International Council for the
Exploration of the Sea

C.M. 1996/B:36
Fish Capture Committee

# SOME PITFALLS OF SHORT-RANGE STANDARD-TARGET CALIBRATION

by

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## ABSTRACT

Often it is necessary or desirable to perform a standard-target calibration at rather short range, for example, because of shallow water or interest in measuring animals at short range. A number of general range-dependent effects may prove especially troublesome at short range. These include effects connected with (1) time-varied gain or similar range compensation, (2) finite size of the target, and (3) pulse repetition frequency. The origins of these effects are reviewed and, where particular to a specific system, illustrated by reference to the SIMRAD EK500 echo sounder.

## INTRODUCTION

Calibration of scientific echo sounders and integrators is essential to their quantitative use in fisheries research, as in the measurement of fish density and stock abundance (MacLennan 1990, Gunderson 1993). This has been widely appreciated, especially by ICES in its publication of recommended procedures in a Cooperative Research Report (Foote et al. 1987). Broadly speaking, the basic method is that of (1) measurement of a standard target suspended on the axis or moved throughout the cross section of the transducer beam when in the transducer farfield, and (2) adjustment of system gain factors according to theoretical expectation based on an *a priori* determination of target strength, assumption of target ranges, and knowledge of signal processing operations in the receiver. The typical standard target is a solid elastic sphere of known material and diameter. Computation of target strength is performed according to a well-established method (Foote 1982, MacLennan 1982, Foote and MacLennan 1984).

In general, it is recommended that calibration be performed at a rather large target range, say 15-25 m. This mitigates a number of recognized problems connected with range, as in its determination or effects due to the manner of range compensation in the receiver. However, it is often convenient or necessary to perform calibration at a rather short range, as due to a shallow bottom or special circumstances, as in measurements in tanks or enclosures (Ona 1994). It may also be highly desirable to perform a calibration at rather short range, as when organisms are to be detected at similar ranges. In this event, range-related effects may be substantial, even to the extent of jeopardizing the integrity of the calibration exercise.

Range- or echo-time-related effects have been documented earlier (Simmonds et al. 1984, MacLennan 1986, Foote et al. 1987, Sawada and Furusawa 1993). As already suggested, some of these effects are connected with signal processing operations in the receiver. Thus, given the comparatively recent introduction of the SIMRAD EK500 echo sounder (Bodholt et al. 1989), with new transducers too, it may be worthwhile to examine range-dependent effects in relation to the specific echo sounder. For completeness, a review of general range-dependent effects is also attempted.

## THEORY

### Time-varied gain (TVG)

Time-varied gain or range compensation is applied to the received echo sounder signal with the intention of cancelling range-dependent effects in the echo signal (Mitson 1983, MacLennan 1990, Gunderson 1993). This would consequently reduce the principal dependences to those of beam pattern and target strength. In practice, however, it is difficult to achieve exact compensation for the range-dependent effects of attenuation, namely those of geometric spreading and absorption. The difficulties arise in connection with the determination of the onset of the echo signal, denoted $t_o$ in Fig. 1, ignoring for now the finite size of the target. Close inspection of the figure may reveal the origins of these difficulties, which are enumerated: (1) noise, which may obscure the earliest arrival of the signal, depending on the signal-to-noise ratio (SNR), (2) bandwidth-related effects, which spread the signal in time and reduce the sharpness of its leading edge, (3) digitization of the echo signal, with loss of information between samples, and (4) sound speed profile.

Clearly, were there no noise, a single target echo would be precisely defined and easily identified. This is a fiction, of course. Noise is a fundamental process associated with every environment, including those of the physical water medium, electromechanical transducer, and electronic part of the receiver. Thus, noise must represent an invariable consideration. If the signal were strong relative to the noise level, then the effect of noise could be small, but the nearly universal use of peak-amplitude criteria for signal detection in the receiver belies this situation.

A component of noise in the present context is that of echoes from two or more scatterers that overlap, that is, interfere. Even under the typically controlled conditions of a calibration exercise, the presence of extraneous scatterers, such as fish, plankton, air bubbles, and macroscopic suspended matter, may obscure the onset of a standard-target echo.

Practical algorithms for the detection of single-target echoes are commonly based on the detection of peak amplitudes. Since the transmitted signal often spans a large number of wavelengths, for example, about 37 in the case of a 1-ms-duration pulse at 38 kHz, the transmitted signal has a rather flat top. Following echo formation and diverse filtering actions in the receiver, including transducer, the signal is literally transformed. This is exaggerated in Fig. 1, although it is probably recognizable to users of short-duration pulses.

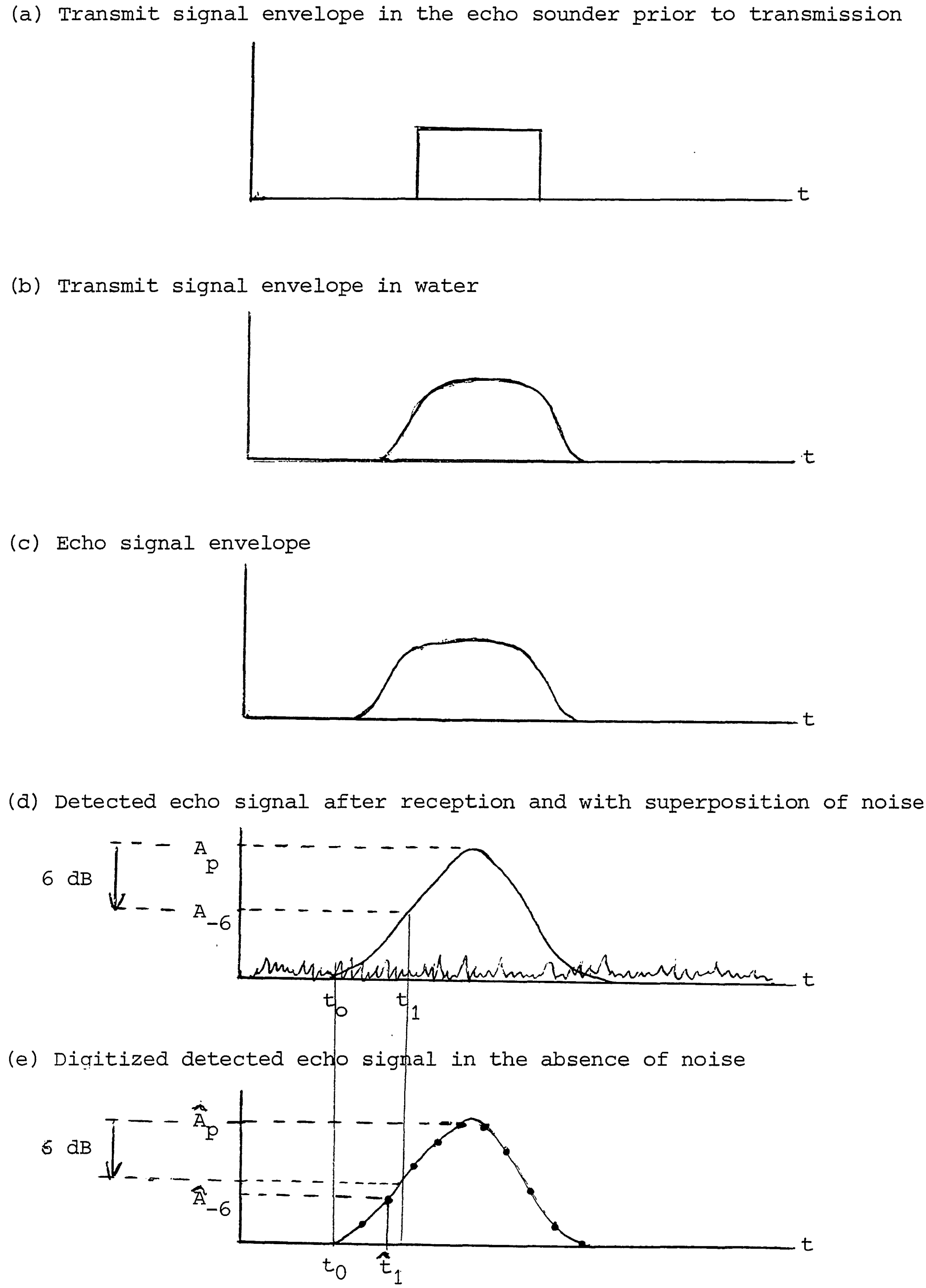


Fig. 1. Evolution of the echo signal from its origin as a trigger pulse in the echo sounder transmitter to the digitized, detected, received echo signal. The amplitude is expressed in arbitrary units at each stage. The time increments are identical, but the time origin or reference is arbitrary in parts a-c but identical in parts d and e.

These described effects, which may perhaps be apprehended more easily in the frequency or spectral domain, affect the detected echo time signal by giving it a more peaked shape. Detection of the peak and use of this to infer $t_o$ cannot be discussed further without reference to a particular algorithm or system realization.

In the case of the EK500 (Bodholt et al. 1989), the detected signal is digitized. A sequence of consecutive amplitudes of sufficient magnitude lying within an operator-defined time window will be recognized as a single-target echo. The peak digital amplitude $\hat{A}_p$ is detected. The time corresponding to that preceding amplitude which is less than the detected peak $\hat{A}_p$ by 6 dB defines the reference time $\hat{t}_1$ for application of TVG, as in Fig. 1e. If no amplitude differs by exactly 6 dB, then the time corresponding to the nearest smaller amplitude is chosen as $\hat{t}_1$. This is the particular case shown in Fig. 1e.

In general, $t_1$ and $\hat{t}_1$ both exceed $t_o$, thereby incurring an error in the application of range compensation, which is a bias. Three effects are seen to underly this error. Reference is made to Figs. 1d and e. (1) That of identification of the peak amplitude $A_p$ is affected by digitization, resulting in the use of the approximate peak amplitude $\hat{A}_p$. (2) The time $t_1$ corresponding to that preceding amplitude, $A_{-6}$, that is 6 dB less than $A_p$, is attributed to the time delay caused by frequency or bandwidth effects. (3) The further uncertainty in time estimate, $\hat{t}_1$ compared to $t_1$, is due to digitization, for $\hat{A}_{-6}$ is generally different, if only slightly so, from $A_{-6}$. In any case, use of $\hat{t}_1$ instead of $t_o$ for application of TVG incurs a measurable error at nearly all ranges.

A fourth effect, often forgotten, is also a potential source of error. This is due to use of the wrong sound speed profile. The target range corresponding to a given echo time depends on the medium sound speed, which is seldom constant. In general, the echo range r is determined by the equation

$$t = 2 \int_0^r \frac{dr'}{c(r')} \quad ,$$

where t is the echo time, and the integration is performed over the path length. This equation is almost always simplified, as by replacing the integral with a ratio of terms involving the average of $c(r')$ rather than the average of the inverse of $c(r')$. Sometimes a constant sound speed is used to represent the average, without allowance being made for variation in the sound speed with range.

Finite target size

Finite targets at finite ranges can appear large compared with the angular resolution size of the echo sounder transducer, as is illustrated in Fig. 2. For example, consider a 38.1-mm-diameter sphere used to calibrate the SIMRAD EK500/120-kHz echo sounder with attached ES120/7 transducer. At a range of 3 m, the target subtends an angle of 0.7 deg, but the angular resolution of the transducer is approximately 0.13 deg.

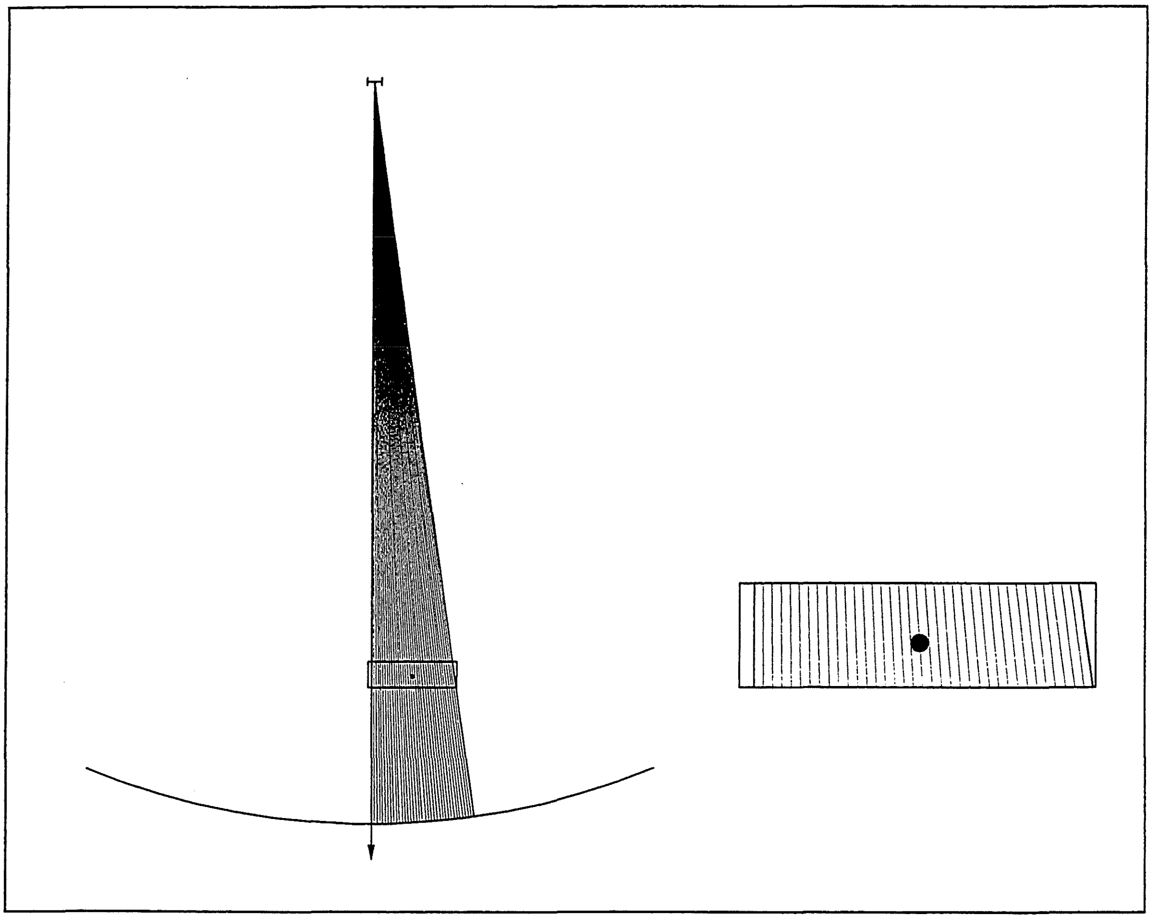

Fig. 2A. One-half of the angular sector covered by the beam of the 38-kHz ES38-12 split-beam transducer, with angular resolution 0.22 deg. The represented range is 10 m, with standard 60-mm-diameter sphere shown at 8-m range.

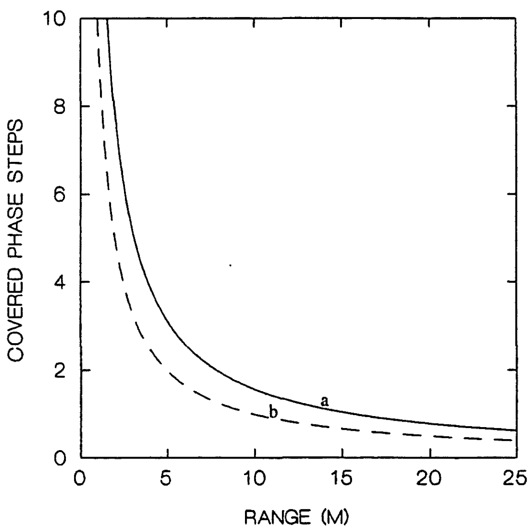


Fig. 2B. Number of covered angular cells, hence phase steps in the EK500 split-beam processor, as a function of range for the ES38-12 transducer by (a) 60-mm-diameter Cu sphere, and (b) 38.1-mm-diameter WC sphere.

When the target subtends two or more angular resolution cells, automatic compensation for the beam pattern loss in dual- and split-beam systems (Ehrenberg 1979) will generally incur an error. This may constitute a bias under very stable on-axis conditions or appear as jitter under less stable conditions or when mapping the beam pattern.

A lesser effect of finite target size, alluded to in the section on TVG, is that the earliest part of the echo signal is due to that part or facet of the target that is nearest the transducer. Except for a point target, the corresponding range is less than that of the target center. For a 38.1-mm-diameter sphere, for example, the range difference is a mere 2 cm, which is considered negligible in this treatment of short-range effects.

It is assumed that measurements are made in every case in the transducer farfield. This distance is typically defined as the square of the diameter of the transducer divided by the acoustic wavelength. For the ES120-9 transducer, this is about 50 cm. Should measurements be attempted at shorter ranges, finite-target-size effects would become apparent.

Pulse repetition frequency

Any electromechanical device that is used in pulsed operation generally has a working range which is defined by the ratio of the pulse duration to the total cycle time. This is called the duty cycle. As the magnitude of the excitation increases, the duty cycle over which the device performs stably is necessarily reduced. Exceeding the _de facto_ maximum duty cycle will result in a reduction in transmitted power. If this is not monitored, then the magnitude of the target echo will be comparably reduced, but without knowledge, hence control.

## MATERIALS AND METHODS

Some of the short-range effects described in the previous section were encountered during repeated, detailed standard-target calibrations of a SIMRAD EK500 echo sounder. This system is being used as the primary acoustic instrument in the EU-project "Acoustic properties of fish and their exploitation in classification schemes for fish stock assessment", RTD contract no. AIR3-CT94-2142, and will be used as a secondary acoustic instrument in another EU-project "Broadband acoustic scattering signatures of fish and zooplankton", RTD contract no. MAS3-CT95-0031. The calibrations were performed within a large, 3500-$m^3$ fish-holding pen at the Austevoll Research Station of the Institute of Marine Research, Bergen, on the island of Austevoll, about 1-2-hours travelling time from Bergen.

Three SIMRAD split-beam transducers were used, models ES18, ES38-12, and ES120-9, with respective nominal operating frequencies of 18, 38, and 120 kHz. The transducers were mounted on a frame, or transducer rig, which was positioned in the center of the holding pen at a depth of 0.7 m. The orientation of the transducers was vertically downwards. The bottom depth of the pen was 21 m; that of the sea bottom was 37 m.

Standard spherical targets were used for the calibrations. A 60-mm-diameter copper sphere, designated CU60, was used at 38 kHz for which it is optimal (Foote 1982). A 38.1-mm-diameter sphere made of tungsten carbide with 6% cobalt binder, designated WC38.1, was used at each of the three frequencies. For the particular conditions of temperature and salinity prevailing at the time of the measurements, the medium sound speed was approximately 1470 m/s. The applicable target strengths TS of the sphere are tabulated.

| Sphere | Frequency (kHz) | TS(dB) |
|---|---|---|
| CU60 | 38 | -33.6 |
| WC38.1 | 18 | -42.9 |
| WC38.1 | 38 | -42.2 |
| WC38.1 | 120 | -39.6 |

During calibration, three lines of 0.4-mm-diameter monofilament nylon were attached to each sphere and to motorized winches with independent control from the instrument barrack. This allowed positioning on axis and controlled measurement of the sphere throughout the transducer beam cross section. The point of attachment to the sphere CU60 was a loop of monofilament nylon with ends cemented in a shallow bore with epoxy. The point of attachment to the sphere WC38.1 was a net bag fashioned from a single strand of monofilament nylon according to the design by F. Armstrong that is shown in Foote et al. (1987).

Basic recorded target strength data consisted of the following elements: time of measurement, target range, echo strength, target strength, and angular position of the target in each of two orthogonal planes. These data, which are broadcast by the EK500 in so-called echo-trace telegrams, were logged by a TCI/486 portable personal computer (PC) connected to the echo sounder by serial line.

A total of five parameters were determined in the course of each split-beam transducer calibration. These are the target strength gain $G_{TS}$ and half-power beamwidths and offset angles in both alongships and athwartships vertical planes. The five parameters were estimated by non-linear regression analysis as described in Ona (1990), using the "Lobe version 5.0" software (Anon. 1992), following collection of 150-400 sets of TS data spread evenly over the cross section of the beam. The calibration values together with other instrument settings are shown in Table 1. Long time series of TS data on the calibration spheres were also logged from the echo trace telegrams using the "Procomm version 2.4" software (Datastorm Technologies, Inc.). Statistical analysis of the data was performed with "SYSTAT" (Wilkinson 1988).

TVG-related measurements

Effects due to the delay in time measurement that arise from the method of target echo extraction in the EK500 were studied through repeated observations of a calibration sphere suspended on the transducer axis. The apparent TS value as registered by the echo sounder was observed over a range of depths. In addition, the same quantity was registered when the sphere was moved over the beam cross section at selected depths.

Since the effect of time delay is reflected in the range compensation, knowledge of the time delay $t_1-t_o$ or corresponding range $r_d=c(t_1-t_o)/2$ is

Table 1. EK500 parameter values used during the reported measurements. In the case of the 38-kHz transmitting power, marked by an asterisk, the default setting of 2000 W was retained, although the transmitter was modified so that the nominal transmitting power was 1000 W. This discrepancy is accounted for in the transducer-gain factor during standard-target calibrations.

| SIMRAD EK500 | 18 kHz | 38 kHz | 120 kHz | |
|---|---|---|---|---|
| **TRANSCEIVER MENU** | | | | |
| Transducer type | ES18-11 | ES38-12 | ES120 | |
| Absorption coefficient | 3 | 10 | 38 | dB/km |
| Pulse duration | Short | Medium | Medium | |
| | ( 0.7 ) | ( 1.0 ) | ( 0.3 ) | ms |
| Bandwidth | Auto | Auto | Auto | |
| | ( 1.8) | ( 3.8) | (12.0) | kHz |
| Maximum transmitting power | 2000 | 2000* | 1000 | W |
| Two way beam angle | -17.3 | -15.5 | -18.5 | dB |
| Alongship angle sensitivity | 13.9 | 12.5 | 17.0 | |
| Athwartship angle sensitivity | 13.9 | 12.5 | 17.0 | |
| $S_V$ transducer gain | 24.4 | 21.2 | 22.9 | dB |
| TS transducer gain | 24.4 | 21.2 | 22.9 | dB |
| Alongship 3 dB beamwidth | 11.2 | 12.0 | 8.6 | degree |
| Athwartship 3 dB beamwidth | 10.7 | 11.7 | 8.3 | degree |
| Alongship offset angle | -0.12 | -0.24 | -0.08 | degree |
| Athwartship offset angle | 0.06 | 0.02 | -0.17 | degree |
| **TS DETECTION MENU** | | | | |
| Minimum TS value | -60 | -60 | -60 | dB |
| Minimum echo length | 0.8 | 0.8 | 0.8 | |
| Maximum echo length | 1.3 | 1.3 | 1.5 | |
| Maximum gain compensation | 6.0&3.0 | 6.0 | 6.0 | dB |
| Maximum phase deviation | 3.0 | 3.0 | 3.0 | |

sufficient for correcting the TVG. To estimate $r_d$, a standard calibration target was suspended on the acoustic axis after routine calibration. Single-target echo data from the sphere were logged via the serial port of the echo sounder using the "Procomm" software. After registration of more than 100 single-target echoes, the sphere was moved to another depth on the acoustic axis and the measurements were repeated. The procedure was repeated over a range of depths, and the average target strength, computed in the logarithmic domain, generally an ill-advised procedure, which in the present case incurs negligible error because of the narrow range of values.

The time delay $t_d$ or corresponding range $r_d$ can be determined from TS measurements performed at two distinct ranges in the transducer farfield. If $\hat{TS}_i$ denotes the apparent TS as determined by the echo sounder with target at range $r_i$, as determined by the echo sounder, then the defining equation is

$$\hat{TS}_i - \hat{TS}_j = 40 \log \frac{r_i}{r_i - r_d} - 40 \log \frac{r_j}{r_j - r_d} \quad .$$

In practice, due to the finite range resolution of the echo sounder as well as random variations in the measured TS, $r_d$ is determined by a best-fitting exercise with the data.

Results of these measurements were reported to the echo sounder manufacturer SIMRAD. Measurements were subsequently performed by SIMRAD engineers at their calibration facility in Horten. The effective range delay $r_d$ was measured with a standard calibration sphere suspended on axis. The actual range was compared with the echo sounder-measured range for a number of frequencies, bandwidths, and pulse durations. Actual ranges to the target, mechanically measured from the transducer face to the center of the target, were 6-7 m. Echo sounder-measured ranges were made with an enhanced digitizing resolution of 2 cm at all frequencies. Results from these measurements at 18, 38, and 120 kHz are presented.

The digitizing rate in the receiver corresponds to 25 cm at 18 kHz, 10 cm at 38 kHz, and 3 cm at 120 kHz. Effects of digitization have not been studied in detail, but have been observed to increase the variability in the calibration data at short range.

Finite target size measurements

The angular resolution of the particular transducers are 0.21 deg at 18 kHz, 0.22 deg at 38 kHz, and 0.16 deg at 120 kHz. Effects of finite target size have been studied by observing the apparent TS for a number of ranges. At the most distant range, the target lies wholly within a single resolution cell. At the shortest range, the target subtends two or three resolution cells.

PRF measurements

The effect of PRF was studied by measuring the apparent TS of a calibration sphere suspended on the acoustic axis over a range of conditions. These were defined by the PRF, pulse duration, and, in the case of maximum-PRF measurements, by the bottom depth and number of operating frequencies and external devices coupled to the processor.

## RESULTS AND DISCUSSION

### Measurements of TVG-related effects

Results of the measurement of effects of time delay are shown in Fig. 3 for each of the investigated frequencies, namely 18, 38, and 120 kHz. The effects are gauged through the apparent target strenth $\hat{TS}$, based on the averaged backscattering cross section, when referred to the theoretical value. The two should coincide at a sufficient range.

The measurements at 38 kHz with 1-ms pulse duration indicate an increasing bias at successively shorter ranges than about 8 m, with a single slight deviation at 2.2 m. At ranges shorter than about 4 m, the delay effect is 1 dB or more. The best fitted value for $r_d$, limiting the increment in investigated values to 10 cm, is 40 cm.

At 18 kHz and 0.7-ms pulse duration, the reference calibration was performed at 9.25-m range. The estimated delay effect is smaller than for 38 kHz. The deviation at 6.25 m is about 0.5 dB; at 15 m, -0.5 dB. The outlying value at 11 m is about 1.0 dB less than expected from the model, which might be attributed to the low digitization rate of 25 cm. The best fitted value in the neglect of this outlier is $r_d$=50 or 60 cm.

At 120 kHz and 0.3-ms pulse duration, the effect of time delay is erratic or insignificant. Within the measurement range 4-13 m, the calibration is generally stable to within 0.1 dB.

The time delays estimated from the calibration exercises are in general agreement with the measurements performed by SIMRAD and repeated in Table 2.

Table 2. Results of the measurement of delay performed by SIMRAD (R. Nilsen, pers. comm.). The delay is expressed in terms of range, using an increased digitizing resolution of 2 cm in the receiver. Most combinations of pulse duration and receiver bandwidth were investigated, with the major exception of the short pulse duration and narrow receiver bandwidth. The three pulse durations are the following: 18 kHz: 0.7, 2, and 7 ms; 38 kHz: 0.3, 1, 3 ms; 120 kHz: 0.1, 0.3, 1 ms. The narrow receiver bandwidth is nominally 1% of the center frequency; the wide bandwidth is nominally 10% of the same. The measurements apply to the EK500 echo sounder.

| Frequency (kHz) | Depth (m) | Short pulse Wide | Short pulse Narrow | Medium pulse Wide | Medium pulse Narrow | Long pulse Wide | Long pulse Narrow |
|---|---|---|---|---|---|---|---|
| 18 | 7.00 | 0.46 | - | 0.52 | 0.96 | - | - |
| 38 | 6.50 | 0.24 | - | 0.30 | 0.52 | 0.32 | 0.84 |
| 120 | 6.00 | 0.08 | - | 0.10 | 0.14 | 0.10 | 0.24 |

These were made under highly controlled conditions using other methods and with a higher digitization rate than is available in the commercial version of the EK500. Using the same combination of short pulse duration and wide receiver bandwidth, the time delays at the three frequencies in ascending

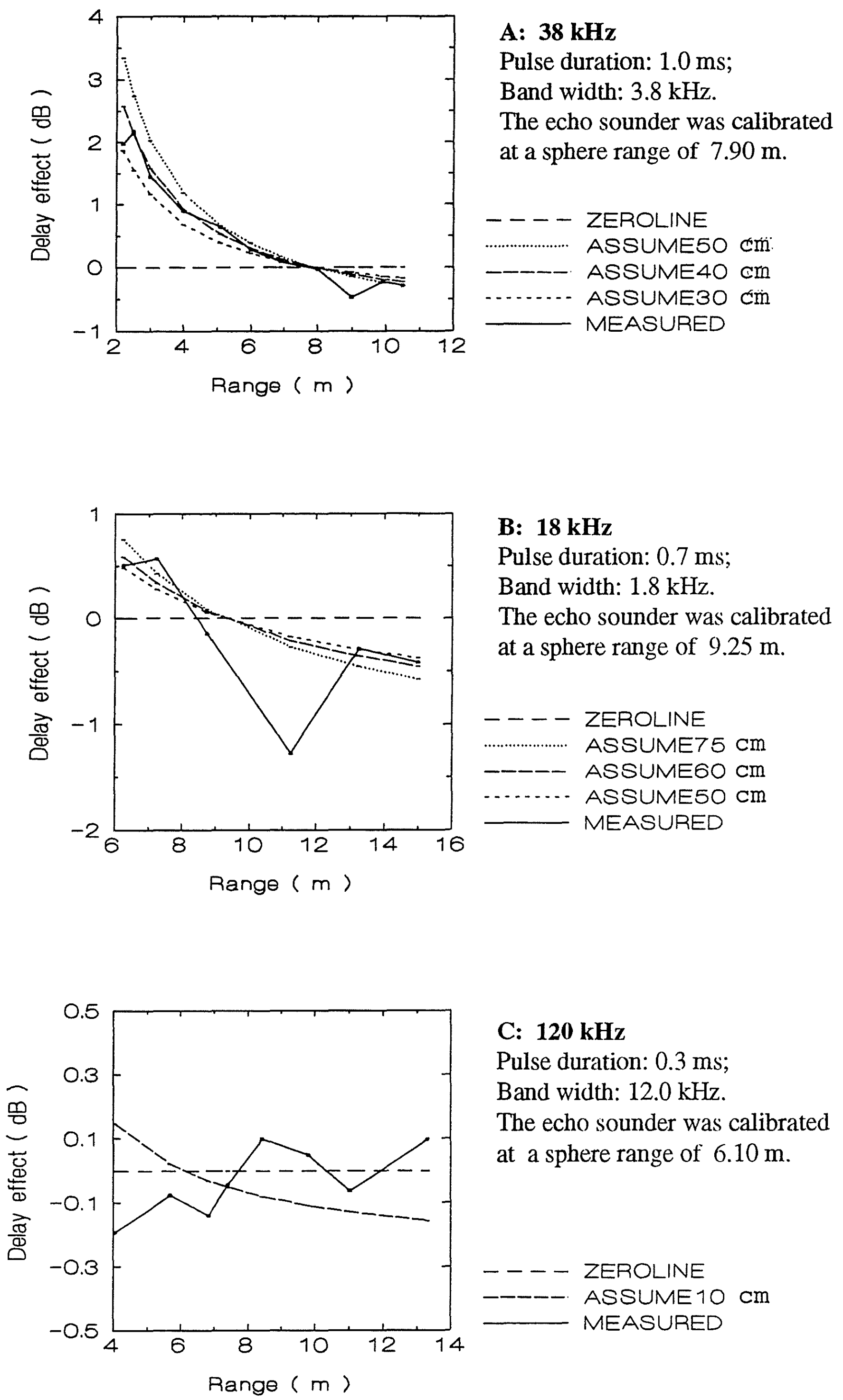


Fig. 3. Effect of time delay on the apparent target strength of a standard calibration sphere, the 38.1-mm-diameter WC sphere, as measured with the EK500 echo sounder, software version 5.0, at each of three frequencies. The time delay is expressed through the range. Measurements are indicated by the points, connected by a solid line. Predicted effects at several assumed delays are shown together with the no-effect "zero-line" for reference.

order were 46, 24, and 8 cm. Time delays were also measured at other combinations of pulse duration and receiver bandwidth. The effects of pulse duration and bandwidth on the time delay agree with theory (MacLennan 1986). Thus the time delay increases with increasing pulse duration and is larger with the narrow bandwidth than with the wide bandwidth.

Improvements in the determination of $t_1$, thence $t_o$, can be made by means of function-fitting to the digitized echo waveform in Fig. 1e. In particular, the approximate peak amplitude $\hat{A}_p$ can be refined by interpolation to yield a closer estimate to the true peak amplitude $A_p$. A similar operation will improve the estimation of $A_{-6}$, thence $t_1$. The results of laboratory measurements can be used for extrapolation to $t_o$.

If neglected during target strength measurements, errors caused by the time delay may significantly affect the accuracy of target strength data, especially if made at short range. At present, if the range $r_d$ corresponding to the time delay is determined, then TS data can be corrected by addition of the term

$$\Delta TS = 40 \log \frac{r_f - r_d}{r_f} - 40 \log \frac{r_s - r_d}{r_s} \quad ,$$

where $r_f$ is the range of the fish or other identified single target, and $r_s$ is the range of the standard target used in the calibration, both ranges being measured by the EK500 in software versions as recent as number 5.0.

Calibration of echo integrators, like those of so-called target strength analyzers, will also be affected by the time delay, although the applied TVG function is based on the compensation term "20 log r" instead of "40 log r". Similarly, acoustic measurements of fish and plankton density will also be biased if allowance is not made for $r_d$. In contrast to the case of TS measurement, "20 log r" TVG is applied monotonically, increasing over the echo pulse duration. Thus the effect of variable receiver gain over the pulse duration requires correction, as has been well elucidated (MacLennan 1986, Sawada and Furusawa 1993).

Measurements of finite-target-size effects

As a standard target is moved toward the transducer, the sphere will gradually cover a larger part of the acoustic beam, occupying an increasing number of angular resolution cells of the split-beam system, illustrated in Fig. 2. Two effects, which are distinct from those of the described TVG effect, seem to affect the accuracy of TS determinations at short ranges. The first depends on the determination of angular location. If this is uncertain because the target spans several angular resolution cells, then the angle determination is accompanied by jitter. The second effect depends on the accuracy of the beam pattern compensation. For targets spanning several cells, the variation in beam pattern over the target diameter can hardly be compensated better than by an average compensation factor. The resolution in beam compensation is thus reduced as the step size increases.

In the present observations, in which the transducers are allowed a certain movement with the sea surface, the effects could not be separated.

Together, they appear as an increased variability during beam calibration at short range. In Figs. 4 and 5, beam pattern measurements are shown at each of three ranges for the 38-kHz transducer. These were made at the 18.5-m range with the ES38B transducer on board R/V "Dr. Fridtjof Nansen", and at the shorter ranges with the ES38-12 transducer at Austevoll. The respective half-power beamwidths for the two transducers are 7.1 and 11 deg. All measurements made in the beam cross section are shown, where the pair of alongship and athwartship angles have been reduced to a single polar angle $\theta$ referred to the acoustic axis. At 18.5 m, the sphere covers only slightly more than one angular resolution cell, 0.13 deg, for this transducer, hence the measurements are close to the compensation model in Fig. 4c. The standard deviation of the corresponding residual in Fig. 5c is also low, varying over 0.09-0.16 dB within 2 deg of the axis, increasing to 0.25 and 0.35 dB in the two outer cells.

At the two shorter ranges, the sphere covers nearly two angular cells, 0.21 deg. A larger spread in calibration data is seen in Figs. 4a and b, which also increases with increasing distance from the acoustic axis. The residuals after beam compensation, Figs. 5a and b, also show a larger spread, with standard deviation that is double the former, 0.15-0.26 dB in the cells 1-2 deg off axis, increasing to 0.57 dB in the cell 7-8 deg off axis.

As is evident from the total spread of the residuals, the accuracy of a particular TS value at the edge of the main lobe is only about ±1 dB; however, the bias remains small. The data quality may be improved further, as by restricting single-target data to a smaller region in the center of the beam, say within the half-power points instead of quarter-power points, which is the present practice in the EK500 target strength analyzer.

Short-range effects on increased variability in beam compensation are not peculiar to the split-beam system in the present illustration. When the target is larger than the angular resolution, it also covers an increasing area of the acoustic beam over which the beam pattern is variable. Compensating for transducer directivity will then be of lower resolution than at a larger range, both for dual-beam and split-beam systems.

Measurements of PRF effects

Examples of reducing the transmit power at high PRF with the EK500/38-kHz echo sounder are shown in Fig. 6. The pulse duration is constant at 1 ms. At ping intervals (1/PRF) lower than 0.6 s, the system performance is gradually reduced. At the highest PRF, the reduction in apparent TS indicates a reduction in output power by 1.3 dB. Even higher PRFs could not be investigated here because the bottom depth was 37 m.

For the EK500/18-kHz echo sounder, which has a minimum ping interval of about 0.5 s or maximum PRF of 120/s, similar effects were not observed at the shortest pulse duration of 0.7 ms. For the EK500/120-kHz echo sounder, with maximum PRFs similar to that for the 38-kHz sounder, no effects were observed with the short, 0.3-ms pulse duration.

A detailed study of this effect is needed to define the performance limits of the EK500 echo sounder with respect to the PRF. Such a study

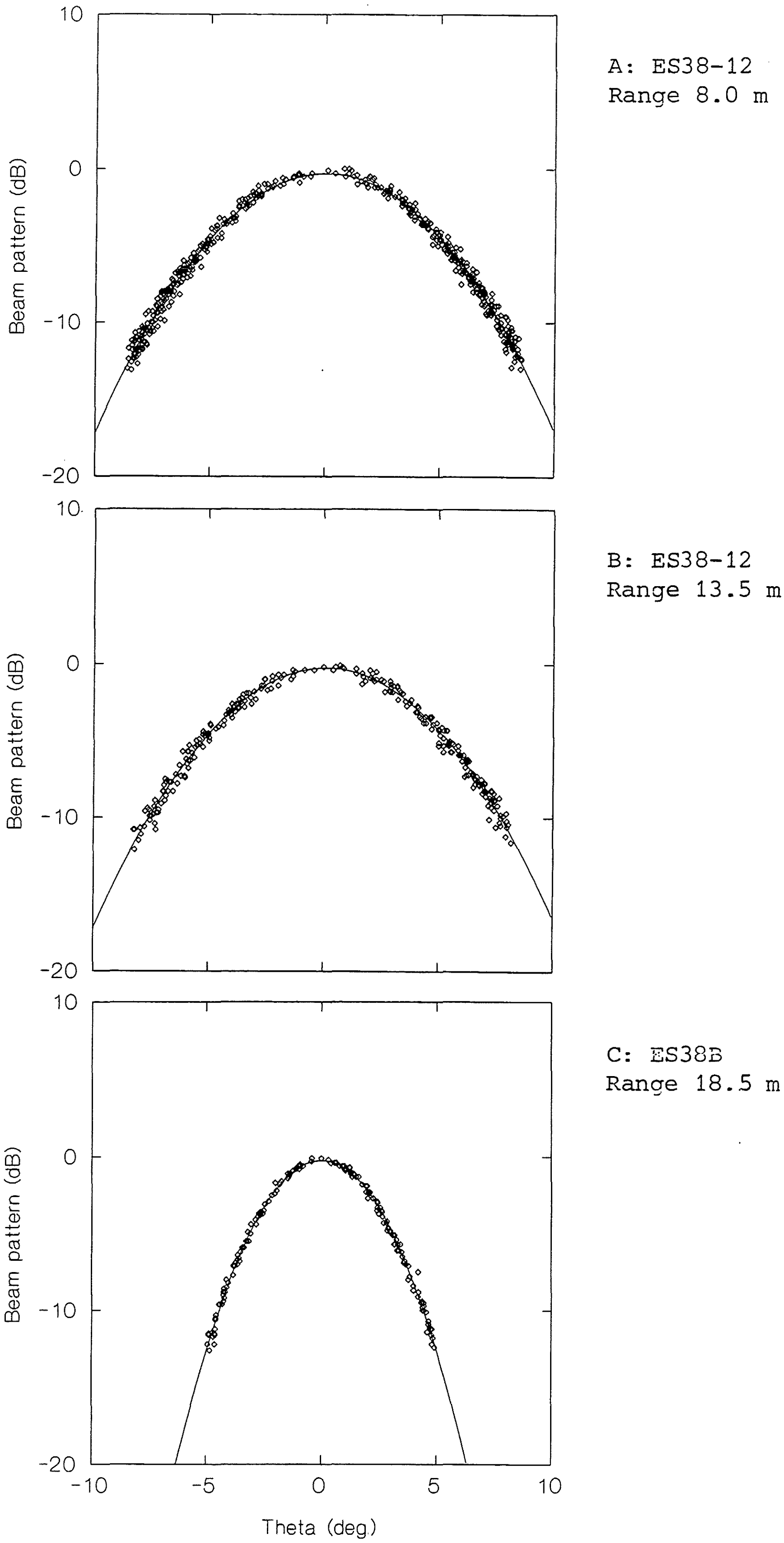


Fig. 4. Measured beam patterns of 38-kHz split-beam transducers at each of three ranges, where the general measurement point in the beam cross section is expressed through the polar angle, denoted "theta".

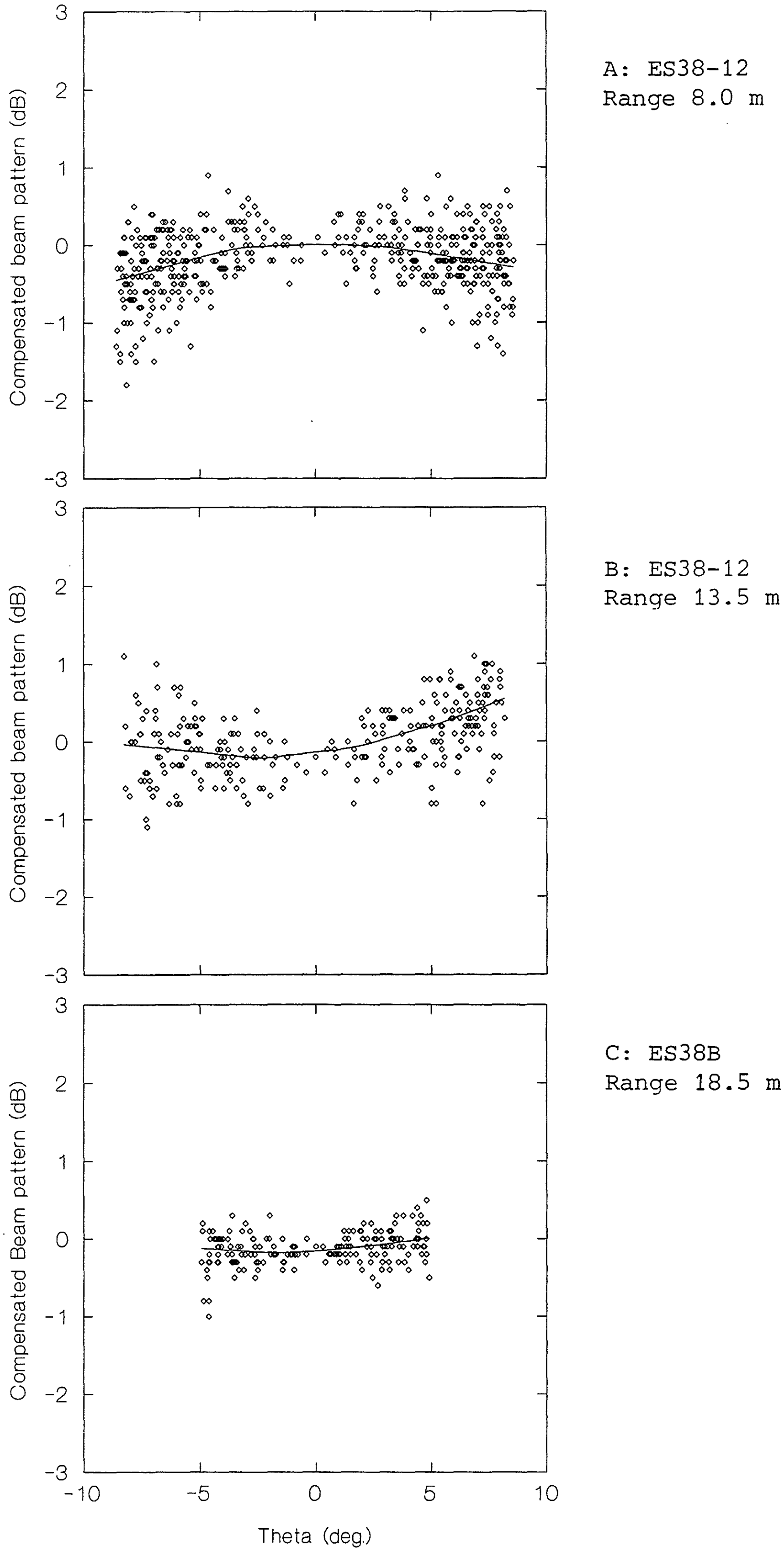


Fig. 5. Error in beam pattern compensation as determined by the residual in apparent target strength value, derived from the data in Fig. 4.

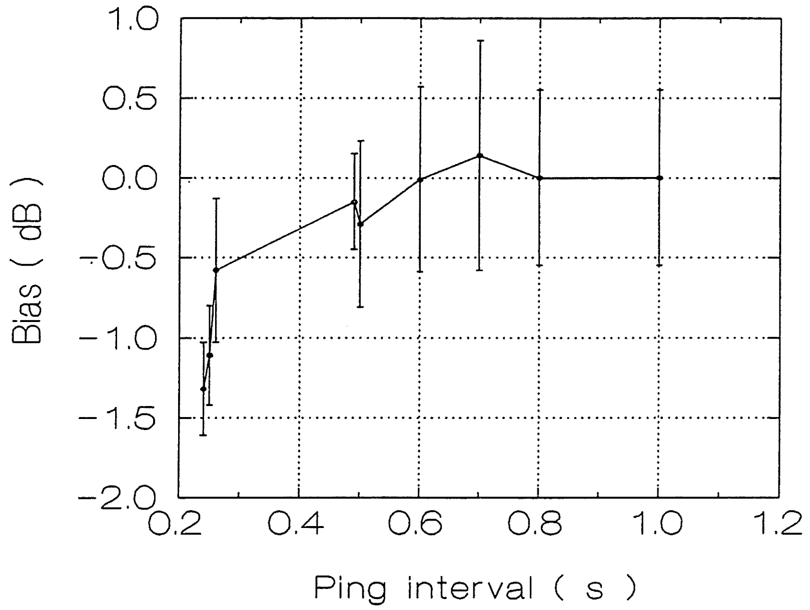


Fig. 6. Bias in the apparent target strength of a standard calibration sphere, the 38.1-mm-diameter WC sphere, as a function of ping interval, or reciprocal PRF. The measurements were performed in the 38-kHz channel of the EK500 echo sounder when configured for three-frequency operation. The maximum transmitting power was 1000 W, and the pulse duration was 1 ms. The indicated range of variation about each measurement point is ±one standard deviation.

should include internal measurements of the battery-capacitor system. In the interim, shallow-water calibration should be made with a fixed upper PRF, say 1/s or 50-60 pings/minute, as has been and is fairly typical during conventional deeper-water oceanic surveys.

## CONCLUSION

Short-range effects have been studied before, but as the new work presented here suggests, the exhaustive treatment remains to be given. This work has attempted to summarize current understanding of short-range effects, illustrating these by new measurements. Three major sources of variability, and potential causes of inaccuracy in calibration or measurements of animals, have been distinguished: time-varied gain, finite target size, and pulse repetition frequency. These affect both single-scatterer measurements of target strength and echo integration. Some remedies have been described. Insofar as these depend on details of processing operations in the echo sounder and integrator, not to mention hardware too, attention must be paid to the acoustic instrument itself. The penalty of inattention to short-range effects including instrument operation is clear: potential bias and increased variability in measurements.

## ACKNOWLEDGEMENTS

Engineers at SIMRAD Subsea A/S, including especially Rolf L. Nilsen, are thanked for discussion and for allowing use of new measurement results on the time-delay effect. This work has been partially supported by each of two European Union projects, AIR3-CT94-2142 and MAS3-CT95-0031.

## REFERENCES

Anon. 1992. SIMRAD EK500 scientific echo sounder: operator manual. SIMRAD report no. P2170E. SIMRAD Subsea A/S, Horten, Norway.

Bodholt, H., Nes, H., and Solli, H. 1989. A new echo-sounder system. Proc. IOA, 11(3): 123-130.

Ehrenberg, J. E. 1979. A comparative analysis of in situ methods for directly measuring the acoustic target strength of individual fish. IEEE J. Oceanic Eng. OE-4: 141-152.

Foote, K. G. 1982. Optimizing copper spheres for precision calibration of hydroacoustic equipment. J. acoust. Soc. Am., 71: 742-747.

Foote, K. G., and MacLennan, D. N. 1984. Comparison of copper and tungsten carbide calibration spheres. J. acoust. Soc. Am., 75: 612-616.

Foote, K. G., Knudsen, H. P., Vestnes, G., MacLennan, D. N., and Simmonds, E. J. 1987. Calibration of acoustic instruments for fish density estimation: a practical guide. ICES Coop. Res. Rep., 144. 69 pp.

Gunderson, D. R. 1993. Surveys of fisheries resources. Wiley, New York. 248 pp.

MacLennan, D. N. 1982. Target strength measurements on metal spheres. Scot. Fish. Res. Rep., 25.

MacLennan, D. N. 1986. Time varied gain functions for pulsed sonars. J. Sound Vib., 110: 511-522.

MacLennan, D. N. 1990. Acoustical measurement of fish abundance. J. acoust. Soc. Am., 87: 1-15.

Mitson, R. B. 1983. Fisheries sonar. Fishing News Books, Farnham, Surrey, England. 287 pp.

Ona, E. 1990. Optimal acoustic beam pattern corrections for split beam transducers. ICES C.M. 1990/B:30. 12 pp. [Mimeo.]

Ona, E. 1994. Detailed in situ target strength measurements of 0-group cod. ICES C.M. 1994/B:30. 9 pp. [Mimeo.]

Sawada, K., and Furusawa, M. 1993. Precision calibration of echo sounder by integration of standard sphere echoes. J. acoust. Soc. Jpn. (E), 14: 243-249.

Simmonds, E. J., Petrie, I. B., Armstrong, F., and Copland, P. J. 1984. High precision calibration of a vertical sounder system for use in fish stock estimation. Proc. IOA, 6(5): 129-138.

Wilkinson, L. 1988. SYSTAT: The system for statistics. SYSTAT, Evanson, Illinois.