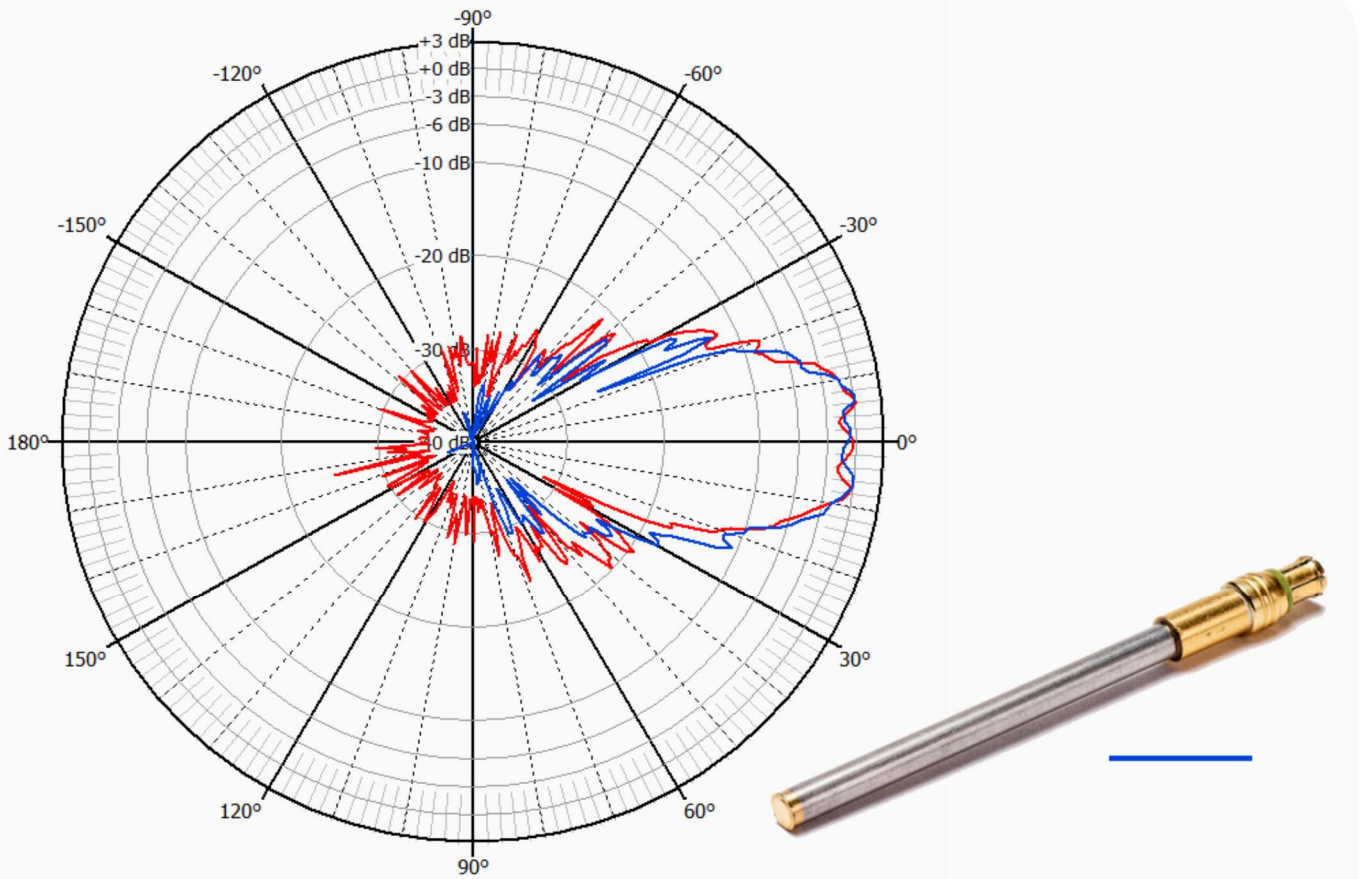


Transducer characterisation 100 kHz to 1 MHz

Andrew Hurrell PhD



This case study discusses how TVR and Beam plot measurements were improved for one of PA's sonar customers, by switching to a 2.0 mm needle hydrophone. Relative to their previous (cylindrical) hydrophone, the much broader frequency response, and different directivity pattern of the PA 2.0 mm needle hydrophone, led to improved experimental outcomes including:

- TVR measures with higher values, and less undulations, attributable to:
 - More recent hydrophone calibration
 - Smoother hydrophone sensitivity over the frequency range
- Beam plots that were consistent with experimental configuration, attributable to:
 - Less sensitivity to reverberant/reflected signals within the measurement tank

CONTENTS

1	Introduction.....	1
2	TVR measurements vs hydrophone frequency response	1
2.1	Transmit voltage response (TVR)	1
2.2	Hydrophone frequency response	1
2.3	Calibration interval.....	2
2.4	Measured TVR for 500 kHz and 850 kHz transducers.....	3
3	Beam plot	4
3.1	Hydrophone directivity response	5
3.2	Measured beam plots for 500 kHz and 850 kHz transducers.....	6
4	Outcomes	7

TABLE OF FIGURES

Figure 1 - Frequency response of two hydrophone types	2
Figure 2 - TVR for 500 kHz transducers measured with both Needle and Cylindrical hydrophones.....	3
Figure 3 - TVR for 850 kHz transducers measured with both Needle and Cylindrical hydrophones.....	3
Figure 4 - Experimental beam plotting.....	4
Figure 5 - Unwanted reflections within a finite sized tank.....	4
Figure 6 - Directivity of 2.0 mm needle hydrophone	5
Figure 7 - Beam plot of source transducer at 500 kHz measured with both hydrophone types. Needle hydrophone (blue); Cylindrical hydrophone (red)	6
Figure 8 - Beam plot of source transducer at 850 kHz measured with both hydrophone types. Needle hydrophone (blue); Cylindrical hydrophone (red)	7

GLOSSARY OF TERMS AND ABBREVIATIONS

<i>IEC</i>	International Electrotechnical Commission
<i>PA</i>	Precision Acoustics Ltd
<i>TVR</i>	Transmit Voltage Response

VERSION HISTORY

Version	Date	Description
1.0	19/03/2026	Document created

1 INTRODUCTION

Many underwater acoustics hydrophones are based upon cylindrical or spherical sensing elements. Typically, these employ piezoelectric ceramics and are either used without any form of preamplification or employ a charge amplifier at the end of the hydrophone cable. Historically, these sorts of sensors were used in the frequency range below 100 kHz. Demand for higher resolution in underwater acoustic and sonar images requires smaller wavelengths and thus higher operating frequencies.

This case study explores the limitations of a smaller piezo-ceramic cylindrical hydrophone and how that impacts the measurement of both TVR and radiated beam plot for one of PA's sonar customers. This is compared with the same measurements conducted with a needle hydrophone based upon a piezo-polymeric sensing element. The customer in this case study makes a range of transducers with operating frequencies ranging from 200 kHz to 1.5 MHz, although measurements over a narrower range are discussed herein.

2 TVR MEASUREMENTS VS HYDROPHONE FREQUENCY RESPONSE

2.1 TRANSMIT VOLTAGE RESPONSE (TVR)

The frequency dependent TVR of an underwater acoustic source, $S_v(f)$, is obtained from the relationship

$$S_v(f) = \frac{P(f) \cdot r}{V(f)} \quad (1)$$

where $P(f)$ is the measured pressure in the acoustic field at that frequency, r is distance and $V(f)$ is the voltage applied across the terminals of the transducer. For convenience, a standard distance of 1 m is often selected in which case the expression becomes

$$S_v(f) = \left. \frac{P(f)}{V(f)} \right|_{r=1m} \quad (2)$$

Determination of the applied voltage is trivial, but evaluating the received pressure at a specific location in the field requires a hydrophone whose sensitivity has been calibrated over the frequency range of interest.

2.2 HYDROPHONE FREQUENCY RESPONSE

The frequency dependent sensitivity of a hydrophone, $M(f)$ is obtained from the relationship

$$M(f) = \frac{V_h(f)}{P(f)} \quad (3)$$

where $V_h(f)$ is the measured hydrophone voltage at that frequency and $P(f)$ is the pressure in the acoustic field at that frequency. To derive the acoustic field pressure for use in the TVR equation, combine equations (2) and (3), to yield Equation (4).

$$S_v(f) = \frac{V_h(f)}{M(f) \cdot V(f)} \quad (4)$$

Below the principal resonance, piezo-ceramic cylindrical hydrophones have a largely flat frequency response. However, at resonance the sensitivity increases by (typically 3-5 dB) before falling rapidly. This can clearly be seen in the orange trace of Figure 1. Given that hydrophone sensitivity is in the denominator of Equation (4), dividing by a numerically small number can lead to computational errors. Furthermore, from a metrology perspective, measurements undertaken at frequencies with low sensitivity are liable to suffer comparatively worse signal-to-noise ratio; this will further increase potential measurement inaccuracy.

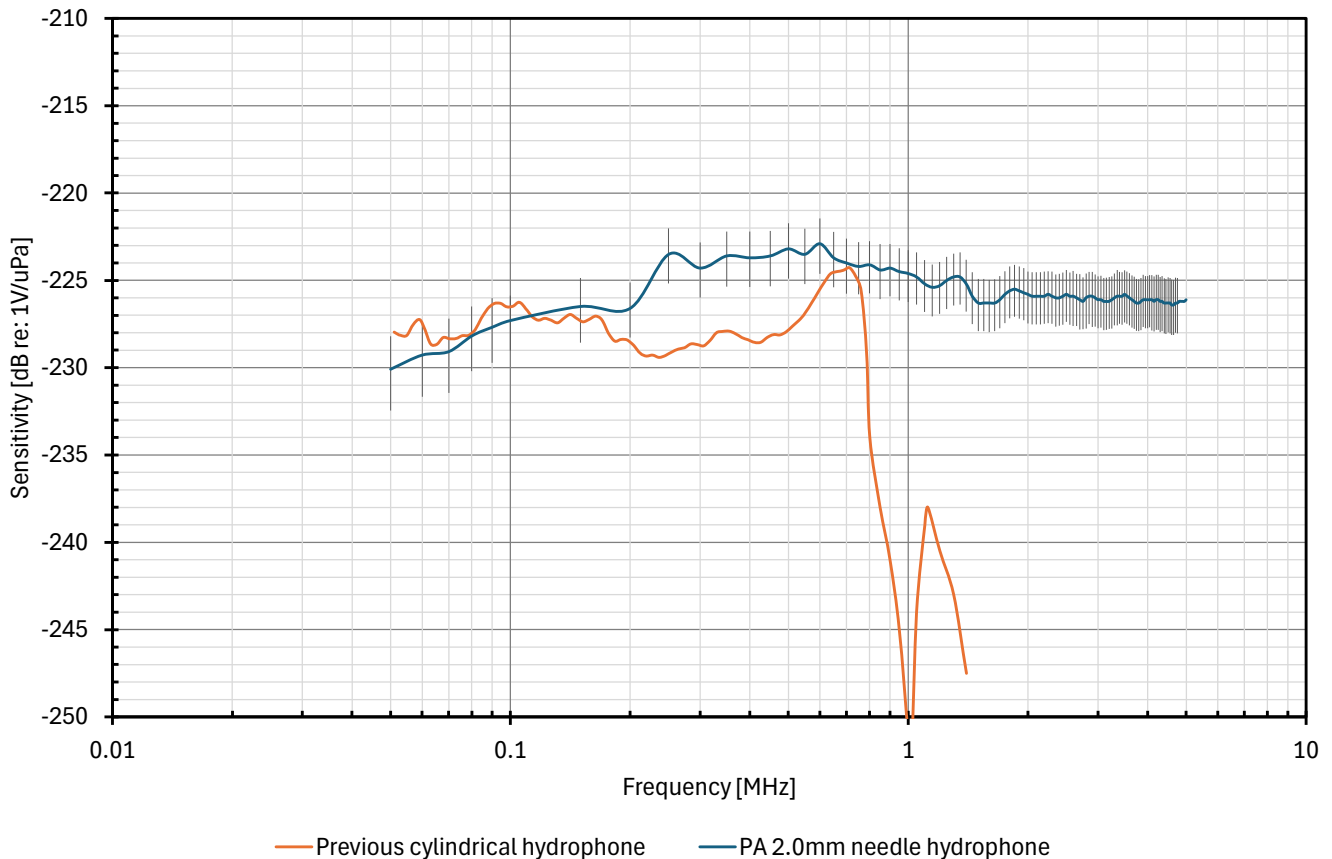


Figure 1 - Frequency response of two hydrophone types

In contrast, the frequency response of the PA 2.0 mm needle hydrophone (shown in blue within Figure 1 along with typical uncertainty bars) maintains a much higher sensitivity all the way out to 5 MHz. This is due to the piezo-polymer active element that has a thickness resonance >10 MHz. The needle hydrophone provides substantially more sensitivity above 800 kHz and thus ensures accurate evaluation of TVR for the customer all the way to their upper frequency of interest.

2.3 CALIBRATION INTERVAL

All hydrophones should be re-calibrated periodically. Hydrophones may suffer damage and/or component degradation and hence frequency response and sensitivity may change over time. Both IEC measurement standards, and PA recommendations, are that hydrophones re-calibration interval is no longer than 12 months. The PA 2.0mm needle hydrophone was calibrated immediately prior to being

supplied to the customer. It is noted that the cylindrical hydrophone was well outside its recommend annual re-calibration interval.

2.4 MEASURED TVR FOR 500 KHZ AND 850 KHZ TRANSDUCERS

Experimentally determined TVR plots for both 500 kHz and 850 kHz transducers can be seen in Figure 2 and Figure 3 respectively. Several features are worthy of comment. Firstly, there is a notable overall level shift between measurements conducted with the two hydrophones; this is evident for both transducer types. This is most likely due to a drift in the calibration of the cylindrical hydrophone and thus reinforces the need for regular re-calibration.

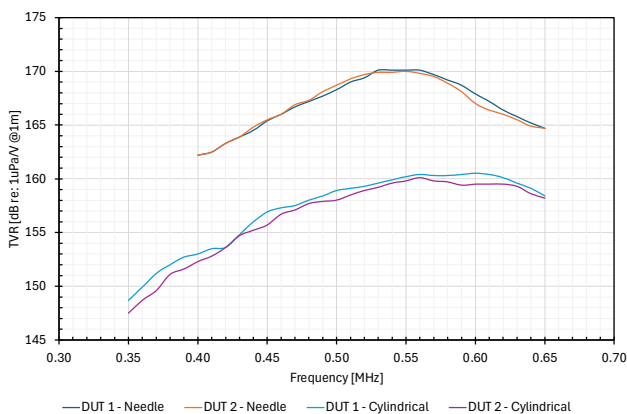


Figure 2 - TVR for 500 kHz transducers measured with both Needle and Cylindrical hydrophones

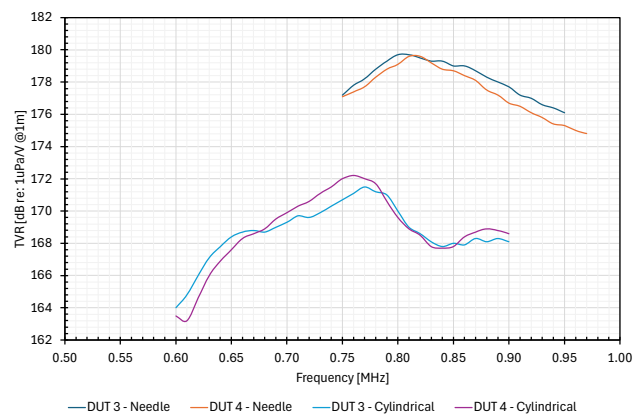


Figure 3 - TVR for 850 kHz transducers measured with both Needle and Cylindrical hydrophones

Secondly, we see that both sets of TVR profiles for the 500 kHz transducer (Figure 2) are smoothly varying, have largely similar shape and central frequency. Recall the hydrophone frequency responses shown in Figure 1. It is evident that these TVR measurements were conducted over a frequency range where the response of both hydrophones is reasonably flat (± 2 dB). Now consider the 850 kHz transducer TVR measurements in Figure 3. These were conducted over a frequency range within which the cylindrical hydrophone displayed a 25 dB fall-off due to its inherent resonance.

Division by small numbers (q.v. the sensitivity term in the denominator of Equation 4) can lead to numerical inaccuracies. In addition to errors associated with representation of floating-point numbers, small changes in either numerator or denominator can lead to large swings in the resultant value. This is almost certainly the cause of the apparent local minimum in TVR for the cylindrical hydrophone measurements around 820 kHz. Without this artefact, the TVR curve would be monotonically decreasing from its peak (approx. 760 kHz) and the calculated centre frequency would increase notably. Thus, this artefact has changed the shape, and the apparent centre frequency, of the TVR curve.

Contrast this with the measurements made with the needle hydrophone – which has a much flatter frequency response all the way to 5 MHz. Here no undulations in TVR are observed, and the centre frequency for both devices is between 800 kHz and 820 kHz; this is completely consistent with the design parameters of the transducer.

3 BEAM PLOT

A common method to determine the beam plot (directivity) of a source transducer is to rotate it through the desired angular range (often a full circle) and to quantify the received pressure signal at some fixed location. This is illustrated in Figure 4, where the source transducer is shown in black with its radiated beam in orange. The receiving transducer (diagonal stripes) is a fixed distance from the source and the direction of rotation of the source is shown as a blue arrow. In open-water conditions this is relatively simple; there are no surfaces to cause unwanted reflections. However, open water testing is often prohibitive in terms of cost and practicality. As an alternative, finite sized measurement environments, such as a tank within a laboratory, are often used. This is illustrated in Figure 5

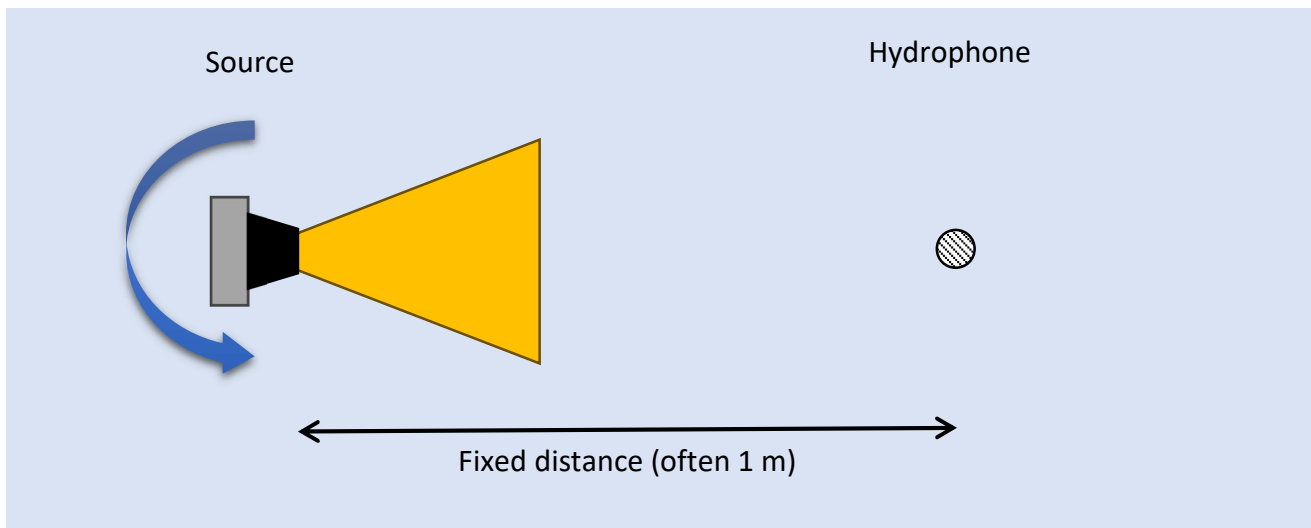


Figure 4 - Experimental beam plotting

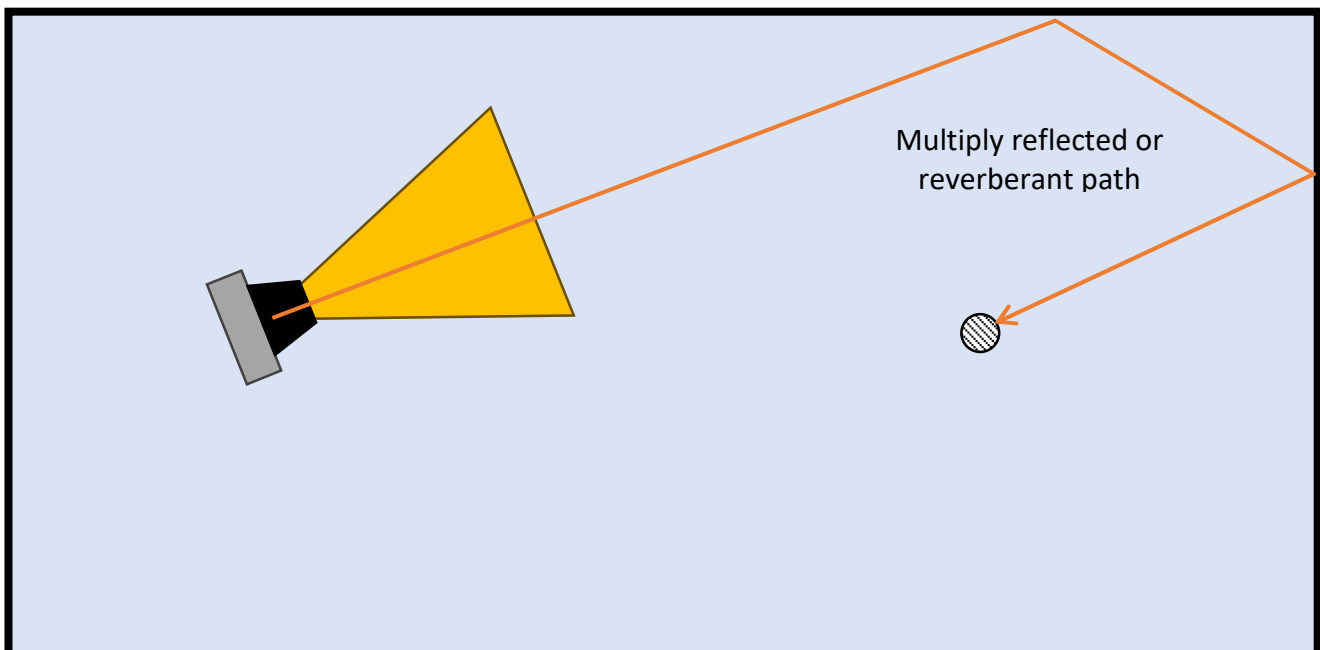


Figure 5 - Unwanted reflections within a finite sized tank

The problem clearly demonstrated within Figure 5 is that of unwanted reflections from the inner surfaces of the tank, which then arrive back at the position of the receiving hydrophone. Time gating of waveforms can help reduce such artefacts, but that too can impose limits:

- If the source transducer is driven by a source signal of long duration, effective separation of directly incident and reflected signals may not be possible.
- Reverberant signals from previous drive signals that have echoed around the tank can still arrive back within the time window of a subsequent acquisition.

Anechoic tank linings are also available (including many from Precision Acoustics Ltd www.acoustics.co.uk), but these may have cost and size implications.

3.1 HYDROPHONE DIRECTIVITY RESPONSE

The cylindrical hydrophone originally used by PA's customer was suspended downwards in the measurement tank. At 250 kHz, it had a directional response that was close to omni-directional in the horizontal plane. In the vertical plane, and at the same frequency, its directional response was close to omnidirectional except for notable minimum that corresponded to the position of the hydrophone structure and cable. No directional response plot was available for this hydrophone at higher frequencies but given the cylindrical symmetry of the active element, an omni-directional response is likely. This omni-directionality means the cylindrical hydrophone is as sensitive to signals arriving directly from the transducer, as it is to those reflected from the inner surfaces of the tank.

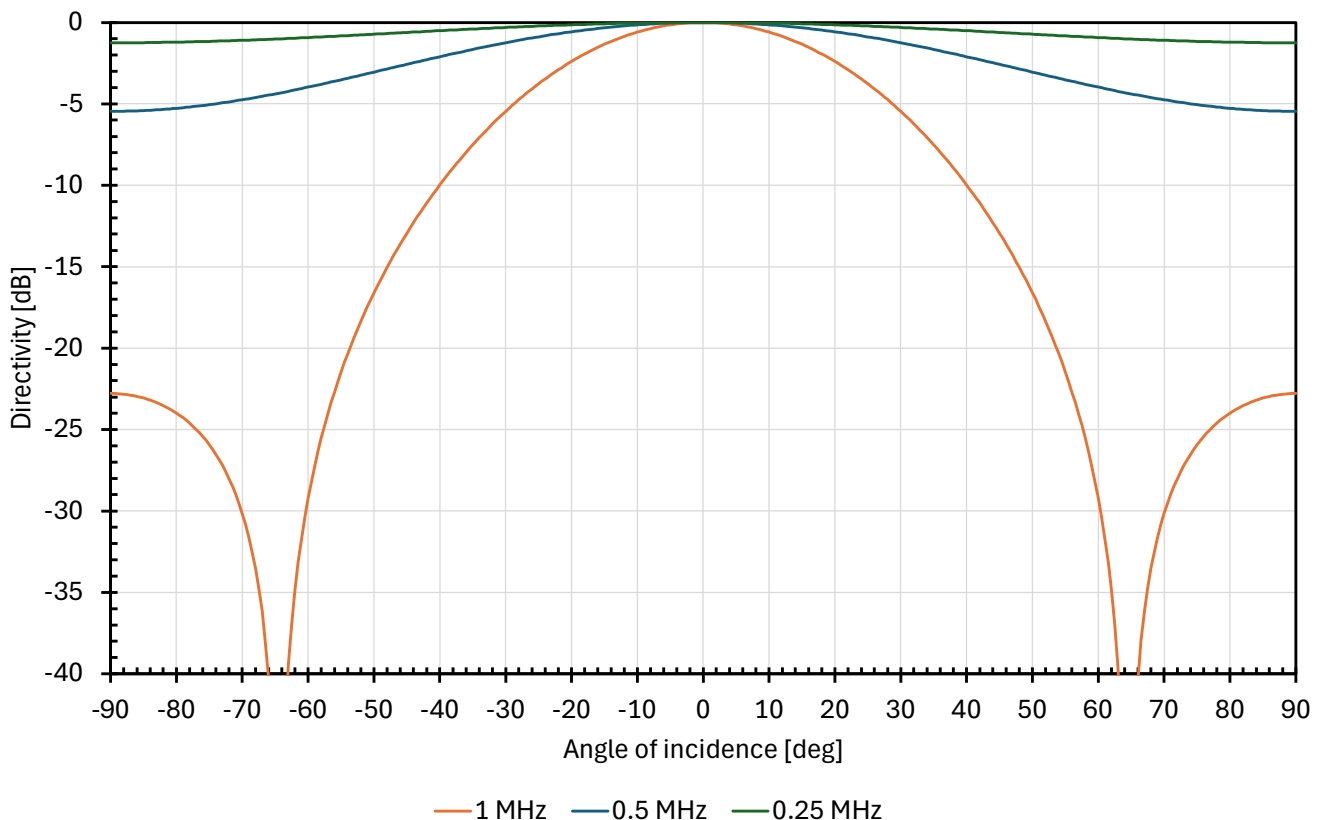


Figure 6 - Directivity of 2.0 mm needle hydrophone

The PA 2.0mm needle hydrophone has a circular disc element mounted onto the end of the needle shaft and as such has a directivity pattern at various frequencies shown in Figure 6.

At 250 kHz, the response varies by less than 1.5 dB over the range -90° to $+90^{\circ}$ where 0° corresponds to the needle hydrophone pointing directly at the source transducer. However, as frequency increases, the angular response becomes increasingly directional.

3.2 MEASURED BEAM PLOTS FOR 500 KHZ AND 850 KHZ TRANSDUCERS

Figure 7 displays the polar beam plot of a 500 kHz transducer determined with both hydrophones. Importantly the mounting fixture for the transducer is acoustically impenetrable. Consequently, when the transducer is rotated 180° (i.e. with its rear surface facing towards the hydrophone) there should be very little direct signal received by the hydrophone. However, as can be seen from the red trace (cylindrical hydrophone) the received signal is only 25-28 dB lower than the peak amplitude even at 180° orientation. The source of this unexpected signal contribution is likely to be internal reverberations and reflections within the tank.

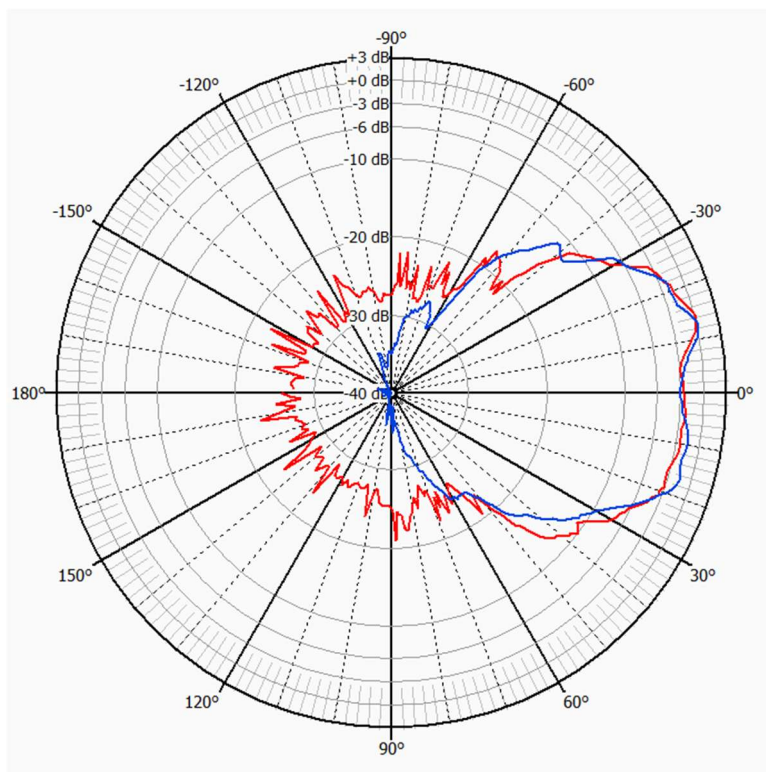


Figure 7 - Beam plot of source transducer at 500 kHz measured with both hydrophone types. Needle hydrophone (blue); Cylindrical hydrophone (red)

In contrast, the measurement with the 2.0 mm needle hydrophone shown as the blue trace in Figure 7, indicates the rearward propagating signal is circa 40 dB below the peak.

A similar measurement set undertaken with an 850 kHz transducer, and shown in Figure 8, also shows a substantial improvement in the beam plot. Clearly then, for measurements within a finite sized

measurement tank as shown in Figure 5, the directional response of the 2.0mm needle hydrophone has led to beneficial experimental outcomes

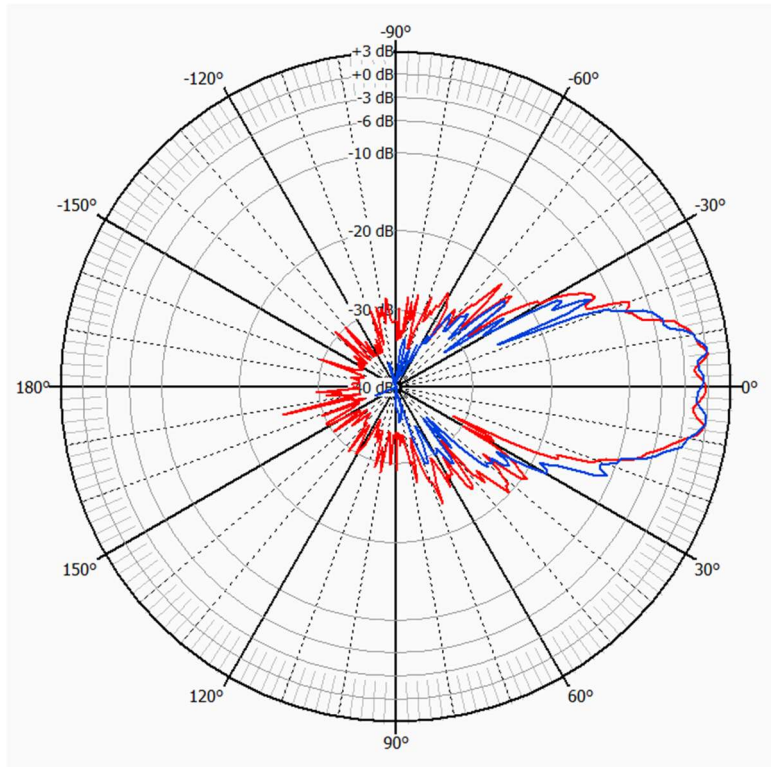


Figure 8 - Beam plot of source transducer at 850 kHz measured with both hydrophone types. Needle hydrophone (blue); Cylindrical hydrophone (red)

4 OUTCOMES

This case study has highlighted several key outcomes

1. It serves to re-emphasise the importance of annual recalibration of all devices used for conducting absolute measurements. This is especially true for hydrophone and annual recalibration is strongly recommended
2. Measurements conducted over a frequency range in which the reference hydrophone exhibits substantial changes in its frequency response should be avoided where possible. This can result in notable changes to apparent TVR and incorrect determination of centre frequency. A hydrophone whose response is smoothly varying and reasonably constant over the frequency range of interest is always preferable to one exhibiting in-band resonant behaviour.
3. Omni-directional devices may seem attractive as it may seem as if they have less stringent alignment requirements. However, if reflected and/or reverberant signals are present, contributions from unwanted signal paths can lead to erroneous evaluation of beam patterns.