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Primary Calibration of 1 mm Membrane Hydrophones for BIPM/CIPM Key Comparison CCAUV.U-K4 – Final Description of NPL Results

Srinath Rajagopal
Chris Fury
Bajram Zeqiri

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Acoustics and Ionising Radiation Division

ABSTRACT

This report describes work undertaken within the project AIR/2013/A3 “Provision of traceable standards for medical ultrasound” supported under the National Measurement System 2013-2016 Programme for Acoustics and Ionising Radiation Metrology. Two 1 mm active element membrane hydrophones have been calibrated using NPL’s primary standard laser interferometer for the BIPM/CIPM key comparison CCAUV.U-K4 “hydrophone free-field open-circuit sensitivity in the megahertz frequency range”. The results of calibration of the two hydrophones carried out at the beginning and at the end of the key comparison are summarised within this report.

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National Physical Laboratory
Hampton Road, Teddington, Middlesex, TW11 0LW

Approved on behalf of NPLML by Dr Giuseppe Schettino, Knowledge Leader, Acoustics and Ionising Radiation Division.

CONTENTS

1 INTRODUCTION

This report describes the absolute calibration of two membrane hydrophones designated as travelling standards for the BIPM/CIPM Key Comparison CCAUV.U-K4: Hydrophone free-field open-circuit sensitivity in the megahertz frequency range. The key comparison involves four national metrology institutes (NPL, PTB, NIM and NMIJ) with NPL as the pilot laboratory. The results of calibration of the travelling standard hydrophones carried out at the beginning and the end of the key comparison are summarised within this report.

2 CALIBRATION BY OPTICAL INTERFEROMETRY

2.1 CALIBRATION METHOD

Miniature medical hydrophones of the membrane type are calibrated at NPL using an optical method based on a Michelson interferometer over the frequency range 100 kHz to 40 MHz. The basic configuration described in this report involves the use of a thin plastic membrane (the pellicle) approximately 5 µm thick to intercept the acoustic field. The thinness of the pellicle ensures that it is effectively transparent to the acoustic beam and so follows the motion of the propagating ultrasonic wave within this operating frequency range. One surface of the pellicle is coated with ~25 nm gold to reflect the optical beam, and interferometry is used to determine the absolute displacement of the membrane and from this, the acoustic pressure within the applied field. The output of the Michelson interferometer, V_I, varies with displacement, a, according to the following relationship [3]:

$$V_I = V_O \sin\left(\frac{4\pi\mu a}{\lambda} + \emptyset\right) \tag{1}$$

where λ is the optical wavelength, V_O is the reference voltage corresponding to the amplitude of the output signal when the displacement exceeds $\lambda/2$, $\emptyset$ represents the phase shift between measurement and reference optical beams and μ is the effective refractive index of the medium. For small ultrasonic amplitudes (less than 5 nm), the output can be assumed to vary linearly with displacement (sin $(\theta) = \theta$ for small θ). Assuming plane-wave conditions, the acoustic pressure in the field may be calculated from the measured displacement by multiplying by the angular frequency, water density and speed of sound. The hydrophone is then substituted for the pellicle, with the acoustic centre placed in the field at exactly the same spatial location interrogated by the interferometer. The hydrophone output voltage, V_H, corresponding to this known acoustic pressure, is then measured, and the hydrophone sensitivity, M_H, derived using the expression:

$$M_{\mathrm{H}} = \frac{V_{\mathrm{H}} V_{\mathrm{O}}}{V_{\mathrm{I}}} \frac{2\mu}{\rho c f \lambda} \quad (2)$$

where *f* is the ultrasonic frequency, *ρ* and *c* are the density and speed of sound of water respectively at the particular temperature of interest.

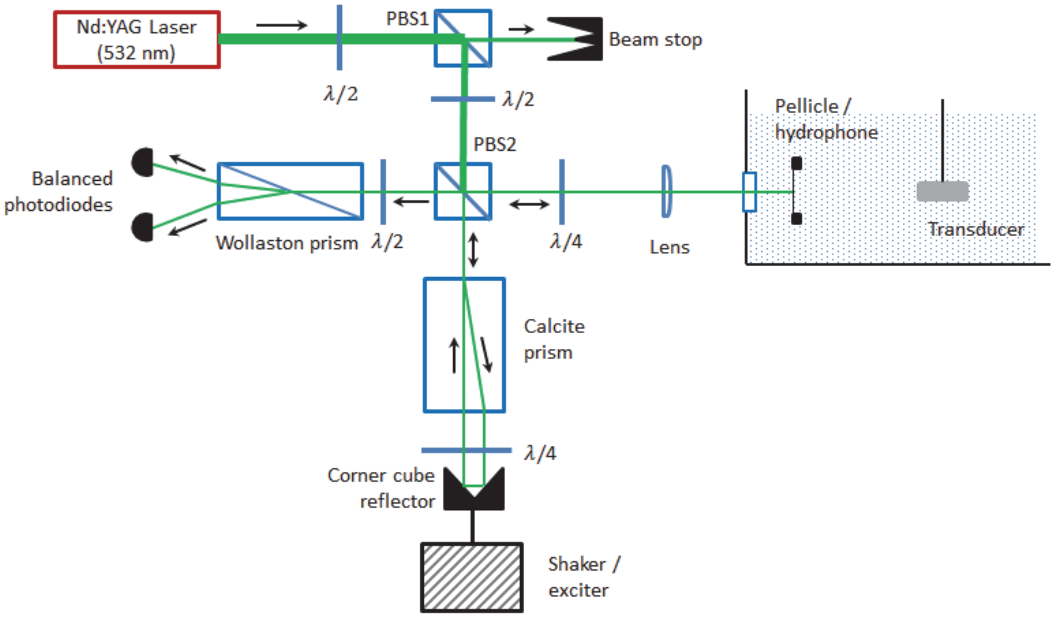

Figure 1: Schematic diagram of the NPL laser Michelson interferometer used for absolute displacement measurements at ultrasonic frequencies.

The current interferometer [1] is an improvement over a previous implementation at NPL [2, 3] which was itself based on the original work of Drain *et al* [4]. The previous interferometer [2, 3] was employed for the original key comparison, CCAUV.U-K2 [5]. Figure 1 shows a schematic diagram of the interferometer. The interferometer is mounted on an optical table of dimensions 2.5 m × 1 m × 0.21 m (l × w × h) supported by self-levelling air-operated anti-vibration legs (0.9 m high). The water tank placed on the optical table has dimensions of 1 m × 0.4 m × 0.4 m. The linearly polarised (vertical) light beam from the laser source passes through a $\lambda/2$ wave-plate into a polarising beam splitter (PBS1). The $\lambda/2$ wave-plate controls the total power going into the interferometer. The incident beam from PBS1 passes through another $\lambda/2$ wave-plate into PBS2, where it is divided into two orthogonally polarised reference (horizontal) and measurement (vertical) beams. The $\lambda/2$ wave-plate positioned before PBS2 controls the division of power between the reference and measurement beams. The reference beam is turned back on its original path by the use of a calcite prism and corner-cube reflector, whereas the measurement beam is reflected from the pellicle and therefore follows the motion of the ultrasonic wave. The lens allows the positioning of the measurement beam on the acoustic centre of the hydrophone. The $\lambda/4$ wave-plates on the reference and measurement beams cause a change in polarisation of reference beam from horizontal to vertical and measurement beam from vertical to horizontal upon their return. The returning beams are combined at PBS2 and then pass through a $\lambda/2$ wave-plate and Wollaston prism. The Wollaston prism is orientated to separate the polarisations in the horizontal plane. By rotating the $\lambda/2$ wave-plate the light intensity in the two beams, which contain contributions from both reference and measurement beams, can be balanced. Each beam emerging from the Wollaston prism is then directed on to a photodiode. Changes in phase between the reference and measurement beams can therefore be detected by the balanced photodiodes and interferometer circuitry providing V_I and V_O signals.

Unfortunately, environmental vibrations cause the movement of the pellicle. Although these vibrations tend to be at low frequencies they are much greater in amplitude than the ultrasonic displacements. This introduces changes in the optical phase of the measurement beam and generates spurious output signals in the interferometer. This problem is overcome by using a feedback system that compensates for the vibration by introducing equal phase changes to the reference beam by means of the electro-mechanical shaker attached to the corner-cube reflector. The feedback circuit is designed to respond only to low frequency signals so that the ultrasonic displacement may still be detected at the interferometer output.

The reference voltage, V_O, which corresponds to the amplitude of the output signal when the displacement exceeds $\lambda/2$ is obtained by moving the corner-cube reflector over a complete interference fringe. In practice this is achieved by electrically exciting the electro-mechanical shaker such that it is displaced by several micro-meters. The amplitude of V_O reaches a maximum whenever the displacement of the corner-cube reflector exceeds odd integer multiples of $\lambda/2$. An average amplitude value of the V_O provides a calibration of the interferometer. If the feedback circuit is adjusted such that $\o$ in Eq. (1) is $\pi/2$ (plus an integer multiple of 2π) then the interferometer is operating in its most sensitive mode to detect the ultrasonic displacement signal V_I.

Many of the systematic uncertainty components for the hydrophone calibration for the current interferometer [1] remain the same in comparison to the previous interferometer [2, 3], except the component related to the photodiodes. The original (avalanche) photodiodes had a significant roll-off of the amplitude frequency response over the operating frequency range and were therefore replaced by PIN photodiodes. The amplitude frequency response of the PIN photodiodes and interferometer electronics is a crucial correction required to derive accurate estimates of ultrasonic displacements. This was determined using an enhanced system [6] of an earlier implementation [7] based on rotational optical components that produce interference fringe patterns scanned through a slit at varying speeds using different deflection mechanisms.

2.2 MEASUREMENTS

In accordance with the protocol document [8], the water in which the measurements were carried out was prepared such that it had a low electrical conductivity which was measured using a Hanna Instruments HI-9835 hand-held meter (Hanna Instruments, Bedfordshire, U.K.). The temperature of the water was not controlled but during any given day the temperature did not increase by more than 0.3 ^{o}C from the starting temperature. The average temperature of the water during the course of the calibrations of the two hydrophones was found to be 19.3 ^{o}C ± 0.4 ^{o}C. The electrical conductivity of the water after freshly filling the measurement tank was < 2 µS and increased to < 5 µS after five days. The water was replaced either every five days or when the electrical conductivity exceeded 5 µS.

The hydrophones were soaked for a minimum of one hour before the measurements started and also continuously during the day. The electrical equipment was switched on at the same time the hydrophones were put in to soak, which also allowed the equipment to warm up and stabilise prior to the start of the measurements.

Amplifier serial number 5564166LF was used for all hydrophone calibrations. The open-circuit correction factors were calculated from impedance measurements of the hydrophone and amplifier. These parameters were stored in the bespoke LabVIEW (National Instruments, Texas, U.S.) software which directly provided the open-circuit sensitivity of the hydrophone by analysing V_H, V_I, and V_O signals, the gain of the 5564166LF amplifier and the impedances of the amplifier and hydrophone. Table 1 presents typical figures for the propagation parameters during the calibration including the ultrasonic displacements measured by the interferometer.

Table 1: Nominal propagation parameters for calibration and displacement measured by interferometer

Source transducer details				Typical propagation distance (mm)	Typical acoustic pressure (kPa)	Typical acoustic displacements measured by the interferometer (nm)
Manufacturer	**Type**	**Nominal frequency (MHz)**	**Active element diameter (mm)**			
Panametrics	V391	0.5	28.6	148	45	9.77
Panametrics	V302	1	25.4	163	46	4.97
Panametrics	V306	2.25	12.7	148	42	2.02
Panametrics	V3225	3.5	12.7	148	34	1.06
Panametrics	V310	5	6.35	148	18	0.38
Panametrics	V312	10	6.35	148	33	0.35
Panametrics	V313	15	6.35	148	42	0.30
Panametrics	V317	20	6.35	222	21	0.11

3 RESULTS

3.1 START OF KEY COMPARISON

The individual calibrations of ER070 and IP999 at the start of the key comparison for each frequency are listed in Tables 2 to 17. Tables 18 and 19 present a summary of open-circuit sensitivity and uncertainty at each frequency for ER070 and IP999.

3.1.1 ER070 – INITIAL

Table 2: Calibration report table for hydrophone ER070 at 0.5 MHz

Participating Laboratory: **NPL**			**Calibration method:** **Optical Interferometry**					
Date(s) of calibrations: **5 February 2014**			**Hydrophone serial number:** **ER070**					
Nominal frequency (MHz): 0.5								
Measurement Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Actual frequency (MHz)	0.500							
Temperature, T (°C)	19.0	19.1	19.1	19.2	19.3	19.3	19.3	-
Water conductivity (μS)	< 3 μS							
Oxygen content (mg l^{-1})	< 10 mg l^{-1}							
Open-circuit sensitivity at T °C (nV/Pa)	116.36	118.20	116.58	119.35	119.45	117.37	118.62	-
Notes (e.g. of any unusual difficulties)								

Table 3: Calibration report table for hydrophone ER070 at 1 MHz

Participating Laboratory: NPL		**Calibration method:** Optical Interferometry						
Date(s) of calibrations: 6 February 2014 – 7 February 2014		**Hydrophone serial number:** ER070						
Nominal frequency (MHz): 1								
Measurement Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Actual frequency (MHz)	1.000							
Temperature, T (°C)	19.6	19.6	19.7	19.5	19.6	-	-	-
Water conductivity (µS)	< 3.5 µS							
Oxygen content (mg l^{-1})	< 10 mg l^{-1}							
Open-circuit sensitivity at T °C (nV/Pa)	120.93	122.67	123.00	122.92	123.32	-	-	-
Notes (e.g. of any unusual difficulties)								

Table 4: Calibration report table for hydrophone ER070 at 2.25 MHz

<table>
<tr><td colspan="2">Participating Laboratory:
NPL</td><td colspan="7">Calibration method:
Optical Interferometry</td></tr>
<tr><td colspan="2">Date(s) of calibrations:
7 February 2014</td><td colspan="7">Hydrophone serial number:
ER070</td></tr>
<tr><td colspan="9">Nominal frequency (MHz): 2.25</td></tr>
<tr><td>Measurement Number</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td></tr>
<tr><td>Actual frequency (MHz)</td><td colspan="8">2.250</td></tr>
<tr><td>Temperature, T (°C)</td><td>19.6</td><td>19.6</td><td>19.6</td><td>19.6</td><td>19.6</td><td>19.6</td><td>-</td><td>-</td></tr>
<tr><td>Water conductivity (μS)</td><td colspan="8">< 4 μS</td></tr>
<tr><td>Oxygen content (mg l^{-1})</td><td colspan="8">< 10 mg l^{-1}</td></tr>
<tr><td>Open-circuit sensitivity at T °C (nV/Pa)</td><td>133.48</td><td>133.25</td><td>129.99</td><td>129.85</td><td>130.23</td><td>132.32</td><td>-</td><td>-</td></tr>
<tr><td>Notes (e.g. of any unusual difficulties)</td><td colspan="8"></td></tr>
</table>

Table 5: Calibration report table for hydrophone ER070 at 3.5 MHz

Participating Laboratory: **NPL**	**Calibration method:** **Optical Interferometry**							
Date(s) of calibrations: **7 February 2014**	**Hydrophone serial number:** **ER070**							
Nominal frequency (MHz): 3.5								
Measurement Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Actual frequency (MHz)	3.500							
Temperature, T (°C)	19.7	19.7	19.7	19.7	-	-	-	-
Water conductivity (μS)	< 4 μS							
Oxygen content (mg l^{-1})	< 10 mg l^{-1}							
Open-circuit sensitivity at T °C (nV/Pa)	137.40	139.51	137.55	138.84	-	-	-	-
Notes (e.g. of any unusual difficulties)								

Table 6: Calibration report table for hydrophone ER070 at 5 MHz

Participating Laboratory: NPL	**Calibration method:** Optical Interferometry							
Date(s) of calibrations: 11 February 2014	**Hydrophone serial number:** ER070							
Nominal frequency (MHz): 5								
Measurement Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Actual frequency (MHz)	5.000							
Temperature, T (°C)	19.5	19.6	19.6	19.6	19.6	-	-	-
Water conductivity (μS)	< 2 μS							
Oxygen content (mg l^{-1})	< 10 mg l^{-1}							
Open-circuit sensitivity at T °C (nV/Pa)	145.26	143.25	146.55	144.03	145.74	-	-	-
Notes (e.g. of any unusual difficulties)								

Table 7: Calibration report table for hydrophone ER070 at 10 MHz

Participating Laboratory: NPL	**Calibration method:** Optical Interferometry							
Date(s) of calibrations: 11 February 2014	**Hydrophone serial number:** ER070							
Nominal frequency (MHz): 10								
Measurement Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Actual frequency (MHz)	10.000							
Temperature, T (°C)	19.6	19.6	19.6	19.6	19.6	19.6	-	-
Water conductivity (μS)	< 3 μS							
Oxygen content (mg l^{-1})	< 10 mg l^{-1}							
Open-circuit sensitivity at T °C (nV/Pa)	178.46	178.16	180.68	184.40	178.69	180.50	-	-
Notes (e.g. of any unusual difficulties)								

Table 8: Calibration report table for hydrophone ER070 at 15 MHz

Participating Laboratory: NPL		**Calibration method:** Optical Interferometry						
Date(s) of calibrations: 12 February 2014		**Hydrophone serial number:** ER070						
Nominal frequency (MHz): 15								
Measurement Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Actual frequency (MHz)	15.000							
Temperature, T (°C)	18.8	18.8	19.0	19.0	19.0	-	-	-
Water conductivity (μS)	< 3 μS							
Oxygen content (mg l^{-1})	< 10 mg l^{-1}							
Open-circuit sensitivity at T °C (nV/Pa)	238.27	242.24	238.04	240.61	238.89	-	-	-
Notes (e.g. of any unusual difficulties)								

Table 9: Calibration report table for hydrophone ER070 at 20 MHz

<table>
<tr><td colspan="2">Participating Laboratory:
NPL</td><td colspan="7">Calibration method:
Optical Interferometry</td></tr>
<tr><td colspan="2">Date(s) of calibrations:
25 February 2014</td><td colspan="7">Hydrophone serial number:
ER070</td></tr>
<tr><td colspan="9">Nominal frequency (MHz): 20</td></tr>
<tr><td>Measurement Number</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td></tr>
<tr><td>Actual frequency (MHz)</td><td colspan="8">20.000</td></tr>
<tr><td>Temperature, T (°C)</td><td>19.2</td><td>19.2</td><td>19.2</td><td>19.2</td><td>19.2</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Water conductivity (μS)</td><td colspan="8">< 2 μS</td></tr>
<tr><td>Oxygen content (mg l^{-1})</td><td colspan="8">< 10 mg l^{-1}</td></tr>
<tr><td>Open-circuit sensitivity at T °C (nV/Pa)</td><td>232.89</td><td>236.50</td><td>234.55</td><td>231.97</td><td>230.32</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Notes (e.g. of any unusual difficulties)</td><td colspan="8"></td></tr>
</table>

3.1.2 IP999 – INITIAL

Table 10: Calibration report table for hydrophone IP999 at 0.5 MHz

Participating Laboratory: NPL	**Calibration method:** Optical Interferometry							
Date(s) of calibrations: 17 February 2014	**Hydrophone serial number:** IP999							
Nominal frequency (MHz): 0.5								
Measurement Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Actual frequency (MHz)	0.500							
Temperature, T (°C)	19.1	19.2	19.2	19.2	19.2	-	-	-
Water conductivity (μS)	< 3 μS							
Oxygen content (mg l^{-1})	< 10 mg l^{-1}							
Open-circuit sensitivity at T °C (nV/Pa)	201.35	206.12	204.78	205.00	203.43	-	-	-
Notes (e.g. of any unusual difficulties)								

Table 11: Calibration report table for hydrophone IP999 at 1 MHz

Participating Laboratory: **NPL**	**Calibration method:** **Optical Interferometry**							
Date(s) of calibrations: **26 February 2014**	**Hydrophone serial number:** **IP999**							
Nominal frequency (MHz): 1								
Measurement Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Actual frequency (MHz)	1.000							
Temperature, T (°C)	19.2	19.2	19.2	19.2	19.2	-	-	-
Water conductivity (μS)	< 3.5 μS							
Oxygen content (mg l^{-1})	< 10 mg l^{-1}							
Open-circuit sensitivity at T °C (nV/Pa)	206.09	208.30	208.51	207.98	207.13	-	-	-
Notes (e.g. of any unusual difficulties)								

Table 12: Calibration report table for hydrophone IP999 at 2.25 MHz

Participating Laboratory: **NPL**	**Calibration method:** **Optical Interferometry**							
Date(s) of calibrations: **14 February 2014**	**Hydrophone serial number:** **IP999**							
Nominal frequency (MHz): 2.25								
Measurement Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Actual frequency (MHz)	2.250							
Temperature, T (°C)	19.0	19.0	19.1	19.1	19.1	-	-	-
Water conductivity (µS)	< 5 µS							
Oxygen content (mg l^{-1})	< 10 mg l^{-1}							
Open-circuit sensitivity at T °C (nV/Pa)	210.22	209.21	207.38	208.47	208.26	-	-	-
Notes (e.g. of any unusual difficulties)								

Table 13: Calibration report table for hydrophone IP999 at 3.5 MHz

Participating Laboratory: NPL	**Calibration method:** Optical Interferometry							
Date(s) of calibrations: 14 February 2014	**Hydrophone serial number:** IP999							
Nominal frequency (MHz): 3.5								
Measurement Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Actual frequency (MHz)	3.500							
Temperature, T (°C)	19.2	19.2	19.2	19.2	-	-	-	-
Water conductivity (μS)	< 4.5 μS							
Oxygen content (mg l^{-1})	< 10 mg l^{-1}							
Open-circuit sensitivity at T °C (nV/Pa)	211.74	211.29	212.24	214.92	-	-	-	-
Notes (e.g. of any unusual difficulties)								

Table 14: Calibration report table for hydrophone IP999 at 5 MHz

Participating Laboratory: NPL		**Calibration method:** Optical Interferometry						
Date(s) of calibrations: 14 February 2014		**Hydrophone serial number:** IP999						
Nominal frequency (MHz): 5								
Measurement Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Actual frequency (MHz)	5.000							
Temperature, T (°C)	19.3	19.3	19.3	19.3	19.3	-	-	-
Water conductivity (μS)	< 4.5 μS							
Oxygen content (mg l^{-1})	< 10 mg l^{-1}							
Open-circuit sensitivity at T °C (nV/Pa)	214.36	215.03	214.21	211.93	213.27	-	-	-
Notes (e.g. of any unusual difficulties)								

Table 15: Calibration report table for hydrophone IP999 at 10 MHz

Participating Laboratory: NPL	**Calibration method:** Optical Interferometry							
Date(s) of calibrations: 17 February 2014	**Hydrophone serial number:** IP999							
Nominal frequency (MHz): 10								
Measurement Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Actual frequency (MHz)	10.000							
Temperature, T (°C)	19.0	19.0	19.0	19.0	19.0	-	-	-
Water conductivity (μS)	< 2 μS							
Oxygen content (mg l^{-1})	< 10 mg l^{-1}							
Open-circuit sensitivity at T °C (nV/Pa)	240.97	240.95	246.28	242.07	242.02	-	-	-
Notes (e.g. of any unusual difficulties)								

Table 16: Calibration report table for hydrophone IP999 at 15 MHz

Participating Laboratory: NPL	**Calibration method:** Optical Interferometry							
Date(s) of calibrations: 18 February 2014	**Hydrophone serial number:** IP999							
Nominal frequency (MHz): 15								
Measurement Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Actual frequency (MHz)	15.000							
Temperature, T (°C)	19.2	19.2	19.2	19.2	19.3	19.3	-	-
Water conductivity (μS)	< 3 μS							
Oxygen content (mg l^{-1})	< 10 mg l^{-1}							
Open-circuit sensitivity at T °C (nV/Pa)	310.24	300.68	298.98	306.73	296.27	298.35	-	-
Notes (e.g. of any unusual difficulties)								

Table 17: Calibration report table for hydrophone IP999 at 20 MHz

Participating Laboratory: NPL				**Calibration method:** Optical Interferometry				
Date(s) of calibrations: 25 February 2014				**Hydrophone serial number:** IP999				
Nominal frequency (MHz): 20								
Measurement Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Actual frequency (MHz)	20.000							
Temperature, T (°C)	19.2	19.2	19.2	19.2	19.2	19.2	-	-
Water conductivity (μS)	< 2.5 μS							
Oxygen content (mg l^{-1})	< 10 mg l^{-1}							
Open-circuit sensitivity at T °C (nV/Pa)	353.46	349.00	354.47	356.68	351.90	350.22	-	-
Notes (e.g. of any unusual difficulties)								

3.1.3 INITIAL SUMMARY

Table 18: Initial calibration report table for hydrophone ER070

Participating Laboratory: NPL				Calibration method: Optical Interferometry				
Date(s) of calibrations: 5 February 2014 to 25 February 2014				Hydrophone serial number: ER070				
Nominal frequency (MHz)	0.5	1	2.25	3.5	5	10	15	20
Actual frequency (MHz)	0.500	1.000	2.250	3.500	5.000	10.000	15.000	20.000
Mean open-circuit sensitivity at T °C (nV Pa^{-1})	118.0	122.6	131.5	138.3	145.0	180.1	239.6	233.2
Type A standard uncertainty (%)	0.40	0.34	0.52	0.37	0.41	0.53	0.33	0.46
Type B standard uncertainty (%)	1.48	1.42	1.42	1.44	1.47	1.55	1.90	1.91
Expanded uncertainty (%)	3.06	2.92	3.03	2.97	3.05	3.28	3.86	3.92

Table 19: Initial calibration report table for hydrophone IP999

Participating Laboratory: NPL				Calibration method: Optical Interferometry				
Date(s) of calibrations: 11 February 2014 to 25 February 2014				Hydrophone serial number: IP999				
Nominal frequency (MHz)	0.5	1	2.25	3.5	5	10	15	20
Actual frequency (MHz)	0.500	1.000	2.250	3.500	5.000	10.000	15.000	20.000
Mean open-circuit sensitivity at T °C (nV Pa^{-1})	204.1	207.6	208.7	212.5	213.8	242.5	301.9	352.6
Type A standard uncertainty (%)	0.40	0.21	0.23	0.38	0.25	0.41	0.73	0.33
Type B standard uncertainty (%)	1.48	1.42	1.42	1.44	1.47	1.55	1.90	1.91
Expanded uncertainty (%)	3.06	2.87	2.88	2.97	2.98	3.21	4.08	3.87

3.2 END OF KEY COMPARISON

The individual calibrations of ER070 and IP999 at the end of the key comparison for each frequency are listed in Tables 20 to 35. Tables 36 and 37 present a summary of open-circuit sensitivity and uncertainty at each frequency for ER070 and IP999.

3.2.1 ER070 – FINAL

Table 20: Calibration report table for hydrophone ER070 at 0.5 MHz

Participating Laboratory: **NPL**		**Calibration method:** **Optical Interferometry**						
Date(s) of calibrations: **30 July 2015 – 31 July 2015**		**Hydrophone serial number:** **ER070**						
Nominal frequency (MHz): 0.5								
Measurement Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Actual frequency (MHz)	0.500							
Temperature, T (°C)	20.0	20.0	19.9	19.9	19.9	19.9	19.9	-
Water conductivity (µS)	< 4 µS							
Oxygen content (mg l^{-1})	< 10 mg l^{-1}							
Open-circuit sensitivity at T °C (nV/Pa)	121.13	119.75	124.26	123.97	120.98	121.21	122.55	**-**
Notes (e.g. of any unusual difficulties)								

Table 21: Calibration report table for hydrophone ER070 at 1 MHz

<table>
<tr><td colspan="3">Participating Laboratory:

NPL</td><td colspan="6">Calibration method:

Optical Interferometry</td></tr>
<tr><td colspan="3">Date(s) of calibrations:

3 August 2015 –
5 August 2015</td><td colspan="6">Hydrophone serial number:

ER070</td></tr>
<tr><td colspan="9">Nominal frequency (MHz): 1</td></tr>
<tr><td>Measurement Number</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td></tr>
<tr><td>Actual frequency (MHz)</td><td colspan="8">1.000</td></tr>
<tr><td>Temperature, T (°C)</td><td>20.1</td><td>20.1</td><td>20.1</td><td>20.3</td><td>20.4</td><td>20.3</td><td>-</td><td>-</td></tr>
<tr><td>Water conductivity (µS)</td><td colspan="8">< 4 µS</td></tr>
<tr><td>Oxygen content (mg l^{-1})</td><td colspan="8">< 10 mg l^{-1}</td></tr>
<tr><td>Open-circuit sensitivity at T °C (nV/Pa)</td><td>123.53</td><td>124.06</td><td>122.31</td><td>124.61</td><td>122.12</td><td>120.98</td><td>-</td><td>-</td></tr>
<tr><td>Notes (e.g. of any unusual difficulties)</td><td colspan="8"></td></tr>
</table>

Table 22: Calibration report table for hydrophone ER070 at 2.25 MHz

Participating Laboratory: **NPL**		**Calibration method:** **Optical Interferometry**						
Date(s) of calibrations: **9 September 2015**		**Hydrophone serial number:** **ER070**						
Nominal frequency (MHz): 2.25								
Measurement Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Actual frequency (MHz)	2.250							
Temperature, T (°C)	20.1	20.2	20.2	20.2	20.2	20.2	-	-
Water conductivity (µS)	< 1.5 µS							
Oxygen content (mg l^{-1})	< 10 mg l^{-1}							
Open-circuit sensitivity at T °C (nV/Pa)	133.62	134.12	133.64	130.87	133.82	132.30	-	-
Notes (e.g. of any unusual difficulties)								

Table 23: Calibration report table for hydrophone ER070 at 3.5 MHz

Participating Laboratory: **NPL**	**Calibration method:** **Optical Interferometry**							
Date(s) of calibrations: **10 August 2015**	**Hydrophone serial number:** **ER070**							
Nominal frequency (MHz): 3.5								
Measurement Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Actual frequency (MHz)	3.500							
Temperature, T (°C)	20.2	20.2	20.2	20.2	20.2	20.2	20.2	-
Water conductivity (µS)	< 4 µS							
Oxygen content (mg l^{-1})	< 10 mg l^{-1}							
Open-circuit sensitivity at T °C (nV/Pa)	141.01	146.04	142.07	142.05	142.34	139.56	143.13	-
Notes (e.g. of any unusual difficulties)								

Table 24: Calibration report table for hydrophone ER070 at 5 MHz

Participating Laboratory: **NPL**	**Calibration method:** **Optical Interferometry**							
Date(s) of calibrations: **22 September 2015**	**Hydrophone serial number:** **ER070**							
Nominal frequency (MHz): 5								
Measurement Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Actual frequency (MHz)	5.000							
Temperature, T (°C)	19.9	19.9	19.9	20.0	20.0	20.0	-	-
Water conductivity (µS)	< 2.5 µS							
Oxygen content (mg l^{-1})	< 10 mg l^{-1}							
Open-circuit sensitivity at T °C (nV/Pa)	145.69	145.02	145.73	144.74	146.74	145.17	-	-
Notes (e.g. of any unusual difficulties)								

Table 25: Calibration report table for hydrophone ER070 at 10 MHz

Participating Laboratory: **NPL**	**Calibration method:** **Optical Interferometry**							
Date(s) of calibrations: **9 September 2015**	**Hydrophone serial number:** **ER070**							
Nominal frequency (MHz): 10								
Measurement Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Actual frequency (MHz)	10.000							
Temperature, T (°C)	20.1	20.2	20.1	20.2	20.2	20.2	-	-
Water conductivity (µS)	< 1.5 µS							
Oxygen content (mg l^{-1})	< 10 mg l^{-1}							
Open-circuit sensitivity at T °C (nV/Pa)	187.26	188.45	184.84	193.15	189.95	186.48	-	-
Notes (e.g. of any unusual difficulties)								

Table 26: Calibration report table for hydrophone ER070 at 15 MHz

Participating Laboratory: **NPL**		**Calibration method:** **Optical Interferometry**						
Date(s) of calibrations: **1 September 2015**		**Hydrophone serial number:** **ER070**						
Nominal frequency (MHz): 15								
Measurement Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Actual frequency (MHz)	15.000							
Temperature, T (°C)	20.3	20.3	20.3	20.3	20.3	20.3	20.3	20.3
Water conductivity (μS)	< 3.5 μS							
Oxygen content (mg l^{-1})	< 10 mg l^{-1}							
Open-circuit sensitivity at T °C (nV/Pa)	242.61	245.80	245.34	242.62	243.84	246.64	249.12	245.26
Notes (e.g. of any unusual difficulties)								

Table 27: Calibration report table for hydrophone ER070 at 20 MHz

Participating Laboratory: **NPL**				**Calibration method:** **Optical Interferometry**				
Date(s) of calibrations: **3 September 2015 –** **4 September 2015**				**Hydrophone serial number:** **ER070**				
Nominal frequency (MHz): 20								
Measurement Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Actual frequency (MHz)	20.000							
Temperature, T (°C)	20.0	19.9	20.0	20.0	19.9	20.0	20.0	20.0
Water conductivity (µS)	< 4.5 µS							
Oxygen content (mg l^{-1})	< 10 mg l^{-1}							
Open-circuit sensitivity at T °C (nV/Pa)	244.68	230.97	237.63	238.90	241.56	242.68	238.68	242.15
Notes (e.g. of any unusual difficulties)								

3.2.2 IP999 – FINAL

Table 28: Calibration report table for hydrophone IP999 at 0.5 MHz

Participating Laboratory: **NPL**	**Calibration method:** **Optical Interferometry**							
Date(s) of calibrations: **11 September 2015**	**Hydrophone serial number:** **IP999**							
Nominal frequency (MHz): 0.5								
Measurement Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Actual frequency (MHz)	0.500							
Temperature, T (°C)	20.0	20.0	20.0	19.9	19.9	19.9	-	-
Water conductivity (µS)	< 2 µS							
Oxygen content (mg l^{-1})	< 10 mg l^{-1}							
Open-circuit sensitivity at T °C (nV/Pa)	210.52	210.15	206.84	208.21	208.97	210.54	-	-
Notes (e.g. of any unusual difficulties)								

Table 29: Calibration report table for hydrophone IP999 at 1 MHz

Participating Laboratory: **NPL**		**Calibration method:** **Optical Interferometry**						
Date(s) of calibrations: **21 September 2015**		**Hydrophone serial number:** **IP999**						
Nominal frequency (MHz): 1								
Measurement Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Actual frequency (MHz)	1.000							
Temperature, T (°C)	20.1	20.1	20.1	20.1	20.2	20.2	-	-
Water conductivity (µS)	< 2.5 µS							
Oxygen content (mg l^{-1})	< 10 mg l^{-1}							
Open-circuit sensitivity at T °C (nV/Pa)	214.13	214.98	216.52	214.52	214.53	214.48	-	-
Notes (e.g. of any unusual difficulties)								

Table 30: Calibration report table for hydrophone IP999 at 2.25 MHz

Participating Laboratory: **NPL**			**Calibration method:** **Optical Interferometry**					
Date(s) of calibrations: **9 September 2015**			**Hydrophone serial number:** **IP999**					
Nominal frequency (MHz): 2.25								
Measurement Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Actual frequency (MHz)	2.250							
Temperature, T (°C)	20.2	20.2	20.2	20.2	20.2	20.2	-	-
Water conductivity (µS)	< 2 µS							
Oxygen content (mg l^{-1})	< 10 mg l^{-1}							
Open-circuit sensitivity at T °C (nV/Pa)	212.16	215.02	212.48	214.29	215.38	213.63	-	-
Notes (e.g. of any unusual difficulties)								

Table 31: Calibration report table for hydrophone IP999 at 3.5 MHz

Participating Laboratory: **NPL**	**Calibration method:** **Optical Interferometry**							
Date(s) of calibrations: **22 September 2015**	**Hydrophone serial number:** **IP999**							
Nominal frequency (MHz): 3.5								
Measurement Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Actual frequency (MHz)	3.500							
Temperature, T (°C)	20.0	20.0	20.0	20.0	20.0	20.0	-	-
Water conductivity (µS)	< 2.5 µS							
Oxygen content (mg l^{-1})	< 10 mg l^{-1}							
Open-circuit sensitivity at T °C (nV/Pa)	214.43	216.54	214.16	213.87	214.43	212.48	-	-
Notes (e.g. of any unusual difficulties)								

Table 32: Calibration report table for hydrophone IP999 at 5 MHz

Participating Laboratory: **NPL**		**Calibration method:** **Optical Interferometry**						
Date(s) of calibrations: **22 September 2015**		**Hydrophone serial number:** **IP999**						
Nominal frequency (MHz): 5								
Measurement Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Actual frequency (MHz)	5.000							
Temperature, T (°C)	20.0	20.0	20.0	20.0	20.0	20.0	-	-
Water conductivity (µS)	< 2.5 µS							
Oxygen content (mg l^{-1})	< 10 mg l^{-1}							
Open-circuit sensitivity at T °C (nV/Pa)	216.47	220.30	217.23	217.37	218.50	216.01	-	-
Notes (e.g. of any unusual difficulties)								

Table 33: Calibration report table for hydrophone IP999 at 10 MHz

Participating Laboratory: **NPL**	**Calibration method:** **Optical Interferometry**							
Date(s) of calibrations: **8 September 2015**	**Hydrophone serial number:** **IP999**							
Nominal frequency (MHz): 10								
Measurement Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Actual frequency (MHz)	10.000							
Temperature, T (°C)	21.1	21.0	21.0	21.0	21.0	20.9	-	-
Water conductivity (µS)	< 1 µS							
Oxygen content (mg l^{-1})	< 10 mg l^{-1}							
Open-circuit sensitivity at T °C (nV/Pa)	248.06	249.85	252.07	244.50	250.47	248.22	-	-
Notes (e.g. of any unusual difficulties)								

Table 34: Calibration report table for hydrophone IP999 at 15 MHz

Participating Laboratory: **NPL**	**Calibration method:** **Optical Interferometry**							
Date(s) of calibrations: **7 September 2015**	**Hydrophone serial number:** **IP999**							
Nominal frequency (MHz): 15								
Measurement Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Actual frequency (MHz)	15.000							
Temperature, T (°C)	19.8	19.8	19.8	19.8	19.8	19.9	-	-
Water conductivity (µS)	< 5 µS							
Oxygen content (mg l^{-1})	< 10 mg l^{-1}							
Open-circuit sensitivity at T °C (nV/Pa)	300.55	302.88	301.27	304.47	305.94	301.73	-	-
Notes (e.g. of any unusual difficulties)								

Table 35: Calibration report table for hydrophone IP999 at 20 MHz

Participating Laboratory: **NPL**	**Calibration method:** **Optical Interferometry**							
Date(s) of calibrations: **4 September 2015 –** **7 September 2015**	**Hydrophone serial number:** **IP999**							
Nominal frequency (MHz): 20								
Measurement Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Actual frequency (MHz)	20.000							
Temperature, T (°C)	20.0	20.0	20.0	20.0	20.0	20.0	19.7	-
Water conductivity (µS)	< 5 µS							
Oxygen content (mg l^{-1})	< 10 mg l^{-1}							
Open-circuit sensitivity at T °C (nV/Pa)	355.38	363.38	351.41	352.48	362.04	355.82	359.42	-
Notes (e.g. of any unusual difficulties)								

3.2.3 FINAL SUMMARY

Table 36: Final calibration report table for hydrophone ER070

Participating Laboratory: NPL			**Calibration method: Optical Interferometry**					
Date(s) of calibrations: **30 July 2015 - 22 September 2015**			**Hydrophone serial number:** **ER070**					
Nominal frequency (MHz)	**0.5**	**1**	**2.25**	**3.5**	**5**	**10**	**15**	**20**
Actual frequency (MHz)	0.500	1.000	2.250	3.500	5.000	10.000	15.000	20.000
Mean open-circuit sensitivity at T °C (nV Pa^{-1})	122.0	122.9	133.1	142.3	145.5	188.4	245.2	239.7
Type A standard uncertainty (%)	0.52	0.45	0.38	0.53	0.20	0.63	0.31	0.62
Type B standard uncertainty (%)	1.48	1.42	1.42	1.44	1.47	1.55	1.90	1.91
Expanded uncertainty (%)	3.14	2.98	2.94	3.07	2.97	3.35	3.85	4.02

Table 37: Final calibration report table for hydrophone IP999

Participating Laboratory: NPL			**Calibration method: Optical Interferometry**					
Date(s) of calibrations: **4 September 2015 - 22 September 2015**			**Hydrophone serial number:** **IP999**					
Nominal frequency (MHz)	**0.5**	**1**	**2.25**	**3.5**	**5**	**10**	**15**	**20**
Actual frequency (MHz)	0.500	1.000	2.250	3.500	5.000	10.000	15.000	20.000
Mean open-circuit sensitivity at T °C (nV Pa^{-1})	209.2	214.9	213.8	214.3	217.6	248.9	302.8	357.1
Type A standard uncertainty (%)	0.29	0.16	0.25	0.25	0.29	0.43	0.28	0.49
Type B standard uncertainty (%)	1.48	1.42	1.42	1.44	1.47	1.55	1.90	1.91
Expanded uncertainty (%)	3.02	2.86	2.88	2.92	3.00	3.22	3.84	3.94

3.3 WEIGHTED AVERAGE

Tables 38 and 39 present a weighted average of open-circuit sensitivities and uncertainty at each frequency calculated from the initial and final calibrations presented in Tables 18 and 36 for ER070, and Tables 19 and 37 for IP999.

Table 38: Weighted average of initial and final calibration results for hydrophone ER070

Participating Laboratory: NPL			**Calibration method: Optical Interferometry**					
Date(s) of calibrations: 5 February 2014 - 25 February 2014; 30 July 2015 - 22 September 2015			**Hydrophone serial number: ER070**					
Nominal frequency (MHz)	**0.5**	**1**	**2.25**	**3.5**	**5**	**10**	**15**	**20**
Actual frequency (MHz)	0.500	1.000	2.250	3.500	5.000	10.000	15.000	20.000
Weighted average open-circuit sensitivity (nV Pa^{-1})	119.9	122.8	132.3	140.2	145.3	184.1	242.4	236.4
Weighted Type A standard uncertainty (%)	0.32	0.27	0.31	0.30	0.18	0.41	0.23	0.37
Type B standard uncertainty (%)	1.48	1.42	1.42	1.44	1.47	1.55	1.90	1.91
Expanded uncertainty (%)	3.03	2.89	2.91	2.94	2.96	3.20	3.83	3.89

Table 39: Weighted average of initial and final calibration results for hydrophone IP999

Participating Laboratory: NPL			**Calibration method: Optical Interferometry**					
Date(s) of calibrations: 11 February 2014 - 25 February 2014; 4 September 2015 - 22 September 2015			**Hydrophone serial number: IP999**					
Nominal frequency (MHz)	**0.5**	**1**	**2.25**	**3.5**	**5**	**10**	**15**	**20**
Actual frequency (MHz)	0.500	1.000	2.250	3.500	5.000	10.000	15.000	20.000
Weighted average open-circuit sensitivity (nV Pa^{-1})	206.7	211.2	211.3	213.4	215.7	245.7	302.4	354.8
Weighted Type A standard uncertainty (%)	0.23	0.13	0.17	0.21	0.19	0.30	0.26	0.27
Type B standard uncertainty (%)	1.48	1.42	1.42	1.44	1.47	1.55	1.90	1.91
Expanded uncertainty (%)	3.00	2.85	2.86	2.91	2.96	3.16	3.84	3.86

4 UNCERTAINTIES

The type 'A' and 'B' uncertainty contributions were combined and multiplied by a coverage factor (*k)* to provide a coverage probability of 95% consistent with UKAS document M3003 [9]. Tables 40 to 42 provide a breakdown of type 'B' uncertainty contributions with respect to frequency.

Table 40: Type B individual components within the uncertainty budget

Symbol	Source of Type B Uncertainty	Probability distribution	Divisor	ci	vi or veff
Pf	Photodiode frequency response	normal	2	1	Infinite
Ig	Interferometer amplifier gain ratio	rectangle	1.732	1	Infinite
Ri	Effective refractive index	rectangle	1.732	1	Infinite
Ao	Acousto-optic interaction	rectangle	1.732	1	Infinite
Sp	Spatial averaging	rectangle	1.732	1	Infinite
Ss	Pellicle transmission coefficient	rectangle	1.732	1	Infinite
Lw	Lamb waves	rectangle	1.732	1	Infinite
Pp	Pellicle position	rectangle	1.732	1	Infinite
Ag	Amplifier (5564166LF) gain and linearity	rectangle	1.732	1	Infinite
Al	Amplifier (5564166LF) loading correction	rectangle	1.732	1	Infinite
Ol	Oscilloscope linearity and range-to-range correction	rectangle	1.732	1	Infinite
Or	Oscilloscope resolution	rectangle	1.732	1	Infinite
U_T	**Total systematic uncertainty**	**normal**			**Infinite**

Table 41: Type B individual component values within the uncertainty budget

Symbol	0.5 MHz		1 MHz		2.25 MHz		3.5 MHz	
	value ± %	ui ± %	value ± %	ui ± %	value ± %	ui ± %	value ± %	ui ± %
Pf	2.00	1.00	1.80	0.90	1.80	0.90	1.80	0.90
Ig	0.70	0.40	0.70	0.40	0.70	0.40	0.70	0.40
Ri	1.00	0.58	1.00	0.58	1.00	0.58	1.00	0.58
Ao	0.02	0.01	0.02	0.01	0.02	0.01	0.02	0.01
Sp	0.10	0.06	0.20	0.12	0.15	0.09	0.40	0.23
Ss	0.10	0.06	0.20	0.12	0.30	0.17	0.30	0.17
Lw	0.05	0.03	0.04	0.02	0.04	0.02	0.04	0.02
Pp	0.02	0.01	0.03	0.02	0.04	0.02	0.05	0.03
Ag	0.54	0.31	0.54	0.31	0.54	0.31	0.54	0.31
Al	0.50	0.29	0.50	0.29	0.50	0.29	0.50	0.29
Ol	1.20	0.69	1.20	0.69	1.20	0.69	1.20	0.69
Or	0.20	0.12	0.20	0.12	0.20	0.12	0.20	0.12
U_T		**1.48**		**1.42**		**1.42**		**1.44**

Table 42: Type B individual component values within the uncertainty budget

Symbol	5 MHz		10 MHz		15 MHz		20 MHz	
	value ± %	ui ± %	value ± %	ui ± %	value ± %	ui ± %	value ± %	ui ± %
Pf	1.80	0.90	1.80	0.90	2.10	1.05	2.30	1.15
Ig	0.70	0.40	0.70	0.40	0.80	0.46	0.70	0.40
Ri	1.00	0.58	1.00	0.58	1.00	0.58	1.00	0.58
Ao	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sp	0.20	0.12	0.70	0.40	1.70	0.98	1.40	0.81
Ss	0.70	0.40	0.90	0.52	1.00	0.58	1.20	0.69
Lw	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Pp	0.05	0.03	0.06	0.03	0.08	0.05	0.10	0.06
Ag	0.54	0.31	0.54	0.31	0.54	0.31	0.54	0.31
Al	0.50	0.29	0.50	0.29	0.50	0.29	0.50	0.29
Ol	1.20	0.69	1.20	0.69	1.20	0.69	1.20	0.69
Or	0.20	0.12	0.20	0.12	0.20	0.12	0.20	0.12
U_T		**1.47**		**1.55**		**1.90**		**1.91**

5 REFERENCES

[1] Bickley, C.J., Zeqiri, B., and Robinson, S.P. Providing primary standard calibrations beyond 20 MHz. *J. Phys.: Conf. Ser.* 2004:1:20-25.

[2] Bacon, D.R, Drain, L.E., Moss, B.C. and Smith, R.A.. A new primary standard for hydrophone calibrations, *Physics in Medical Ultrasound, Institute of Physical Sciences in Medicine* 1986:47:30-35.

[3] Bacon, D.R.. Primary calibration of ultrasonic hydrophones using optical interferometry. *IEEE Trans. Ultrason. Ferroelec. Freq. Contr* 1998:35:152-161.

[4] Drain, L.E., Speake, J.H. and Moss, B.C. Displacement and vibration measurement by laser interferometry. *Proceedings of the European Congress on Optics applied to Metrology, SPIE* 1977:136:52-57.

[5] Zeqiri, B. and Lee, N.D. BIPM/CIPM Key Comparison CCAUV.U-K2: Comparison of 1 mm hydrophone calibrations in the frequency range 1 MHz to 15 MHz. *NPL Report DQL-AC RES 013*, National Physical Laboratory, UK, 2005.

[6] Koukoulas, T., Rajagopal, S., Robinson, S., Moss, B., Zeqiri, Z., and Theobald, P. Primary ultrasonic interferometer photodiode characterization using frequency-modulated laser wavefront radiation. Metrologia 2013:50:572-579.

[7] Robinson, S.P., Bacon, D.R. and Moss, B.C. The measurement of the frequency response of a photodiode and amplifier using an opto-mechanical frequency response calibrator. *Meas. Sci. Technol* 1990:1:1184-1187.

[8] Rajagopal, S. and Zeqiri, B. Comparison of ultrasonic hydrophone calibrations in the frequency range 0.5 MHz to 20 MHz. CIPM/BIPM Protocol Document CCAUV.U-K4.

[9] UKAS. The Expression of uncertainty and confidence in measurement, UKAS Publication number M3003, Edition 3, United Kingdom Accreditation Service, 2012.