Calibration methods for two scientific multibeam systems

Egil Ona, Valerie Mazauric, and Lars Nonboe Andersen

Ona, E., Mazauric, V., and Andersen, L. N. 2009. Calibration methods for two scientific multibeam systems. – ICES Journal of Marine Science, 66: 1326–1334.

The new Simrad scientific multibeam systems, the MS70 sonar and the ME70 echosounder, each transmit over many electronically formed beams with centre frequencies spanning from 70 to 120 kHz. Calibrations of these systems are therefore more complex than for conventional split-beam echosounder systems. Two large tungsten-carbide spheres (75 and 84 mm diameter) were designed and manufactured to facilitate accurate field calibrations over the entire operational bandwidth. These are heavy and therefore stable when suspended beneath a ship, and have target strengths much larger than those of biological targets potentially within the measurement volume. This paper presents procedures for calibrating each system in the field and the results from two such experiments. Detailed inspections of the results for individual beams indicate that minor adjustments in the described procedures might further improve the reported calibration accuracy.

Keywords: acoustic surveys, calibration, echosounder, ME70, MS70, multibeam, sonar.

Received 8 August 2008; accepted 18 February 2009; advance access publication 8 May 2009.

E. Ona: Institute of Marine Research, PO Box 1870 Nordnes, NO 5817 Bergen, Norway. V. Mazauric: Ifremer—Paris, Direction des Moyens et Opérations Navals, 155 rue Jean-Jacques Rousseau, 92138 Issy-Les-Moulineaux, France. L. N. Andersen: Simrad, PO Box 111, NO 3191 Horten, Norway. Correspondence to E. Ona: tel: +47 55 23 84 55; fax: +47 55 23 85 31; e-mail: egil.ona@imr.no.

Introduction

Acoustic surveys for pelagic fish stock assessment mainly use vertical-beam echosounders (VBEs). The standard method for abundance estimation is based on the integration of the backscattered acoustic signal. Several physical factors cause potential uncertainties. One of the most serious is vessel avoidance (Olsen *et al.*, 1983; Misund, 1990; Gerlotto and Fréon, 1992; Vabø *et al.*, 2002; Gerlotto *et al.*, 2004; Ona *et al.*, 2007). Noise and other vessel-associated stimuli from the survey vessel are sensed by the fish long before the VBE has measured their abundance. Consequently, the acoustically estimated density is potentially biased, usually negatively, by horizontal movements and diving of the fish. The limited horizontal coverage when using single, narrow beams (e.g. 7–10°) makes VBE observations especially susceptible to bias from horizontal movements of fish schools, and, at best, they only sample an arbitrary cross section of isolated schools (Korneliussen *et al.*, 2008). VBEs also fail to detect species residing close to the seabed and located inside the acoustic "dead zone" (Ona and Mitson, 1996), whose extent depends on the seabed depth and topography, and the echosounder beam width and pulse duration.

This paper describes two, new multibeam systems (Simrad MS70 sonar and Simrad ME70 echosounder) that were specifically designed to mitigate some of these problems and facilitate measurements of pelagic fish schools close to the sea surface or to the seabed. They also measure in a larger observation volume than traditional sonars and echosounders (Trenkel *et al.*, 2008). The concepts of observing and measuring an entire school or even "an entire school in one ping" were conceived during the early planning stage of the systems. Both systems are based on the same innovative design, with a transducer matrix of 800 individually controlled elements operating during both transmission and reception to achieve notable side-lobe suppression, for example, to −70 dB, two-way, depending on the beam configuration.

MS70 specifications

The MS70 provides a three-dimensional observation from each ping, each potentially imaging one or more entire fish school. The MS70 transmits using a technique called "Frequency Rotated Sector Transmission". The operational bandwidth from 70 to 120 kHz is divided into 20 sub-bands. The system transmits at the centre frequency of each sub-band, insonifying 20 horizontal sectors that are narrow in the vertical plane and 60° wide on the port side of the vessel. During reception, 25 narrowbeams are formed for each sector, resulting in 500 narrow receiving beams.

ME70 specifications

The ME70 insonifies a vertical swathe through the water column with each ping and images a three-dimensional volume by combining data from successive pings. The system transmits using a similar scheme, called "Frequency Rotated Directional Transmission".

Common features

Both systems have a "blind zone" in front of the transducer, in the direction of the beams, with a range corresponding to the duration of one pulse × the number of transmissions. To reduce this blind zone, up to four beams (ME70) or four sectors (MS70) can be transmitted simultaneously. These systems complement the commonly used multifrequency VBEs because they allow for a high degree of user-controlled flexibility, at the same time offering refined angular resolution in a wider athwartship sector.

Multibeam calibrations

Calibrations of acoustic-survey equipment must be conducted at sea, several times a year. During the calibration experiments, the survey vessel is commonly anchored or fixed to the shore in a sheltered area. Large standard targets provide large echoes relative to the background reverberation and any individual fish present in the measurement volume by chance. For these experiments, two large spheres (75 mm diameter, 3.3 kg and 84 mm diameter, 4.6 kg diameter), made from tungsten carbide (WC) with a 6% cobalt binder, were designed and constructed to span the operational bandwidth complementarily. The expected values of target strength (*TS*; dB re 1 m^2) were computed for these spheres (Foote, 2006) by weighting their scattering spectra by the receive bandwidths in each beam or sector (Table 1). The material properties assumed in these calculations were checked by wideband measurements in a tank at the Physics Laboratory of the University of Bergen (H. Hobek, unpublished data). This paper describes the first complete field calibrations of the MS70 and ME70 using these two spheres.

Methods

System calibrations

The equations used in the two multibeam systems for estimating *TS* and S_v are the same as those used for split-beam VBEs:

$$TS = 10\ \log(P_r) + 40\ \log(r) + 2\alpha r - 10\ \log\left[\frac{P_t\lambda^2}{16\pi^2}\right] - 2G(\theta,\ \phi), \tag{1}$$

and

$$S_v = 10\ \log(P_r) + 20\ \log(r) + 2\alpha r - 10\ \log\left[\frac{P_t\lambda^2 c}{32\pi^2}\right] - 2G_0 - (10\ \log\tau_{\mathrm{nom}} + 2S_{a,\mathrm{corr}}) - 10\ \log\psi, \tag{2}$$

where P_r is the power of the received signal measured at the transducer terminal (W), P_t the power of the transmitted signal referred to the transducer terminal (W), G the transducer gain in the target direction (θ, Φ; dB), G_0 the on-axis transducer gain (dB), r the range of the target sensed by the transducer (m), c the sound speed (m s^{-1}), α the absorption coefficient of the medium (Bel m^{-1}), λ the wavelength (m), ψ the equivalent beam angle (sr), τ_{nom} the nominal pulse duration (s), and $S_{a,\mathrm{corr}}$ is the integration correction (dB).

The sum of τ_{nom} and $S_{a,\mathrm{corr}}$ equals the effective pulse duration. From both Equations (1) and (2) it is evident that accurate *TS* and S_v measurements require accurate estimates of many parameters (i.e. P_r, r, α, P_t, θ, ϕ, λ, ψ, c, $S_{a,\mathrm{corr}}$, G_0, and $G(\theta,\ \phi)$). Some of these parameters depend on the environment. However, as for conventional split-beam echosounders (Simrad, 1996), the goals of the MS70 and ME70 calibrations are to estimate $G(\theta,\ \phi)$, G_0, and $S_{a,\mathrm{corr}}$ for each of the numerous beams.

Although many of the following procedures are identical to those used to calibrate modern split-beam VBEs, some features of the two multibeam systems ease the process of calibrating their individual beams. First, to facilitate the split-beam measurements of target position with the sonar beams, each has four overlapping, electronically synthesized beams. This allows measurements of the target position in the entire observation volume relative to the transducer face.

Table 1. Theoretical *TS* for the standard spheres computed for the centre frequencies and bandwidths (CW) of each sector or beam, using measured sound speed, and the respective pulse durations of 2.048 and 1.024 ms for the MS70 and ME70 systems; sector and beam steering are displayed.

MS70				ME70			
Sector centre frequency (Hz)	Sector steering (°)	75 mm (dB)	84 mm (dB)	Beam centre frequency (Hz)	Beam steering (°)	75 mm (dB)	84 mm (dB)
111 075	−45.0	−34.12	–	71 943	−41.5	−33.49	–
109 225	−42.6	−34.73	–	76 449	−35.3	−33.18	–
107 375	−40.3	–	−31.20	80 956	−29.9	−33.95	–
105 525	−37.9	–	−31.75	85 462	−25.1	−34.23	−32.64
103 675	−35.5	–	−31.78	89 969	−20.7	–	−32.29
101 825	−33.2	−33.61	–	94 476	−16.6	−33.66	–
99 975	−30.8	−33.36	–	98 982	−12.8	−33.18	–
98 125	−28.4	−33.15	–	103 489	−9.2	–	−31.63
96 275	−26.1	−33.44	–	107 995	−5.8	–	−31.39
94 425	−23.7	−33.80	–	112 502	−2.6	−34.23	–
92 575	−21.3	−33.62	–	118 057	0.4	−32.69	−32.51
90 725	−19.0	−33.37	–	114 755	3.5	−32.92	–
88 875	−16.6	–	−32.30	110 249	6.7	−34.53	–
87 025	−14.2	–	−32.20	105 742	10.0	–	−31.66
85 175	−11.8	–	−32.67	101 235	13.5	−33.31	−32.59
83 325	−9.5	−33.78	–	96 729	17.3	−33.51	–
81 475	−7.1	−33.72	–	92 222	21.3	−33.40	−32.73
79 625	−4.7	−34.06	–	87 716	25.6	–	−32.28
77 775	−2.4	−33.70	–	83 209	30.3	−33.69	−32.52
75 925	0.0	−33.09	–	78 702	35.6	−33.70	–
–	–	–	–	74 196	41.6	−33.14	–

Second, detailed tank measurements of the MS70 and ME70 beam patterns indicate virtually perfect matches to their theoretical designs. This allows theoretical considerations, rather than measurements, to be used for estimating beam width, shape, and ψ for each beam. Therefore, system calibrations for TS measurements involve the straightforward procedure of guiding the sphere through each of the beams, measuring its TS, correcting for beam gain, and adjusting G_0 to compensate for the difference between the measured and the theoretical TS of the sphere. Similarly, to calibrate the systems for measurements of S_v, the integrated echo energy from the sphere is measured for each target location, corrected for beam gain, and compared with the theoretical value.

For both the MS70 and ME70 systems, each beam is treated as a split beam and its total power budget, as described by Equations (1) and (2), is estimated by the instrument. For example, for each element in the array, account must be taken of changes in the beam pattern vs. frequency, c and λ. Ideally, the nominal G_0 for each beam should be predicted correctly by theory, and minor adjustments according to the calibration results should be random across the beams. If not, some of the parameters have not been estimated correctly or the system is not operating correctly. Therefore, if required, more elaborate split-beam calibrations can be performed for individual beams. In this case, non-linear regression is used to estimate also the half-power beam widths in the alongship and athwartship directions, as well as the beam offsets, i.e. the difference between the electrical beam axis (zero-phase difference) and the estimated acoustic axis in the same directions (Simrad, 1996), from all the measured data within each beam.

Following data collection, the measurements for each beam are compared with the theoretical values for the sphere, averaged over the bandwidth for that particular beam. Calibrated values for $G(\theta, \phi)$, G_0, and $S_{a,\mathrm{corr}}$, defined from any differences between measurement and theory, are input to the system software.

MS70 calibration

The MS70 (Figure 1a) was calibrated on RV “G. O. Sars”, anchored bow and stern, in good weather conditions, at Sandviksflaket, outside Bergen harbour, on 7 February 2007. Before the calibration, sea temperature (T) and salinity vs. depth were measured, from which the c in the sonar observation volume was estimated (Mackenzie, 1981). Using the mean $c = 1487\ \mathrm{m\ s^{-1}}$, TS values were computed for each sphere at the centre frequencies and bandwidths used in each beam and sector (Table 1). From the depth of the transducer (8–25 m), the ranges of T and c were 8–9°C and 1485–1489 $\mathrm{m\ s^{-1}}$, respectively. A value of $c = 1485\ \mathrm{m\ s^{-1}}$ was entered into the calibration configuration and used to calculate the beam elements, weightings, and widths, as well as ψ, α, nominal G_0, and r.

In succession, each sphere was suspended by monofilament nylon lines and positioned at ~13 m from the transducer, using two 6-m long rods extending outward from the port side of the vessel and two hand winches (Figure 2a). From this two-point rig, each sphere was moved slowly across the entire 500-beam array, ensuring multiple detections in each beam. A large number of detections was made in a few of the beams.

During calibration of the MS70, the 75-mm diameter sphere was used for 14 sectors and the 84-mm diameter sphere was used for the remaining six sectors. The smaller sphere was first guided through the 14 sectors indicated in Figure 3a, moving the sphere slowly in the alongship direction at a constant depth. The sonar detected the target several times, as it passed through each beam, each time graphing the target position and displaying its measured TS, range, and angular positions within the beam. After the 14 sectors had been covered in this way, the calibration program was stopped, and the sphere was recovered and replaced by the larger sphere. The larger sphere was then guided through the remaining six sectors in a similar manner. Using manual winches, the entire 500-beam calibration lasted ~3 h.

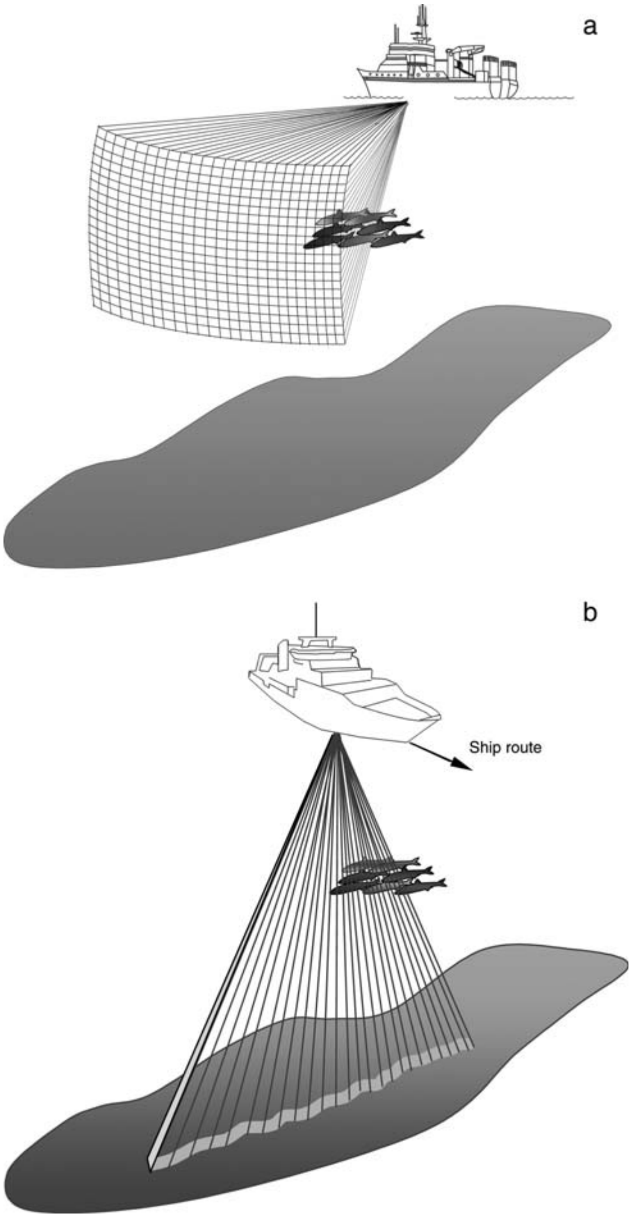

Figure 1. (a) Observation volume of the Simrad MS70 multibeam sonar, illustrating the 25 × 20 beam configuration, permitting three-dimensional (space) and four-dimensional (space and time) measurements of fish schools. (b) Observation volume of the ME70 multibeam echosounder permitting two- and three-dimensional measurements of fish schools and direct comparisons with single- and split-beam echosounder systems.

ME70 calibration

The ME70 (Figure 1b), configured with a user-selectable beam and frequency combination, was calibrated on RV “Thalassa”,

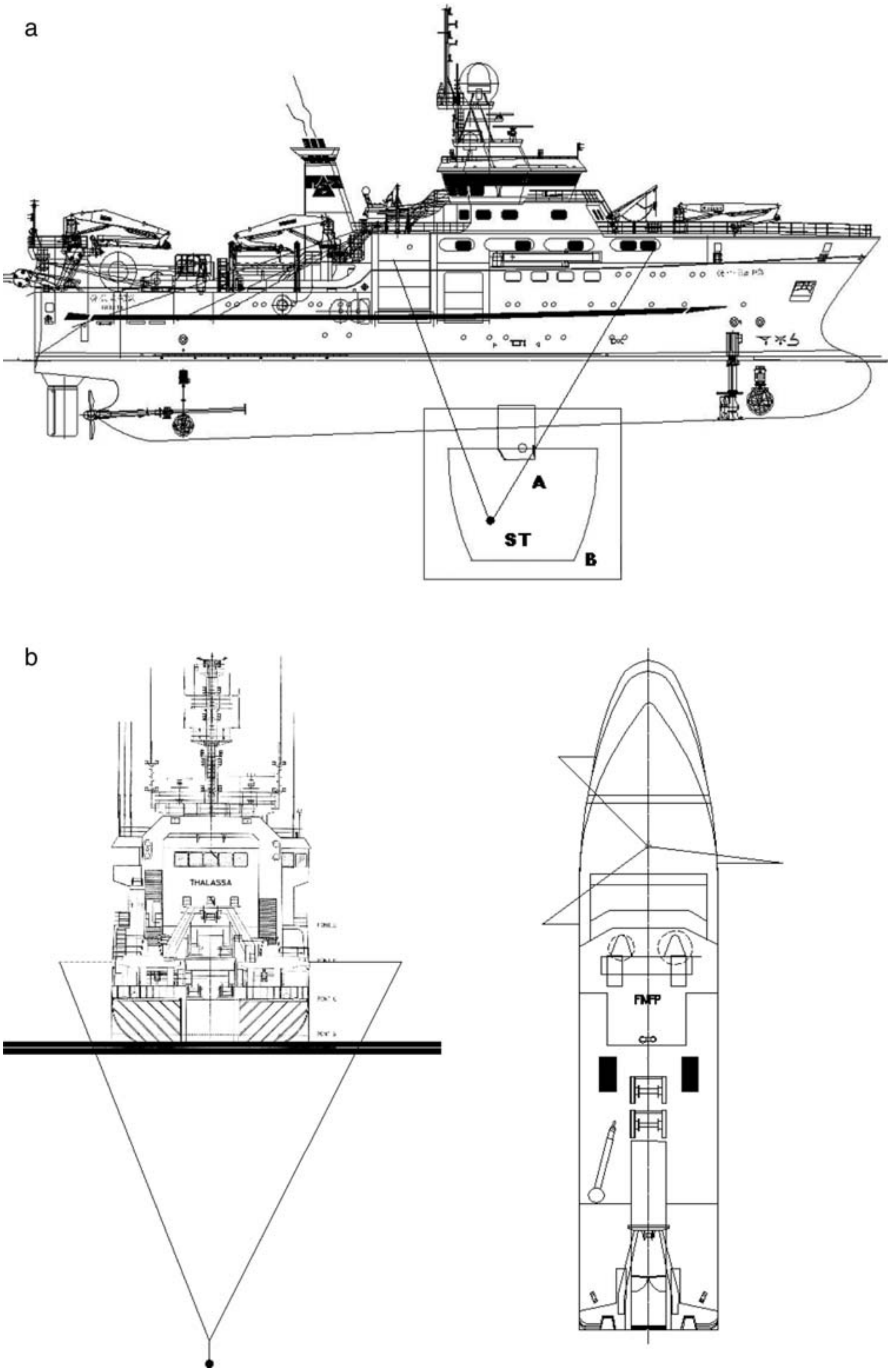

Figure 2. (a) The two-point calibration apparatus used on RV "G. O. Sars" for guiding the standard sphere (ST) through a section of the observation volume of the MS70; the MS70 transducer is mounted on the port side of the port drop keel; the ST-guidance area is indicated. (b) For the ME70 on RV "Thalassa", a three-point apparatus with 4- and 7-m long rods was used to guide the ST.

anchored from the bow, in variable weather in the Bay of Douarnenez (Brittany) on 17 March 2008. Three motorized winches controlled the monofilament lines attached to the spheres. Three rods extending 7 m outward from the ship were used to position the spheres in the outer beams (Figure 2b).

Temperature and salinity were measured with a thermosalinograph sampling at the transducer depth. The estimated c at 10°C (1488 m s^{-1}) was input into the ME70 to calculate the beam elements, weightings and widths, as well as values for ψ, α, nominal G_0, and r. During surveys aboard RV "Thalassa", c is

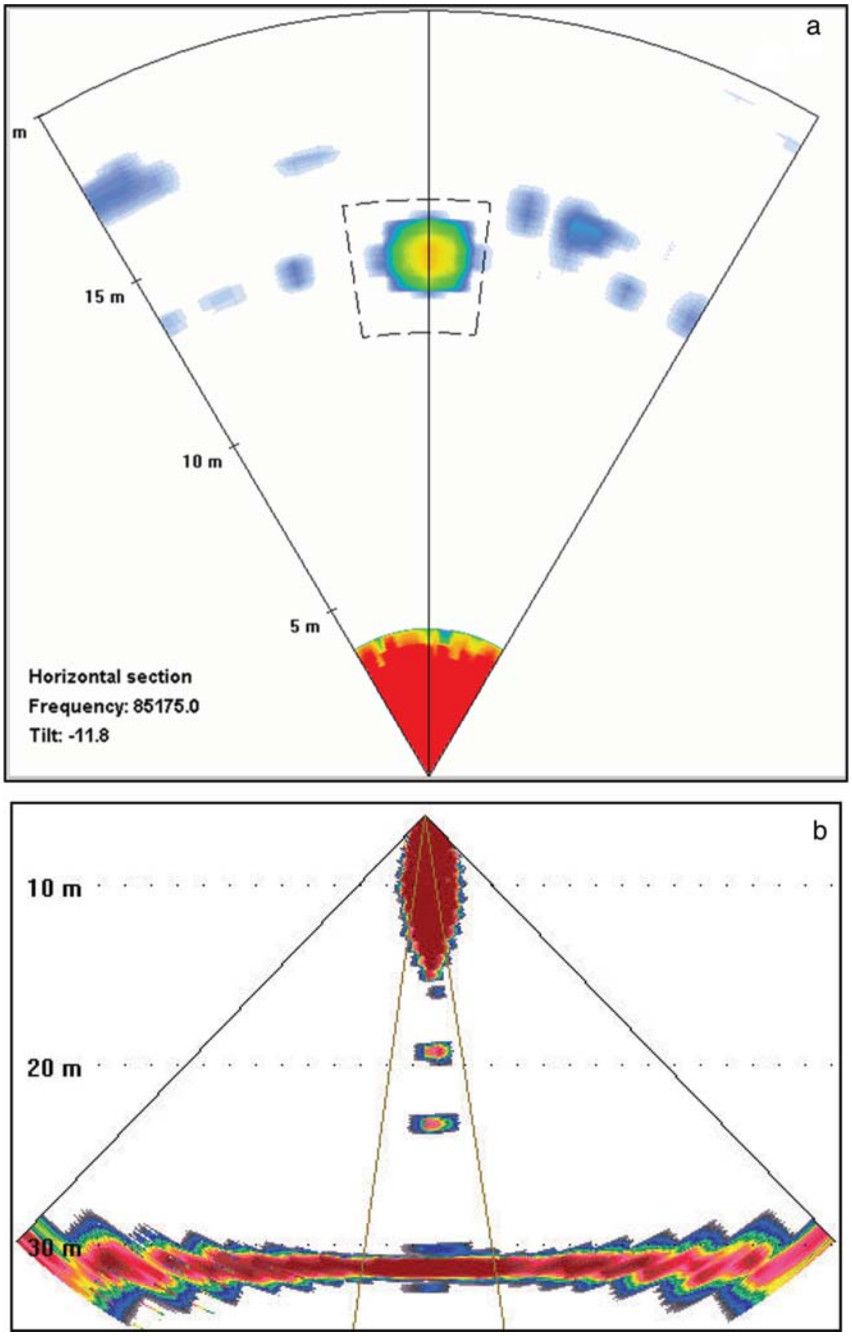

Figure 3. (a) Detected echoes of the 75-mm standard sphere in one of the horizontal sectors of the MS70 sonar; the range to the target is 13.3 m, and the full observation range during the calibration is 20 m; colour indicates echo strength. (b) Detected echo of the 75- and 84-mm spheres using the ME70 21-beam configuration.

adjusted for significant changes in ambient conditions, whereas the beam weights and steering are held constant according to the results of the last calibration.

To expedite the ME70 calibration, both spheres were deployed together, one above the other with a vertical separation of 4 m (Figure 3b). This is not recommended, however, because the presence of the upper sphere can affect the echo from the lower one (K. Foote, pers. comm.; Ona and Svellingen, 1998). To minimize the potential effects of shadowing and forward-scattering, the 75-mm diameter sphere, used to calibrate the near-vertical beams, was suspended above the 84-mm diameter sphere, used to calibrate the outer beam. The effectiveness of this remedy must be evaluated by comparing results from experiments using two spheres deployed concurrently vs. sequentially. Inclement weather made it difficult to position the spheres in the outer beam (i.e. >30°). In good weather conditions, the 21-beam configuration can be calibrated in ~1 h.

Results

MS70 results

The MS70 calibration included 15 090 *TS* measurements in 500 beams, averaging ~30 beam^{-1}. Some of the beams were inspected in more detail, with up to 192 accepted measurements. In this first field trial, the mean adjustment to gain for all beams of the MS70 was 0.45 dB. The gain adjustments were highly correlated between neighbouring beams, both horizontally and vertically (Figure 4a and b). The gain adjustments were largest for the most steered, outer beams of the MS70 array. This was especially true for the beams in the bottom of the array, where the gain adjustments slightly exceeded 1 dB.

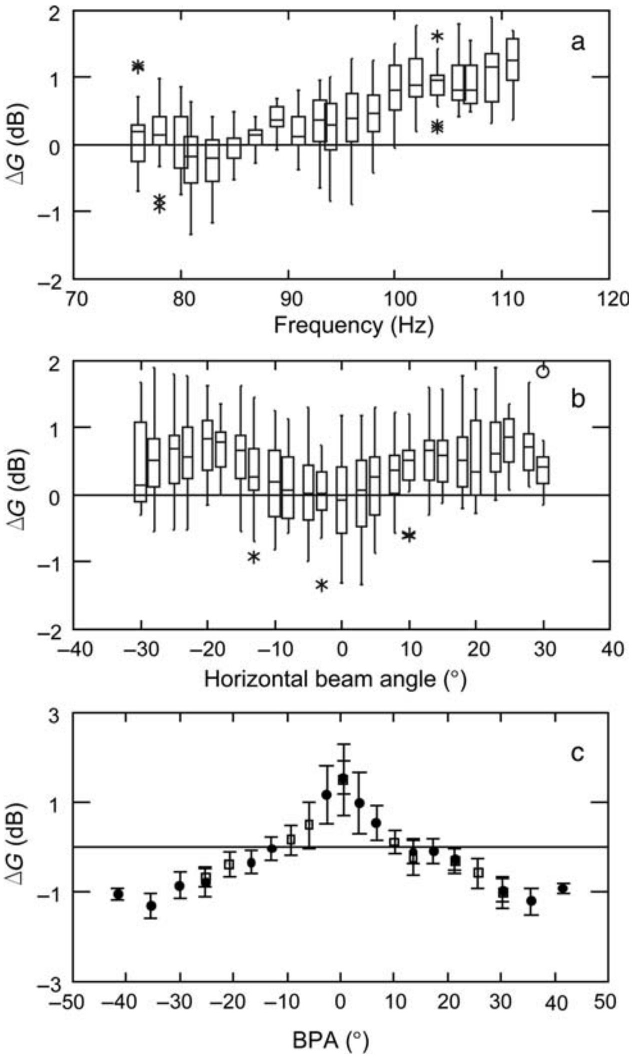

Figure 4. Gain corrections in the two sonars using the new calibration spheres; different spheres were used to calibrate each sector, as presented in Table 1. (a) The mean gain corrections for the MS70 across all sectors at each frequency, including beam-to-beam variability; the box plot displays mean, s.d., and maximum difference. (b) The gain corrections across all vertical beams, at all horizontal pointing angles, for the MS70, including beam-to-beam variability. (c) The mean gain adjustment in all 21 beams of the ME70 as a function of beam-pointing angle (BPA), including the s.d. of the measured sphere *TS*. In the beams where both spheres could be used, data from the 75-mm (black dots) and 84-mm (square dots) diameter spheres are displayed along with their standard deviations. For this "inverted-V" configuration, the high frequencies are in the centre beams, gradually reducing towards each side.

A larger number of *TS* measurements were made in a few beams to model their beam patterns and estimate their G_0 and beam offsets. One examined beam (number 475, at $x = 0$ and $y = -30°$) had maximum steering in the horizontal direction (Figure 5c and d). Even for this worst-case beam, the necessary adjustment to G_0 was only −0.1 dB, following a full split-beam calibration (Figure 5d), where the effects of the offsets were removed.

ME70 results

The ME70 calibration included 3526 *TS* measurements in 21 beams. Inclement weather during this calibration made it difficult to obtain acceptable measurements in the outer beams (e.g. there were <20 *TS* measurements in beams at ±41.5° relative to vertical). For the 21 beams of the ME70, the mean adjustment to gain was −0.12 dB. The gain adjustments were larger for the higher vs. the lower frequencies (Figure 4c).

Because the *TS* spectra for the two spheres overlapped in a few measurement bandwidths, the gain adjustments estimated for these beams were compared. The mean gain adjustment for the vertical beam, measured with the 84-mm diameter sphere, was 1.54 dB. This was negligibly different from the 1.50 dB measured with the 75-mm diameter sphere. However, as expected, the gain adjustment was more stable for the measurements made with the upper, smaller sphere (s.d. = 0.37 dB) than with the lower, larger sphere (s.d. = 0.80 dB).

One of the ME70 beams (92 kHz, −21°) was calibrated more thoroughly (Figure 5a and b), using the 84-mm diameter sphere. The results indicate that the estimated beam axis was very close to the actual beam axis, rendering additional non-linear fitting of the beam patterns superfluous. Moreover, the residuals were evenly distributed across the beam and of the magnitude generally expected for split-beam VBEs operating near this frequency.

Discussion

Traditional fishery sonars have been used both qualitatively and quantitatively for many years (Misund *et al.*, 1995; Gerlotto *et al.*, 1999), but they have often suffered from low resolution and lacking data output and calibration procedures. Therefore, the new multibeam systems were designed to include high-quality, raw-data output, large observation volumes, and procedures for accurate calibrations. The method of calibrating with standard targets (Foote *et al.*, 1987) routinely used for split-beam VBEs was implemented for both the ME70 and MS70. The ability to calibrate each beam thoroughly with frequencies ranging from 70 to 120 kHz is a distinct improvement on earlier calibrations of multibeam systems (Cochrane *et al.*, 2003; Melvin *et al.*, 2003; Foote *et al.*, 2005).

These results indicate, in practical terms, that if surveys were conducted with the MS70 and ME70 systems, without calibration corrections, the systematic errors in the resulting acoustically derived density estimates would be approximately +20% and −5%, respectively, i.e. twice the gain adjustments, converted to the linear domain. The reason for this could be that it is more difficult to compute nominal gains for 500 beams than for 21 beams.

The gain adjustments for both systems were larger for the higher frequencies than for the lower frequencies (Figure 4a–c). This result indicates that the initial modelling of beam steering

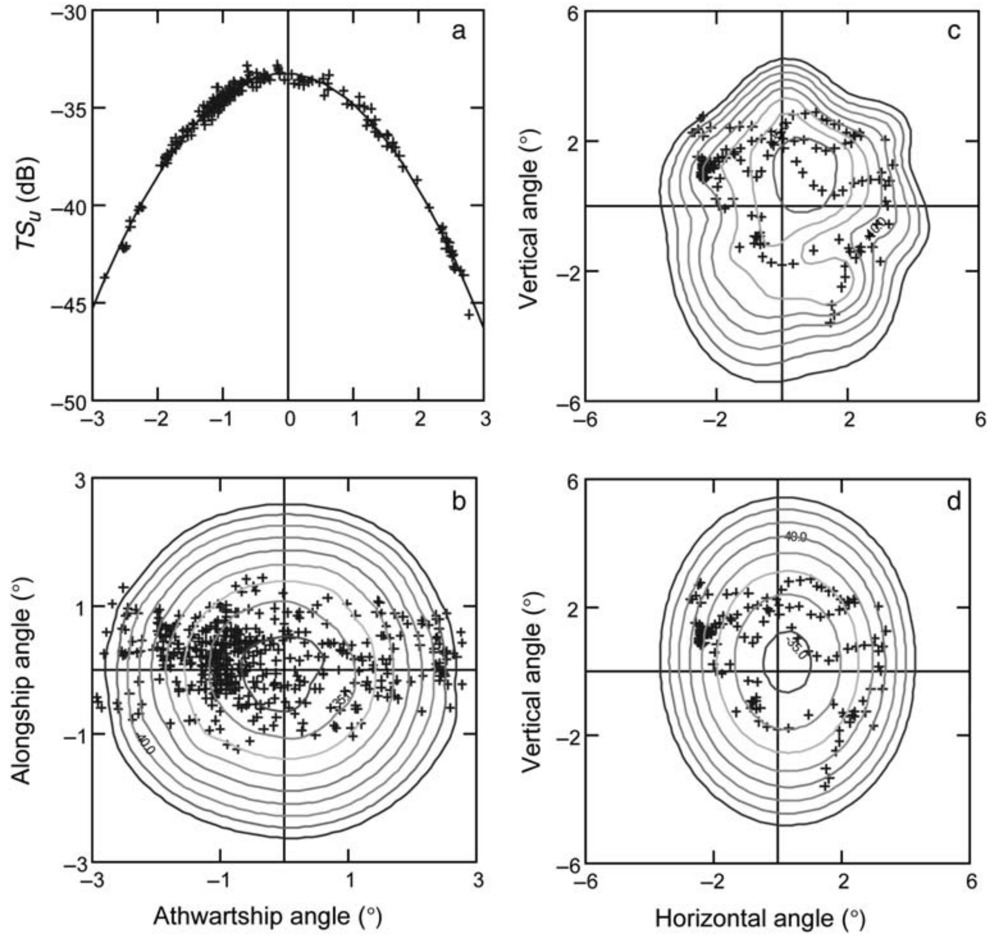

Figure 5. (a, b) Inspections of beam 16 (92 kHz) of the ME70 measured with the 84-mm sphere, demonstrating good agreement and minimal offset between the theoretical and measured beam patterns; TS_u is measured *TS* before beam compensation. (c and d) Inspections of one of the most steered beams of the MS70, number 475, with good agreement between beam patterns, but a large offset. Displayed are the raw data (c) and the result of the non-linear regression of the same data (d).

and frequency rotation was not wholly adequate and could benefit from further refinements.

Because the *TS* measurements were compensated for beam gain, the observed variability in gain adjustments could have been the result of stochastic variability of echoes from a sphere in a fixed position, small discrepancies between the acoustic vs. modelled beam centres, or errors in split-beam phase-angle measurements. The latter two can contribute large errors in estimates of *TS*. To mitigate such potential problems in conventional split-beam VBEs (e.g. Simrad EK500 and EK60), the beam axis is more accurately modelled with two beam offsets.

Large and stable standard targets are important for ensuring a high signal-to-noise ratio during calibration. The trials using very large WC spheres for calibrating the new MS70 and ME70 systems have indicated that it is possible to achieve calibration precisions for the entire 500 or 21 beam arrays close to the precisions expected for conventional split-beam VBEs. The time required for a complete calibration is tolerable, and the work may be performed at the usual calibration sites. The observed spread in the compensated *TS*, after gain adjustment, is slightly higher than for comparable scientific split-beam echosounders at similar frequencies. In part, this is the result of non-ideal beam compensation, especially in highly steered beams. The larger gain adjustments in the more steered beams cannot be explained. Higher variability was also observed in measurements made with the outer beams and will be investigated further. Time permitting, better coverage of individual beams is needed to calibrate these systems more thoroughly and to refine and perhaps finalize their calibration protocols. If future experiments confirm that the split-beam accurately measures the physical angles to the target, extra refinements could be implemented in future calibration procedures.

Further work will include detailed studies of individually inspected beams and verification of the spectral responses of the 75- and 84-mm diameter WC spheres. As used, they simplified the procedures and improved the precisions of the sonar calibrations compared with having a smaller standard target. At this stage, when the sonar and echosounders are properly calibrated in the seawater of the survey, or in similar waters, the uncertainty arising from the calibrations should, as in earlier studies (Aglen, 1994; Simmonds and MacLennan, 2005), be insignificant. Løland *et al.* (2007) investigated the total uncertainty of a typical herring survey conducted with calibrated, split-beam VBEs. Decomposing the total uncertainty, they concluded that the major components were survey-stock coverage, vessel avoidance, trawl sampling and ageing, *TS*, and acoustic extinction, listed in

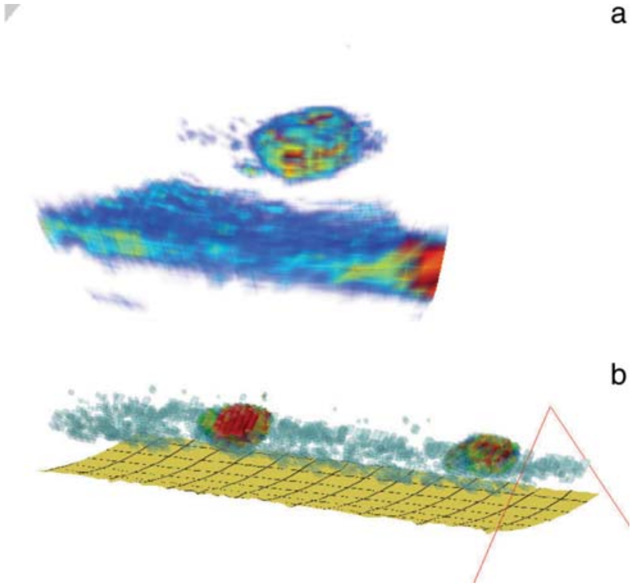

Figure 6. (a) A single school of sprat at Uggedal, south of Bergen, recorded with the MS70 system; the horizontal, blue carpet under the fish school is the echo from the seabed. (b) Sardine schools feeding in plankton layers recorded in shallow water with the ME70 system. The colour scales indicate the magnitude of the calibrated S_v: brighter colours correspond to larger values.

order of importance. If the acoustic systems are properly calibrated according to internationally accepted procedures before and, preferably, also after a survey, the uncertainty component from the calibration is probably going to be very small compared with the total uncertainty. We would claim that this is also a valid assumption for calibrated ME70 and MS70 systems.

The next challenges for multibeam-sonar surveys will be to establish accurate models of mean *TS* vs. incidence angle for a variety of fish species and to estimate for each school their orientation relative to the acoustic beams. The reason is that most pelagic fish are directional scatterers at the operating frequency of the sonars and the angles of incidence will greatly modulate their reflectivity (Cutter and Demer, 2007). Therefore, it is extremely important to obtain ancillary measures of mean swimming direction (Misund and Aglen, 1992) and its variability within the measured schools. Towards this goal, algorithms are being implemented in the MS70 and other multibeam sonars to track school movements in geographic coordinates between successive detections. Even with such developments, however, uncertainty regarding acoustic-incidence angles could ultimately limit the use of multibeam for fish-abundance estimations. Nevertheless, if fish *TS* can be accurately modelled vs. all potentially encountered angles of incidence and *in situ* fish orientations relative to the acoustic beams can be accurately estimated, biomass estimations using multibeam sonars may be no more complicated than current VBE methods.

Finally, the potential of the calibrated multibeam sonars is illustrated for a single school of sprat at Uggedal, south of Bergen, recorded by the MS70 (Figure 6a) and sardine schools feeding in plankton layers in the English Channel, recorded using the ME70 system (Figure 6b). These illustrate the beginning of a new era in acoustic surveys of fish schools.

Acknowledgements

The team of scientists involved in the development of the two new sonars at IMR, Ifremer, and Simrad are all thanked for their contributions to the SMS project. Three anonymous reviewers and David Demer are thanked for their valuable comments on the paper and their good suggestions for improving its readability.

References

Aglen, A. 1994. Sources of error in acoustic estimation of fish abundance. *In* Marine Fish Behaviour Related to Capture and Abundance Estimation, pp. 107–133. Ed. by A. Fernø, and S. Olsen. Fishing News Books, Oxford. 221 pp.

Cochrane, N. A., Li, Y., and Melvin, G. D. 2003. Quantification of a multibeam sonar for fisheries assessment applications. Journal of the Acoustical Society of America, 114: 745–758.

Cutter, G. R., and Demer, D. A. 2007. Accounting for scattering directivity and fish behaviour in multibeam-echosounder surveys. ICES Journal of Marine Science, 64: 1664–1674.

Foote, K. G. 2006. Optimizing two targets for calibrating broadband multibeam sonar. Proceedings from the IEEE, OCEANS 2006 Conference, Boston, doi: 10.1109/OCEANS.2006.306944: 1–4.

Foote, K. G., Chu, D., Hammar, T. R., Baldwin, K. C., Mayer, L. A., Hufnagle, L. C., and Jech, J. M. 2005. Protocols for calibrating multibeam sonar. Journal of the Acoustical Society of America, 117: 2013–2027.

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, 144. 69 pp.

Gerlotto, F., Castillo, J., Saavedra, A., Barbieri, M. A., Espejo, M., and Cotel, P. 2004. Three-dimensional structure and avoidance behaviour of anchovy and common sardine schools in central southern Chile. ICES Journal of Marine Science, 61: 1120–1126.

Gerlotto, F., and Fréon, P. 1992. Some elements on vertical avoidance of fish schools to a vessel during acoustic surveys. Fisheries Research, 14: 251–259.

Gerlotto, F., Soria, M., and Fréon, P. 1999. From two dimensions to three: the use of multibeam sonar for a new approach in fisheries acoustics. Canadian Journal of Fisheries and Aquatic Sciences, 56: 6–12.

Korneliussen, R. J., Diner, N., Ona, E., Berger, L., and Fernandes, P. G. 2008. Proposals for the collection of multifrequency acoustic data. ICES Journal of Marine Science, 65: 982–994.

Løland, A., Aldrin, M., Ona, E., Hjellvik, V., and Holst, J. C. 2007. Estimating and decomposing total uncertainty for survey-based abundance estimates of Norwegian spring-spawning herring. ICES Journal of Marine Science, 64: 1302–1312.

Mackenzie, K. V. 1981. Nine-term equation for sound speed in the oceans. Journal of the Acoustical Society of America, 70: 807–812.

Melvin, G. D., Cochrane, N. A., and Li, Y. 2003. Extraction and comparison of acoustic backscatter from a calibrated multi- and single-beam sonar. ICES Journal of Marine Science, 60: 669–677.

Misund, O. A. 1990. Sonar observations of schooling herring: school dimensions, swimming behaviour, and avoidance of vessel and purse seine. Rapports et Procès-Verbaux des Réunions du Conseil International pour l'Exploration de la Mer, 189: 135–146.

Misund, O. A., and Aglen, A. 1992. Swimming behaviour of fish schools in the North Sea during acoustic surveying and pelagic trawl sampling. ICES Journal of Marine Science, 49: 325–334.

Misund, O. A., Aglen, A., and Frønæs, E. 1995. Mapping the shape, size, and density of fish schools by echo integration and a high-resolution sonar. ICES Journal of Marine Science, 52: 11–20.

Olsen, K., Angell, J., and Løvik, A. 1983. Quantitative estimations of the influence of fish behaviour on acoustically determined fish abundance. FAO Fisheries Report, 300: 131–138.

Ona, E., Godø, R., Handegard, N. O., Hjellvik, V., Patel, R., and Pedersen, G. 2007. Silent research vessels are not quiet. Journal of the Acoustical Society of America, 121: EL145.

Ona, E., and Mitson, R. B. 1996. Acoustic sampling and signal processing near the seabed: the deadzone revisited. ICES Journal of Marine Science, 53: 677–690.

Ona, E., and Svellingen, I. 1998. Improved calibration of split-beam echosounders. ICES FAST WG document, La Coruna, Spain, April 1998.

Simmonds, E. J., and MacLennan, D. 2005. Fisheries Acoustics; Theory and Practice, 2nd edn. Blackwell Science, Oxford. 437 pp.

Simrad Norge 1996. Simrad EK500 Scientific Echosounder. Instruction Manual, P2172E.

Trenkel, V. M., Mazauric, V., and Berger, L. 2008. The new fisheries multibeam echosounder ME70: description and expected contribution to fisheries research. ICES Journal of Marine Science, 65: 645–655.

Vabø, R., Olsen, K., and Huse, I. 2002. The effect of vessel avoidance of wintering Norwegian spring spawning herring. Fisheries Research, 58: 59–77.

doi:10.1093/icesjms/fsp125