CALIBRATION OF ACOUSTIC INSTRUMENTS FOR FISH DENSITY ESTIMATION: A PRACTICAL GUIDE

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SUMMARY

The acoustic estimation of fish biomass, as currently practiced, requires calibrated equipment. A good calibration is essential to good biomass estimates although it cannot guarantee these. We describe how to perform a high-precision calibration by means of a standard target sphere. This involves primary measurements of three quantities: (1) on-axis sensitivity of the overall echo-sounding and integrating system, (2) time-varied-gain function of the receiver, and (3) equivalent beam angle of the transducer. If the transmitter, transducer, receiver or echo-integrator perform poorly, however, a good calibration is not possible. Measurement of the electrical properties of the system components is therefore included as an element of calibration. In this paper each of the four mentioned elements of calibration are described both in principle and in practice, with detailed examples drawn from experience. Calibration accuracy and inter-ship calibration are also described in some detail. In conclusion, the provisional nature of this work is emphasized, as new developments will undoubtedly continue to improve on present techniques.

LIST OF SYMBOLS

A	arbitrary constant
$b^2(\hat{r})$	beam pattern product; combined transmit and receive intensity in direction $\hat{r}$
c	speed of sound
c(z)	depth dependent function of speed of sound
C	calibration factor
C_I	the "instrument" constant
C_s	constant in the equation for $\Phi_{o,\,i}(R)$
$d\Omega$, $\Delta\Omega$	element of solid angle
D	attenuation
D_1	attenuator setting
E(R)	time-varied-gain (TVG) error for a target at range R
E_r	average TVG error over depth channel of interest
E_1	integral of the standard target echo, without TVG correction
g	TVG correction factor
G	total receiver amplification
I	electrical current
M	echo-integrator output from fish targets
M_1	echo-integrator output from the standard target, with TVG correction
P	average power input to the transducer
R	range of fish
R_a	upper limit of depth channel of interest
R_b	lower limit of depth channel of interest
R_i	range corresponding to t_i
R_1	range of standard target
R_2	expiration range of TVG function

SL	source level on transmit
S_c	transmitting current response
S_p	transmitting power response
t	time after start of transmit pulse
t_g	time delay or start time for TVG function
t_h	correction factor which allows for delay introduced by electronic filters and transducer response
t_i	time at which gain is measured
t_s	mid point of gate pulse used to sample receiver output
t_1	time from transmit pulse to received echo half-amplitude point
TS	target strength in dB
TS_1	target strength of the standard target
U_{gen}	output voltage of signal generator
U_i	receiver input signal amplitude
U_{in}	voltage on transducer terminals
U_{max}	receiver output signal amplitude, at TVG expiration
U_{20m}	receiver output signal amplitude, at time corresponding to 20 m range
U_r	calibrated output signal amplitude
U_{p-p}	peak to peak voltage of the transmitter output
U_1	sphere echo level
V(R,t)	receiver output amplitude from a target at range R
VR	voltage response of transducer and echo-sounder at expiration range of TVG function
W_i	TVG sample interval
z	depth parameter
z_1	depth of transducer
z_2	depth of standard target
Z_3	transducer impedance at the centre frequency

α	acoustic absorption coefficient (measured in dB/m)
β	acoustic absorption coefficient (measured in nepers/m)
$\phi(t)$	receiver voltage gain (amplitude) as a function of time
$\phi_i(t)$	ideal TVG function
$\phi_m(t)$	measured TVG function
$\Phi(R)$	receiver voltage gain (amplitude) as a function of range
$\Phi_i(R)$	ideal receiver voltage gain (amplitude) as a function of range corresponding to time t_i
$\Phi_{m,i}(R)$	measured gain as a function of the nominal range $R = \frac{1}{2} c (t_i - t_g)$
$\Phi_{o,i}(R)$	measured gain function optimised to give g = 1 at range of fish
ρ	quantity of fish per unit area. The quantity may be either the number or the weight of fish.
Ψ	equivalent beam angle
σ	backscattering cross section
$\langle\sigma\rangle$	average backscattering cross section of unit quantity of fish. To satisfy equation (1), the same units of fish quantity (number or weight) must be used in the definition of ρ and $\langle\sigma\rangle$.
σ_1	effective backscattering cross section of standard target
Θ	beam angle of circular transducer between 3 dB down points
Θ_A, Θ_B	3 dB angles of beam from a rectangular transducer

1 INTRODUCTION

This report has been prepared as a result of discussions in the Fisheries Acoustics Science and Technology (FAST) working group of the ICES, particularly at meetings in Hirtshals, Denmark, 2-4 May 1984; Tromsø, Norway, 22-24 May 1985; and Hull, England, 14-16 May 1986.

Acoustic instruments such as the echo-sounder have long been used in fisheries research. For more than two decades, there has been increasing interest in obtaining quantitative as well as qualitative information from fish echoes, especially for biomass estimation. This requires careful calibration of the acoustic equipment. Further, when more than one research ship is engaged on an acoustic survey, it is essential to ensure that calibrations are performed with sufficient accuracy by all concerned.

1.1 The Application

Echo integration is the most widely applied acoustic method for estimating the abundance of scattering organisms in the sea (Johannesson and Mitson, 1983; MacLennan and Forbes, 1984, 1986). The technique depends upon measuring the energy in the echoes received by an echo-sounder. The echoes are observed at the echo-sounder output as electrical signals which are applied to the echo-integrator. Thus the equipment performs an electrical measurement which then has to be converted to the estimate of fish density.

1.2 Scope of the Report

According to the McGraw-Hill Dictionary of Scientific and Technical Terms, to calibrate means "to determine by measurement or comparison with a standard the correct value of each scale reading on a meter or other device or the correct value for each setting of a control knob". In the case of the acoustic equipment used for fish stock surveys, the "scale reading" is the echo-integrator output and the "correct value" is the fish density in the transducer beam. The purpose of the calibration is to measure or deduce the conversion factors which relate the fish density to the echo-integrator output. To do this, we require knowledge of (a) the scattering properties of the targets which caused the echoes, normally described by the target strength, and (b) the performance of the equipment itself, such as the transducer sensitivity. Both (a) and (b) are relevant to the relationship between the fish density and the echo-integrator output. However, the study of fish target strength is itself a major research topic and will not be considered here. In this report, we confine attention to the performance of echo-sounder and echo-integrator equipment, and how this performance should be measured.

1.3 Calibration Techniques

Blue (1984) and Robinson (1984) have reviewed various techniques for measuring the performance of acoustic survey equipment. A brief summary is presented below.

The calibration may be performed as a single measurement of the complete acoustic system, as in (a) and (b) below, including the fish target strength. However, this approach provides no information about the cause of observed variations which could be associated with equipment malfunction or changes in fish behaviour. The alternative is to perform separate measurements on component parts of the equipment, as in (c-e). These are techniques for determining the on-axis sensitivity. In addition, to complete the equipment calibration, two other parameters must be measured or estimated. These are the equivalent beam angle and the time-varied gain (TVG) function, which will be discussed in detail later in this report.

(a) Measurements with caged fish (Johannesson and Losse, 1977). A known quantity of fish in a cage is insonified. Thus the calibration includes the fish target strength. However, the effect of captivity on the fish behaviour and hence the target strength is uncertain, so the results may not be representative of fish in the wild. Caged fish measurements are now considered to be too inaccurate for the calibration of fishery echo-sounders.

(b) The inter-ship calibration (MacLennan and Pope, 1983) is a direct comparison between the integrator outputs of two ships as they steam over the same area. This is a relative measurement and not an absolute calibration, unless one ship is regarded as a "standard reference". The measurement may be subject to large fluctuations because of differences in fish density below the two ships, when the accuracy will be poor. The inter-ship calibration is inadequate by itself. Absolute calibration of the acoustic equipment is essential.

(c) Reciprocity calibration (Robinson and Hood, 1983). This determines the combined source level and receiving sensitivity of the survey transducer by making acoustic measurements involving two other transducers. There are practical difficulties in aligning the transducers and achieving the necessary free-field conditions which limit accuracy, especially when calibrating in less than ideal conditions at sea.

(d) Calibrated hydrophone. This device is a secondary standard which is placed below the survey transducer to measure the source level. The accuracy depends upon the stability and alignment of the calibrated hydrophone and is generally very poor.

(e) Standard target (Foote and MacLennan, 1984). A standard or reference target, normally a sphere which has known acoustic scattering properties, is suspended below the survey transducer. The received echo is a measure of the combined source level and receiver sensitivity. It is now generally accepted that the standard target technique provides the most accurate measurement of the on-axis transducer sensitivity of fishery echo-sounders (Robinson, 1984).

Techniques for hydroacoustic calibration have developed rapidly in recent years (Foote et al., 1981; Simmonds et al., 1984). Standard calibration targets with well defined acoustic scattering properties have become available, in particular solid spheres of either copper or tungsten carbide cermet (Foote and MacLennan, 1984). The development of techniques for beam pattern measurement has led to more precise estimates of the equivalent beam angle (Simmonds, 1984a). As a result, calibration errors are no longer an important limitation on the accuracy of acoustic stock estimates, provided the calibration is performed competently and in accordance with the procedures described in this report.

1.4 Organisation of the Report

In this report, we begin with a discussion of the theoretical background to modern calibration technique. Then we go on to consider the several measurements which comprise the calibration. These are discussed under four headings. The first three, of on-axis sensitivity, time-varied gain, and equivalent beam angle, are primary measurements in the sense that they are required in calculating the fish density from the echo-integrator reading. The fourth category, electrical measurements, are secondary insofar as they are performed to check on the equipment.

Finally, we discuss the accuracy of present calibration technique, and we describe a method of inter-ship calibration. Although the latter method is not a substitute for the full calibration technique described in the earlier sections, it does allow direct comparison of the complete systems of two or more ships.

2 THEORY AND DEFINITIONS

The output of the echo-integrator is used to estimate the quantity of fish per unit area, ρ, according to the equation

$$\rho = \{Cg/(\Psi\langle\sigma\rangle)\}M \quad \text{........ (1)}$$

where C is a calibration factor, g is the time-varied gain (TVG) correction, Ψ is the equivalent beam angle of the transducer, $\langle\sigma\rangle$ is the average backscattering cross section per unit quantity of fish, and M is the echo-integrator output.

The "quantity" may be either the number or weight of fish. To satisfy equation (1), the same units of fish quantity must be used in the definition of ρ and $\langle\sigma\rangle$.

The purpose of the complete equipment calibration is to determine values for the three factors C, g and Ψ. They are defined and discussed in the following paragraphs.

2.1 On-axis Sensitivity

The calibration factor C is estimated by integrating the signal from a standard target. If M_1 is the echo-integrator output when the target is on the acoustic axis, then

$$C = \sigma_1/(R_1^2 M_1) \quad \text{....... (2)}$$

where σ_1 is the effective backscattering cross section of the standard target, as defined by Foote (1982) to take account of the frequency response of the echo-sounder and the bandwidth of the transmitted pulse, and R_1 is the target range, namely the distance from the target centre to the transducer face or, more strictly, the centre of spherical spreading. The target strength (TS) is related to σ in the normal way (Urick, 1975).

$$TS = 10 \log (\sigma/4\pi) \quad .... \quad (3)$$

It is important to note that σ_1 depends upon the pulse duration and echo-sounder bandwidth as well as the scattering properties of the standard target per se.

An alternative definition of target strength, equivalent to (3), is given by the equation $TS = 10 \log (I_1/I_o)$. I_o is the incident acoustic intensity at the target and I_1 is the backscattered intensity referred to a range 1 m from the target centre.

R_1 may be measured directly or it may be estimated by timing the received echo. It is necessary to measure the echo time with reference to a precise point on the echo waveform. This might be the start of the echo. However, a more accurate technique is to time the echo at a point where the amplitude is a given proportion of the maximum echo amplitude. The measured time can then be corrected to obtain the time corresponding to the target range. For example, it is important to note that σ_1 depends upon the pulse duration and echo-sounder, if t_1 is the time delay between the start of the transmitter pulse and the half-amplitude point on the leading edge of the target echo, then

$$R_1 = c(t_1 - t_h)/2 \quad .... \quad (4)$$

where c is the speed of sound, and t_h is the correction factor which allows inter alia for the signal transmission delay introduced by the electronic filters (MacLennan, 1982).

The same TVG which will be used during the survey, namely the "20 log R" type, must also be selected during the measurement of M_1 and t_1. Equation (2) and (4) assume that "20 log R" TVG has been applied, notwithstanding that the signal comes from one target.

When t_1 is large compared with the pulse length (the target is at long range), the correction t_h is small. It may then be sufficiently accurate to estimate R_1 by measuring the time to the start of the echo pulse, and the small correction may be neglected.

2.2 Time-Varied Gain

The receiver amplitude gain is increased in proportion to the TVG function $\phi(t)$ where t is the time from the start of the transmitter pulse. The factor g in (1) is included to take account of the deviation of $\phi(t)$ from the ideal TVG function between the times of the standard target echo and the fish signals. If the fish of interest are within a thin range slice close to range R, and if they are randomly distributed over the cross section of the acoustic beam, it can be shown (MacLennan and Forbes, 1986) that

$$g = [R \exp(bR)/\Phi(R)]^2 / [R_1 \exp(\beta R_1)/\Phi(R_1)]^2 \text{ .... } (5)$$

where β is the acoustic absorption coefficient expressed in nepers per metre and $\Phi(R)$ is the effective TVG function. $\Phi(R)$ depends upon $\phi(t)$ and its variation over the signal received from a signal target at range R. If the amplitude of this signal is V(R,t), including the effect of TVG, then

$$\Phi^2(R) = \int_0^\infty | V(R,t) |^2 dt / \int_0^\infty | V(R,t)/\phi(t) |^2 dt \text{ .... } (6)$$

Note that Φ and g are functions of range, not of time. The ideal TVG function $\phi_i(t)$ is such that g = 1 for all R, or $\Phi_i(R) = R \exp(\beta R)$. This is the so-called "20 log R + 2αR" form of TVG which is derived by expressing Φ_i in decibels (dB).

In the case of real (non-ideal) TVG functions, g is estimated as follows. The waveform function V(R,t) is deduced from theory or it may be measured. The calibration procedure includes the measurement of $\phi(t)$.

In practice, however, the rigorous evaluation of $\Phi(R)$ is complicated and an approximate calculation will often suffice. At long ranges, when R is much larger than the pulse length in water, $\Phi(R)$ is approximately equal to $\phi(2R/c)$.

At short ranges, particularly at the range of the standard target when calibrating a transducer in a towed body, it is necessary to take account of system delays. Accordingly, we can write

$$\Phi(R) = \phi(2R/c - t_g) \text{ .... } (7)$$

where t_g is a delay, sometimes referred to as the "TVG start time". The approximation is to consider t_g as a constant independent of R. The delay t_g is a function of the echo-sounder pulse duration and bandwidth. It may be estimated from theory or from an empirical equation, as described later in this report.

If $\phi_m(t)$ is the measured TVG function of the equipment, g is estimated by comparing $\phi_m(t)$ with the ideal TVG function. For this purpose, a reasonable approximation to the ideal function is one which begins at time t_g and then increases in proportion to the time after t_g.

It is often convenient to calculate g with the aid of a tabulation of the error function E(R) which is defined by:

$$R = \tfrac{1}{2}c(t_s - t_g) \text{ .... } (8a)$$

$$E(R) = A\phi_m(t_s) / \{ R \exp(\beta R) \} \text{ .... } (8b)$$

where t_s is the midpoint of the gate pulse used to sample the receiver output when measuring $\phi_m(t)$, and A is an arbitrary constant. If R is the range of the fish targets and R_1 is the range of the standard target in the on-axis sensitivity measurement, then

$$g = E(R_1)/E(R) \quad \text{............ (9)}$$

In practice, the range of the fish targets may not be known precisely. It may be known that the fish are in the range interval R_a to R_b, when the average value E_r should be substituted for the denominator of (9).

This average is simply calculated as

$$E_r = \int_{Ra}^{Rb} E(R)dR/(R_b-R_a) \quad \text{............ (10)}$$

and

$$g = E(R_1)/E_r \quad \text{............ (11)}$$

When working from a graph of E(R), it is convenient to choose A such that $E_r = 1$ over the depth interval R_a to R_b where the fish of interest are expected to be found. Thus

$$A = (R_b-R_a)/ \int_{Ra}^{Rb} [\phi_m(t_s)/ \{ R \exp(\beta R) \}]dR \quad \text{............ (12)}$$

2.3 Equivalent Beam Angle

ψ is a measure of the cross-section area of the acoustic beam. It is defined by an integral over the echo-sounder beam pattern. See, for example, Simmonds (1984a).

$$\psi = \int_{4\pi} b^2(\hat{r})\, d\Omega \quad \text{............ (13)}$$

where $b^2(\hat{r})$ is the combined transmit-receive intensity response of the transducer in the direction $\hat{r}$ of the solid angle element $d\Omega$, normalised to unity on the acoustic axis of the transducer.

ψ is estimated from measurements of $b^2(\hat{r})$. If sufficient measurements are available, the integral in (13) is evaluated by summing the measurements according to Simpson's rule. Alternatively, the measurements may be used to determine reference points such as the 3 dB down points of the beam pattern. Knowledge of the theoretical beam pattern may then be used to determine $b^2(\hat{r})$ at other points and thus to calculate ψ.

In the case of narrow beams, say less than 10° between 3 dB down points, a small-angle approximation for ψ may be used (Ona and Vestnes, 1985).

3 ELEMENTS OF CALIBRATION

The main purpose of the calibration is to estimate the factors in equation (1) which relate the fish density to the echo-integrator output. Three of these factors are considered in sections 3.1-3.3 below. The electrical measurements discussed in section 3.4 are not required for the application of equation (1). However, they are nevertheless an important part of the calibration procedure which must be done at intervals to ensure that the equipment remains within specification, and to detect malfunctions.

The particular form of equation (1) is appropriate to calibration by the standard target method in which the source level and voltage response are combined in a single measurement of on-axis sensitivity. The standard-target technique is the preferred method for calibrating fishery echo-sounders and the only one considered in detail in this report. It is important to note that the standard target backscattering cross section σ_1 depends upon the bandwidth and other features of the echo-sounder as well as the physical properties of the target itself. In particular, σ_1 will be altered if the transmitter frequency and the receiver passband are misaligned, although of course it is possible to revise the calibration post-cruise. Careful attention to the electrical measurements discussed in section 3.4 will avoid this source of possible error.

3.1 On-axis Sensitivity

3.1.1 Introduction

The purpose of this measurement is to evaluate the on-axis performance of the echo-sounder and echo-integrator as a complete system. By using a standard target as a known reflector, the combined performance of transmitter, transducer, receiver, and integrator is measured. Thus the transmit signal amplitude, centre frequency and duration, the transducer bandwidth and sensitivity, the receiver bandwidth and gain, and the echo-integrator transfer function are all taken into account. The measurement requires the standard target to be aligned with the acoustic axis of the transducer.

Below, two examples are presented which illustrate measurement of the on-axis sensitivity of the overall system. In the first, the calibration sphere is positioned and then held stationary on the acoustic axis. In the second, the sphere is moved systematically through the central region of the transducer beam and the on-axis response is estimated by interpolation.

Tabulated target strength values for recommended calibration spheres are given in Appendix 2.

3.1.2 Example: stationary-sphere method

Measurement of the on-axis sensitivity is performed to determine the calibration factor C in equation (1). This can be accomplished directly by locating a standard target on the acoustic axis and integrating the echo. Measurement of the target range R_1 and the echo-integrator output M_1, together with knowledge of two other system parameters, the TVG correction factor g at the sphere depth and equivalent beam angle Ψ, allows C to be determined.

The procedure of the stationary-sphere measurement method is now described. In an example, reference is made to the echo-sounding and echo-integrating equipment used by the Institute of Marine Research, Bergen.

3.1.2.1 Rigging

The vessel is anchored in calm and sheltered water. The depth must be sufficient for separation of sphere and bottom echoes. It is desirable, moreover, to work in water as deep as possible, consistent with maintaining a stable platform. Both bow and stern anchoring or tying are recommended. This is illustrated in Figure 1.

Winches to guide and steer lines to the sphere for its centering in the echo-sounder beam are affixed to the deck railing. This is done in accordance with detailed ship drawings. The first winch is placed in the transverse plane of the ship running through the transducer. The second and third winches are placed on the opposite boat side and at equal distances from the transverse section containing the transducer and first winch. Each winch is provided with a long spool of 0.60 mm diameter monofilament nylon, which is marked with small lead weights at 5 m intervals, beginning 10 m from the loose end.

Prior to commencing the sphere measurements, the lines from the two winches on the same side of the boat are drawn beneath the hull to the other winch by means of a line passed under the keel before anchoring. The appropriate sphere, with affixed loop, is attached to the three suspension lines, cf Figure 1. It is then immersed in a solution of soap and freshwater and lifted overboard by the fastened lines without being touched. The sphere is lowered beneath the vessel to the desired depth, for example, 25 m, which is determined roughly by counting the lead marker-weights on each line.

The sphere depth or range from the transducer is determined by several considerations. The minimal allowable range to the sphere is the greater of the Rayleigh distance, or square of the largest transducer dimension divided by the acoustic wavelength, which defines the nearfield/farfield transition, and the least range for which the sphere echo does not saturate the electronics at the required gain.

Two further considerations in choosing the range are the transducer beamwidth and vessel geometry. The physical width of the beam, which increases linearly with range, should be sufficiently great so that the sphere echo is unaffected by the small, perhaps pendular movements to which it is inevitably subjected. The minimal range must also be convenient with respect to the vessel geometry. In particular, if the suspension lines do not hang freely, then control of the sphere may be hindered by friction or possible obstructions on the hull. Despite the number and variety of these considerations, it is seldom difficult in practice to find a suitable range which satisfies all of the above criteria.

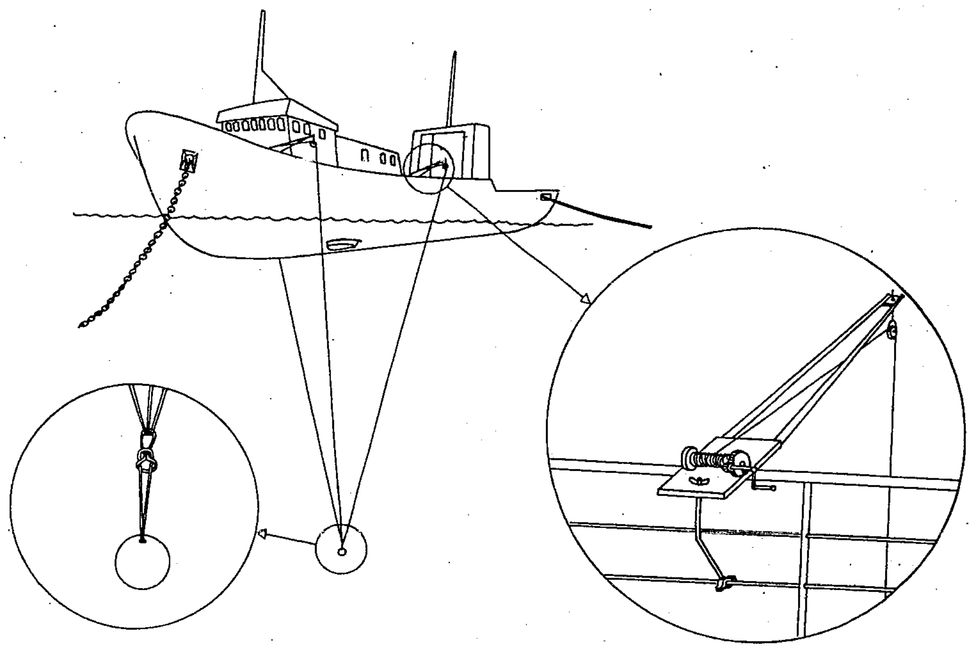


Figure 1. Rigging of a research vessel for stationary-sphere calibration.

3.1.2.2 Hydrography

During the anchoring and rigging operations, the temperature and salinity profiles should be taken. These will allow computation of the sound speed both at discrete depths and cumulatively to the depths of possible sphere suspension. The second computation will allow determination of the exact depth of eventual sphere suspension from the echo time delay. When this depth is applied in the first computation, the temperature correction to the target strength of the calibration sphere may be obtained from a reference graph or table.

3.1.2.3 Centering

The purpose of this crucial operation is to move the immersed, suspended sphere onto the acoustic axis of the transducer. Movement of the sphere occurs by turning of the various hand-winches, always singly and upon specific command by the director of this procedure, who is guided by constant observation of the echo waveform on an oscilloscope. The two principles guiding the search for the beam center are (i) preliminary exploration of the beam to ensure location of the sphere in the mainlobe, and (ii) further probing to find the position of strongest echo. In the case of highly directional transducers, determination of the ultimate axial location is made when any movement of any winch, in or out, cannot increase the echo amplitude.

3.1.2.4 Sphere range

Measurement of the sphere range is necessary for determining the equivalent scatterer density ρ and the TVG correction factor g in equation (1). The sphere range is determined indirectly by measurement of the echo time delay t and computation of the average sound speed c between transducer and sphere from the measured hydrographic data. The sphere range R_1 is then computed as $R_1 = ct/2$. If, for example, the echo time delay were observed to be 30.7 ms and the average sound speed 1490 m/s, then the sphere range would be 22.9 m.

The present method of determining the sphere range is subject to three sources of error. (1) The time delay between the start of transmission, as marked by the trigger pulse, and acoustic response of the transducer is finite. This is a simple consequence of the electromechanical inertia of the transmitting system. (2) The rise-time of the sphere echo out of the background noise and reverberation is finite. (3) The echo time delay t is properly specified through an integral,

$$t = 2\int_{z_1}^{z_2} \frac{dz}{c(z)}$$

where z_1 and z_2 are the respective depths of transducer and sphere, and c(z) is the depth dependent function of sound speed. Use of the average sound speed c in the equation for the sphere range thus involves an approximation.

These errors, however, are of little significance in big-system calibrations, when the transducer-to-sphere distance lies in the typical range 15-25 m and the signal-to-noise ratio is high. Under such conditions the cumulative effect of the first two error sources is a slight, generally negligible overestimate of the range. The effect of the third source of error is also typically small.

3.1.2.5 Echo-integration

Integration of the sphere echo links the many individual instruments or processes involved in echo surveying into a single, repeatable operation.

The sphere is maintained at its stationary position on the acoustic axis. Three 5 m depth channels are defined in the integrator. The middle of the three exactly straddles the sphere, whose depth is in the middle of the 5 m channel. The other depth channels are placed immediately above and immediately below the sphere channel. These are used to confirm the absence of unwanted echoes which might disturb the sphere measurements. No threshold is used.

The echo-sounder and integrator should be set to those operating parameters which will be most often used during the survey. In the case of the Simrad EK38 echo-sounder, for example, these might be the following:

transducer	30 x 30
pulse duration	external, 0.6 ms
TVG	"20 log R"
attenuator	20 dB
bandwidth	3 kHz
range	0-250 m

Simrad integrators require a vessel-speed input. Since the vessel is at rest during the calibration, a constant speed must be simulated. This might be 10 knots, for example. Given an observation time of six minutes, the simulated sailed distance would be one nautical mile. The integration period, or printout interval, can be set to a smaller distance, but the output values must then be normalized to the average per nautical mile of sailed distance.

All correction factors and the calibration constant are equated to unity during this process. That is, neither correction factors nor the instrument constant is applied during the calibration. In this way, all doubt about the values adopted is avoided.

The relative echo energy, or echo energy expressed in the units of the echo-integrator, is computed for each of a large number of pings. The largest of these, if within about 10% of the average, is extracted. If the deviation is greater than 10%, then the centering operation should be repeated and the acoustic measurements performed anew. The largest echo energy finally selected has arisen from a known target and echo-integrator system. Given the relationship of echo-integrator output to backscattering cross section of the standard target, future measurements with the echo-integrator may be expressed as absolute fish quantities.

3.1.2.6 SL + VR

The sum of transmitter source level SL and receiver voltage response VR can be measured while the echo-integrator is being calibrated. Again, the echo derives from a known, on-axis target, and the "sonar equation" (Urick, 1975) can be solved for the named quantity. It is, in the absence of TVG correction,

$$SL + VR = U_1 - TS_1 + 20 \log R_2 + 2\alpha R_2 + D_1 + 20 \log R_1 \quad \ldots\ldots\ldots (14)$$

where U_1 is the sphere echo level, TS_1 is the target strength of the standard target sphere, R_2 is the expiration range of the "20 log R" TVG function, α is the absorption coefficient used in the TVG function, G is the nominal gain, and R_1 is the sphere range. The gain is often described through the so-called attenuator setting. It should be noted that a positive attenuation is equivalent to a negative gain of the same magnitude. The units of the several quantities are shown in the following table. The reference voltages and pressures may be either root-mean-square (rms) or peak-to-peak values. However, consistent use of rms or peak-to-peak is essential to ensure that equation (14) is satisfied.

TABLE

Quantity	Symbol	Units
Source level	SL	dB // 1 μPa at 1 m
Voltage response	VR	dB // 1 V per μPa
Echo Voltage level	U_1, U_2	dB // 1 V
Target strength	TS	dB
Ranges	R, R_1, R_2	m
Absorption coefficient	α	dB/m
Attenuator setting	D_1	dB

The measured output quantity is the peak or rms echo amplitude. For a constant-amplitude sinusoidal signal, the rms value is the peak amplitude divided by $2^{\frac{1}{2}}$.

Correction of the equation for SL + VR for a possible deviation in TVG at the sphere depth is straightforward. If, for example, the first determination of SL + VR yields 141.2 dB, and the TVG is 0.3 dB too high at the sphere range, then the correct value for SL + VR is 140.9 dB.

3.1.3 Example: moving-sphere method

A system has been developed for moving a standard target automatically through the transducer beam, and computing the on-axis sensitivity by interpolation. The present system has been designed for use with towed bodies, but a scaled up version could be used with a hull-mounted transducer.

Experiments with the stationary-sphere technique reveal that a ball hung on monofilament nylon is liable to move. Results over a period of hours may be quite variable. This seems to be due to three main effects: ship movement, water currents and water absorption in the monofilament nylon which alters the twine length. An alternative technique is to move the sphere successively to a number of positions in a scan through a plane section of the acoustic beam. A curve is fitted to the echo-integrals recorded at each position. The procedure is repeated for a second scan in a section at right angles to the first, and including the maximum of the first fitted curve. The curve maxima rapidly converge to give a consistent estimate of the on-axis sensitivity.

In practice, the echo-integrals might be accumulated over 30 transmissions at each position, and the curve might be fitted to 11 points per scan. In ideal conditions, a series of 80 such scans produced results within ±1%. However, when the same quantity of data was collected with the sphere stationary at the apparent beam centre, the results covered a range of more than ±5%. The scanning technique uses the curved beam pattern to best advantage and increases the precision considerably. It is therefore recommended that wherever practicable, a scanning method should be used.

3.1.3.1 Method

The measurement is performed using a standard target (38.1 mm diameter tungsten carbide sphere) suspended on three strands of monofilament nylon each attached to an adjuster placed at the end of an arm positioned above the transducer and towed body (Figs 2 and 3). The construction of the nylon twine container for the target is illustrated in Figure 4. Encoders on the motor output shafts allow the twine lengths to be displayed. The adjusters may be controlled manually or by computer. The output of the echo-sounder is connected to an integrator or sample gate which should be set to include the complete echo. The adjusters may be controlled to move the sphere in two independent planes. For the system used at the Aberdeen Marine Laboratory, the sphere is hung on 5.5 m lengths of nylon and the three arms are arranged radially so that the suspension points are 3 m apart. The adjusters provide ±100 mm of twine movement to an accuracy of 0.33 mm.

The full extent of adjustment is used for the first scan. A series of 21 points is selected by adjusting the length of one twine in 10 mm steps. Thirty transmissions are carried out at each point and the total echo-integral recorded. These data are then used to compute a parabola by least squares fit. The curve is fitted to the 4th root of the data in order to reduce errors due to the non-parabolic shape of the beam pattern. The maximum value and the position of the

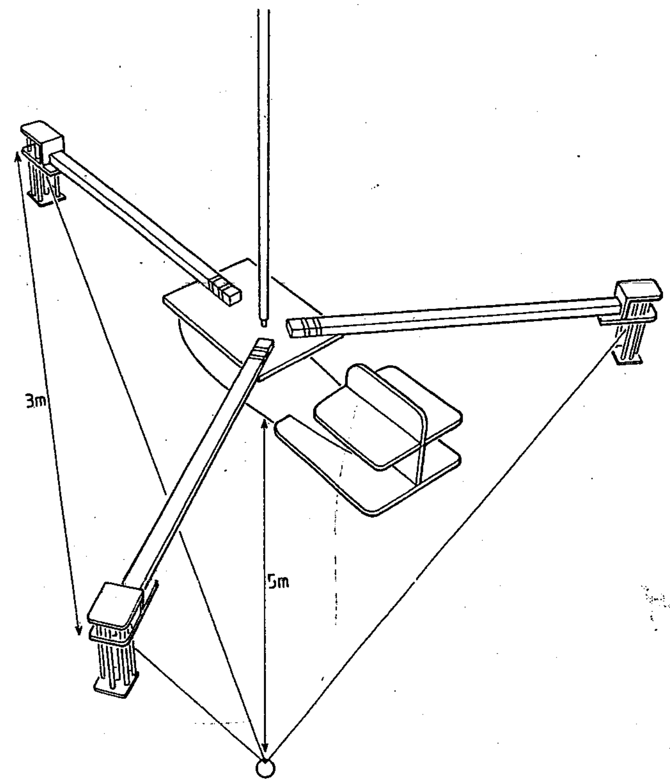


Figure 2. Rig and target suspension for towed-body calibration: moving sphere method.

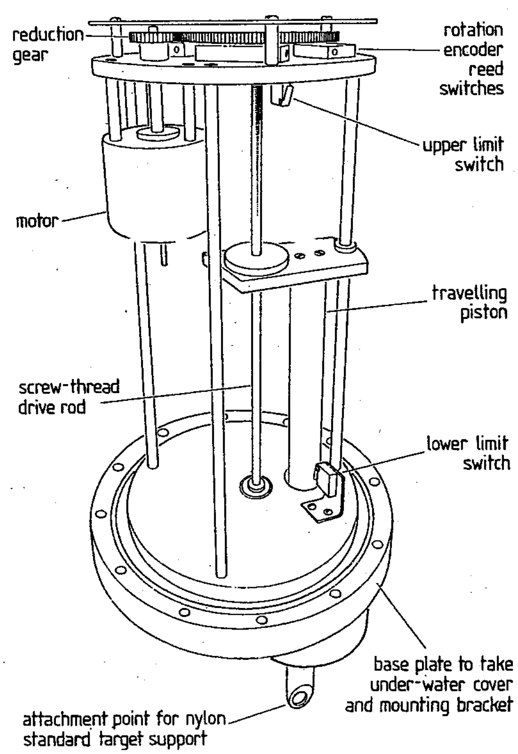


Figure 3. Mechanism for adjusting the length of twine supporting the standard target. Three such adjusters are shown at the arm ends in Figure 2.

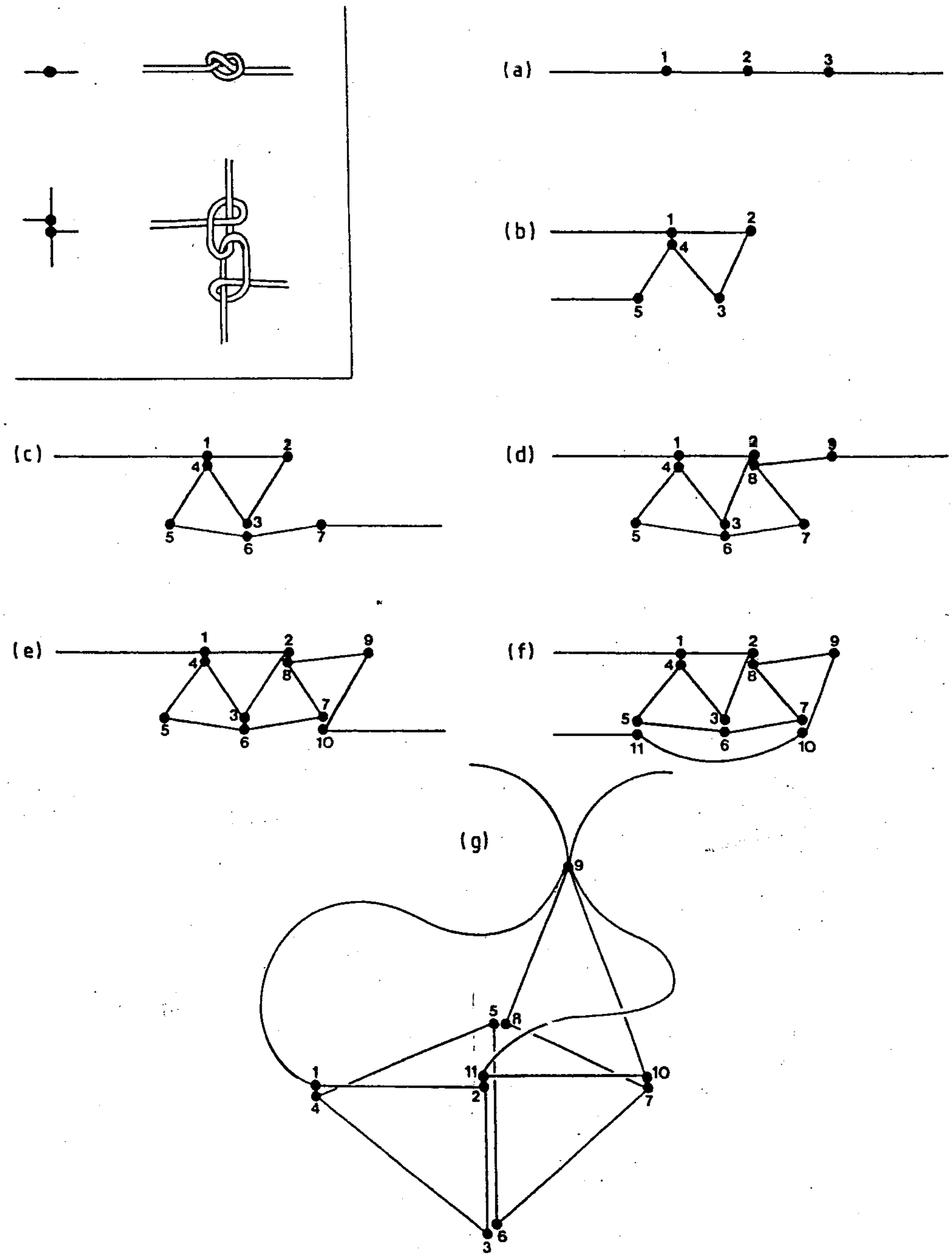


Figure 4. Construction of a monofilament container for standard target spheres. The numbers show the order of tying knots. Successive knots are one quarter of the sphere circumference apart.

maximum are computed from the equation for the parabola and the adjuster is moved to this position. Then the second scan is performed by adjusting the other two twines, one is lengthened and the other shortened, to move the sphere in a section at right angles to that of the first scan. The curve fitting procedure is repeated to determine the maximum echo-integral and the corresponding position. The adjusters are moved to the computed position, then the first section is scanned again. Following the first two scans, only 60 mm of adjustment and 13 points per scan are required. For each completed scan a maximum echo-integral and the corresponding position are computed. The maxima rapidly converge upwards and under good conditions will vary by ±1% only. This dynamic measurement procedure produces significantly superior results to the stationary-sphere technique used with the same rig.

3.1.3.2 Sphere range

In order to calculate the on-axis sensitivity of the echo-sounder, the range to the standard target must be measured. This could be done directly, by tape measure, but a more practical and accurate alternative is to measure the time of the echo from the target. The half voltage point on the leading edge of the received echo is a well defined reference time. This can be measured by examining amplitude samples from the echo, if such are available, or by triggering the oscilloscope with a delayed pulse so that the echo waveform near the half voltage point is visible on an expanded scale. The time between the transmission and the delayed trigger pulse may be accurately measured using a counter timer. Measurement of the time delay by visual examination of the oscilloscope trace is inaccurate and should be avoided if at all possible. To calculate the range of the target, the system delay t_h due to bandwidth must be subtracted from the measured echo time. Tables 1(a) and 1(b) show values of the system delay appropriate to copper and tungsten carbide calibration spheres. The value of t_h is selected according to the echo-sounder parameters being used, and the range R_1 of the target may now be computed from equation (4).

3.1.3.3 TVG correction

There is an additional correction required which corrects for TVG errors at that point of the TVG where the calibration is carried out. If E_1 is the echo integrator reading, then $M_1 = E_1/g(R_1)$. The correction factor g is obtained from Table 2, corresponding to the target range R_1, and the calibration factor C may now be calculated from equation (2).

3.1.3.4 Worked examples

Echo-sounder	EK400, 38 kHz
Transducer	34 elements, beamwidth 8° x 13° (3 dB down points)
Pulse duration	1.0 ms
Bandwidth	3.3 kHz
TVG	"20 log R"
Control settings	High output power; receiver gain -10 dB

TABLE 1

Echo-timing Data for Target Range Calculation

(a) Echo-sounder: Simrad EK400 Target: 60 mm copper sphere

Bandwidth	1 kHz	1 kHz	3 kHz	3 kHz
Pulse duration	1 ms	3 ms	1 ms	3 ms
Half-peak time t_1 (ms)	Signal delay t_h (ms)			
7.0	0.697	0.788	0.473	0.503
8.0	0.692	0.773	0.473	0.496
10.0	0.690	0.753	0.472	0.487
20.0	0.681	0.712	0.471	0.471
30.0	0.683	0.699	0.470	0.470
infinity	0.670	0.689	0.469	0.468

(b) Echo-sounder: Simrad EK400 Target: 38.1 mm tungsten carbide sphere

Bandwidth	1 kHz	1 kHz	3 kHz	3 kHz
Pulse duration	1 ms	3 ms	1 ms	3 ms
Half-peak time t_1 (ms)	Signal delay t_h (ms)			
7.0	0.680	0.768	0.458	0.484
8.0	0.677	0.753	0.457	0.477
10.0	0.675	0.733	0.457	0.469
20.0	0.660	0.693	0.455	0.454
30.0	0.658	0.679	0.454	0.453
infinity	0.655	0.669	0.450	0.451

NOTES

The target range R_1, from the target centre to the transducer centre of spreading, is estimated as $R_1 = c\ (t_1 - t_h)/2$, where c is the speed of sound, and t_1 is the time from the beginning of the transmitter pulse to the point on the receiver output waveform at half the peak amplitude, with time varied gain applied. The signal delay t_h has been calculated for a receiver with "20 log R" time-varied gain.

TABLE 2

Data from TVG Measurement

Measured input U_i (mV)	Time of sample t_i (ms)	Range of sample R_i (m)	Theoretical TVG $\Phi_i(R)$	Sample interval W_i (m)	Optimised measured TVG $\Phi_{o,i}(R)$	Error function g(R)
541.4	9.6	6.5	43.27	4	43.66	1.009
332.1	15.0	10.5	114.6	4	116.1	1.013
242.7	20.4	14.5	221.8	4	217.2	0.979
184.7	25.8	18.5	366.4	4	571.0	1.024
151.0	31.1	22.5	550.0	4	561.5	1.021
128.4	46.5	26.5	774.3	4	775.6	1.002
110.9	41.9	30.5	1041	4	1040	0.999
97.3	47.2	34.5	1351	4	1351	1.000
87.5	52.6	38.5	1708	4	1670	0.978
78.5	58.0	42.5	2112	4	2074	0.982
70.5	63.3	46.5	2566	4	2578	1.004
65.0	68.7	50.5	3072	4	3027	0.985
59.9	74.1	54.5	3631	4	3570	0.983
55.7	79.4	58.5	4245	4	4118	0.970
51.0	84.8	62.5	4918	4	4916	1.000
47.9	90.2	66.5	5650	4	5577	0.987
44.4	95.6	70.5	6444	5	6497	1.008
42.6	100.9	74.5	7303	4	7047	0.965
39.5	106.3	78.5	8229	4	8186	0.995
37.0	111.7	82.5	9223	5	9329	1.011
34.2	119.7	88.5	10850	7	10950	1.010
31.4	130.5	96.5	13290	8	12970	0.976
28.0	141.2	104.5	16050	8	16340	1.018
25.9	151.9	112.5	19160	8	19040	0.994
24.0	162.7	120.5	22630	8	22290	0.985
24.0	162.7	120.5	22630	8	22290	0.985
22.1	173.4	128.5	26510	8	26240	0.990
20.5	184.1	136.5	30810	8	30520	0.991
19.0	194.9	144.5	35560	8	35620	1.002
17.5	205.6	152.6	40790	8	41650	1.021
16.6	216.4	160.5	46530	8.8	46300	0.995
15.1	229.1	170.0	54060	10.8	56130	1.017
13.9	245.2	182.0	64760	12	65800	0.998
12.9	261.3	194.0	76910	12	76780	0.998
11.1	293.5	218.0	106100	12	104100	0.981
10.3	309.6	230.0	123400	12	120900	0.980
9.5	325.8	242.0	142800	13.5	141000	0.978
8.5	345.9	257.0	170200	15.5	178800	1.050
7.9	367.4	273.0	203800	16	207100	0.997
7.3	388.8	289.0	242200	16	241500	0.976
6.8	410.3	305.0	286100	16	279400	0.975
6.2	431.8	321.0	336200	17	327700	0.975
5.6	456.0	339.0	400700	19	402700	1.005
5.2	482.0	359.0	483700	20	469300	0.970
4.7	509.6	379.0	483700	20	583900	1.006
3.9	565.3	420.5	832400	22.8	845500	1.016
3.5	597.6	444.5	1016000	24.0	1045000	1.028
3.3	629.8	468.5	1233000	24.1	1205000	0.977
2.9	662.3	492.8	1416000	26.1	1508000	1.011
2.6	699.9	520.8	1847000	28	1889030	1.023

TABLE 3

Estimation of the On-axis Sensitivity by Moving the Target Through the Transducer Beam

Scan 1 (Forward Adjusters)			Scan 2 (Rear Adjusters)		
Encoder position	Echo integral (V^2 ms)	Fitted parabola (V^2 ms)	Encoder position	Echo integral (V^2 ms)	Fitted parabola (V^2 ms)
315	.1194	.1195	290	.1140	.1142
335	.1203	.1203	310	.1162	.1159
335	.1207	.1208	330	.1180	.1175
375	.1212	.1211	350	.1186	.1139
395	.1214	.1211	370	.1295	.1200
415	.1210	.1209	390	.1205	.1209
435	.1205	.1204	410	.1216	.1216
435	.1191	.1196	430	.1227	.1222
475	.1182	.1186	430	.1228	.1225
495	.1179	.1180	470	.1224	.1225
415	.1159	.1159	490	.1222	.1224
Solve for Maximum					
387		.1212	466		.1226

Table 3 shows the standard target echo integral against the encoder position, from the 11 points of the first scan. The base of the Table shows the maximum value estimated from a least squares parabolic fit to the fourth root of the data, and the right hand columns show similar data for the second scan. Again the maximum value is estimated by curve fitting. In the second scan, although adjusters 2 and 3 are moved together, only 2 is used to define the abscissa and 3 is assumed always to remain in step. These two scans, moving the sphere in mutually perpendicular planes, are used to define the position of the centre of the beam and the corresponding echo integral E_1.

To locate the beam centre, a pair of scans over the full range of the adjusters are carried out first. These data are not used to compute a maximum echo integral. The curve-fitting procedure underestimates the maximum echo integral because the parabola is an approximation to the true beam shape. In order to reduce this bias, subsequent scans are carried out over a smaller section of the beam, adjusting the nylon twine length by only ±3 cm. The error due to the parabolic approximation is now less than 0.1% and can be ignored.

To correct for the range of the target, the time to the half voltage point of the echo waveform is measured. This will be nearly independent of movement in the second scan, when two adjusters are moved together (in opposite directions). However, the range does change significantly during the first scan, when one adjuster is moved on its own. In addition, the nylon can absorb water and stretch, thus altering the target range during the calibration. Therefore, it is important to measure the range frequently, near the times of echo amplitude measurement. The estimated value of the on-axis echo-integral is the mean result from pairs of scans. Four or five pairs of scans should be performed and their results averaged, after omitting any spurious values.

The time-delay to the half voltage point is measured as $t_1 = 9.14$ ms. The system delay t_h from Table 1(b) is 0.46 ms. E_1 from Table 2 is 0.1226 V^2 ms but, from Table 2, it is subject to a TVG correction factor of 1.009. The sound speed c, estimated from hydrographic data, is 1490 ms^{-1}. Hence

$$R_1 = 1.49\ (9.14 - 0.46)/2 = 6.47 \text{ m}$$

$$M_1 = 0.1226/1.009 = 0.1215 \ V^2 \text{ ms}$$

The target strength of the 38.1 mm tungsten carbide sphere, for c = 1490 ms^{-1} and 1 ms pulse duration, is -42.35 dB. Hence $\sigma_1 = 7.315$ cm^2 and, from equation (2)

$$C = 7.315 \times 10^{-4}/(6.47^2 \times 0.1215) = 0.0001438\ (V^2 \text{ ms})^{-1}$$

3.2 Time-Varied Gain

3.2.1 Introduction

The time-varied-gain (TVG) function of the typical echo-sounder generally deviates measurably and not insignificantly from the nominal or ideal specification. This means that echoes from fish at different ranges may be compensated inaccurately, thereby biasing estimates of fish density with respect to depth. This biasing may occur irrespective of whether the TVG is correct at the depth of the standard target during the calibration. It is therefore necessary to measure the actual gain of the echo-sounder over the range of applicability. This range generally extends from the start of the TVG to the so-called expiration range, when the receiver gain attains, and remains at, maximum value.

The TVG correction factor is determined by comparing the observed TVG with the ideal or desired gain over the entire compensation range. Specifically, the factor g in equation (1) is determined as a function of range by computing the ratio of measured and ideal gains as a function of time.

Measurement of the TVG generally requires instrumentation external to the echo-sounding and echo-integrating equipment. Signals are applied to the echo-sounder input, and the corresponding receiver output is measured.

The estimation of the ideal TVG function and the TVG error depends upon knowledge of the sound speed (c) and acoustic absorption coefficient (β or α). Both parameters, depend upon hydrographic factors such as temperature, salinity and depth (Foote, 1981). Error in the values assumed for sound speed and absorption leads to error in the TVG function and hence to bias in the fish density estimate.

It is usually most convenient to estimate c and β (or α) as functions of the hydrographic parameters, using empirical equations. Many different equations will be found in the literature, but those which are currently recommended for acoustic survey purposes are shown in Appendix I.

It is important that adequate hydrographic information is obtained relevant to the area surveyed, to allow the sound speed and absorption coefficient to be estimated. To some extent, temperature and salinity data may be obtained from charts or other literature, but it is recommended that temperature - salinity - depth (TSD) data be collected at intervals during the survey, including any anchorage where calibration is performed.

There are two basic approaches to the problem of TVG measurement. In one, the input signal is held constant, and the echo-sounder output signal is measured. A disadvantage of this approach is that in order to avoid saturation at the expiration of the TVG function, the output signal must be very weak initially. In the second approach, the output voltage is held constant, and the input signal is varied. The disadvantage with this method is that the input voltage must be very large at the beginning of the TVG ramp, which can result in the amplifier saturating. This may be avoided by careful choice of signal level and echo-sounder repetition rates.

The two methods are now described. In the first example, illustrating the constant output method, the measurement is effected by widely available laboratory instruments. In the second method, adapted from the constant-input technique, the measurement is performed by a specially-built instrument, the Time-Amplitude-Frequency (TAF) Unit (Knudsen, 1985).

3.2.2 Example: constant-output method

This method has several advantages. It may be carried out automatically or manually; it requires standard commercially available equipment, and relies only on the calibration of a single voltmeter for its accuracy. One limitation is that the output level must be chosen carefully, so as to avoid saturating the receiver amplifiers while short range values are being measured. It helps to run the echo-sounder at the fastest repetition rate possible for any given measurement point.

3.2.2.1 Method

A signal source is connected to the input of the echo-sounder (test input). A sampling gate, or an echo-integrator which serves the same function, is connected to the output of the echo-sounder (calibrated output). An AC voltmeter is also connected to the echo-sounder input unless the signal source is programmable and accurate.

The sampling gate width is set equal to the transmitter pulse duration to be used on the survey (or as similar as practicable). The sampling gate is set to the first range point. The time to the start of the sampling gate must be known or measured. The signal source is then adjusted to give the chosen output from the sampling gate. The input level is then recorded along with the gate time measurement. The gate is moved to the next range point and the input level adjusted to give the chosen output again. The time measurement and input level are recorded, and further measurements repeated over the full range of the TVG function.

An automated measurement procedure may be based on a synthesised signal generator (Fluke 6011 or equivalent) as the signal source. A crystal controlled range gate is used to sample the echo-sounder output and the gate output is read by a computer. The signal generator may be programmed to control the gate output to within ±1%. The gain is then the gate output divided by the programmed voltage input to the echo-sounder. A series of transmissions may be averaged to improve accuracy. In the case of the EK400 at 38 kHz, for example, take the average of 10 transmissions at range points up to 300 m, and 40 transmissions at greater ranges. A total of 50 range points are required to give ±1% precision for the TVG correction factor g.

3.2.2.2 Calculation of the TVG error function

The measurements discussed above give a set of times t_i, from the start of the transmit pulse to the mid point of the sampling gate, and a set of corresponding input voltages, U_i. Suppose the ideal TVG is $\Phi_i(R)$, where $R = R_i$ is the nominal range corresponding to the time t_i.

For 20 log R + 2 αR as the ideal TVG function in dB:

$R_i = \frac{1}{2} c (t_i - t_g)$ .... (15)

$\Phi_i(R) = R_i^2 (10^{2 \alpha R_i/10})$ .... (16)

$\Phi_{m,i}(R) = (1/U_i)^2$

where $\Phi_{m,i}(R)$ is the measured TVG, t_i is the time at which the measurement of the echo-sounder output is made, c is the sound speed appropriate to the hydrographic conditions expected during the survey, t_g is the TVG start time, see Table 4, and α is the acoustic absorption coefficient in dB m^{-1}.

The measured gain may be multiplied by a constant C_s to minimise the error over any given range interval. The minimum error TVG function is:

$\Phi_{o,i}(R) = \Phi_{m,i}(R)\, C_s = (1/U_i)^2\, C_s$ .... (17)

where

$C_s = (R_a - R_b)^{-1} \Sigma\, W_i\, \Phi_{m,i}(R)/\Phi_i(R)$ .... (18)

W_i is the sample interval, equal to $(R_{i+1} - R_{i-1})/2$. The range interval R_a to R_b is selected to include the depths at which the fish of interest are expected to be found. The sum is taken over all readings for which $R_a < R_i < R_b$. The values of $\Phi_{o,i}(R)$ may then be computed as described above. This provides an error function $g(R) = \Phi_{o,i}(R)/\Phi_i(R)$ which has been minimised for the depth range of interest but which indicates the magnitude of the TVG error at other ranges also.

The error function may now be used to calculate the error at the range of the standard target during the calibration. Any integrator measurement may be corrected by dividing the energy integral by the error function g(R) for the appropriate range.

3.2.2.3 Worked example

Echo-sounder: EK400, 38 kHz
Constant output level: 0.5 V peak-to-peak

This output level is about the middle of the 50 dB dynamic range of the echo-sounder. It is also small enough not to overload the receiver, provided the echo-sounder repetition rate is kept as fast as possible. The sample gate width is set to 1 ms, equal to the pulse duration. The measurements of input U_i and time t_i are shown in columns 1 and 2 of Table 2.

TABLE 4

Ideal TVG Start Time for Exact Range Compensation

(a) Echo-sounder: EK400
Target: 60 mm copper sphere

Bandwidth	1 kHz		3 kHz	
Pulse duration	1 ms	3 ms	1 ms	3 ms
Echo half peak t_1 (ms)	TVG start time t_g (ms)			
7.0	1.203	2.220	0.938	1.978
8.0	1.203	2.213	0.937	1.971
10.0	1.201	2.203	0.936	1.661
20.0	1.199	2.185	0.935	1.942
30.0	1.198	2.178	0.934	1.935
infinity	1.196	2.167	0.933	1.923

(b) Echo-sounder: EK400
Target: 38.1 mm tungsten carbide sphere

Bandwidth	1 kHz		3 kHz	
Pulse duration	1 ms	3 ms	1 ms	3 ms
Echo half peak t_1 (ms)	TVG start time t_g (ms)			
7.0	1.185	2.229	0.920	1.983
8.0	1.184	2.213	0.919	1.969
10.0	1.182	2.195	0.918	1.952
20.0	1.179	2.168	0.916	1.925
30.0	1.179	2.160	0.915	1.917
infinity	1.177	2.148	0.914	1.904

For a 3 kHz bandwidth at 1.0 ms pulse duration t_g = 0.92 ms (Table 4b). The calculated R_i for c = 1490 ms^{-1} are shown in column 3 of Table 2. The theoretical TVG in dB is "20 log R + 2 αR", with α = 0.008 dB m^{-1}. The TVG has been optimised for its full range. From equations (15-18), C_s is calculated as .07812, for R_a = 2.5 and R_b = 529 m. Column 7 of Table 2 gives g(R), the error for a target at range R = R_i.

From this it is seen that errors are typically less than ±3%. If a standard target calibration were carried out at 6.5 m range, the error there would be +0.9%. Thus the echo energy recorded during the standard target calibration must be corrected by dividing by 1.009. This is the factor $g(R_1)$ used to calculate M_1 (cf section 3.1.3). The factor g in equation (1) is the mean value of g(R) over the depth range of interest. If all depths are equally of interest, then g=1 by virtue of the optimisation.

3.2.3 Example: measurement by a special-purpose unit

Until recently, measurement of TVG has generally been accomplished by standard instruments. These typically include a signal generator, frequency counter, voltmeter, and oscilloscope.

The value of a special electronics unit which can measure the TVG function without requiring a large number of separate instruments is thus evident. The resultant simplification may also increase the reliability of the measurement.

The following example refers to Simrad echo-sounding and echo-integration equipment. Full details of the design and operation of the special purpose unit will be found in Knudsen (1985).

3.2.3.1 The Time-amplitude-frequency (TAF) unit

In order to simplify the procedure, a specially constructed test generator is used. This controls the time, amplitude and frequency, hence the acronym TAF. The test generator produces a number of pulses, generally 20, which simulate fixed depths. In this manner it is sufficient to know the pulse number, without having to measure the time.

The amplitude is regulated in two steps. The first is high for the period corresponding to 100 m range. For the remaining TVG range, the amplitude is reduced by 20 dB. This ensures both a sufficiently strong signal at the beginning of the TVG range and avoidance of saturation in the preamplifier at greater ranges.

The frequency of the TAF unit is determined by a crystal. Adjustment of the frequency is therefore unnecessary.

3.2.3.2 Measurement of the TVG deviation with TAF

It is assumed in the following that reading of the TAF instrument occurs manually by means of an oscilloscope.

(1) The TRIGGER signal from the echo-sounder is connected to the input port TRIGGER IN.

(2) The SIGNAL OUT is connected to the TEST INPUT of the attenuator, which is internal in both the EK and EK-S models.

(3) The echo-sounder is run with 250 m main range, and the 3 kHz bandwidth is selected.

(4) The TRIGGER OUT signal is connected to the EXTERNAL TRIGGER on the oscilloscope.

(5) Pulse number 20 is selected, and the CAL OUT signal is adjusted to 10 V_{p-p}. Pulse number 20 is well outside the TVG range, hence the receiver has reached its maximum amplification.

The amplitudes of the preceding pulses are now determined relative to the last.

3.2.3.3 Worked example

Consider computation of the amplitude of pulse number 2, given that the amplitude of pulse number 20 is 10 V_{p-p}, or 11 dB re 1 V rms, for the EK400/38.

Pulse number 2 simulates 20 m depth. At depths less than 100 m, the signal generator output is 20 dB higher and the computation takes this into account.

$$U_{20\ m} = U_{max} - (20 \log R + 2\alpha R) + (20 \log 20 + 2 \times \alpha \times 20) + 20$$
$$= 11 - 64.58 + 26.34 + 20 = -7.24 \text{ dB or } 1.23\ V_{p-p}$$

where R = 581 m approximates the cutoff range of the "20 log R" TVG function for this echo-sounder, and α = 0.008 dB/m is the absorption coefficient. The quantity $U_{20\ m}$ is the theoretical value for the voltage, which can be compared with that read off the oscilloscope. Tables 5 and 6 show the computed values for the EK38 and EK400/38, respectively.

3.3 Equivalent Beam Angle

3.3.1 Introduction

A transducer radiates and receives energy with different sensitivity according to the target position in the surrounding volume. In order to use a transducer for fish surveys, it is necessary to know the total energy transmitted and received. Normally this is determined by the on-axis sensitivity and a measure of the beamwidth which is called the equivalent beam angle. The latter has been defined in equation (13).

A theoretical value of Ψ may be calculated for any transducer. However, experience has shown that precise measurement is necessary. Whether or not the equivalent beam angle is specified by

TABLE 5

Theoretical voltage amplitude U_r at range r for the calibrated output signal of the EK38 echo-sounder, based on the maximum output signal amplitude U_{max} = 10 V_{p-p} at the expiration range R = 503.29 m, given that α = 0.0105 dB/m. Note that the signal is reduced by 20 dB for ranges greater than 100 m.

Pulse number	Depth (m)	Voltage amplitude U_r (dB)	(V_{p-p})	$(U_r/U_{max})^2$
1	10	-13.40	0.61	0.0037
2	20	-7.16	1.24	0.0154
3	30	-3.43	1.90	0.0363
4	40	-0.72	2.60	0.0677
5	50	1.42	3.33	0.1110
6	60	3.22	4.10	0.1678
7	70	4.77	4.90	0.2397
8	80	6.14	5.73	0.3286
9	90	7.37	6.61	0.4365
10	100	8.49	7.52	0.5656
11	150	-6.93	1.27	0.0162
12	200	-3.38	1.92	0.0367
13	250	-0.40	2.70	0.0730
14	300	2.24	3.66	0.1339
15	350	4.63	4.82	0.2521
16	400	6.84	6.21	0.3861
17	450	8.91	7.89	0.6223
18	500	10.87	9.89	0.9783
19	550	11.00	10.00	1.0000
20	600	11.00	10.00	1.0000

TABLE 6

Theoretical voltage amplitude U_r at range r for the calibrated output signal of the EK400/38 echo-sounder, based on the maximum output signal amplitude U_{max} = 10 V_{p-p} at the expiration range R = 581.31 m, given that α = 0.0080 dB/m. Note that the signal is reduced by 20 dB for ranges greater than 100 m.

Pulse number	Depth (m)	Voltage amplitude U_r (dB)	(V_{p-p})	$(U_r/U_{max})^2$
1	10	-13.43	0.60	0.0036
2	20	-7.25	1.23	0.0151
3	30	-3.57	1.88	0.0352
4	40	-0.91	2.55	0.0649
5	50	1.19	3.24	0.1052
6	60	2.93	3.96	0.1572
7	70	4.43	4.71	0.2220
8	80	5.75	5.49	0.3009
9	90	6.94	6.29	0.3951
10	100	8.01	7.11	0.5060
11	150	-7.67	1.17	0.0137
12	200	-4.37	1.71	0.0293
13	250	-1.63	2.34	0.0550
14	300	0.75	3.08	0.0952
15	350	2.89	3.95	0.1557
16	400	4.85	4.94	0.2445
17	450	6.68	6.10	0.3721
18	500	8.39	7.43	0.5522
19	550	10.02	8.96	0.8033
20	600	11.00	10.00	1.0000

the manufacturer, it should be measured by the user at least once after mounting the transducer. This is important both for hull- and towed-body-mountings, and the type of mounting is likely to modify the beamwidth (Simmonds, 1984b).

Only one method for measuring Ψ is presently fully developed. This method is primarily suited to towed-body systems and requires a special rig. However recent developments (Ona and Vestnes, 1985; Reynisson, 1985) suggest other methods suitable for vessels with hull-mounted transducers.

To a first approximation, the equivalent beam angle changes in proportion to the square of the sound speed. It is therefore important to note the sound speed when the equivalent beam angle is measured.

3.3.2 Example: towed-body transducer

The measurements are carried out in Loch Duich on the west coast of Scotland. The underwater equipment is suspended below a raft which is moored about 600 m from the shore. The raft is connected by cable to a cabin on the shore.

3.3.2.1 Method

The transducers are Simrad type 38-26/22-E, constructed from 34 elements resonant at 38 kHz, arranged in a rectangular pattern. The beam dimensions are assymetrical, nominally 8 by 13 degrees between the 3 dB down points.

The transducer is placed at the centre of a motorised gimbal table supported by a triangular frame suspended on three 15 m wires at a depth of 20 m below the raft. A 38.1 mm diameter tungsten carbide sphere is hung 5 m below the triangular frame by three strands of monofilament nylon. The rotation of the gimbals is determined using digital angle encoders. The angular information is transmitted by a serial communications link to the shore, and the drive motors for the gimbals are remotely controlled over the same link.

3.3.2.2 Data collection

A Computer Automation 4/90 computer is used to control the gimbal table and the transmitter. It also performs a preliminary analysis of the received echo data. The 38 kHz transmitter provides a 0.5 ms pulse. The frequency is crystal controlled. The receiver is a switched gain amplifier with 7 gain steps of 3 dB and a single tuned filter of 4 kHz bandwidth. The signal is envelope-detected and sampled every 100 µs. Each sample is converted to a 12 bit binary number and passed to the computer. The samples are squared and summed to give an estimate of energy within the returned echo. The system provides 50 dB of dynamic range with an accuracy of ±0.1 dB and a further 25 dB with the same linearity but lower precision. In practice, only 30 dB of dynamic range is required to provide acceptable results.

The measurement of the transducer beam pattern is performed by recording integrals of the energy in the echo from a sphere suspended below the triangular frame. The transducer is used both as projector and receiver, as in the echo-sounder, to evaluate the combined response. Data are collected at 0.2° intervals along ±15° scans in one direction, that of the narrower beamwidth, and at 0.5° intervals over ±15° in the perpendicular direction. The sections of the hemisphere from which data are collected are restricted to ±15° movements of the gimbal in order to save time. Errors caused by this restriction are negligible, about 0.01 dB.

At each point, 40 transmissions are carried out and the standard deviation computed. Data are accepted only if the standard deviation of a set of 40 echo-integrals is less than 2% for signals down to about 15 dB below the on-axis level, 8% for the next 20 dB down and 40% for the remainder.

3.3.2.3 Data processing

The data from the grid of 61 by 151 points are inspected and any obviously spurious values replaced by linear interpolation from adjacent points. This correction procedure has a negligible effect upon the final results (less than 0.001 dB). The individual values are multiplied by $\Delta\Omega$, the element of solid angle associated with each point, and summed. The data are processed to give the following estimate of the equivalent beam angle.

$$\Psi = \Sigma\, b^2 (\hat{r})\, \Delta\Omega / b^2_{max} \quad \text{............} \quad (19)$$

where b^2_{max} is the estimated on-axis sensitivity.

3.3.3 Example: hull-mounted transducer

The following description is derived from Reynisson (1985).

3.3.3.1 Principle

The beam pattern of the transducer is sensed by moving a target sphere systematically along arcs in each of several different vertical planes passing through the acoustic axis. The equivalent beam angle is computed in accordance with its definition in equation (13).

3.3.3.2 Materials

The vessel is rigged similarly to that for measurement of on-axis sensitivity by the stationary-sphere method, cf section 3.1.2.1 and Figure 1. The arms holding the sphere suspension lines away from the hull may have to be extended to avoid contact between the suspension lines and the hull.

The suspension lines should be made of stainless steel wire or other similarly stiff material. Distances along the lines should be accurately marked at intervals of 1 m. Use of a meter rod beside each winch, cf Figure 5, will aid the positioning procedure.

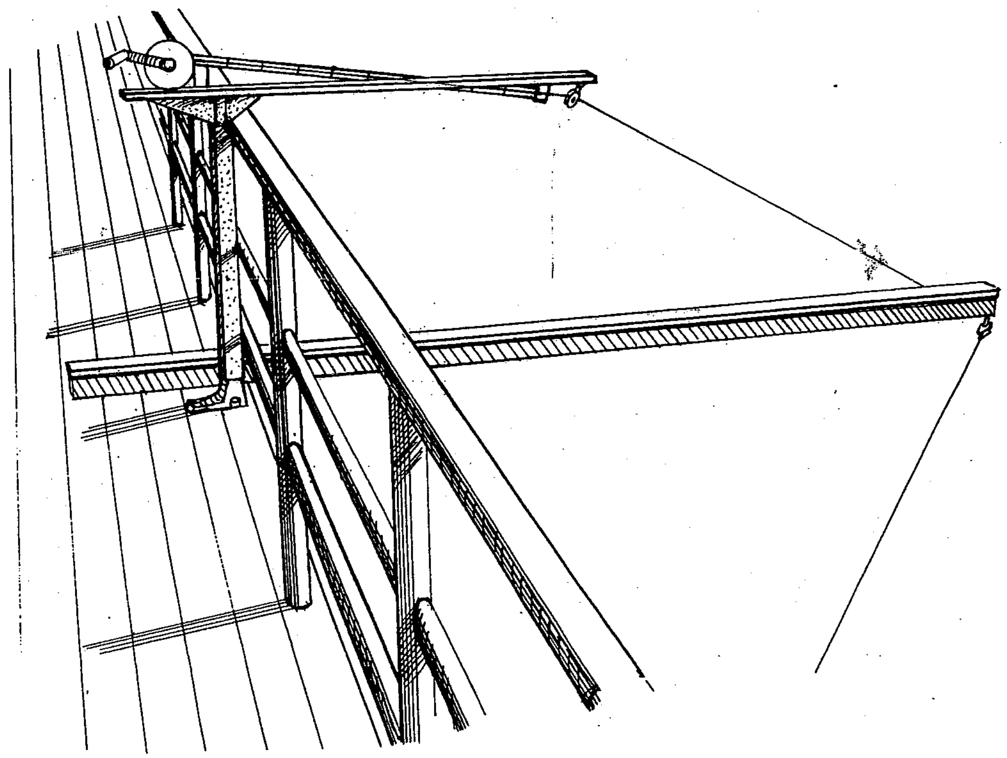


Figure 5. Equipment for transducer beam pattern measurement. The meter rod is used for precise length control of one of the lines suspending the sphere.

If the target sphere is relatively light, then weight suspended, beneath it will add inertia, hence stability, to the suspension system. The distance between the stabilizing weight and the target sphere should be large enough so that the two echoes do not overlap.

3.3.3.3 Method

To begin each measurement series, the target sphere is centred in the transducer beam. This may be done as described in section 3.1.2.3. The lengths of the three suspension lines, from the common attachment point on or near the net bag to the points of first contact with the winch system, are noted. The energy contained in the sphere echo is measured for each of 100 echo-sounder transmissions, and the arithmetic average energy is computed.

The length of one of the suspension lines is then increased or decreased in small steps. For calibration of typical ocean-going research vessels, with calibration sphere ranges of 15-25 m, an increment of 5-10 cm is convenient. At each new step or distance the measurements of echo energy are repeated. The length of the suspension line under adjustment is increased or decreased until the echo strength has fallen by at least 3 dB with respect to the on-axis value. The length is then changed systematically in the opposite direction, pulling the sphere through and past the acoustic axis until the -30 dB level is again reached.

The sphere is returned to the acoustic axis. Another suspension line is now shortened or lengthened in the same manner as the first, and the measurements repeated as before. The procedure is finally repeated for the third suspension line.

3.3.3.4 Analysis

In describing the beam pattern, the measurements of echo energy are compensated for the precise distance of the sphere from the transducer at each measurement step. This distance is determined by geometry.

An example of measurement results for the 38 kHz transducer mounted on the hull of "Bjarni Saemundsson" is shown in Figure 6. Equal-energy contours derived from these data are presented in Figure 7.

The data illustrated in Figures 6 and 7 are used to determine the equivalent beam angle, by a approximate calculation based on equation (13). The result for this particular transducer is Ψ = 0.00933 sr (10 log Ψ = -20.3 dB).

It is interesting to compare this value with that determined from the beam pattern published by the manufacturer, pertaining to a similar transducer <u>before mounting</u>, cf Figure 8. This is 0.0132 sr (-18.8 dB).

If the nominal value specified by the manufacturer for the unmounted transducer were to be used, then the fish density would be underestimated by 29%, since Ψ occurs in the denominator of

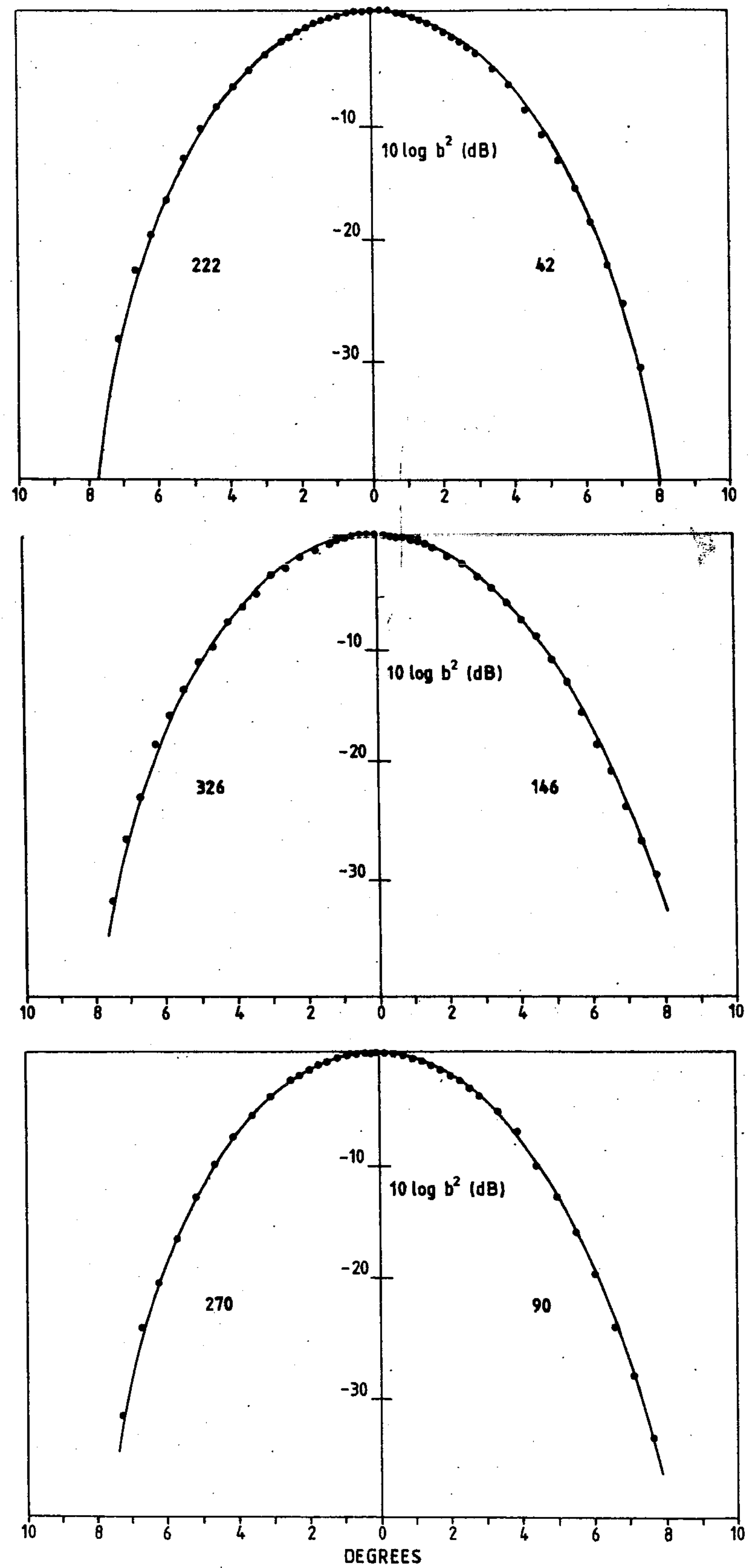


Figure 6. Measured two-way directivity patterns of the 38 kHz hull-mounted transducer on "Bjarni Saemundsson".

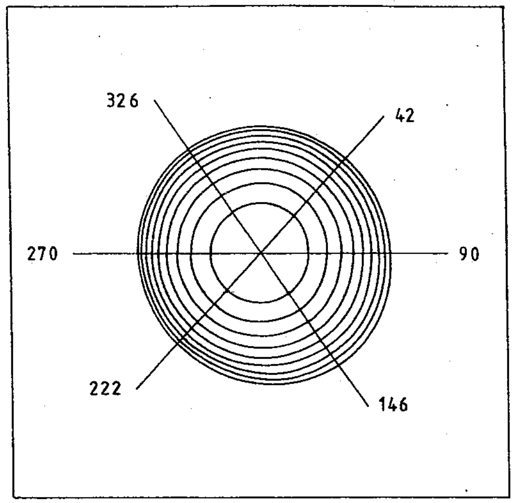


Figure 7. Equal-energy contours derived from the directivity patterns in Figure 6.

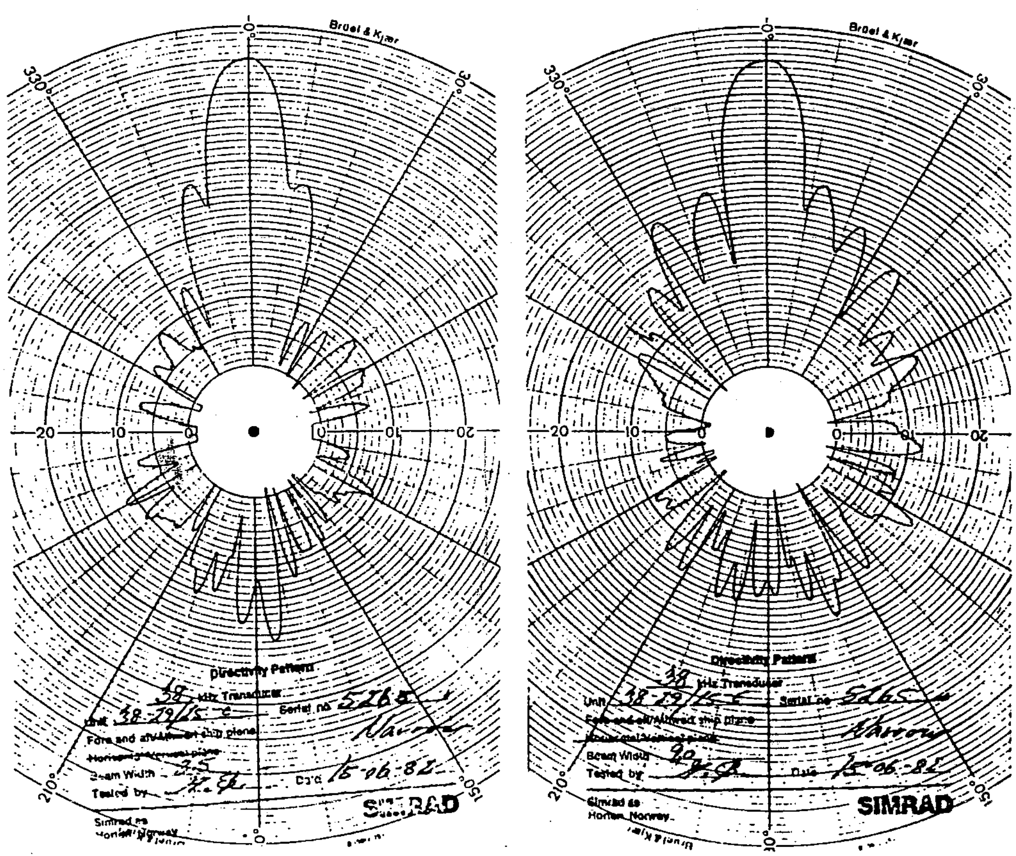


Figure 8. Laboratory measurements of the beam pattern of an unmounted transducer of the same model as that on "Bjarni Saemundssón".

equation (1). To avoid this source of bias, measurement of the transducer beam pattern after mounting is recommended.

3.4 Electrical Measurements

In order to monitor system performance, a number of parameters not directly involved in equation (1) ought to be regularly and frequently measured. These include characteristics of transmitter, transducer, receiver, and echo-integrator. Such measurements are often specific to particular instruments. The examples worked below apply to Simrad equipment.

3.4.1 Transmitter

It is important to check the transmitter output power. For pulsed echo-sounders, the power is normally determined by means of an oscilloscope used with either a voltage probe or current probe. Both methods are now considered for the case of a 1 ms pulse applied to the transducer.

3.4.1.1 Power measurement with a voltage probe

A 100 x probe that is properly compensated for high frequencies should be used. This is connected to the terminals of the subject transducer. Exactly where this is done depends on the particular equipment that is to be measured and how it is mounted. What is important is that the voltage that drives the transducer be measured. Figure 9a shows an oscilloscope photograph of a transmitter pulse measured with a voltage probe.

There are often irregularities at the beginning and end of the pulse. These frequently take the form of overshoots or tails. They have only a slight effect with respect to the energy contained in the total pulse, but should the voltage be read off at an irregularity, large errors may result. The voltage of a 1 ms pulse should be read 0.5 ms after its start.

3.4.1.2 Example

The voltage of a 1 ms pulse is determined from an oscilloscope to be 1250 V_{p-p} (peak to peak) 0.5 ms after the start. The impedance Z_3 at the nominal centre frequency of the transducer was found earlier to be 63 Ω. The average power is thus

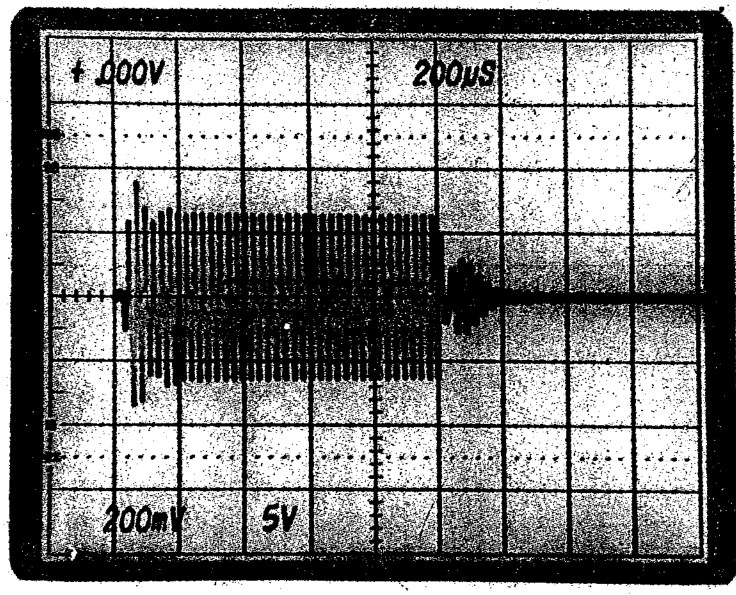
$$P = U^2_{p-p}/(8\ Z_3) = 1250^2/504 = 3100\ W$$

where U_{p-p} denotes the peak-to-peak voltage. According to the manufacturer's specifications, the transmitting power response S_p is 196.0 dB//1 µPa at 1 m per W. The expected source level is thus

$$SL = S_p + 10 \log P = 196 + 10 \log 3100 = 230.9\ dB//1\mu Pa \text{ at } 1\ m$$

The method in this example must be considered unreliable because the phase relationship between voltage and current is unknown, and

(a)



(b)

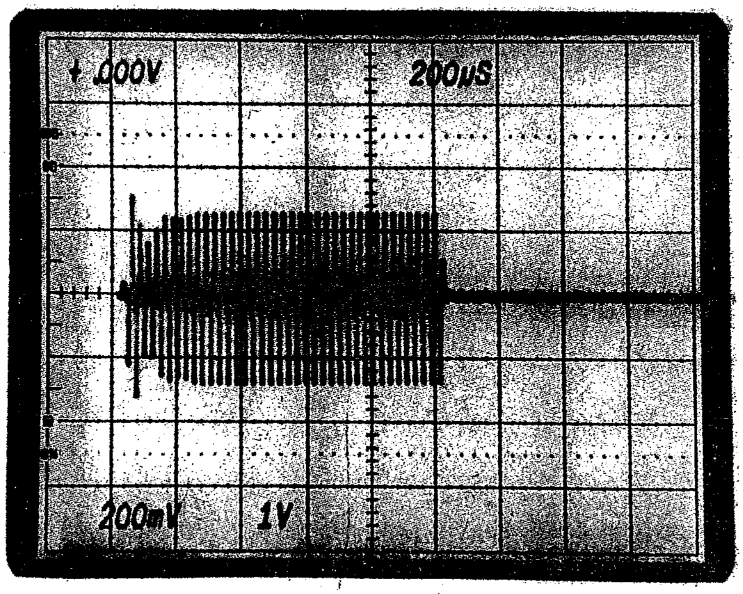


Figure 9. Oscillographs of a 1 ms transmitter pulse measured (a) with a voltage probe; 100 x amplification; scales: 500 V/cm vertical, 0.2 ms/cm horizontal; and (b) with a current probe, conversion factor 10 mA/mV; scales: 10 A/cm vertical, 0.2 ms/cm horizontal.

the voltage probe can be frequency sensitive if not properly compensated. Results from this method are nonetheless useful as a rough check on the transmitter performance.

3.4.1.3 Power measurement with a current probe

Measurements with a current probe are preferred to measurements with a voltage probe. The current probe is inductively coupled to the transducer cable, hence it has no metallic contact with the circuit under measurement.

A voltage is measured on the oscilloscope proportional to the current in the transducer (Fig. 9b).

3.4.1.4 Example

Measurement with the oscilloscope gives 2500 mV_{p-p}. The current probe conversion factor is 10 mA/mV. The current in the transducer is thus

$$2500 \text{ mV} \cdot 10 \text{ mA/mV} = 25 \text{ A}_{p-p}$$

and the root-mean-square (rms) current is thus

$$\frac{25}{2.2^{\frac{1}{2}}} \text{ A}_{p-p} = 8.84 \text{ A}_{rms}$$

The transducer is the same as in the previous example, hence the average pulse power for current I is

$$P = I^2 \cdot Z_3 = 8.884^2 \cdot 63 = 4923 \text{ W}$$

The source level is estimated as in the previous example:

$$SL = S_p + 10 \log P = 196 + 10 \log 4923 = 232.9 \text{ dB//1µPa at 1 m}$$

If the transducer's transmitting current response S_c is known, then the expected source level can be computed without knowing the transducer's impedance. According to the manufacturer's specifications.

$$S_c = 213.2 \text{ dB//1 µPA per A at 1 m}$$

Thus the source level for current I is

$$SL = S_c + 20 \log I = 213.2 + 20 \log 8.84 = 232.1 \text{ dB//1µPa at 1 m}$$

3.4.2 Transducer

The two most common kinds of transducers are ceramic, which is electrostrictive, and nickel, which is magnetostrictive. Ceramic transducers are now the more widely used. These are often built up by an array of individual elements embedded in a polyester fibre glass casting in the transducer housing. Because of the method of mounting, adjustment of the individual elements is not generally possible. Schematic diagrams of the two transducer types are shown in Figure 10a.

The manufacturer of the transducer generally specifies a number of factory-measured parameters. Some of these should be confirmed at the time of installation, in particular the impedance and beamwidth. The transducer insulation resistance is also most important in any application of the equipment. Here we consider only the impedance measurement.

3.4.2.1 Impedance measurement

This is necessary for computation of the transmitter output power. The instrument configuration is shown in Figure 11. The measurement is performed by comparing the voltage across the transducer terminals at different frequencies with the voltage over a potentiometer. That potentiometer resistance which gives the same voltage drop as the transducer at a given frequency approximates the transducer impedance at that frequency.

3.4.2.2 Example

Measurement of the insulation between the individual wires and the salt water in which the transducer is immersed should precede the impedance measurement. This example concerns a ceramic transducer connected to the Simrad EK400 echo-sounder and integrator. The manufacturer supplies a two-beam transducer with standard colour coding on the several wires of the cable, cf Figure 10b. For the wide beam, only the blue and black leads are used. For the narrow beam, the echo-sounder is connected to the yellow/green and blue leads joined together on one side and to the brown lead on the other side, while the black lead is not used. The measurements are facilitated by removing the transducer plug.

In measuring the wide beam, the test clips are connected to the B and D terminals in the plug. In measuring the narrow beam, the terminals D and E are short-circuited, and the test clips are connected to the terminals D/E and A.

NB In many systems only the narrow beam is used. For these, the yellow/green and blue leads are permanently joined, and the single common wire is coupled to the transducer plug. The test clips are connected in this case to terminals A and E.

The nominal value of the transducer impedance is 60 Ω. Experience demonstrates, however, that the value can generally lie anywhere in the range from 50 to 80 Ω. The impedance at the nominal centre frequency was denoted Z_3 above. A typical impedance characteristic is shown in Figure 10c.

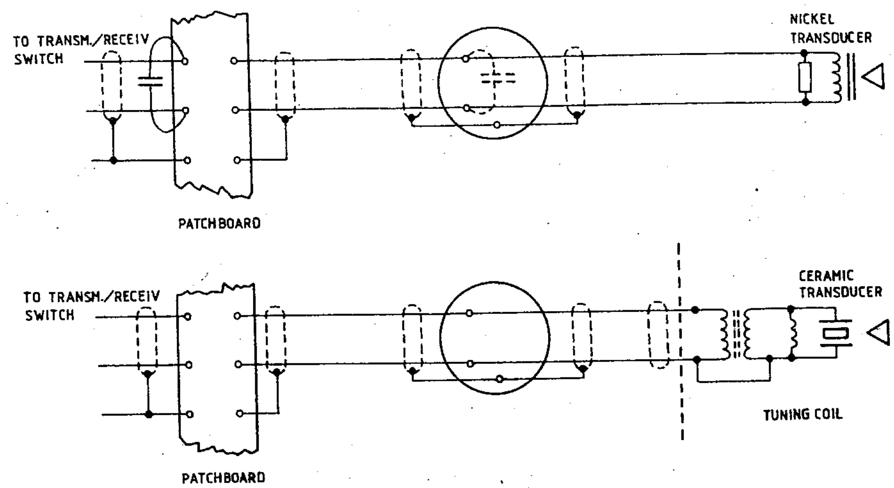


Figure 10a. Principal circuit diagram for nickel and ceramic transducers (ref 3.4.2).

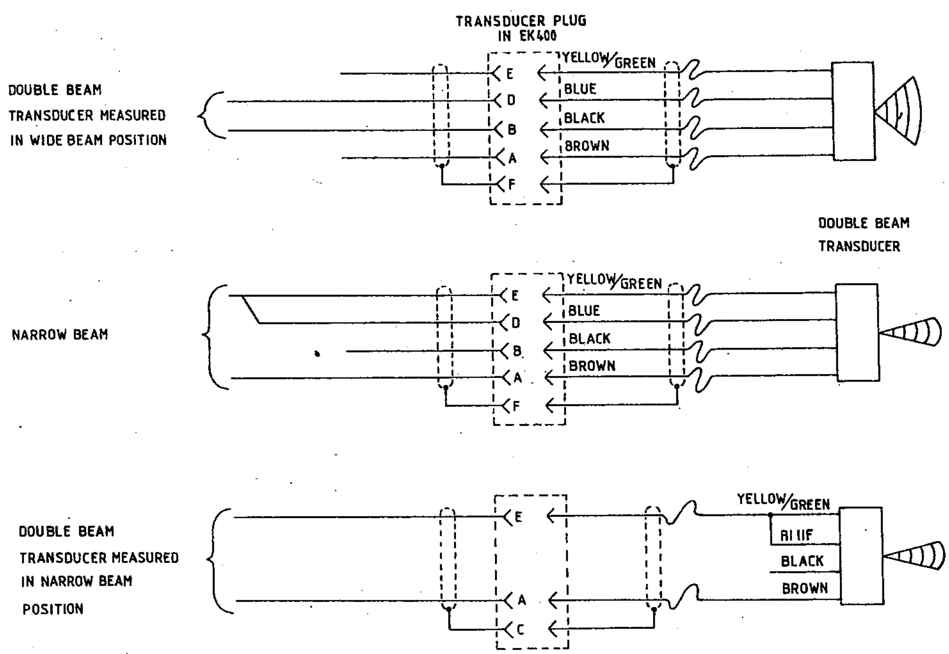


Figure 10b. Transducer connections for impedance measurement of the EK400 (ref 3.4.2.1).

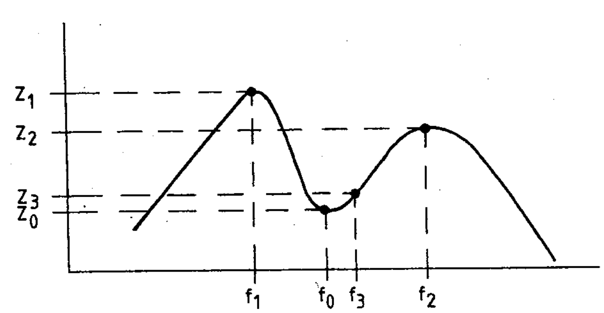


Figure 10c. Typical impedance characteristic.

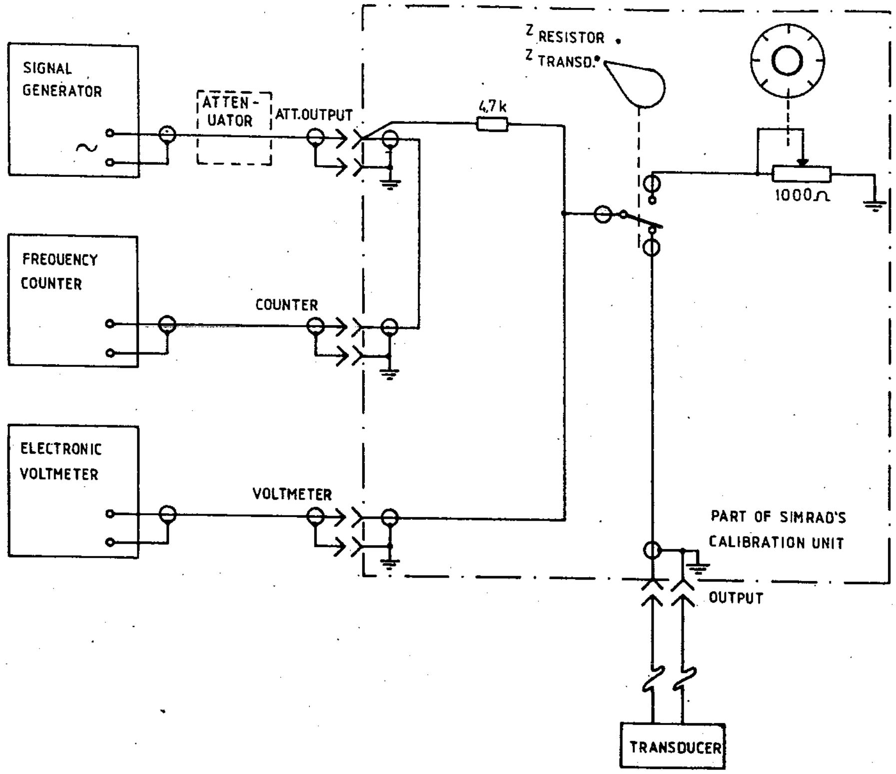


Figure 11a. Instrument configuation for impedance measurement.

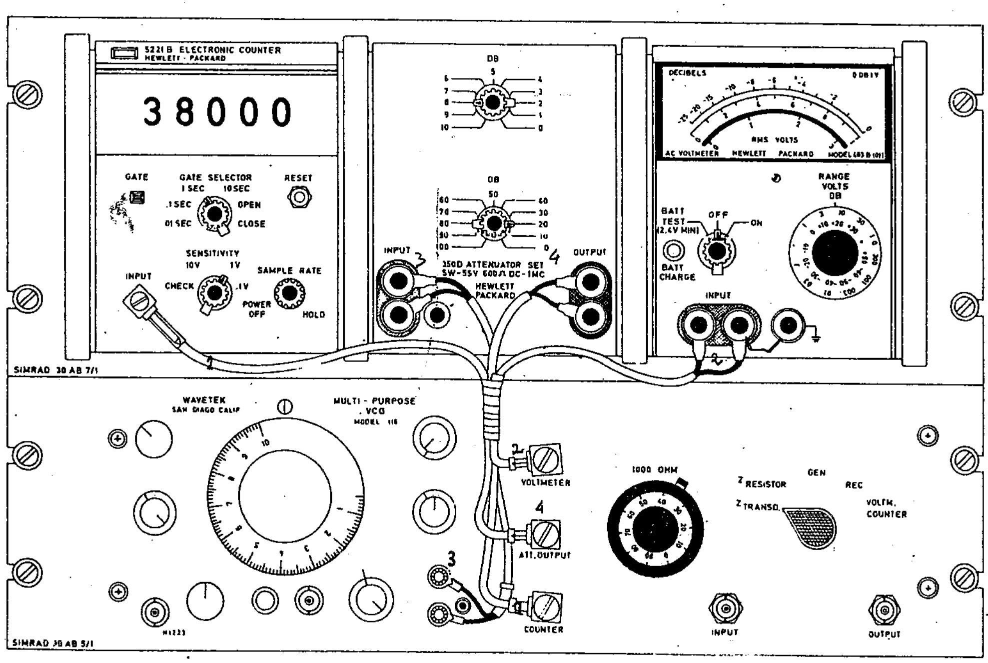


Figure 11b. Typical testing instruments.

3.4.3 Receiver: total amplification

It is important to be able to verify quickly the total, non-dynamic amplification of the receiver. This is nominally 85 dB, a voltage amplification of 17783 times. Figure 12 shows how the measurement is performed in two operations by means of an attenuator.

The attenuation, about 50 dB, must be checked. In some echo-sounders, such as the EK and EK-S, the attenuator is built-in, and is coupled whenever the OPERATE/TEST switch is on TEST. The attenuator for the EK400 is a separate unit which must be connected to one of the transducer terminals.

3.4.3.1 Measurement procedure

(1) Set the echo-sounder attenuator to 0 dB.

(2) Stop the recorder stylus to disable the TVG function. In the special case of the EK400, remove the TVG generator to avoid the risk of the TVG being left at an intermediate position.

(3) Adjust the signal generator to the nominal frequency, and drive this at maximum amplitude when connected to the echo-sounder test input (TEST IN on the test attenuator).

(4) Measure the generator output U_{gen} and the voltage on the transducer terminals, U_{in}.

(5) Compute the attenuation $D = U_{in} - U_{gen}$.

(6) Adjust the signal generator level until $U_{cal\ out} = 0$ dB, and read U_{gen}.

(7) Compute the total amplification $G = U_{cal\ out} - (U_{gen} + D)$

3.4.3.2 Example: measurement of the attenuator

The signal generator (Wavetex Model 115) is set to its maximum amplitude, and the output voltage level U_{gen} is measured as 12.5 dB. The voltmeter is switched to the transducer terminals, and the input voltage level V_{in} is measured as -37.3 dB. The attenuation is thus

$$D = U_{in} - U_{gen} = -37.3 - 12.5 = -49.8 \text{ dB}$$

For the EK and EK-S the voltmeter is connected inside the cabinet to pins 9 and 10 on T502 in order to measure V_{in}. For the EK400, with external attenuator, V_{in} is measured at the terminal marked TX OUT. In both cases the measurement is made across the receiver input terminals.

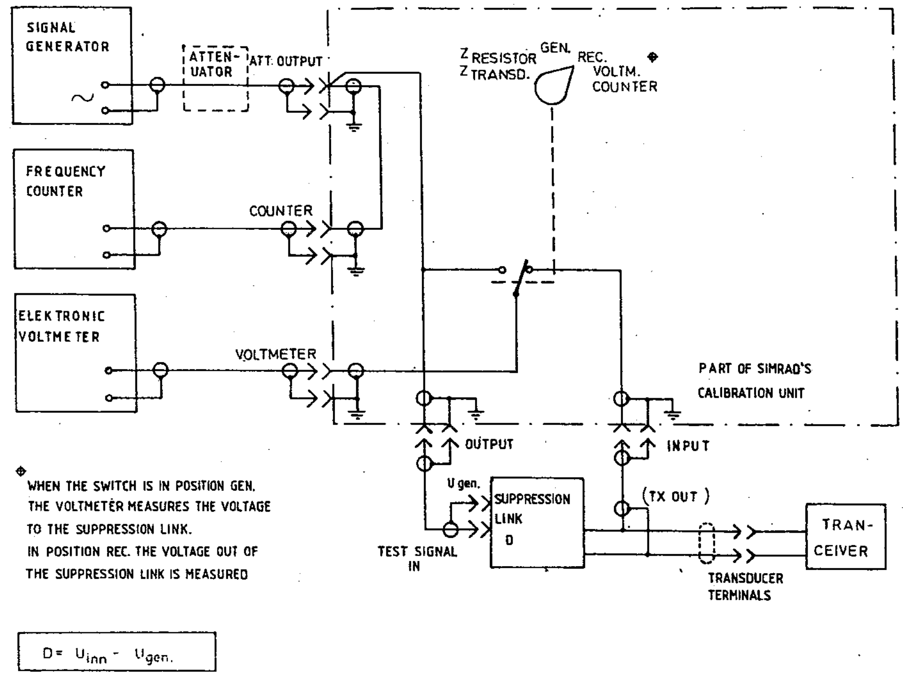


Figure 12a. Equipment set up for measuring the attenuator (ref 3.4.3.2).

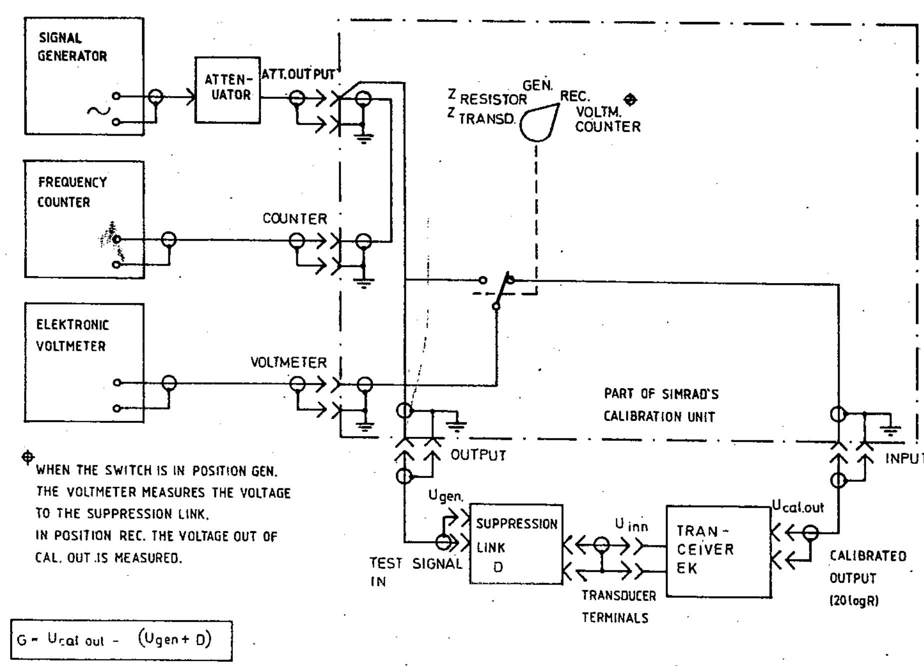


Figure 12b. Equipment set up for measuring the amplification (ref 3.4.3.3).

When another type of signal generator is used, any output level in the range 10 to 15 dB is adequate. If the maximum output is less than this, then the maximum should be used.

3.4.3.3 Example: measurement of the total gain

The signal generator remains connected to TEST IN. The voltmeter is connected to CALIBRATED OUTPUT ("20 log R"), and the level is adjusted until $U_{cal\ out} = 0$ dB. U_{gen} is read off the voltmeter as -35.4 dB. The total receiver amplification is thus

$$G = U_{cal\ out} - (U_{gen} + D) = 0 - (-35.4 + (-49.8)) = -(-85.2) = 85.2 \text{ dB}$$

That the amplification is 0.2 dB higher than the nominal value is unimportant as long as it remains constant. If G is more than 0.5 dB different from the nominal value, an equipment malfunction is likely and the cause should be investigated.

3.4.3.4 Attenuator setting

For the EK and EK-S, the attenuator switch, called GAIN, has two steps: 0 and -20 dB. For the EK400, the ATTENUATOR has four steps: 0, 10, 20 and 30 dB. The amplification is measured at those settings likely to be used during acoustic abundance estimation. Note that a positive attenuation is equivalent to a negative gain of the same magnitude.

3.4.3.5 Example: measurement of amplification at the attenuator setting 20 dB (gain -20 dB)

The 20 dB attenuator is selected, and the input voltage is increased until $U_{cal\ out}$ again equals 0 dB. U_{gen} is read off the voltmeter as -15.5 dB. The receiver amplification at this setting is thus

$$G = U_{cal\ out} - (U_{gen} + D) = 0 - (-15.5 + (-49.8)) = -(-65.3) = 65.3 \text{ dB}$$

As the previous example, the difference between the 19.9 dB attenuation and the nominal 20.0 dB is insignificant as a measure of the correct performance of the electronics but should be taken into account if used in the calculation of system performance.

3.4.4 Echo-integrator

In this report we have not yet specified the units of the echo-integrator output. For historical reasons, millimetres of equivalent pen deflection remain surprisingly popular and are used in the following examples of Simrad echo-integrators. This should not detract from the general discussion since the measurement techniques can be applied to other equipment, in which alternative more natural units are used.

3.4.4.1 Scaling

By definition, given a 30 m depth interval, 0 dB gain factor, and input signal of 0 dB//1 V_{rms}, the output of the Simrad echo-integrator, whether analog or digital, is 47 mm per nautical mile. When referred to 40 dB amplification, the deflection should be 470 000 mm. Echo-integration measurements performed by the Bergen Institute are usually referred to 40 dB amplification.

3.4.4.2 Linearity

The relationship between the input and output signals of the integrator should be linear.

3.4.4.3 Test measurement of linearity

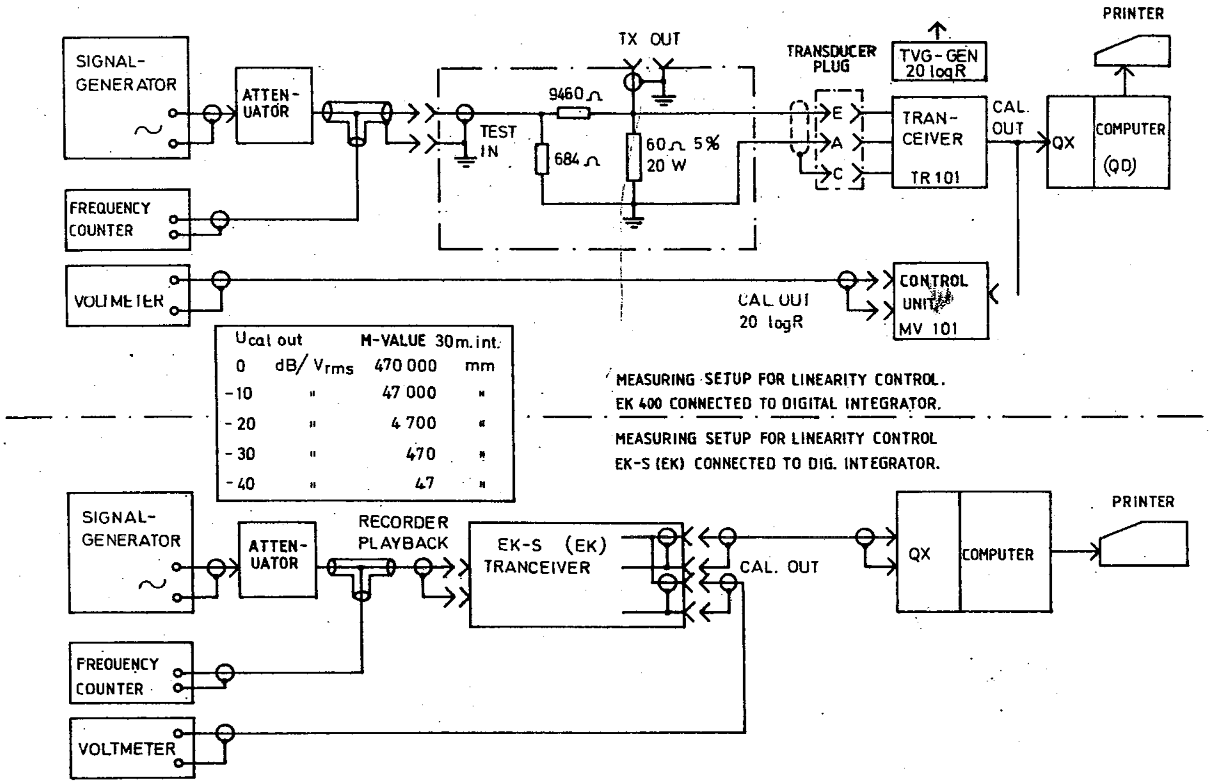
(1) The signal is obtained from the echo-sounder without TVG. For the EK and EK-S, the signal is entered at the RECORDER PLAYBACK port. For the EK400, the TVG generator must be removed from the transceiver compartment. Figure 13 shows the measurement set up.

(2) The voltage of the CALIBRATED OUTPUT signal, with "20 log R" TVG, is measured with an electronic voltmeter, and the input voltage is adjusted until the voltmeter reads 0 dB//1 V_{rms}.

(3) The integrator threshold is set to 0 and the bottom discriminator is set to the highest voltage. A series of 30 m depth intervals is chosen, e.g., 20-50, 50-80, 80-110 m. The particular interval 500-530 m should be included, because some EK400 receivers are disturbed during the start of transmission when the TVG generator is not connected. The signal in such cases follows a descending curve and is not stable for about 500 m. The vessel's speed is simulated as 10 knots. Integration for a period of six minutes thus corresponds to a sailed distance of one nautical mile. With an on-board computer, the various adjustments mentioned above may be performed automatically. Printouts may be produced more often than at an equivalent distance of one nautical mile, but the numbers are compensated in such a way that they represent the same distance in the mean.

(4) With the CAL OUT signal at 0 dB gain, the integrator should record 470 000 mm in each 30 m interval. A deviation of 10% corresponds to 0.5 dB in signal strength. The deviation ought to be less than 5%. If it is greater, the equipment ought to be adjusted again.

(5) The input signal is reduced in 10 dB steps and the same measurements repeated. The following list shows the connection between the CAL OUT signal and the registered echo-integrator output for a 30 m depth interval:



$U_{cal\ out}$		M-VALUE 30m. int.	
0	dB/ V_{rms}	470 000	mm
-10	"	47 000	"
-20	"	4 700	"
-30	"	470	"
-40	"	47	"

Figure 13. Equipment set up for checking the echo-integrator linearity (ref 3.4.4.3).

0 dB	-	470 000 mm
-10 dB	-	47 000 mm
-20 dB	-	4 700 mm
-30 dB	-	470 mm
-40 dB	-	47 mm

For most systems the -40 dB signal is dominated by the echo-sounder self noise. The requirement that the deviation must not exceed ±5% cannot then be maintained.

3.4.4.4 Dynamic range

The integrator itself, as a digital computer, introduces no limitations in the dynamic range. The QX preprocessor has a specified dynamic range from + 18 to -50 dB, 68 dB altogether. The echo-sounder, with TVG function in operation, has a dynamic range that varies from 15 dB//1 V for the EK400, and 10 dB//1 V for the EK or EK-S, to the self-noise level, which should not exceed about -40 dB//1 V for either system.

3.4.4.5 Adjustment of the QX preprocessor

The QX preprocessor occasionally requires an offset/gain adjustment. The following routine can accomplish this.

(1) Analog MUX detector

(a) The CAL OUT signal is the input to the QX. Adjust the CAL OUT signal level to 0 dB//1 V. The signal passes through the echo-sounder at the nominal frequency and is measured in the CAL OUT channel. The echo sounder paper recorder is stopped. Measure the voltage at the TP2 terminal of the analog MUX with a digital voltmeter. Adjust the R11 (gain) until the meter reads 1.000 V.

(b) Adjust the CAL OUT signal to -40 dB. Adjust R07, the offset potentiometer, until the meter reads 10 mV.

(2) A/D converter

(a) High level: Input a 2.5 V_{rms} signal. Switch the test panel selector to SIGNAL. With this input the indicator 2^{10} should just begin to light. Adjust with R01 (gain).

(b) Low level: Input an 8.4 mV signal, and adjust, as necessary, R02 (offset) such that the indicator 2^2 just begins to light. The indicators 2^0, 2^1, and 2^2 are then weakly lit. Each bit represents an incremental peak voltage of 3.45 mV. The 8.4 mV signal thus lies between $2^0 + 2^1$ and 2^2. Because of ripple, it is difficult to make a perfect adjustment.

4 CALIBRATION ACCURACY

The performance of a system is only as good as the test equipment used to check it. Care must always be taken to ensure that test equipment is itself tested regularly and maintained up to specification. Do not try to make do with poor quality equipment or inferior techniques. To measure time, use a timer counter, not an oscilloscope; if a voltage measurement is required, use a precise voltmeter; and if pulse energies are required, the echo-integrator itself is a good choice. Avoid visual measurement using an oscilloscope. Measurement of time or voltage on an analogue display can only be made generally to about 1% or worse and the equipment error is bound to be 1% or worse in addition to this. Digital instruments are more precise. A few examples of measurement accuracy are given below as an indication of what can be achieved by careful practice.

Errors and accuracies quoted in this section are 95% confidence limits, unless otherwise stated.

4.1 Time-Varied Gain

The measurement accuracy of the constant-output technique (ref 3.2) depends mainly on the amplitude linearity of the input signal synthesiser. The sampling error is ±0.25% on each measurement. There is also a bias due to non-linearity in the signal source of ±1%.

4.2 Equivalent Beam Angle

The towed body measurement (ref 3.3) includes errors of ±1.6% (Simmonds, 1984). This is the only method for which the measurement precision has been evaluated so far.

4.3 On-axis Sensitivity Measurement

The error reduces as more time is spent in collecting the data. For one hour of data collection, or about five pairs of scans, the error in the mean sensitivity estimate is ±0.68%. There is also a small bias introduced by the parabolic fitting procedure, about -0.1% because the parabola is an approximation to the true beam shape.

The range of the target is estimated from the time between the leading edge of the transmitter pulse and the half voltage point on the received echo waveform. This time can be measured to better than 1 μs. However, the triggering point of the transmitter is uncertain due to the phase difference between the transmit trigger pulse and the gated 38 kHz waveform that is transmitted. This causes errors up to half of a period (7 μs). In addition, the finite system bandwidth increases the echo delay. The calculated value of this extra delay may be in error due to uncertainty in the system bandwidths. For a 3 kHz bandwidth and 1.0 ms pulse duration, the extra delay might be in error by ±17 μs. These equipment errors combine to give a bias of ±0.3% and random errors of ±0.02% in the range estimate. An other variable to be considered is the sound speed c. This should vary by less than ±1% in the North Atlantic, but it is the most significant factor in the range estimation error. Larger errors in c may occur in parts of the world where the water temperature fluctuates more widely.

The absolute error of the calibration depends upon the accuracy of the standard target. The target strength of the tungsten carbide sphere is known to ±2.2%, when the target is suspended in a monofilament bag (MacLennan and Armstrong, 1984).

4.4 Summary of Errors

The errors above are listed in Table 7 as random and systematic errors. They apply to a single measurement carried out with a known transducer, in known mountings, with any 38.1 mm tungsten carbide standard target, in sea water within the range of temperature and salinity found around the Scottish coast.

The accuracy is dominated by three main sources of error: the standard target; the equivalent beam angle; and the sound velocity. To improve on the first two would be very difficult. However, the sound velocity is a function of temperature and salinity. Hydrographic measurements taken at the time of the calibration should improve the estimate of the target range. The total error could be reduced to around ±3%. This is negligible compared to some other errors in acoustic stock estimates.

It should be pointed out that the errors quoted above are near the lower limit of what can be achieved with present techniques, and they apply only if care is taken. In addition it is stressed that if the measurements appear variable, there is no substitute for repeating the calibration to ensure satisfactory results.

5 INTER-SHIP CALIBRATION

This section has been adapted from an internal memorandum by Kaare Hansen, Institute of Marine Research, Bergen.

5.1 Introduction

In principle, all absolutely calibrated echo-sounders, operating at the same frequency, will measure the same value for a given fish aggregation. This can be verified through an inter-ship calibration, or "intercalibration". In this, two or more vessels sail over the same aggregation, and afterwards compare their acoustic observations. Under suitable conditions, large errors in the absolute calibrations may be detected. If only one of the vessels has been absolutely calibrated, then the others can be calibrated against it. In general, intercalibration is highly desirable, if not necessary, whenever several vessels work together on echo surveys of the same fish stock. It should not however be used as a substitute for a standard target calibration except when absolutely unavoidable.

TABLE 7

Components of Calibration Error

Source of error	Systematic	Random
Equivalent beam angle	± 1.6%	
TVG gain	± 1.0%	± 0.25%
Target range: electrical	± 0.6%	± 0.04%
sound velocity	± 2.0%	
Evaluation of on-axis echo (1 hour)		± 0.68%
Target accuracy	± 2.2%	
Cumulative error at 95% confidence level	± 3.6%	± 0.73%
Total error	± 3.7%	

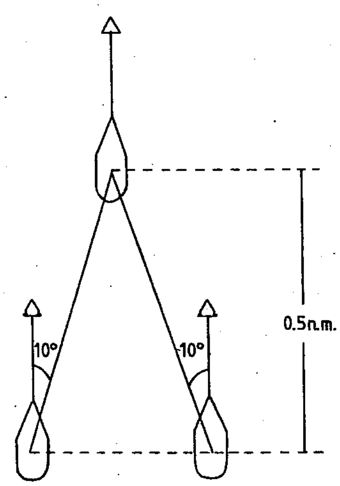


Figure 14. Sailing formation during an intercalibration of three vessels.

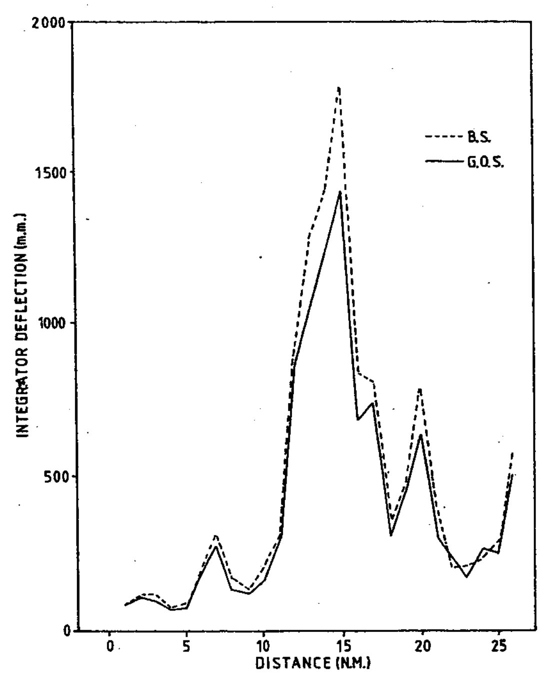


Figure 15. Illustration of echo abundance measures displayed for each mile sailed along a 26 mile course, obtained during the intercalibration of "Bjarni Saemundsson" and "G O Sars", October 1982.

Intercalibration is also useful when echo-sounders operating at different frequencies are used to survey the same fish stock. The observed frequency dependence of scattering by the fish aggregation may reveal variations in size or species composition, or the intercalibration may help to distinguish between plankton and fish is the surveyed area. In this type of investigation, of course, absolute calibration of the acoustic equipment is also required.

There are many ways to execute an intercalibration. In the following, the usual method employed by the Institute of Marine Research, Bergen, is described.

5.2 Method

In order to obtain a good result, it is necessary to find an area with either layered or dispersed fish aggregations of varying density and varying depth. The weather conditions should be good, and the vessel's course ought to be determined as favourably as possible with respect to the direction of wind and waves. The speed is similarly determined.

A typical sailing formation is shown in Figure 14 for the case of three vessels. One vessel leads the other two by a distance of 0.5 nautical miles. The following vessels maintain the lead vessel at a bearing of 10°, to port or starboard, to avoid the wake of the first. Following course changes, it is imperative that the rearmost vessels adapt their courses or relative positions to avoid the wake of the lead vessel.

The instrument settings ought to be the same as those generally used in cruise operation. The depth channel selected on the integrator, of course, must be adjusted for the transducer depth, so that the actual depth range is the same for the several echo-integrators being intercalibrated.

The integrator values should be registered for each nautical mile of sailed distance. If practicable, one vessel log should be taken as the reference. This can be done by operating all the integrator resets manually, prompted by signals transmitted on VHF radio from the vessel with the reference log.

A sailed distance of from 20 to 30 nautical miles is often sufficient for accomplishing the intercalibration. However, when the calibration of one of the vessels is being performed for the first time, it may be necessary to sail further in order to observe sufficiently varied aggregations of fish.

Upon completion of the data collection the echo-sounder paper recordings must be examined and compared mile for mile together with the corresponding echo-integrator values. Examples of intercalibration data are illlustrated in Figures 15 and 16 for the case of two vessels. In Figure 15 the echo-integrator values are displayed in succession for each sailed mile. In Figure 16 corresponding values for the two echo integrators are shown on a scatter diagram, and the echo traces are shown in Figure 17.

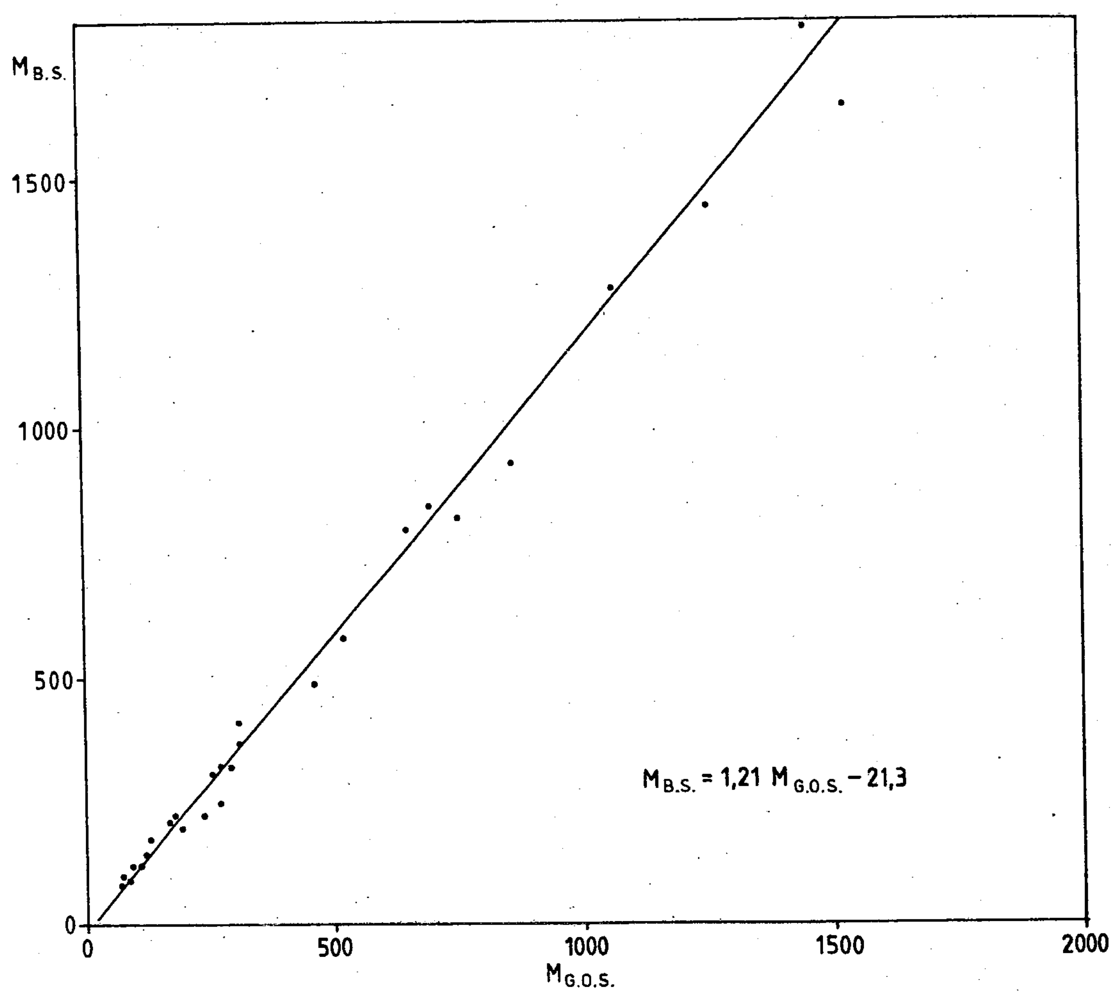


Figure 16. Scatter diagram with regression line of echo abundance measures of "Bjarni Saemundsson" and "G O Sars" during intercalibration.

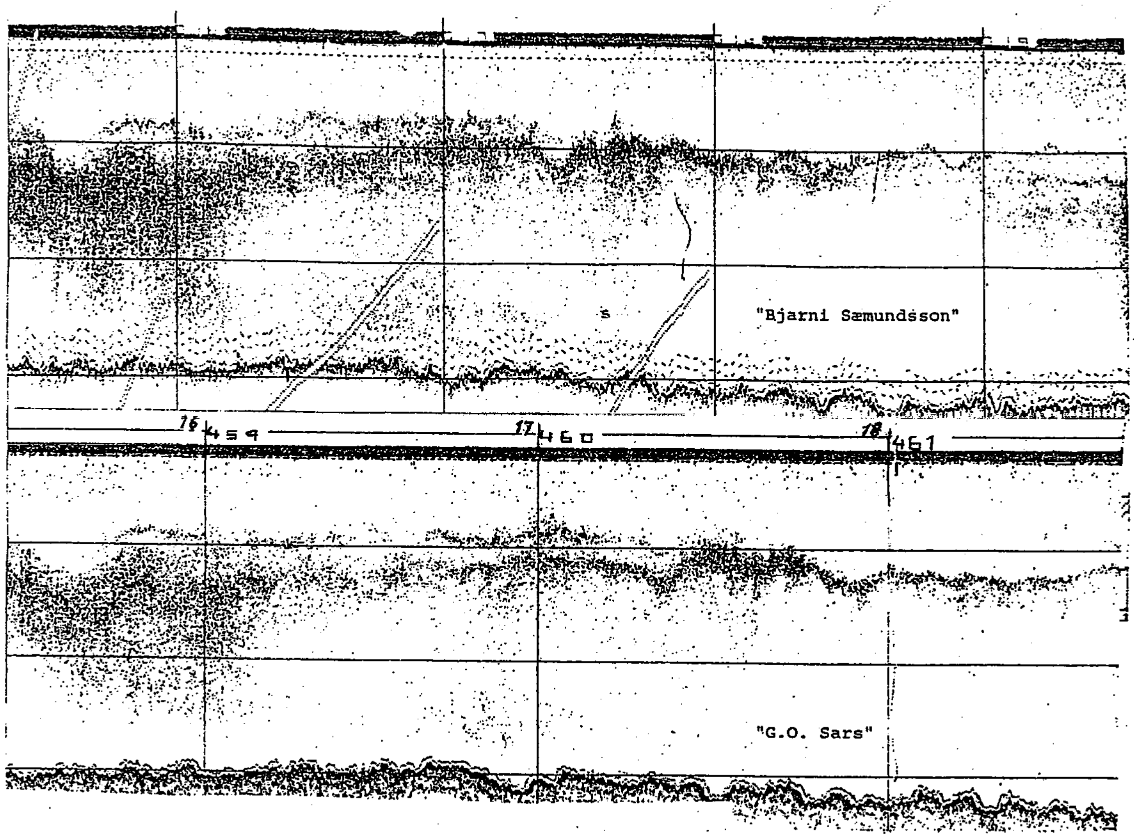


Figure 17. Echo traces obtained by "Bjarni Saemundsson" and "G O Sars" during intercalibration.

An intercalibration equation can now be determined. This may be done by visually fitting a straight line to the scatter diagram or, more quantitatively, by performing a functional regression analysis (MacLennan and Pope, 1983). When the data are gathered under good conditions, the result of using a functional regression analysis will be indistinguishable from the simpler linear regression analysis.

The results of the intercalibration must be documented, at least in a working paper or memorandum to be distributed to interested parties. An example is presented below.

The success of an intercalibration depends on many factors. These include intrinsic properties of the fish aggregation, such as its lateral extent and variation with depth, and external influences like weather and sea state. If the circumstances of the intercalibration are unfavorable, the results may be doubtful, and should only be used with great caution and in the absence of an absolute calibration for one of the vessels.

5.3 Example

The 38 kHz echo-sounders of the research vessels "Bjarni Saemundsson" and "G O Sars" were each calibrated using a 60 mm diameter copper standard sphere. The results are summarized in Table 8.

In order to establish a conversion factor for the integrator outputs of the two vessels, intercalibration was carried out in the area between longitude 12°40' and 13°50'W at latitude 66°15'N. The sailed distance was 26 nautical miles. The prevailing weather conditions were favourable, with a light breeze and little swell.

The intercalibration was performed with "G O Sars" steaming 0.5 nautical miles ahead and 10° to port side of "Bjarni Saemundsson". The navigational log counter on "Bjarni Saemundsson" was used as the distance reference, and the integrator reset function on "G O Sars" was operated manually each nautical mile on a radio signal from "Bjarni Saemundsson".

The echo signals were integrated in two depth channels which together covered the range 10 to 100 m. It was assumed that the fish targets consisted mainly of O-group capelin. The integrator outputs varied between 15 and 1800 mm per nautical mile. The settings of the instruments during the intercalibration were the same as used during the survey. Some details are given in Table 9.

Following the measurement part of the exercise, the echo recordings and related integrator values were scrutinized. Since the registrations on the recording papers of the two vessels showed great similarity over the entire distance, all the integrator data could be used in the regression analysis. Examples of the echo recordings are shown in Figure 17. Figures 15 and 16 compare the integrator data recorded mile by mile on the two vessels.

TABLE 8

Summary of Results from the Standard-sphere Calibrations

	"G O Sars"	"B Saemundsson"
Date	02.10.82	03.10.82
Transducer impedance	76Ω	69Ω
Transmitter power	6600 W	2450 W (dummy load)
Receiver gain, ref 0 dB attn	85.1 dB	85.3 dB
Performance (SL + VR), ref 0 dB attn	134.8 dB	136.3 dB
Integral, ref 1 m depth, 1 m distance and 10 dB attenuation	2170 mm	3072 mm

TABLE 9

Instrument Settings During the Intercalibration Experiment

	"G O Sars"	"B Saemundsson"
Echo-sounder	EK400	EK400
Frequency	38 kHz	38 kHz
Transducer	69C (5°x5, 5°stab)	69C (4, 5°x5°)
Transmitter Power	5.0 kW	2.5 kW
TVG	20 log R	20 log R
Gain	-10 dB	-10 dB
Bandwidth	3.3 kHz	3.3 kHz
Pulse duration	1.0 ms	1.0 ms
Recorder gain	8	8
Range	0-250 m	0-250 m
Integrator	ND-10	QD
Gain (ref output)	40 dB	40 dB
Threshold	16 mV	15 mV
Interval	10-100 m	10-100 m

The following equation was derived by regression analysis of the data in Figure 16.

$$M_{BS} = 1.21\ M_{GOS} - 21.3$$

where M is the echo abundance in millimetres of equivalent pen deflection per nautical mile of sailed distance. The squared correlation coefficient is 0.99. This equation agreed closely with results from the standard-target calibrations and was used in analysing the integrator data obtained during the cruise.

6 CONCLUSIONS

The accuracy of acoustic calibration technique has improved greatly as a result of research and development work in recent years, and now the calibration, if performed correctly, is no longer one of the more significant sources of error in acoustic biomass estimates.

In this report, we have described the calibration techniques currently used by experienced acousticians in fishery research institutes. This report is not the last word on the subject, however. There will no doubt continue to be improvements in the equipment and techniques used for acoustic calibration. Science and technology, perhaps more in acoustics than in most fields, do not stand still.

It is recommended that the procedures outlined in this report be followed carefully, to ensure that the calibration error remains acceptably small. Careful attention to the calibration may not of itself guarantee success in acoustic surveys of fish stocks. However, if the calibration is performed carelessly or not at all, that could well guarantee failure!

7 ACKNOWLEDGEMENTS

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APPENDIX I

EQUATIONS FOR SOUND SPEED AND ABSORPTION COEFFICIENT

(a) Sound speed

The recommended method for estimating the sound speed for use in fisheries acoustics is the nine-term equation presented by Mackenzie (1981). This equation has a standard error of 0.07 m/s. For shallow water, the TD^3 terms may be omitted with a standard error of 0.092 m/s.

The equation is valid for temperatures between -2°C and 30°C; for salinity from 25 to 40‰; and for depths of 0 to 8 000 m. However it is expected that the Mackenzie equation will be adequate for temperatures as high as 35°C because of the limited ranges of other parameters over which such temperatures exist. This equation should provide calculated values to better than 1 m/s for all cases. For salinity lower than 25‰, a comparison has been made between calculations from a formula presented by Chen and Millero (1976) for pure water and the formula given below with S=0. The agreement is better than 1 m/s for all temperatures and depths, suggesting that the Mackenzie formula can be used for low salinity or freshwater to better than 2 m/s.

Equation:

$$c = 1448.96 + 4.591\,T - 5.304\;10^{-2}T^2 + 2.374\;10^{-4}T^3 + 1.340\,(S-35) + 1.630\;10^{-2}D + 1.675\;10^{-7}D^2 - 1.025\;10^{-2}T\,(S-35) - 7.139\;10^{-13}T\,D^3$$

where
- c is the sound speed (m/s)
- T is the temperature (°C)
- S is the salinity (‰)
- D is the depth (m)

(b) Absorption coefficient

The recommended method for estimating the acoustic absorption for use in fisheries acoustics is to use the formula of Francois and Garrison (1982). This is a three-term equation, representing pure water, magnesium, sulphate and boric acid contributions. For most frequencies used in fisheries acoustics, all three terms are significant.

The Francois-Garrison (FG) equation is the result of fits to measured data and is quoted for temperatures -1.8°C to 30°C, for frequencies 0.4 to 1000 kHz and salinities of 30 to 35‰, to an accuracy of 5%, which increases to 10% outside these ranges. The results from the FG equation lie between those from earlier equations proposed by Schulkin and Marsh (1962) and Fisher and

Simmons (1977). The FG equation is applicable to a wider frequency range than Schulkin and Marsh and is based on ocean data rather than the laboratory experiments on prepared solutions of Fisher and Simmons. It is considered that the FG equation is the best method available at present for calculating the absorption of sound in sea water. However, this and other equations still leave a great deal of uncertainty in the true value of the absorption coefficient, and it is hoped that future research in this field will improve matters.

Equation:

$$\alpha = \frac{A_1 P_1 f_1 f^2}{f_1^2 + f^2} + \frac{A_2 P_2 f_2 f^2}{f_2^2 + f^2} + A_3 P_3 f^2$$

where α is the absorption coefficient in dB/m, and

$$A_1 = \frac{8.86}{c} 10^{(0.78\text{pH} - 5)}$$

$$P_1 = 1$$

$$f_1 = 2.8\ (S/35)^{0.5} 10^{[4-1245/(T+273)]}$$

$$A_2 = 21.44\ (1 + 0.025\ T)\ S/c$$

$$P_2 = 1 - 1.37\ 10^{-4}\ D + 6.2\ 10^{-9}\ D^2$$

$$f_2 = \frac{8.17\ 10^{[8-1990/(T+273)]}}{1 + 0.0018\ (S-35)}$$

For $T < 20°C$

$$A_3 = 3.967\ 10^{-4} - 2.59\ 10^{-5}\ T + 9.11\ 10^{-7}\ T^2 - 1.50\ 10^{-8} T^3$$

For $T > 20°C$

$$A_3 = 3.964\ 10^{-4} - 1.146\ 10^{-5}\ T + 1.45\ 10^{-7} T^2 - 6.5\ 10^{-10} T^3$$

$$P_3 = 1 - 3.83\ 10^{-5}\ D + 4.9\ 10^{-10} D^2$$

where c is the sound speed (m/s)
D is the depth (m)
T is the temperature (°C)
S is the salinity (‰)
P is the sea water pH value

It can be assumed that pH=8 for typical ocean conditions, if the true pH is unknown. This results in an error of 0.1 dB/km, almost independent of frequency, for a pH range of 7.8 to 8.2, which is typical of the northern North Sea.

The above equations may be used to estimate β, the absorption in nepers/m, by using the conversion $\beta = 8.68\ \alpha$.

APPENDIX II

TARGET STRENGTHS OF CALIBRATION SPHERES

The following table gives the calculated target strengths in decibels of two commonly used calibration spheres, as a function of c, the sound velocity in water, at 38 kHz. The calculations have been performed for continuous wave (zero-bandwidth) transmission. Physical characteristics of the spheres are given in Foote and MacLennan (1984).

TABLE

Target strengths in dB at 38 kHz

Sphere material	Copper	Tungsten carbide
Diameter (mm)	60.0	38.1
c (m/s)		
1430	-34.0	-41.8
1440	-33.9	-42.0
1450	-33.8	-42.1
1460	-33.7	-42.2
1470	-33.6	-42.3
1480	-33.6	-42.3
1490	-33.6	-42.4
1500	-33.6	-42.4
1510	-33.6	-42.4
1520	-33.6	-42.4
1530	-33.6	-42.4
1540	-33.7	-42.3
1550	-33.8	-42.2
1560	-33.9	-42.1

APPENDIX III

A Calibration Narrative

The following report is derived from a calibration exercise on the Norwegian research vessel "Michael Sars" in January 1982. This concerns the Simrad EK38R echo-sounder and attached echo integrator, standard equipment widely used in the acoustic estimation of fish abundance.

The exercise began at 0800 hours with the departure of the boat for Skogsvaagen, an inlet of the island of Sotra, about a one-hour sail from Bergen, where the sphere measurements were to be conducted. While underway, the performance of the equipment was measured. The TVG function was accurate to within measurement accuracy over the 15-25 m depth range. In the case of other electrical measurements, no serious deviations from the specifications were discovered, precluding special adjustments. In addition to these preparatory measurements, the three outriggers with hand-winches were attached to the deck railing in their usual positions and the several copper target spheres were immersed in fresh water and detergent.

At Skogsvaagen the boat was anchored by both bow and stern, in water of 100 m depth. Immediately upon anchoring, the temperature and salinity profiles, measured by a standard CTD-sonde, were logged automatically by the central computer and computations of sound speed and density performed. At the anticipated calibration depth of 24 m, the temperature and salinity were found to be about 6°C and 33 ppt, implying a local sound speed of 1472 m/s and density of 1026 kg/m³. The average sound speed from the transducer to this depth was found by computation to be 1466 m/s.

Calibration of the 38 kHz equipment generally has the highest priority in this kind of exercise, hence the 60 mm copper sphere was immersed first. Its echo was observed on the oscilloscope immediately upon lowering to approximate 24 m depth, suggesting its location in the mainlobe. This was confirmed by routine exploration of the beam.

After fine adjustment, the sphere was assumed to be on the acoustic axis of the transducer and the measurements were begun. These are now described for the "20 log R" TVG function and external transmitter, the standard combination for many acoustic surveys.

The echo time delay t was measured as 25.2 ms on the oscilloscope. Use of the average sound speed c = 1466 m/s determined the sphere range $R_1 = ct/2 = 18.5$ m. The peak-to-peak sphere echo U_{p-p} was measured with the attenuator setting $D_1 = 20$ dB with the result $U_{p-p} = 3.35$ V. This was converted to the echo level $U_1 = 20 \log U_{p-p}/(2.2^{\frac{1}{2}}) = 1.5$ dB. The cutoff range R_2 of the "20 log R" TVG function was assumed to be 502 m. The absorption coefficient α assumed in the echo-sounder TVG function is 0.0105 dB/m. For the exact sphere depth, the hydrography dictated a target strength TS = -33.6 dB. The sum of the source level SL and voltage response VR was determined according to the usual sonar equation (14):

$$\begin{aligned} SL + VR &= U_1 - TS + 20 \log R_2 + 2\alpha R_2 + D_1 + 20 \log R_1 \\ &= 1.5 + 33.6 + 54.0 + 10.5 + 20.0 + 25.3 \\ &= 144.9 \text{ dB} \end{aligned}$$

In practice, reference is generally made to the actual attenuator setting of the measurement, which is also that of greatest use in survey work, namely D_1 = -20 dB. According to this reference, SL + VR = 124.9 dB.

Following calibration of the echo-sounder, the echo-integrator was readied for its calibration. Because of the sphere range of 18.5 m, the central 5 m thick integration volume was defined as [17, 22] m. The adjacent channels were defined as [12, 17] and [22, 27] m.

The results of integrating the sphere echo for six minutes at the standard ping rate of 48 pings per minute are the following: average echo energy of 6934 mm and maximum echo energy of 7356 mm. The observed excursion of 6% was considered acceptable. Further evidence for the acceptability of the measurement was provided by the measurements of echo energy, viz reverberation, in each of the adjacent channels. The peak echoes lay between 10 and 20 mm, ie about 25 to 30 dB below the sphere echo, which is typical. It was concluded from these measurements that there were no extraneous scatterers such as fish in the integration volume. This was also confirmed by observation of the oscilloscope during the integration: the sphere echo appeared entirely stable.

Calibration of the echo-integrator was now completed by determining the so-called instrument constant, namely the factor Cg/Ψ in equation (1). In the units adopted by the Bergen Institute this is

$$C_I = 3.43 \ 10^6 \ \sigma_1/(M_1 \ R^2{}_1 \ \Psi)$$

where the numerical factor is the number of square meters in a square nautical mile, and the subscript "1" refers to the standard target in each case. Substituting for the several quantities,

$$C_I = 3.43 \ 10^6 \ 4\pi \ 10^{-3.36}/(7356 \ 18.5^2 \ 0.011) = 0.68$$

Because σ_1 is expressed as an area (m^2), the average backscattering cross section of fish, $\langle \sigma \rangle$ in equation (1), must be expressed in the same units.

Measurements of the source level and voltage response of the echo-sounder were also made for other equipment settings, namely for other transmitters and for both the "20 log R" and "40 log R" TVG functions. Documentation was collected, copied, and the originals deposited at the Institute upon completion of the cruise on the same day.

The derived numbers are compared with previous calibration results for the same boat in the table, where the sum of source level and voltage response is referred to the usual -20 dB attenuator setting. The consistency of corresponding numbers witnesses both to the precision of the calibrations and to the long-term stability of the equipment.

Summary of calibrations of the Simrad EK38 echo-sounder and attached echo integrator on board "Michael Sars".

Date of Exercise	SL + VR (dB)	Instrument (dB) constant C_I
January 1980	125.5	0.67
July 1980	124.9	0.73
January 1981	124.6	0.71
June 1981	124.9	0.69
January 1982	124.9	0.68

APPENDIX IV

Calibration Worksheets

It is recommended that the measurements made during a calibration should be recorded on a worksheet. This is a form which lists the parameters of interest against spaces where background information and measurements are recorded. An important advantage of using a worksheet is that it helps to ensure that no important details are forgotten.

An example worksheet is shown here. After the initial header which records where and when the work was done, the worksheet is laid out in six sections as follows:

1 Transducer
2 Transmitter
3 Receiver
4 On-axis sensitivity
5 Time-varied gain
6 Conversion factor

Primary measurements are recorded in Sections 1-5, then the data are used to calculate the conversion factor as shown in Section 6.

Further information about the parameters listed in the worksheet and the measurement procedure will be found in the relevant section of the main text.

Any worksheet is to some extent specific to the particular equipment being calibrated, to local conventions on measurement units and work procedures. The example shown here is a specimen which may be modified to suit any application. In designing a worksheet, the important points to bear in mind are (a) to include all the essential measurements, (b) to include notes on procedures and warnings to avoid common mistakes, and (c) to exclude irrelevant information which distracts attention from what is important.