A multiple-frequency hydrophone calibration technique

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A method is described for comparing the sensitivity of two hydrophones over the frequency range 1–15 MHz. This technique forms the basis for the dissemination of national ultrasonic standards in the U.K. over this frequency range. A reference hydrophone is placed in an ultrasonic field and then the device being calibrated is substituted and the two output voltages are compared. This substitution method utilizes a broadband ultrasonic field produced by nonlinear propagation. Thus it is possible to cover the whole frequency range with a single measurement on each hydrophone. The overall uncertainty in the intercomparison of two hydrophones increases from $\pm 4.2\%$ at 1 MHz to $\pm 8.2\%$ at 15 MHz (95% confidence level). The method has been compared with discrete-frequency substitution, time-delay spectrometry, and absolute calibrations using the National Physical Laboratory (NPL) Primary Standard Laser Interferometer. Various designs and sizes of hydrophones were compared, and agreement was within the combined random uncertainties for all the comparisons.

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I. BACKGROUND

There is an increasing requirement to calibrate hydrophones used for the characterization of medical ultrasonic fields.[1–4] This arises from the need to specify the acoustic output of equipment, in absolute terms, for safety and standardization purposes. A calibration method must have the potential to cover the range of typical transducer frequencies in common use (1–10 MHz) and also the higher frequencies present in waveforms from medical diagnostic equipment, which are distorted due to nonlinear propagation.[5–9] Most absolute calibration techniques are too time-consuming to perform on every hydrophone manufactured. However, it is possible to calibrate a hydrophone by using a substitution technique in which the hydrophone to be calibrated is compared with a reference hydrophone, and this may result in only a small reduction in accuracy. A review of the various available calibration techniques available in 1986[10] concluded that further work was required to develop and validate such intercomparison techniques.

The present technique is now in routine use to provide the basis for national ultrasonic standards dissemination in the U.K.[11] Secondary standard hydrophones are calibrated using the National Physical Laboratory (NPL) Primary Standard Laser Interferometer. These hydrophones then become the reference devices for the present substitution technique that is used to calibrate working standard hydrophones. A wide range of hydrophones have been calibrated using this method. These include ceramic needle probes,[12,13] polyvinylidene fluoride (PVDF) needle probes,[14–16] and PVDF membrane hydrophones.[17,18] Much of this paper concentrates on the latter type of hydrophone. However, experience has been gained with many different electrical shielding arrangements, electrical impedances, and element sizes from 2 to 0.1 mm in diameter.

There are certain problems involved with substitution techniques, most of which have to be addressed separately for each technique. First, there is the correction for the load impedance used when measuring the hydrophone voltage, which will affect the hydrophone sensitivity by an amount dependent on both the hydrophone and load impedances. This problem is common to all substitution techniques, but, if the technique allows the use of a low-capacitance load, then the correction can be reduced. A correction formula can be applied utilizing the complex impedances of the hydrophone and load.[3,4,10,19]

Second, it is necessary for the calibration to be performed under free-field conditions so that the calibrated hydrophone measures the acoustic pressure that would exist in its absence. This entails the elimination of both electrical interference, caused by the transducer drive signal, and acoustical reflection or diffraction artifacts. An example of the latter is the effect of spatial averaging over the hydrophone element which integrates the acoustic pressure over its effective area.[1,3,4] This is not a problem if the hydrophones to be compared have identical effective areas or if they are calibrated in a plane-wave acoustic field. However, if neither of these is the case, then the effective areas of the hydrophones have to be determined at each frequency of calibration,[1,3,4] and a correction applied that is dependent on the type of acoustic field and the position of the hydrophone in it.[20] Thus, for substitution techniques where this effect is important, it may be necessary to recalculate the correction for each different hydrophone, transducer, frequency, and separation.

A third difficulty is that of positioning each hydrophone at exactly the same place in the acoustic field and then aligning it such that the sensitivity that is determined corresponds to the peak of the mainlobe of the hydrophone's directional response.

Several techniques for the intercomparison of hydrophone sensitivities have been described in the literature. The simplest of these is the discrete-frequency method,[10,17] where the substitution of hydrophones takes place in the farfield of a plane piston transducer that is excited with short tone bursts. This enables the simulation of free-field conditions by using a time gate to remove reflections and electrical interference. However, due to the structure of the acoustic field, a correction is required for spatial averaging whenever the hydrophone size is different from that of the reference hydrophone. At the NPL, the latter correction is performed using the method described by Brendel and Ludwig[20] for determining the G_2 correction in two-transducer reciprocity. Positioning and alignment of hydrophones are usually accomplished by simple maximization while viewing the amplified peak of the tone burst on an oscilloscope. The technique is relatively time-consuming, taking approximately 10 min per hydrophone per frequency point per repeat measurement. However, it provides a simple and accurate reference method that can be used over a wide range of frequencies. Typical random uncertainties in the discrete-frequency technique used at NPL are estimated to be less than $\pm 3\%$ (95% confidence level); overall uncertainties in the intercomparison of the two hydrophones are $\pm 5\%$ over the range 1–15 MHz. The procedure used at the NPL has been described previously.[10]

A development of the substitution method, suggested by several authors,[21–24] provides a calibration over a range of frequencies simultaneously. The technique uses a short pulse of ultrasound containing a broad spectrum of frequencies, and measurements are usually performed in the plane-wave region near to the transducer. The hydrophones are substituted into this field and a Fourier analysis is performed on each hydrophone signal. The technique assumes that the hydrophone need be aligned at only one frequency. In addition, the frequency range is limited by the availability of sufficiently broadband transducers. A full validation of this technique has not been reported as it is primarily used as a qualitative method for determining frequency response.

Another development has been the use of time-delay spectrometry (TDS).[13,15,25–28] In this technique, a broadband transducer is driven with a continuous-wave signal. The frequency of this signal is swept such that a given frequency transmitted by the transducer is received by the hydrophone after a delay equal to the propagation time. Thus, by sweeping the center frequency of a filter on the received signal at the same sweep rate as the drive signal but delayed by the propagation time, most of the electrical and acoustical noise can be filtered from the signal to obtain approximately free-field conditions. In practice, a spectrum analyzer and tracking generator are used to implement the technique. If the sizes of the hydrophones differ, there is a need to correct for spatial averaging as a function of frequency.

Lewin[15] has used TDS to calibrated hydrophones from 1 to 10 MHz by comparison with a reference hydrophone calibrated by reciprocity. The calibration had an estimated random uncertainty of $\pm 6\%$ and an overall uncertainty of $\pm 19\%$ (including an unknown contribution from the absolute calibration of the reference hydrophone). Chivers[13] has used the TDS technique to intercompare the frequency responses of hydrophones and has estimated the random uncertainties in this procedure to be $\pm 12\%$, mainly arising from difficulties in alignment. Ludwig and Brendel[27] have presented a comprehensive discussion of the TDS method with estimated uncertainties that depend on the hydrophones being intercompared. For two hydrophones of a similar type and frequency response, the estimated uncertainty is less than $\pm 3.5\%$ in the frequency range 1–15 MHz. When intercomparing two hydrophones of different types and frequency responses, these uncertainties rise to between $\pm 4.7\%$ and $\pm 12\%$ over the same frequency range. However, these uncertainties were determined by a simple repeat intercomparison of the same two hydrophones. Hence, they represent only the degree of self-consistency of the technique and do not include any contribution from systematic effects. The TDS method is ultimately limited by the accuracy of the spectrum analyzer and this is not included in the above state-

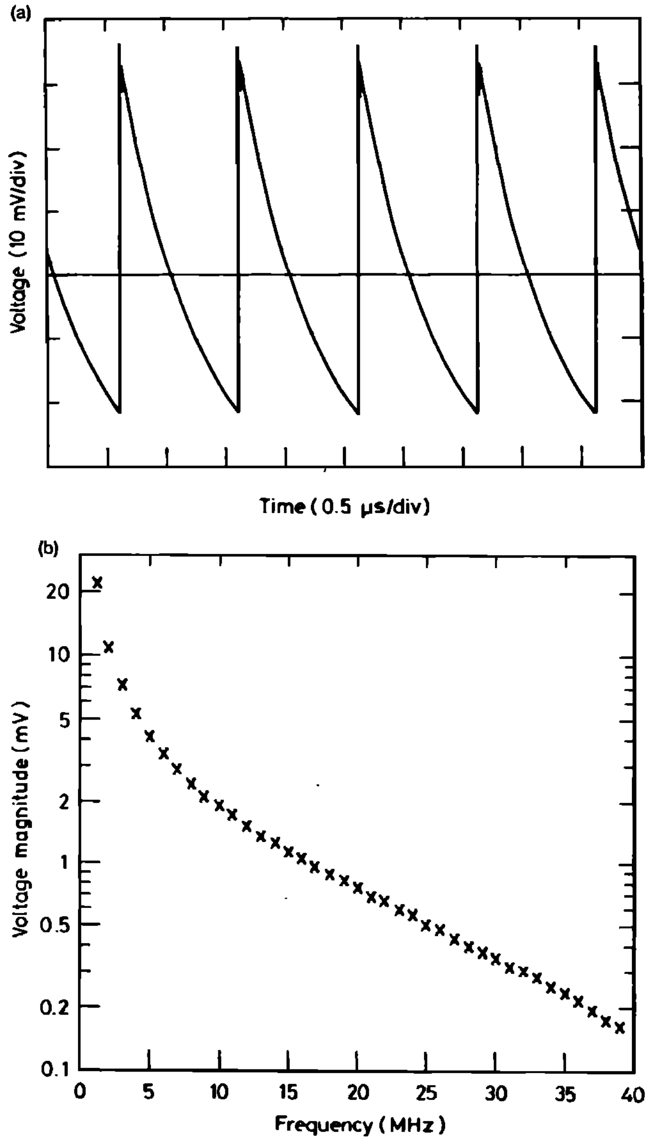


FIG. 1. (a) A typical sawtooth acoustic waveform as measured by a 1-mm-diam coplanar shielded membrane hydrophone made from 25-μm-thick polyvinylidene fluoride (PVDF) film; (b) the frequency content of such a waveform.

ment of self-consistency. A further problem arises if the direction of maximum sensitivity of the hydrophone is not the same at all frequencies. This is also a problem with the present technique and will be discussed in Sec. III. Advantages of TDS are a large increase in speed and a continuous frequency sweep. For some applications, these benefits may outweigh the limitations of the technique in accuracy and frequency range.

The principle of the present multiple-frequency technique is to use a substitution process in which each hydrophone is placed at a position in the ultrasonic field where the temporal waveform has a sawtooth shape due to nonlinear propagation. A typical waveform used in this technique is shown in Fig. 1(a). The asymmetrical appearance is due to shifts in the relative phases of the harmonics due to diffraction.[6] The harmonics present in such a waveform can extend over a wide range of frequencies enabling a calibration to be obtained at each harmonic frequency simultaneously. Figure 1(b) shows the voltage amplitude at each harmonic frequency as a result of taking the fast Fourier transform (FFT) of Fig. 1(a). The amplitude of the fundamental is typically 35% of the original peak-to-peak voltage, and the amplitude of the nth harmonic generally varies as $1/n$. The method has been used to intercompare hydrophone sensitivities up to 25 MHz in 1-MHz intervals[8,29] and up to 85 MHz in 5-MHz intervals.[18,29] There is no requirement for a broadband transducer, and the technique is much faster than the discrete-frequency method, requiring (when 15 frequency points are used) about 1 min per hydrophone per frequency point per repeat measurement (cf. 10 min for the discrete-frequency method). Other advantages of this technique are the ease of positioning and alignment of the hydrophones and the absence of a significant spatial-averaging effect due to the lack of structure and broadness of the ultrasound beam (see Sec. III). Hence, there is no requirement to calculate G_2 corrections at each frequency. Typical random uncertainties increase from $\pm 2\%$ at 1 MHz to $\pm 4\%$ at 10 MHz and $\pm 7\%$ at 15 MHz (95% confidence level); overall uncertainties in the intercomparison of the two hydrophones increase from $\pm 4.2\%$ at 1 MHz to $\pm 5.7\%$ at 10 MHz, and $\pm 8.2\%$ at 15 MHz. The aims of this paper are to describe the implementation of this technique at the NPL, to present the results of comparisons with three other independent techniques, and to produce a full treatment of the uncertainties in the method.

II. THE CALIBRATION FACILITY

A facility has been purpose-built for the calibration and characterization of hydrophones in a temperature-controlled room. The main components are a polycarbonate water tank of internal dimensions 1800 mm long, 300 mm wide, and 310 mm deep, and two coordinate-positioning systems: one for holding a transducer, and the other a hydrophone. These can be seen in Fig. 2. Two steel bars extend over the length of the tank, defining the z axis and providing the horizontal longitudinal guides for the two coordinate positioning systems. These consist of a horizontal (x axis) and vertical (y axis) translation slide. Each has a vertical rod which supports the hydrophone or transducer mount and also provides adjustment of rotation (about the y axis) and tilt (about the x axis). An essential additional feature of the overall arrangement is the ability to position the hydrophone element such that it is at the intersection of the rotation and tilt axes. This allows all five degrees of freedom to be totally independent, making alignment in an acoustic field easier.

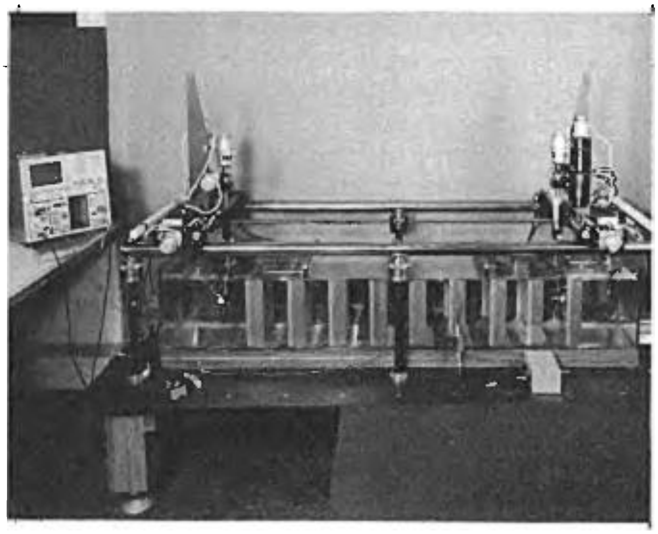


FIG. 2. The NPL hydrophone characterization facility.

To prevent both cavitation due to dissolved gas in the water and changes in hydrophone sensitivity due to high water conductivity, the tank is filled with degassed and deionized water with a conductivity less than 2 μS/cm. The schematic diagram in Fig. 3 illustrates the remaining apparatus. A 1-MHz transducer is placed at one end of the tank and the drive signal is provided through an impedance-matching network (Matec Inc) by an ENI AP400 power amplifier with a maximum power output of 400 W. The choice of power amplifier and matching network was determined by the requirement to produce high acoustic pressures at the face of transducers with low electrical impedances (about 10 Ω, see Sec. III). Instability of the drive signal can cause problems, but the ENI AP400 has a facility that maintains the maximum undistorted output and provides a drive signal that was measured to be stable to within

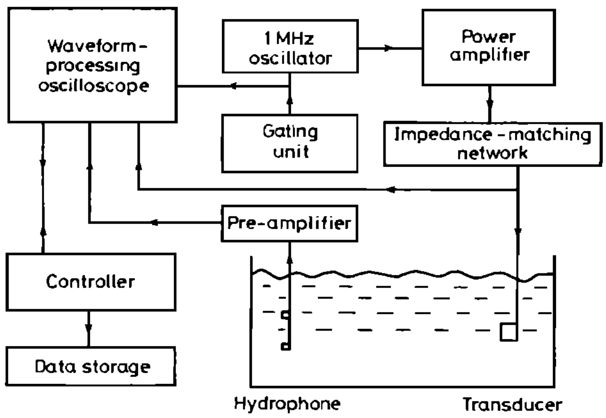


FIG. 3. Schematic diagram of the characterization facility.

$\pm 0.5\%$ over the time taken to intercompare a group of hydrophones (up to an hour). To determine this stability, peak-to-peak and rms drive voltages were measured at the transducer terminals using a high-impedance oscilloscope probe. Any harmonic distortion in the drive signal is reduced by the impedance-matching network and the narrow-band transducer. The tone-burst signal to the power amplifier is provided by a gated sinusoidal oscillator, the frequency of which is monitored by a frequency meter, as a small change in this frequency can change the higher harmonic frequencies significantly.

The hydrophone is mounted at the opposite end of the tank to the transducer, the total path length being greater than 0.8 m. To prevent interference due to glancing reflections from the tank sides or the water surface, the tank is lined with 2-mm-thick stainless steel baffles angled at 30 deg. to the tank side. Each baffle has a sharp edge pointing into the tank, and the distance of this edge from the tank side is deliberately randomized to reduce the constructive interference of reflections from these edges. A hydrophone preamplifier is used, which was developed and characterized at NPL.[17] It has an input impedance of 6 pF in parallel with 150 kΩ, a $-$3-dB bandwidth of 60 MHz, a gain of 0.3 dB, and a linearity within ± 0.05 dB up to a peak-to-peak output voltage of 1.5 V over the frequency range of interest. The output of this amplifier is connected via a 50-Ω load to a calibrated Tektronix 7854 waveform-processing oscilloscope with 10-bit resolution and 1024 samples at a sample rate of 0.5 megasamples per second. This is used to perform several averages of the signal and then the digitized waveform is transferred to a computer (Hewlett–Packard 9000 Series, model 320), where an FFT is performed. The magnitudes and relative phases of the harmonics are then stored on disc for comparison with those from the reference hydrophone.

The choice of digitizer and power amplifier is important, as the sample rate and duty cycle determine the waveform-acquisition time and therefore the speed of the intercomparison process. Unlike some power amplifiers, the ENI AP400 has no in-built limitation on duty cycle. However, to prevent heating of the transducer, the maximum pulse repetition rate used during calibrations is 150 Hz (equivalent to a duty cycle of 0.3%). This duty cycle gives a time-averaged output power of less than 0.5 W. The heating caused at this power level was estimated to give no significant change in transducer output due to effects such as thermal expansion and change in the piezoelectric coefficients of the transducer with temperature. The waveform-acquisition time could be decreased further by using a faster digitizer, but the present system performs eight averages of the waveform in less than 2 min; this is less than the 5 min required to align each hydrophone between acquisitions. The Tektronix 7854 oscilloscope has an advantage over many faster digitizers because it fits the 1024 digitization points into exactly ten divisions on the trace. This gives an increment between frequency points of 0.20 MHz after performing the FFT. Many other digitizers use 100 points per division, giving a frequency increment of approximately 0.195 MHz. This is a useful attribute when the digitized waveform will be used for an FFT.

III. OPTIMIZATION OF THE METHOD

The usefulness of a hydrophone calibration technique is determined not only by its speed, but also by the precision and accuracy obtainable. To optimize the latter for the present method, certain criteria must be satisfied. The first requirement is an adequate signal-to-noise ratio for all the harmonics in the received acoustic waveform up to the 15th harmonic. Second, it must be possible to align each hydrophone precisely and quickly.

The signal-to-noise requirement can be achieved by producing a large acoustic pressure at the transducer face and by carefully choosing the propagation distance. The transducers used in the NPL system are made from air-backed PZT and have diameters of 40 and 50 mm. To achieve a signal-to-noise ratio of at least 10 at 15 MHz, peak-to-peak drive voltages in excess of 100 V are required with an electrical transducer impedance as low as 10 Ω. It is not necessarily beneficial to use the largest propagation distance possible, as the harmonic generation due to nonlinear propagation is counteracted by the attenuating effect of the water (see Fig. 4). Although Fig. 4 suggests that the optimum distance is 0.4 m, the propagation distances used for calibration range from 0.8–1.2 m. There are several advantages of choosing this range of distances: Spatial averaging over the hydrophone element is reduced, alignment of the hydrophones is less critical, a close approximation to a sawtooth waveform is obtained [Fig. 1(a)], and the peak-to-peak acoustic pres-

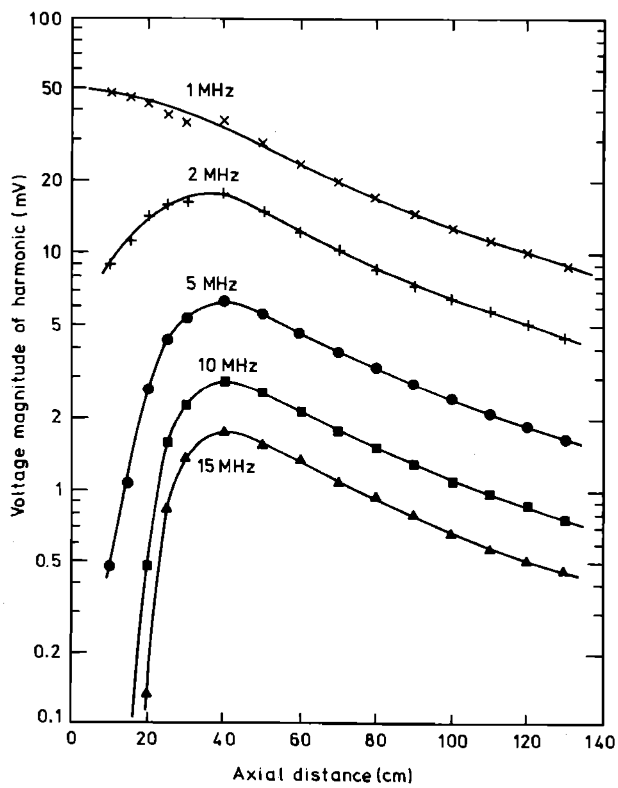


FIG. 4. The axial harmonic beam profile of the 50-mm transducer measured with a 9-μm-thick membrane hydrophone under the drive conditions mentioned in the text.

sure is still as high as 1 MPa.

Accurate reproducibility of the position and alignment of hydrophones has been achieved by careful development of the coordinate-positioning system and the alignment procedure. At the beginning of each set of measurements, the transducer and first hydrophone are positioned midway between the four sets of baffles described in Sec. II. The transducer is rotated and tilted to maximize the signal at the hydrophone, thus aligning the acoustic axis with the longitudinal axis of the tank (z axis). Within each set of measurements, the hydrophone mount can be easily raised out of the water, the hydrophone replaced, and the mount lowered again so that the element of the substituted hydrophone is close to the position of the previous one.

The final alignment of each hydrophone, to ensure that all hydrophones are placed at an identical position and orientation in the field, is achieved using the following procedure. The time delay between the transducer pulse and the hydrophone signal is matched to within ± 50 ns using the delayed time base of the oscilloscope. This gives a positioning reproducibility of $\pm 75\ \mu$m in the z direction. Then the hydrophone signal is maximized by optimizing the orientation (rotation and tilt) and position (x and y directions) of the hydrophone. A 20- or 40-MHz high-pass filter is temporarily inserted between the hydrophone amplifier and the oscilloscope to increase the sensitivity to misalignment. The advantage of this method can be seen by reference to Figs. 5 and 6, where both the directional response and the beam profile are narrower at higher frequencies.

The validity of this alignment method depends on the assumption that the peak of the directional response of the hydrophone occurs at the same angle for all the harmonic frequencies from 1 to 40 MHz. To test this assumption, the present calibration technique can be adapted to rapidly determine the directional response of a hydrophone from 1 to 30 MHz. The hydrophone is placed in the acoustic field as if for calibration. It is then rotated in known angular steps and the magnitudes of the harmonics determined at each angle of incidence of the ultrasound (cf. Ref. 30). Directional responses over this frequency range have been determined at the NPL using this method (see Fig. 5 for example) and so far there has been no indication of a deviation from co-axiality with PVDF membrane hydrophones. However, the directional responses of two PVDF needle-probe hydrophones of a new design[16] showed a marked deviation from co-axiality (see Fig. 7). Chivers[13] has found some evidence that needle-probe hydrophones may deviate from co-axiality over the frequency range 1–18 MHz.

An important advantage of this technique is that the effect of spatial averaging over the hydrophone element is negligible because the acoustic beam is broad, even at the higher harmonic frequencies (see Fig. 6). In fact, the beamwidth of the nth harmonic is relatively large because of finite-amplitude saturation effects and also decreases more slowly with increasing n than the $n^{-1/2}$ dependence found by Du and Breazeale.[31] Consequently, there is no need to apply a spatial-averaging correction, although a systematic uncertainty due to this effect has been included in the assessment of uncertainties.

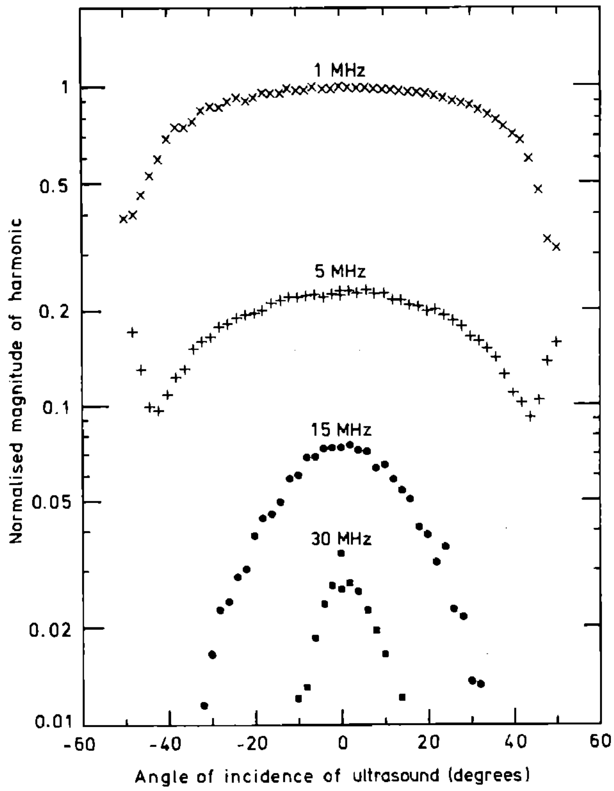


FIG. 5. The normalized output of a 0.2-mm-diam, 18-μm-thick membrane hydrophone as a function of the angle of incidence of the ultrasound beam.

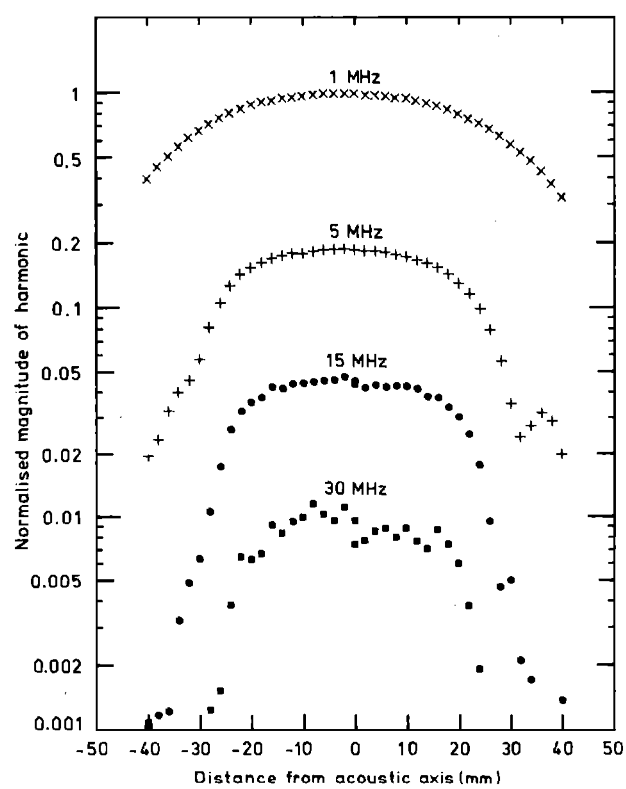


FIG. 6. The normalized output of a 1-mm-diam, 9-μm-thick membrane hydrophone as a function of distance from the acoustic axis, measured at a distance of 1 m from the 50-mm-diam transducer.

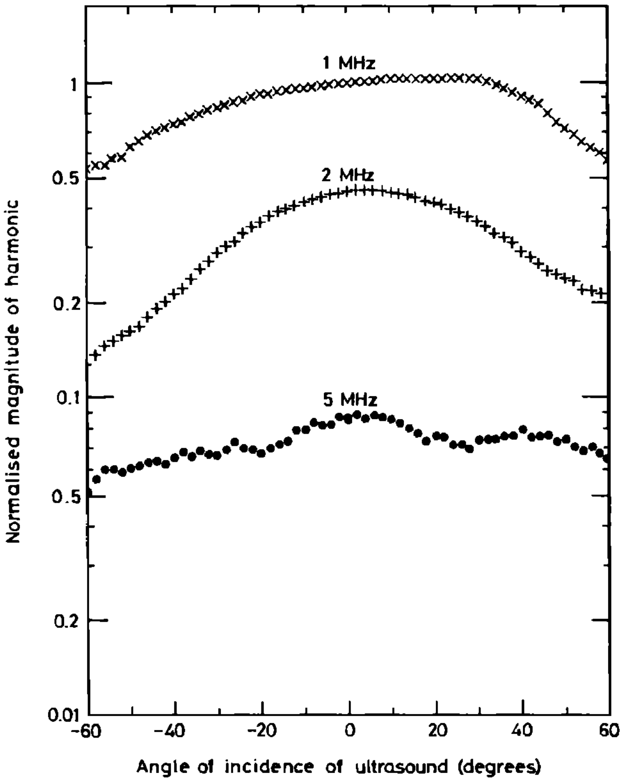


FIG. 7. The normalized output of a new design of PVDF needle-probe hydrophone (cf. Ref. 16) as a function of angle of incidence of the ultrasound beam.

IV. THE CALIBRATION PROCEDURE

The calibration procedure used at the NPL involves a group of up to five hydrophones under test and two reference hydrophones with known absolute sensitivities. The measurements are repeated four times, using different transducers or propagation distances. For each measurement set, the hydrophones under test are substituted in the field in a random order with the first and last hydrophones being reference devices. The calibration process, including four repeated measurements and calculation of results and uncertainties, can be completed in approximately 6 hours for a batch of five hydrophones.

The power amplifier remains switched on for a complete set of measurements in order to reduce output fluctuations. Before each measurement of the hydrophone voltage, the peak-to-peak and rms drive voltages are measured over the same cycles as are used for the hydrophone measurement. If this voltage varies by more than $\pm 0.5\%$ during a set of measurements, the set is repeated in order to avoid a systematic error.

The oscilloscope's delayed retrigger capability provides a stable measurement of the waveform even if the hydrophone moves slightly in the tank. The optimum stability occurs when the oscilloscope is triggered on the steep rising edge of the waveform. One waveform, $v(t)$, is acquired for each hydrophone using eight averages and five cycles of the tone burst on the oscilloscope trace. Thus 40 complete cycles are averaged. The effective noise reduction due to averaging is nominally equivalent to 40 averages of one cycle, but the acquisition time is 25 times shorter. This is because the oscilloscope (which uses repetitive sampling and samples at a fixed rate of 0.5 megasamples per second) acquires a five-cycle waveform in one-fifth of the time taken to acquire a single cycle. Thus 8 five-cycle waveforms can be acquired five times faster than 8 single-cycle waveforms, and 25 times faster than 40 single-cycle waveforms. An added advantage is a fivefold improvement in the frequency-domain resolution. However, the data for the very high harmonics become less reliable as fewer points are acquired per cycle, and hence the number of cycles must be chosen to suit the requirements. To ensure that the five consecutive cycles are of equal amplitude, the tone burst is 20 cycles long and the 11th to 15th cycles (inclusive) are used for the measurements.

It is important that the waveform used for the FFT contain exactly an integer number of cycles. To check that this is the case, the computer examines the phase continuity between the beginning and end of the acquisition frame. If a discontinuity exists, then it is necessary to adjust the "sweep calibration" of the oscilloscope time base.

When the stored magnitudes of the harmonic components $V(f)$ are analyzed, a simple ratio of the magnitudes from the hydrophone being calibrated $[V_1(f)]$ to those from one of the reference hydrophones $[V_0(f)]$ gives the ratio of sensitivities at each harmonic frequency:

$$M_{L1}(f)/M_{L0}(f) = V_1(f)/V_0(f),$$

where $M_{L1}(f)$ and $M_{L0}(f)$ are end-of-cable loaded sensitivities.[3]

The final stage uses the known end-of-cable loaded sensitivity of the reference hydrophone $M_{L0}(f)$ to yield the end-of-cable loaded sensitivity of the hydrophone being calibrated $M_{L1}(f)$. In practice, this calculation is performed using both reference hydrophones and the results are combined, thus reducing the random uncertainties.

The end-of-cable open-circuit sensitivity M_c can be calculated by correcting for the amplifier load impedance Z_{el}, using an equation[3] derived from the work of Beissner:[19]

$$M_c = M_L\left[\frac{[\mathrm{Re}(Z_{el}) + \mathrm{Re}(Z)]^2 + [\mathrm{Im}(Z_{el}) + \mathrm{Im}(Z)]^2}{\mathrm{Re}(Z_{el})^2 + \mathrm{Im}(Z_{el})^2}\right]^{1/2},$$

where $Z_{el} = \mathrm{Re}(Z_{el}) + j\,\mathrm{Im}(Z_{el})$ is the electrical load impedance and $Z = \mathrm{Re}(Z) + j\,\mathrm{Im}(Z)$ is the electrical hydrophone impedance. NPL hydrophone calibration certificates present the end-of-cable open-circuit sensitivities along with the electrical impedance of the hydrophone at each frequency to facilitate conversion to the end-of-cable loaded sensitivity.

V. ACCURACY ASSESSMENT—RANDOM UNCERTAINTIES

Random uncertainties are calculated at the 95% confidence level from four repeat measurements, each using a different transducer or propagation distance. They typically increase smoothly from $\pm 2\%$ at 1 MHz to $\pm 4\%$ at 10

MHz and $\pm 7\%$ at 15 MHz (95% confidence level). Several potential sources of random uncertainty exist in the calibration procedure, including: reproducibility of hydrophone alignment; signal-to-noise ratio variation between measurement sets; temperature changes between measurements; resolution of the digitizer; averaging errors by the oscilloscope; trigger instability; and instability of the transducer drive signal. Several hydrophones have been recalibrated more than ten times using this technique and, for each hydrophone, the standard deviation can be used to represent the long-term variability between calibrations. It has been found that this variability increases from $\pm 2\%$ at 1 MHz to $\pm 3\%$ at 10 MHz and $\pm 5\%$ at 15 MHz (95% confidence level, i.e., approximately twice the standard deviation).

Various measurements have been made to study individual sources of random uncertainty. Most of these are covered in Sec. VI, as they are also sources of systematic uncertainty. In many cases, the calibration procedure (see Sec. IV) has been deliberately designed to randomize some of the effects, such as hydrophone misalignment and transducer drive signal instability. Typically, the water temperature varies by less than 0.5 °C during a calibration and the drive signal is stable to within $\pm 0.5\%$.

TABLE I. Uncertainties (percent) in the intercomparison of two hydrophones. All uncertainties are given as semi-range values unless otherwise specified.

Source	1 MHz	15 MHz	Section
Oscilloscope			
Linearity	2.0	2.0	VI A
Resolution	0.3	1.1	VI B
Range-to-range variation of gain	0.3	0.3	VI C
Temperature and time dependence	0.1	0.1	VI D
Hydrophone			
Signal-to-noise ratio	0.1	0.7	VI E
Temperature dependence of sensitivity	0.3	0.3	VI F
Extraneous areas of sensitivity	0.5	0.5	VI G
Linearity	1.0	1.0	VI H
Directional response coaxiality between frequencies	1.0	1.0	VI I
Spatial averaging over element	0.1	0.1	VI J
Amplifier			
Linearity	0.6	0.6	VI K
Correction to open-circuit sensitivity	0.8	0.8	VI L
Method			
Alignment of hydrophone	0.1	0.1	VI M
Capture of the waveform	0.3	2.5	VI N
Reflections from baffles in tank	1.5	0.5	VI O
Smoothing of frequency response (depends on hydrophone)	0.1	0.1	VI P
Totals			
Total systematic uncertainty (95% confidence level)	3.6	4.3	VI
Typical random uncertainty (95% confidence level)	2.0	7.0	V
Typical overall uncertainty (95% confidence level)	4.2	8.2	VII

VI. ACCURACY ASSESSMENT—SYSTEMATIC UNCERTAINTIES

Systematic uncertainties arise from various sources, some of which are dependent on the type of hydrophone or amplifier used, and others depend on the particular oscilloscope or digitizer. These sources of uncertainty have been investigated for the NPL facility and are itemized in Table I.

The total systematic uncertainty in the intercomparison of the two hydrophones increases from $\pm 3.6\%$ at 1 MHz to $\pm 4.2\%$ at 15 MHz. However, the uncertainty due to the absolute calibration of the reference hydrophone contributes significantly to the total systematic uncertainty in the final sensitivity values. The contributions are combined in quadrature after converting each one to the 95% confidence level [see NAMAS document B3003 (Ref. 32)].

A. Linearity of the oscilloscope

For a given range setting on the amplifier of the oscilloscope, there may be a nonlinear response to input voltage. In order to test this in a situation approximating to that during the calibration, a stable oscilloscope calibrator was used to generate a square wave at 1 MHz. A 1500-pF capacitor was connected in parallel to produce a waveform with features similar to a sawtooth waveform (i.e., a steep rising edge followed by a decay). This signal was applied to the oscilloscope amplifier via a switchable Wavetek attenuator (which had been calibrated at NPL to an accuracy of ± 0.005 dB) and a 50-Ω termination. The measured waveform was acquired for several different attenuation levels on each voltage range of the oscilloscope. At least 10 dB of attenuation was used at all times to prevent the calibration of the attenuator being affected by the impedance mismatch at its input. By comparing the magnitudes of the harmonic components in these waveforms, it was possible to determine the linearity of the system over the frequency range 1–15 MHz.

B. Resolution of the oscilloscope

The Tektronix 7854 oscilloscope has a 10-bit accuracy which corresponds to a resolution of $\pm 25\,\mu$V. However, the effect of this resolution limit is reduced by the acquisition of $5n$ cycles of the nth harmonic and by repeating the measurements four times (hence a total of $20n$ acquisitions). Thus the effective resolution is reduced to $\pm 25\,(20n)^{-1/2}\,\mu$V. The lowest measurable hydrophone sensitivity (approximately 10 nV/Pa) would give a signal with a typical amplitude of approximately $2/n$ mV at the nth harmonic. The quotient of the effective resolution and this typical amplitude gives the uncertainty due to this effect, which can be as large as $\pm 0.28\,n^{1/2}\%$ for a hydrophone with low sensitivity. Note that this is the worst case, and it is often possible to obtain a signal giving ten times better resolution (using a hydrophone with 100-nV/Pa sensitivity).

C. Range-to-range variation of gain

The variation in the calibration of the oscilloscope amplifier for each voltage range was determined at two frequencies using a stable sine-wave generator and a calibrated attenuator (see Sec. VI A). A correction based on these measurements is applied to each acquired waveform before performing the FFT. A residual systematic uncertainty remains due to the accuracy of the calibration method. The accuracy of the absolute measurement of voltage is not important for intercomparison techniques, as only relative measurements are required.

D. Temperature and time dependence of the oscilloscope

This systematic uncertainty is based on the specification of the oscilloscope amplifier and mainframe, combined with an estimate of the expected temperature variation and time taken for a calibration.

E. Signal-to-noise ratio

At each harmonic frequency, the noise level is that present within a 0.2-MHz frequency band (the bandwidth of the system). The primary source of noise is the hydrophone preamplifier with an rms noise level of approximately 19 μV in each frequency band (measured using an analog rms voltmeter). Digitization noise contributes an rms voltage of 4 μV per frequency band (this was measured by capturing a grounded signal and taking the FFT). This gives a *peak* noise amplitude of 28 μV in a 0.2-MHz frequency band, decreasing to approximately 10 μV after performing eight averages. The smallest signal used has a typical amplitude of $2/n$ mV at the nth harmonic frequency. Thus the signal-to-noise ratio (S_r) would be $200/n$. Assuming the noise is incoherent and the signal and noise combine in quadrature, the systematic increase in the measured value due to this contribution would be given by

$$\text{systematic increase}(\%) \approx 100 \times 1/(2S_r^2).$$

Hence, the largest systematic uncertainty contribution is $-n^2/800\%$ (i.e., the measured voltage is an overestimate of the true value).

There is also a mechanism by which the noise could systematically reduce the measured magnitudes of the harmonics. The time base of the oscilloscope is triggered when the leading edge of the hydrophone signal exceeds a preset threshold level, and in the presence of significant noise, this is an unreliable procedure. The *peak* noise level in the total 60-MHz bandwidth of the system is approximately 0.33 mV (not including digitization noise, as this would not cause jitter on the trigger). The trigger is taken from the steep rising edge of the sawtooth waveform, which has a slope of between 0.8 and 2 MV/s, depending on both sensitivity and bandwidth of the hydrophone. In the worst case of a slope of 0.8 MV/s, the jitter on the trigger would be less than 0.5 ns. However, the specification of the Tektronix 7000 series time base gives the internal jitter as 1 ns or less. Thus the combined jitter would be approximately $0.0012n$ as a fraction of the period of the nth harmonic. At 15 MHz, this corresponds to an amplitude reduction by approximately $1-\cos(0.0024n\pi)$, which is equivalent to an uncertainty of $+0.7\%$ at 15 MHz (i.e., the measured value is an underestimate of the true value).

The assumption is made, when calculating the above systematic uncertainties, that the reference hydrophone measurement does not suffer from these effects. This provides the worst-case estimate and is a reasonable assumption, considering the reference hydrophones usually have signal-to-noise ratios exceeding those used for the above calculations by a factor of 4. Also, the steep rising edge on their waveforms can have a slope of over 5 MV/s.

F. Temperature dependence of hydrophone sensitivity

The variation of hydrophone sensitivity with temperature has been measured for several types of PVDF membrane hydrophones using the NPL Primary Standard Laser Interferometer and the results reported.[33] The systematic uncertainty has been based on the largest temperature dependence measured and a typical temperature drift during a complete calibration.

G. Extraneous areas of sensitivity

Due to the broadness of the ultrasound beam used for this calibration method, any areas of sensitivity outside the region of the active element could contribute and interfere with the main signal from the element. This problem is considered here because it would have a larger effect on the present calibration technique than on other techniques that use narrower beams. Hydrophones for use in measurements are not expected to have extraneous sensitive areas which contribute more than 0.5% to the overall sensitivity; and, hence, only areas contributing less than 0.5% need be considered here.

H. Linearity of the hydrophone

This has been dealt with for PVDF membrane hydrophones,[34] and an estimate of the associated systematic uncertainty has been assigned, which represents the accuracy with which the linearity has been measured at the NPL.

I. Directional response coaxiality between frequencies

For this calibration technique, the hydrophones are aligned for maximum signal using a 20- or 40-MHz high-pass filter in order to increase the sensitivity to misalignment. However, an assumption is made that the peak of the directional response occurs in the same direction at all the frequencies below this. The uncertainty reflects the confidence in this assumption, as discussed in Sec. III.

J. Spatial averaging over the hydrophone element

As mentioned in Sec. III, no correction for this effect is required because the ultrasound beam lacks structure and is sufficiently broad at all the frequencies in the range used. The uncertainty reflects the insignificance of spatial averaging in this calibration technique.

K. Amplifier linearity

This uncertainty has been determined at NPL in the first instance by measurements of the amplifier gain with peak-to-peak output voltages ranging from 1 mV–1.2 V at 5 and 10 MHz. Further measurements have been carried out using the method described in Sec. VI A to simulate a steep rising edge. Those measurements checked the dependence of the linearity on frequency from 1 to 15 MHz.

L. Correction to open-circuit sensitivity

The procedure described in Sec. IV for converting the end-of-cable loaded sensitivity to an end-of-cable open-circuit sensitivity relies primarily on accurate impedance measurements. The systematic uncertainty reflects the effect of the manufacturer's specification of accuracy for the Hewlett–Packard HP 4193A vector impedance meter. This corresponds to an uncertainty of approximately $\pm 15\%$ for most of the range of impedances measured. The quoted uncertainty is based on a load capacitance of approximately 6 pF and would be larger if the hydrophone were connected directly to an oscilloscope with a 20- or 30-pF input capacitance because the correction itself would be much larger.

M. Alignment of the hydrophone

The effect of not locating each hydrophone element at the same place and in the same orientation has been included in the random uncertainties due to the four repeat measurements undertaken. However, there is a very small systematic uncertainty arising from the fact that some hydrophones are more difficult to align than others. The uncertainty arising from the difficulty of positioning each hydrophone at the same distance from the transducer is less than 0.01%. This is derived from the reproducibility of the position along the z axis combined with the slope of the curves in Fig. 4.

N. Capture of the waveform

When the computer performs the FFT, the time window used for digitization is assumed to be equal to a multiple of the period of the waveform. Thus a contribution to the systematic uncertainty arises from failing to digitize exactly an integer number of cycles in the waveform. To minimize this effect, the computer fits a straight line to the last 15 points on each end of the waveform to enable the operator to check whether they line up to within a required tolerance. For this purpose, the digitized window is positioned to start on a moderately steep part of the hydrophone waveform. A series of measurements was performed with a range of deliberately incorrect window lengths and the results showed a definite trend with the greatest errors at the higher frequencies.

O. Reflections from baffles in the tank

This systematic uncertainty has been assessed by measurements with the direct ultrasound beam blocked by a good absorber. The uncertainty only applies if the hydrophone is sufficiently far from the transducer for the reflected wave to interfere with the 20-cycle tone burst of the direct beam. With separations no greater than a meter, it is likely that this uncertainty could be reduced by removing the baffles completely.

P. Smoothing of the frequency response

The bandwidth of the method is less than 0.2 MHz due to the sample waveform length of 5 μs and the 10 μs of the tone burst occurring before this sample is taken. The fundamental frequency is set by adjusting the frequency of the transducer drive to within 50 Hz of 1 MHz. Thus a systematic uncertainty arises from the variation of hydrophone sensitivity over the ± 0.1-MHz frequency band. The following relationship, based on the curvature of the frequency response curve $[\partial^2 M(f)/\partial f^2]$, can be used to calculate the systematic uncertainty at a frequency f:

$$\text{systematic uncertainty}(\%) = \frac{(\Delta f)^2}{6M(f)} \frac{\partial^2 M(f)}{\partial f^2} \times 100,$$

where Δf is the half-bandwidth of the system (0.1 MHz) and $M(f)$ is the hydrophone sensitivity as a function of frequency. This relationship was obtained by calculating the mean sensitivity over the indicated frequency range as a Taylor Series expansion.

VII. ACCURACY ASSESSMENT—OVERALL UNCERTAINTIES

The overall uncertainty is determined by combining in quadrature the typical random uncertainties and the total systematic uncertainties (see Table I). Typical overall uncertainties range from $\pm 4.2\%$ at 1 MHz to $\pm 8.2\%$ at 15 MHz. These are comparable with the uncertainties attributed to the discrete-frequency substitution method (see Sec. I), but with a reduction in the calibration time of approximately a factor of 8. The random uncertainties estimated by Ludwig and Brendel[27] for their TDS facility are similar to those for the present method, but they do not state any systematic uncertainties.

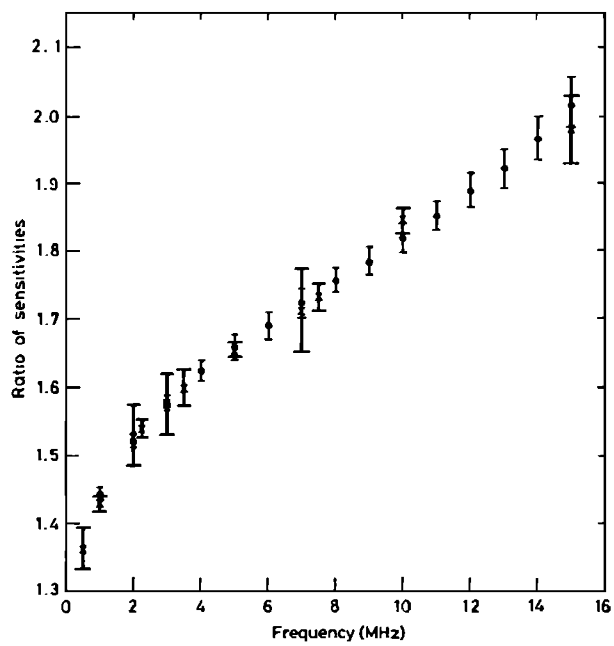


FIG. 8. Ratio of sensitivities of a bilaminar to a coplanar shielded membrane hydrophone, both of 1-mm diameter, using: ×, discrete-frequency technique and ●, multiple-frequency technique. Error bars denote the 95% confidence level random uncertainties in the values from the two techniques, derived from several independent calibrations.

TABLE II. Percentage difference between the multiple- and discrete-frequency methods. The standard hydrophone was a 1-mm-diam coplanar shielded membrane hydrophone, except for the PVDF needle probe, which was compared with another PVDF needle probe but of diameter 0.6 mm.

Hydrophone type/thickness	Diameter (mm)	Cable length (m)	Frequency (MHz) 1	2	5	10	15
Bilaminar/50 μm	1	0.70	+0.9	−0.6	+0.3	−1.5	+2.0
Bilaminar/50 μm	0.5	0.70	+1.6	+1.6	+0.8	−2.8	−0.2
Coplanar/25 μm	1	0.15	+1.9	+1.2	+1.0	+0.8	...
Coplanar/25 μm	0.5	0.15	+1.7	−3.1	+0.3	−1.4	...
Coplanar/9 μm	1	0.15	+1.5	+1.1	−0.4	−1.1	+1.7
Coplanar/25 μm	0.5	0.70	+0.8	+1.6	−1.4	−5.9	−2.6
PVDF Needle probe	1	0.90	+3.3	−4.5	+3.0	+3.0	...
rms difference (%)			1.8	2.3	1.4	2.9	1.9
Mean difference (%)			+1.7	−0.4	+0.5	−1.3	+0.2

VIII. VALIDATION OF THE METHOD

A. Comparison with the discrete-frequency method

The discrete-frequency substitution technique is well established at NPL as a hydrophone intercomparison method and has been described fully in Sec. I. It is a suitable reference method for validation purposes because it is simple and less demanding on hydrophone and measurement system performance. For instance, the present technique utilizes a waveform with a steep rising edge that puts demands on the frequency and slew-rate responses of the hydrophone. In addition, any nonlinearity in the measurement system, or under-sampling of the signal, could lead to errors that would depend on the bandwidth of the hydrophone. For this reason, several different types and sizes of hydrophone have been calibrated using both the discrete- and the multiple-frequency techniques. The combined results from several comparisons of two different PVDF membrane hydrophones[17] are shown in Fig. 8. One of the devices (a bilaminar shielded type) had a thickness-mode resonance at 24 MHz, while the other [a coplanar shielded device as used to obtain Fig. 1(a)] resonated at 45 MHz. Both devices had 75-cm cables that would resonate at approximately 60 MHz. The effect of these resonances is to cause ringing after the steep rising edge of the waveform [see Fig. 1(a)],[8] and it is important for the technique still to be valid with these resonances present. For these two hydrophones, the techniques were in agreement within the 95% confidence level random uncertainties shown in Fig. 8.

Further intercomparisons have been performed using several different types of membrane hydrophone having active element diameters of 0.5 and 1 mm, cable lengths ranging from 15–75 cm and membrane thicknesses of 9, 25, and 50 μm. The same 1-mm-diam coplanar shielded device was used as the reference hydrophone for each intercomparison. Table II gives the difference between the methods at several harmonic frequencies along with the rms differences which give an indication of the overall agreement between techniques at each frequency. The difference was calculated using

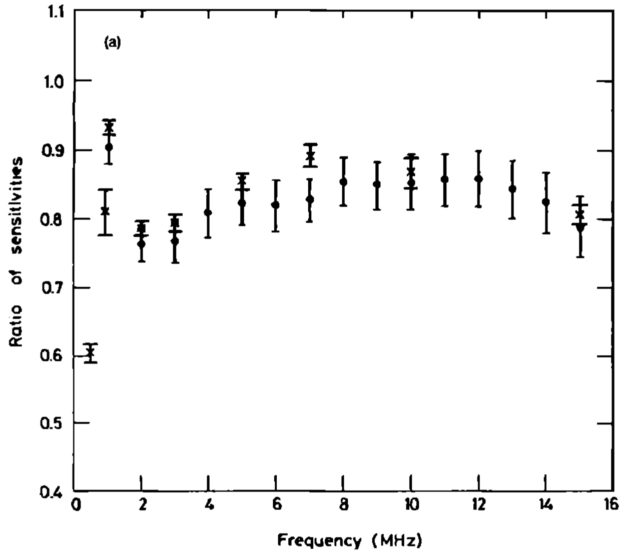
$$\text{difference}(\%) = \frac{\text{multiple} - \text{discrete}}{\text{discrete}} \times 100,$$

which means, for example, that a difference of -1.5% indicates that the ratio of the two sensitivities determined by the multiple-frequency technique was 1.5% lower than that from the discrete-frequency method. The table shows that, for all the hydrophones measured, the two techniques were in agreement within the combined random uncertainties which increase from $\pm 3.5\%$ at 1 MHz to $\pm 7.5\%$ at 15 MHz (95% confidence level).

B. Comparison with interferometry

Although the discrete-frequency method is a good reference technique, at NPL the same hardware is used to perform the waveform acquisition as for the present method. Thus it is useful to compare the technique with an independent calibration method.

The absolute technique used at the NPL for hydrophone calibration is based on optical interferometry and has been described elsewhere.[35] Several hydrophones have been calibrated on the NPL Primary Standard Laser Interferometer from 1 to 15 MHz, and the ratio of their sensitivities can be compared with the results of the present technique. Figure 9(a) shows the results for the ratio of a needle-probe hydrophone to a coplanar shielded membrane hydrophone, and Fig. 9(b) shows the intercomparison of a bilaminar shielded membrane hydrophone to a coplanar shielded device, both with 1-mm-diam active elements. Table III gives a summary of the differences between the methods from several different types of hydrophone including two of the PVDF needle-



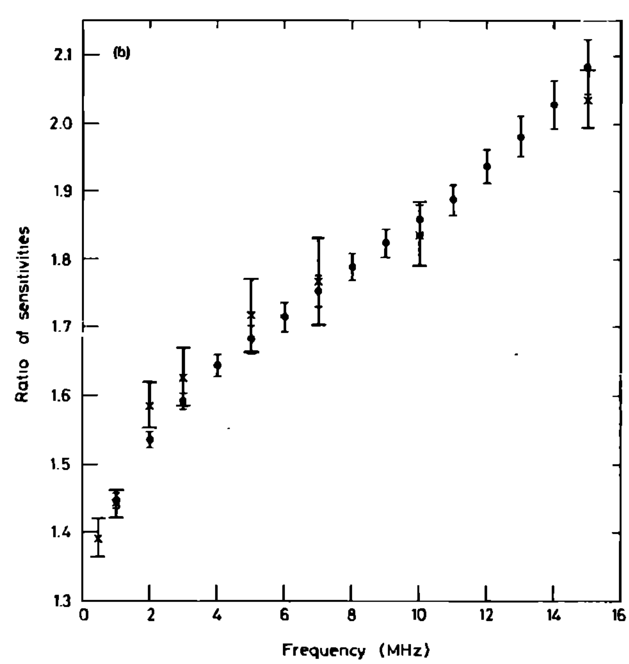


FIG. 9. Ratio of sensitivities of (a) a PVDF needle-probe hydrophone and (b) a bilaminar shielded membrane hydrophone to a coplanar shielded membrane hydrophone (all of element diameter 1 mm) using: ×, interferometry and ●, multiple-frequency technique. Error bars denote the 95% confidence level random uncertainties in the two techniques.

probe type.[14] It should be noted, with reference to Fig. 9(a), that large discrepancies can occur below 3 MHz when intercomparing the latter type of hydrophone. This may be due to the rapid fluctuations in their sensitivity at frequencies below 3 MHz, combined with slight variations in the calibration frequency (see below for further discussion). Apart from these discrepancies for PVDF needle-probe hydrophones, agreement between the two techniques was within the combined uncertainties.

C. Comparison with time-delay spectrometry

Two PVDF needle-probe hydrophones[14,15] have been intercompared using the discrete- and multiple-frequency techniques. These probes were supplied with calibrations obtained by the manufacturer using the TDS technique (see description in Sec. I). Thus the ratio of the two hydrophone sensitivities as determined by TDS can be calculated, and this ratio is independent of both the reference hydrophone used in the original TDS intercomparison and the absolute calibration method. The three techniques are compared in Fig. 10 and, with the exception of 1 MHz, the results agree to within the typical individual random uncertainties (95% confidence level) in the multiple- and discrete-frequency techniques. In addition there is a random uncertainty of at least $\pm 4\%$ in the TDS technique, as mentioned in Sec. I. A possible reason for the discrepancy at 1 MHz is the rapid fluctuation in sensitivity of the 0.6-mm-diam probe between 1 and 2 MHz. These fluctuations were resolved only by the TDS technique and may depend on the effective number of cycles used in the measurement or on the mounting configuration used.

IX. DISCUSSION

The multiple-frequency intercomparison technique described in this paper is the basis for the dissemination of U.K. national ultrasound standards in the frequency range 1–15 MHz, for which the NPL Primary Standard Laser Interferometer provides the absolute calibration. The technique has been shown to give values in agreement with well-established techniques. Both random and systematic uncertainties have been rigorously assessed and are presented here for a typical calibration. Typical overall uncertainties in the intercomparison of two hydrophones range from $\pm 4.2\%$ at 1 MHz to $\pm 8.2\%$ at 15 MHz. The largest source of systematic uncertainty ($\pm 2\%$) is the nonlinearity and distortion in the digitizer, but, at high frequencies, the random uncertainties dominate. The decrease in calibration time over the discrete-frequency technique is estimated to be a factor of 8 for 15 frequency points. This is limited mainly by the time required to align each hydrophone, but also by the acquisition time of the digitizer and the ultrasonic duty cycle. The calibration time would be unchanged by the use of more harmonic frequencies.

The method requires that the direction of maximum sensitivity of the hydrophone be the same at all frequencies. If this is not the case, then a discrete-frequency method must be used. It is also likely that hydrophones with resonances or other fine structure in their frequency response below 15 MHz may be subject to uncertainties higher than stated. The lowest hydrophone sensitivity that can be measured using this method is approximately 10 nV/Pa, and the highest sensitivity is limited only by the maximum input voltage of the hydrophone preamplifier.

It is possible to obtain information above 15 MHz using this technique, and harmonic frequencies up to 30 MHz have been used to determine the directional response of hydrophones. This has shown that the technique can determine the

TABLE III. Percentage difference between the multiple-frequency method and interferometry. The standard hydrophone for the above measurements was a 1-mm-diam coplanar shielded membrane hydrophone of thickness 25 μm.

Hydrophone type	Diameter (mm)	Cable length (m)	Frequency (MHz) 1	2	5	10	15
	1	0.70	+0.3	−3.3	−1.9	+1.2	+2.2
Bilaminar	1	0.70	+1.5	−2.1	−0.7	+2.0	+0.4
	1	0.70	−0.6	−0.4	+3.0	−2.5	−1.7
Coplanar	1	0.70	+2.9	−1.3	+0.6	+3.0	+2.7
PVDF	1	0.90	−3.0	−3.2	−3.8	−1.9	−2.0
Needle probe	1	0.90	+10.5	+2.3	−3.7	−5.8	−9.8
rms difference (%)			4.7	2.3	2.6	3.1	2.4
Mean difference (%)			+1.9	−1.3	−1.1	−0.7	−1.4

sensitivity as a function of both frequency and direction. However, the information above 15 MHz will only be of use for calibration purposes when reliable absolute calibrations are possible at these frequencies. Alternatively, it would be possible to increase the fundamental frequency to obtain information at even higher frequencies.

Although the equipment used in this implementation of the method is relatively complex, the technique could be implemented on most ultrasonic test facilities that incorporate a computer-controlled digitizer. In contrast, the TDS method requires a sophisticated spectrum analyzer as well as a broadband transducer. At present, no use is made of the information on the phase response of the hydrophones that is obtained by the method. In the future, such information could be exploited in the study of hydrophone performance and use.

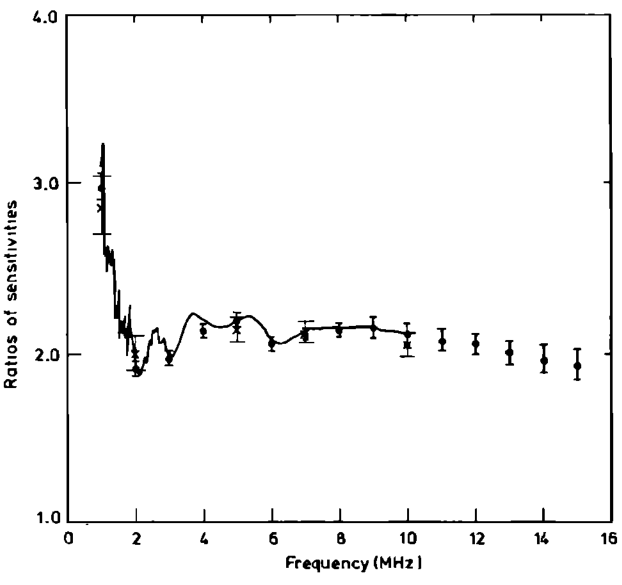


FIG. 10. Ratio of sensitivities of a 1-mm to a 0.6-mm-diam PVDF needle probe using: ×, discrete-frequency technique and ●, multiple-frequency technique; —time-delay spectrometry. Error bars denote the 95% confidence level random uncertainties for the first two techniques, but these were not available for the time-delay spectrometry data.

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