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STANDARD CALIBRATION OF ECHO SOUNDERS AND INTEGRATORS WITH OPTIMAL COPPER SPHERES

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ABSTRACT

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Calibration of fisheries echo sounders and integrators by means of optimal copper spheres is reviewed. The standard procedure is elaborated. Maintenance of 0.1 dB precision is described for a wide range of temperatures and for untuned equipment. The method is illustrated by reference to a calibration exercise of R/V "Michael Sars". The long-term stability of quoted, cumulative calibration results for the same vessel witnesses to the reliability and precision of the method.

INTRODUCTION

In essence, calibration of hydroacoustic equipment by spherical targets is simple. The target is placed at a known position in the transducer beam, ensonified, and the properties of the echo related to the known scattering characteristics of the target. Specification of the relationship between the target and response of the acoustic equipment, including signal processing hardware and software, constitutes the calibration.

In practice, however, calibration is seldom a simple matter. Getting a 130 g, 30 mm-diameter sphere to hang virtually motionless in the center of an 8° beam, 20 m beneath the hull of a 1500 ton research vessel is not undertaken lightly. Yet the success of this operation is absolutely essential to even an ordinary calibration, not to mention precision calibration with expected 0.1 dB accuracy.

Appreciation of this fact has prompted the present contribution, a sequel to Foote *et al.* (1981). It is with design, therefore, that the method of calibration with spherical targets is described in detail. In order that any possibility of performing a precision calibration be seized, the particular application of optimal copper spheres to the routine is elaborated. The abstractions of the method and theory are offset by a practical example: calibration of R/V

"Michael Sars". Data from both an individual calibration exercise and from the semi-annual series of calibration exercises are presented. In addition to commenting on these, the problem of intercalibration and the improvement of present procedures are discussed.

THE METHOD

The general process of large-system calibration is now described. This is oriented towards the ocean-going research vessel, but may be applied whenever and wherever echo sounders or echo integrators must be calibrated.

1. PRELIMINARY PERFORMANCE MEASUREMENT AND ADJUSTMENT OF EQUIPMENT

Six basic tasks are enumerated here. These should precede the physical part of the calibration. They may be conducted expeditiously while the vessel is underway, for example, when sailing to its calibration anchorage.

(i) Measure and record transducer insulation and impedance.

(ii) Check and adjust, as necessary, the mains voltage and all critical voltages in the transmitter and receiver.

(iii) Check and record the two time-varied-gain functions; namely, the $20 \log r + 2\alpha r$ and $40 \log r + 2\alpha r$ functions.

(iv) Check and record total gains, bandwidths, and accuracy of the -10 and -20 dB attenuators.

(v) Measure and record the various effects for all combinations of transmitters and pulse durations of common or possible use during the preceding or following cruise program, for which the calibration is being undertaken.

(vi) Confirm the echo integrator performance by playing in a known signal and observing, hence recording, the output. Adjust the electronics as necessary to meet specifications. Confirm the vessel log compensation.

2. RIGGING FOR SPHERE MEASUREMENTS

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

Winches to guide and steer lines to the sphere for its centering in the echo sounder beam are affixed to the deck railing. This is done in accordance with detailed ship drawings. The first winch is placed in the transverse plane of the ship running through the transducer. The second and third winches are placed

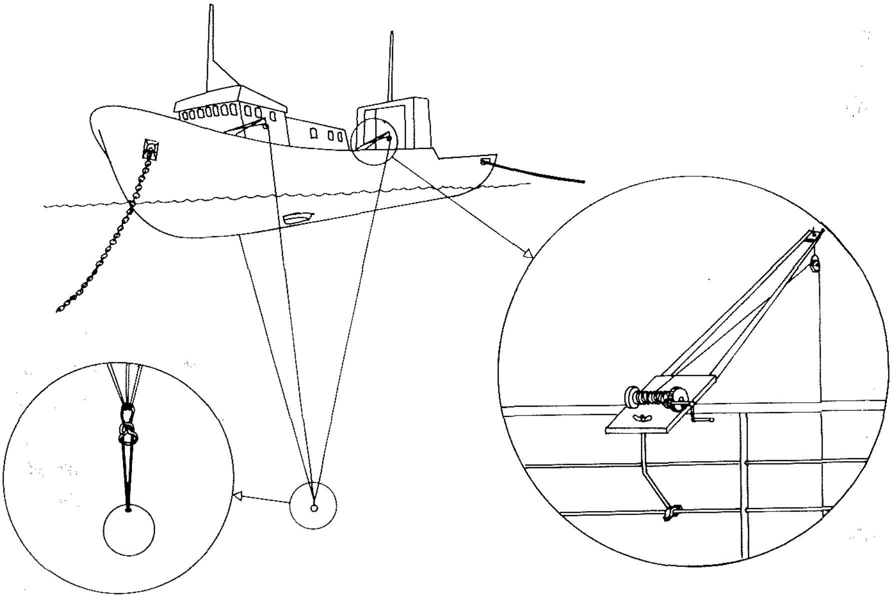


Fig. 1. Rigging of a research vessel for calibration.

on the opposite boat side and at equal distances from the transverse section containing the transducer and first winch. Each winch is provided with a long spool of 0.60 mm-diameter monofilament nylon, which is marked with small lead weights at five-meter intervals, beginning 10 m from the loose end.

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

The sphere depth or range from the transducer is determined by several considerations. The minimal allowable range to the sphere is the greater of the Rayleigh distance, or square of the largest transducer dimension divided by the acoustic wavelength, which defines the nearfield/farfield transition, and the least range for which the sphere echo does not saturate the electronics, e.g., the preamplifier. Two further practical considerations in choosing the range are the transducer beamwidth and vessel geometry. The physical width of the beam, which increases linearly with range, should be sufficiently great so that the sphere echo is unaffected by the small, perhaps pendular movements to which it is inevitably subjected. The minimal range must also be convenient with respect to the boat geometry. In particular, if the suspension lines do not hang freely, then control of the sphere may be hindered by friction or possible obstructions on the hull. Despite the number and variety of these considerations, it is seldom difficult in practice to find a suitable range which satisfies all of the above criteria.

3. HYDROGRAPHY

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

4. CENTERING

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

5. COMPUTATIONS FOR ECHO SOUNDER CALIBRATION

The sphere range is measured in units of milliseconds from the echo on the oscilloscope. The range r in meters is then given by $r = ct/2$, where t is the measured echo time delay and c is the average speed of sound from transducer to sphere depth. The approximate root-mean-square (rms) echo amplitude u_{rms} is determined from the peak-to-peak amplitude u_{pp} by assumption of a rectangular echo pulse, hence $u_{rms} = u_{pp}/2 \cdot 2^{\frac{1}{2}}$. This is converted to logarithmic units by the definition: $U = 20 \log u_{rms}$, where u_{rms} is expressed in volts. The sum of source level SL and voltage response VR is now determined from the target strength TS of the calibration sphere, after appropriate fine adjustments. The specifying equations are

$$SL + VR = U_1 - TS + 20 \log R_1 + 2\alpha R_1 - G + 20 \log r$$
$$\text{for "20 log r" TVG,}$$

and

$$SL + VR = U_2 - TS + 40 \log R_2 + 2\alpha R_2 - G$$
$$\text{for "40 log r" TVG,}$$

where U_1 and U_2 are respective echo levels with "20 log r" and "40 log r" TVG functions, r is the sphere range, R_1 and R_2 are the respective cutoff ranges of the two TVG functions, α is the absorption coefficient used in the TVG functions, and G is the attenuator setting. The units of the various quantities are stated in Table 1.

Table 1. Units of quantities in calibration equations.

Quantity	Symbol	Units
Source level	SL	dB//1μPa
Voltage reponse	VR	dB//1v/μPa
Echo level	U_1, U_2	dB//1v
Target strength	TS	dB
Ranges	r, R_1, R_2	m
Absorption coefficient	α	dB/m
Gain or attenuator setting	G	dB//1v

6. *READINESS OF ECHO INTEGRATOR*

The echo sounder is adjusted to its normal cruise settings. For the Simrad EK-38 echo sounder, for example, these might be the following: selected transducer: 30 × 30, transmitter: external, pulse duration: 0.6 ms, TVG: "20 log r", attenuator setting: –20 dB, bandwidth: 3 kHz, range scale: 0–250 m. The vessel speed is simulated as 10 knots and the observation time chosen to be six minutes, corresponding to a sailed distance of 1 n.m. Three 5 m-thick echo integration channels or layers are defined: the central channel is centered at the sphere depth and the others are placed immediately above and below, thus sharing common limits with the central channel. No threshold is used. The middle channel will thus contain the contribution from the sphere echo; the others will measure noise including volume reverberation.

7. *COMPUTATIONS FOR ECHO INTEGRATOR CALIBRATION*

The echo energy from each of a large number of pings is computed. The largest of these, if within about 10% of the average, is extracted. If the deviation is larger, then the centering operation should be repeated and the acoustic measurements performed anew. The product of the largest echo energy finally selected and the total number of pings in its sequence is expressed in terms of the arbitrary, historical units of millimeters of pen deflection per meter of sailed distance at 10 knots speed and the ping rate of most common use, for the given target referred to 1 m range. Despite the *a priori* oddity of this conversion, the fact of all pertinent calibration data being stored guarantees the possibility of intercalibration with other echo integrators, on other research vessels, by citation of the peak echo energy, for example.

8. DOCUMENTATION.

Special preprinted forms are filled in during the entire course of measurements. Collateral documentation in the form of oscilloscope photographs and hydrographic measurements are attached to these forms, all of which are identified for future reference. Copies are left onboard, distributed otherwise as necessary, and the originals are filed in the archives of the institute.

PRESERVING PRECISION

As mentioned above under "Computations for echo sounder calibration", the calibration value of target strength is adjusted for the temperature. In more general terms, the target strength depends on the hydrography, or temperature and salinity of the immersion medium at the depth of sphere suspension. This is clearly seen in the first paper on acoustic scattering by solid elastic spheres, Faran 1951, as well as in many later works, e.g., Hickling 1962, Vogt *et al.* 1975, Flax *et al.* 1978, MacLennan 1981. In each of these, the hydrographic dependence appears implicitly through the density and sound speed of the medium. The connections between these parameters and the hydrography are well known. Two standard references are Dietrich (1952) and Del Grosso (1974).

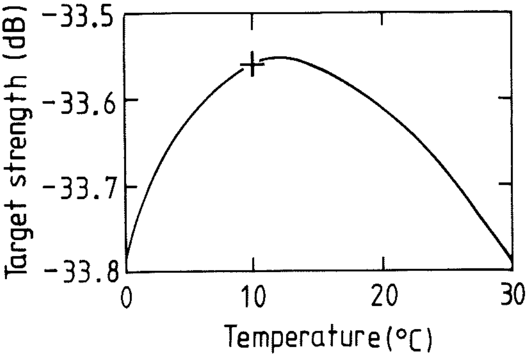
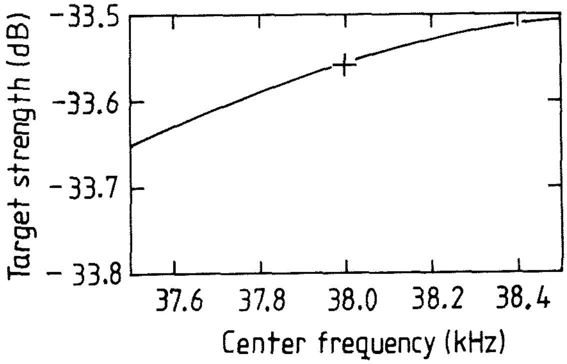


Fig. 2. Effects of temperature variations on the target strength of the 60 mm copper sphere for calibration of the EK-38 echo sounder. The plus indicates a common datum with the other computations, which are represented here by the constant center frequency of 38 kHz and pulse duration of 0.6 ms.

Fig. 3. Dependence of the target strength of the 60 mm copper sphere on the transmitter center frequency of the EK-38 echo sounder. The plus indicates a common datum with Figs. 2 and 4.



The influence of temperature on the target strength of the 60 mm copper sphere has already been investigated (FOOTE 1981, 1982b). The result of this is presented in Fig. 2 for marine calibrations of the Simrad EK-38 echo sounder, when operated under the following nominal conditions: 38 kHz center frequency, 0.6 ms pulse duration, and 3 kHz receiver bandwidth. The temperature is varied from 0 to 30°C, assuming a constant salinity of 35 ppt.

Evidently, use of a target strength of –33.7 dB will ensure a precision calibration over the entire 30°C range, without requiring temperature compensation. This is a direct consequence of the method of determining the sphere diameter, given its composition of electrical-grade copper (FOOTE *et al.* 1981, FOOTE 1982). Application of the temperature-correted target strength will, however, contribute to the overall control of potential calibration errors, hence is recommended in the general case. In the present case, use of the nominal target strength of –33.6 dB for temperatures from 4 to 22°C will assist this control, as the single value of–33.7 dB does ot make allowance for rounding errors.

Both the center frequency and duration of the transmit pulse can also influence the calibration value of target strength (FOOTE 1981, 1982, 1983). These dependences are shown in Figs 3 and 4, respectively, for the following nominal

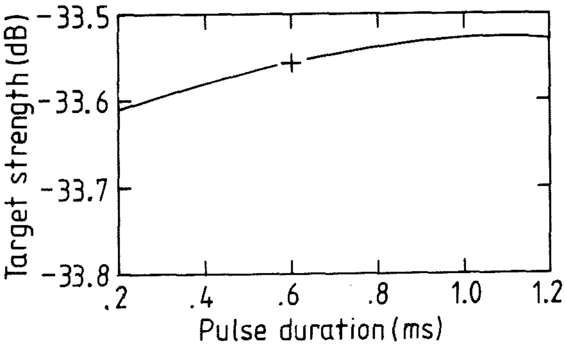


Fig. 4. Dependence of the target strength of the 60 mm copper sphere on the duration of the transmit pulse of the EK-38 echo sounder. The plus indicates a common datum with Figs. 2 and 3.

hydrographic state: temperature of 10°C and salinity of 35 ppt, hence medium density of 1027 kg/m^3 and sound speed of 1490 m/s.

Again, as with the temperature, the dependences are weak, and use of the nominal value, –33.6 dB after rounding, would permit neglect of variations in the two parameters over the considered ranges. However, since both equipment parameters can be measured with high accuracy, control of the calibration process would dictate adjustment of the target strength.

It might be thought that it is best to maintain a tuned condition for the sake of calibration. In fact, this is unnecessary, for the acoustic robustness of optimal copper spheres, a consequence of their design by optimization, allows their use over a wide range of conditions departing from nominality. Thus, equipment that is discovered to be out of tune or that cannot be tuned easily, because of age, for instance, can be calibrated by the same sphere by a slight modification in the target strength.

EXAMPLE

The method of calibration is illustrated by an example derived from the exercise with R/V "Michael Sars" on 5 January 1982. This concerns the Simrad EK-38R echo sounder and attached echo integrator, standard equipment widely used in the acoustic estimation of fish abundance.

The exercise began at 0800 hours with departure of the boat for Skogsvaagen, an inlet on the island of Sotra, about a one-hour sail from Bergen, where the sphere measurements were to be conducted. While underway, the performance of the equipment was measured. This followed the task list of item (1) of the method. No serious deviations from the specifications were discovered, precluding special adjustments. In addition to these preparatory measurements, the three outriggers with hand-winches were attached to the deck railing in their usual positions and the several copper spheres to serve as targets were immersed in a bucket of fresh water and detergent.

At Skogsvaagen the boat was anchored near the northern shoreline of the inlet, hugging a rock wall affording shelter from a light north breeze. Both bow and stern were anchored in water of 100 m depth. Owing to local geography, tidal flow and other submarine currents are completely negligible in the inlet, hence these were not considerations in choosing the anchoring location.

The hydrography was performed immediately upon completion of the anchoring. The temperature and salinity profiles measured by a standard CTD-sonde were logged automatically by the central computer and computations of sound speed and density performed. At the anticipated calibration depth of 24 m, the temperature and salinity were found to be about 6°C and 33 ppt, implying a local sound speed of 1472 m/s and density of 1026 kg/m^3. The average sound speed from the transducer to this depth was found by computation to be 1466 m/s.

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

After fine adjustment, the sphere was assumed to be on the acoustic axis of the transducer and the measurements were begun. These are now described for the "20 log r" TVG function and external transmitter, the standard combination for many acoustic surveys. The sequences of items (5) and (7) of the method are followed below.

The echo time delay t was measured as 25.2 ms on the oscilloscope. Use of the average sound speed $c = 1466$ m/s determined the sphere range $r = ct/2 = 18.5$ m. The peak-to-peak sphere echo u_{pp} was measured with the attenuator setting or gain $G = -20$ dB with the result $u_{pp} = 3.35$ V. This was converted to the echo level $U_l = 20 \log u_{pp}/2 \cdot 2^{\frac{1}{2}} = 1.5$ dB. The cutoff range R_l of the "20 log r" TVG function is 502 m. The absorbtion coefficient α for the particular echo sounder is 0.0105 dB/m. For the exact sphere depth, the hydrography dictated a target strength $TS = -33.6$ dB, cf. Fig 2. The sum of the source level SL and voltage response VR can now be determined:

$$\begin{aligned} SL + VR &= U_l - TS + 20 \log R_l + 2\alpha R_l - G + 20 \log r \\ &= 1.5 + 33.6 + 54.0 + 10.5 + 20.0 + 25.3 \\ &= 144.9 \text{ dB} \end{aligned}$$

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

Following calibration of the echo sounder, the echo integrator was prepared for its calibration. This was performed in the manner described in item (6) of the method. Because of the sphere range of 18.5 m, the central 5 m-thick integration volume was defined as [17, 22] m. The adjacent channels were defined as [12, 17] and [22, 27] m.

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

Calibration of the echo integrator can now be completed by reference of the peak echo energy to a 1 m-sailed distance and 1 m-depth. The calibration value is expressed thus:

$$\text{Integral (mm//1 m-sailed distance} \cdot \text{1 m-depth)} = \frac{7356 \cdot 18.5^2}{1852 \text{ m/n.m.}} = 1359$$

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

The derived numbers are compared with previous calibration results for the same boat in Table 2, where the sum of source level and voltage response is referred to the usual —20 dB attenuator setting. The consistency of corresponding numbers witnesses both to the precision of the calibrations and to the long-term stability of the equipment.

Table 2. Summary of calibrations of the EK-38 echo sounder and attached echo integrator on board R/V "Michael Sars".

Date of exercise	SL + VR (dB)	Integral (mm)
January 1980	125.5	1387
July 1980	124.9	1264
January 1981	124.6	1291
June 1981	124.9	1330
January 1982	124.9	1359

DISCUSSION

Calibration of echo sounders and integrators is a straightforward process, but one that requires vigilance at all stages for its success. This evidently has been the case with calibration of the 38 kHz echo sounder and echo integrator of R/V "Michael Sars", as illustrated in Table 2. A detailed analysis of the errors in a routine exercise has suggested a precision well under 0.5 dB, if not approaching 0.1 dB. The consistency of the tabulated numbers for the five cruises supports this, for the greatest excursion from the average sum of source level and voltage response for the echo sounder is 0.5 dB, while the corresponding deviation in echo integral from the average is 5%.

The present procedures can be improved, of course, and the Institute of Marine Research is continuing its work on this. In particular, measurement of the time-varied-gain function has proved to be problematical. To facilitate its measurement, special circuitry for performing the determination automatically is being designed. Eventually, it is planned to incorporate a TVG correction in the software of the echo integrator, to reduce what hardware errors may exist or develop with time.

Another procedure which could be improved is that of centering of the sphere. At present, the angular position of largest echo is sought. This is rather time consuming because of the relative broadness of the main lobe, hence insensitivity of the echo to fine adjustments in position. Were it possible to operate the same or similar transducer in a split-beam mode, in which four quadrant beams are separately formed, then generation of the difference responses in the fore-and-aft and athwartships planes would enable very sensitive minima – ideally sharply defined nulls – to be sought. Not only would this accelerate the alignment process, but it would also effect a demonstrably highly accurate positioning. Additionally, observation of the sphere echo on the oscilloscope during calibration of the echo sounder would enable the data goodness to be confirmed without having to study the statistics.

When and if both improvements are made, it should be easy to establish the accuracy of calibrations of echo sounders and integrators. This is expected to approach 0.1 dB.

Intercalibration is entirely feasible given the present calibration procedures based on the use of optimal copper spheres. To determine the relative performances of two systems, either the same or similar spheres can be used. Different spheres could also be employed, if their target strengths were known with sufficient accuracy.

The significance of the present calibration method to multiple-vessel acoustic surveys of fish stocks is that intercalibration of the several instruments can be effected without requiring the vessels to meet and perform a simultaneous survey of the same fish aggregation. Use of optimal copper spheres is especially advantageous here, for the properties of copper as a standards material are unalloyed, and offer an immediate, potential accuracy of 0.1 dB, with the possibility of further improvements.

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