Interlaboratory Comparison of Hydrophone Calibrations

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Abstract—**The results of an interlaboratory comparison of hydrophone calibration techniques in the frequency range 1-10 MHz are reported. Two membrane hydrophones were circulated to six laboratories, and each laboratory determined the end-of-cable loaded sensitivities using their normal calibration methods; these included optical interferometry, planar scanning, reciprocity combined with time-delay spectrometry, and suspended-sphere radiometry. After converting the results to end-of-cable open-circuit sensitivities, in most cases agreement between the various values was within ±10 percent at all frequencies.**

I. INTRODUCTION

CONSIDERABLE effort has been devoted in recent years to the development and calibration of miniature hydrophones used for the characterization of medical ultrasonic fields in the frequency range 0.5-15 MHz. The most suitable devices are those with active elements made from the piezoelectric polymer polyvinylidene fluoride (PVDF), and the AIUM/NEMA Safety Standard [1] specifically recommends the use of such devices. Although various calibration techniques have been developed, few intercomparisons have been undertaken to compare calibration results obtained at different laboratories. The only published results are those given by Gloersen *et al.* [2], in which results obtained using the planar-scanning technique were compared with those obtained using reciprocity. More recently, interferometry has been developed as a primary standard for the calibration of hydrophones [3] at the National Physical Laboratory (NPL), UK, and a number of membrane hydrophones are now being used in the United States with calibrations traceable to this standard. With the increased use of calibrated membrane hydrophones, there has been an interest in comparing the calibration results obtained at various laboratories in the United States with those obtained using interferometry at NPL. It was therefore decided to organize an informal intercomparison between NPL and the Center for Devices and Radiological Health of the US Food and Drug Administration. The intercomparison was subsequently extended to other laboratories in the US who had expressed an interest in the exercise.

Two membrane hydrophones with 1-mm-diameter active elements were used for the intercomparison. Both were manufactured by GEC Research Ltd., Marconi Research Centre, Chelmsford, UK, and are of the design previously published [4], [5]. The first was a coplanar shielded device, type Y-33-6524, serial B679, and the second was a bilaminar device, type Y-33-7611, serial IP026. The purpose of the exercise was to determine the end-of-cable loaded sensitivity of the devices at frequencies chosen by the various laboratories. In all cases, the laboratories were to report to NPL only the sensitivity figures together with electrical loading information and temperature during the calibration. In addition, a short description of each calibration method was prepared.

II. CALIBRATION METHODS AND COMMUNICATED RESULTS

A. Drexel University

The two membrane hydrophones were calibrated by comparison with a standard hydrophone using time-delay spectrometry (TDS) [8], [9]. The membrane hydrophones and the standard hydrophone were exposed to the same free-field pressure and the electrical output voltages of the hydrophones were compared.

The standard hydrophone was a needle-type 0.6-mm miniature PVDF hydrophone probe [6] manufactured by the Danish Institute of Biomedical Engineering, DK 2605 Copenhagen, Denmark. The probe had been calibrated using a modified two-transducer reciprocity technique [7]. In the conventional technique, first the ultrasound transmitter is calibrated using self-reciprocity. Once the transmit transfer function is known, the sensitivity of the miniature ultrasound probe is determined by placing the probe

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in the known acoustic field. This conventional reciprocity calibration is usually carried out at discrete frequencies. To provide a calibration of the standard hydrophone as a continuous function of frequency, a modified two-transducer reciprocity in combination with the TDS technique has been employed [8]. The mechanical positioning system, including a large plane reflector, was similar to the one described in [7]. The appropriate voltages and transmitting current were recorded in the frequency range from 1 to 10 MHz using a measurement arrangement similar to the one described in [9].

The calibration of the membrane hydrophones was carried out in the following way. The reciprocity-calibrated needle-type hydrophone was placed in the far field (near the last pressure maximum) of a wide-band PVDF acoustic source of diameter 10 mm [10]. The hydrophone was positioned for maximum output voltage and the signal measured and stored using a Hewlett-Packard spectrum analyzer, type 3585A. The reciprocity-calibrated hydrophone was then replaced by the membrane hydrophone of unknown sensitivity. The output voltage from the membrane hydrophone was recorded and compared with that measured at the terminals of the standard needle-type hydrophone. The corresponding end-of-cable loaded sensitivities were then calculated in terms of dB re 1 V/μPa and are given in Table I.

The pressure level during calibration was chosen to be approximately 10 kPa, sufficiently low to minimize the possible errors due to nonlinear propagation [11]. During calibration, degassed and deionized water was used with a conductivity less than 3 μS. The hydrophones were terminated with the input impedance of the spectrum analyzer which, according to HP specifications, is nominally 1 MΩ in parallel with 30 pF. The overall uncertainty of calibrations (including systematic and random uncertainties) is estimated to be less than ±10 percent [2].

B. General Electric Company (GE)

The planar-scanning method was used to calibrate the hydrophones, in a manner similar to that described elsewhere in this issue [12]. The important aspects of the transducer calibration are as follows. A B-scan transducer (2.0-cm nominal diameter, 10-cm focus), KB-Aerotek 3.5 MHz, type K, was used as the ultrasound source. It was electrically excited using a Hewlett-Packard function generator, type 8116A, generating a ten-cycle gated burst at each of the three frequencies, 2.65, 3.71, and 4.78 MHz. The burst was subsequently amplified and low-pass filtered to exclude any harmonic distortion. The three frequencies were chosen to correspond to calibration frequencies of a National Bureau of Standards (NBS) lithium niobate source transducer [14].

The hydrophone was translated under computer control using a Klinger CC1.2 motorized translation unit, and the beam profiles were sampled at 0.5-mm increments. The output of the hydrophone was recorded using a Tektronix 7D20 digital oscilloscope (sampling rate 40 MHz) that had an input impedance of 1 MΩ in parallel with 20 pF.

TABLE I
CALIBRATION RESULTS OBTAINED BY DREXEL UNIVERSITY AT 22 ± 1°C

	End-of-Cable Loaded Sensitivity (dB re 1 V μPa) (Load: 1 MΩ ‖ 30 pF)	
Frequency (MHz)	Bilaminar IP026	Coplanar B679
1	−260.09	−261.24
2	−259.86	−261.26
3	−259.96	−261.36
4	−259.67	−261.07
5	−259.48	−261.08
6	−259.42	−261.22
7	−259.01	−261.15
8	−258.81	−261.26
9	−258.59	−261.24
10	−258.17	−261.12

The power output of the B-scan source for the various output intensities was measured separately using a Cahn 25 electrobalance with a SOAB rubber absorber (B.F. Goodrich). The balance was calibrated using the NBS source transducer driven at each of the calibration frequencies [13].

Typical excitation conditions of the transducer corresponded to a spatial-peak pulse-average intensity of 2–3 W cm^{-2} and a total power approximately 20 mW. The beam profiles were generated by calculating the pulse intensity integral (mean square voltage) as a function of position. The calibration was performed at a transducer-hydrophone separation of 10 cm at all frequencies and using de-ionized water. The results of the calibration are given in Table II.

C. Center for Devices and Radiological Health (CDRH)

The two hydrophones were calibrated by placing them in the field of narrow-band source transducers having intensity distributions that had been previously determined by the planar-scanning technique. The planar-scanning procedure was essentially the same as that described in [14], the only difference being that the rms rather than the temporal-peak hydrophone voltage was measured and recorded at each spatial point. This was done to minimize any errors that may arise due to finite amplitude distortion of the transmitted pressure wave [12].

Two types of source transducer were used, both employing lithium niobate as the piezoelectric element. One transducer, obtained from NBS [13], had a 1.59-cm active element diameter and a fundamental thickness resonance at 0.5 MHz. It was driven at overtone frequencies for which NBS calibration data had been obtained, namely 2.649 MHz and 5.839 MHz. The second transducer, constructed at CDRH, had an active element diameter of 1.27 cm and a thickness resonance frequency of 3.510 MHz. Its radiation conductance [14], [15] was determined by NBS.

The ultrasonic powers from these sources were in the range 50–250 mW, and hydrophone measurements were

TABLE II
CALIBRATION RESULTS OBTAINED BY GENERAL ELECTRIC COMPANY AT 24°C

Frequency (MHz)	End-of-Cable Loaded Sensitivity (μV Pa^{-1}) (Load: 1 MΩ ∥ 20 pF) Bilaminar IP026	Coplanar B679
2.65	0.132	0.088
3.71	0.112	0.090
4.78	0.114	0.085

made near the last axial pressure maximum. The hydrophone end-of-cable loaded sensitivities were computed using a water density of 1000 kg m^{-3} and a sound speed of 1490 m s^{-1}, the latter chosen to correspond to a water temperature of 22 ± 1°C, the range for these measurements. The water conductivity was <2 μS, and the hydrophone cables were connected to an oscilloscope having a vertical amplifier input impedance of 1 MΩ in parallel with 22 pF. The results are given in Table III and the uncertainty for these calibrations is estimated to be less than 10 percent [14].

D. University of Illinois

The hydrophones were calibrated by placing them in an unfocused sound field that had been characterized by the Bioacoustics Research Laboratory's primary calibration technique, the suspended ball [16]. A steel ball is glued to a nylon filament with a small amount of Silastic and is suspended vertically in the sound beam axis. With the application of ultrasonic energy, the displacement of the steel ball is measured with a cathetometer. For small angular deflections, the spatial-peak temporal-average intensity (I_{SPTA}) is determined by

$$I_{\mathrm{SPTA}} = \frac{dm_b gc}{la^2Y}$$

where d is the horizontal ball displacement, m_b is the buoyant mass of the ball, g is the gravitation constant, c is the speed of sound in water, l is the suspension length, a is the ball radius, and Y is the acoustic force function. Y depends on the ratio of the ball size to the wavelength in the medium, the medium density, and the elastic properties of the ball. Y has been determined for the three sizes ($a = 0.099$, 0.119, and 0.159 cm) of the grade 10 440C stainless steel used in the study [16].

With the ball positioned at the point of maximum intensity, I_{SPTA} was determined, and then each hydrophone was placed with its active element at the same position as the ball and aligned for maximum signal. One half the peak-to-peak voltage V_{op} at the hydrophone output was measured using an oscilloscope. The procedure was repeated for various intensity levels, the field intensity being varied by changing the voltage applied to the transducer. The inverse intensity response factors $1/K_f^2$, were determined from the slope of the resulting plot of I_{SPTA} versus V_{op}^2 using the relationship

$$I_{\mathrm{SPTA}} = V_{\mathrm{op}}^2/2K_f^2.$$

TABLE III
CALIBRATION RESULTS OBTAINED BY CDRH AT 22°C

Frequency (MHz)	End-of-Cable Loaded Sensitivity (μV Pa^{-1}) (Load: 1 MΩ ∥ 22 pF) Bilaminar IP026	Coplanar B679
2.649	0.101	0.0875
3.510	0.116	0.0976
5.839	0.112	0.0897

Degassed and distilled water was used for all the measurements, and the results are given in Table IV. Intensities were chosen such that the acoustic-pressure waveforms measured with the hydrophones were sinusoidal. The ranges of I_{SPTA} used to determine the response factors were 0.05–1 W/cm^2 for the 1-MHz data, 0.01–0.5 W/cm^2 for the 3-MHz data, and 0.01–0.1 W/cm^2 for the 5-MHz data. The -1-dB beamwidths for the field were approximately 4 mm at the location used for the calibration measurements.

E. Hewlett-Packard (HP)

The two hydrophones were calibrated by two methods; planar scanning using an NBS reference transducer and comparison (or substitution) using a reference standard hydrophone. The planar-scanning method was a modified version of the standard procedure [1]. A lithium niobate standard transducer made by NBS [13] was used in a tone-burst mode with its drive peak-to-peak amplitude adjusted to give the same as that used for an 800 mW continuous-wave acoustic output, with no planar reflector in the acoustic path. The hydrophones were mounted on a radial arm whose pivot axis was aligned with the center of the face of the source transducer. Four equiangular radial scans were made with the mean square hydrophone output recorded at each angular increment in each scan. A scan was also made with the source off to determine the mean square noise level. This noise level was subtracted from each mean square voltage in the scan data sets, and all scans were used to estimate the power passing through a spherical cap containing the scans. A correction was applied for the water attenuation at the axial hydrophone distance of 18 cm [14]. The hydrophone was connected to a GEC Research (Marconi) amplifier which had an input impedance equivalent to 50 kΩ in parallel with 4.8 pF. No correction was made for the electrical loading of the hydrophone by the amplifier although all measurements made at the output of the amplifier were corrected for the known gain of the amplifier. Results are given in Table V, columns HP(A).

The second calibration method employed was the comparison of the "unknown" hydrophones with a reference

TABLE IV
CALIBRATION RESULTS OBTAINED BY THE UNIVERSITY OF ILLINOIS AT 23°C

Frequency (MHz)	Inverse Intensity Response Factor (kW cm^{-2} V^{-2}) (Load: 1 MΩ ∥ 15 pF)	
	Bilaminar IP026	Coplanar B679
1	5.2	7.8
3	4.6	7.0
5	4.8	5.0

TABLE V
CALIBRATION RESULTS OBTAINED BY HEWLETT-PACKARD AT 24°C

Frequency (MHz)	End-of-Cable Sensitivity (μV Pa^{-1})			
	Bilaminar IP026		Coplanar B679	
	HP(A)	HP(B)	HP(A)	HP(B)
2.649	0.1361	0.1270	0.1061	0.1018
4.775	0.1380	0.1418	0.1031	0.1106

[a] Two sets of calibration results are given: HP(A) refer to those obtained using planar scanning and are sensitivities (loaded) into a load of 50 kΩ in parallel with 4.8 pF; HP(B) refer to those obtained using substitution and are end-of-cable open-circuit sensitivities.

standard hydrophone. The reference was also a Marconi device, bilaminar type with an active element of diameter 0.5 mm, and had been previously calibrated at NPL. The same NBS reference source was driven with tone-burst excitation, with the hydrophone 15 cm from the transducer, and the rms hydrophone voltage recorded at each frequency. This procedure was repeated for the two "unknown" hydrophones and also for the reference hydrophone. The sensitivity for the unknown hydrophone was determined by scaling the known open-circuit sensitivity of the reference standard hydrophone by the ratio of the rms voltage recorded for the unknown hydrophone to that for the reference hydrophone. The sensitivities are given as open-circuit values after applying a small correction to take account of the difference in electrical impedance between the reference and the unknown hydrophones.

F. National Physical Laboratory (NPL)

The two hydrophones were calibrated using two methods, both traceable to the NPL primary standard laser interferometer. The first method used was the normal procedure adopted at NPL for the routine calibration of hydrophones. This involves a substitution procedure in which the device to be calibrated is compared with a reference hydrophone by placing them sequentially in the same acoustic field. To cover the frequency range 1–15 MHz, an acoustic field is employed containing many harmonically related frequency components and can thus be used to calibrate the hydrophones at a number of frequencies simultaneously. The method used to produce the required acoustic field is to excite a 1-MHz transducer of diameter 40 mm with a high-amplitude tone burst. At a sufficiently large distance from the transducer (typically 1 m), the ultrasonic wave becomes distorted due to nonlinear propagation and contains component frequencies at integer multiples of 1 MHz. The reference hydrophone is first placed in this field and the output waveform recorded using a high-speed digitizer. The digitized waveform is analyzed using a fast Fourier transform algorithm to calculate the amplitude of the harmonic components. The reference hydrophone is then replaced by the device to be calibrated with its active element at the same position in the acoustic field. After optimization for maximum signal, the output waveform is recorded as before and harmonically analyzed. The ratio of the amplitudes at each harmonic for the two devices are directly related to the ratios of the hydrophone sensitivities. As the sensitivities of the reference hydrophone had previously been determined using the NPL primary standard laser interferometer, the sensitivities of the device being calibrated are readily determined.

Deionized and degassed water with a conductivity of less than 5 μS was used for the measurements, and the results are given in Table VI under column NPL(A). Overall uncertainties at the different frequencies, given at the 95 percent confidence level, were

±6 percent at 1–7 MHz
±7 percent at 8–9 MHz
±8 percent at 10–12 MHz
±9 percent at 13 MHz
±10 percent at 14 MHz
±11 percent at 15 MHz.

The two hydrophones were also calibrated directly against the primary standard. The primary standard consists of a phase-locked Michelson interferometer [3]. A transducer produces an acoustic field that is detected with a thin plastic pellicle, acoustically transparent but optically reflecting. The displacement of the pellicle is determined using the interferometer and the corresponding acoustic pressure in the field calculated. The hydrophone to be calibrated is then placed in the field in place of the pellicle and calibrated by measuring the output voltage corresponding to the known acoustic pressure. This procedure was used to calibrate both hydrophones, and the results are given in Table VI under the column NPL(B) after applying electrical loading corrections. Overall uncertainties at the 95 percent confidence level (including both random and systematic components) were

±4 percent at 1, 2.649 and 3.51 MHz
±5 percent at 5.839 and 10 MHz
±8 percent at 15 MHz.

The calibrations described above were undertaken after the hydrophones had been returned to NPL. However, before the intercomparison, the devices had been calibrated at five frequencies between 1 and 10 MHz. For the co-

TABLE VI
CALIBRATION RESULTS OBTAINED BY NPL[a]

Frequency (MHz)	End-of-Cable Open-Circuit Sensitivity (μV Pa^{-1}) Bilaminar IP026 NPL(A)	Bilaminar IP026 NPL(B)	Coplanar B679 NPL(A)	Coplanar B679 NPL(B)
1	0.1221	0.1292	0.1047	0.1086
2	0.1340	—	0.1067	—
2.649	—	0.1372	—	0.1083
3	0.1375	—	0.1057	—
3.51	—	0.1405	—	0.1101
4	0.1406	—	0.1066	—
5	0.1458	—	0.1071	—
5.839	—	—	—	0.1094
6	0.1493	—	0.1067	—
7	0.1523	—	0.1066	—
8	0.1567	—	0.1071	—
9	0.1610	—	0.1077	—
10	0.1673	0.1614	0.1083	0.1121
11	0.1733	—	0.1082	—
12	0.1798	—	0.1096	—
13	0.1869	—	0.1105	—
14	0.1958	—	0.1120	—
15	0.2091	0.2051	0.1141	0.1221

[a] Two sets of results are given; NPL(A) refer to the substitution technique at 19°C and NPL(B) refer to the direct calibration using interferometry at 17.5°C.

planar shielded device, B679, the maximum difference between pre- and post-intercomparison was one percent at all frequencies (rms difference 0.6 percent). For the bilaminar device, IP026, the maximum difference was nine percent (rms 4.7 percent). The larger differences for this device were only at 1 and 2.25 MHz and were probably caused by alignment uncertainties. Overall, there is no evidence to suggest that there was any systematic difference between the pre- and post-intercomparison results, a conclusion confirmed by the overall results given in Section III.

III. COMPARISON OF RESULTS

To compare the results given in Tables I–VI, it is necessary to convert them to a common quantity, the most convenient being the end-of-cable open-circuit sensitivity. This is done by correcting the various results for both the different electrical loadings and the temperatures used.

However, an additional calculation is required in the case of the results from the University of Illinois. These are first converted to end-of-cable pressure sensitivity figures. The intensity response factor K_f^2 V^2 W^{-1} cm^2 is related to the end-of-cable pressure sensitivity M_f V Pa^{-1} by the following relation

$$M_f = \frac{0.01}{z^{1/2}} K_f$$

where z is the acoustic impedance of water (taken as 1.485×10^6 kg m^{-2} s^{-1}).

As the electrical loading of the hydrophones during calibration differed among the laboratories, all results were first converted to end-of-cable open-circuit sensitivities. To do this, the electrical impedances of the hydrophones were determined using a Hewlett–Packard vector impedance meter, type 4193A, and the correction applied using the equation given in [17]. Although the complex impedance (real and imaginary parts) was used, both devices could be considered to be capacitative in the frequency range 1 to 5 MHz; with capacitances of 85 and 118 pF for the bilaminar device IP026 and coplanar device B679, respectively (the latter measured in deionized water).

Where appropriate, calibration results for the coplanar shielded device were corrected to yield sensitivities at 22°C using a figure for the temperature sensitivity of 0.6 percent °C^{-1} [18]. No corrections were applied to the bilaminar results as the temperature sensitivity is between 0 percent °C^{-1} and 0.2 percent °C^{-1} [18].

Table VII and Fig. 1 give the end-of-cable open-circuit sensitivities of the bilaminar membrane hydrophone IP026 for the various laboratories after applying the electrical loading corrections. Table VIII and Fig. 2 give the results for the coplanar membrane hydrophone, B679.

Figs. 1 and 2 demonstrate interesting and relevant features concerning the overall frequency response of the hydrophones. The increase in sensitivity of the bilaminar device IP026 shown in Fig. 1 is due to the thickness resonance of the 50 μm PVDF membrane, occurring at about 23 MHz [19], [20]. In addition, there is also a gradual increase in sensitivity caused by the decrease in dielectric constant at PVDF with increase in frequency [20]. For the coplanar device, B679, the thickness resonance occurs at a higher frequency, namely, 40 MHz [4], [20], and there is a negligible contribution due to the variation of the di-

TABLE VII

END-OF-CABLE OPEN-CIRCUIT SENSITIVITIES FOR THE 1-mm BILAMINAR MEMBRANE HYDROPHONE IP026 AT 22°C

Frequency (MHz)	End-of-Cable Open-Circuit Sensitivity (μV Pa^{-1})							
	Drexel	GE	CDRH	Illinois	HP(A)	HP(B)	NPL(A)	NPL(B)
1	0.1323	—	—	0.1331	—	—	0.1221	0.1292
2	0.1376	—	—	—	—	—	0.1340	—
2.649	—	0.1637	0.1277	—	0.1438	0.1279	—	0.1372
3	0.1369	—	—	0.1430	—	—	0.1375	—
3.51	—	—	0.1472	—	—	—	—	0.1405
3.71	—	0.1394	—	—	—	—	—	—
4	0.1422	—	—	—	—	—	0.1406	—
4.78	—	0.1422	—	—	0.1458	0.1428	—	—
5	0.1457	—	—	0.1404	—	—	0.1458	—
5.839	—	—	0.1428	—	—	—	—	—
6	0.1470	—	—	—	—	—	0.1493	—
7	0.1543	—	—	—	—	—	0.1523	—
8	0.1577	—	—	—	—	—	0.1567	—
9	0.1619	—	—	—	—	—	0.1610	—
10	0.1091	—	—	—	—	—	0.1673	0.1614
11	—	—	—	—	—	—	0.1733	—
12	—	—	—	—	—	—	0.1798	—
13	—	—	—	—	—	—	0.1869	—
14	—	—	—	—	—	—	0.1958	—
15	—	—	—	—	—	—	0.2091	0.2051

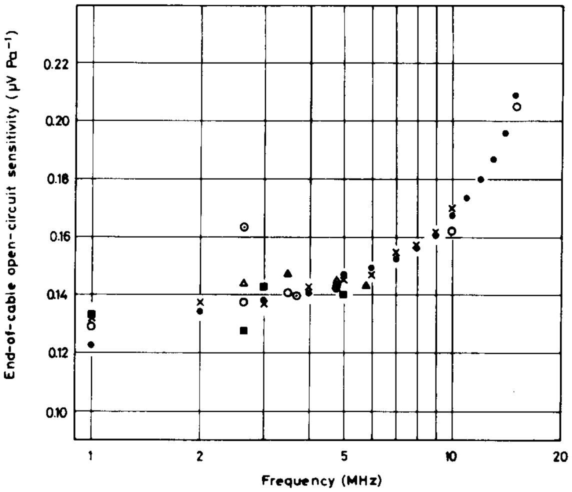

Fig. 1. Values of end-of-cable open-circuit sensitivity determined at various laboratories for bilaminar membrane hydrophone, IP026. A key to symbols follows. ×—Drexel University. ⊙—General Electric Co. (GE). ▲—Center for Devices and Radiological Health (CDRH). ■—University of Illinois. △—Hewlett-Packard (HP(A)). □—Hewlett-Packard (HP(B)). ●—National Physical Laboratory (NPL(A)). ○—National Physical Laboratory (NPL(B)).

electric constant of PVDF. Both features are evident in the results obtained by Drexel University and NPL.

Table IX gives the differences between the various calibration results and those of NPL(A), giving the mean and rms differences. The NPL(A) results were used as a reference as they are the most extensive results and are representative of the routine calibration process at NPL. If the two results representing the largest differences are excluded, then all individual differences are within ±10 percent of the NPL(A) results for both hydrophones, consistent with the various estimates of total uncertainty. These results demonstrate agreement that is within the individual assessments of uncertainty at all but two frequencies. The calibration result obtained by the University of Illinois for B679 at 5 MHz which showed a maximum difference of 19.5 percent was performed within one hour of the source transducer failing. This could have led to a decrease in its efficiency at the time of calibration.

IV. CONCLUSION

Results of an interlaboratory comparison of hydrophone calibration techniques have been given in the frequency

TABLE VIII
END-OF-CABLE OPEN-CIRCUIT SENSITIVITIES FOR THE 1 mm COPLANAR MEMBRANE HYDROPHONE B679 AT 22°C

Frequency (MHz)	End-of-Cable Open-Circuit Sensitivity (μV Pa^{-1})							
	Drexel	GE	CDRH	Illinois	HP(A)	HP(B)	NPL(A)	NPL(B)
1	0.1086	—	—	0.1044	—	—	0.1066	0.1099
2	0.1086	—	—	—	—	—	0.1086	—
2.649	—	0.1018	0.1040	—	0.1091	0.1006	—	0.1096
3	0.1073	—	—	0.1097	—	—	0.1076	—
3.51	—	—	0.1158	—	—	—	—	0.1114
3.71	—	0.1040	—	—	—	—	—	—
4	0.1109	—	—	—	—	—	0.1085	—
4.78	—	0.0983	—	—	0.1060	0.1093	—	—
5	0.1107	—	—	0.1303	—	—	0.1090	—
5.839	—	—	0.1063	—	—	—	—	0.1107
6	0.1088	—	—	—	—	—	0.1086	—
7	0.1093	—	—	—	—	—	0.1085	—
8	0.1079	—	—	—	—	—	0.1090	—
9	0.1079	—	—	—	—	—	0.1096	—
10	0.1091	—	—	—	—	—	0.1102	0.1134
11	—	—	—	—	—	—	0.1101	—
12	—	—	—	—	—	—	0.1116	—
13	—	—	—	—	—	—	0.1125	—
14	—	—	—	—	—	—	0.1140	—
15	—	—	—	—	—	—	0.1162	0.1236

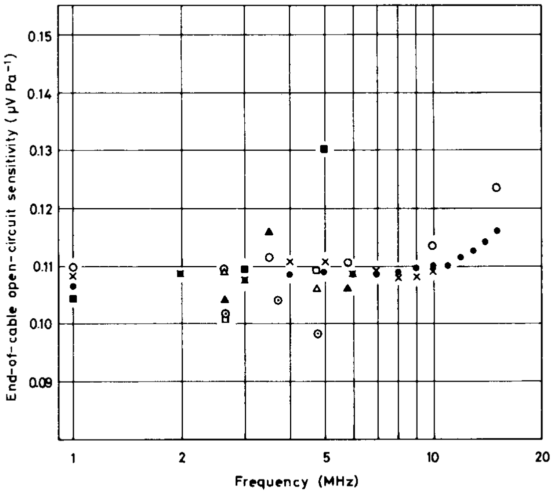

Fig. 2. Values of end-of-cable open-circuit sensitivity determined at various laboratories for coplanar shielded membrane hydrophone, B679. (See Fig. 1 for key to symbols).

TABLE IX
PERCENTAGE DIFFERENCES BETWEEN THE VARIOUS CALIBRATION RESULTS AND THOSE OBTAINED BY NPL(A) FOR THE TWO HYDROPHONES

	Drexel	GE	CDRH	Illinois	HP(A)	HP(B)	NPL(B)
	1-mm bilaminar device, IP026						
Maximum	+8.4	+20.0	−6.7	+9.0	+5.4	−6.2	+5.8
Mean	+1.4	+6.1	−1.6	+3.1	+3.2	−3.6	+0.4
RMS	2.9	11.5	5.5	6.1	3.9	4.5	3.2
	1-mm coplanar device, B679						
Maximum	+2.2	−9.7	+7.2	+19.5	−2.7	−6.9	+6.0
Mean	+0.3	−6.4	−0.9	+6.5	−0.9	−3.3	+0.4
RMS	1.3	6.9	4.7	11.3	2.0	4.9	3.6

range 1-10 MHz. Two membrane hydrophones were circulated to six laboratories. The laboratories employed a range of different calibration techniques including optical interferometry, planar scanning, reciprocity, time-delay spectrometry, and suspended sphere radiometry. All results had to be converted to end-of-cable open-circuit sensitivities to enable them to be intercompared. This stresses the need to report carefully the loading conditions of the hydrophone probes together with appropriate parameters such as cable length between the hydrophone output terminals and any amplification stage and also the input impedance of any such amplifier. Although of minor importance, the temperature at which measurements were taken was also taken into account as it contributes to the overall measurement or calibration uncertainty.

The conclusion of the present intercomparison is that the results are within the estimated overall uncertainties. The results also show that the various laboratories are capable of performing reliable and repeatable calibrations. Although most results were in the range 1-6 MHz where calibration difficulties are less severe than at higher frequencies, only in two cases did the values differ by more than 10 percent from the reference measurements. Considering the wide range of techniques employed and the estimates of overall uncertainty (typically ±10 percent), these results are particularly satisfactory. On the other hand, the overall calibration results indicated that discrepancy can be as high as 20 percent. This indicates the need for the development of procedures which allow minimization of these discrepancies [21].

In the future, it would be desirable to extend intercomparison to higher frequencies, beyond 10 MHz. Knowledge of the frequency response and sensitivity of the hydrophone probes at frequencies beyond 10 MHz is becoming a necessity especially when the measured acoustic waveforms are highly distorted and contain a significant level of higher harmonics. It would also be desirable to repeat the intercomparison in the future extending the number of laboratories involved.

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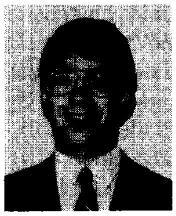
David R. Bacon, for a biography and photograph see page 121 of this issue.

Scott S. Corbett III, for a biography and photograph see page 167 of this issue.

Gerald R. Harris (S'76-M'79-SM'82), for a biography and photograph see page 86 of this issue.

Peter A. Lewin (SM'85), for a biography and photograph see page 86 of this issue.



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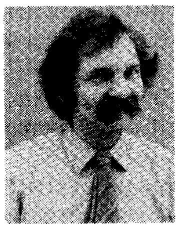
William D. O'Brien (S'64-M'70-SM'79), for a biography and photograph see page 33 of this TRANSACTIONS.



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