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Free-field calibration of hydrophones at frequencies from 250 Hz to 1 kHz

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Free-field calibration of hydrophones at frequencies from 250 Hz to 1 kHz

by

Gary Hayman, Graham O. Wells,
Philip J. Boys and Clive Chambers

ABSTRACT

In this report, a description is given of the techniques employed to extend the frequency range over which free-field calibrations can be performed at the UK National Physical Laboratory. These techniques were developed at NPL's open-water calibration facility, based on a reservoir at Wraysbury, with the aim of extending the low frequency limit from 1 kHz down to 250 Hz. A discussion of the requirements for free-field conditions is presented with a description of the methods employed to achieve these by use of the device mounting arrangement, choice of source transducers and signal analysis methods. The sources of uncertainty relating to the calibration methods are discussed and the levels of the individual contributions assessed. Finally, results of the calibrations performed are presented along with comparisons with measurements made in the NPL primary coupler and pistonphone facilities.

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1. INTRODUCTION

The largest number of requests received by NPL for improvements to the underwater acoustics services is for provision of traceable free-field standards at frequencies below 1 kHz. This frequency range covers a number of applications including low frequency active and passive sonar, seismic surveying for hydrocarbons, acoustic tomography and thermometry. In addition, hydrophones are routinely used to measure ocean noise at sub-kilohertz frequencies, both man-made and naturally occurring. Other applications include detection of leaks in fluid filled pipes [1].

The 2001-2004 NMS programme has seen the coupler reciprocity method [2] established as a primary standard for frequencies below 1 kHz. However, this method is not cost effective to operate as a service and is limited regarding which hydrophone may be calibrated by the physical size of the coupler chamber. It is proposed that free-field calibrations are used to transfer the standards realised using the primary coupler and such measurements require a large volume of water.

Fig 1.1 The Underwater Acoustic Calibration Facility located on Wraysbury reservoir

A major dissemination route for the UK underwater acoustic primary standard is NPL's open-water calibration facility based on a reservoir at Wraysbury, about 8 miles from the main NPL laboratories in Teddington. The facility consists of a calibration raft in the centre of a 1 km x 2 km fresh water reservoir with an average water depth of over 20 m and can be seen in Figure 1.1. Here, free-field calibrations and measurements are undertaken in the frequency range from 1 kHz to 350 kHz to characterise the performance of acoustic transducers or complete sonar systems. The calibration raft has three separate, fully instrumented measurement stations, with hoists and handling equipment capable of deploying large sonar arrays up to 1.5 tonne. The facility is integrated into the provision of acoustical standards under the auspices of the National Measurement System, providing a high volume of calibrations traceable back to primary standards maintained at NPL Teddington.

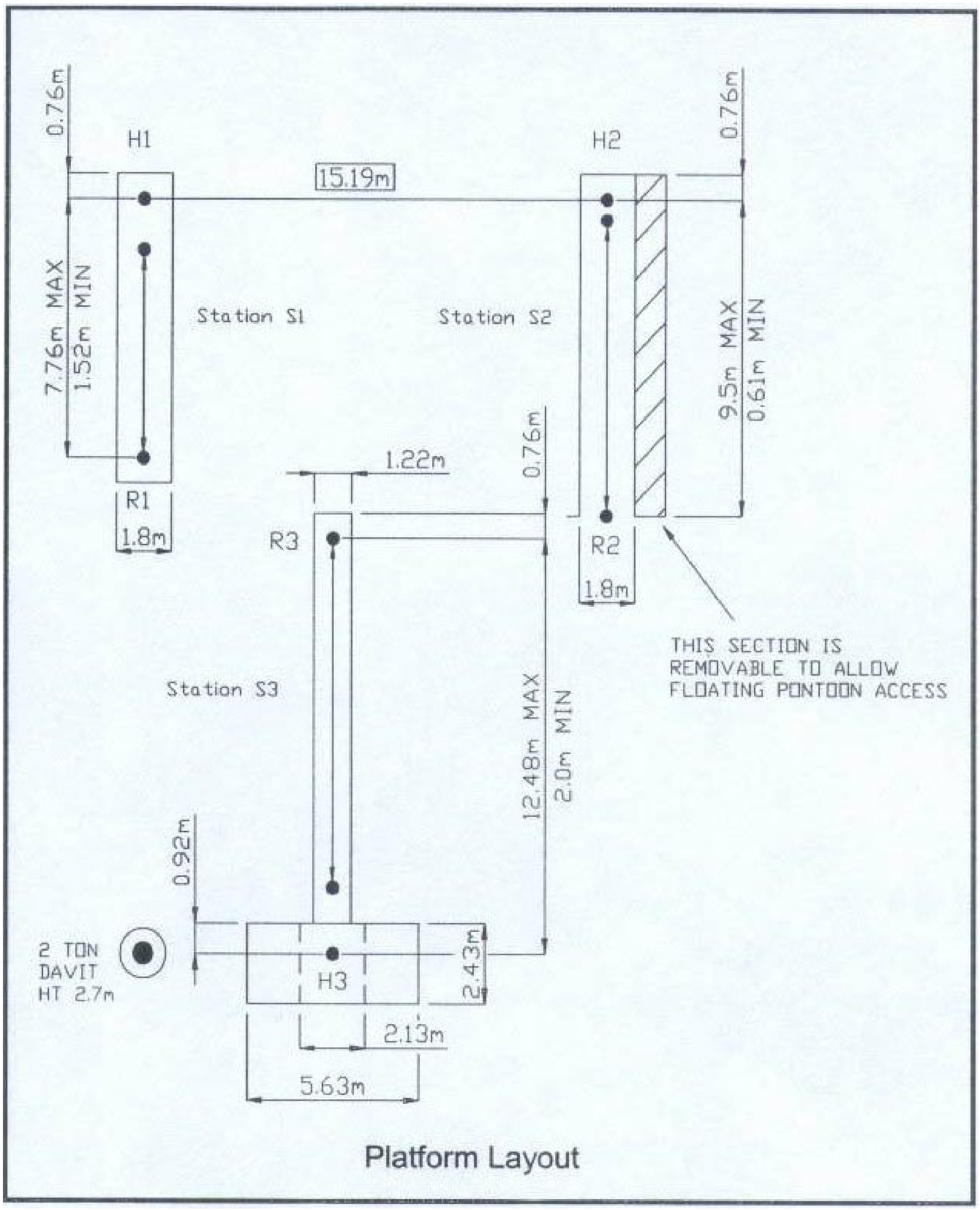

Fig 1.2 Measurement station layout on the Wraysbury platform

The Wraysbury calibration raft is a floating structure moored at the four corners. This means that there is no significant supporting steelwork below the waterline, which could act as a source of reflections during acoustic measurements, apart from the other measurement hoist stations. Figure 1.2 shows the layout of the measurement stations on the raft. The ones marked H1, H2 and H3 are the fixed hoist stations used to deploy devices under test. Those marked R1, R2 and R3 are the corresponding rolling stations used to deploy the laboratory's reference transducers. On each of these stations are mounted four reference devices, which between them cover the frequency range 1 kHz to 350 kHz. Each rolling station can be moved in relation to the corresponding hoist station to give a range of transducer separations. From Figure 1.2 it can be seen that three sets of measurement stations are several metres apart and reflections from one station to another should not be significant.

Currently, there are three main limitations of the measurement method used which make free-field calibrations below 1 kHz at the facility impractical: the depth at which the measurements are performed, the signal analysis method used and the low frequency source transducer. These limitations, and the methods employed to overcome them, are described in the following sections.

2. METHODOLOGY

2.1 REQUIREMENTS FOR FREE-FIELD

For a measurement to be considered free-field, it has to be made in an environment free from reflections. Generally, in a laboratory tank, the sources of the largest reflections are the boundaries of the medium i.e. the bottom and sides of the tank and the surface of the water. The Wraysbury calibration raft is located 300 metres from the nearest bank, and so any reflections from the sides of the reservoir will be strongly attenuated due to propagation losses and therefore negligible. With a typical reservoir water depth of 20 metres, the ideal depth at which to perform measurements would be 10 metres. This would give the greatest echo-free time before the arrival of reflections from the reservoir bottom or water surface. However, the mounting flange of the hoist stations used to deploy devices under test reaches to a maximum depth of 5 metres, and so, with the addition of some form of mounting bracket, measurements at the facility are typically performed at a depth of 5-6 metres.

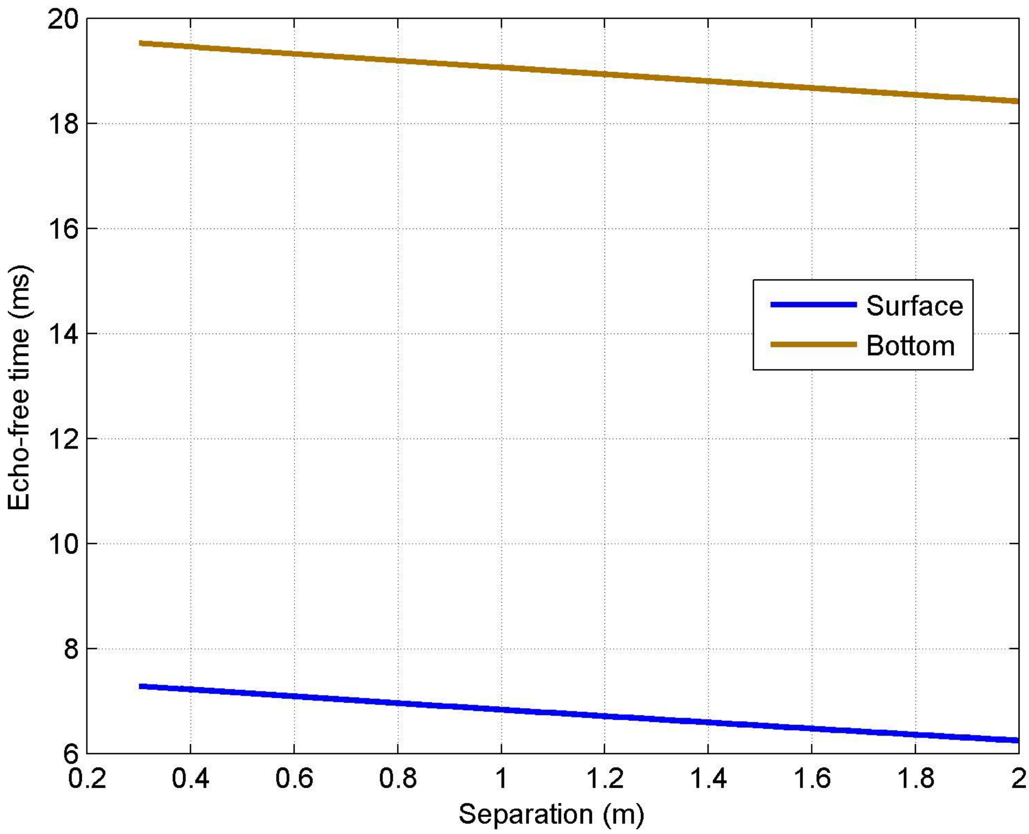

Fig 2.1 Echo-free time before arrival of surface and bottom reflections

In order to window out any reflections present during the measurements, tone burst signals and time gating techniques are used. Figure 2.1 shows the echo-free time available, before the arrival of reflections from the surface of the water and the bottom of the reservoir, for various transducer separations. The assumptions made are that the water depth in the reservoir is 20 metres and the devices are deployed at a depth of 5.5 metres. It can be seen that any reflections from the reservoir bottom take over 18 ms to arrive and are easily windowed out.

But for a separation of 1 metre there is only around 7 ms of measurement time available before the arrival of the first reflection from the water surface. This equates to 7 cycles of a 1 kHz signal.

The measuring instrument used at the facility is an Agilent 89410A Vector Signal Analyzer, and the current method used to obtain the amplitude of the tone burst signal from the receiving hydrophone is as follows. The received signal is captured by the analyzer and a measurement window is set on the steady state portion of the time waveform. The analyzer then performs a FFT on the signal within this window and returns the amplitude of the peak at the measurement frequency. In order to produce an accurate measurement of the amplitude by this method, the analyzer requires at least four cycles of the frequency of interest within the measurement window. While accurate free-field measurements can be made down to 1 kHz, at frequencies much less than this the echo-free time is not sufficient for the measurement of four steady state cycles before the arrival of any reflection from the water surface.

2.2 SOURCE TRANSDUCERS

The low frequency source transducers used at the facility have a nominal resonance frequency of 8 kHz and are seven element vertical arrays with an overall length of 665 mm. This means that they are directional in the vertical plane at kilohertz frequencies, which helps to reduce the effect of any possible reflections from the surface or reservoir bottom, but they become increasingly more omnidirectional as the frequency falls to 1 kHz and below. The transmitting voltage response (TVR) of the transducers is approximately 142 dB re 1µPa·m/V at the 8 kHz resonance frequency, but it is typically down to around 93 dB re 1µPa·m/V at 1 kHz and falls off at a rate of 16 dB/octave. This makes them unsuitable for measurements down to 250 Hz, as the source level produced will be low, giving a poor signal-to-noise ratio on the received signal.

As an alternative, moving coil low frequency projectors were considered. These can produce high source levels down to a few tens of Hertz, but tend to be large, heavy devices making them difficult to deploy. They also take a relatively long time to reach steady state, which makes them unsuitable for use with tone burst signals in situations where there is limited echo-free time.

The device chosen as the main low frequency source was an ITC-1007 transducer. This is a spherical transducer with a diameter of approximately 165 mm and a resonance frequency of around 11.5 kHz. Although the output from this device is much lower than would be expected from a moving coil projector, it is significantly higher than that produced by the standard 8 kHz transducers, with a TVR at 1 kHz of around 107 dB re 1µPa·m/V, falling off at rate of only 12 dB/octave.

The combination of relatively small transducers (compared to the standard 8 kHz array) and low measurement frequencies means that measurements can be performed in the far field with device separations of less than half a metre. This goes some way towards compensating for poor signal levels at the lower end of the frequency range. The use of a shorter distance between devices means that the separation needs to be known accurately, as any error in the measurement of the separation will have a correspondingly larger effect on the accuracy of the sensitivity measurements than at greater device separations. This can be better achieved by mounting both projector and receiver on the same bracket, but as the devices will be omnidirectional below 1 kHz, there is therefore a need to avoid reflections from the mounting bracket as well as the water surface and reservoir bottom.

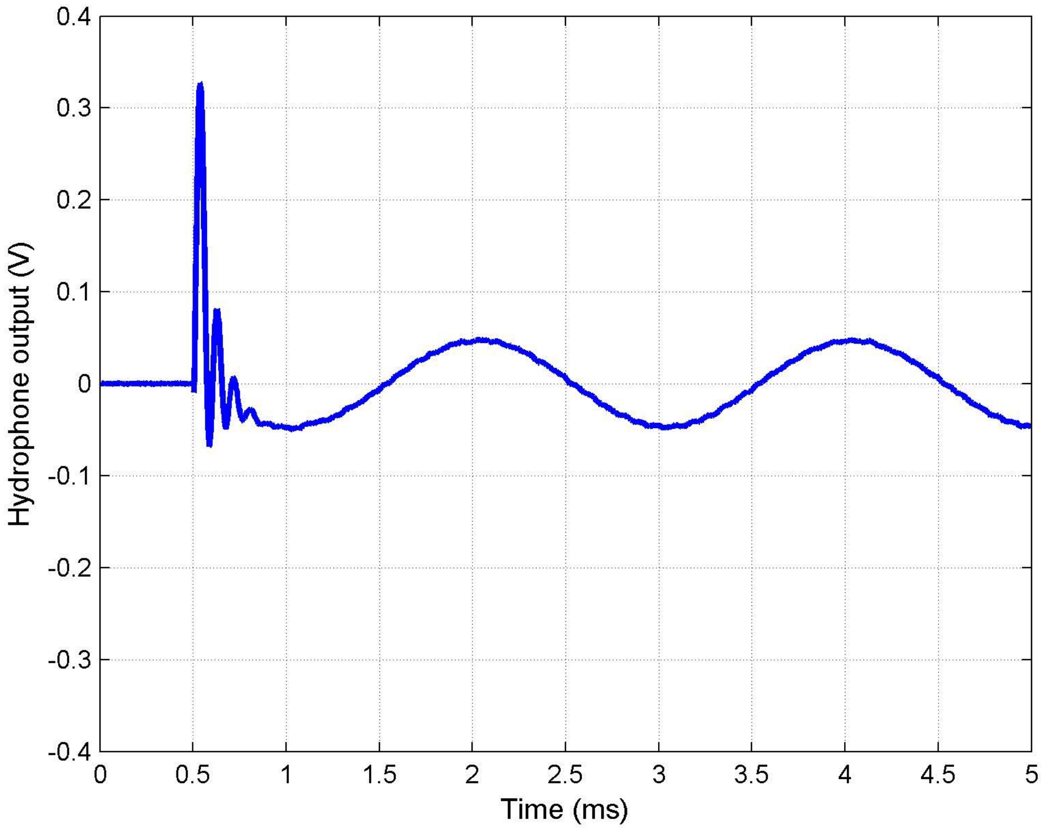

Fig 2.2 Time taken to reach steady state for ITC-1007 transducer

Figure 2.2 shows the time taken for the ITC-1007 transducer to reach steady state. The ITC-1007 transducer was driven with a 500 Hz tone burst signal and the output from a Reson TC4032 hydrophone captured on the Vector Signal Analyzer. It can be seen that there are around three cycles of the resonance frequency of the ITC-1007 (11.5 kHz), or approximately 0.3 ms from the start of the tone burst, before the 500 Hz signal reaches steady state.

2.3 MOUNTING

Figure 2.3 shows the mounting arrangement used for low frequency calibrations. The mounting bracket was custom-made from steel at the Wraysbury facility and consists of a short horizontal crossbeam, with adapter bracket to mate to the hoist station flange, to which two vertical legs are attached. It can be seen that, while both of the legs terminate at the same distance from the hoist station flange, one of them is angled. This is so that the two legs are different lengths and thereby have different resonance frequencies. The two legs are detachable from the horizontal crossbeam, which has multiple mounting holes to enable the transducer separation to be varied. Both the two legs and the crossbeam have a V-shaped cross section designed to minimise reflections from the bracket in the direction of the transducers. In order to minimise transmission of the drive signal through the bracket, the source transducer and hydrophone are not attached directly to he bracket, but hung approximately 0.7 metre from the ends of the legs. The overall distance from the transducers to the hoist station mounting flange is approximately 2.5 metres.

Fig 2.3 Mounting arrangement used for low frequency calibrations

Figure 2.4 shows an analysis of the sources of reflections for the mounting arrangement described above. As in figure 2.1, the available echo-free time is shown as a function of transducer separation, but as well as the reflections from the water surface and reservoir bottom, reflections from the bracket mounting flange are also shown. The analysis assumes that the water depth in the reservoir is 20 metres, the bracket mounting flange is at a depth of 5 metres and the transducers are a further 2.5 metres below the mounting flange. As expected, since the transducers are now deployed at a greater depth, the reflection from the bottom of the reservoir arrives earlier and the reflection from the water surface arrives later. With the mounting arrangement described, the transducer separation will typically be in the range 0.3 metre to 0.5 metre. For this order of separation, the bottom reflection arrives after approximately 17 ms and there is now around 10 ms of echo-free time before the arrival of any reflection from the water surface. Although, as described above, the horizontal crossbeam of the mounting bracket has a V-shaped cross section designed to minimise reflections, with omni-directional transducers mounted on the same bracket, reflections from this and the hoist station behind it have to be considered as a potential source of interference in any calibration. Figure 2.4 shows that the echo-free time available before the first arrival of any reflections from these sources is approximately 3 ms and, by referring back to figure 2.2, it can be seen that in this time period there is only around one cycle of 500 Hz available for measurement once the signal has reached steady state.

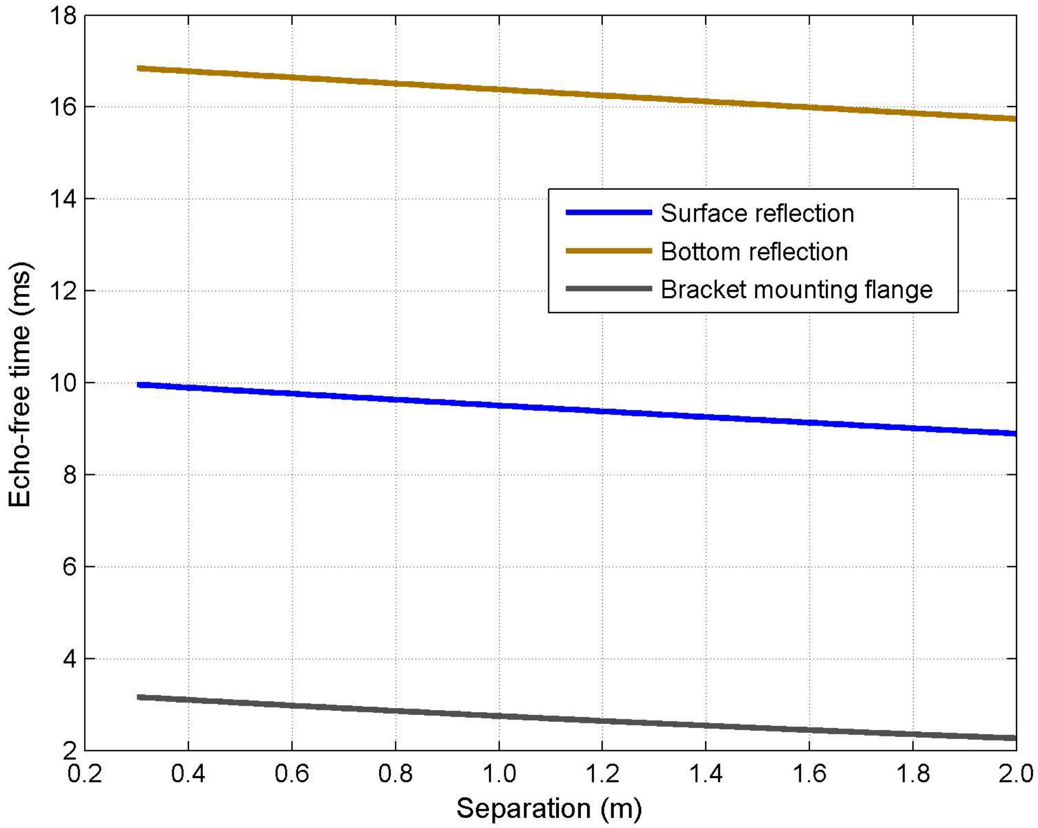

Fig 2.4 Echo-free time before arrival of reflections from various sources

2.4 ANALYSIS ROUTINES

As stated in section 2.1, the standard method of determining the amplitude of the received signal, whereby the Vector Signal Analyzer performs a FFT on the windowed time waveform and returns a single voltage value, requires a minimum of four cycles to produce an accurate result. The above echo-free time analysis has shown that there is only one steady state cycle available for a free field measurement at 500 Hz, and consequently only half a cycle available at 250 Hz. Two signal analysis methods which can accomplish such measurements have been incorporated into the measurement software, and these are described below.

2.4.1 Discrete Fourier Transform

Here, the windowed, steady state portion of the time waveform is transferred from the Vector Signal Analyzer to the computer where a software algorithm performs a discrete Fourier transform on an integer number of cycles of the signal, calculating only the amplitude of the spectral component at the acoustic frequency. The method requires at least one cycle of signal and therefore may be used successfully down to 500 Hz.

2.4.2 Fitting a Sinusoidal Model

In this case, the windowed, steady state portion of the time waveform is again transferred to the computer where a software algorithm performs a fit of a sinusoidal waveform using a least-squares estimation [3,4]. In the model, the frequency of the sinusoidal wave is constrained to be the acoustic frequency and the amplitude of the fitted sine wave provides the measurement of the signal amplitude. Unlike the discrete Fourier transform method, this method does not require an integer number of cycles and may be used successfully on less than one cycle of signal. The measurement of the amplitude of signals at frequencies as low as 250 Hz can therefore be accomplished by this method.

The signal analysis methods described will provide some discrimination against noise and perform effective averaging of small amplitude variations within the tone-burst if many cycles are contained within the time window. However, with only one cycle or less available, the accuracy of both of these methods will be compromised by poor signal-to-noise. Therefore, for weak signals, it is necessary to perform on-board averaging of the time waveform prior to transfer to the computer for analysis.

2.5 MEASUREMENT METHODS

The various measurement methods used at the Wraysbury facility are described below.

2.5.1 Reciprocity

Three-transducer spherical-wave reciprocity is an absolute calibration method involving measurements on three transducers designated as projector (P), reciprocal transducer (T) and hydrophone (H). P is only ever used to project, H is only ever used to receive and T must be a reciprocal device as it is used both to project and receive. Three sets of measurements in the following configurations are made: P transmitting to T, P transmitting to H and T transmitting to H. In each case, the transfer impedance is determined by taking the quotient of the receive voltage and drive current. At the Wraysbury facility, the drive voltage is measured and the drive current is then calculated using a prior measurement of the transducer electrical impedance. The receive sensitivity of the hydrophone (H) is then given by:

$$M_H = \sqrt{J \frac{d_{PH}\, d_{TH}}{d_{PT}} \frac{Z_{PH}\, Z_{TH}}{Z_{PT}}}$$

where d is the separation of the transducers and Z is the electrical transfer impedance. The subscripts refer to which hydrophones are used for the transfer impedance measurement. The reciprocity parameter, J, is given by

$$J = \frac{2 d_0}{\rho f}$$

where d_0 is the reference distance in the definition of the transmitting response (usually equal to 1 metre and so omitted from the equation), ρ is the water density and f is the acoustic frequency.

Whilst this method has the lowest uncertainties, it is also the most time-consuming due to the number of measurements involved. It is therefore generally only used for the calibration of the in-house reference transducers.

2.5.2 Calibrated Projector

A reference projector is used to calibrate an unknown hydrophone. The transmitting voltage response (TVR) of the projector has previously been determined by an absolute calibration by three-transducer spherical-wave reciprocity. By monitoring the drive voltage and knowing the separation between the projector and hydrophone, the sound pressure level at the hydrophone can be determined. A measurement of the electrical signal produced by the hydrophone will then enable the calculation of the receive sensitivity as below:

$$M_H = \frac{V_H}{V_P} \times \frac{D}{TVR_P}$$

where:-

M_H = hydrophone sensitivity;
V_H = receive voltage from unknown hydrophone;
V_P = projector drive voltage;
D = transducer separation;
TVR_P = transmitting voltage response of projector.

2.5.3 Calibrated Hydrophone

A reference hydrophone is used to calibrate an unknown projector. This is effectively the reverse of the calibrated projector method described above. The measurement setup is the same except that this time the receive sensitivity of the reference hydrophone has previously been determined by an absolute calibration by three-transducer spherical-wave reciprocity. The sound pressure level produced by the unknown projector can be calculated from the signal received by the reference hydrophone, and by measuring the drive voltage the TVR can be determined.

$$TVR_P = \frac{V_H}{V_P} \times \frac{D}{M_H}$$

2.5.4 Comparison

A reference hydrophone is used to calibrate an unknown hydrophone. A projector, which may be an uncalibrated device, is used to transmit a signal to the reference hydrophone. The reference hydrophone is then replaced by the unknown hydrophone. A second measurement is made using the same drive conditions and from these two measurements the receive sensitivity of the unknown hydrophone can be calculated as follows:

$$M_H = \frac{V_H}{V_{REF}} \times M_{REF}$$

where:-

V_H = receive voltage from unknown hydrophone;
V_{REF} = receive voltage from reference hydrophone;
M_{REF} = reference hydrophone sensitivity.

3. EXPERIMENTAL PROCEDURE

Measurements were performed at the Wraysbury facility in the frequency range 250 Hz to 1 kHz using the three-transducer spherical-wave reciprocity and calibrated projector methods. The reciprocity method was used to obtain absolute calibrations of an ITC-1007 projector and a Reson TC4032 hydrophone in order that they could be used as reference devices in calibrated projector/hydrophone measurements. The ITC-1007 transducer was then used to derive the receive sensitivity of a Reson TC4023 hydrophone by use of the calibrated projector method. The Reson TC4023 is a small spherical hydrophone, which had previously been calibrated using both the NPL primary coupler and NPL pistonphone. A comparison of the results of the calibrations would thereby provide a traceability route for the low frequency calibrations performed at the Wraysbury facility. Reciprocity measurements were performed at different temperatures in order to assess the temperature stability of the transducers used as reference devices. The results of the above calibrations are presented in section 5.

The mounting arrangement described in section 2.3 is used for both three-transducer spherical-wave reciprocity calibrations and measurements using the calibrated projector/hydrophone method. For the reciprocity method, the calibration is performed in three stages, with each pair of transducers mounted on the bracket in turn. After mounting, the separation between the centres of the transducers is measured with a rule. Before deployment the transducers are wetted with a weak solution of detergent to reduce the surface tension and prevent trapped air. The hoist station is then lowered to a depth of 5 metres, positioning the devices at a depth of approximately 7.5 metres. Before starting any measurements, the transducers are left to soak for at least two hours to ensure that thermal equilibrium is reached.

In calm weather conditions, the separation of the transducers can be determined accurately by physical measurement. As the devices are hanging some distance below the bracket, windy conditions can cause the transducers to swing, making an accurate physical measurement of the separation difficult. In such cases it has been found that the device separation can be determined more accurately by making a measurement of the time-of-flight of the acoustic signal travelling from the projector to the hydrophone. Due to the physical size of the devices, a correction has to be made to the distance calculated from the time-of-flight in order to derive the separation between the centres. By experimentation, it has been found that the addition of one third of the sum of the diameters of the devices to the distance calculated from a time-of-flight measurement at 20 kHz gives a close approximation to the distance between the centres of the transducers.

For a three-transducer spherical-wave reciprocity calibration, it is necessary to measure the electrical impedance of the two devices used to transmit (P and T) in order to derive the drive current from the monitored drive voltage. The measurement software uses a Hewlett Packard 4192A Impedance Analyzer to measure the impedance of the device at the calibration frequencies and stores the values for later use. For the calibrated projector method, such an impedance measurement is not required as the reference projector sensitivity values are the transmitting voltage response, so the measured drive voltage is used directly in the determination of the receive sensitivity of the hydrophone.

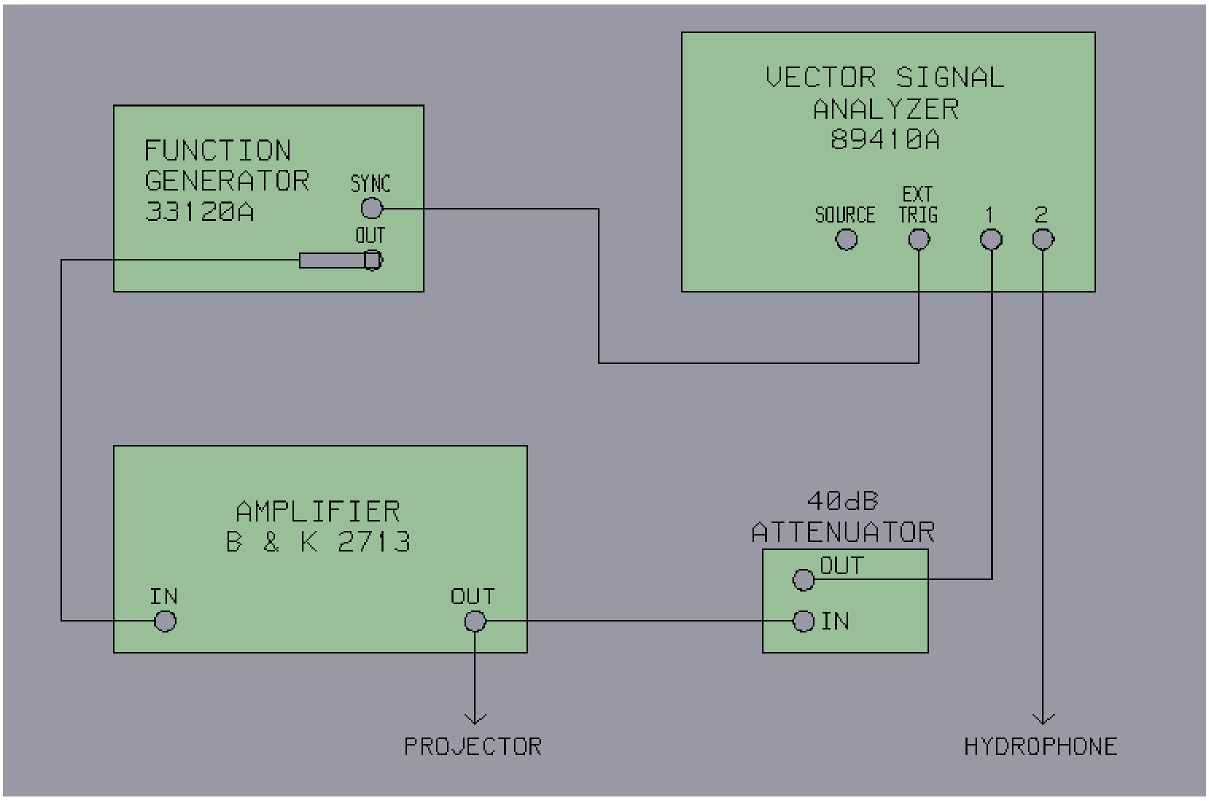

Fig 3.1 Equipment setup for measurements

The equipment setup used for making voltage measurements is the same for both the three-transducer spherical-wave reciprocity method and the calibrated projector/hydrophone method, and is shown in figure 3.1. A Hewlett Packard 33120A Function Generator is used to provide a tone burst signal at the frequency of interest. This is then fed to the input of a Brüel & Kjær 2713 power amplifier, which drives the projector at a typical level of 100 Vrms. The measuring instrument is a Hewlett Packard 89410A Vector Signal Analyzer (VSA) and this is used to capture both the drive and receive waveforms. As the VSA inputs can only handle signals up to 20 Vpk, the drive signal is monitored via a calibrated 40 dB attenuator. Both the function generator and VSA are controlled via a GPIB interface by a computer running the measurement software, and the signal waveforms captured by the VSA are transferred to the computer for analysis.

4. UNCERTAINTIES

For the standard reciprocity and calibrated projector/hydrophone calibrations at frequencies of 1 kHz and above performed at the Wraysbury facility, the sources of uncertainty have previously been assessed and uncertainty budgets produced by following the guidance given in the ISO *Guide to the Expression of Uncertainty in Measurement* [5,6]. Typical overall uncertainties, for a confidence level of 95%, are 0.7 dB for reciprocity calibrations and 1.0 dB for calibrated projector/hydrophone measurements. While the *sources* of uncertainty will generally be the same for frequencies below 1 kHz, the *levels* of individual contributions will be different to those at higher frequencies. Furthermore, it is expected that the levels of some of the contributions will vary within the frequency range 250 Hz to 1 kHz. The sources of uncertainty, and their variation with frequency, have been assessed and are presented here for three frequencies: 250 Hz, 500 Hz and 1 kHz.

4.1 TYPE B COMPONENTS

The sources of the Type B uncertainty components for both three-transducer spherical-wave reciprocity and calibrated projector/hydrophone calibrations are described below.

4.1.1 VSA channel match

The Vector Signal Analyzer is a two-channel instrument with channel one used to measure the drive signal and channel two used to measure the signal received by the hydrophone. The resulting sensitivity is derived from the ratio of these two measurements and so the match between the two channels is a contributing factor to the overall uncertainty of the calibration. This contribution has a value of 2.9%, taken from the manufacturer's specification for the instrument (checked annually by UKAS calibration), and has a rectangular probability distribution.

4.1.2 Attenuator

During the measurements, the projector is driven at a typical level of 100 Vrms. In order to reduce this to a level which can be fed to the input of the Vector Signal Analyzer, a 40 dB attenuator is used and a corresponding correction made within the measurement software. The uncertainty of the attenuation applied will contribute to the uncertainty of the drive signal measurement. The 40 dB attenuator is calibrated in-house and has an expanded uncertainty of 2.3% with a normal probability distribution.

4.1.3 Separation

Calibrations above 1 kHz at the Wraysbury facility are generally performed using transducer separations of 2 metres and above, and for such separations it has been established that the distance between the transducers can be set to an accuracy of 1%. The transducer separations used for the low frequency calibrations are typically in the range 0.3 m to 0.5 m. Small errors in the measurement of the transducer separation over this range will result in correspondingly greater errors in the final sensitivity values than when compared to larger separations. For low frequency calibrations, the transducers are both mounted on the same bracket but, to achieve greater depth in the water and reduce signal transmission through the steelwork, the devices are hung from the bracket some distance below. The distance between the transducers is measured using a rule before lowering into the water. While the accuracy of the separation measured this way will be good in calm weather conditions, movement of the transducers in windier conditions will lead to inaccuracies in the measurement. In these circumstances, a check of the transducer separation is made using an acoustic time-of-flight measurement. A straightforward calculation of distance, from the time taken for the signal to travel from the projector to the receiver, will produce a value which is less than the separation between the acoustic centres of the transducers due to the physical size of the devices. In order to correct this value we need to know the element size of the devices accurately. This information is often not readily available and for some devices the element may not necessarily be positioned centrally within the boot. Experimentation has shown that a good approximation to the distance between the acoustic centres for the devices used here is

$$D = c\Delta t + \frac{1}{k}\left(d_1 + d_2\right)$$

where

D is the distance between the acoustic centres
c is the speed of sound in water
Δt is the acoustic time-of-flight
d_1 and d_2 are the outer diameters of the transducers
$k = 3$ is a good approximation for the devices used in this work

In order to validate this calculation, measurements were performed in the NPL small open tank facility. This tank has two motorised carriages which can be moved with an precision of 10 µm. Initially, the ITC-1007 transducer was mounted on one carriage and the Reson TC4032 hydrophone on the other. The carriages were set to a position where the two devices were just touching and then the positioning system was zeroed. A physical measurement of the two devices gave the distance between the acoustic centres at this point. The carriages were then moved to various separations and a calculation of the separation from the time-of-flight compared to the actual distance between the acoustic centres. The measurements were then repeated using different devices.

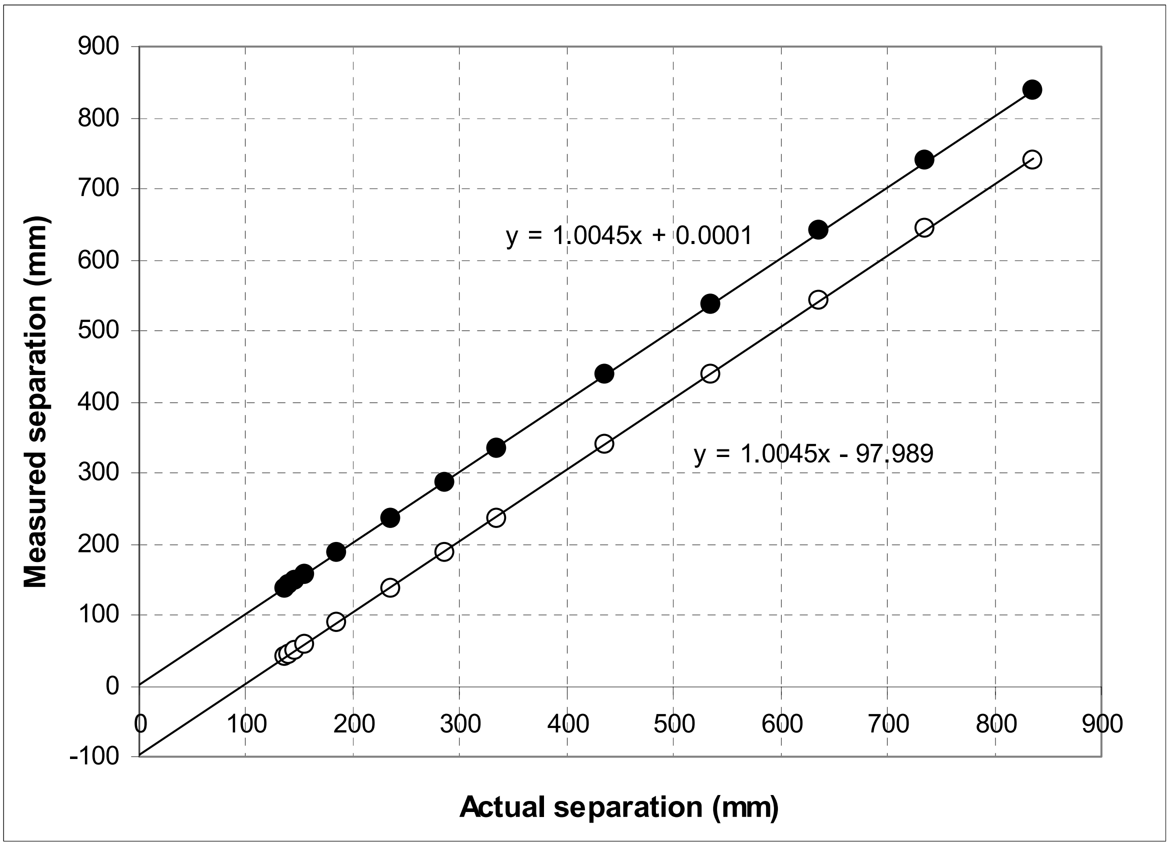

Fig 4.1 Comparison of measured and actual separations

Figure 4.1 shows an example of the results obtained for the ITC-1007 and ITC-1001 transducer pair and plots the acoustically measured separation against the actual separation between the acoustic centres of the devices. The lower trace shows the values calculated purely from the acoustic time-of-flight measured at 20 kHz with no correction applied for the physical size of the devices, and it can be seen that this produces values which are less than the actual device separation by approximately 98 mm. The upper trace shows the same data after a correction has been applied, as in the above equation, such that a straight line though the data passes through zero. To achieve this for this particular pair of devices a value of k = 2.77 was required.

4.1.4 Noise/electrical/loading

As the frequency decreases the output from the source transducer will generally decrease. This can lead to poor signal-to-noise ratios, with greater signal fluctuation, and have a correspondingly larger effect on the accuracy of the calibration. For the ITC-1007 transducer, the signal output at 250 Hz is approximately 24 dB lower than at 1 kHz. The signal-to-noise has been assessed to be better than 20 dB, and this can be improved by the use of on-board time averaging of the signal within the measuring analyzer. For hydrophones without an in-built preamplifier, the capacitance of the input of the measuring amplifier will have a loading effect. This can be corrected for [7] and consequently the contribution to the measurement uncertainty will be the error in the correction and will therefore be small. The contribution to the overall measurement uncertainty from the noise/electrical/loading component has a rectangular probability distribution and is increased as the frequency decreases.

4.1.5 Non steady state

It is a requirement of the measurement that the beginning of the measurement window be set at a point where the received signal has reached steady state. For the ITC-1007 transducer we have seen that the initial turn-on transient lasts for approximately 0.3 ms before the signal reaches steady state, giving around half a cycle of 250 Hz to measure before the arrival of any major reflections. This contribution has a rectangular probability distribution and will increase as the frequency decreases up to a value of 5% at 250 Hz. Where a transducer with a higher *Q* than the ITC-1007 is used as a projector, the time taken for the signal to reach steady state will need to be assessed and the value for this contribution adjusted accordingly.

4.1.6 Reflections

As with the non steady state contribution above, it is a requirement that the end of the measurement window be set at a point in the steady state portion of the received signal, prior to the arrival of any significant reflections. It has been seen that, for the mounting configuration and deployment depth used, there is approximately 3 ms of echo-free time before the arrival of any reflection from the bracket mounting flange and significantly longer before the arrival of any reflection from the water surface or reservoir bottom. For the ITC-1007 transducer, this is enough time to perform measurements down to 250 Hz. While the mounting bracket has been designed such that reflections in the direction of the devices from the legs of the bracket are minimal, there will nevertheless be a small effect on the overall uncertainty due to reflections from the mount appearing within the measurement window and this will have a rectangular probability distribution.

4.1.7 Non-spherical wave field

The three-transducer spherical-wave reciprocity and calibrated projector/hydrophone methods assume that the acoustic field generated by the transmitting transducer propagates as a spherically diverging wave. Typically, the $(d_1^2 + d_2^2 + d_1 d_2) / \lambda$ criterion of reference [8] is used to derive a minimum device separation, where d_1 and d_2 are the largest dimension of the radiating face of the transducers and λ is the acoustic wavelength. Due to the large wavelengths involved, the actual separation used is generally much greater than this minimum. Nevertheless, the acoustic field will still only approximate a spherically diverging wave, and so an allowance has to be made in the uncertainty budget for this contribution. This will have a rectangular probability distribution and has been estimated at 1%.

4.1.8 Orientation and alignment

When the projector and hydrophone are mounted they are aligned according to their 0° reference marks. Any rotational error in this alignment, or any vertical misalignment, could potentially lead to an error in the measurement. At frequencies below 1 kHz the devices will generally be omnidirectional and consequently any error due to incorrect alignment will be small. This uncertainty will have a rectangular probability distribution and has been estimated at 0.5%.

4.1.9 Wetting

Before deployment, the transducers are wetted with a weak solution of detergent to reduce the surface tension and prevent trapped air and, before starting any measurements, the devices are left to soak for at least two hours to ensure that thermal equilibrium is reached. With unknown devices, this can be checked by monitoring any drift in the received signal over time and waiting for stability before any measurements are started. The contribution to the overall uncertainty due to wetting will therefore be small and has been estimated at 0.5%, with a rectangular probability distribution.

4.1.10 Non-reciprocal behaviour

This uncertainty contribution only applies to three-transducer spherical-wave reciprocity calibrations, where it is a requirement of the method that the transducer designated as T be a reciprocal device. Reciprocal behaviour can be checked by performing a T to P measurement, as well as P to T, and comparing the transfer impedances for the two measurements. For higher frequencies, the value of this component has been assessed as 1.5%. At low frequencies, well away from the resonance frequency of the device, the uncertainty due to non-reciprocal behaviour will be less and has been estimated at 1% with a rectangular probability distribution.

4.1.11 Transducer impedance

This contribution again only applies to three-transducer spherical-wave reciprocity calibrations, where it is necessary to measure the transducer impedance to derive the drive current from the drive voltage measurement. The value 2% is taken from the manufacturer's specification for the Hewlett Packard Impedance Analyzer and has a rectangular probability distribution. Like the Vector Signal Analyzer, this instrument is checked annually by UKAS calibration.

4.1.12 Reference transducer calibration

This contribution applies to calibrated projector/hydrophone calibrations and is the uncertainty of the calibration of the reference transducer. The value is frequency dependent and is the final uncertainty value for the three-transducer spherical-wave reciprocity calibration, with a normal probability distribution.

4.1.13 Reference transducer linearity

This uncertainty contribution applies to the calibrated projector method and allows for any non-linearity in the source transducer when driven at different levels. As the frequency range is well below the resonance frequency of the source transducers used, and they are generally driven at the same level as for the reciprocity calibration, this contribution will be small. The value has been estimated at 0.5% and has a rectangular probability distribution.

4.1.14 Temperature

This uncertainty contribution again only applies to the calibrated projector/hydrophone method. The calibration may be performed when the water temperature is different to that at which the reference transducer was calibrated, and so an allowance has to be made for any change in the sensitivity of the device due to this change in temperature. The value of 2.5% allows for the typical range of water temperature encountered in the reservoir. This uncertainty contribution has a rectangular probability distribution and is derived from the results presented in the following section.

4.2 TYPE A UNCERTAINTY

Repeated measurements at each frequency are made during the calibrations (typically 5) and the data used to calculate the Type A component of uncertainty. If weather conditions are poor the signal fluctuation may increase, causing an increase in the uncertainty. A typical value of 2.5% with a normal probability distribution has been included in the uncertainty budget for the Type A uncertainty.

The uncertainty budget for three-transducer spherical-wave reciprocity calibrations is shown in Table 4.1. The final overall uncertainty for calibrations by this method varies from 0.77 dB at 250 Hz to 0.68 dB at 1 kHz. These values are based on a standard uncertainty multiplied by a coverage factor $k = 2$, providing a level of confidence of approximately 95%. Table 4.2 shows the uncertainty budget for calibrated projector calibrations. From this it can be seen that the final overall uncertainty values vary from 1.0 dB to approximately 1.2 dB as the frequency decreases from 1 kHz to 250 Hz.

						250 Hz		500 Hz		1 kHz	
						Est.	Std. unc	Est.	Std. unc	Est.	Std. unc
Symbol	Source of uncertainty	Probability distribution	Divisor	c_i	v_i or v_{eff}	value ± %	u_i ± %	value ± %	u_i ± %	value ± %	u_i ± %
f	Acoustic frequency	rectangular	1.73	0.5	infinity	0.2	0.06	0.2	0.06	0.2	0.06
ρ	Water density	rectangular	1.73	0.5	infinity	0.2	0.06	0.2	0.06	0.2	0.06
J_{NON}	Non-reciprocal behaviour	rectangular	1.73	0.5	infinity	1.5	0.43	1.5	0.43	1.5	0.43
Z_{PT}, Z_{TP}	**Transfer impedance:**										
D_{PT}	Separation	rectangular	1.73	0.5	infinity	3.0	0.87	3.0	0.87	3.0	0.87
S_{PT}	Non-spherical field	rectangular	1.73	0.5	infinity	1.0	0.29	1.0	0.29	1.0	0.29
T_{PT}	Non steady-state	rectangular	1.73	0.5	infinity	5.0	1.44	4.0	1.15	3.0	0.87
O_{PT}	Orientation & alignment	rectangular	1.73	0.5	infinity	0.5	0.14	0.5	0.14	0.5	0.14
N_{PT}	Noise/electrical/loading	rectangular	1.73	0.5	infinity	3.0	0.87	2.5	0.72	2.0	0.58
W_{PT}	Wetting	rectangular	1.73	0.5	infinity	0.5	0.14	0.5	0.14	0.5	0.14
L_{PT}	Transducer impedance	rectangular	1.73	0.5	infinity	2.0	0.58	2.0	0.58	2.0	0.58
A_{PT}	Attenuator calibration	normal	2.00	0.5	infinity	2.3	0.58	2.3	0.58	2.3	0.58
G_{PT}	VSA Channel match	rectangular	1.73	0.5	infinity	2.9	0.84	2.9	0.84	2.9	0.84
Z_{PH}	**Transfer impedance:**										
D_{PH}	Separation	rectangular	1.73	0.5	infinity	3.0	0.87	3.0	0.87	3.0	0.87
S_{PH}	Non-spherical field	rectangular	1.73	0.5	infinity	1.0	0.29	1.0	0.29	1.0	0.29
T_{PH}	Non steady-state	rectangular	1.73	0.5	infinity	5.0	1.44	4.0	1.15	3.0	0.87
O_{PH}	Orientation & alignment	rectangular	1.73	0.5	infinity	0.5	0.14	0.5	0.14	0.5	0.14
N_{PH}	Noise/electrical/loading	rectangular	1.73	0.5	infinity	3.0	0.87	2.5	0.72	2.0	0.58
W_{PH}	Wetting	rectangular	1.73	0.5	infinity	0.5	0.14	0.5	0.14	0.5	0.14
L_{PH}	Transducer impedance	rectangular	1.73	0.5	infinity	2.0	0.58	2.0	0.58	2.0	0.58
A_{PH}	Attenuator calibration	normal	2.00	0.5	infinity	2.3	0.58	2.3	0.58	2.3	0.58
G_{PH}	VSA Channel match	rectangular	1.73	0.5	infinity	2.9	0.84	2.9	0.84	2.9	0.84
Z_{TH}	**Transfer impedance:**										
D_{TH}	Separation	rectangular	1.73	0.5	infinity	3.0	0.87	3.0	0.87	3.0	0.87
S_{TH}	Non-spherical field	rectangular	1.73	0.5	infinity	1.0	0.29	1.0	0.29	1.0	0.29
T_{TH}	Non steady-state	rectangular	1.73	0.5	infinity	5.0	1.44	4.0	1.15	3.0	0.87
O_{TH}	Orientation & alignment	rectangular	1.73	0.5	infinity	0.5	0.14	0.5	0.14	0.5	0.14
N_{TH}	Noise/electrical/loading	rectangular	1.73	0.5	infinity	3.0	0.87	2.5	0.72	2.0	0.58
W_{TH}	Wetting	rectangular	1.73	0.5	infinity	0.5	0.14	0.5	0.14	0.5	0.14
L_{TH}	Transducer impedance	rectangular	1.73	0.5	infinity	2.0	0.58	2.0	0.58	2.0	0.58
A_{TH}	Attenuator calibration	normal	2.00	0.5	infinity	2.3	0.58	2.3	0.58	2.3	0.58
G_{TH}	VSA Channel match	rectangular	1.73	0.5	infinity	2.9	0.84	2.9	0.84	2.9	0.84
V	Random uncertainty	normal	1.00	1.0	3 (n-1)	2.5	2.5	2.5	2.5	2.5	2.5
$u_c(M_H)$	Combined uncertainty	normal					4.66		4.33		4.05
U	Expanded uncertainty	normal (k=2)					9.31		8.66		8.11
U_{dB}	Expanded uncertainty (dB)	normal (k=2)					0.77		0.72		0.68

Table 4.1 Uncertainty budget for three-transducer spherical-wave reciprocity calibrations

						250 Hz		500 Hz		1 kHz	
						Est.	Std. unc	Est.	Std. unc	Est.	Std. unc
	Source of uncertainty	Probability distribution	Divisor	c_i	v_i or v_{eff}	value ± %	u_i ± %	value ± %	u_i ± %	value ± %	u_i ± %
1	Reference transducer calibration	normal	2.00	1.0	infinity	9.31	4.66	8.66	4.33	8.11	4.06
2	Calibrated attenuator accuracy	normal	2.00	1.0	infinity	2.30	1.15	2.30	1.15	2.30	1.15
3	VSA channel match	rectangular	1.73	1.0	infinity	2.90	1.67	2.90	1.67	2.90	1.67
4	Separation distance	rectangular	1.73	1.0	infinity	3.00	1.73	3.00	1.73	3.00	1.73
5	Non-spherical field	rectangular	1.73	1.0	infinity	1.00	0.58	1.00	0.58	1.00	0.58
6	Non-steady state conditions	rectangular	1.73	1.0	infinity	5.00	2.89	4.00	2.31	3.00	1.73
7	Orientation & alignment	rectangular	1.73	1.0	infinity	1.00	0.58	1.00	0.58	1.00	0.58
8	Reflections	rectangular	1.73	1.0	infinity	2.00	1.15	1.50	0.87	1.00	0.58
9	Noise/electrical/loading effects	rectangular	1.73	1.0	infinity	3.00	1.73	2.50	1.44	2.00	1.15
10	Wetting	rectangular	1.73	1.0	infinity	0.50	0.29	0.50	0.29	0.50	0.29
11	Reference transducer linearity	rectangular	1.73	1.0	infinity	0.50	0.29	0.50	0.29	0.50	0.29
12	Temperature coefficient of transducer	rectangular	1.73	1.0	infinity	2.50	1.45	2.50	1.45	2.50	1.45
13	Type A (random) uncertainty	normal	1.00	1.0	3 (n-1)	2.50	2.50	2.50	2.50	2.50	2.50
	Combined uncertainty	normal					7.12		6.57		6.12
	Expanded uncertainty	normal (k=2)					14.23		13.15		12.23
	Expanded uncertainty (dB)	normal (k=2)					1.16		1.07		1.00

Table 4.2 Uncertainty budget for calibrated projector calibrations

5. RESULTS

In this section, results are presented which show the sensitivity of transducers measured as described above using both the three-transducer spherical-wave reciprocity method and the calibrated projector method. The hydrophone sensitivities obtained from these calibrations are compared with those obtained from calibrations of the same hydrophones using the NPL primary coupler [2] and also the NPL pistonphone. A comparison of the results from two reciprocity calibrations performed at widely differing water temperatures is presented to illustrate the temperature characteristics of the reference transducers used. Finally, results are presented which show the differences in the sensitivities obtained from two reciprocity calibrations performed using different transducer separations.

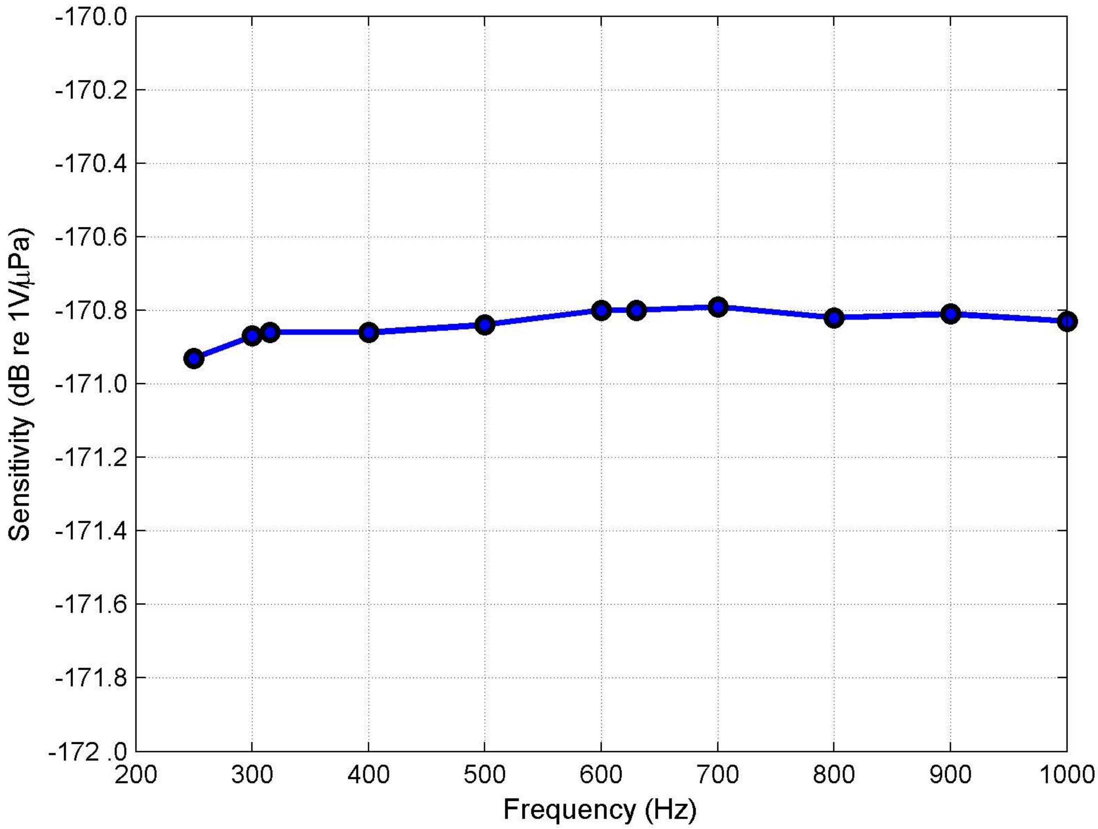

Fig 5.1 Receive sensitivity of the Reson TC4032 hydrophone

Figures 5.1 and 5.2 show the sensitivities for the frequency range 250 Hz to 1 kHz of two transducers obtained from an absolute calibration by three-transducer spherical-wave reciprocity.

Figure 5.1 shows the receive sensitivity of the Reson TC4032 hydrophone. This device was designated as H (hydrophone) during the calibration, as it has a built-in preamplifier and can therefore only be used as a receiver. Since the frequency range of the measurements is well below the resonance frequency of the device, it is expected that the receive sensitivity would be flat over this range [9]. This assumes that there is no roll-off due to filtering effects from the built-in preamplifier. It can be seen from figure 5.1 that the variation in the receive sensitivity is less than 0.1 dB throughout most of the measured frequency range. This is well within the overall expanded measurement uncertainty, which varies from 0.8 dB at 250 Hz to 0.7 dB at 1 kHz.

Figure 5.2 shows the transmitting voltage response (TVR) of the ITC-1007 transducer obtained from the reciprocity calibration. This device was designated as P during the calibration and consequently only used as a projector. Again, the frequency range of the measurements is well below the resonance frequency of the device and, for a projector, it is expected that the TVR should fall off at a constant dB/octave rate as the frequency decreases [9]. The graph in figure 5.2 has been plotted with a logarithmic frequency axis and shows that the TVR values obtained from the calibration fall off at a constant rate of approximately 12 dB/octave.

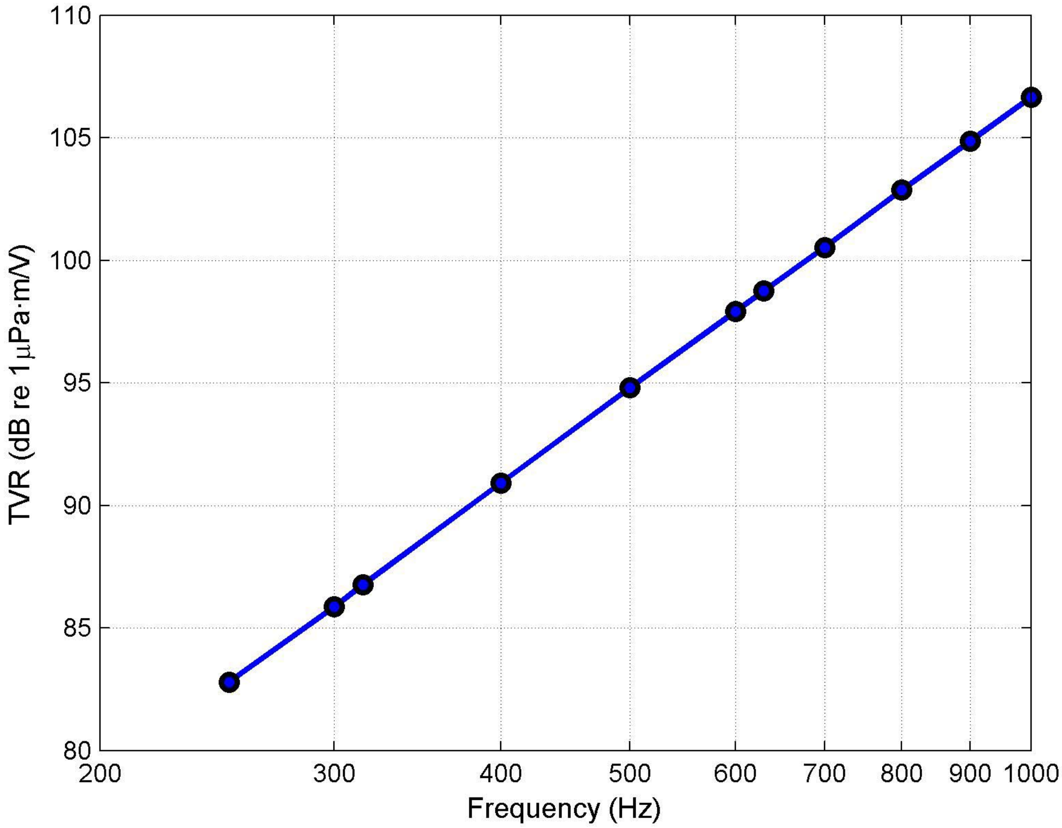

Fig 5.2 Transmitting voltage response of the ITC-1007 transducer

In order to validate the above measurements, the ITC-1007 transducer was used as the source transducer to measure the receive sensitivity of a Reson TC4023 hydrophone by the calibrated projector method. The sensitivities obtained from the above reciprocity calibration were used as the reference TVR values in the calculation of the TC4023 hydrophone sensitivities. The Reson TC4023 is a spherical hydrophone and was chosen because it is small enough to fit into the NPL coupler. A further calibration was also performed using the NPL pistonphone. Figure 5.3 shows a comparison of the results from the three calibrations. The pistonphone calibration is a standard calibration at third-octave frequencies with an upper limit of 315 Hz and therefore has only a small overlap with the Wraysbury measurements. As both the Wraysbury calibrated projector measurements and the coupler calibration were performed up to 2 kHz, all the sensitivity values obtained up to this frequency are shown. For the pistonphone and coupler calibrations error bars indicate the expanded measurement uncertainties, which are 0.7 dB for the pistonphone calibration and 0.5 dB for the coupler calibration. The three sets of measurements were all performed at temperatures within the range 20 °C to 22 °C. It can be seen from figure 5.3 that the

Wraysbury calibrated projector measurements show good agreement with both the pistonphone calibration and the coupler calibration with differences of less than 0.3 dB, well within the measurement uncertainties.

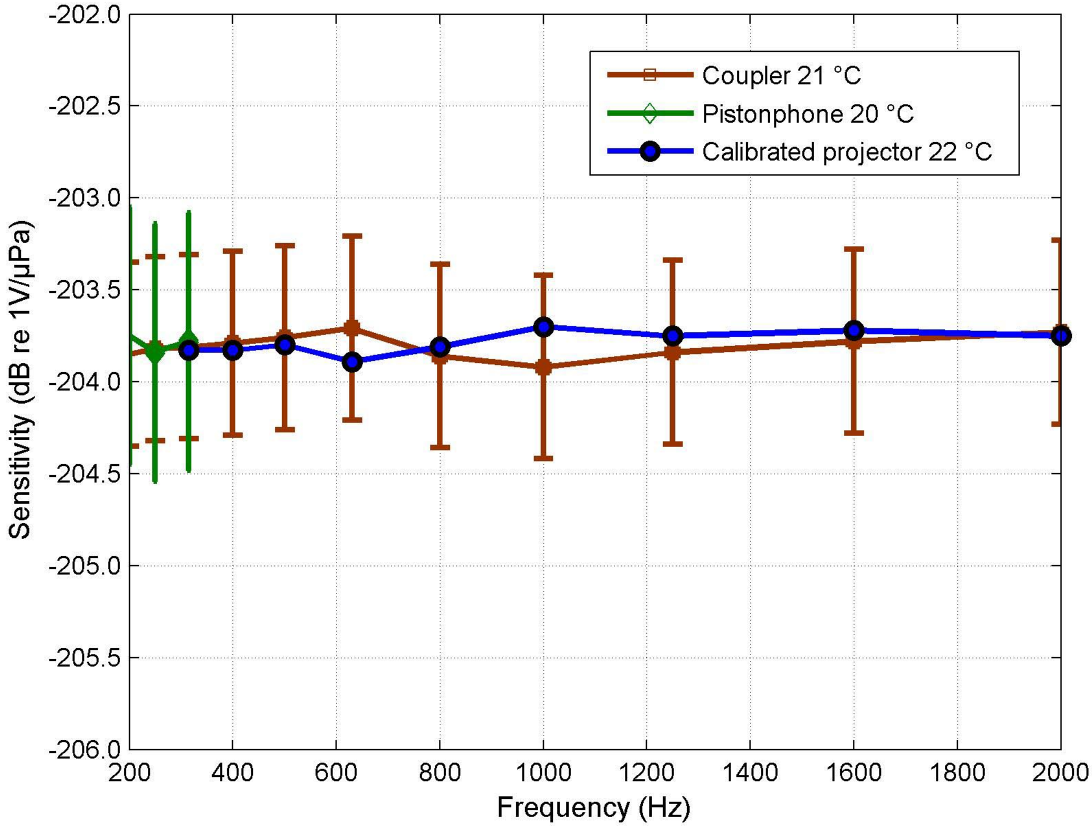

Fig 5.3 Comparison of calibration methods for Reson TC4023 hydrophone

As a further validation exercise, the Reson TC4032 hydrophone used in the Wraysbury reciprocity calibration was also calibrated in the NPL pistonphone. This provided a comparison at the lower end of the frequency range. As stated above, the TC4032 hydrophone has a built-in preamplifier and this makes the device too large to fit into the NPL coupler. So, to provide a comparison at the upper end of the frequency range, the TC4032 was used as the hydrophone in a standard reciprocity calibration of the Wraysbury 8 kHz reference transducers. This produced a receive sensitivity calibration of the TC4032 down to 1 kHz by a proven method. The results of the three calibrations are shown in figure 5.4, with error bars indicating the measurement uncertainties for the pistonphone calibration and standard reciprocity calibration. It can be seen that again there is good agreement, well within the measurement uncertainties, at both ends of the frequency range. While the water temperature was 19 °C for both of the reciprocity calibrations, the pistonphone calibration was performed at a temperature of 21.6 °C. This difference will account, to some extent, for the discrepancy seen between the pistonphone calibration and the low frequency reciprocity calibration, as the Reson TC4032 hydrophone is later shown to have a negative temperature coefficient.

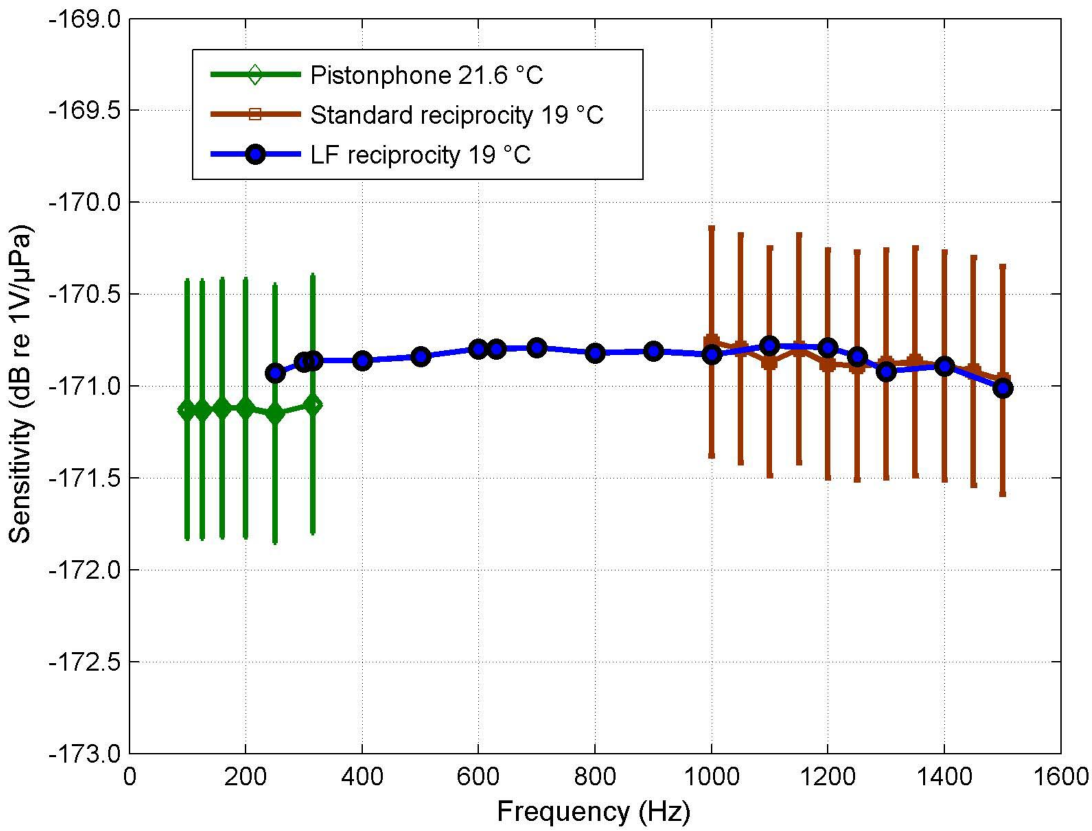

Fig 5.4 Comparison of calibration methods for Reson TC4032 hydrophone

The above sensitivity values for the frequency range 250 Hz to 1 kHz, of both the ITC-1007 source transducer and Reson TC4032 hydrophone, were derived from a three-transducer spherical-wave reciprocity calibration performed at a water temperature of 19 °C. The Wraysbury facility is an open-water site, situated on a reservoir, and consequently there is no control over the temperature of the water, which varies according to the weather. While short-term fluctuations are small due to the large volume of the water, it is nevertheless desirable that the sensitivity of any device used as a reference transducer should show little change with variations in the water temperature. In order to ascertain the temperature stability of the two transducers, a second calibration was performed at a water temperature of 4.5 °C, and the differences between the results of these two calibrations are shown in figures 5.5 and 5.6.

Figure 5.5 shows the differences between the sensitivities of the ITC-1007 transducer obtained from the 19 °C calibration and those obtained from the 4.5 °C calibration. It can be seen that this device has good temperature stability over this frequency range. The transducer exhibits only a small increase in sensitivity, of the order of 0.2 – 0.3 dB, for an increase in water temperature of 14.5 °C.

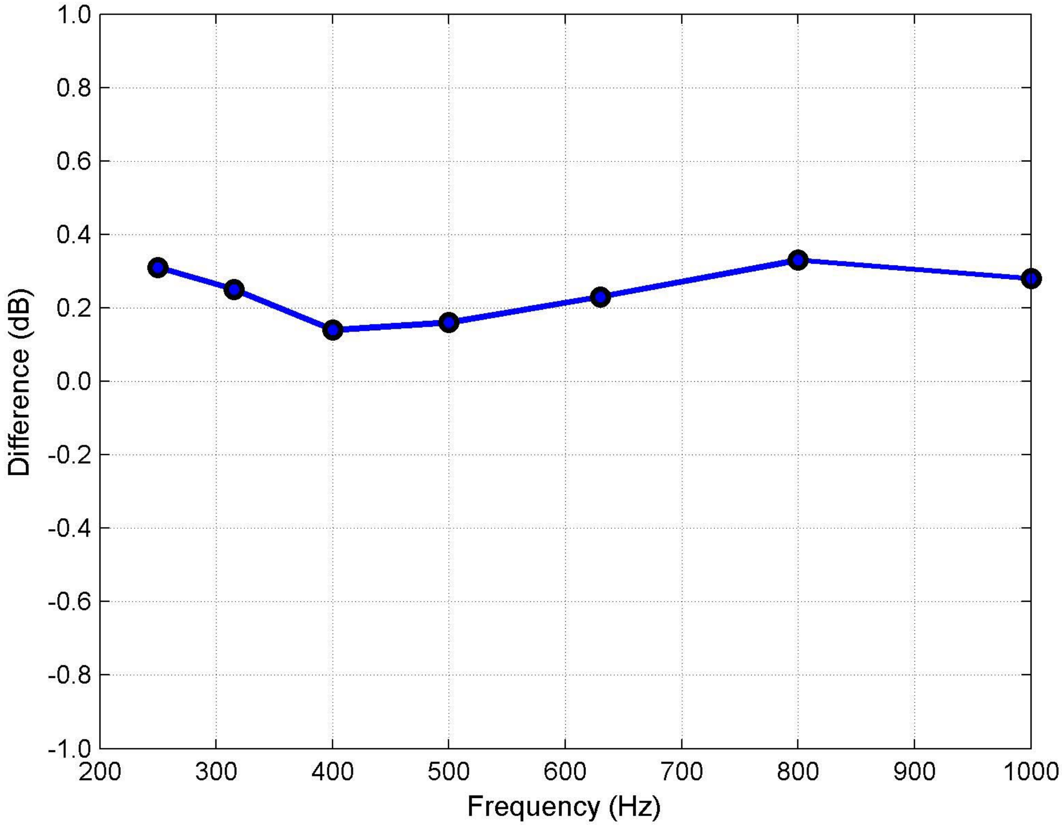

Fig 5.5 ITC1007 temperature comparison 19.0 °C relative to 4.5 °C

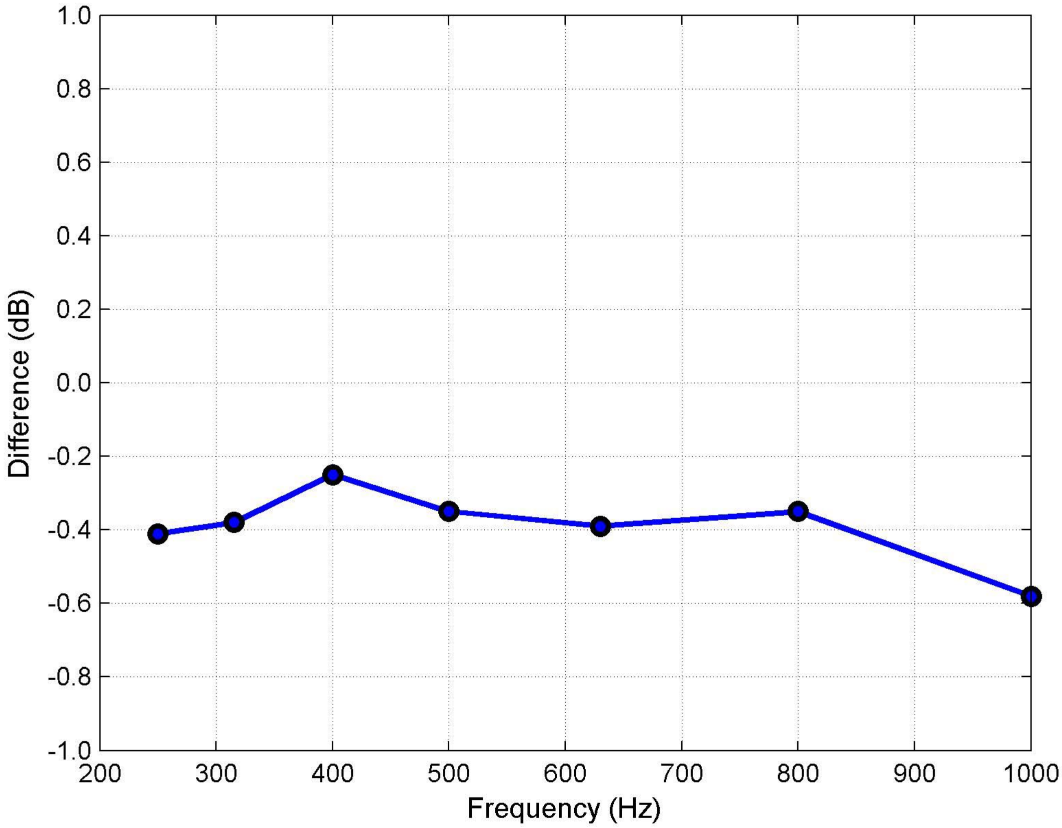

Fig 5.6 Reson TC4032 temperature comparison 19.0 °C relative to 4.5 °C

Similarly, figure 5.6 shows the differences between the sensitivities of the Reson TC4032 hydrophone obtained from the 19 °C calibration and those obtained from the 4.5 °C calibration. It can be seen that this device has a negative temperature coefficient, showing a decrease in sensitivity as the water temperature increases. Once again the stability is good over this frequency range, with only a small change in sensitivity of approximately 0.4 dB for a variation in water temperature of 14.5 °C.

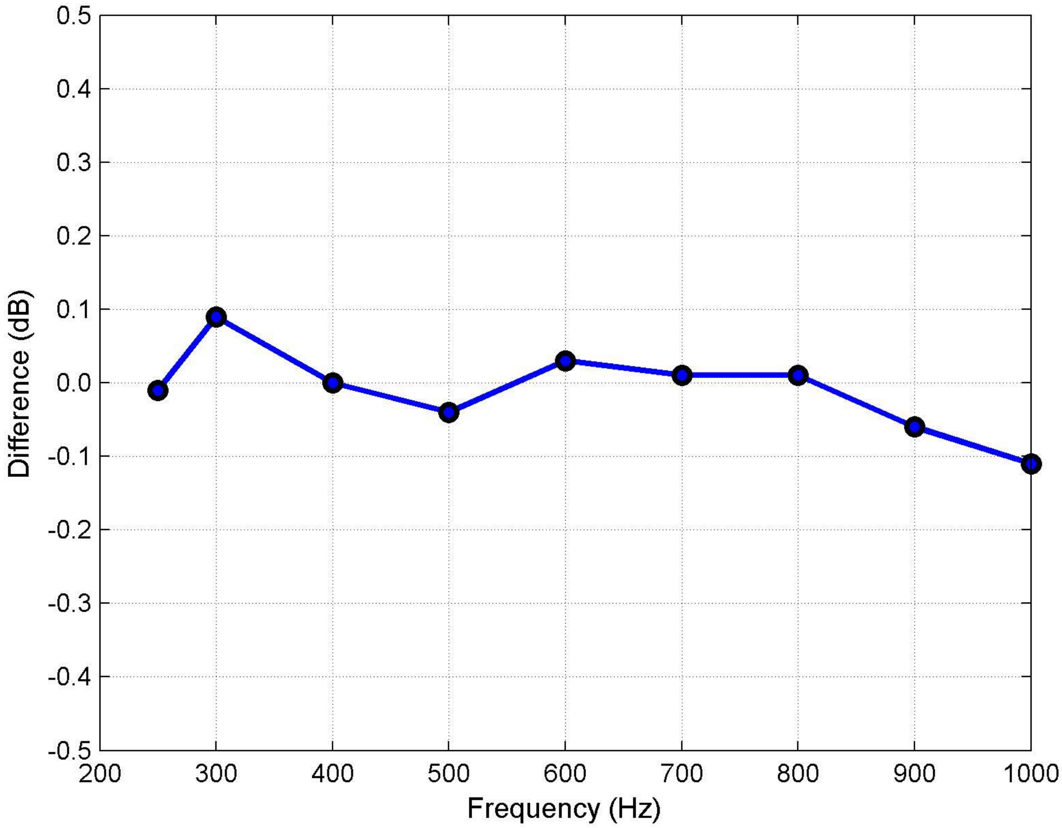

Fig 5.7 Reson TC4032 calibration separation comparison 0.5 m relative to 0.3 m

As stated previously, when calibrating transducers using a small device separation, an accurate measurement of this distance becomes even more important when compared to calibrations using a larger device separation, as any error in this measurement has a correspondingly greater effect on the accuracy of the resulting sensitivities. The method used to establish the device separation has been described in section 3, and the measurements made to check the accuracy of this method have been described in section 4. In order to quantify any errors in the resulting sensitivities caused by inaccuracies in the measurement of the device separation, two reciprocity calibrations were performed: one using a device separation of 0.5 metres and the other using a device separation of 0.3 metres. Figure 5.7 shows a comparison of the results for the Reson TC4032 hydrophone, and it can be seen that the differences between the sensitivities obtained from the two calibrations are typically less than ± 0.1 dB, which is within the random uncertainty assessed for the calibrations.

6. CONCLUSIONS

6.1 SUMMARY

The techniques employed to extend the frequency range over which free-field calibrations can be performed at the NPL Wraysbury open-water calibration facility have been described. A discussion of the requirements for the establishment of a free field has been presented with a description of the methods employed to achieve these conditions over the frequency range 250 Hz to 1 kHz. The sources of uncertainty relating to the calibration methods have been discussed and the levels of individual contributions assessed. Results of calibrations performed have been presented along with comparisons to measurements made in the NPL primary coupler and pistonphone facilities.

The results have shown that free-field calibrations by three-transducer spherical-wave reciprocity can be performed over the frequency range 250 Hz to 1 kHz with a measurement uncertainty of 0.7 – 0.8 dB, depending on the measurement frequency. A device calibrated by this method can then be used as a reference transducer in free-field measurements by the calibrated projector/hydrophone method. Calibrations by this method have been shown to have a measurement uncertainty of 1.0 – 1.2 dB depending on the measurement frequency. The results presented show good agreement with calibrations performed in the NPL primary coupler and pistonphone facilities, with any differences well within the measurement uncertainties.

The main limitations of the methods are the size and weight of the devices which can be deployed using the mounting arrangement described, as the transducers have to be small enough and light enough to be hung from the mounting bracket. The limited device separation and the requirement to be in the far field will also limit the size of the devices which can be calibrated by these methods. It has been seen that the time taken of the ITC-1007 source transducer to reach steady state allows the calibration of a hydrophone by the calibrated projector method down to 250 Hz. However, the low frequency limit for the calibration of a projector using a reference hydrophone will be determined by the Q of the device under test and may be much higher.

6.2 RECOMMENDATIONS

There is a continuing demand from NPL customers to provide free-field calibrations at frequencies even lower than 250 Hz. It should be feasible to extend the frequency range covered by the methods described in this report down to around 100 Hz by further improvements to the mounting arrangement in order to achieve a longer echo-free time. Below 100 Hz hydrophone calibrations could be achieved by the use of non-free field methods. Such calibrations could still provide accurate results as long as any reflections present are suitably attenuated by propagation losses. The use of the comparison method described in section 2.5 would also be less influenced by any reflections present. A further limitation at such low frequencies is poor signal-to-noise, so it may be desirable to use CW signals and perform the measurement using a lock-in amplifier to achieve stable and accurate results.

7. ACKNOWLEDGEMENTS

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