# Spatial Averaging Correction for Ultrasound Hydrophone Calibrations

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## ABSTRACT

The use of medical diagnostic ultrasound has been increased significantly during the past few decades. For safety reasons, the ultrasonic pressure-time waveforms produced at the output of medical ultrasound transducers must be determined. However, if the effective diameter of the hydrophone probe is greater than the dimensions of the incident ultrasonic beam, the measured ultrasonic pressure-time waveforms would be incorrect. Therefore, the objective of this work is to apply the spatial averaging corrections to the frequency responses of the tested hydrophone probes for the hydrophone calibrations in order to obtain the true pressure-time waveforms. Two hydrophone probes, one membrane hydrophone and one needle hydrophone, were calibrated in the frequency range from 1 MHz to 40 MHz with the combination of Time Delay Spectrometry (TDS) and substitution calibration techniques. In addition, two circular focused ultrasound transducers with focal numbers 10 and 20 were used as transducer sources. The frequency responses of the tested hydrophone probes with and without spatial averaging correction are presented. The hydrophone sensitivities with spatial averaging correction are in excellent agreement for both focal numbers of the transducer sources. The discrepancies between the two corrected sensitivities are found to be within ±1 dB. These results indicate that the spatial averaging correction could be successfully applied to determine true sensitivities of the hydrophone probes.

**Keywords**: Ultrasound hydrophone probes; Hydrophone's effective diameter; Hydrophone spatial averaging corrections; Ultrasound metrology; Biomedical ultrasound.

## 1. INTRODUCTION

Medical diagnostic ultrasound has become one of the most important imaging modalities during the past few decades because it does not use ionizing radiation such as X-ray and also give real time images of the anatomical structure. However, other possible biological effects associated with medical diagnostic ultrasound devices such as thermal or mechanical effects may be introduced [1]. Therefore, the safety indicators such as Mechanical Index (MI) and Thermal Index (TI) are required to be displayed on the ultrasound imaging systems [2-4]. In order to determine these two indices, a faithful recording of the ultrasonic pressure-time waveforms produced by an ultrasound transducer is needed.

A universal tool for obtaining the ultrasonic pressure-time waveforms from the ultrasound transducer is the "ultrasound hydrophone". AIUM/NEMA standards and FDA guidelines recommend that ultrasound hydrophone probes should be calibrated up to eight times the center frequency of the ultrasound transducer [2-4] in order to take into account for nonlinear propagation phenomena from the examined tissue (harmonics in the pressure-time waveform). In general, medical ultrasound imaging operates in the frequency range from 1-15 MHz. Therefore, if the ultrasound transducer is used in the frequency range of 12-15 MHz, the ultrasound hydrophone probe has to be calibrated in the range of 100 MHz bandwidth [2-5]. In addition, there are currently many new application of ultrasound imaging with the frequency range beyond 15-20 MHz to improve the image resolution [6-9]. In this context, it shows that the characterization of the ultrasound hydrophone probes in the frequency range greater than 20 MHz is significantly required to ensure adequate characterization of applicable ultrasound devices. However, the frequency response of the hydrophone probes is typically available only in the frequency range from 1 to 20 MHz since the hydrophone calibration above 20 MHz is time consuming and relatively difficult to perform due to the effects of spatial averaging.

To obtain the true pressure-time waveform, the effective diameter of the hydrophone probes, diameter obtained from the directional response [2], has to be smaller than the dimensions of the ultrasonic beam or half-wavelength of an ultrasound wave propagating in the medium. If the effective diameter (or aperture) of the hydrophone probe is larger than the dimensions of the incident ultrasonic beam, the measured ultrasonic pressure-time waveforms would be incorrect as shown in Figure 1. The error between the amplitude of the measured pressure-time waveform and the amplitude of the actual pressure-time waveform occurs because the hydrophone probe respond to the space integral of ultrasonic pressure over its active surface area. This problem is called "spatial averaging effect". Therefore, to avoid the spatial averaging effects, the hydrophone probes should be able

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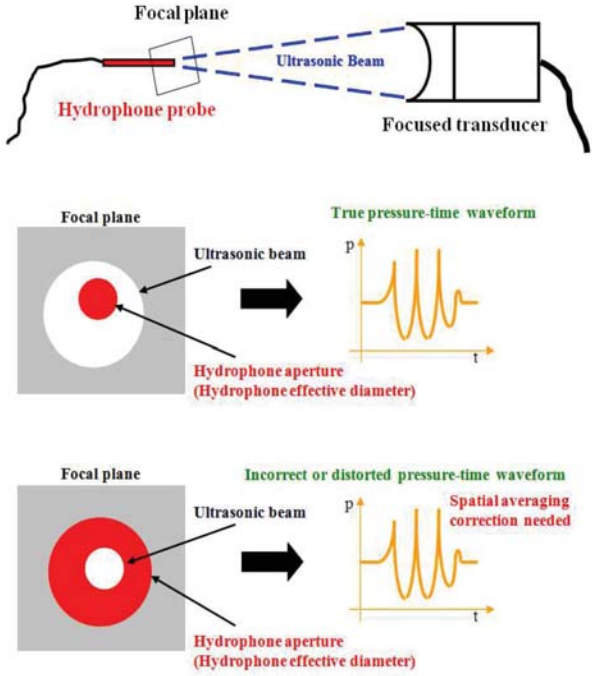



***Fig.1:***: The ultrasonic pressure-time waveforms related to the dimensions of the ultrasonic beam and the effective diameter of the hydrophone probes.

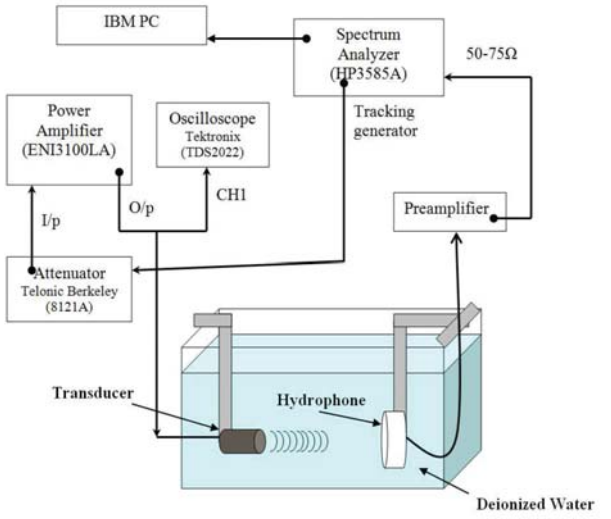



***Fig.2:***: The experimental set-up for the calibration of the hydrophone probes using the combination of Time Delay Spectrometry (TDS) and substitution calibration techniques.

to sample the ultrasound field with a minimum of half-wavelength resolution. In general, most of the commercially available hydrophone probes have an effective diameter on the order of 500 $\mu$m. Such an aperture is too large for ultrasonic measurements in the fields beyond 3 MHz without spatial averaging effect. Therefore, a procedure called "spatial averaging correction" is needed to obtain a faithful ultrasonic pressure-time waveforms.

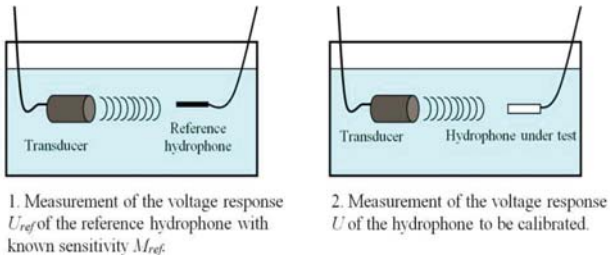
In view of the above, it is clear that the spatial averaging correction is required to account for the errors from the spatial averaging effects. Therefore, this work describes the mathematic model used to determine the spatial averaging correction factors in order to apply for the hydrophone calibrations in the frequency range from 1 to 40 MHz.

## 2. MATERIALS AND METHODS

In this work, two hydrophone probes, one membrane hydrophone and one needle hydrophone, are calibrated in the frequency range from 1 MHz to 40 MHz with substitution calibration technique combined with Time Delay Spectrometry (TDS). The experimental set-up for the calibration of the hydrophone probes is shown in Figure 2.

The details of the TDS calibration have been explained in [10-14]. A spectrum analyzer HP 3585A generates a swept frequency sinusoidal signal from the tracking generator. This swept signal is transferred to a 50 Ω adjustable attenuator (up to 60 dB attenuation, 8121A, Telonic Berkeley) before being amplified by a 55 dB power amplifier (3100LA, ENI, Rochester, NY) in order to obtain the optimized excitation voltage applied to the ultrasound transducer [15], which is around 5 Vpp (peak-to-peak voltage). This amplitude of the excitation voltage is good enough to avoid the nonlinearity effects in water and also adequate to maintain the signal-to-noise ratio (up to 60 dB) during the calibration. The electrical voltage giving to the ultrasound transducer is monitored in real-time with an oscilloscope, Tektronix TDS2022. Two circular focused ultrasound transducer sources (focal numbers 10 and 20) are used to produce ultrasound fields in the calibration. In addition, two ultrasound hydrophone probes under test including one membrane hydrophone with an effective diameter of 1200 $\mu$m and one needle hydrophone with an effective diameter of 130 $\mu$m are calibrated in this work. The effective diameters of these hydrophone probes are measured using the method explained in [16]. The results of the same hydrophone calibration with the two transducer sources will be compared in the results section. Since the calibration here is based on not only the TDS calibration but also substitution technique, the reference hydrophone is needed. In this work, the reference hydrophone used is a 500 $\mu$m effective diameter membrane hydrophone, which was previously calibrated by the National Physical Laboratory, NPL, UK.

The substitution calibration in this work is performed as shown in Figure 3 in the following steps: First, the reference hydrophone is placed at the focal plane of the ultrasound transducer [17] using the X-Y-Z alignment system to obtain the frequency response. After the frequency spectrum of the reference hydrophone is found and stored, the hydrophone under test is substituted at the same position as the reference hydrophone in the water tank. After the maximum signal amplitude of the hydrophone under




1. Measurement of the voltage response $U_{ref}$ of the reference hydrophone with known sensitivity $M_{ref}$.

2. Measurement of the voltage response $U$ of the hydrophone to be calibrated.

***Fig.3:***: The procedure of the substitution calibration.

test is acquired and stored, the sensitivity of the hydrophone under test ($M$) is then determined by relating it to the sensitivity of the reference hydrophone ($M_{ref}$) and to the measured voltages according to Equation 1 [11].

$$M = (U/U_{ref})M_{ref} \quad (1)$$

where $U$ and $U_{ref}$ are the voltage responses of the hydrophone under test and the reference hydrophone, respectively.

A computer gathers all the measurement data and then analyzes the results for the hydrophone calibration. The hydrophone calibration charts of both membrane and needle hydrophones are presented in the results section. However, it is found that if the effective diameter of the hydrophone under test is smaller than the effective diameter of reference hydrophone, the hydrophone sensitivity obtained will be higher than the true one. This error will be greater with lower focal numbers of the transducer source and higher frequency [18]. This discrepancy is found to be related to the cross section area of the beam in the focal plane and the size of the effective diameters of the reference and tested hydrophone probes or it is governed by the spatial averaging effect.

The spatial averaging correction model is needed to account for these errors. The spatial averaging correction model requires the properties of the transducer source, pulsing conditions and characteristics of the hydrophone probe (such as the effective diameter and frequency response of the hydrophone) as the input parameters to the model.

The cross-section of the ultrasonic beam from the circular focused ultrasound source at the focal plane can be explained as shown in Equation 2 [19, 20].

$$\frac{p(r)}{p(0)} = exp\left(\frac{ikr^2}{2D}\right)\frac{2J_1\left(\frac{kar}{D}\right)}{\left(\frac{kar}{D}\right)} \quad (2)$$

where $p(r)$ is the ultrasonic pressure from the ultrasonic axis at the focal plane with a radial distance $r$, $p(0)$ is the ultrasonic pressure from the ultrasonic axis at the focal plane, $J_1$ is the first order Bessel function, $a$ is the source radius, $k$ is the wave number and $D$ is the radius of curvature of the source transducer.

In addition, the averaging pressure on the active area of the ultrasound hydrophone probes at the focal plane can be predicted using Equation 3 [21].

$$P_{average}(M,R) = \frac{\iint_{aperture} r \cdot p(M,r) \cdot dr \cdot d\varphi}{\iint_{aperture} r \cdot dr \cdot d\varphi} \quad (3)$$

where $P_{average}(M,R)$ is the effective hydrophone response after the integration of the instantaneous acoustic pressure $p$ over the hydrophone's active element area at the point $M$ of the acoustic field; $R$ is the radius of the hydrophone aperture, and $r$ and $\varphi$ are the polar integration coordinates.

The models in Equations 2 and 3 are used to determine the spatial averaging correction factor using MATLAB programming for two circular focused ultrasound transducers with focal numbers 10 and 20, and tested ultrasound hydrophone probes having effective diameters of 130 and 1200 $\mu$m. The graphs of the spatial averaging correction factors with the reference hydrophone having 500 $\mu$m effective diameter are presented in the results section. In addition, the true frequency responses of the tested hydrophone probes are presented in the results section by adding the correction factors to the uncorrected sensitivities of the hydrophone probes.

## 3. RESULTS

Two hydrophone probes, one membrane hydrophone and one needle hydrophone, were calibrated using Time Delay Spectrometry (TDS) and substitution techniques with two transducer sources (focal numbers 10 and 20). The calibrations were carried out in the frequency range from 1 to 40 MHz with the focal number 20 transducer source. However, the focal number 10 source could provide the maximum frequency only up to 32 MHz since this transducer source was not able to maintain enough signal to noise ratio (20 dB) beyond this frequency.

The results of the calibrations without spatial averaging correction are presented in Figure 4 for the 1200 $\mu$m effective diameter membrane hydrophone probe and Figure 5 for the 130 $\mu$m effective diameter needle hydrophone probe. The 500 $\mu$m effective diameter membrane hydrophone probe was used as a reference hydrophone.

The graphs of the spatial averaging correction factors for the 1200 $\mu$m effective diameter membrane hydrophone probe is shown in Figure 6. Also, Figure 7 shows the plots of the spatial averaging correction factors for the 130 $\mu$m effective diameter needle hydrophone probe.

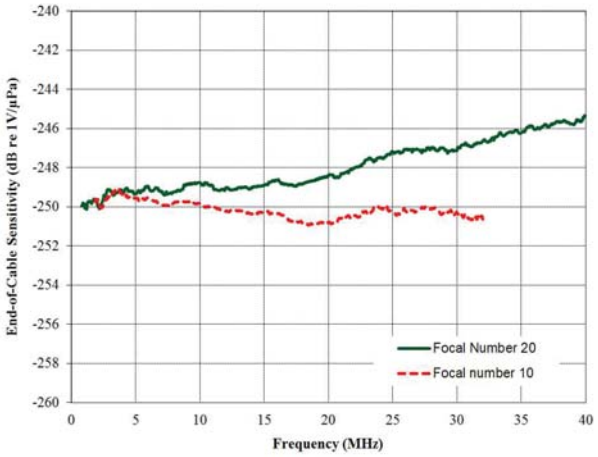



***Fig.4:***: The sensitivity of the 1200 $\mu$m effective diameter membrane hydrophone probe without the spatial averaging correction using focal numbers 10 and 20.

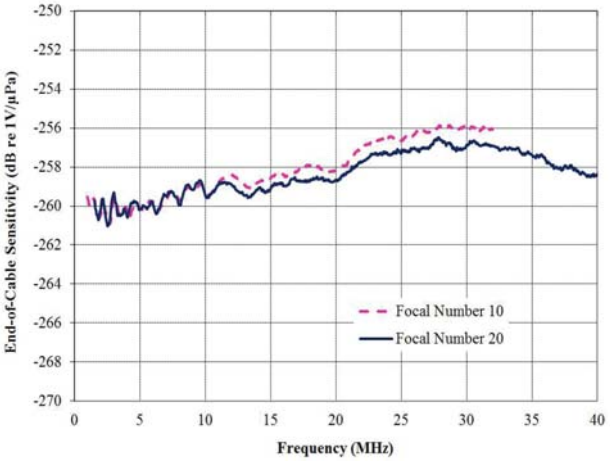



***Fig.5:***: The sensitivity of the 130 $\mu$m effective diameter needle hydrophone probe without the spatial averaging correction using focal numbers 10 and 20.

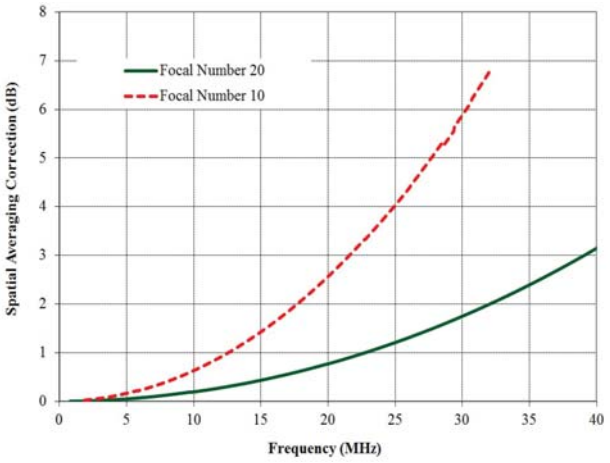



***Fig.6:***: The spatial averaging correction factors for the 1200 $\mu$m effective diameter membrane hydrophone probe when the 500 $\mu$m effective diameter membrane hydrophone probe was used as a reference hydrophone.

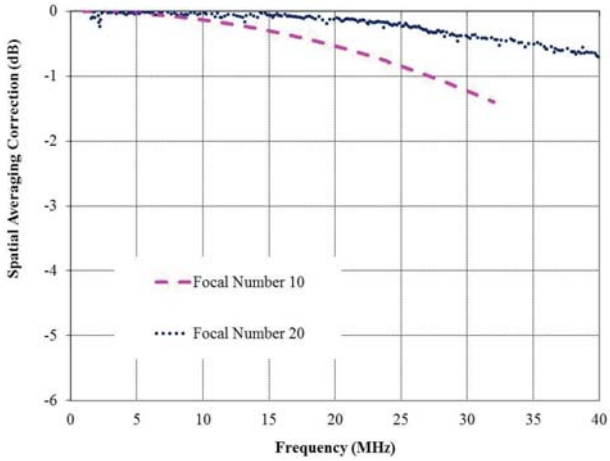



***Fig.7:***: The spatial averaging correction factors for the 130 $\mu$m effective diameter needle hydrophone probe when the 500 $\mu$m effective diameter membrane hydrophone probe was used as a reference hydrophone.

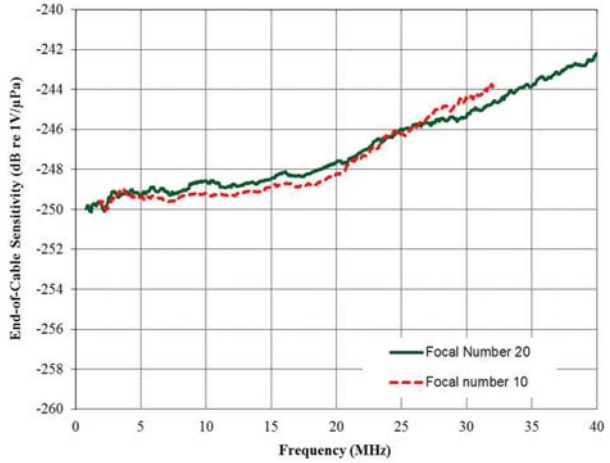



***Fig.8:***: The sensitivity of the 1200 $\mu$m effective diameter membrane hydrophone probe with the spatial averaging correction using focal numbers 10 and 20.

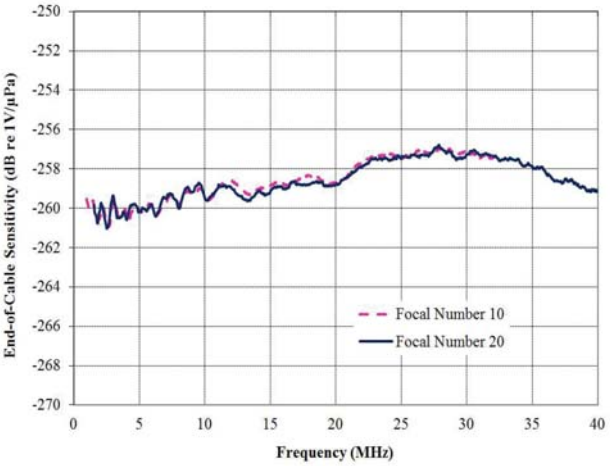



***Fig.9:***: The sensitivity of the 130 $\mu$m effective diameter needle hydrophone probe with the spatial averaging correction using focal numbers 10 and 20.

## 4. DISCUSSION AND CONCLUSIONS

The hydrophone calibrations obtained from one membrane hydrophone probe having 1200 $\mu$m effective diameter and one needle hydrophone probe having 130 $\mu$m effective diameter using Time Delay Spectrometry (TDS) and substitution techniques without the use of spatial averaging correction are presented in Figures 4 and 5, respectively. The results show that the hydrophone probes with effective diameters greater than the effective diameter of the reference hydrophone provided hydrophone sensitivity lower than the true one (see Figure 4). Conversely, the sensitivity of the hydrophones with effective diameters smaller than the effective diameter of the reference hydrophone is higher than the true frequency response (see Figure 5). The values of the spatial averaging corrections in Figure 6 are positive because the 1200 $\mu$m effective diameter of the tested hydrophone is larger than the 500 $\mu$m effective diameter of the reference hydrophone whereas the correction factors in Figure 7 are negative because the 130 $\mu$m effective aperture of the hydrophone under test is smaller than the diameter size of the reference hydrophone.

The correct sensitivities of the hydrophone probes can be obtained by algebraically adding the spatial averaging correction factors shown in Figures 6 and 7 to the uncorrected calibration data in Figures 4 and 5, respectively. The hydrophone sensitivities with spatial averaging correction can be obtained and they indicate that they are in excellent agreement and independent on the focal number of the transducer sources (see Figures 8 and 9). The discrepancies between the corrected sensitivities of two transducer sources shown in Figures 8 and 9 are found to be within $\pm 1$ dB. Such uncertainty is acceptable in the hydrophone calibrations. Therefore, the results shown in Figures 8 and 9 clearly supported that the spatial averaging correction here can be successfully used to determine true sensitivities of the hydrophone probes.

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