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HIGH PRECISION CALIBRATION OF A VERTICAL SOUNDER SYSTEM FOR USE IN FISH STOCK ESTIMATION

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1 Introduction

Acoustic surveys of pelagic fish populations require good system calibration since any error in the system performance produces an equal error in the fish stock estimate. Calibration and equipment measurement procedures have been developed over a number of years in order to reduce the measurement errors to an acceptable level. This paper describes the three main measurements that are used to define the echo sounder performance. These are the transducer equivalent beam angle, the receiver Time Varied Gain (TVG) range compensation function and the combined "on axis" transmit receive response of the system. The three measurement methods are described briefly, their accuracy predicted and the overall accuracy of the system performance is discussed.

A system used for fish stock estimation can be approximated by a sonar equation Forbes and Nakken (1977):-

$$S_v = 20 \log V_o - SL - 10 \log \frac{c\tau}{2} - 10 \log \psi - RG - 20 \log R - 2\alpha R$$

where
S_v = volume back scattering strength
V_o = system output voltage
SL = source level
R = range
α= attenuation coefficient
c = sound velocity
τ= pulse length
ψ= equivalent beam angle
RG = receiver gain (including transducer on axis voltage response)

This provides a relationship between S_v the volume backscattering strength and V_o the system output voltage. The remaining terms in the equation are the subject of the calibration measurements. 10 log ψ the equivalent beam angle of a survey transducer is measured once a year on a specially built rig in a sea loch on the west coast of Scotland. The TVG ($20 \log R + 2\alpha R$) is measured at sea twice per survey in order to check system stability and estimate the errors between the theoretically required compensation function and the function provided by the echo sounder receiver. The third measurement of SL + RG + 10 log $\frac{c\tau}{2}$ is carried out at sea twice per survey using a simple rig to move a standard target through the main lobe of the sounder beam in order to estimate the on axis sensitivity. All three measurements are computer controlled and have been carried out repeatedly to establish the likely precision.

2 Equivalent Beam Angle Measurement

This factor ψ is defined as (Urick, 1967):-

$$\psi = \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi/2} B^2(\theta,\phi) \sin\theta d\theta d\phi$$

$B(\theta, \phi)$ is beam pattern (intensity) at angle θ, ϕ.

2.1 Experimental procedure

The measurements were carried out at Loch Duich on the west coast of Scotland. The underwater equipment was suspended below a raft which was moored about 600 m from the shore. The raft was connected by cable to a portacabin on the shore.

The transducers were placed, one at a time, at the centre of a motorised gimbal table supported by a triangular frame suspended on a 15 m three point suspension at a depth of 20 m below the raft. A 6.35 cm diameter stainless steel ball was hung 5.175 m below the triangular frame by three strands of monofilament nylon. The angular positions of the gimbals were determined using a pair of digital angle encoders which provided an output with a resolution and accuracy of 16 binary bits with respect to the triangular supporting frame. The angular information was transmitted by a serial communications link to the shore, and the drive motors for the gimbals were remotely controlled by the same link (Copland, 1984).

A Computer Automation 4/90 computer was used to control both the gimbal table and a sonar transmitter and receiver system, and to carry out preliminary analysis of the received echo data. The transmitter was a Loughborough University design (Pratt, 1975) which provided a crystal controlled 38 kHz 0.5 ms pulse. The receiver was a switched gain amplifier, providing 16 computer controlled 3 dB gain steps, and a single tuned filter of 4 kHz bandwidth. In practice only the top 7 gain steps were used. The signal was envelope detected and sampled every 100 µs, then converted to 12 bit binary and passed to the computer. The samples were squared and summed to give an estimate of energy within the returned echo. Some quantisation and sampling error occurred, typically a standard deviation of 0.5% of the mean from a group of transmissions can be attributed to sampling errors. This indicates a high degree of precision in the mean value. The system provided 50 dB of dynamic range with accuracy of ±0.1 dB and a further 25 dB with the same linearity but lower precision. In practice, it was found that only 30 dB of dynamic range were required to provide acceptable results.

The transducers were Simrad type 38-26/22-E constructed from 34 elements resonant at 38 kHz, arranged in a rectangular pattern. The beam width was asymmetrical, nominally 8 by 13 degrees between the half power points.

The measurement of the transducer beam pattern was carried out by recording integrals of the echo energy from the ball suspended below the triangular frame, the transducer being used both as projector and receiver to evaluate the combined response. The measurement of a single transducer was automated by taking values at 0.2° intervals along $\pm15°$ scans in one direction, spaced at 0.5° intervals over $\pm15°$ in the perpendicular direction. The higher definition data were collected in the direction across the narrow beam width. The section of the hemisphere from which data is collected is restricted to $\pm15°$ arcs on each axis of the gimbal in order to reduce time taken for each measurement. Errors caused by this restriction are of the order of 0.01 dB.

At each point 40 transmissions were carried out and the standard deviation computed. Data was accepted only if the standard deviation of a set of transmissions was 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.

2.2 Data processing

The data from the grid of 61 by 151 points were inspected and any obviously spurious values replaced by linear interpolation from adjacent points. An example of uncorrected data is shown in Figure 1. This correction procedure had a negligible effect upon the final results (less than .001 dB). The individual values were multiplied by the element of solid angle associated with each point and summed. The data were processed to give a value for the equivalent beam angle.

$$\psi = \frac{\Sigma\, B^2(\theta,\phi)\ \Delta\theta\Delta\phi\ \sin\theta}{B^2_{max}}$$

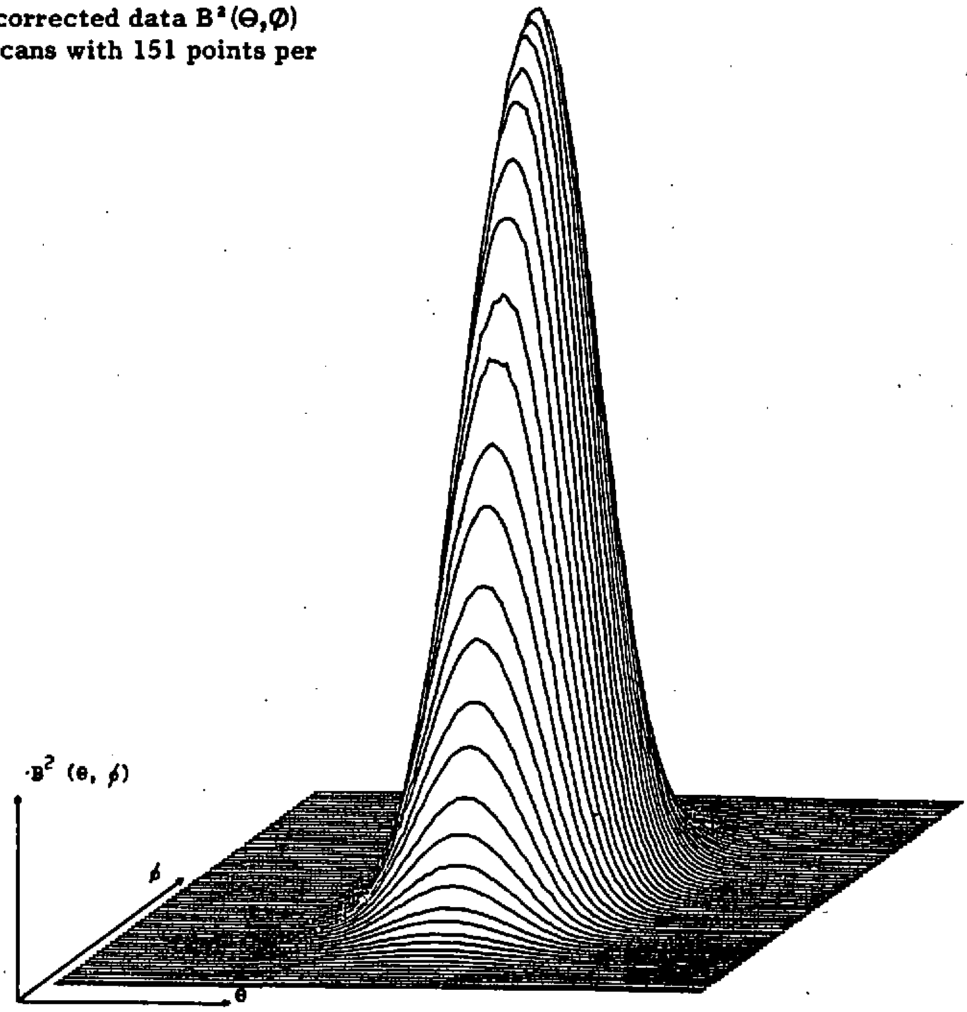
where

$B^2(\Theta,\phi)$ is energy integral at Θ,ϕ

$\Delta\Theta\ \Delta\phi \sin\Theta$ is element of solid angle at Θ,ϕ

B^2_{max} is estimated on axis senstivity

Figure 1 Uncorrected data $B^2(\Theta,\phi)$ for $\pm 15°$; 61 scans with 151 points per scan.



The repeat measurements were used to determine confidence limits for the measurement procedure. These were calculated as:

$$x = \frac{\pm\, t_f \sqrt{\Sigma\,(x_m - x_{mi})^2/F}}{\sqrt{n_m}}$$

where

x_m is the mean for the m^{th} transducer
t_f is Student's "t" parameter for total number of degrees of freedom
F is number of degrees of freedom
x_{mi} is i^{th} measurement on the m^{th} transducer
n_m is number of measurements on the m^{th} transducer

Results

The measured values for the equivalent beam angle of the seven transducers are shown in Table 1. The theoretical value is -17.06 dB at 1500 m/sec sound velocity. The data are divided into four sets to show the differences between transducers and the effects of the mounting methods and also the stability between measurements carried out in 1983 and the earlier measurements from 1980 to 1982.

TABLE 1 Equivalent beam angles (dB//1 steradian) and 95% confidence limits for seven transducers for plate, point and towed body mountings

	MOUNTING TYPE			
	Plate 1980-82	Point 1983	Plate 1983	Towed Body 1983
1	-17.04 ± 0.12			-17.10 ± 0.08
2	-17.04 ± 0.08	-16.87 ± 0.08	-17.14 ± 0.08	-17.10 ± 0.06
3	-16.85 ± 0.16			-17.41 ± 0.08
4	-17.42 ± 0.12			-17.27 ± 0.08
5	-17.12 ± 0.08			-17.31 ± 0.08
6	-17.75 ± 0.12	-17.64 ± 0.08	-17.74 ± 0.08	-17.84 ± 0.06
7	-17.78 ± 0.12			-17.90 ± 0.08

These results show a wide range of values obtained from nominally similar transducers, with differences of up to 0.9 dB between transducers with the same mounting and up to 0.5 dB for the same transducer with different mountings. They indicate the importance of measuring the transducer in the mounting in which it will be used and ensuring that the transducer used for a survey is recorded and the correct value of ψ is used for that transducer.

3 Time Varied Gain Function Measurement

An input is connected to the sounder on the transducer terminals with the transducer removed. This signal is provided by a programmable frequency synthesiser (FLUKE 6011) which has an output with a frequency accuracy of better than ±3 ppm and an amplitude accuracy of better than ±0.05 dB (1% of energy) to a precision of four figures.

The output of the sounder is connected to a sampling circuit. The signal is envelope detected and sampled at 20 kHz to 12 bit binary precision. The envelope detector provides 50 dB of dynamic range with 1% linearity. The samples are arranged to be random with respect to the transmit pulse and the sample gate is formed by taking a fixed number of samples starting at a defined range. The start of the sample gate is crystal controlled to an accuracy of 10 ppm and a range precision of .01 metres. The output samples are passed to a computer and the input is adjusted until a fixed level of output is observed from a defined gate width at a defined range. The program makes measurements at ranges which should be 1 dB apart in gain. At each range, sets of 10 transmissions are carried out and the output of the frequency synthesiser adjusted by the computer until a set of measurements has been obtained with a mean differing by less than 1% from a fixed value, and with a standard deviation of less than 1%. The range is then automatically changed and the next reading taken. When the full extent of the TVG has been measured (about 50 readings) the error between the theoretical TVG function and the measured curve is calculated.

3.1 Data processing

In order to minimise errors during a particular survey, the program provides optimisation over a selected depth range. The error between the theoretical and measured TVG functions is calculated for the selected depth interval and this is used to calculate the error at the depth of calibration.

The theoretical curve is calculated as

$$g_t = 20 \log c(T-T_D) + 2\alpha\, c(T-T_D)$$

where: g_t is gain in (dB), c is sound velocity (m/ms), T is time from transmit trigger (ms), α is attenuation coefficient (dB/m), T_D is system delays (ms), and, $T_D = 0.47/B + \tau/2 + 0.16$ ms .... (MacLennan 1984), B is bandwidth kHz, τ is pulse length (ms).

This delay is a shift in the starting point of the TVG to take account of pulse length and bandwidth. This formula is based on theoretical predictions from measured bandwidths of the echosounder and transducer.

The optimum gain difference is then calculated as

$$g_d = 10 \log \frac{\sum_{r=R_1}^{R_2} \Delta r \; 10^{((g_{mr}-g_{tr})/10)}}{(R_2-R_1)}$$

where: R_1 and R_2 are limits of range used on survey, g_{tr} is theoretical gain at range r, g_{mr} is measured gain at range r.

The gain error between the theoretical curve and the optimised measured curve is calculated as:

$$\delta g = g_{tr} - g_{mr} - g_d \text{ at any range } r$$

This formula provides a gain correction at the range used for the standard target calibration to remove bias caused by a fixed deviation between the actual TVG function and the optimised measured function for the survey, and a series of values for correction of samples taken from defined depth slices during the survey.

Examples of the optimised measured TVG function over 5 to 100 and 5 to 500 metres for EK400 sounder is shown in Figure 2. The error at 5.2 m, the depth of standard target calibration, is also shown. In addition to the TVG measurement the bandwidth which is also checked automatically is displayed on the same figure.

This constant output technique is used to provide a measurement with precision that depends only on the amplitude linearity of the frequency synthesiser. The sampling precision gives rise to ±0.25% confidence limits for each point which gives negligible errors in the complete function and errors of ±0.25% in gain at standard target depth. The main source of error is the bias due to non-linearity in the signal source of ±1%.

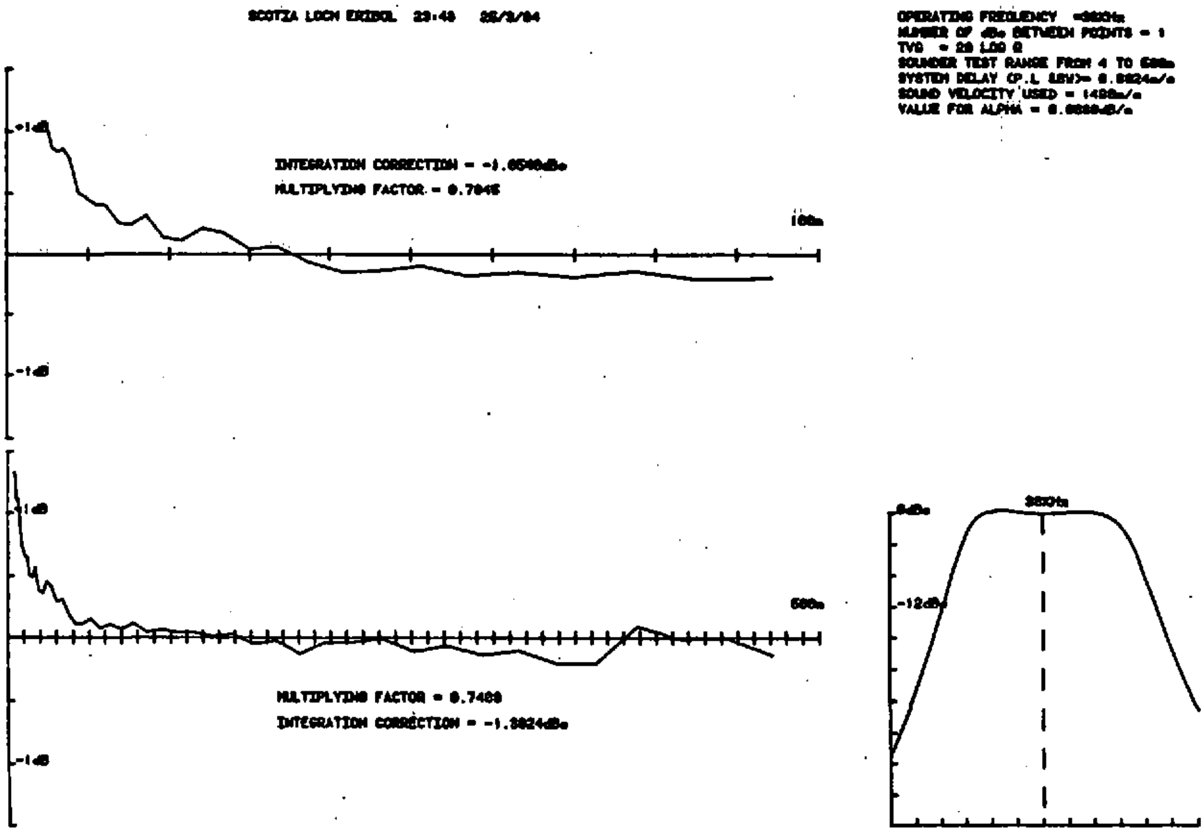


Figure 2 Optimal TVG function and bandwidth for EK400 sounder.

4 Standard target Acoustic Axis Sensitivity Measurement

This measurement is to evaluate the source level, pulse length and overall receiver gain and pulse performance.

In addition to the gated sampling system described above in section 3, a motorised control system is provided to adjust the relative position of the ball and transducer.

The sounder is switched to standard survey settings of pulse length, output power, receiver gain and receiver bandwidth. The calibration rig is attached to the towed body as shown in Figure 3. This rig consists of three motorised adjusters at the ends of three supporting arms. These adjusters are used to suspend a Tungsten Carbide ball on three strands of monofilament nylon. The ball is situated below the transducer at approximately 5.2 m range. Each adjuster provides a range of ±100 mm of adjustment with a resolution and accuracy of ± 0.3 mm to each of the three supporting strings. Figure 4 shows one adjuster. A reversible DC motor is geared to drive a screwed rod, and three magnetically operated reed switches at the top of the rod are decoded to drive a bidirectional counter which records the rod position. Two more reed switches are situated near the ends of the screwed rod to act as limit switches. The normal practice is to drive the adjuster to the upper limit defined by the limit switch and zero the counter, then adjustments can be made on each arm relative to this position. One count on the counter corresponds to 1/3 of a revolution or 0.3 mm of adjustment.

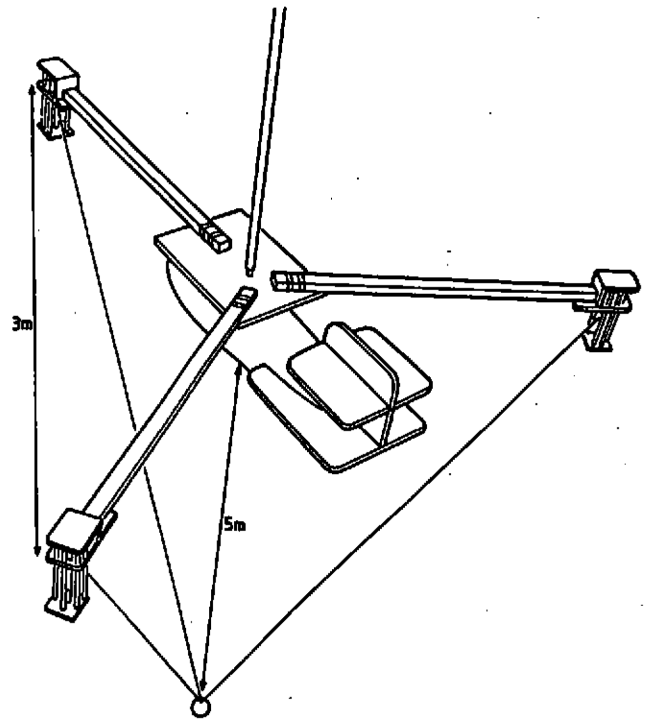


Fig 3. Rig for "on axis" sensitivity measurements showing towed body, three arms and standard target.

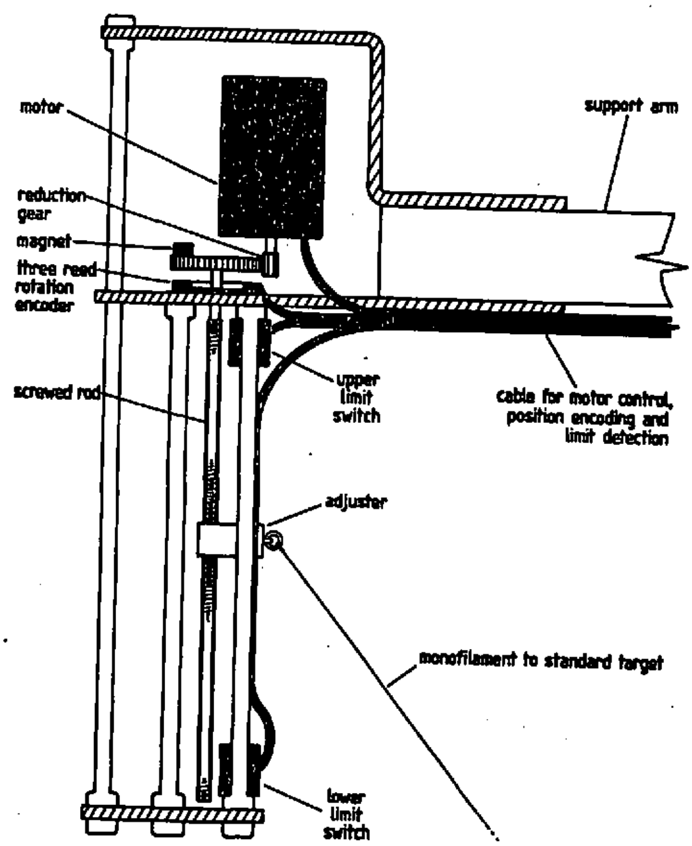


Fig 4. One adjuster giving ±100mm of movement.

4.1 Measurement procedure

The equipment is connected to the computer and this is used to control the motorised adjusters and compute the calibration factor. The computer takes samples around the standard target echo and adjusts the limits of the sample gate to ensure all the energy is included. The samples on the leading edge of the ball are used to define the range of the ball. The delay, between the leading edge half voltage point on the echo pulse and the leading edge of the transmitter pulse due to limited system bandwidths is calculated and subtracted from the measured time. The range is defined as:

$$r = C(t_m - t_d)$$

where: r is range, t_m is measured time to received echo half voltage point, t_d is calculated delay of half voltage point (MacLennan, 1982), C is sound velocity in sea water.

The alignment of the standard target on the acoustic axis is combined with a curve fitting procedure to estimate the maximum signal during a sweep across the centre of the beam.

One of the adjusters is moved in steps over the full length of adjustment and the echo-integral E at each step is stored in an array. Data from thirty transmissions are collected at each point and the data must have a standard deviation of less than 5% to be acceptable. The fourth root of E is proportional to the one way transducer sensitivity. A parabola is fitted to the fourth root data and the position and value of the maximum calculated. This adjuster is then moved to that position. The two remaining adjusters are then moved together in opposite directions. This moves the target in a plane at right angles to that of the first movement. The two adjusters are moved together over their full length and the data are checked to ensure standard deviations of less than 5%. The maximum signal and the corresponding position are again calculated by parabolic fit. The two adjusters are then set to the calculated position and the first adjuster used again. From now on the adjustment is over a smaller arc of 1/3 of that available and a standard deviation limit of 2% is used to define acceptable data for each point. Following each scan the maximum and its position are computed and the adjuster is moved to this point before the next orthogonal scan is carried out. Normally the maximum value is measured to within ±1% precision after 4 scans. An example of the first 6 scans is shown in Figure 5. In order to calculate the constant for integration, the target strength of the ball, the transducer equivalent beam angle and the target strength of the fish must be known. In addition, to compute the range of the ball the delay to the half voltage point on the pulse must be calculated and the bias on the TVG function mentioned above must be included. The constant is calculated as suggested by Simmonds and Stewart (1981):

$$K = \frac{1}{I_{IC} E_{ST}} 10^{((TS_T - 20 \log R_T - 10 \log \psi - 30 - TS_F - \delta g_T)/10)}$$

where TS_T is target strength of standard target
- R is calculated range of target
- 10 log ψ is equivalent beam angle of transducer
- TS_F is target strength of fish
- E_{ST} Estimated Maximum Echo Integral from standard target
- I_{IC} conversion constant between calibration integrator and survey integrator
- g_T is gain deviation on TVG at range R_T

The programme is then able to give a series of values which converge to a lowest value for the calibration constant. This is shown on the right of Figure 5 along with the measured range and the positions of the three adjusters where a count of 1 is a 0.3 mm change in string length.

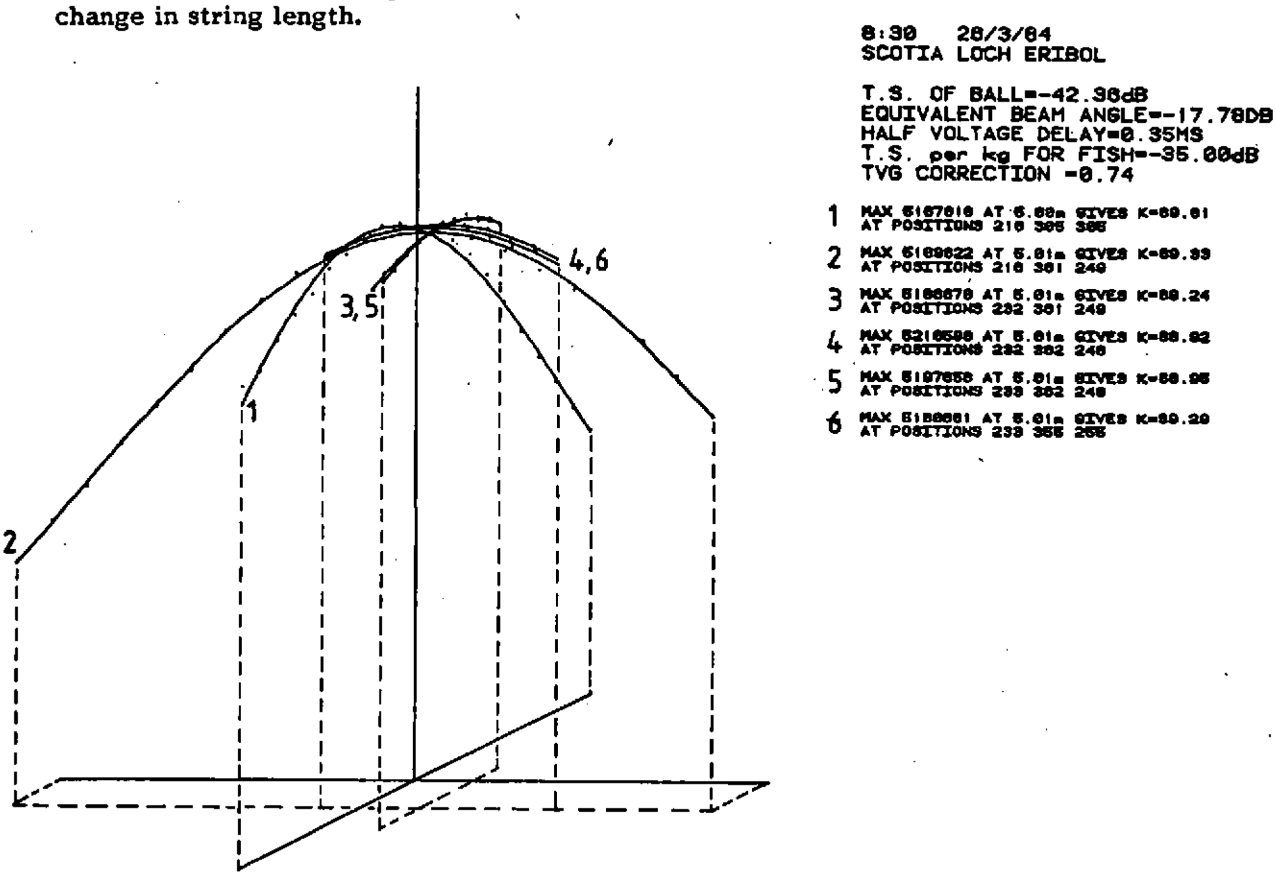


Figure 5 Six scans showing fitted curves and values for on axis energy

4.2 Measurement errors

There are several sources of error associated with this measurement procedure. As indicated above the sampling procedure gives rise to random errors, as does the positioning of the target, movement of the rig and background reverberation. On one occasion in order to investigate these errors 80 scans were carried out over a period of 15 hours. The 95% confidence limits for an individual scan were calculated to be 1.00% either side of the mean. In normal practice data is collected for about one hour or five scans and the confidence limits for this mean value is 0.68% of the mean.These figures compare well with results reported by MacLennan (1984) using a different experimental rig to compare two standard targets. These results show 95% confidence limits of 0.86% for one hour data sets. There is also a small error introduced by the parabolic fitting procedure, a bias of -0.1% because high order terms in the beam pattern are ignored. In addition to the on axis energy estimate, the range of the target must be estimated. This is done electronically. The position of the half voltage point on the received echo can be evaluated to a precision of better than 1μsec. The triggering point of the transmitter can lead to some error due to phase relationship between transmit trigger and the gated 38 kHz waveform that is transmitted. This can produce errors up to ¼ wavelength or 7 μsec. In addition, the system bandwidths add to the delay between the leading edge of the transmitted pulse and the half voltage point on the received pulse. The calculated value of this delay may be in error due to uncertainty in the system bandwidths. The limit to this error is in the region of 5%, and for a 3 kHz bandwidth and 1.0 msec pulse it would be ±17 μsec. These equipment errors combine to give bias of ±0.3% and random errors of ±0.02% in electrical measurements. The other variable in the range measurement is the sound velocity in sea water. This should vary by less than ±1%, but is the most significant factor in the range estimation error.

The absolute error of the calibration depends upon the accuracy of the standard target, the tungsten carbide ball. The accuracy of these targets is reported by MacLennan (1984) and he indicates a 95% confidence limit of 2.2% for these balls suspended in a monofilament bag.

5 Summary of Errors

The errors discussed above are shown in Table 2 as random and systematic errors for a single measurement carried out with a known transducer in known mountings with any 38.1 mm tungsten carbide standard target in seawater within the range of temperature and salinity found around the Scottish coast.

Table 2

Source of Error		Systematic Errors	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%	
95% confidence level total error		±3.6%	±0.73%
Total		±3.7%	

The accuracy is dominated by three main errors, the standard target, the equivalent beam angle and the uncertainty in the sound velocity. To improve on the first two of these is very difficult. The third item is however fairly simple to measure or compute from a temperature and salinity measurement with sufficient precision to greatly improve the accuracy of the range measurement. This would reduce the 95% confidence levels to ±3.0% which is regarded as a negligible system error compared to some of the other errors in the stock estimates.

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