

Comparing two 38-kHz scientific echosounders

J. Michael Jech, Kenneth G. Foote, Dezhang Chu,
and Lawrence C. Hufnagle Jr.

Jech, J. M., Foote, K. G., Chu, D., and Hufnagle, L. C., Jr. 2005. Comparing two 38-kHz scientific echosounders. — ICES Journal of Marine Science, 62: 1168–1179.

The EK500 has been the state-of-the-art scientific echosounder for surveying marine fish stocks for over a decade; the EK60 is its successor. Ensuring comparability in performance is vital during the transition from the EK500 to the EK60. To quantify the respective performances, each echosounder was calibrated in tandem by the standard-target method using the same 38-kHz, 12° beam width, split-beam transducer, with alternating pinging by means of an external triggering-and-switching system. The principal measurements comprised split-beam-determined angle and target strength, on-axis sensitivity, and directionality in the plane normal to the acoustic axis, as measured with a 60-mm-diameter copper sphere. Ambient noise, including volumetric reverberation, was also measured. Principal comparisons included those of the time-series and histograms of split-beam-determined target strength; respective alongship and athwartship angles as determined by the split-beam system; and as expected, difference in the split-beam-determined and experimental target-strength values in the plane normal to the acoustic axis. The mean absolute difference in off-axis angle values was also compared. While the performance of the two echosounders is generally similar, systematic differences exist. For the particular calibration measurements, the time variability in measurements of on-axis target strength was of the order of 1 dB for the EK500 and 2 dB for the EK60. The target-strength distribution for measurements made with the EK500 was normal, with standard deviation 0.2–0.3 dB, whereas for the EK60, the target-strength distribution was distinctly skewed and the standard deviation varied over 0.3–0.5 dB. Differences were found between the split-beam and physical-angle measurements. They were noticeably larger in the case of the EK60. Differences in performance between the two echosounders suggest refinements to the new system that will help realize its full potential in scientific work.

Published by Elsevier Ltd on behalf of International Council for the Exploration of the Sea.

Keywords: calibration, echosounder, fisheries acoustics.

Received 14 September 2004; accepted 7 February 2005.

J. M. Jech: Northeast Fisheries Science Center (NOAA/NMFS), 166 Water Street, Woods Hole, MA 02543, USA. K. G. Foote and D. Chu: Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA. L. C. Hufnagle, Jr.: Northwest Fisheries Science Center (NOAA/NMFS), 2725 Montlake Blvd. E., Seattle, WA 98112, USA. Correspondence to J. M. Jech: tel: +1 508 495 2353; fax: +1 508 495 2258; e-mail: michael.jech@noaa.gov.

Introduction

The SIMRAD EK500 scientific echosounder (Bodholt *et al.*, 1989) has defined the state-of-the-art since its introduction. It has been in worldwide use in the service of fisheries research for over a decade. (Any use of trade names does not imply endorsement by NOAA.) However, changes in the manufacture of solid-state electronics, specifically in the availability of components, rendered a number of essential components obsolete by 2000. At the same time, advances in data technology were sufficient to compel a fundamental redesign, resulting in the successor echosounder, the EK60 (Andersen, 2001).

Consistency in performance of the two systems is naturally a major concern to users, whether for water

column or seafloor measurements, as well as to fishery managers using data derived from echo-integrator surveys of fish and zooplankton stocks (MacLennan, 1990; Gunderson, 1993; Foote and Stanton, 2000). It is the goal of the present study to investigate the performance of the two echosounders and to verify or quantify differences.

The basis of the comparison is the standard-target method of calibration (Foote, 1983; Foote *et al.*, 1987) using optimal and other standard solid, elastic sphere targets (Foote, 1982; Foote and MacLennan, 1984). This method is well suited to measuring the overall system response both on and off the transducer axis. Specific parameters that can be derived from such measurements include the on-axis combined transmit-and-receive

sensitivity, product of the transmit- and receive-beam patterns, and the two-way directivity index, also called the equivalent beam width (Urick, 1983), equivalent beam angle (MacLennan, 1990), and integrated beam pattern (Medwin and Clay, 1998).

Two technical challenges have been met in the course of performing the comparison. Firstly, a new capability for determining the target position relative to the transducer axis has been exploited. This is available at a special facility, allowing a greater degree of control than was previously possible. Previous methods depended on using a fixed sphere-suspension system attached near the transducer and configured by an underwater diver, with angles controlled by trimming the vessel (Ona and Vestnes, 1985), making use of the split-beam functionality in moving the target through the beam (Kieser and Ona, 1988), and using extended outriggers (Reynisson, 1990, 1998). The *in situ* advantages of these methods are forfeited in return for much greater angular accuracy and precision. Secondly, conditions for making the comparative measurements have been rendered very similar by making the measurements in tandem via the alternate triggering of the two echosounders from ping to ping. Details are given below.

Comparisons based on the respective measurements are presented and discussed. While the results apply strictly to two particular 38-kHz units of the EK500 and EK60, they are believed to be indicative of these models.

Material and methods

Acoustic-backscatter data were collected with a SIMRAD EK500 scientific echosounder and a SIMRAD EK60 Mark I scientific echosounder, each operating at 38 kHz, during 6–7 January 2003. The experiments were conducted in a sea well on Iselin Dock at the Woods Hole Oceanographic Institution (Doherty *et al.*, 2002). The echosounders shared the same 38-kHz split-beam transducer, SIMRAD model number ES38-12, by means of a multiplexing junction box (Figure 1). The beam width of this transducer was 12° as measured by the manufacturer between the half-power points.

The transducer was mounted facing sideways on a 6-m vertical shaft suspended at a water depth of approximately 3 m. The transducer-alongship axis was orientated in the vertical plane with positive angles up and with the athwartship angles oriented in the horizontal plane with positive angles to the right. The shaft was secured within a section of antenna tower and attached to a computer-controlled rotator. The accuracy of the rotator was better than $\pm 0.1^\circ$. A personal computer (PC) controlled the rotational parameters such as the beginning and end degree of rotation, rotation increment, speed of rotation, and the number of pings-per-rotation increment (Doherty *et al.*, 2002). For each rotation increment, the EK500 and EK60 were alternately triggered in tandem at a rate of two pings

per second, i.e. one ping per second for each echosounder. The trigger generator was connected to each echosounder and to a set of mechanical relays in the transducer junction box. The relays were coordinated to synchronize transmit and receive signals to and from the transducer for each echosounder. The EK500 and EK60 transmit data via Ethernet connections to another PC for analysis.

Operation of both echosounders was software-controlled through selection of parameter values. Operational parameters were: 1-ms pulse duration, wide receiver bandwidth, nominally 10% of the centre frequency, time-varied gain (TVG) of $40 \log_{10}(r) + 2\alpha r$, where r is the range, and $\alpha = 10 \text{ dB km}^{-1}$, the attenuation coefficient. These operational parameters were chosen as they are used for surveys conducted at the Northeast Fisheries Science Centre (Jech *et al.*, 2000).

Two general sets of measurements were performed: on-axis sensitivity, nominally within 1–2° of the transducer axis, and transducer beam directionality. A 60-mm-diameter copper calibration sphere (Foote, 1982) suspended with a monofilament line was used as the standard target. For on-axis measurements, the sphere was positioned on the geometric axis of the transducer by measuring the depth of the transducer and aligning the sphere by means of a laser mounted on the rotator perpendicular to the transducer face. The sphere was placed at a range of approximately 11.5 m from the transducer, well in the far field of the transducer, which is nominally 0.5 m (Gaunaud, 1985). At this range, a normal distance of 20 cm subtends an arc of about 1°. On-axis measurements consisted of 1000 pings per echosounder to evaluate the sensitivity and stability of echo amplitudes and angular locations derived by each instrument.

The transducer directivity was measured by rotating the transducer about its vertical axis spanning a set of athwartship angles, and raising and lowering the sphere over a set of alongship angles. Athwartship angles spanned 30°, from -15° to $+15^\circ$ in 0.5° increments (a “sweep”). Alongship angles spanned 18°, from -9° to $+9^\circ$ in 1° increments. One ping per echosounder was collected at each angle. A total of 21 sweeps was completed. The first sweep was performed at 0° alongships. Nine sweeps were then performed at successively greater positive alongship angles. The sweep at 0° was repeated, followed by nine sweeps at successively greater negative alongship angles. The final sweep was again performed at 0° . The three 0° alongship sweeps were done to verify the alignment of the sphere relative to the transducer.

The EK500 (Bodholt *et al.*, 1989; Demer *et al.*, 1999) and EK60 (Andersen, 2001; SIMRAD, 2001) have common, individual target-detection parameters and detect individual targets based on the amplitude and width of the echo. In one experiment involving 1000 ensonifications of the same target near or on the transducer axis by each echosounder, the number of single-target detections was 932 with the EK500 and 220 with the EK60 Mark I.

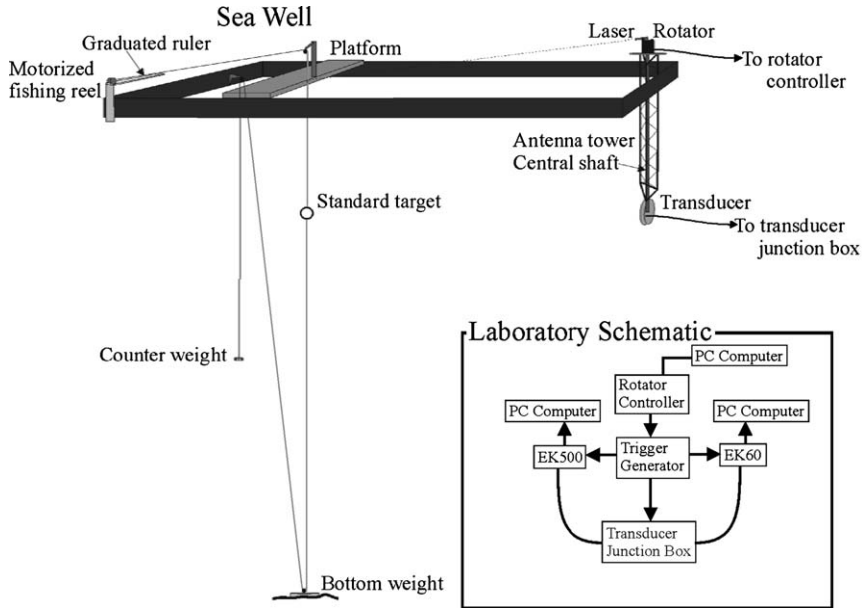


Figure 1. Schematic diagrams of the experimental set-up in the sea well and the EK500 and EK60 configuration. The transducer shaft was approximately 6 m long and the horizontally-orientated transducer was placed approximately 3 m below the water surface. The bottom weight was located approximately 20 m below the water surface.

Because of difficulties in configuring the respective post-processing systems with equivalent parameter settings, the raw echosounder data were exported to the Echoview post-processing software, version 3.00.80.04, developed by SonarData Pty Ltd. (GPO Box 1387 Hobart, Tasmania, Australia, www.sonardata.com). Use of the single-target-detection algorithm in Echoview (split-beam method 1) resolved the discrepancies, providing a constant basis for comparing the two sets of data.

Single-target detection parameters were: -54 -dB threshold, 6 -dB maximum two-way beam-pattern compensation, and a maximum phase deviation of four phase steps. For reference, the EK500 has 64 phase steps and the EK60 has 128 phase steps per 180 electrical degrees. The angular locations of single targets are determined with the split-beam transducer according to electrical-phase differences between half-beam signals. Half-beam signals are formed by adding received signals from adjacent quadrants of the split-beam transducer (Ehrenberg, 1979; Foote *et al.*, 1986). Data exported from Echoview were the range, echo strength, target strength, and alongship and athwartship angles of the detected calibration target. In the manufacturer's terminology, the echo strength is sometimes referred to as the "uncompensated target strength", while the target strength is analogously called the "compensated echo strength".

Transducer beam patterns were determined by measurement in each of two ways: first the use of the split-beam-determined angles, and second, as determined by the external, sea-well instrumentation. Corresponding beam

patterns could thus be compared, i.e. beam patterns determined by the split-beam function of each echosounder with those determined by the experimental geometry, as well as between echosounders.

Both the EK500 and Echoview softwares assume a small-angle approximation to define the beam pattern. The effective one-way beam pattern is given in the logarithmic domain as

$$B(\alpha_{SB}, \beta_{SB}) = -3.0103 \left[\left(\frac{2\alpha_{SB}}{BW_{\alpha}} \right)^2 + \left(\frac{2\beta_{SB}}{BW_{\beta}} \right)^2 - 0.18 \left(\frac{2\alpha_{SB}}{BW_{\alpha}} \right)^2 \left(\frac{2\beta_{SB}}{BW_{\beta}} \right)^2 \right], \quad (1)$$

where α is the alongship angle, β is the athwartship angle, subscript "SB" denotes split-beam-determined angles, BW_{α} is the total angular beam width measured at the half-power points in the alongship direction, and BW_{β} is the total angular beam width measured at the half-power points in the athwartship direction. For the 38 -kHz transducer, BW_{α} and BW_{β} are 12° . Equation (1) is used to compensate echo-strength measurements for angular location in the acoustic beam, since the echo strength is the sum of beam pattern and target strength.

An empirical compensation function was derived by fitting a second-order polynomial to the alongship and athwartship angles and echo-strength measurements. The form of the polynomial is:

$$\hat{B}(\alpha, \beta) = G + c_0\alpha + c_1\alpha^2 + c_2\beta + c_3\beta^2, \quad (2)$$

where G is the overall echo-strength compensation value, and c_0 , c_1 , c_2 , and c_3 are the empirically determined coefficients.

Given the potential for discrepancies between the split-beam-determined angles and the angles based on the experimental geometry, the split-beam-determined angles could be adjusted *a posteriori* for an offset. The offset was computed using the slopes and intercepts from linear regressions of the split-beam-determined and geometry-based angles in both the alongship and athwartship directions. An empirically derived transducer directivity ($\hat{B}$) was computed using the angles adjusted for the offset and then compared with the small-angle-approximation compensation.

To measure consistency between the experimental-geometry-based and split-beam-determined directivity, an index was defined. This was the mean, absolute difference per each 1° off-axis interval. A similar index was computed to determine the consistency between the experimental-geometry-based and adjusted transducer directivities. The absolute values of the differences were computed to determine the magnitudes of the discrepancies.

The equivalent beam angle ψ or its logarithmic form $\Psi = 10 \log_{10}(\psi)$ can be calculated from the measured far-field transmit- and receive-beam patterns, b_T and b_R , respectively (Urlick, 1983), by integrating their product over the half space in front of the transducer:

$$\psi = \int_0^{2\pi} \int_0^\pi b_T(\theta, \phi) b_R(\theta, \phi) \sin \theta \, d\theta \, d\phi. \quad (3)$$

The beam patterns are evaluated here in the field direction (θ, ϕ) , which can be expressed in terms of rectangular coordinates. For the field point $\mathbf{r} = (x, y, z)$, where the magnitude of $\mathbf{r}$ is the range, the unit vector $\hat{\mathbf{x}}$ is coincident with the alongship axis $\hat{\mathbf{y}}$ with the athwartship axis, and $\hat{\mathbf{z}}$ with the transducer axis. In these coordinates, the polar angle $\theta = \arccos(z/r)$ and azimuth $\phi = \arctan(y/x)$. When measured by the split-beam function of the echosounder, however, the beam patterns are expressed in terms of the alongship angle $\alpha = \arctan(x/z)$ and the athwartship angle $\beta = \arctan(y/z)$. The transformation between the spherical angles (θ, ϕ) and split-beam angles (α, β) is (Foote, 1986):

$$\phi = \tan^{-1} \left(\frac{\tan \beta}{\tan \alpha} \right),$$

$$\theta = \tan^{-1} \sqrt{\tan^2 \alpha + \tan^2 \beta} \quad (4)$$

which enables the split-beam angles to be converted to the spherical angles used in Equation 3.

Results and discussion

Tidal stages for the measurements are given in Table 1. The copper-sphere, beam-pattern measurements were done during mid-flood tide, and the on-axis measurements were done near slack tide. The on-axis sensitivity measurements using the tungsten-carbide and aluminium-alloy spheres were conducted approximately mid-ebb tide. A vertical Conductivity–Temperature–Depth (CTD) profile conducted prior to each trial indicated that the seawater at the sea well was well mixed. The CTD was then placed at the depth of the transducer to collect time-series of temperature and salinity over the duration of each trial. The average temperature, salinity, and sound speed were $2.88 \pm 0.02^\circ\text{C}$, 31.60 ± 0.25 PSU, and $1457.51 \pm 0.37 \text{ m s}^{-1}$, respectively.

On-axis angular measurements

Based on the geometry of the transducer mounting, the 60-mm-diameter copper calibration sphere was aligned on the geometric axis of the transducer. Observations of the alongship (vertical) and athwartship (horizontal) split-beam-determined angular locations of this target show that it was closely aligned with the alongship axis but not with the athwartship axis (Figure 2). Mean alongship angles were -0.08° for the EK500 and -0.14° for the EK60 (Table 2), with a total variation of about $\pm 0.5^\circ$ for both echosounders. The mean athwartship angles were -0.62° for the EK500 and -0.71° for the EK60, with a total variation of about $\pm 1.5^\circ$ for both echosounders. For the EK500, the mean alongship angle was well within the angular resolution of 0.225° , whereas the mean alongship angle for the EK60 was slightly greater than the angular resolution of 0.1125° (SIMRAD, 2001). The difference of about 0.7° between the mean EK500 and EK60 athwartship angles and the axis is greater than the angular resolutions of both echosounders, and is indicative of an offset in the

Table 1. Sphere type, time, experimental trial, and tidal stage. These measurements were conducted on 7 January 2003. Sphere types are: 60-mm-diameter copper (CU60), 60-mm-diameter aluminium alloy (AL60), and 38.1-mm-diameter tungsten carbide with 6% cobalt binder (WC38.1). Values in parentheses indicate the number of hours after the start of flood or ebb tide that the measurements were taken. The tides at Iselin Dock are semi-diurnal, but rectified at the sea well, with significant current only during the flood.

Sphere	Time (EST)	Trial	Tide stage
CU60	1040–1215	Beam pattern	Flood (+4 to +6)
CU60	1220–1240	On-axis	Ebb (+0)
WC38.1	1540–1600	On-axis	Ebb (+2)
AL60	1640–1650	On-axis	Ebb (+3)

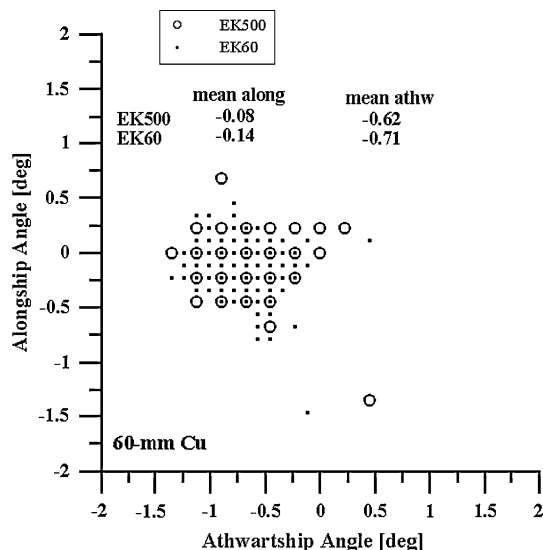


Figure 2. On-axis, split-beam-determined angular locations of a single target, the 60-mm-diameter copper sphere, from 1000 EK500 and EK60 tandem pings. The solid dots denote the EK60 single-target angular locations, and the open circles denote EK500 single-target angular locations.

experimental apparatus or the angular locations derived by the echosounders, or a mixture of both these factors.

To investigate the possibility that the angular offsets were sphere related, on-axis measurements were conducted with other sphere types. On-axis measurements with a 60-mm-diameter aluminium-alloy sphere showed a total variation in alongship and athwartship angles of about $\pm 0.5^\circ$ and $\pm 0.75^\circ$, respectively (Figure 3). On-axis measurements with a 38.1-mm-diameter tungsten-carbide sphere with a 6% cobalt binder showed alongship and athwartship angle variation of approximately $\pm 1^\circ$ and $\pm 1.5^\circ$, respectively (Figure 4). Mean alongship angles ranged from -0.18° to 0.18° (Table 2) and are within or near the angular resolution of the echosounders. Mean athwartship angles ranged from -0.63° to -0.69° , which are also indicative of an athwartship offset.

On-axis target-strength measurements

The 60-mm-diameter copper sphere was placed on the geometric axis of the transducer, 0° alongship and 0° athwartship, and 1000 transmissions per echosounder were collected to evaluate the on-axis sensitivity and time-based stability of the echo-amplitude measurements. Echo strengths were compensated using Equation (1) to give split-beam-determined target strengths (TS) of the sphere. A 100-ping subset of the time-series was arbitrarily chosen to investigate consistency in the target-strength measurements

Table 2. Means and standard deviations of alongship angle, athwartship angle, and target strength (TS) from the on-axis measurements. The mean and standard deviation of target-strength values were calculated from Gaussian fits to the target-strength distributions. Sphere types and measurement parameters are given in Table 1.

Sphere		Alongship angle ($^\circ$)		Athwartship angle ($^\circ$)		TS (dB)	
		EK500	EK60	EK500	EK60	EK500	EK60
CU60	Mean	-0.08	-0.14	-0.62	-0.71	-33.6	-33.6
	s.d.	0.17	0.14	0.23	0.22	0.2	0.3
AL60	Mean	0.08	0.18	-0.63	-0.68	-34.9	-35.3
	s.d.	0.19	0.17	0.24	0.28	0.2	0.5
WC38.1	Mean	-0.17	-0.18	-0.69	-0.65	-42.4	-42.6
	s.d.	0.28	0.35	0.41	0.50	0.3	0.5

between the EK500 and EK60 (Figure 5). A general pattern of coherence does not appear to exist in target-strength measurements between the two echosounders over the 100 pings. The EK500 target strengths are more or less constant, with a jitter of about 0.3 dB. The EK60 target strengths show a basic decrease, with much larger jitter of about 1 dB.

Observations of split-beam target strength over the 1000-ping trial (Figure 6) from both echosounders showed both short-term variability and longer-term trends. The short-term variations, or jitter, spanned about 0.5 dB for the EK500 and 1 dB for the EK60, not inconsistent with the observations over the 100-ping interval. The total variations in target strength over the measurements were about 1 dB for the EK500 and 1.5 dB for the EK60.

Means of split-beam target strengths were -33.6 dB for both EK500 and EK60, which were nearly equivalent for means derived from a Gaussian fit to the measurements (right panels, Figure 6). Gaussian fits to the EK500 and EK60 target-strength distribution resulted in a standard deviation of 0.2 dB for the EK500 and 0.3 dB for the EK60 data (Table 2). Both split-beam target-strength distributions were unimodal. However, EK500 distribution was narrower, with about 1.5 dB of total variability and greater than 70% of the target strengths within ± 0.2 dB of the mean, whereas the EK60 distribution was skewed towards target strengths greater than the mean, had approximately 3-dB total variability, and only 55% of the values were within ± 0.2 dB of the mean.

As with the copper sphere, EK500 split-beam target strengths were less variable than the EK60 split-beam-derived target strengths for the aluminium-alloy sphere (Figure 3) and tungsten-carbide sphere (Figure 4), and the target-strength distributions had similar skewness. Split-beam target strengths from the EK500 varied about 1 dB for the aluminium-alloy sphere and 1–1.5 dB for the tungsten-carbide sphere. Target strengths from the EK60 varied by approximately 1.5 dB for

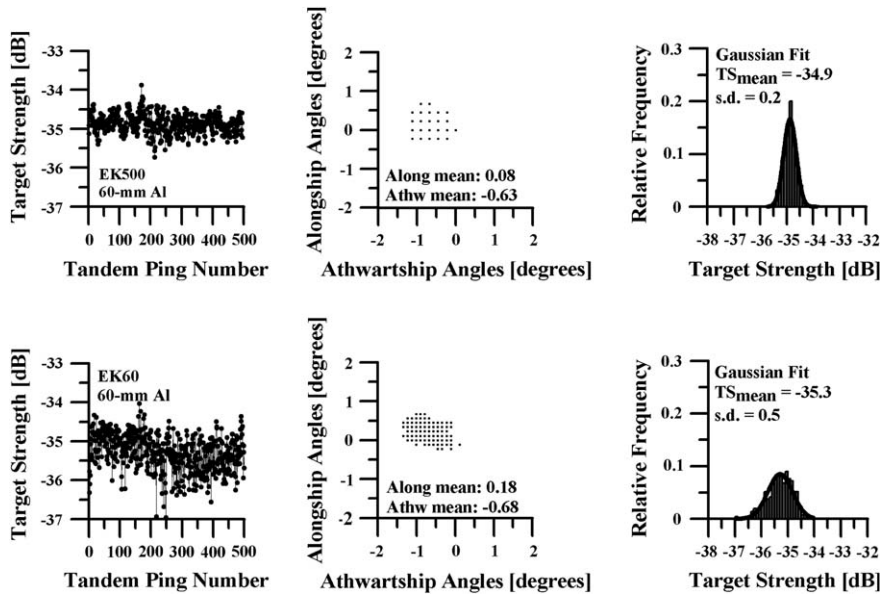


Figure 3. Time-series of split-beam-determined target strength, split-beam-determined angular locations, and histograms of split-beam-determined target strength for a 60-mm-diameter sphere made of an aluminium alloy. Five hundred tandem pings were collected with the EK500 (upper panels) and the EK60 (lower panels). The mean alongship and athwartship angles are given. Mean split-beam target strength (TS) and standard deviation (s.d.) are derived from a Gaussian fit to the data.

the aluminium-alloy sphere and more than 2 dB for the tungsten-carbide sphere.

Beam-pattern measurements

Regression analyses were performed to determine the linear relationships between split-beam-determined and the ex-

perimentally known angles for each of the echosounders (Figure 7). Slopes of the linear regressions were near 1 for the alongship angles (1.06 for the EK500 and 1.08 for the EK60) and athwartship angles (1.02 for the EK500 and 1.02 for the EK60). Intercepts for alongship angles were 0.11° for the EK500 and 0.06° for the EK60. As in the on-axis

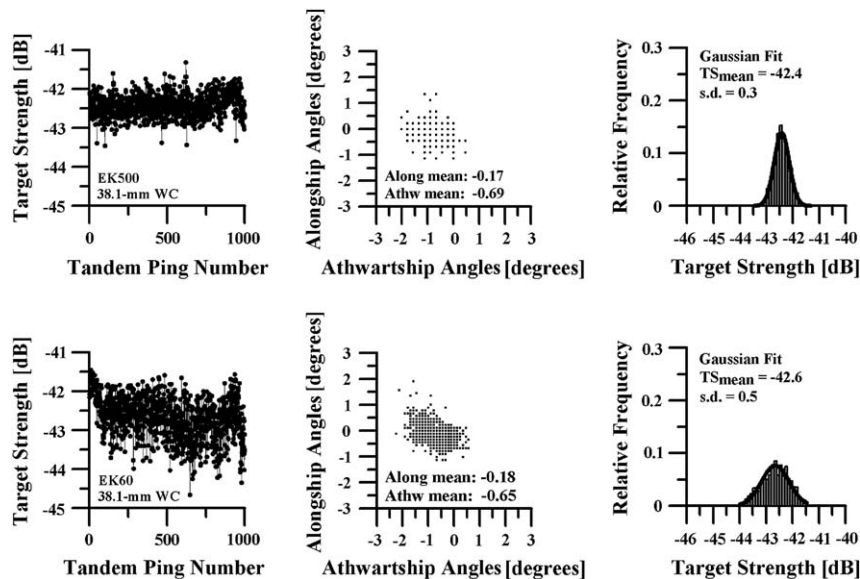


Figure 4. Time-series of split-beam-determined target strength, split-beam-determined angular locations, and histograms of split-beam-determined target strength for a 38.1-mm-diameter sphere made of tungsten carbide with 6% cobalt binder. One thousand tandem pings were collected with the EK500 (upper panels) and the EK60 (lower panels). The mean alongship and athwartship angles are given. Mean split-beam target strength (TS) and standard deviation (s.d.) are derived from a Gaussian fit to the data.

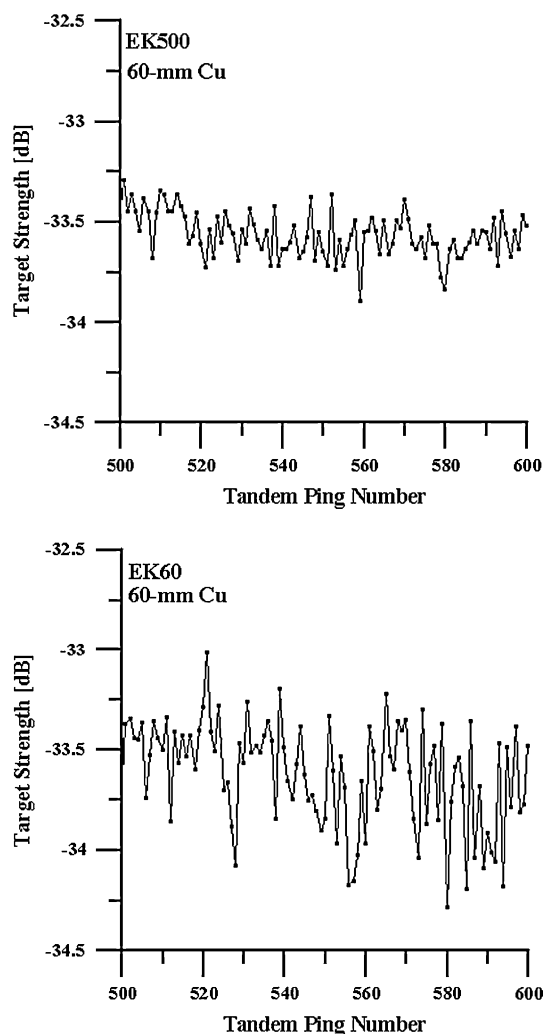


Figure 5. Time-series of split-beam-determined target strength for on-axis measurements of a 60-mm-diameter copper sphere from the EK500 (top panel) and EK60 (lower panel). The nominal ping rate was 1 ping s^{-1} for each echosounder, hence the reported time period is about 100 s. This time-series was extracted from the full time-series given in Figure 6 (pings 500–600).

measurements, alongship intercepts were within or near the angular resolution of each echosounder. Athwartship intercepts for athwartship angles were -0.86° for the EK500 and -0.87° for the EK60. Consistent with on-axis measurements, the magnitude of the intercepts indicates an athwartship-angle offset.

Beam-pattern measurements were conducted to assess the transducer directivity relative to that based on the experimental geometry and the SIMRAD-defined directivity. Transducer directivity was calculated using the SIMRAD beam pattern defined in Equation (1) and the alongship and athwartship angles based on the geometrical

Table 3. Beam widths (degrees) of the EK500 and EK60 observed beam patterns. G (decibels) is derived from Equation (2).

	EK500	EK60
Alongship beam width	11.4	11.4
Athwartship beam width	12.0	12.2
G (dB)	-33.6	-33.5

relationship of the transducer and 60-mm-diameter, copper calibration sphere. Similarly, the transducer directivities based on echo strengths and split-beam-determined angular locations of target detections were calculated. Differences between the directivities were computed by subtracting the split-beam-determined target strengths from the target strengths based on experimental geometry at each angular location: $\Delta TS = TS - TS_{SB}$.

In general, positive differences between geometry-based and split-beam determined target strengths occurred at negative athwartship angles, while negative differences occurred at positive athwartship angles (Figure 8).

Beam-pattern comparisons

The polynomial constant (G) in Equation (2) is the on-axis, echo-strength compensation value assuming 0° alongship and 0° athwartship angles. G sets the overall compensation level for echo-strength measurements. Differences between G and the calibrated on-axis sensitivity may affect the accuracy of split-beam-compensated target strengths. The value of G for the EK500 was within 0.05 dB of the theoretical target strength of the 60-mm-diameter copper calibration sphere (-33.6 dB). However, G for the EK60 was 0.1 dB greater than the theoretical value.

The split-beam-determined angles were adjusted with the slope and intercepts derived from the linear regressions of the experimental-geometry-based and split-beam-determined alongship and athwartship angles (Table 3). The mean of the absolute differences between the geometry-based, split-beam-determined, and adjusted beam patterns was computed. Figure 9 displays the mean of the magnitudes of the differences between the geometry-based and split-beam-determined beam patterns and between the geometry-based and adjusted beam patterns for the EK500 and EK60, respectively. The mean difference was computed for each 1° interval.

The mean of the absolute differences between geometry-based and split-beam-determined, with or without offset adjustment, increased with angular distance off-axis (Figure 9). The mean of the absolute differences was greater for the geometry-based vs. split-beam-determined beam patterns than for the geometry-based vs. adjusted beam patterns. The intercept of the geometry-based vs. split-beam determined beam patterns is a consequence of the athwartship angular offset. The difference between the

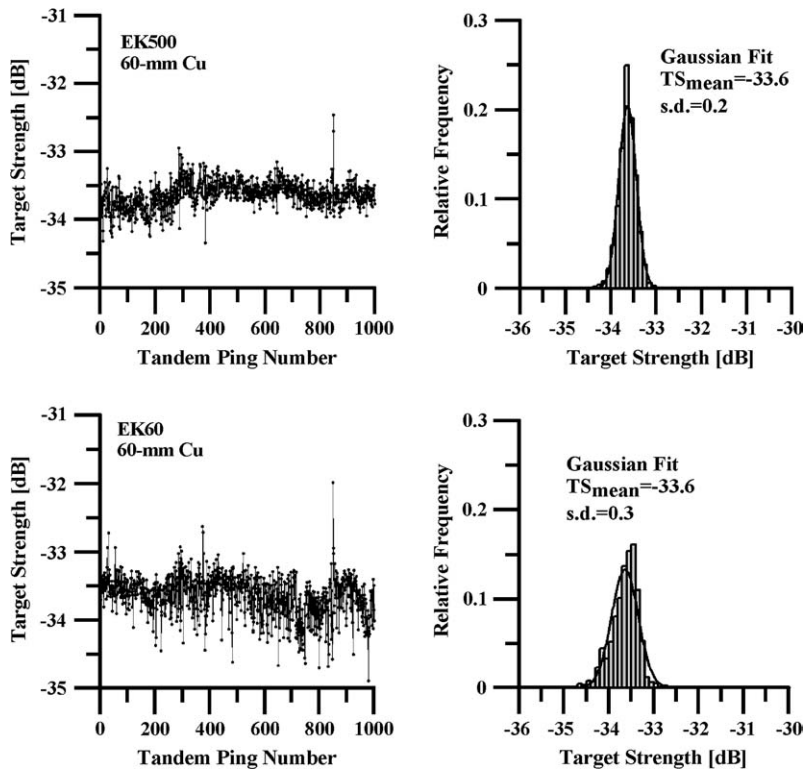


Figure 6. Time-series and histograms of split-beam-determined target strength for a 60-mm-diameter copper-sphere target on the acoustic axis. The ping rate was 1 ping s^{-1} per echosounder, and 1000 tandem pings represent approximately 17 min. Mean split-beam target strength (TS) and standard deviation (s.d.) are derived from a Gaussian fit to the data.

geometry-based and the split-beam-determined beam patterns ranged from 0.3 to 1.6 dB for both the EK60 and EK500. Adjusting the beam pattern for the athwartship and alongship offsets decreased the mean differences, as the differences between the geometry-based and the adjusted beam patterns ranged from near 0 to 0.3 dB.

An interesting result is that adjusting the EK60 beam pattern did not completely remove the error between the geometry-based and split-beam-determined beam patterns for off-axis angles less than 1° , whereas adjustments to the EK500 did nearly eliminate the error (Figure 9). This may be due in part to the value of G for the EK60 (Table 3), and potentially due to the skewed target-strength distribution from the EK60 (Figure 6). The TS distribution for the EK500 is unimodal and has a Gaussian shape, whereas the TS distribution for the EK60 is unimodal but skewed towards higher TS values. This skewed distribution may affect calculations of the empirical beam pattern and ultimately degrade the ability to compensate single-target, echo-strength measurements for location in the beam.

Beam width comparisons

Beam widths of the observed EK500 and EK60 beam patterns were compared with the manufacturer's stated

beam width of 12° . The beam width was measured as the total angular distance between the quarter-power points of the two-way beam pattern, which corresponds to the distance between the half-power points of the one-way beam pattern. Although beam widths were similar between the EK500 and EK60, athwartship beam widths for the EK60 and EK500 were closer to the specified 12° than were alongship beam widths (Table 2). Athwartship beam widths were within 0.2° of the manufacturer specification, whereas alongship beam widths differed by 0.6° .

Equivalent beam angle

Alongship and athwartship angles from beam-pattern measurements were converted to spherical coordinates, and the measured composite beam pattern $b_T(\alpha, \beta)b_R(\alpha, \beta)$ was integrated. In reality, measurements encompassing the entire beam pattern are difficult to acquire. In the case of only measuring the central region of the target plane, the equivalent beam angle Ψ will be determined based on a threshold. The computed equivalent beam angle Ψ with a two-way threshold of -12 dB was -15.2 dB. This is consistent with the manufacturer-specified value of -15.5 ± 1.0 dB. For comparison, the equivalent beam angle computed with a threshold of -6 dB was -17.6 dB.

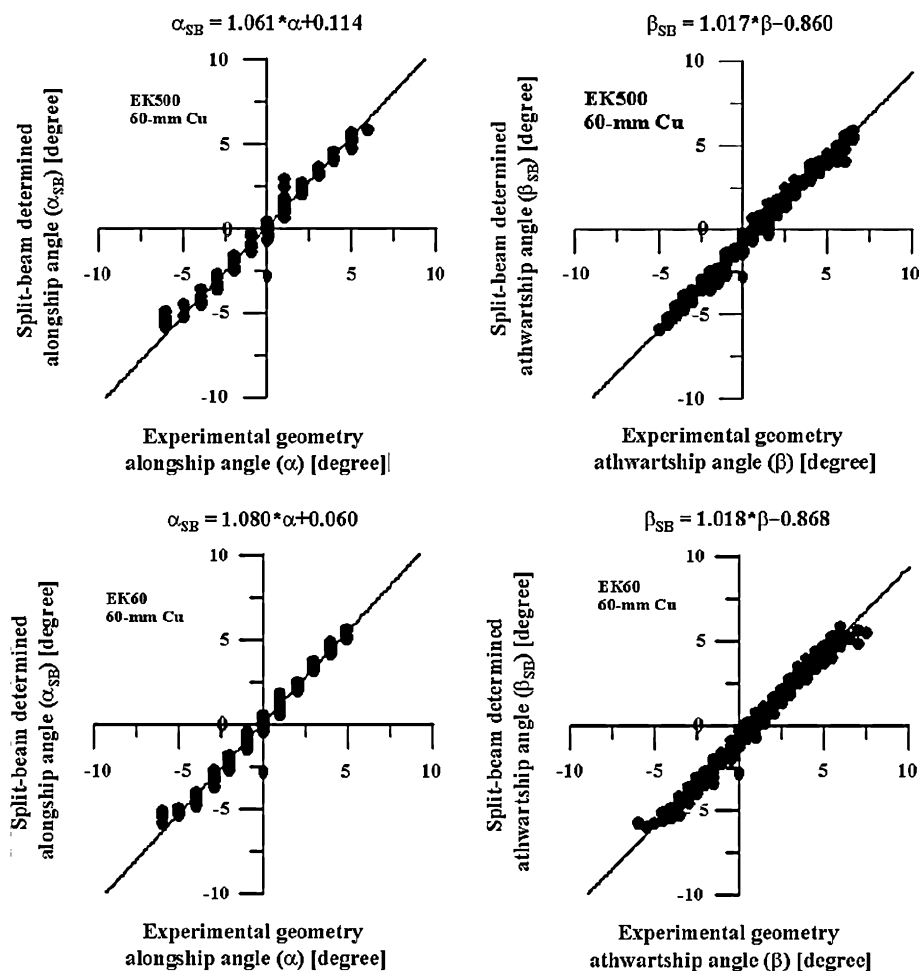


Figure 7. Split-beam-determined angular locations vs. those based on the known experimental geometry for a 60-mm-diameter copper-sphere target together with corresponding least-mean-squares linear regressions.

Outstanding issues

The cause of the offset in the athwartship direction between the geometric axis and acoustic axis is uncertain at this time. This discrepancy could be due to inaccurate measurements of the geometry or inaccurate computation of the angular locations. Environmental conditions such as tidal currents or temperature and salinity discontinuities are not believed to be contributory because of the tidal mixing and the range of tidal states under which the trials were performed.

A relationship between the variability in angular locations and target strengths may exist, as the tungsten-carbide sphere had the greatest variability in target strength and split-beam-determined angles among the spheres. This relationship may be tidal-stage dependent, but it is difficult to discern owing to the lack of a systematic attempt to measure the tidal-current effects during the trials. Even

though the angular variability was different among spheres, mean alongship and athwartship angles were similar among trials, suggesting a potential alignment error with the apparatus or misalignment of the acoustic and geometric axes of the transducer. However, the angles are so small that the split-beam compensation should be fully adequate to eliminate such variability in target strength. The issue of apparatus alignment errors vs. split-beam, target-localization errors will be addressed in a future planned trial.

Greater variability in target strength derived from EK60 data relative to target strength derived from EK500 data, and the skewed target-strength distributions derived from EK60 data remain unresolved issues. On-axis time-series measurements on the 60-mm-diameter copper sphere show “ping-to-ping” variability of up to 2 dB in the target strengths from the EK60 echosounder, whereas ping-to-ping variability in target strengths from the EK500 was less than 1 dB. Additionally, target strengths derived from

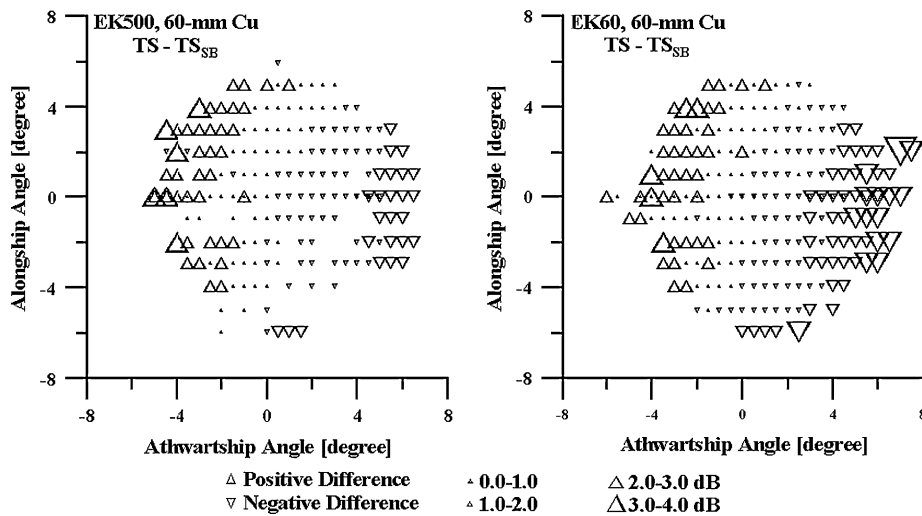


Figure 8. Differences in target strength from split-beam-determined angles (TS_{SB}) and angles based on the experimental geometry (TS) of a 60-mm-diameter copper sphere when traversing the main lobe of the transducer beam pattern. Gaps in the measured beam pattern indicate that the calibration sphere was not detected as a single target for that angular location.

EK60 data were not normally distributed. Departures of target strength from the mean in the EK60 on-axis time-series tended to be less than the mean, which is reflected in the skewed target-strength distribution. On-axis time-series are fundamental measurements of echosounder performance and calibration, and are a basis for determining the accuracy and precision of acoustic estimates. Observations of increased variability and skewed distributions from the EK60 relative to an echosounder that has been a scientific standard for a decade and to tolerances that have been developed for scientific echosounder calibrations (e.g.

Simmonds *et al.*, 1984; Foote *et al.*, 1987; Simmonds, 1990) are disconcerting.

In addition to the ping-to-ping variability, an oscillatory trend in the on-axis time-series was observed in target strength derived from EK500 and EK60 data. The magnitude of the trend was more pronounced in the EK60 data, of the order of 0.5–0.75 dB, and cycled on the order of a few minutes. Longer-term measurements were not made, but it would be useful to investigate variability on the time scale of a survey. Variability in target-strength measurements is expected, but the variability is typically

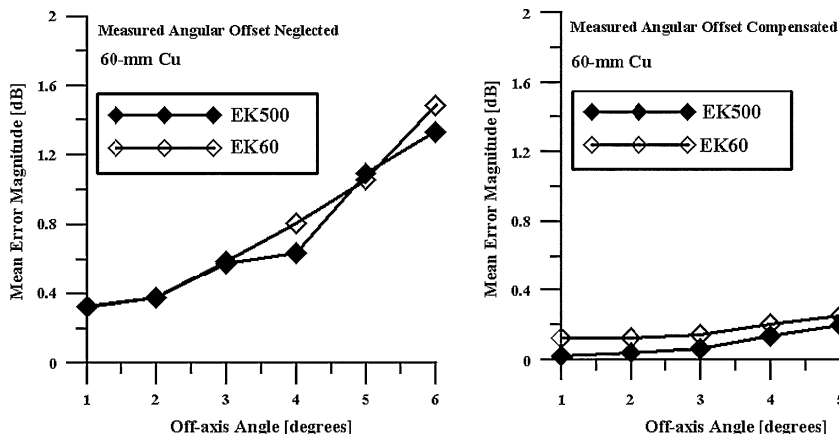


Figure 9. Mean of the absolute error between target strength based on the experimental geometry (TS) and split-beam-determined target strength (TS_{SB}) of a 60-mm-diameter copper sphere corresponding to the data in Figure 8. Left panel: split-beam compensation as determined by the echosounder without use of the measured angular offset. Right panel: split-beam compensation with use of the measured angular offset according to the regression analysis in Figure 7.

random and normally distributed, as observed in target-strength distributions from the EK500. However, observed, skewed, target-strength distributions, and larger oscillatory trends in time-series data suggest biases in EK60 target-strength measurements.

The reason for these biases is unknown, but probably lies in the electronics or digital processing internal to the EK60. For the standard 1-ms-duration transmit pulse, the sampling rate of the EK60 is about half that of the EK500. This reduced sampling rate will lead to increased variability in EK60-measured target strengths (R. Kieser, pers. comm.). The consequences are clear, however: a bias will affect the distribution of characteristic target strengths and hence conversion of measurements of acoustic density to measures of biological density.

The longer-term stability in EK60 performance remains to be established. This may be determined directly by the measurement of lengthy time-series of standard-target echoes under good conditions, indirectly by comparing EK60 performance measures among calibration exercises, or by comparing data collected during surveys.

Analyses presented in this paper used a common single-target-detection algorithm, so comparisons do not characterize the implementation of the single-target-detection algorithms in the EK500 and EK60. Rather, comparisons underscore differences in the data- and signal-processing methods of the echosounders. Measurement and simulation efforts need to be conducted to determine the sources of these inconsistencies and to develop methods to rectify these concerns. Such efforts need to be collaborative endeavours among the scientific community, echosounder manufacturers, and third-party software developers, and discussions are ongoing.

Acknowledgements

The authors thank T. R. Hammar for the construction of the transducer-mounting apparatus and general logistics, S. P. Liberatore for providing trigger signals to the rotator and switching unit, D. A. Demer for the design of the switching unit, R. Holley for construction of the switching unit, J. Condiotty for assistance with the EK60 echosounder, and R. Kieser for critical comments on the manuscript. The work was supported by National Science Foundation Grant No. OCE-0002664, the Northeast Fisheries Science Center (J. M. Jech) and the Northwest Fisheries Science Center (L. C. Hufnagle, Jr.). This is Woods Hole Oceanographic Institution contribution number 11220.

References

Andersen, L. N. 2001. The new Simrad EK60 scientific echosounder system. *Journal of the Acoustical Society of America*, 109: 2336.

- Bodholt, H., Nes, H., and Solli, H. 1989. A new echosounder system. *Proceedings of the Institute of Acoustics*, 11(3): 123–130.
- Demer, D. A., Soule, M. A., and Hewitt, R. P. 1999. A multiple-frequency method for potentially improving the accuracy and precision of *in situ* target-strength measurements. *Journal of the Acoustical Society of America*, 105: 2359–2376.
- Doherty, K. W., Hammar, T. R., and Foote, K. G. 2002. Transducer mounting and rotating system for calibrating sonars in a sea well. *Oceans 2002 MTS/IEEE Conference Proceedings*, pp. 1407–1410.
- Ehrenberg, J. E. 1979. A comparative analysis of *in situ* methods for directly measuring the acoustic target strength of individual fish. *IEEE Journal of Oceanic Engineering*, OE-4(4): 141–152.
- Foote, K. G. 1982. Optimizing copper spheres for precision calibration of hydroacoustic equipment. *Journal of the Acoustical Society of America*, 71: 742–747.
- Foote, K. G. 1983. Maintaining precision calibrations with optimal spheres. *Journal of the Acoustical Society of America*, 73: 1054–1063.
- Foote, K. G. 1986. Digital representation of split-beam-transducer beam patterns. *ICES C.M. 1986/B: 2*. 7 pp.
- Foote, K. G., Aglen, A., and Nakken, O. 1986. Measurement of fish target strength with a split-beam echosounder. *Journal of the Acoustical Society of America*, 80: 612–621.
- 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 Cooperative Research Report*, 44.
- Foote, K. G., and MacLennan, D. N. 1984. Comparison of copper and tungsten carbide spheres. *Journal of the Acoustical Society of America*, 75: 612–616.
- Foote, K. G., and Stanton, T. K. 2000. Acoustical methods. *In* *ICES Zooplankton Methodology Manual*, pp. 223–258. Ed. by R. Harris, P. Wiebe, J. Lenz, H. R. Skjoldal, and M. Huntley. Academic Press, San Diego (ch. 6).
- Gaunaurd, G. C. 1985. Sonar cross-section of bodies partially insonified by finite sound beams. *Oceanic Engineering*, OE-10: 213–230.
- Gunderson, D. R. 1993. *Surveys of Fisheries Resources*. Wiley, New York. 248 pp.
- Jech, J. M., Michaels, W., Overholtz, W., Gabriel, W., Azarovitz, T., Ma, D., Dwyer, K., and Yetter, R. 2000. Fisheries acoustic surveys in the Gulf of Maine and on Georges Bank at the Northeast Fisheries Science Center. *In* *Proceedings of the Sixth International Conference on Remote Sensing for Marine and Coastal Environments*. 1–3 May, Charleston, South Carolina, USA. Veridian ERIM International, Ann Arbor, Michigan, USA.
- Kieser, R., and Ona, E. 1988. Comparative analysis of split-beam data. *ICES C.M. 1988/B: 44*. 9 pp. + 7 Figures.
- MacLennan, D. N. 1990. Acoustical measurement of fish abundance. *Journal of the Acoustical Society of America*, 87: 1–15.
- Medwin, H., and Clay, C. S. 1998. *Fundamentals of Acoustical Oceanography*. Academic Press, New York. 712 pp.
- Ona, E., and Vestnes, G. 1985. Direct measurements of equivalent beam angle on hull-mounted transducers. *ICES C.M. 1985/B: 43*. 6 pp. + 5 figs.
- Reynisson, P. 1990. A geometric method for measuring the directivity of hull-mounted transducers. *Rapports et Procès-Verbaux des Réunions du Conseil International pour l'Exploration de la Mer*, 189: 176–182.
- Reynisson, P. 1998. Monitoring of equivalent beam angles of hull-mounted acoustic survey transducers in the period 1983–1995. *ICES Journal of Marine Science*, 55: 1125–1132.
- Simmonds, E. J. 1990. Very accurate calibration of a vertical echosounder: a five-year assessment of performance and accuracy. *Rapport et Procès-Verbaux des Réunions du Conseil International pour l'Exploration de la Mer*, 189: 183–191.

- 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. *Proceedings of the Institute of Acoustics*, 6(5): 129–138.
- SIMRAD. 2001. Simrad EK60 Scientific Echosounder Instruction Manual — Base Version. Simrad AS, Horton, NO. 246 pp.
- Urick, R. J. 1983. *Principles of Underwater Sound*, 3rd edn. McGraw-Hill, New York. 423 pp.