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IMPROVED CALIBRATION OF HYDROACOUSTIC EQUIPMENT WITH COPPER SPHERES

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ABSTRACT

Calibration of hydroacoustic equipment used in fisheries research has been effected to within 0.1 dB by copper spheres. This has required extending scattering theory to finite transmit signals and non-vanishing receiver bandwidths. The sphere diameters have been determined by solution of the optimization problem for commercial, electrical-grade copper. Application of this solution to conventional echo sounders with operating frequencies of 38 and 120 kHz has been successful. In addition to describing these developments, the paper summarizes current Norwegian methodology for calibrating echo sounders and echo integrators.

INTRODUCTION

The importance of calibrating hydroacoustic equipment is well known in fisheries research. Acoustic assessment of fish abundance by conventional algorithms, for instance, is impossible without calibration. Relative assessment is similarly precluded by the failure to maintain calibration. The very aims of the *ad hoc* Study Group on Acoustic Techniques at its meeting in Nantes during the week 25-29 May 1981 were to "propose standard targets" and "recommend calibration procedures" (C. Res. 1980/2:9). Research in progress at the institutes in Aberdeen, Bergen, and Lowestoft, reported in part at that meeting, further witnesses to the currency of the calibration problem.

Each of the two classes of solutions, the active and passive methods, has been and is being used in fisheries research. The diversity of techniques within each class - see, for example, the pertinent bibliographies of Urick (1975) and Wallace *et al.* (1975) - suggests a difficulty with calibration in general, hence the need for *ad hoc* methods to meet the individual case. This certainly describes the situation for fisheries echo sounders operating at ultrasonic frequencies. To give two examples, calibrations performed with hydrophones and with ping pong balls are suspect - in the first case because of apparent environment-induced variations in responsiveness of the calibrating hydrophone, and in the second, because of uncertainty in knowledge of the target strength, notwithstanding Welsby and Hudson (1972).

It is precisely this dissatisfaction with current methods that has motivated the present study. Simply stated, this has attempted to find a robust and expedient method of calibrating fisheries echo sounders and echo integrators. Classical work on the scattering of sound by elastic spheres has suggested the possibility of using such bodies as calibration targets, although not quite, perhaps, in the traditional manner.

The aim of this paper is twofold: to outline the process by which *copper spheres* have been found and demonstrated to be outstanding calibration targets and to provide a summary review of current Norwegian calibration methodology.

THEORY

To the theoretician the problem of calibrating hydroacoustic equipment by passive targets is larely a matter of knowing the backscattering cross section or target strength for the conditions of observation. For robust physical bodies possessing spherical symmetry, i.e., solid, homogeneous, elastic spheres, the role of elasticity cannot be underestimated. This understanding was obtained first through the seminal work of Faran (1951) and confirmed by the experiments of Hampton and McKinney (1961) and further modelling by Hickling (1962), *inter alia*. In brief, this work confutes the too-oft-quoted hard approximation or, worse, geometrical approximation. The approximations fail, incidentally, because the basic physics of the scattering process does not support asymptotic theorizing. In terms of the material properties of the sphere: the density ρ_1 and longitudinal and transverse sound speeds, c_1 and c_2, respectively, and medium density ρ and sound speed c, the corresponding ratios are not very large, but, in fact, are in the quite interesting range of 1 to 10. For the example of steel, $\rho_1/\rho \sim 8$, $c_1/c \sim 4$, and $c_2/c \sim 2$, which denies the hard approximation.

In addition to the influence of elasticity, the conditions of observation must be considered in the general calibration exercise. The finiteness of signal duration and use of receivers with narrow, but not extremely narrow bandwidths demand that the observation/interpretation of sphere echo heed these facts. Hickling (1962) has already described the effect of the first. The effect of the second is to filter the echo signal spectrum. Since the processes of nearly universal interest and use in fisheries research are linear, the spectrum of the received echo signal is

$$S'(\omega) = H(\omega)F(\omega)S(\omega) \quad , \qquad (1)$$

where H is the receiver frequency response function, F is the scattering amplitude of the subject sphere, and S is the spectrum of the ensonifying signal, all of which are functions of the angular frequency ω. Use of Rayleigh's theorem (Strutt 1889), the analogue of Parseval's theorem for Fourier series, shows that the observed or perceived backscattering cross section is

$$\sigma = 4\pi \int_0^\infty |S'(\omega)|^2 d\omega \Big/ \int_0^\infty |S(\omega)H(\omega)|^2 d\omega \quad . \qquad (2)$$

The corresponding observed, or effective, or apparent, or perceived target strength is related to this by the usual logarithmic transformation (Urick 1975).

What should be noted here is that it is energy, or integrated acoustic intensity, and not amplitude or level which is the decisive quantity in observing or measuring the target strengths of elastic spheres with ordinary echo sounders, hence, too, with echo integrators.

Through this extension of scattering theory it is now possible to attack the problem of designing elastic spheres for use as calibration targets. This involves choosing the material and specifying the diameter for given echo sounder.

Choice of material. There are many factors to be considered in choosing the material. It should be hard, homogeneous with the possible exception of the immediate surface layer, which should, however, be stable; amenable to working such as machining, globally accessible, conforming to ordinary standards specifications, of known or controllable elasticity. The candidate material, perhaps not surprisingly, is copper, whose noble qualitities need no burnishing for proposal as a standard in calibration work.

Determination of diameter. The diameter is to be chosen to satisfy specific requirements of target strength and to be stable with respect to variations in temperature typically encountered in calibrating echo sounders used in marine fish abundance assessment. The problem can thus be formulated as an optimization: Find the sphere radius a such that

$$\left.\frac{d\sigma}{dT}\right|_{T_o} = 0 \quad , \tag{3}$$

where T is the temperature variable and T_o is the nominal calibration temperature, given that the backscattering cross section σ lies in a pre-defined range, for example,

$$\sigma \in (\sigma_1, \sigma_2) \quad . \tag{4}$$

The salinity will be nominally 35 ppt, but any other number may be used in effecting the optimization.

Solution example. For calibrating a typical 38 kHz echo sounder by copper sphere with target strength to lie in the vicinity of -35 dB and nominal calibration hydrography of 10^{o}C and 35 ppt, the diameter should be 60.00 $\pm$ 0.06 mm. This will ensure a nominal target strength of -33.7 $\pm$ 0.1 dB over the temperature range from 0 to 30^{o}C. The Voigt-Reuss-Hill approximation (Anderson 1965) is adequate for specifying the material elasticity from the best available single crystal data (Hearmon 1979). Deviations in elasticity for the individual copper sample may be determined and used either in a new optimization calculation or to make a fine adjustment to the target strength given here.

EXPERIMENTS

The Institute of Marine Research commenced its research program on calibration in 1979. In addition to the theoretical work outlined above, collateral experiments have been performed. These are described here in their chronological, and natural order.

1. Skogsvaag 1980

This first experiment was designed to confirm the described extension of theory and to gather acoustic data on a range of candidate elastic materials. The measurements were made with four Simrad echo sounders: the EK-38, EK-50, EY-M, and EK-120 units, with nominal center frequencies of 38, 49.5, 70, and 120 kHz, respectively. The transmit pulse length was nominally 0.6 ms. The target spheres were of two types: machined spheres and steel ball bearings. Materials for the machined spheres included aluminium, brass, copper, duralin, several steels, and zinc. Sphere diameters varied from 35 to 130 mm, thus implying a range in wavenumber-radius product from about 2.5 to 30.

Agreement with theory was very fine for the copper spheres at all frequencies. This is illustrated in Fig. 1 for the case of measurements with the EK-50 echo sounder. The measurements, which were deliberately relative, are expressed here as backscattering cross sections normalized to that of the 35 mm copper sphere. Theory and experiment disagreed otherwise except for a few spheres at the lowest frequencies. The explanation is simple: the elasticity was known with good accuracy for the copper, but with less accuracy for the other materials. The fact that there was some agreement for several non-copper spheres at the lower frequencies, but not at the higher , shows the increasing importance of accurate knowledge of material elasticity with increasing frequency.

Another example of this finding was provided by the observations on three identically sized, machined steel spheres. Significant differences were observed between the two stainless steels, and among these and the axle steel sphere. Perhaps this should not be surprising, for there are literally hundreds, if not thousands of steels whose precise alloying is dictated by the need to meet a specific use, often with respect to its structural, hence elastic properties. The value of elemental metals is raised by such experience.

2. Skogsvaag 1981

The success of the first experiment led to the selection of copper as the most promising material and to the exercise of theory to optimize the sizes of copper spheres. Solutions were derived for the 38 and 120 kHz echo sounders: optimal diameters of spheres of commercial, electrical-grade copper are 60.00 and 30.05 mm, respectively. These solutions, after realization in several sets of independently machined, independently procured copper, were tested through a second experiment conducted at Skogsvaag, a deep, mostly sheltered fjord easily accessible from Bergen.

The new measurements were made absolutely, in contrast to the measurements of the 1980 experiment, which were made relatively to avoid possible prejudicing of their interpretation, consistency being the guiding rule or criterion for acceptance.

The new measurements thus demanded use of calibrated equipment. This consisted of the new EK-400 echo sounder with dual receivers and associated full-size transducers resonant at 38 and 120 kHz. It was calibrated first on station in Horten, and later, on the measurement platform, the adapted 125-ton side-trawler "Rønner". The measurements of source level and voltage response, shown in Table 1, were made on both occasions in the conventional manner (Bodholt et al. 1979). The fact of their being different "in the field" reinforced earlier experience and, as on those occasions, the hydrophone calibration performed on station was used.

Other quantities required for absolute determination of the target strength from the active sonar equation (Urick 1975) were characteristics of the echo sounder, were measured directly, or were obtained from the literature. These included the cutoff depth of the echo sounder TVG function, absorption coefficient, equivalent beam angle, sound speed in water, and transmitter pulse duration, which was 1.0 ms. These quantities were combined with the source level and voltage response to form the echo sounder constant. Their individual logging in the programmable part of the Simrad QD digital echo integrator allowed computation of the mean volume backscattering coefficient. The sphere target strength was derived from this through knowledge of the integration volume.

To facilitate the comparison of measured and predicted target strengths, measurements of the hydrography were made periodically throughout the experiment. The frequency response functions of the receivers were also measured. These are presented in Figs. 2 and 3.

Results of theory based on the measured hydrography and measured frequency response functions are shown in Table 2 with the actual observations. If the agreement appears to be too good it should be noted that the intrinsic accuracy of a hydrophone calibration performed on station in Horten is about 0.5 dB.

Several additional measurements were made to explore, among other things, different suspension methods. These included net bags specially made of monofilament nylon, and loops of the same affixed either to an eyebolt or epoxy weld made in a shallow bore. The resultant measurements with the 60 mm sphere were identical at 38 kHz, showing the acoustic equivalence of the various suspensions. Corresponding measurements on the 30.05 mm sphere at 120 kHz were inconclusive, probably owing to the inertia, hence unresponsiveness of supporting wires holding the spheres in the transducer beam. This problem has since been remedied in the conduct of calibration exercises.

3. Direct measurements of target strength

Three separate measurements of the target strengths of the optimal 60 mm spheres at 38 kHz were performed by the direct hydrophone method. This involves interposing a hydrophone between transducer and sphere, and measuring the incident signal and echo. The target strength can then be computed from the characteristic amplitudes, measurement geometry, and known structure of the acoustic field.

Two of the measurements were made in a small tank at the Department of Physics of the University of Bergen. For each of these it was necessary to remove the noise component. In the case of the first measurement, which was made with a standard 10x10 cm nickel transducer resonant at 38 kHz, the noise was removed by substracting the rms noise amplitude from a calculated rms signal-plus-noise amplitude based on a series of measurements in which the sphere was moved over a distance of the order of a wavelength along the transducer-hydrophone axis. For the second measurement, which was effected by means of a 38 kHz signal generated parametrically, the noise and signal-plus-noise waveforms were sufficiently clean and stable, of course, to permit direct in-phase subtraction. This second measurement was performed by G. Lien and P. Meldahl at the Department.

The accuracies of the two methods have not been finally determined. Execution of the first method was patently crude; its accuracy is probably of the order of 0.5 dB. Preliminary evaluation of the second method indicates an accuracy better than 0.1 dB.

The third measurement was accomplished with a special rig suspended from a vessel in Oslofjord. The equipment was standard; noise level, negligible; and measurements, uncomplicated. The accuracy is 0.1 dB.

Results of the several measurements are shown in Table 3. Attached theoretical values were derived by appropriate averaging over the signal spectrum for the respective measured hydrographies.

4. Indirect measurements of target strength

In addition to all the foregoing measurements of target strength, there has been a large number of indirect measurements in which the reference may be considered to be a sphere of unknown target strength. These relative measurements, which include those gathered during the described experiments and also during recent calibration cruises, have been uniformily consistent and justify stating differences in target strengths to the nearest 0.01 dB. Agreement with theory has been excellent. Additional confirmation of this by parameter-fitting in the spirit of Neubauer *et al.* (1974) has suggested a new method of determining the rigidity modulus of elastic materials. This and other work mentioned here is being published.

DISCUSSION

Results of theoretical and experimental work have already been presented, but are summarized here with related conclusions for convenience of reference.

1. Scattering theory has been extended to finite transmit pulses and non-vanishing receiver bandwidths.

2. The optimization problem for calibration spheres has been formulated, and solved for the case of copper.

3. Copper is the superior metal for calibration spheres, both in principle and in practice. Its commercial, electrical-grade form is recommended as the standard.

4. Optimal copper spheres for calibrating 38 and 120 kHz echo sounders have diameters of 60.00 and 30.05 mm, respectively. One part in one thousand is a sufficient and readily attainable tolerance for the spheres when machined from rod.

5. The sphere suspension may be accomplished for the 38 kHz echo sounder by net bag, or by eyebolt or loop of monofilament nylon fastened to the sphere in a single shallow bore. The effect of the bore is still undetermined in the case of the 120 kHz echo sounder.

6. The present accuracy in calibration of echo sounders and echo integrators, i.e., in determining the sum of source level and voltage response in the first instance and integrator constant in the second, is 0.1 dB.

An important theme running through the described work is that the conditions of observation must generally be considered in assigning the target strength during calibration. The reason is that the target strength, while rather insensitive to deviations in temperature and salinity from the nominal conditions of the optimization calculation, will in general vary with these quantities. They are both systematic and calculable, however, so do not present a serious problem. Small corrections to the nominal target strength could be made, for instance, by reference to a table. Other deviations from nominality, for example, in center frequency or in pulse length of the transmitter, may be compensated for in similar manner.

These same remarks also apply to the use of other types of copper than the recommended commercial, electrical-grade form. Changes in copper type will generally be reflected in the elasticity, hence in the acoustic properties of the metal. The changes in target strength due to changes in elasticity may be calculated and applied in the same manner as those due to variations in medium hydrography or equipment parameters from the nominal state.

The possibility of precision calibration of echo sounders and echo integrators is thus apparent. This may be facilitated in the case of echo sounders-without-integrator by the addition of a single instrument, a spectrum analyzer, e.g., HP 8568A, to the usual complement of electronics gear available during calibration exercises. Such a tool will increase the precision in determining echo amplitudes from the calibrated output signal beyond the 0.1 dB level, allowing a comparable accuracy in the determination of the sum of source level and voltage response. For echo sounders-with-integrator the accuracy of echo sounder calibration may be increased beyond the 0.1 dB level by using the integrator to determine the true rms echo amplitude with much greater precision than is possible by assuming a rectangular echo waveform. Calibration of the echo integrator itself, if comparable to the Simrad QD, may already be effected to within the named accuracy.

In other words, calibration is a solved problem. The fisheries researcher wanting to assess fish abundance by acoustic means may, with a proper technique and optimal copper sphere, expect to attain a calibration accuracy sufficient to warrant its complete neglect when attaching confidence levels to biomass estimates.

SUMMARY OF CALIBRATION METHODOLOGY

Specifying the acoustic backscattering cross section of an elastic sphere is one thing; using it to best advantage is another. The most elaborate calculations or highly controlled measurements are to nought if only one of the many tasks of a calibration is done poorly. It is from an intimate acquaintance with the scope of calibration exercises that the following summary is offered. This is not meant to be definitive or final in any sense; it is, in fact, under critical review.

Illustration by numerical computation is duly avoided, especially since some new definitions and variants of present procedures are likely soon to be introduced for the calibration of echo integrators. This is currently being performed with reference to standard analogue integrators which employ the vivid, but arbitrary units of millimetres of pen deflection on a strip chart to represent the cumulative effect, thence large-scale density of acoustic scatterers. Even the procedure of calibrating echo sounders may be refined through the concerted use of echo integrators, as mentioned in the Discussion. The structure of the calibration programme, however, is fast and should indicate the need for detailed planning and careful execution.

For the sake of definiteness in the following enumeration, the example is used of ocean-going research vessels equipped with Simrad Scientific Echo Sounders and Integrators and the usual auxilliary instrumentation.

1. Preparations

A number of measurements of equipment parameters can and should be made in advance of the physical part of the calibration. Six basic measurements are listed here.

(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 1/10 and 1/1 effects for both the normal and extra transmittters for the various available pulse lengths.

(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 ships-log compensation.

2. Rigging for sphere measurements

The vessel is anchored in calm and sheltered water with depth about 50 m. For stable measurements the stern should be tied to land or anchored. This is illustrated in Fig. 4.

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, referred to as winch no. 1, is placed in the transverse plane of the ship running through the transducer. The second and third winches, nos. 2 and 3, are placed on the opposite boat side and at equal distances from the transverse section containing the transducer and winch no. 1. 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 winch nos. 2 and 3 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. 4. It is then immersed in a solution of soap and fresh water and lifted overboard by the attachment lines without being touched. The sphere is lowered beneath the vessel to the desired depth, for example, 25 m, determined roughly by counting the lead marker-weights on each line.

3. Centering

The sphere is moved onto the acoustic axis of the transducer by adjustment of the several winches. This is coordinated by observation of the echo waveform on an oscilloscope. The center is reached when the slightest movement of suspension line either in or out results in a decrease in the echo level.

4. Computations for echo sounder calibration

The range from transducer to sphere is measured in units of milliseconds from the calibrated output signal displayed on an oscilloscope. The sound speed c is determined by measurement of the temperature and salinity at sphere depth by means of a CTD sonde. The range r in metres is then given by r=ct/2, where t is the measured propagation time from transmission to receipt of sphere echo. The approximate rms echo amplitude u_{rms} is determined from the peak-to-peak amplitude u_{pp} by assumption of a rectangular echo pulse, i.e., $u_{rms}=u_{pp}/2\cdot 2^{\frac{1}{2}}$. 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 for each of the two TVG functions:

$$SL+VR = U-TS+ 40 \log R +2\alpha R - G \quad \text{for "40 log r" TVG}$$

and

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

where SL is expressed in dB//1µPa; VR, in dB//1v/µPa; R is the range, expressed in metres, where the TVG function ends; and G is the attenuator setting in dB.

5. Readiness of echo integrator

The echo sounder is adjusted to its normal cruise settings. For the EK-38 echo sounder, for example, these might be the following: selected transducer: 30x30, range scale: 0-250 m, transmitter: external, TVG: "20 log r" with attenuator setting of -20 dB, bandwidth: 3 kHz, pulse length: 0.6 ms. The vessel speed is simulated as 10 knots and the observation time chosen to be 6 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.

6. Computations for echo integrator calibration

The total average echo contribution over a simulated nautical mile is referred to the 0 dB gain of the standard analogue integrator, the Simrad QM. The average is then divided by the number of pings emitted over the six-minute integration period. This number is finally referred to 1 m depth and 1 ms pulse length. It thus represents the average echo contribution from centered sphere of known target strength.

7. 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.

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Table 1. Hydrophone calibrations of an EK-400 echo sounder over a three-week period, showing differences with measurement site. Calibration units are decibels.

Frequency (kHz)	Site	SL	VR	SL+VR
38	Horten - station	231.1	-92.2	138.9
38	Skogsvaag - vessel	232.6	-91.5	141.1
120	Horten - station	222.7	-103.9	118.8
120	Skogsvaag - vessel	224.8	-103.4	121.4

Table 2. Comparison of theoretical and experimental target strengths of two optimal copper spheres, based on measurements made during the Skogsvaag 1981 experiment.

Nominal sphere diameter (mm)	Frequency (kHz)	Target strength (dB)	
		Theory	Experiment
60.00	38	-33.7	-33.7
30.05	120	-36.9	-37.0

Table 3. Comparison of theoretical and experimental target strengths of optimal 60 mm copper spheres, based on direct measurements made at the design frequency of 38 kHz.

Type	Removal of noise	Pulse duration (ms)	Target strength (dB)	
			Experiment	Theory
Tank	Subtraction of rms amplitudes	0.2	-33.9	-34.2
Tank	Subtraction of in-phase amplitudes	0.12	-34.1	-34.2
Fjord	Unnecessary: noise negligible	0.5	-33.5	-33.6

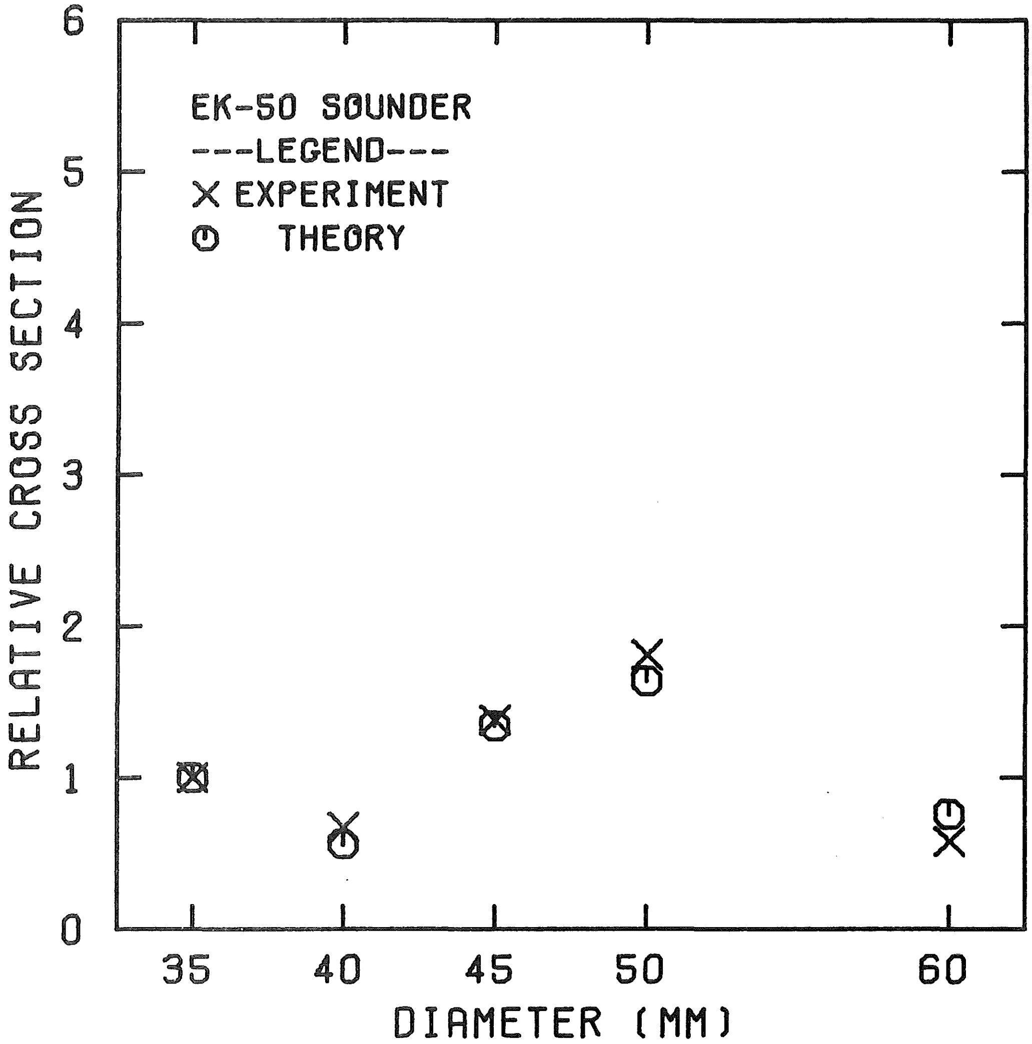

Fig. 1. Comparison of theoretical and experimental backscattering cross sections of copper spheres observed with the EK-50 echo sounder, expressed in normalized units, based on measurements made during the Skogsvaag 1980 experiment.

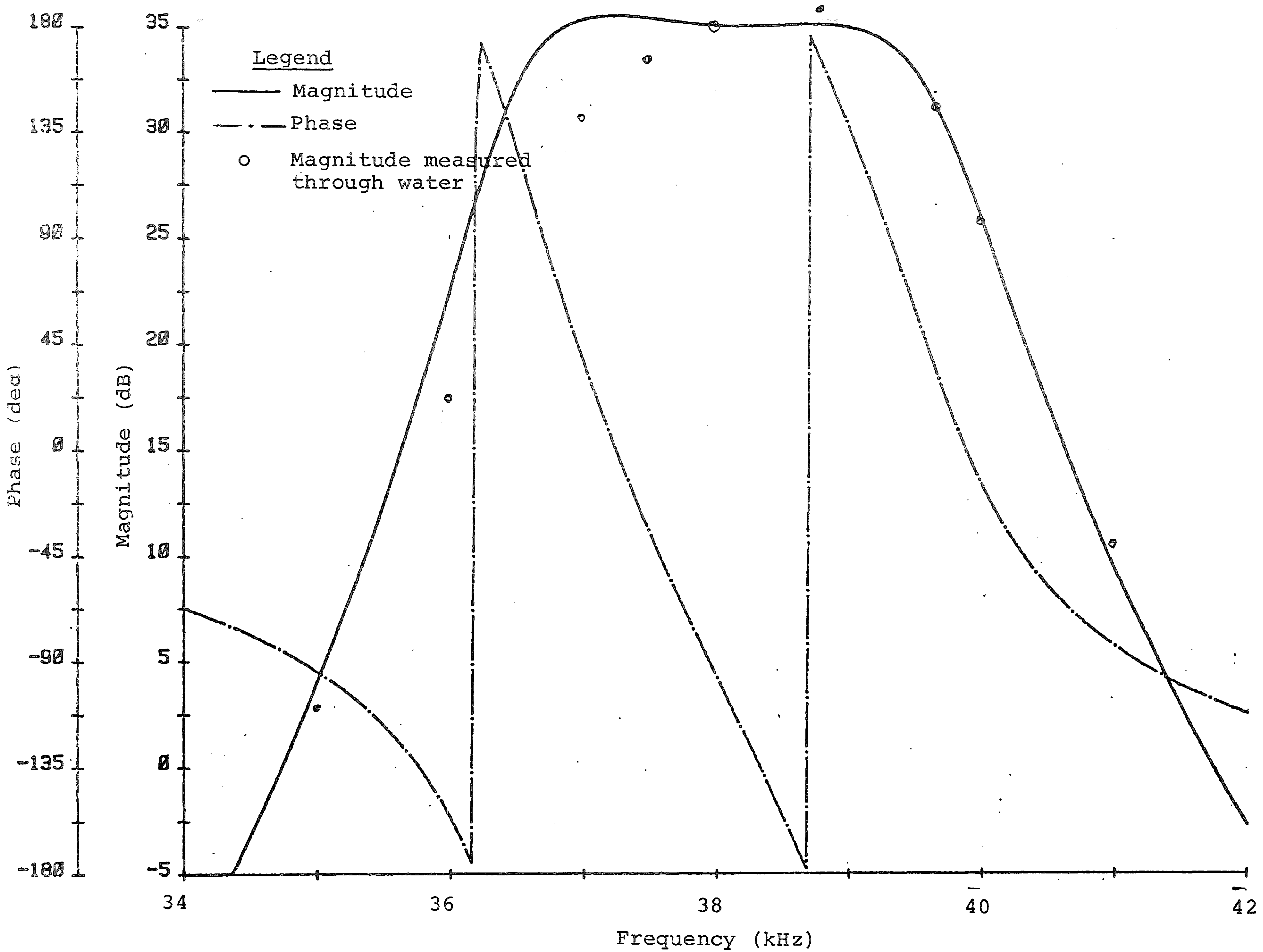

Fig. 2. Measurements of the frequency response function of the 38 kHz unit of the EK-400 echo sounder, made in conjunction with the Skogsvaag 1981 experiment.

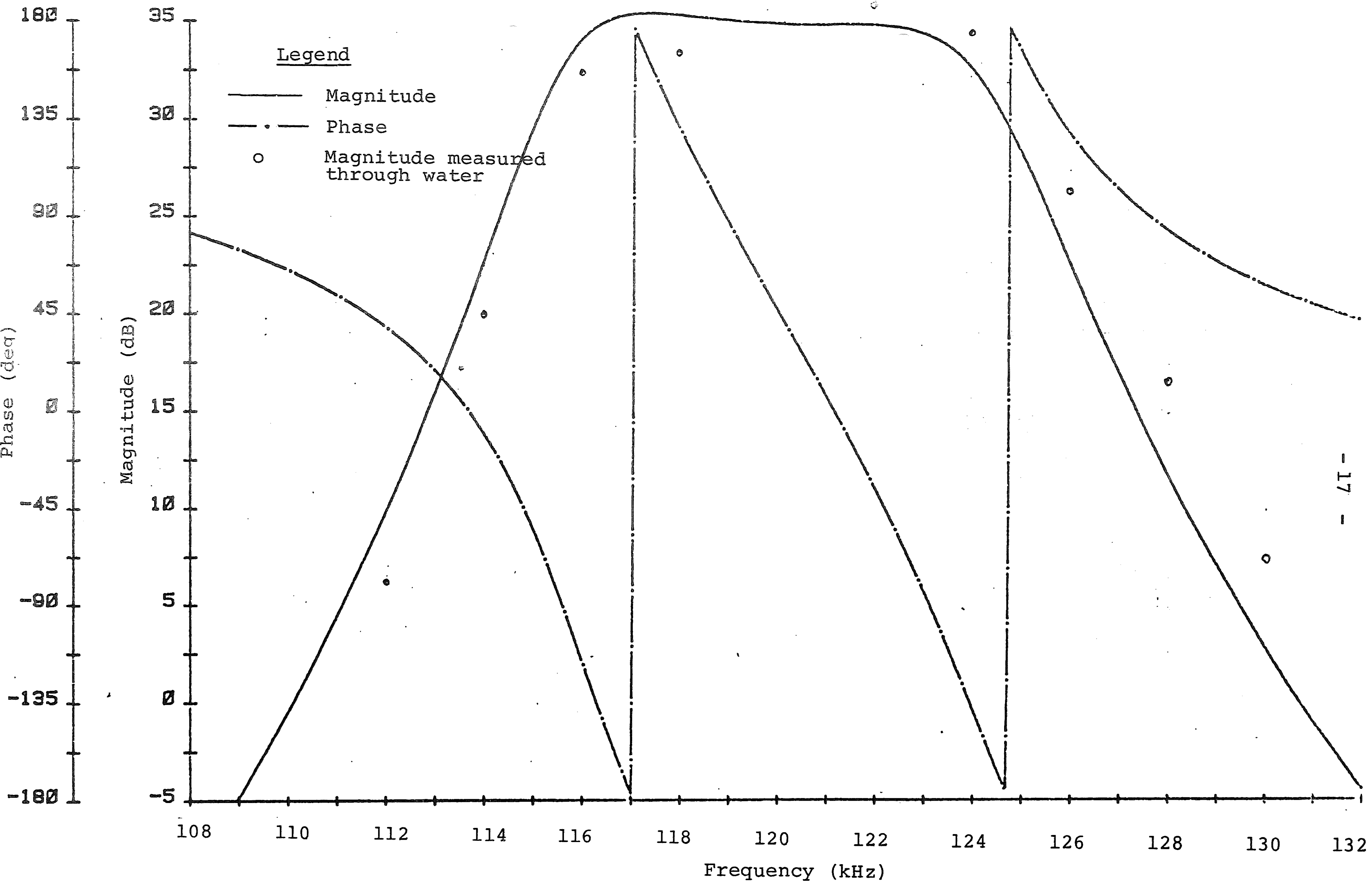

Fig. 3. Measurements of the frequency response function of the 120 kHz unit of the EK-400 echo sounder, made in conjunction with the Skogsvaag 1981 experiment.

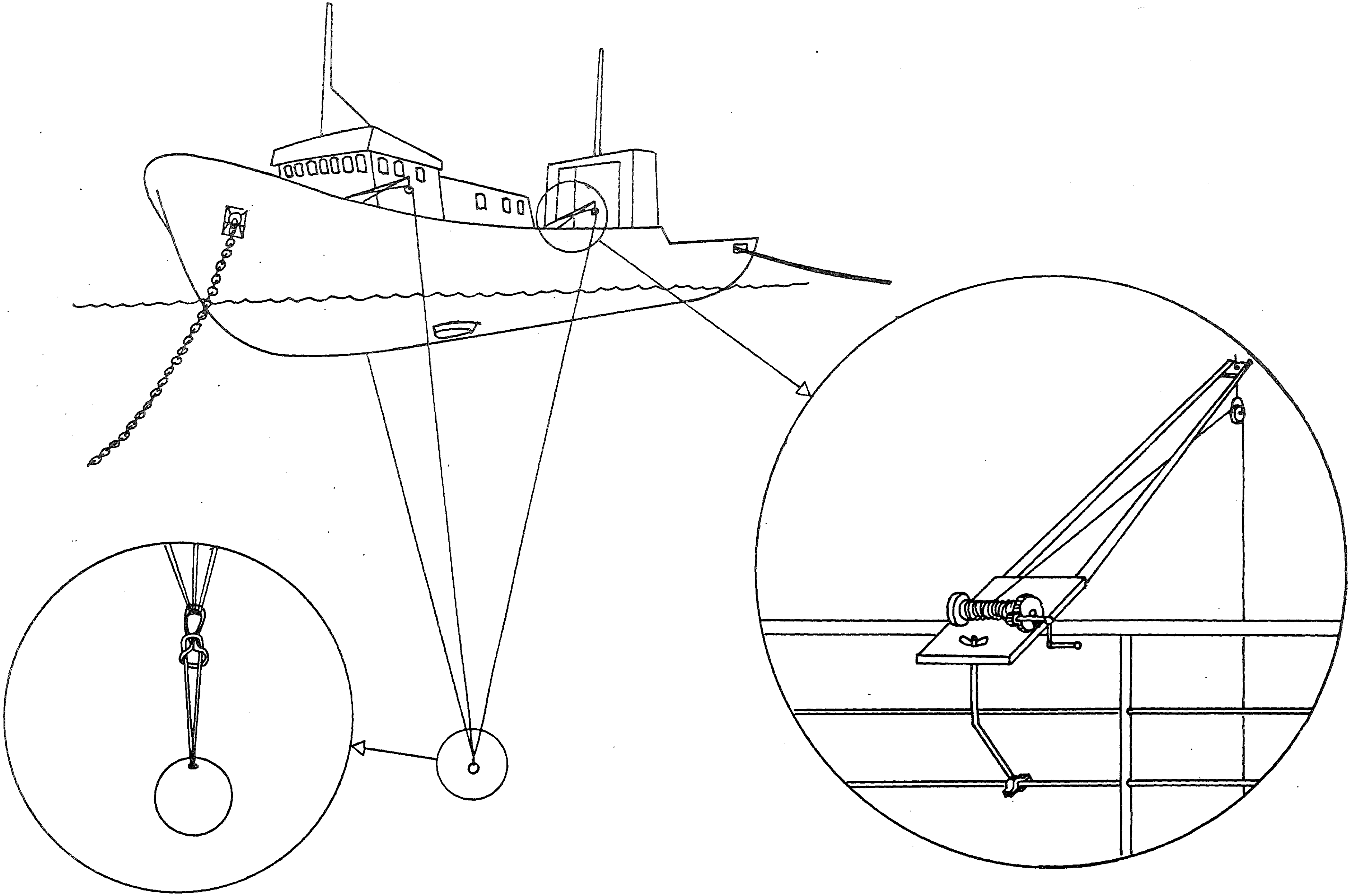

Fig. 4. Measurement configuration and sphere suspension during a calibration exercise.