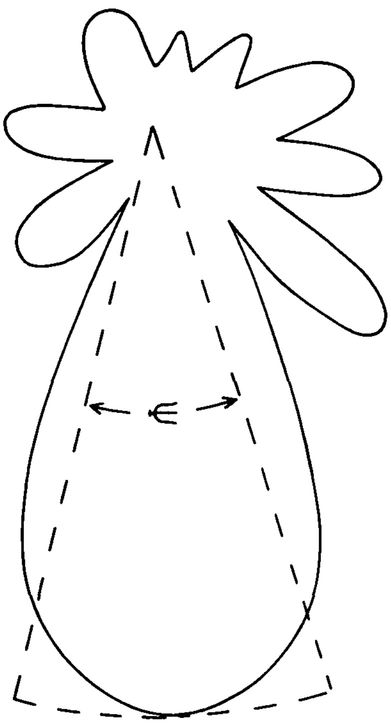

Figure 1. The directivity pattern of an echo sounder (full line) and the equivalent beam pattern (dotted line). (After Urick (1967), Fig. 4.1).

The important point is that the sampling volumes in the two systems differ. The single fish system demands a sampling volume for each size of fish, each of which is a noise limited one. Most populations in a given survey area comprise animals of limited size ranges and so a range of sampling volumes can be specified for particular depths (see Cushing, 1973). Those in the biomass system are larger and the biomass is recorded as beneath a larger area, or less biomass per unit area. The biomass per unit volume is the same in both systems, but the biomass system includes animals smaller than those specified in the single fish system. This bias (with respect to that sampled by the single fish system) is additional to that mentioned above.

Either method is valid, but the objectives differ. The single fish system which demands a separate estimate of sampling volume and of target strength is aimed at a size distribution of fishes greater than a minimum. The biomass system, with sampling volume and target strength linked, is aimed at biomass. Provided that the targets are not adulterated with smaller animals, the two methods should give the same result; if, however, smaller animals are present, the biomass system is open to the greater bias.

Discussion

An acoustic survey is made to estimate the stock (in numbers) or biomass (weight) of a particular population. There are two types of stock estimate needed, an exploratory one or a quantitative one. An exploratory stock estimate is made to establish whether a given stock is large or small and such a stock is usually unexploited. A quantitative stock estimate would be used when there is need to make an estimate independently of other methods. In the first, the bias in unintended living material in the biomass method is perhaps acceptable, *if recognized*. In the second, such bias should be reduced as much as possible and the single fish method is to be preferred.

At the present time the stock of blue whiting to the west of the British Isles is estimated using the biomass method, primarily because the counting technique does not work well at ranges greater than 300 m on such small fish. The fish live in a characteristic layer between 300 and 500 m, which extends 30–60 miles off the continental shelf. When a midwater trawl is shot in the layer, only blue whiting are caught. However, with the biomass method we recall that the system is open to the biomass of small animals, perhaps pearlsides (*Maurolicus mulleri*). If a small meshed cover is put on the trawl and no pearlsides are caught, the potential bias does not exist; if they are caught, the quantity can be estimated and the bias calculated. In this way the potential bias to the system is removed. However, not all exploratory surveys will be as simple and lucky as this.

There is a stock of mackerel in the western English Channel which spawns in spring in the Celtic Sea; the older fish may migrate north to the Shetlands in summer. This stock is exploited and a quantitative and independent stock estimate is needed at the present time. At the moment the acoustic survey covers an area south of Devon and Cornwall to mid-Channel in winter time. There are dense shoals of small mackerel which are located in Mount's Bay and off the Dodman and Manacles and which disperse at night. There are dispersed layers in the west of the area. Herring, sprat and horse mackerel live in the east. Such different species can only be eliminated by trawling for identification purposes on a fairly extensive scale. Within a "mackerel area" a counting-cum-integrator system would work well because (a) the water is shallow (b) there are extensive areas of dispersed fish in daytime (c) the fish disperse at night. The quantities of single fish in a survey worked by day and night may well predominate. The dense shoals are probably exclusively of mackerel and so the potential bias in the integrator is very much reduced. The lower limit of size might be set at 20–25 cm (when the target strength of mackerel has been more firmly established), which is about the lower size limit caught by the local fleets. There is no reason why such an estimate should not be a quantitative one of considerable value in the study of the exploited stock.

There will always be a case for an exploratory survey, particularly in under-developed seas. As exploitation extends, the fisheries biologist should prefer the quantitative survey, if only because in the end he prefers to use a size distribution. Perhaps we should return to the use of high frequency (100–500 kHz) with higher resolution for counting and a reduction of the biomass (and others) biases in shoals.

References

Bodholt, H. 1969. Quantitative measurement of scattering layers. Simrad Bull., 3: 9 pp.

Craig, R. E. & Forbes, S. 1969. Design of a sonar for fish counting. FiskDir. Skr., (Ser. Havunders.), 15: 210–19.

Cushing, D. H. 1968. Direct estimation of a fish population acoustically. J. Fish. Res. Bd Can., 25: 2344–64.

Cushing, D. H. 1973. Computations with the sonar equation. J. Cons. int. Explor. Mer, 35: 22–6.

Cushing, D. H. 1977. Observations on fish shoals with the ARL scanner. Rapp. P.-v. Réun. Cons. int. Explor. Mer, 170: 15–20.

Fryer, G. & Iles, T. D. 1972. The Cichlid fishes of the great lakes of Africa; their biology and evolution. Oliver & Boyd, Edinburgh, 641 pp.

Johanneson, K. A. 1975. Preliminary quantitative estimates of pelagic fish stocks in Lake Tanganyika by use of echo integration methods. EIFAC Tech. Pap. Suppl. 1: 292–306.

Midttun, L. & Saetersdal, G. 1957. On the use of echo-sounder observations for estimating fish abundance. ICNAF Spec. Publ., 2, Paper 29, 4 pp.

Nakken, O. 1975. On the problem of determining the relationship between intergrated echo intensity and fish density. ICES CM 1975/B: 26, 7 pp. (mimeo).

Raitt, R. W. 1948. Sound scatterers in the sea. J. mar. Res., 7: 393–409.

Røttingen, I. 1976. On the relation between echo intensity and fish density. FiskDir. Skr., (Ser. Havunders.), 16: 301–14.

Urick, R. J. 1967. Principles of underwater sound for engineers. McGraw-Hill, New York, 342 pp.

Weihs, D. 1973. Hydromechanics of fish schooling. Nature, Lond., 241: 290–1.