Report on BIPM/CIPM Key Comparison CCAUV.U-K4: Absolute Calibration of Medical Hydrophones in the Frequency Range 0.5 MHz to 20 MHz

Final Report

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1 INTRODUCTION

The central objectives of the Mutual Recognition Agreement (MRA) drawn up by the International Committee of Weights and Measures (CIPM) and signed by representatives of Member States of the Bureau international des poids et mesures (BIPM) are i) to establish the degree of equivalence of national measurement standards maintained by NMIs, ii) to provide for the mutual recognition of calibration and measurement certificates issued by NMIs and iii) thereby to provide governments and other parties with a secure technical foundation for wider agreements related to international trade, commerce and regulatory affairs (CIPM-MRA 2003). The degree of equivalence of national measurement standards supporting ultrasound exposimetry at medical ultrasound frequencies is established by international comparison of measurements known as key comparisons, providing a realisation of the acoustic pascal in water. The pascal is measured using transfer standard acousto-electric devices known as hydrophones, which are calibrated on various realisations of primary standard methods directly traceable to Système International (SI) units.

This document constitutes the ***Final*** report of the key comparison CCAUV.U-K4, undertaken under the auspices of BIPM/CIPM Consultative Committee for Acoustics, Ultrasound and Vibration (CCAUV). This is a repetition of the key comparison CCAUV.U-K2 “Comparison of 1 mm hydrophone calibrations in the frequency range 1 to 15 MHz” (1999 – 2003), but whose scope has been extended upwards to 20 MHz and downwards to 0.5 MHz. A report of the previous key comparison is available on the BIPM web-site under report number NPL Report DQL-AC (RES) 013 (Zeqiri and Lee 2005). The reduction in the lower frequency for CCAUV.U-K4 ensures that it will overlap with the Underwater Acoustics key comparison CCAUV.W-K1 which covers the range 1 kHz to 0.5 MHz. This report makes recommendations regarding the key comparison reference values (KCRVs) and their associated uncertainties. From these KCRV values, the report specifies the deviations from the reference value and the uncertainty of this deviation for each of the individual participant laboratories. The individual reports supplied by participant laboratories are presented in the Appendices of this report.

2 THE COMPARISON

Two GEC Marconi, bilaminar type membrane hydrophones of 1 mm active element diameter were employed for the purpose of this key comparison. NPL was the Pilot or the Co-ordinating Laboratory. The other participating laboratories were PTB (Germany), NMIJ/AIST (Japan), NIM (China) and INMETRO (Brazil). The detailed protocol of the key comparison is provided in the Appendix A. The key comparison was organised as a “star” comparison, with the two hydrophones being returned to the Pilot Laboratory to enable stability checks to be completed. The schedule of the key comparison is shown below.

Name of institute	Start date	Finish date
NPL, UK	15th Mar, 2014	15th May, 2014
PTB, Germany	16th June, 2014	15th Aug, 2014
NMIJ, Japan	1st Sep, 2014	31st Oct, 2014
NIM, China	16th Nov, 2014	31st Jan 2015
INMETRO, Brazil	16th Feb, 2015	15th April, 2015
NPL, UK	30th July, 2015	22nd Sep, 2015

A few issues arose during the course of the key comparison requiring mention in this ***Final*** report.

1) The original data received from NIM upon review at NPL were identified as discrepant. NIM was invited to check their data as per BIPM/CIPM key comparison guidelines. NIM identified a problem with their setup in their measurement of the NPL supplied hydrophone amplifier gain which was essentially caused by a mismatch of the input electrical impedance. Given the mild nature of the error, NPL as pilot laboratory agreed to comply with NIM's request for re-measurement of the gain of the NPL preamplifier. NIM re-measured the gain, corrected their sensitivity data and supplied a revised report. The original and revised data sets from NIM are provided respectively in Appendix E and F.
2) Certain data from INMETRO upon review at NPL were identified as discrepant. INMETRO was invited to review their results and report their findings. INMETRO checked for numerical errors and advised NPL to proceed with using the originally supplied data for the KCRV analysis.
3) The final measurements at NPL were undertaken between July and September 2015 due to a delayed necessary infrastructure upgrade on the primary standard interferometer. The final measurement data set is not included in this report.

3 FINAL DECLARED PARTICIPANT VALUES

Tables 3.1 and 3.2 represent a summary of the open-circuit free-field sensitivity values for hydrophones IP999 and ER070 respectively declared by NPL, PTB, NMIJ, NIM and INMETRO. The table includes the original data and the revised data provided by NIM; there were marginal changes to the uncertainty figures declared for the two sets of data. Only the revised data provided by NIM is considered in the KCRV analysis presented in Section 5. The data from NPL used in the KCRV analysis is the data set obtained at the start of the key comparison.

Table 3.1: **Summary of end-of-cable open-circuit sensitivities, expressed in nV Pa^{-1}, for the hydrophone IP999 derived by the five participants taking part in this key comparison. Revised and original values are presented for NIM (China). Declared values of the expanded uncertainty, given in nV Pa^{-1}, have been derived using standard uncertainties supplied by participants and multiplied by a coverage probability, *k* = 2. The data from NPL used in the KCRV analysis is the data set obtained at the start of the key comparison.**

Participant	Frequency (MHz)							
	0.5	1	2.25	3.5	5	10	15	20
NPL	204.1 (6.2)	207.6 (6.0)	208.7 (6.0)	212.5 (6.3)	213.8 (6.4)	242.5 (7.8)	301.9 (12.3)	352.6 (13.6)
PTB	207.9 (12.3)	210.2 (15.5)	213.5 (14.6)	213.4 (14.0)	214.9 (13.8)	238.8 (14.5)	294.1 (19.1)	339.5 (25.0)
NMIJ	211.8 (8.5)	210.6 (8.4)	213.0 (8.5)	214.9 (8.6)	218.8 (8.8)	241.1 (12.1)	297.7 (16.1)	354.3 (25.2)
NIM	101.8 (7.1)	102.8 (7.2)	104.6 (7.2)	106.2 (7.3)	108.5 (7.5)	124.4 (8.7)	141.0 (9.8)	172.2 (13.1)
NIM (revised)	205.0 (14.3)	207.2 (14.5)	211.6 (14.7)	215.3 (14.9)	220.2 (15.2)	251.1 (17.6)	279.8 (19.5)	344.1 (26.3)
INMETRO	191.0 (12.8)	184.7 (12.4)	187.9 (12.0)	192.6 (12.1)	204.9 (13.1)	187.2 (12.0)	161.2 (11.4)	-

Table 3.2: **Summary of end-of-cable open-circuit sensitivities, expressed in nV Pa^{-1}, for the hydrophone ER070 derived by the five participants taking part in this key comparison. Revised and original values are presented for NIM (China). Declared values of the expanded uncertainty, given in nV Pa^{-1}, have been derived using standard uncertainties supplied by participants and multiplied by a coverage probability, *k* = 2. The data from NPL used in the KCRV analysis is the data set obtained at the start of the key comparison.**

Participant	Frequency (MHz)							
	0.5	**1**	**2.25**	**3.5**	**5**	**10**	**15**	**20**
NPL	118.0 (3.6)	122.6 (3.6)	131.5 (4.0)	138.3 (4.1)	145.0 (4.4)	180.1 (5.9)	239.6 (9.2)	233.2 (9.1)
PTB	119.5 (7.0)	123.8 (8.1)	133.0 (8.2)	138.2 (8.3)	145.7 (8.6)	178.2 (10.2)	234.4 (13.8)	221.0 (14.1)
NMIJ	122.1 (4.9)	125.0 (5.0)	131.6 (5.3)	139.0 (5.6)	147.3 (5.9)	181.6 (9.6)	236.2 (12.8)	233.4 (16.6)
NIM	59.1 (4.2)	61.9 (4.3)	64.5 (4.5)	68.6 (4.7)	74.3 (5.1)	91.6 (6.9)	111.9 (8.0)	112.3 (8.0)
NIM (revised)	118.9 (8.4)	124.7 (8.8)	130.5 (9.1)	139.0 (9.6)	150.8 (10.5)	185.0 (13.9)	222.1 (16.0)	224.5 (16.1)
INMETRO	109.0 (7.1)	111.2 (7.9)	117.2 (7.6)	125.5 (8.3)	138.4 (9.1)	146.5 (9.8)	133.1 (8.5)	-

4 STABILITY OF REFERENCE HYDROPHONES

Upon their return to NPL, the key comparison hydrophones were subject to intermediate checks to monitor their stability. An initial check was carried out before sending the two hydrophones to the first participant and subsequent checks were carried out after receiving the hydrophones from the participant and before sending them to the next participant in the schedule. The checks were carried out employing a comparison method using a secondary standard hydrophone which itself was previously calibrated using the NPL primary standard. The acoustic field used in the secondary method was a nonlinear spatially-broad acoustic field (Smith and Bacon 1990) produced using a 1 MHz transducer which generated harmonic components up to 40 MHz. A total of six checks were carried out on the two hydrophones.

The ratio of the two hydrophone sensitivities i.e. IP999/ER070 obtained from the comparison method is presented in Figure 4.1 through to Figure 4.7 for frequencies closely to, although not exactly the same as, those used within this key comparison. The standard deviation in the six ratios for all frequencies varied in the range 0.5 % – 1.5 %. The temperature of the water over the course of the stability checks ranged from 18.9 ^{O}C – 21.1 ^{O}C and the same secondary standard hydrophone was employed throughout. Therefore, the measurement systematics were virtually identical but the ratios should be unaffected regardless provided both hydrophones are stable. At some frequencies, the graphs appear to show a weak systematic trend as a function of time. Given the long term historical data NPL has on the stability of these two hydrophones, it is very unlikely that both hydrophones would change by the same amount over the period of the key comparison. The cause for the variation in the ratios which is noticeably higher for the first three data points for all frequencies could not be traced and hence a clear trend cannot not be ascertained. It should be noted that a worst case variation of 1.5 % observed in Figure 4.7 is a relatively small value when considered in light of participant reported expanded uncertainties. Hence, the hydrophones were concluded to be stable during the course of the key comparison.

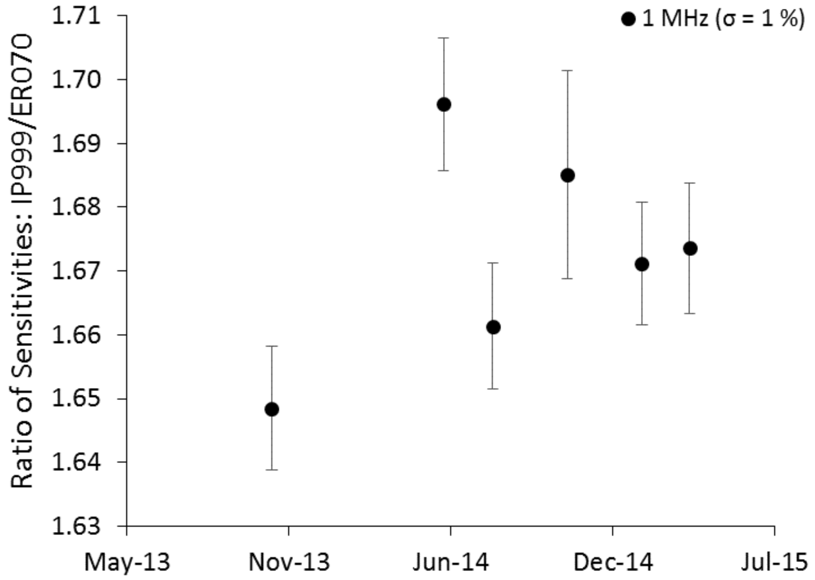

Figure 4.1. Stability checks carried out at NPL during the course of the key comparison. Values of the ratio of the end-of-cable open-circuit sensitivities of the two hydrophones used, IP999 and ER070, are derived at a frequency of 1 MHz. Standard uncertainties are presented for the ratios.

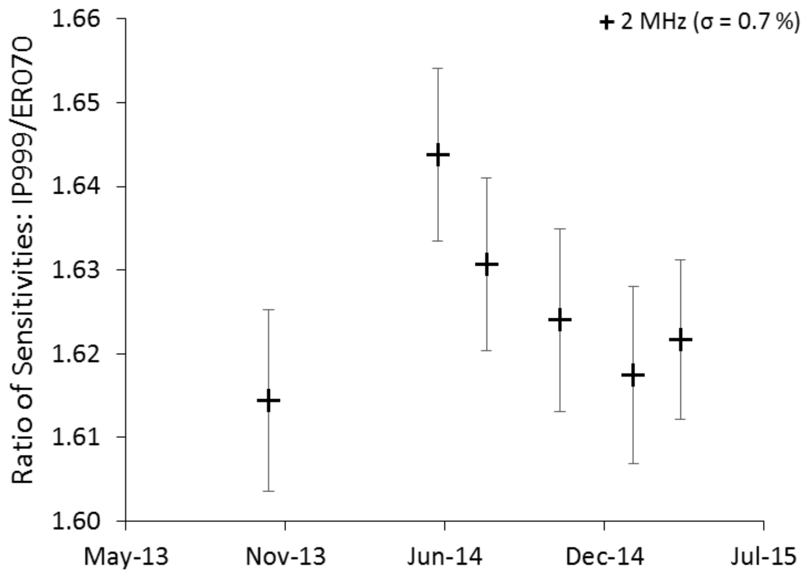

Figure 4.2. Stability checks carried out at NPL during the course of the key comparison. Values of the ratio of the end-of-cable open-circuit sensitivities of the two hydrophones used, IP999 and ER070, are derived at a frequency of 2 MHz. Standard uncertainties are presented for the ratios.

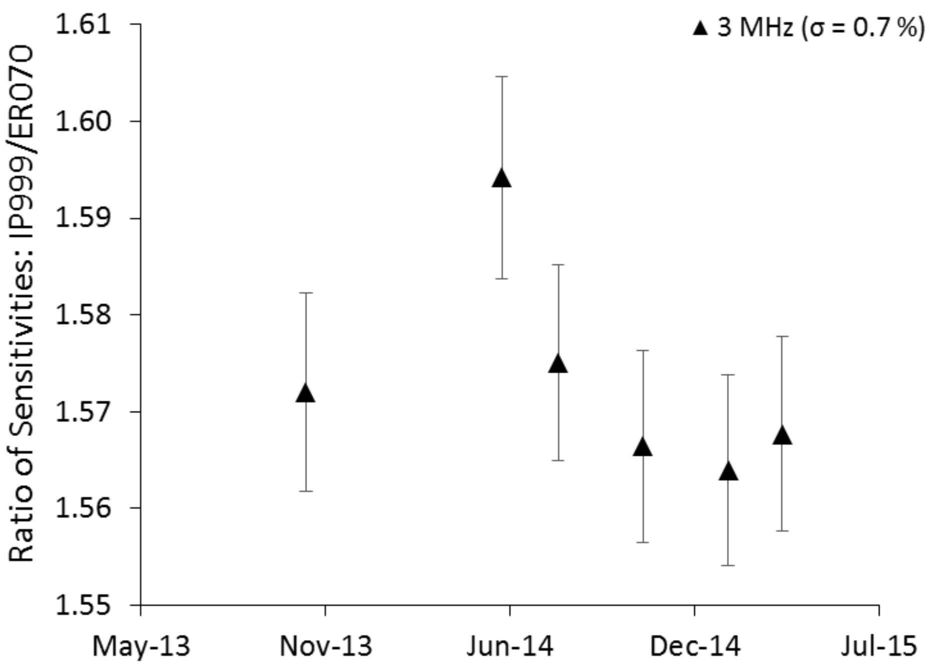

Figure 4.3. Stability checks carried out at NPL during the course of the key comparison. Values of the ratio of the end-of-cable open-circuit sensitivities of the two hydrophones used, IP999 and ER070, are derived at a frequency of 3 MHz. Standard uncertainties are presented for the ratios.

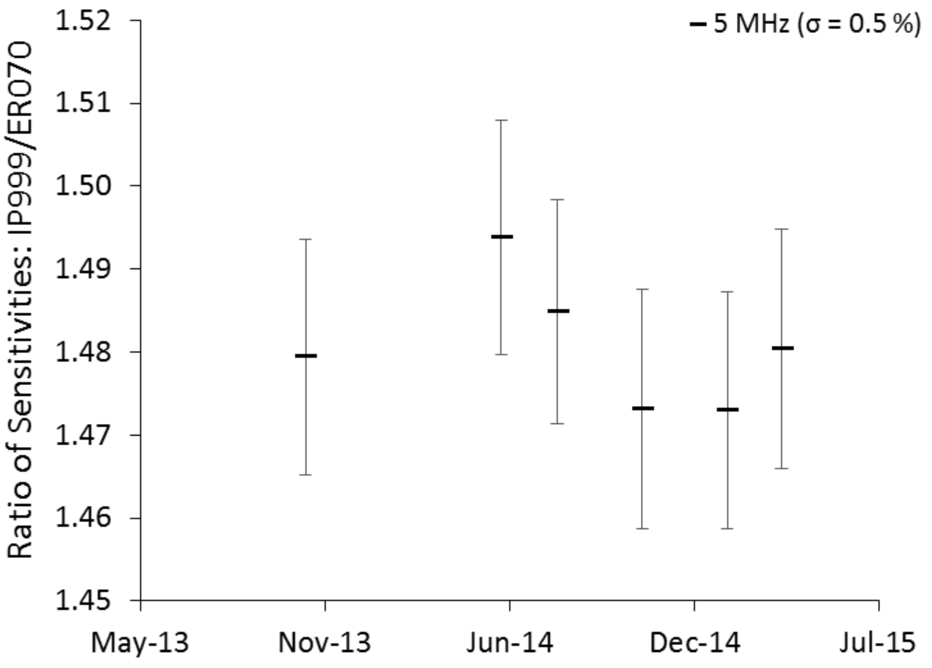

Figure 4.4. Stability checks carried out at NPL during the course of the key comparison. Values of the ratio of the end-of-cable open-circuit sensitivities of the two hydrophones used, IP999 and ER070, are derived at a frequency of 5 MHz. Standard uncertainties are presented for the ratios.

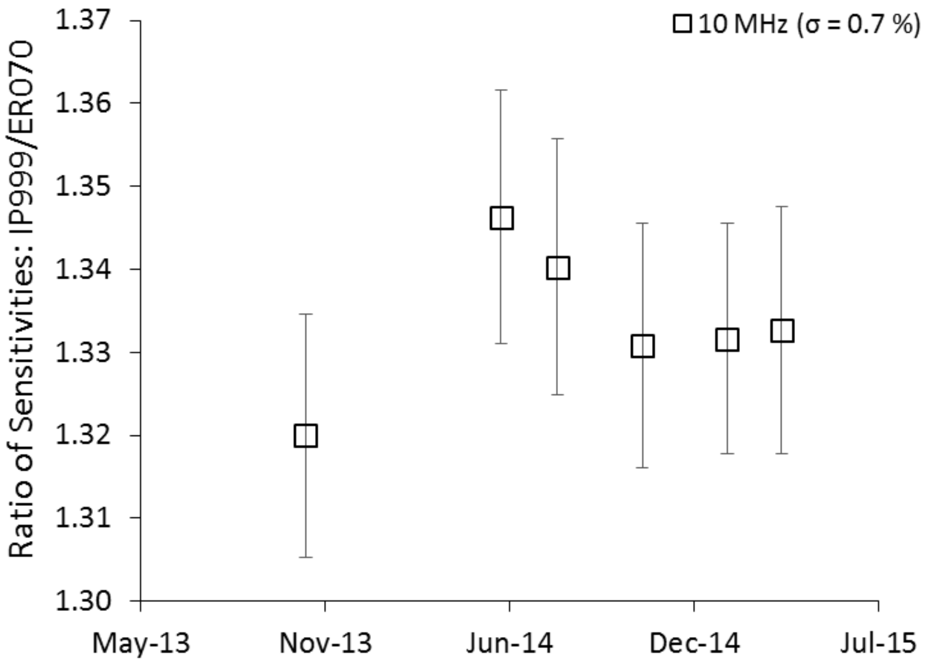

Figure 4.5. Stability checks carried out at NPL during the course of the key comparison. Values of the ratio of the end-of-cable open-circuit sensitivities of the two hydrophones used, IP999 and ER070, are derived at a frequency of 10 MHz. Standard uncertainties are presented for the ratios.

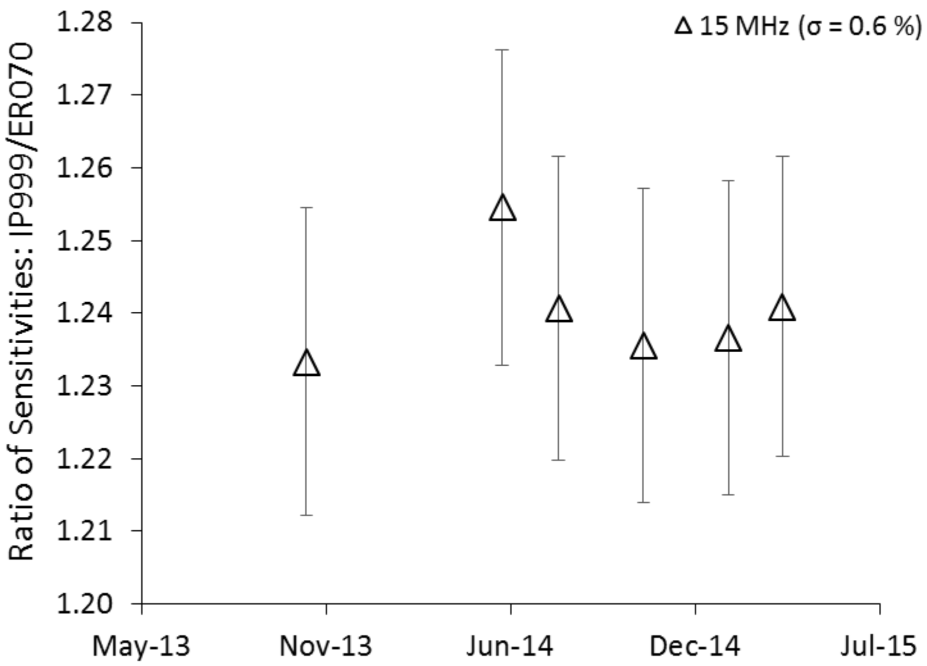

Figure 4.6. Stability checks carried out at NPL during the course of the key comparison. Values of the ratio of the end-of-cable open-circuit sensitivities of the two hydrophones used, IP999 and ER070, are derived at a frequency of 15 MHz. Standard uncertainties are presented for the ratios.

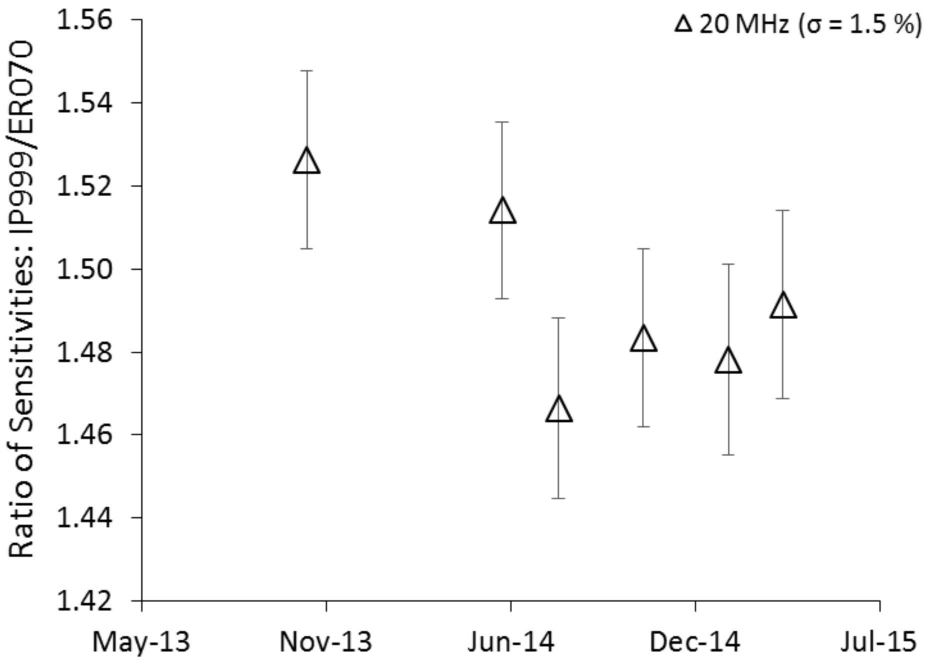

Figure 4.7. Stability checks carried out at NPL during the course of the key comparison. Values of the ratio of the end-of-cable open-circuit sensitivities of the two hydrophones used, IP999 and ER070, are derived at a frequency of 20 MHz. Standard uncertainties are presented for the ratios.

5 ANALYSIS OF KEY COMPARISON REFERENCE VALUES (KCRVs)

The analysis method applied in determining the KCRVs follows the guidance procedure outlined by the key comparison Working Group (KCWG) for the CCAUV (CCAUV-GoC 2013) which is itself derived based on the work of Cox MG (2002). Chi-squared (χ^2) tests were applied to determine the consistency of the measurements and for the identification of discrepant results. The consistent measurement set was combined using the weighted mean method to obtain an unbiased estimator of the KCRVs at all frequencies. The results of only unilateral Degree of Equivalence (DoE) alongside the KCRV is presented for all participants as requested in the guidance of the KCWG. However, individual participants are welcome to undertake their own Bilateral-DoE analysis if they wish.

The sensitivity values and the associated standard uncertainties at each frequency for the two hydrophones were used in the KCRV analysis without being subject to any corrections or adjustments. For example, the sensitivity of Marconi hydrophones varies with temperature but the variation is small compared to the overall calibration uncertainty. Also, the coefficients for temperature dependent sensitivity for Marconi hydrophones are available only at 1 and 10 MHz (Bacon and Robinson 1990). Therefore, participants were asked to undertake their measurements by maintaining the temperature of water close to 20 ^{O}C. However, the temperatures reported by participants had a range of 2.9 ^{O}C with a mean value of 20.3 ^{O}C. NMIJ reported the smallest range of 0.2 ^{O}C with a mean value of 20.5 ^{O}C and NIM reported a maximum range of 2.8 ^{O}C with a mean value of 21.4 ^{O}C. Table 5.1 provides the mean water temperature calculated from the values reported by participants for each frequency and hydrophone together with minimum and maximum recorded values. It is clear that KCRVs might be subject to small participant induced biases due to a spread in the temperature of water. Since temperature coefficients are not available at every frequency and the only available values of –0.3 % C^{-1} and 0.2 % $^{O}C^{-1}$ at 1 and 10 MHz respectively are considered to be small in relation to the overall uncertainty, the impact on the KCRVs due to temperature was ignored in the analysis.

Table 5.1: Summary of temperature of water values reported by all participants.

Participant	Water temperature (°C)					
	ER070			IP999		
	Mean	Min	Max	Mean	Min	Max
NPL	19.4	18.9	19.7	19.2	19.0	19.3
PTB	20.4	20.1	20.5	20.5	20.1	20.9
NMIJ	20.5	20.4	20.6	20.5	20.4	20.6
NIM	21.4	19.3	22.5	21.4	19.3	22.2
INMETRO	19.2	18.7	19.8	19.4	18.9	20.0

5.1 KEY FORMULAE

5.1.1 DERIVING THE KCRV FROM THE WEIGHTED MEAN

The x_{KCRV}, is given by:

$$\frac{x_{KCRV}}{u_{KCRV}^2} = \sum_{j=1}^{N} \frac{x_j}{u_j^2} \quad (1)$$

where N is the number of values in the comparison, and x_j is the j_{th} comparison value.

5.1.2 THE UNCERTAINTY IN THE KCRV VALUE

The standard uncertainty associated with the KCRV, u_{KCRV} is given by:

$$\frac{1}{u_{KCRV}^2} = \sum_{j=1}^{N} \frac{1}{u_j^2} \quad (2)$$

where u_j is the standard uncertainty of the key comparison value provided by j_{th} participant.

5.1.3 CONSISTENCY CHECKS

The consistency check applied to the data sets at each of the frequencies involved the standard chi-squared test, where the observed chi-squared value, χ_{obs}^2 is given by:

$$\chi_{obs}^{\ 2} = \sum_{j=1}^{N} \frac{(x_j - x_{KCRV})^2}{u_j^{\ 2}} \quad (3)$$

The data set is judged to be inconsistent if the probability of occurrence of a χ^2 value greater than χ_{obs}^2 is less than 5%, or:

$$\Pr\left\{\chi^2(\nu) > \chi_{obs}^{\ 2}\right\} < 0.05. \quad (4)$$

Here, ν represents the degrees of freedom (ν = N-1). Within the analysis presented in this report, KCRV values are analysed using typically four participants (ν = 3), and this effectively sets an upper limit to the value of χ^2_{obs} of approximately 8. Therefore, in cases where the derived value of $\chi^2_{obs} > 8$, the results may be considered to be inconsistent.

A point of interest for the key comparison lies in the methods used to identify discrepant participants. Cox MG (2002) provide guidance on identifying discrepant participants, and, for information, the main features of the analysis will be presented.

From the KCRV values calculated in Section 5.1.1, and the individual values of the participant participants (x_j), the DoE of the participant may be described by the pair of values (d_j, $U(d_j)$) given by the two equations:

$$d_j = x_j - x_{KCRV} \tag{5}$$

and

$$U(d_j) = 2u(d_j) \tag{6}$$

where the uncertainty in the DoE, or the deviation from the KCRV, is given by the expression:

$$u^2(d_j) = u^2(x_j) - u^2(x_{KCRV}). \tag{7}$$

A discrepant participant is identified as one for which:

$$\left| d_j \right| > 2u(d_j). \tag{8}$$

If this inequality is satisfied, then the particular value x_j is described as discrepant at an approximate 5% level of significance.

The uncertainty in the DoE for a particular value x_j, identified as discrepant is given by the expression:

$$u^2(d_j) = u^2(x_j) + u^2(x_{KCRV}). \tag{9}$$

5.2 REDUCED DATASET EMPLOYED FOR KCRV ANALYSIS

The consistency check employed on the participant provided dataset, listed in Tables 3.1 and 3.2 using equations (3) and (4) proved to be inconsistent for the majority of the frequencies for both key comparison hydrophones. In particular, the chi-squared test was passed, only at 0.5 and 5 MHz for hydrophone IP999 and 0.5, 3.5 and 5 MHz for hydrophone ER070. The comparison of the participants' unilateral DoE data considering the x_{KCRV} computed using all participant data against the criteria quoted in equation (8) revealed that INMETRO's data were discrepant. Therefore, INMETRO's sensitivity values were not included in the final calculation of KCRV. The reduced dataset employed for the final computation of the KCRV are listed in Tables 5.2 and 5.3.

Table 5.2: **Summary of end-of-cable open-circuit sensitivities and uncertainties (*k* = 2), expressed in nV Pa^{-1}, for the hydrophone IP999 derived by the following listed participants were used in the calculation of the KCRV.**

Participant	Frequency (MHz)							
	0.5	**1**	**2.25**	**3.5**	**5**	**10**	**15**	**20**
NPL	204.1 (6.2)	207.6 (6.0)	208.7 (6.0)	212.5 (6.3)	213.8 (6.4)	242.5 (7.8)	301.9 (12.3)	352.6 (13.6)
PTB	207.9 (12.3)	210.2 (15.5)	213.5 (14.6)	213.4 (14.0)	214.9 (13.8)	238.8 (14.5)	294.1 (19.1)	339.5 (25.0)
NMIJ	211.8 (8.5)	210.6 (8.4)	213.0 (8.5)	214.9 (8.6)	218.8 (8.8)	241.1 (12.1)	297.7 (16.1)	354.3 (25.2)
NIM (revised)	205.0 (14.3)	207.2 (14.5)	211.6 (14.7)	215.3 (14.9)	220.2 (15.2)	251.1 (17.6)	279.8 (19.5)	344.1 (26.3)

Table 5.3: **Summary of end-of-cable open-circuit sensitivities and uncertainties (k = 2), expressed in nV Pa^{-1}, for the hydrophone ER070 derived by the following listed participants were used in the calculation of the KCRV.**

Participant	Frequency (MHz)							
	0.5	**1**	**2.25**	**3.5**	**5**	**10**	**15**	**20**
NPL	118.0 (3.6)	122.6 (3.6)	131.5 (4.0)	138.3 (4.1)	145.0 (4.4)	180.1 (5.9)	239.6 (9.2)	233.2 (9.1)
PTB	119.5 (7.0)	123.8 (8.1)	133.0 (8.2)	138.2 (8.3)	145.7 (8.6)	178.2 (10.2)	234.4 (13.8)	221.0 (14.1)
NMIJ	122.1 (4.9)	125.0 (5.0)	131.6 (5.3)	139.0 (5.6)	147.3 (5.9)	181.6 (9.6)	236.2 (12.8)	233.4 (16.6)
NIM (revised)	118.9 (8.4)	124.7 (8.8)	130.5 (9.1)	139.0 (9.6)	150.8 (10.5)	185.0 (13.9)	222.1 (16.0)	224.5 (16.1)

5.3 KEY COMPARISON REFERENCE VALUES AND UNCERTAINTIES

Table 5.4: **Summary of key comparison values, *KCRV* for hydrophone IP999, including expanded uncertainty calculated using a coverage factor, *k* = 2. Participant data judged discrepant by the χ^2 probability (5%) was removed from these calculations.**

Frequency (MHz)	*KCRV* (nV / Pa)	U_{KCRV} (nV / Pa)	χ^2_{obs}	$\chi^2(v=3)$	$\chi^2_{obs} < \chi^2(v)$
0.5	206.8	4.4	2.2	7.82	Pass
1	208.6	4.4	0.4	7.82	Pass
2.25	210.6	4.4	0.9	7.82	Pass
3.5	213.5	4.6	0.3	7.82	Pass
5	215.9	4.6	1.2	7.82	Pass
10	242.5	5.6	1.3	7.82	Pass
15	295.9	7.9	3.8	7.82	Pass
20	349.5	10.0	1.2	7.82	Pass

Table 5.5: **Summary of key comparison values, *KCRV* for hydrophone ER070, including expanded uncertainty calculated using a coverage factor, *k* = 2. Participant data judged discrepant by the χ^2 probability (5%) was removed from these calculations.**

Frequency (MHz)	*KCRV* (nV / Pa)	U_{KCRV} (nV / Pa)	χ^2_{obs}	$\chi^2(v=3)$	$\chi^2_{obs} < \chi^2(v)$
0.5	119.4	2.6	1.8	7.82	Pass
1	123.6	2.6	0.7	7.82	Pass
2.25	131.6	2.8	0.2	7.82	Pass
3.5	138.5	2.9	0.1	7.82	Pass
5	146.2	3.1	1.2	7.82	Pass
10	180.5	4.3	0.7	7.82	Pass
15	235.3	6.1	3.6	7.82	Pass
20	229.3	6.4	2.7	7.82	Pass

5.4 DEVIATIONS OF INDIVIDUAL PARTICIPANT VALUES FROM THE DERIVED KCRVs

This section provides tables for the deviations of the individual participant results from the KCRV values previously derived. Tables 5.6 and 5.7 contain each of the frequencies over the range 0.5 to 20 MHz, with the results for each hydrophone presented separately. Within these tables, the deviation, $d_{j,R}$, is calculated relative to the magnitude of the derived KCRV value, stated as a percentage, using the expression:-

$$d_{j,R} = \frac{x_j - x_{KCRV}}{x_{KCRV}} \times 100 \qquad (10)$$

where x_j is the value provided by the j_{th} participant and x_{KCRV} is the relevant KCRV. Expressions for the derivation of the uncertainty in the deviation have already been presented in Section 5. Within Tables 5.6 and 5.7, the relative expanded uncertainties in the deviation are given using k = 2. These deviations have been normalised to the KCRV using:

$$U(d_{j,R}) = \frac{U(d_j)}{x_{KCRV}} \times 100. \qquad (11)$$

Table 5.6: Hydrophone IP999, % deviation of the individual participant results from the derived KCRV value.

		NPL	PTB	NMIJ	NIM	INMETRO
0.5 MHz	d_i	-1.3	0.5	2.4	-0.9	-7.6
	$U(d_i)$	2.1	5.5	3.5	6.6	6.5
1.0 MHz	d_i	-0.5	0.8	1.0	-0.7	-11.5
	$U(d_i)$	1.9	7.1	3.4	6.6	6.3
2.25 MHz	d_i	-0.9	1.4	1.1	0.5	-10.8
	$U(d_i)$	1.9	6.6	3.5	6.6	6.1
3.5 MHz	d_i	-0.5	0.0	0.7	0.8	-9.8
	$U(d_i)$	2.0	6.2	3.4	6.6	6.1
5 MHz	d_i	-1.0	-0.5	1.3	2.0	-5.1
	$U(d_i)$	2.0	6.0	3.5	6.7	6.4
10 MHz	d_i	0.0	-1.5	-0.6	3.5	-22.8
	$U(d_i)$	2.2	5.5	4.4	6.9	5.5
15 MHz	d_i	2.0	-0.6	0.6	-5.4	-45.5
	$U(d_i)$	3.2	5.9	4.7	6.0	4.7
20 MHz	d_i	0.9	-2.9	1.4	-1.5	-
	$U(d_i)$	2.7	6.6	6.6	6.9	-

Table 5.7: Hydrophone ER070, % deviation of the individual participant results from the derived KCRV value.

ER070		NPL	PTB	NMIJ	NIM	INMETRO
0.5 MHz	d_j	-1.2	0.1	2.3	-0.4	-8.7
	$U(d_j)$	2.1	5.5	3.5	6.7	6.3
1.0 MHz	d_i	-0.8	0.2	1.1	0.9	-10.0
	$U(d_i)$	2.0	6.2	3.4	6.8	6.7
2.25 MHz	d_i	-0.1	1.1	0.0	-0.8	-10.9
	$U(d_i)$	2.1	5.8	3.4	6.5	6.2
3.5 MHz	d_i	-0.1	-0.2	0.4	0.4	-9.4
	$U(d_i)$	2.1	5.6	3.4	6.6	6.3
5 MHz	d_i	-0.8	-0.3	0.8	3.1	-5.3
	$U(d_i)$	2.1	5.5	3.4	6.9	6.6
10 MHz	d_i	-0.2	-1.3	0.6	2.5	-18.8
	$U(d_i)$	2.2	5.1	4.8	7.3	5.9
15 MHz	d_i	1.8	-0.4	0.4	-5.6	-43.4
	$U(d_i)$	3.0	5.2	4.8	6.3	4.4
20 MHz	d_i	1.7	-3.6	1.8	-2.1	-
	$U(d_i)$	2.9	5.5	6.7	6.4	-

5.5 DEGREE OF EQUIVALENCE GRAPHS

The DOEs graphs in figures 5.1 through 5.16 depict the percent deviations of the participants' data from the KCRV value for IP999 and ER070. Not all participants are shown but only those participants' that contributed to the determination of KCRV.DoEs for INMETRO are not presented in these graphs but are shown separately in section 5.5.3.

5.5.1 DoE Graphs for Hydrophone IP999

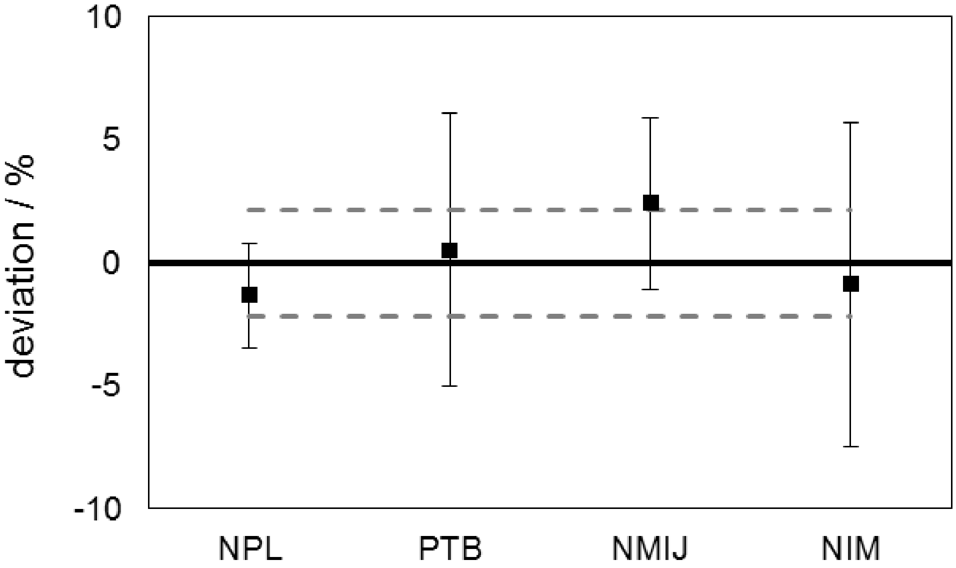

Figure 5.1: DoE results obtained at a frequency of 0.5 MHz for the hydrophone IP999. The KCRV is depicted by the bold horizontal line (zero-line) and the two horizontal broken lines represent the expanded relative uncertainty limits of the KCRV,U_{KCRV}(%) calculated using k = 2. The black squares along with their relative expanded uncertainties, $U(d_j)$(%) calculated using k = 2, depict the deviation in percent between each participant value and the KCRV.

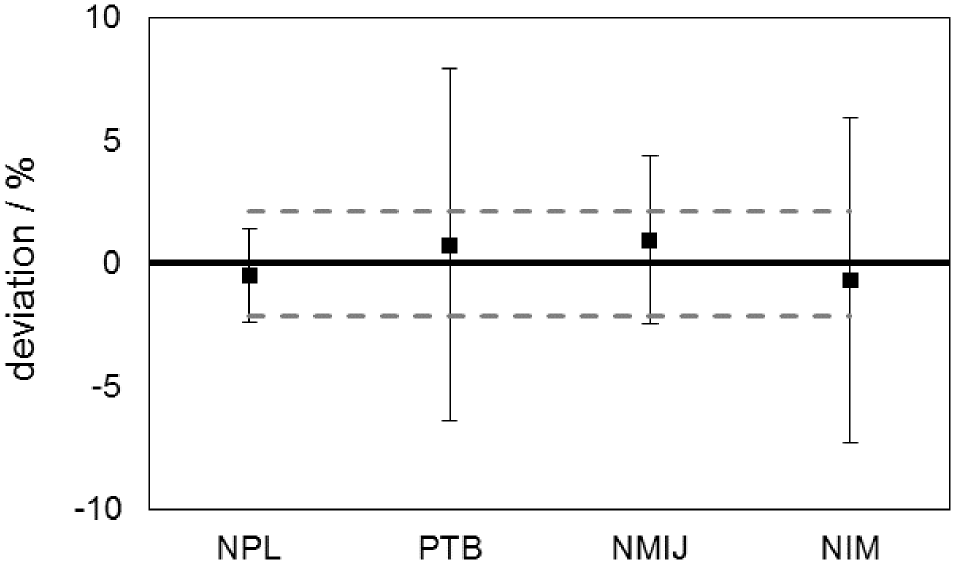

Figure 5.2: DoE results obtained at a frequency of 1 MHz for the hydrophone IP999. The KCRV is depicted by the bold horizontal line (zero-line) and the two horizontal broken lines represent the expanded relative uncertainty limits of the KCRV,U_{KCRV}(%) calculated using k = 2. The black squares along with their relative expanded uncertainties, $U(d_j)$(%) calculated using k = 2, depict the deviation in percent between each participant value and the KCRV.

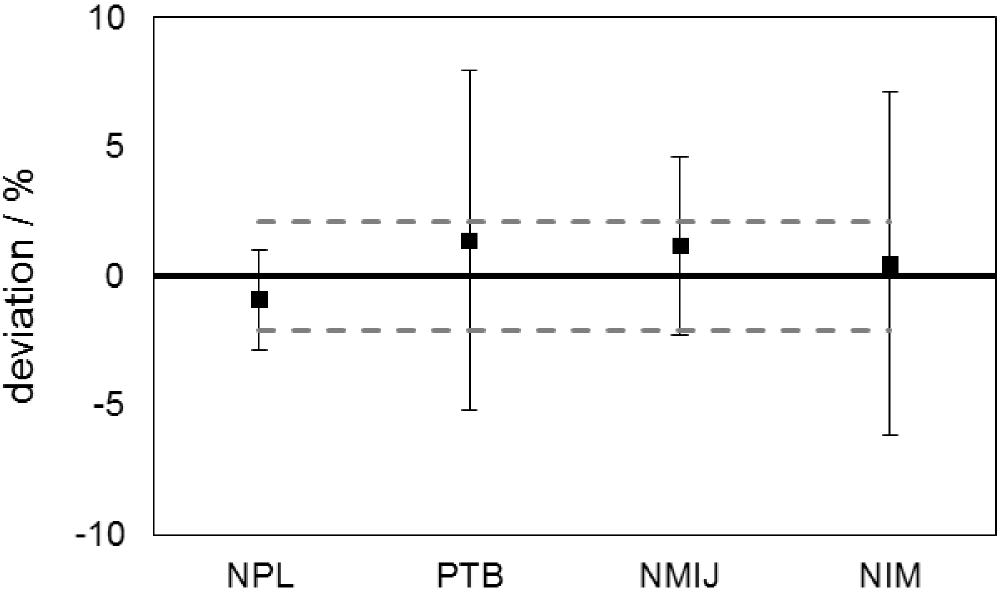

Figure 5.3: DoE results obtained at a frequency of 2.25 MHz for the hydrophone IP999. The KCRV is depicted by the bold horizontal line (zero-line) and the two horizontal broken lines represent the expanded relative uncertainty limits of the KCRV,$U_{KCRV}(\%)$ calculated using $k = 2$. The black squares along with their relative expanded uncertainties, $U(d_j)(\%)$ calculated using $k = 2$, depict the deviation in percent between each participant value and the KCRV.

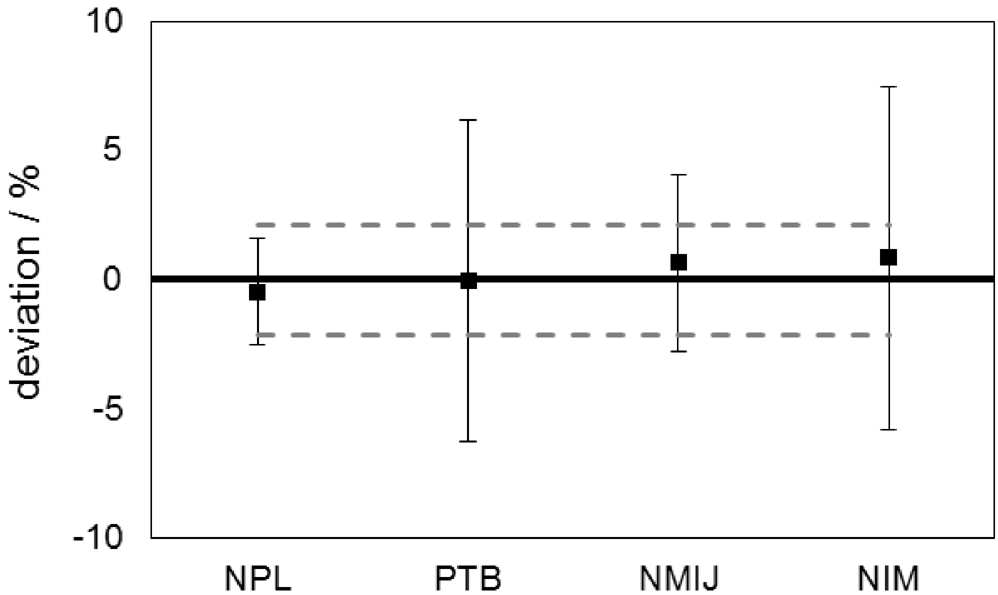

Figure 5.4: DoE results obtained at a frequency of 3.5 MHz for the hydrophone IP999. The KCRV is depicted by the bold horizontal line (zero-line) and the two horizontal broken lines represent the expanded relative uncertainty limits of the KCRV,$U_{KCRV}(\%)$ calculated using $k = 2$. The black squares along with their relative expanded uncertainties, $U(d_j)(\%)$ calculated using $k = 2$, depict the deviation in percent between each participant value and the KCRV.

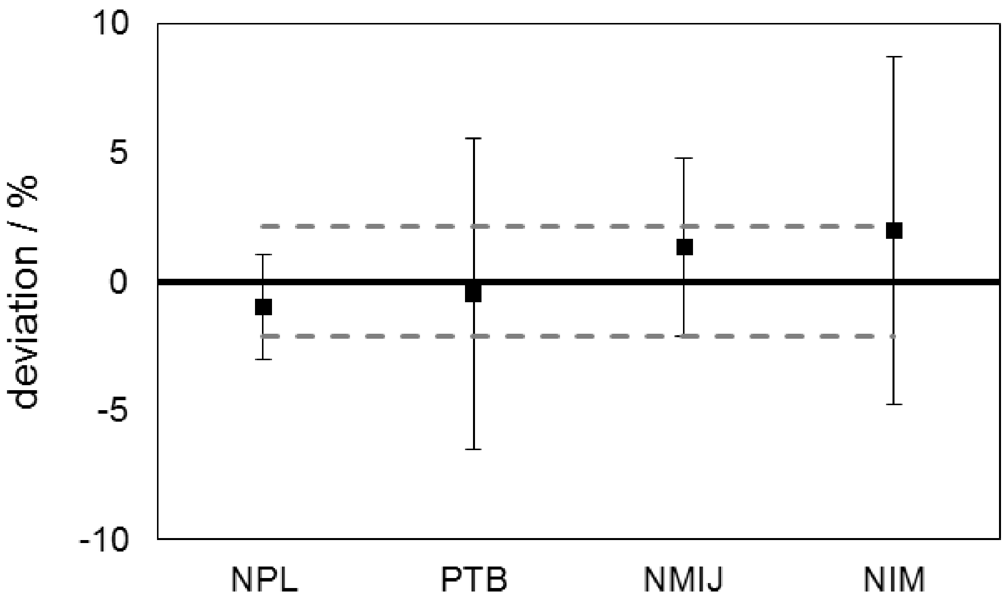

Figure 5.5: DoE results obtained at a frequency of 5 MHz for the hydrophone IP999. The KCRV is depicted by the bold horizontal line (zero-line) and the two horizontal broken lines represent the expanded relative uncertainty limits of the KCRV, $U_{KCRV}(\%)$ calculated using $k = 2$. The black squares along with their relative expanded uncertainties, $U(d_j)(\%)$ calculated using $k = 2$, depict the deviation in percent between each participant value and the KCRV.

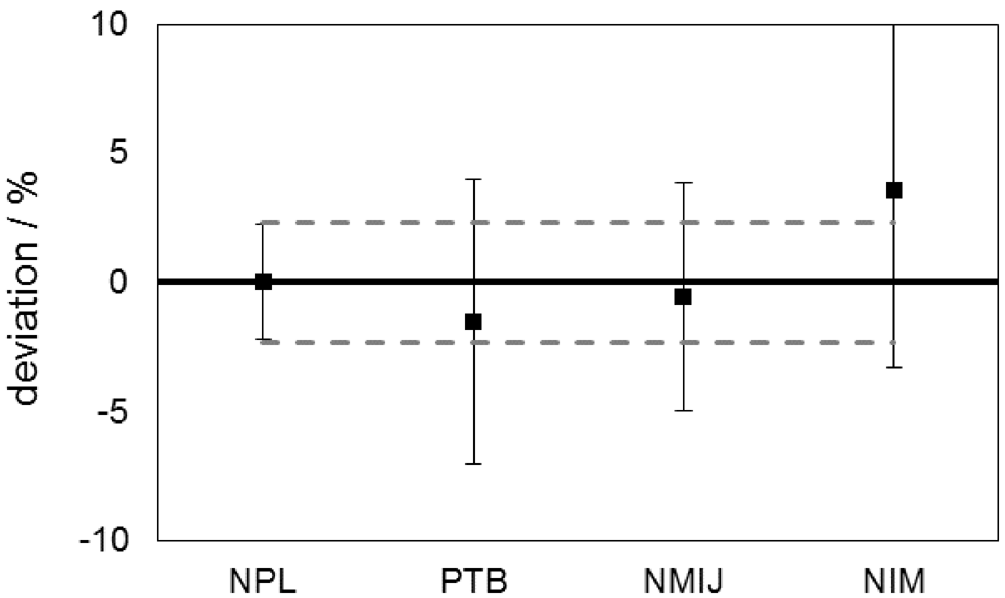

Figure 5.6: DoE results obtained at a frequency of 10 MHz for the hydrophone IP999. The KCRV is depicted by the bold horizontal line (zero-line) and the two horizontal broken lines represent the expanded relative uncertainty limits of the KCRV, $U_{KCRV}(\%)$ calculated using $k = 2$. The black squares along with their relative expanded uncertainties, $U(d_j)(\%)$ calculated using $k = 2$, depict the deviation in percent between each participant value and the KCRV.

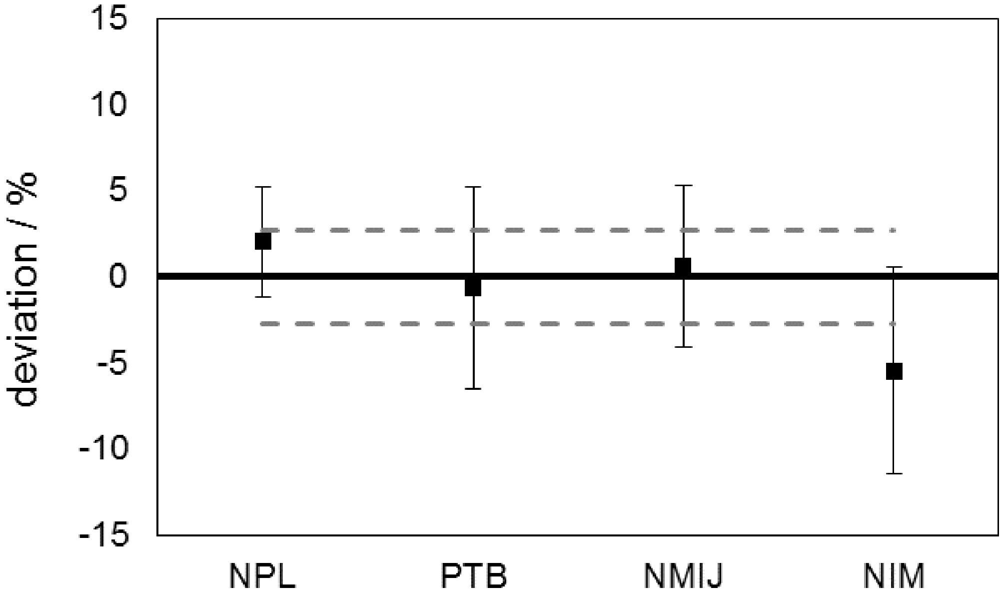

Figure 5.7: DoE results obtained at a frequency of 15 MHz for the hydrophone IP999. The KCRV is depicted by the bold horizontal line (zero-line) and the two horizontal broken lines represent the expanded relative uncertainty limits of the KCRV, $U_{KCRV}(\%)$ calculated using $k = 2$. The black squares along with their relative expanded uncertainties, $U(d_j)(\%)$ calculated using $k = 2$, depict the deviation in percent between each participant value and the KCRV.

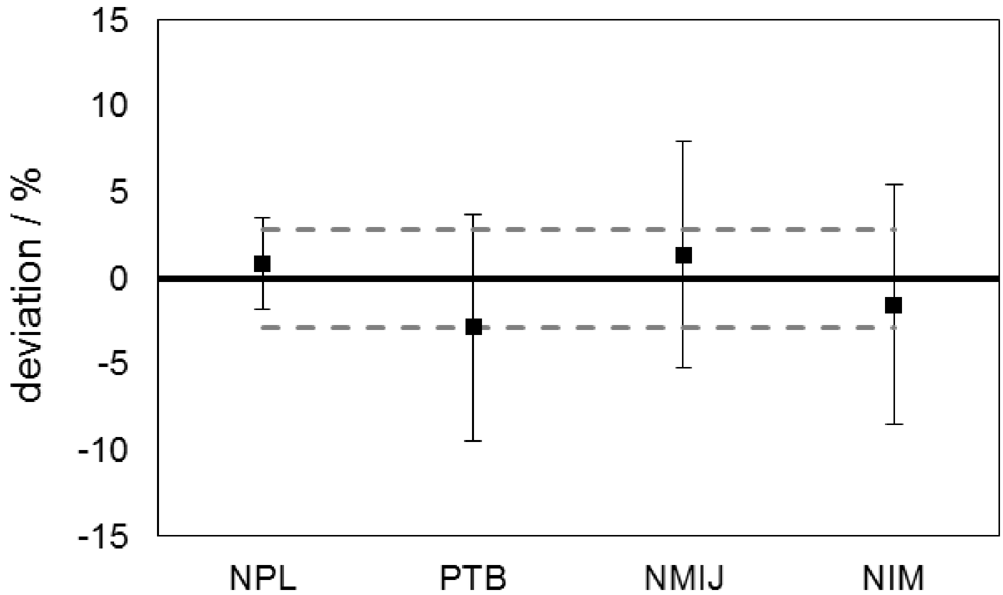

Figure 5.8: DoE results obtained at a frequency of 20 MHz for the hydrophone IP999. The KCRV is depicted by the bold horizontal line (zero-line) and the two horizontal broken lines represent the expanded relative uncertainty limits of the KCRV, $U_{KCRV}(\%)$ calculated using $k = 2$. The black squares along with their relative expanded uncertainties, $U(d_j)(\%)$ calculated using $k = 2$, depict the deviation in percent between each participant value and the KCRV.

5.5.2 DoE Graphs for Hydrophone ER070

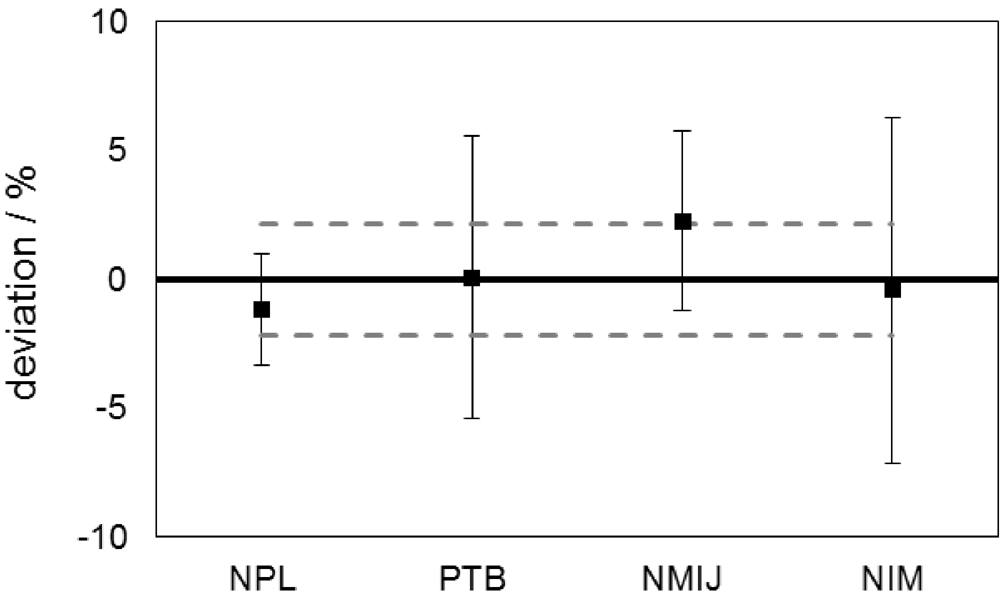

Figure 5.9: DoE results obtained at a frequency of 0.5 MHz for the hydrophone ER070. The KCRV is depicted by the bold horizontal line (zero-line) and the two horizontal broken lines represent the expanded relative uncertainty limits of the KCRV, $U_{KCRV}(\%)$ calculated using $k = 2$. The black squares along with their relative expanded uncertainties, $U(d_j)(\%)$ calculated using $k = 2$, depict the deviation in percent between each participant value and the KCRV.

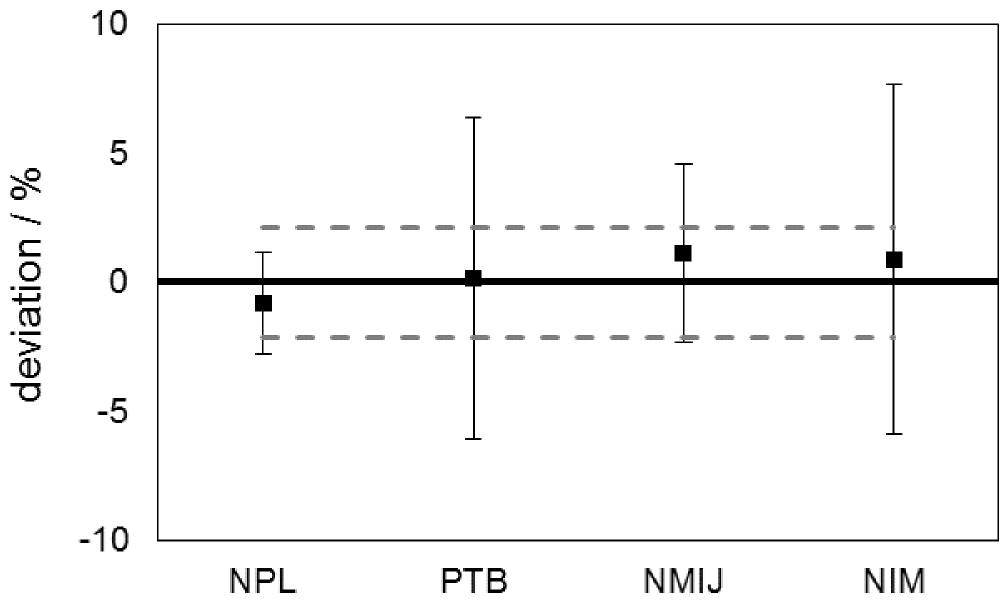

Figure 5.10: DoE results obtained at a frequency of 1 MHz for the hydrophone ER070. The KCRV is depicted by the bold horizontal line (zero-line) and the two horizontal broken lines represent the expanded relative uncertainty limits of the KCRV, $U_{KCRV}(\%)$ calculated using $k = 2$. The black squares along with their relative expanded uncertainties, $U(d_j)(\%)$ calculated using $k = 2$, depict the deviation in percent between each participant value and the KCRV.

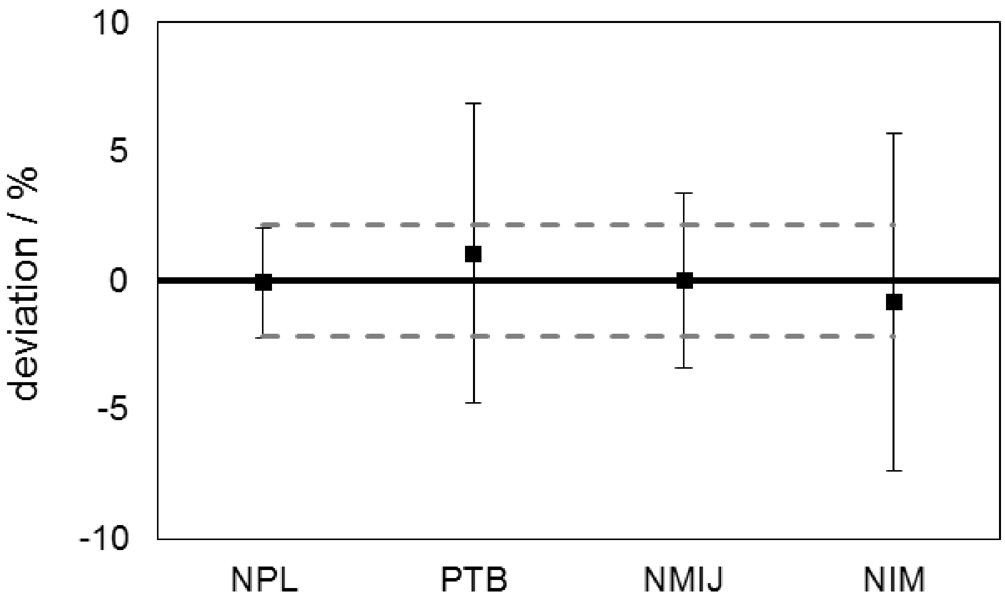

Figure 5.11: DoE results obtained at a frequency of 2.25 MHz for the hydrophone ER070. The KCRV is depicted by the bold horizontal line (zero-line) and the two horizontal broken lines represent the expanded relative uncertainty limits of the KCRV, $U_{KCRV}(\%)$ calculated using $k = 2$. The black squares along with their relative expanded uncertainties, $U(d_j)(\%)$ calculated using $k = 2$, depict the deviation in percent between each participant value and the KCRV.

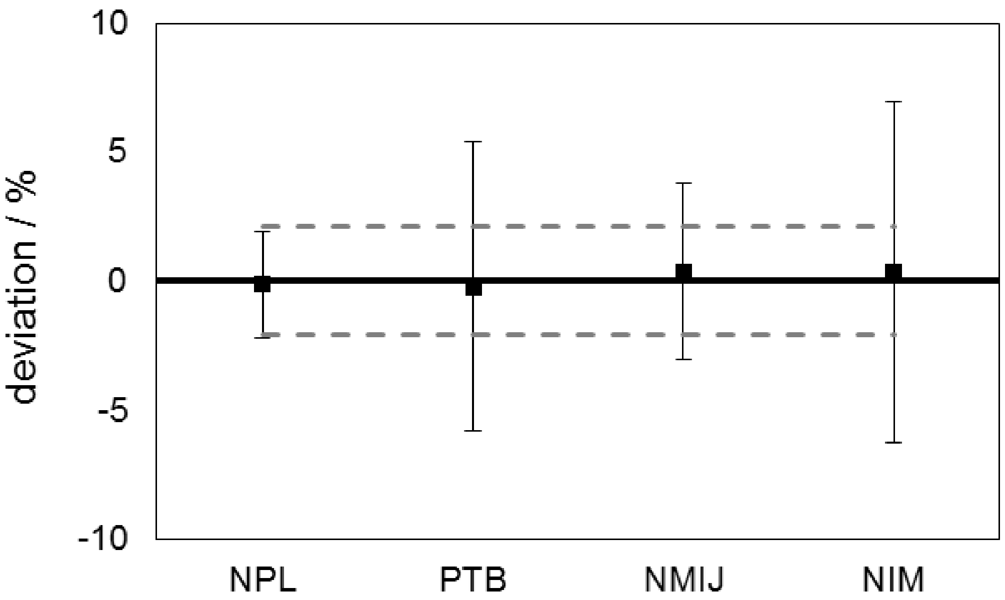

Figure 5.12: DoE results obtained at a frequency of 3.5 MHz for the hydrophone ER070. The KCRV is depicted by the bold horizontal line (zero-line) and the two horizontal broken lines represent the expanded relative uncertainty limits of the KCRV, $U_{KCRV}(\%)$ calculated using $k = 2$. The black squares along with their relative expanded uncertainties, $U(d_j)(\%)$ calculated using $k = 2$, depict the deviation in percent between each participant value and the KCRV.

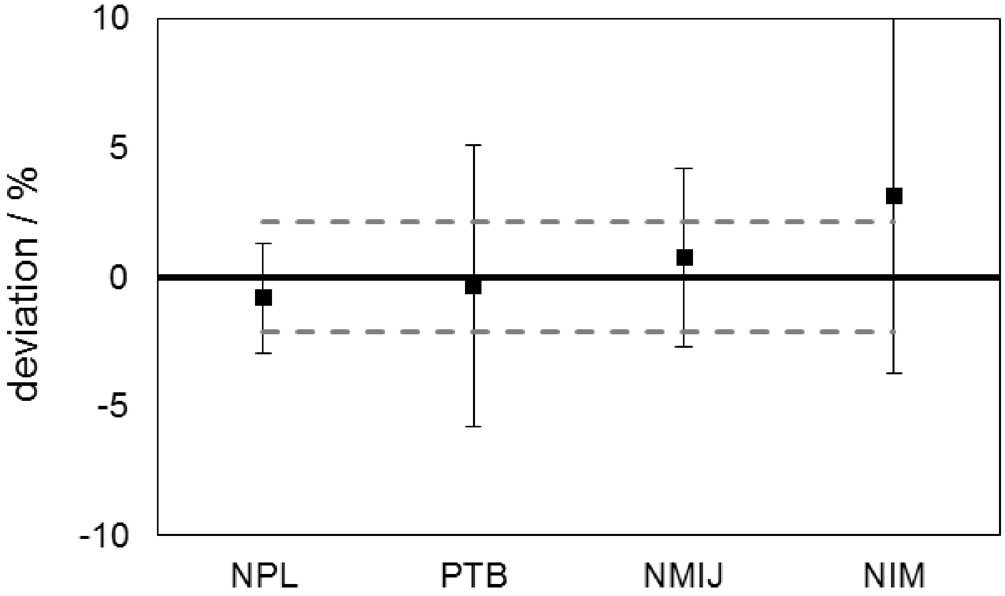

Figure 5.13: DoE results obtained at a frequency of 5 MHz for the hydrophone ER070. The KCRV is depicted by the bold horizontal line (zero-line) and the two horizontal broken lines represent the expanded relative uncertainty limits of the KCRV,$U_{KCRV}(\%)$ calculated using $k = 2$. The black squares along with their relative expanded uncertainties, $U(d_j)(\%)$ calculated using $k = 2$, depict the deviation in percent between each participant value and the KCRV.

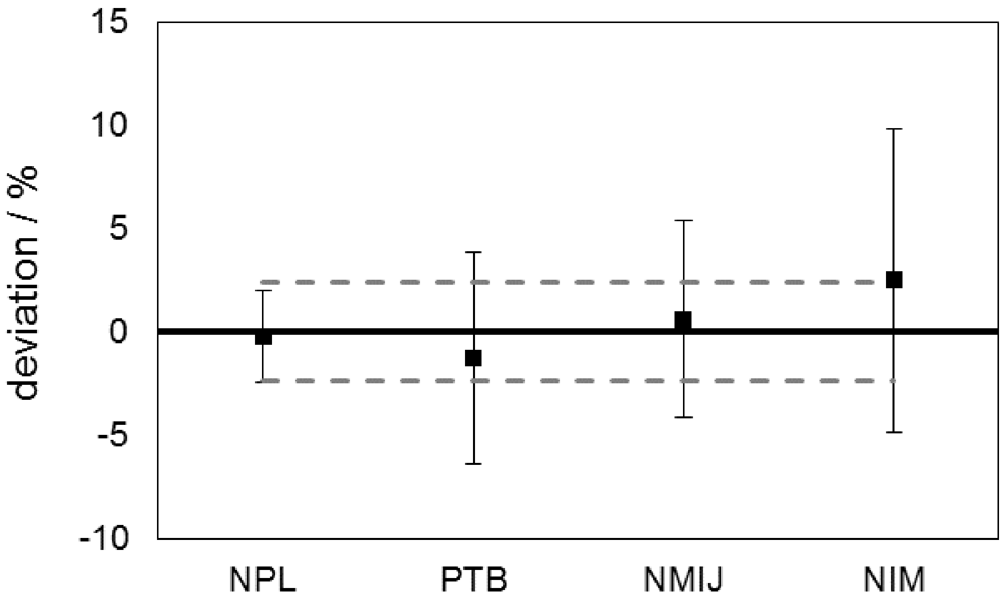

Figure 5.14: DoE results obtained at a frequency of 10 MHz for the hydrophone ER070. The KCRV is depicted by the bold horizontal line (zero-line) and the two horizontal broken lines represent the expanded relative uncertainty limits of the KCRV,$U_{KCRV}(\%)$ calculated using $k = 2$. The black squares along with their relative expanded uncertainties, $U(d_j)(\%)$ calculated using $k = 2$, depict the deviation in percent between each participant value and the KCRV.

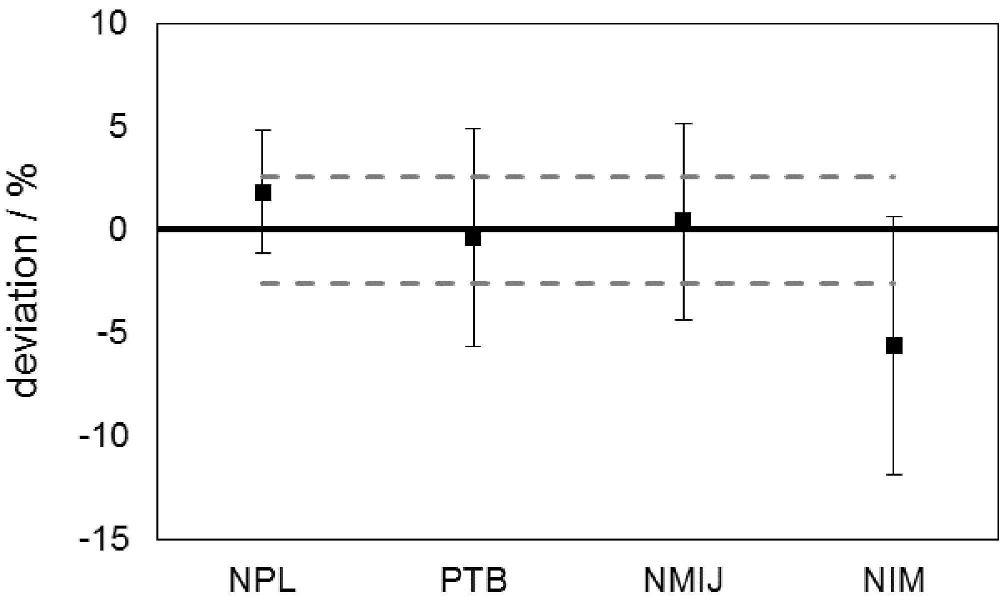

Figure 5.15: DoE results obtained at a frequency of 15 MHz for the hydrophone ER070. The KCRV is depicted by the bold horizontal line (zero-line) and the two horizontal broken lines represent the expanded relative uncertainty limits of the KCRV, $U_{KCRV}(\%)$ calculated using $k = 2$. The black squares along with their relative expanded uncertainties, $U(d_j)(\%)$ calculated using $k = 2$, depict the deviation in percent between each participant value and the KCRV.

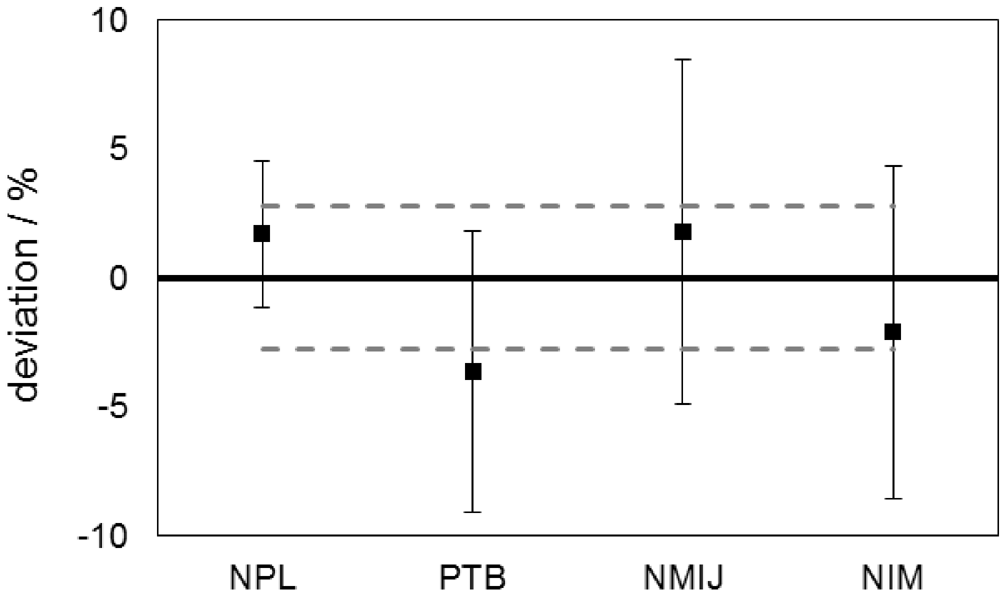

Figure 5.16: DoE results obtained at a frequency of 20 MHz for the hydrophone ER070. The KCRV is depicted by the bold horizontal line (zero-line) and the two horizontal broken lines represent the expanded relative uncertainty limits of the KCRV, $U_{KCRV}(\%)$ calculated using $k = 2$. The black squares along with their relative expanded uncertainties, $U(d_j)(\%)$ calculated using $k = 2$, depict the deviation in percent between each participant value and the KCRV.

5.5.3 DoE Graphs For INMETRO

DoEs for INMETRO are presented separately in figures 5.17 and 5.18 for the two key comparison hydrophones. The graphs below summarises the relative deviation expressed in percent between INMETRO and the KCRV which is depicted as a bold horizontal line (zero-line) covering the frequency range relevant to INMETRO. The error bars on the KCRV represent the relative expanded uncertainty limits of the KCRV,$U_{KCRV}(\%)$ calculated with $k = 2$ at each frequency. The relative expanded uncertainties of the % deviation with $k = 2$, $U(d_{INMETRO})(\%)$ was calculated using equations (6), (9) and (11) since there exists no correlation between $x_{INMETRO}$ and x_{KCRV}.

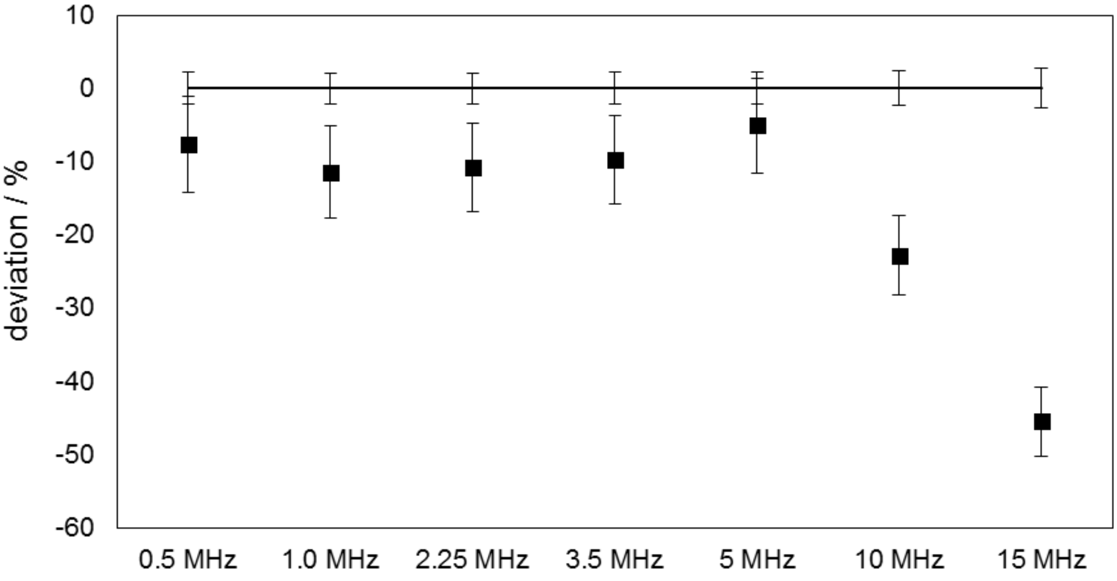

Figure 5.17: DoE results between INMETRO and the KCRV for the hydrophone IP999.

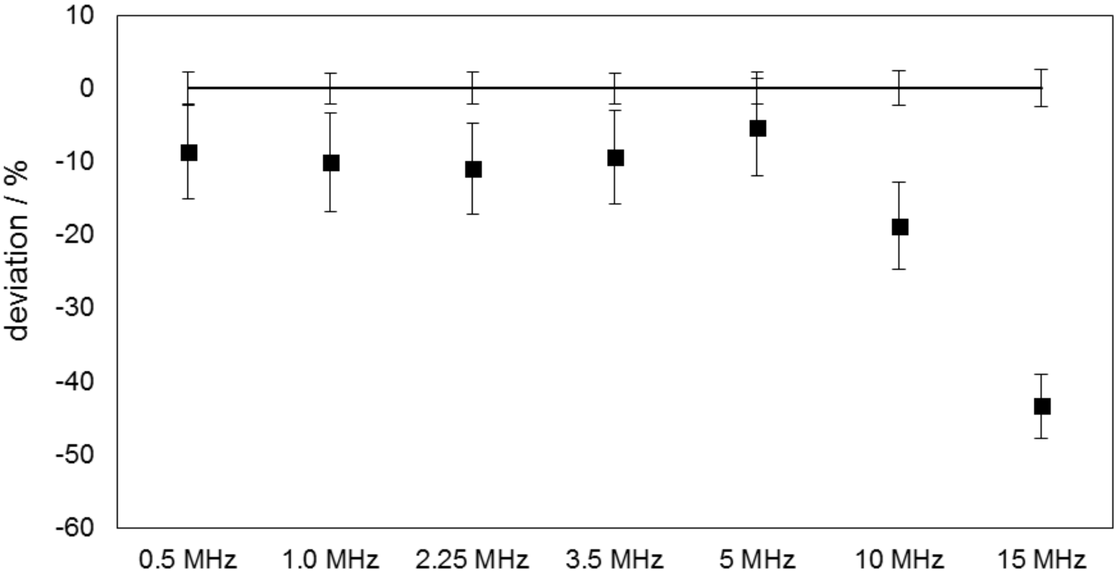

Figure 5.18: DoE results between INMETRO and the KCRV for the hydrophone ER070.

6 SUMMARY

A number of points may be made summarising the findings of the completed key comparison CCAUV.U-K4:

- NMIs involved in this key comparison cover a wide spread of continents, with NPL (UK), PTB (Germany), NIM (China), NMIJ (Japan) and INMETRO (Brazil);

- The two hydrophones were found to be stable during the course of the key comparison. This was determined via stability checks carried out using a secondary comparison method each time the hydrophone was returned to NPL before and after a participant measurement. The systematics were virtually identical each time the stability measurements were carried out with the exception of the temperature of the water which ranged from 18.9 ^{O}C – 21.2 ^{O}C;

- The mean value of participant reported water temperature at which the two hydrophones were calibrated was 20.3 ^{O}C with a standard deviation of 0.8 ^{O}C and a range of 2.9 ^{O}C. No temperature dependent sensitivity corrections were applied to the participants' data for the two hydrophones when deriving KCRV;

- The KCRV values at the eight frequencies of interest have been calculated using the weighted mean approach;

- The INMETRO dataset was found to be discrepant;

- The final KCRVs were calculated using only four participants, NPL, PTB, NIM and NMIJ.

7 REFERENCES

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8 ACKNOWLEDGMENTS

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APPENDIX A: KEY COMPARISON PROTOCOL DOCUMENT CCAUV.U-K4.

COMPARISON OF ULTRASONIC HYDROPHONE CALIBRATIONS

IN THE FREQUENCY RANGE 0.5 MHz to 20 MHz

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TECHNICAL PROTOCOL DOCUMENT COVERING THE BIPM/CIPM Key Comparison

CCAUV.U-K4 (hydrophone free-field open-circuit sensitivity in the megahertz frequency range).

COMPARISON OF ULTRASONIC HYDROPHONE CALIBRATIONS

IN THE FREQUENCY RANGE 0.5 MHz TO 20 MHz

1 INTRODUCTION

1.1 Purpose of the document

This document describes the procedure to be used during the BIPM/CIPM Key Comparison CCAUV.U-K4. This comparison covers the calibration of ultrasonic hydrophones used within the megahertz frequency range i.e. 0.5 MHz to 20 MHz, and in particular the determination of their free-field open-circuit sensitivity.

This is a repetition of the Key Comparison CCAUV.U-K2 "Comparison of 1 mm hydrophone calibrations in the frequency range 1 to 15 MHz" (1999 – 2003), but whose scope has been extended upwards to 20 MHz and downwards to 0.5 MHz. A report of the previous Key Comparison is available on the BIPM web-site under report number NPL Report DQL-AC (RES) 013 (2005). The reduction in the lower frequency for CCAUV.U-K4 ensures that it will overlap with the Underwater Acoustics Key Comparison CCAUV.W-K1 which covers the range 1 kHz to 0.5 MHz.

1.2 Organisation of key comparison

The co-ordinating institute (Pilot Laboratory) is the United Kingdom National Physical Laboratory (NPL). As well as organising the key comparison, NPL will perform reference calibrations of the hydrophones prior to and after the completion of the comparison. NPL will also be responsible for collating the reports received from the Participating Laboratories and generating the final Key Comparison Report. Additionally, it will undertake spot-checks on the devices during their return from participating institutes to ensure their stability. Four other institutes (Participating Laboratories) whose contact details may be found in Annex A have agreed to take part in the comparison and these are:

PTB (Germany)

NMIJ/AIST (Japan)

NIM (China)

INMETRO (Brazil).

1.3 Schedule of calibrations

The Key Comparison has been organised as a "star" comparison, with the two hydrophones being returned to the Pilot Laboratory to enable stability checks to be completed. The time-table is shown below.

No.	Name of institute	Starting date	Finishing date
1	NPL, UK	15th Mar, 2014	31st May, 2014
2	PTB	16th June, 2014	15th Aug, 2014
3	NPL, UK (spot-check measurements)	16th August, 2014	31st August, 2014
4	NMIJ	1st Sep, 2014	31st Oct, 2014
5	NPL, UK (spot-check measurements)	1st Nov, 2014	15th Nov, 2014
6	NIM	16th Nov, 2014	31st Jan 2015,
7	NPL, UK (spot-check measurements)	1st Feb, 2015	15th Feb, 2015
8	INMETRO	16th Feb, 2015	15th April, 2015
9	NPL, UK	16th April, 2015	15th July, 2015

1.4 Hydrophone details

The type of hydrophone to be used within the comparison is a polyvinylidene fluoride (*pvdf*) membrane hydrophone of the bilaminar design manufactured by Marconi Technology Centre. Two hydrophones will be circulated to each of the Participants Laboratories for calibration. Their active element diameters of 1 mm have been chosen to provide sufficient sensitivity for them to be calibrated using absolute methods. Figure 1 represents a photograph of such a hydrophone. If required, NPL can provide participants with a similar membrane hydrophone prior to their calibrations, in order that appropriate mounts may be designed and experience in their use gained. Other hydrophones will be kept at NPL and recalibrated periodically to check the stability of the reference measurement facility at NPL. Additional devices will be held in reserve in case the main hydrophones are damaged.

1.5 Hydrophone pre-amplifier details

In calibrating a hydrophone it is often necessary to use a preamplifier which has a low input capacitance (less than 10 pF) as this reduces the effect of electrical loading on the hydrophone. A suitable amplifier [1] will be circulated with the hydrophones which the participants may use if they wish. The amplifier operates from voltages of 0 and $\pm$ 15 V which is to be supplied by the user. The input impedance of the amplifier has been measured at NPL and is approximately equivalent to 6 pF in parallel with 50 kΩ. Correction factors are given in Table 1 which will permit the measured sensitivities to be corrected to open-circuit values. The gain of the amplifier should be measured by the participant at each calibration frequency and should be reported along with the other calibration results.

1.6 Parameter to be reported – the Measurand

The sensitivity of the hydrophone which must be reported is the end-of-cable open-circuit sensitivity [2]. This is defined as the ratio of the instantaneous open-circuit voltage at the end of any integral cable or output connector of a hydrophone to the instantaneous acoustic pressure in the undisturbed free field of a plane wave in the position of the reference centre of the hydrophone if the hydrophone were removed [2].

The sensitivity should be measured for each of the two hydrophones at frequencies of 0.5, 1, 2.25, 3.5, 5, 10, 15 and 20 MHz. The measurement temperature should be specified by all participants, with NPL correcting the results to 20 °C. Purely for information purposes, the temperature variations in sensitivity of this type of hydrophone at various frequencies varies within the range -0.05 and +0.2 % $°C^{-1}$.

1.7 Transportation

Participating Laboratories are responsible for transporting the hydrophones back to the Pilot Laboratory. It is preferable that the hydrophones are hand-carried and transported in the passenger cabin. If this is not possible the hydrophones must be transported back to NPL by air freight using temperature controlled pressurised cargo hold.

The two hydrophones and preamplifier will be packaged in a transit case and accompanied by an ATA carnet. Participating institutes shall comply with customs regulations. When the package is transported back to NPL unaccompanied, the carnet must be included with other forwarding documents so that the handling agent can obtain customs clearance. In no case should the carnet be packed within the package.

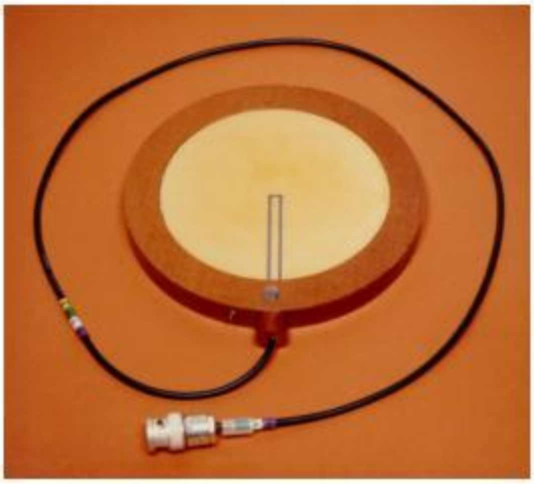

Figure 1: Photograph of a Marconi bilaminar membrane hydrophone of the type which will be used within the key comparison. The outside diameter of the supporting ring is 130 mm.

2 PRACTICAL NOTES

2.1 Receipt of hydrophones

The Participating Laboratory shall inform the Pilot Laboratory of the arrival of the hydrophones unless the pilot institute was involved in transporting the hydrophones in-person. After receipt the participating institute shall immediately check the hydrophones for any damage and ensure they are working correctly.

2.2 Care of the hydrophones

The hydrophones should not be subject to temperatures outside the range 0 – 40 °C or exposed to continuous bright sunlight. They should not be driven electrically as this could cause damage: however, if it is necessary to measure the electrical impedance, the voltage used should be less than 0.5 V (*rms*). The impedances have been measured at NPL (see Table 2) so it should not be necessary for the participants to do this.

2.3 Condition of water for calibrations

The conductivity of the water used in the calibrations should be noted during the measurements and should ideally be below 5 μS (resistivity greater than 0.5 MΩ cm). The water should have been degassed prior to use, as this eliminates the possibility of air bubbles forming on the hydrophone and reduces the probability of cavitation occurring. After about 7 hours in a test tank, degassed water becomes saturated with air again, but at NPL it has not been found necessary to repeat the degassing process each day. As an extra precaution against bubble formation, it is advisable to soak the hydrophone in freshly degassed water for at least 30 minutes before use.

For membrane hydrophones, it is possible for large air bubbles to become entrapped under the supporting ring. Such bubbles should be removed carefully using a small soft brush. The membrane hydrophones are supplied with an earthing pin which should be connected to a metallic object in the tank, such as the hydrophone mount. The conductivity and oxygen content of the water should be measured during the calibrations and recorded on the reporting sheet (Table 3).

The temperature of the water should be measured (preferably to an accuracy of ± 0.1 °C) throughout the calibration.

2.4 Guidelines on the use of hydrophones

2.4.1 Alignment

The definition of hydrophone sensitivity given in Section 1.5 is incomplete, because it does not define the orientation of the hydrophone with respect to the incoming wave. To find this direction, the hydrophone should be placed with its active element (the side where the membrane is almost flush with the ring) pointing towards the transducer and roughly perpendicular to the incoming wave, and then it should be rotated in two directions about its active element until the maximum received signal is obtained. To obtain this maximum it should only be necessary to rotate the hydrophone by a few degrees.

2.4.2 Spatial-averaging

If it is necessary to make corrections for spatial-averaging at the hydrophone element it should be noted that the effective radius of a membrane hydrophone can be significantly different from its geometrical radius, particularly at frequencies below 2 MHz and below, where the effective radius can be much larger than expected. The frequency dependent radii of the two membrane hydrophones are given in Table 3.

3 EXPERIMENTAL PROCEDURE

3.1 Perform calibrations, taking particular note of the water temperature and calibration frequency. If any problems arise that may delay the measurements please contact NPL immediately to arrange a revised completion date.

3.2 At each frequency perform at least 4 independent calibrations of each hydrophone, preferably on different days and with the hydrophone removed from the tank between measurements. Report each set of results on one of the sheets provided (see Table 4).

3.3 Calculate the mean of the measurements and the Type A (random) standard uncertainty.

3.4 Report the final result on the summary sheet (Table 5), along with the estimated Type B (systematic) standard uncertainty and the expanded (overall) uncertainty at each frequency. The expanded uncertainty should be obtained by combining Type A and Type B uncertainties according to the procedure given in reference [3].

3.5 Provide a full written description of the calibration method, detailing the information required in Annex B and in particular noting any special problems encountered during the measurements.

3.6 Having previously made appropriate arrangements with NPL, return the hydrophones and results to NPL, preferably by a member of the participating institute's staff. Failing this, they should be transported back to NPL by air freight using temperature controlled pressurised cargo hold.

4 REPORTING

4.1 After the Participating Laboratories have completed their measurements, they must draft a report describing their measurements using the Guidelines contained within Annex B of this technical Protocol. This should be submitted to the Pilot Laboratory no later than **one month** after the completion of the measurements of the Participating Laboratory.

4.2 The Pilot Laboratory will complete the Key Comparison Draft A Report following the Guidance provided in the document "Guidance for carrying out key comparisons with the CCAUV", generated by the CCAUV Key Comparison Working Group (www.bipm.org/utils/en/pdf/CCAUV-GoC). This will be submitted to the Participant Laboratories for comment by the Pilot Laboratory no later than **three months** after the final checks on the hydrophones have been completed at the Pilot Laboratory.

5 UNCERTAINTIES

CIPM guidelines require participating institutes submit their complete uncertainty budget in advance of participation. An uncertainty budget must therefore be submitted by each Participating Laboratory to the Pilot Laboratory prior to the commencement of their measurements. Changes in this declared uncertainty budget, subsequent to the Laboratory completing measurements, are acceptable, providing the reasons for the change in expanded uncertainty and/ or any specific uncertainty components is explained in detail.

The uncertainty budget must include the principal components of uncertainty contributions at each frequency, and all necessary information justifying how these were derived [3]. In addition to these principal components of the uncertainty, common to all of the participants, individual institutes may add any others they consider appropriate, again sufficient explanatory background information.

6 REFERENCES

[1] PRESTON, R.C., BACON, D.H., LIVETT, A.J. and RAJENDRAN, K., 1983. PVDF membrane hydrophone performance properties and their relevance to the measurement of the acoustic output of medical ultrasonic equipment. *J. Phys. E: Sci. Instrum.*, 16, pp.786-796.

[2] INTERNATIONAL ELECTROTECHNICAL COMMISSION, 2013. IEC 62127-2 ed1.1 Consol. with am1: Ultrasonics - Hydrophones - Part 2: Calibration for ultrasonic fields up to 40 MHz. Geneva: IEC.

[3] BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML, JCGM 100:2008, *Evaluation of measurement data-Guide to the Expression of Uncertainty in Measurement*. Joint Committee for Guides in Metrology, First Edition, September 2008.

Table 1: Open-circuit correction factors for the hydrophones utilised within this comparison, when used with the NPL preamplifier serial number 5564166LF. The measured sensitivity should be multiplied by the numbers given below.

Hydrophone serial number	Frequency (MHz)							
	0.5	1	2.25	3.5	5	10	15	20
ER070	1.0519	1.0545	1.0584	1.0603	1.0620	1.0641	1.0627	1.0578
IP999	1.0722	1.0748	1.0787	1.0805	1.0823	1.0854	1.0858	1.0835

Table 2: Impedance of hydrophones in Ω.

Hydrophone serial number		Frequency (MHz)							
		0.5	1	2.25	3.5	5	10	15	20
ER070	Real	292.54	175.85	89.29	59.96	43.15	23.27	17.04	14.39
	Imaginary	-2554.70	-1351.04	-644.67	-429.63	-307.75	-155.22	-98.19	-66.18
IP999	Real	299.89	175.87	86.78	57.77	41.50	22.79	16.97	14.43
	Imaginary	-3559.52	-1855.93	-868.45	-573.03	-407.92	-206.18	-133.82	-94.96

Table 3: Effective radius of hydrophones in mm (from IEC standard 62127-3-am1. Ed1.0; Ultrasonics - Hydrophones - Part 3: Properties of hydrophones for ultrasonic fields up to 40 MHz, Geneva, IEC).

Hydrophone serial number	Frequency (MHz)							
	0.5	1	2.25	3.5	5	10	15	20
ER070	0.98	0.74	0.62	0.57	0.55	0.54	0.54	0.54
IP999	0.98	0.75	0.60	0.55	0.53	0.52	0.52	0.52

Table 4: Calibration report Sheet.

Participating Laboratory:		**Calibration method:**		
Date(s) of calibrations:		**Hydrophone serial number:**		
Nominal frequency (MHz):				
Measurement Number	**1**	**2**	**3**	**4**
Actual frequency (MHz)				
Temperature, T (°C)				
Open-circuit correction				
Water conductivity (μS)				
Oxygen content (mg l^{-1}), or alternative (ppm or % saturation)				
Amplifier gain (dB)				
Measured sensitivity (nV/Pa)				
Open-circuit sensitivity at T °C (nV/Pa)				
Notes (e.g. of any unusual difficulties)				

Table 5: Summary sheet.

<table>
<tr><td colspan="3">Participating Laboratory:</td><td colspan="6">Method:</td></tr>
<tr><td>Dates:</td><td colspan="8">Hydrophone Serial Number:</td></tr>
<tr><td>Nominal frequency (MHz)</td><td>0.5</td><td>1</td><td>2.25</td><td>3.5</td><td>5</td><td>10</td><td>15</td><td>20</td></tr>
<tr><td>Actual frequency (MHz)</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Mean open-circuit sensitivity at T °C (nV/Pa)</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Type A (random) standard uncertainty (%)</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Type B (systematic) standard uncertainty (%)</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Coverage factor (k)</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Expanded uncertainty (%)</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

Annex A: Addresses and contact details

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Annex B: Contents of the final calibration report.

The following provides a checklist of the information required for the final report supplied to NPL which describes the hydrophone calibrations carried out by the participants.

1. How was the water prepared for the calibration?
2. Was the hydrophone soaked in degassed water before use, and for how long?
3. Was the NPL preamplifier used? If not, describe how the open-circuit correction was obtained.
4. Was it necessary to determine the gain of the preamplifier? If so, describe the method, and estimate its accuracy.
5. What type of tank was used (give the size and material used in construction) and how were any earth or shielding connections made?
6. How were any corrections for spatial-averaging obtained?
7. What acoustic pressure was used at each frequency of calibration?
8. What propagation distance(s) was (were) used at each calibration frequency?

Describe the calibration method used, including any special features and any difficulties that were encountered during the measurements.

APPENDIX B: REPORT SUBMITTED BY THE NATIONAL PHYSICAL LABORATORY, UNITED KINGDOM.

Appendix B includes measurements undertaken at the start of the key comparison.

NPL
National Physical Laboratory

NPL REPORT AC 10

Primary Calibration of 1 mm Membrane Hydrophones for BIPM/CIPM Key Comparison CCAUV.U-K4

Srinath Rajagopal
Bajram Zeqiri

APRIL 2014

National
Measurement
System

Primary Calibration of 1 mm Membrane Hydrophones for BIPM/CIPM Key Comparison CCAUV.U-K4

Srinath Rajagopal
Bajram Zeqiri

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".

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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.

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 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:

$$M_H = \frac{V_H V_O}{V_I}\frac{2\mu}{\rho c f \lambda} \tag{2}$$

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.

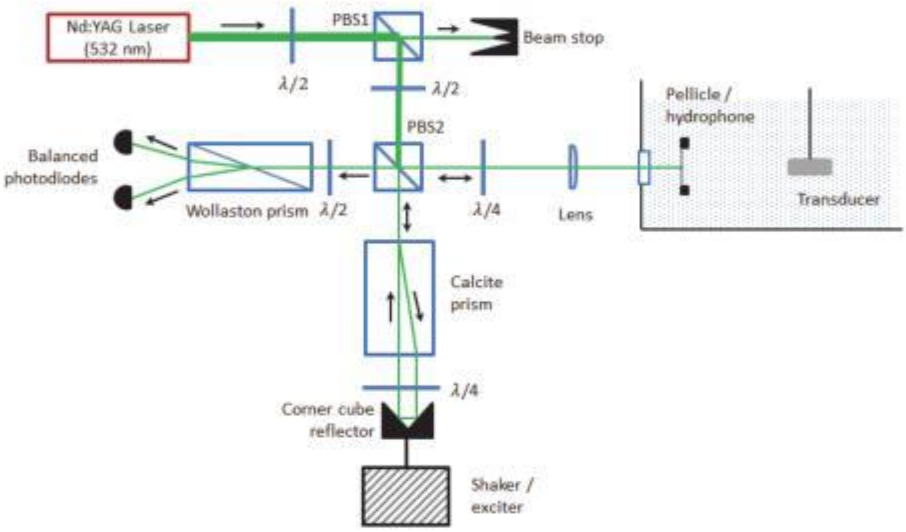

Figure 1: Schematic diagram of the NPL laser Michelson interferometer used for absolute displacement measurements at ultrasonic frequencies.

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 which 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 $\varnothing$ 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 role-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 °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 °C ± 0.4 °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: Propagation parameters for calibration and displacement measured by interferometer

Source transducer details				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

The individual calibrations of ER070 and IP999 at each frequency are listed in Tables 2 to 9 and Tables 11 to 18 respectively. Tables 10 and 19 present a summary of Open-circuit sensitivity and uncertainty at each frequency for ER070 and IP999.

3.1 ER070

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}), or alternative (ppm or % saturation)	< 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), or alternative (ppm or % saturation)	< 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

Participating Laboratory: NPL		**Calibration method:** Optical Interferometry						
Date(s) of calibrations: 7 February 2014		**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)	19.6	19.6	19.6	19.6	19.6	19.6	-	-
Water conductivity (µS)	< 4 µS							
Oxygen content (mg l^{-1}), or alternative (ppm or % saturation)	< 10 mg l^{-1}							
Open-circuit sensitivity at T °C (nV/Pa)	133.48	133.25	129.99	129.85	130.23	132.32	-	-
Notes (e.g. of any unusual difficulties)								

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}), or alternative (ppm or % saturation)	< 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}), or alternative (ppm or % saturation)	< 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}), or alternative (ppm or % saturation)	< 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), or alternative (ppm or % saturation)	< 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

Participating Laboratory: **NPL**	**Calibration method:** **Optical Interferometry**							
Date(s) of calibrations: **25 February 2014**	**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)	19.2	19.2	19.2	19.2	19.2	-	-	-
Water conductivity (µS)	< 2 µS							
Oxygen content (mg l^{-1}), or alternative (ppm or % saturation)	< 10 mg l^{-1}							
Open-circuit sensitivity at T °C (nV/Pa)	232.89	236.50	234.55	231.97	230.32	-	-	-
Notes (e.g. of any unusual difficulties)								

Table 10: 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

3.2 IP999

Table 11: 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), or alternative (ppm or % saturation)	< 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)								

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Table 12: 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}), or alternative (ppm or % saturation)	< 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)								

17

Table 13: 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}), or alternative (ppm or % saturation)	< 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 14: 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), or alternative (ppm or % saturation)	< 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 15: 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}), or alternative (ppm or % saturation)	< 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)								

20

Table 16: 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}), or alternative (ppm or % saturation)	< 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)								

21

Table 17: 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), or alternative (ppm or % saturation)	< 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 18: 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}), or alternative (ppm or % saturation)	< 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)								

23

Table 19: 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

4 UNCERTAINTIES

The type 'A' random and type 'B' systematic uncertainty contributions for each hydrophone are presented in Tables 10 and 19. 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 20 to 22 provide a breakdown of type 'B' uncertainty contributions with respect to frequency.

Table 20: 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 21: 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 22: 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**

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APPENDIX C: REPORT SUBMITTED BY THE PHYSIKALISCH-TECHNISCHE BUNDESANSTALT, GERMANY.

Physikalisch-Technische Bundesanstalt
Braunschweig und Berlin

Report

COMPARISON OF ULTRASONIC HYDROPHONE CALIBRATIONS IN THE FREQUENCY RANGE 0.5 MHz to 20 MHz

M. Brandt, V. Wilkens, C. Koch

Abstract: This report contains all documentation of the calibration measurements carried out in the Sound department of Physikalisch-Technische Bundesanstalt on the occasion of the CIPM/BIPM key comparison CCAUV.U-K4. Two membrane hydrophones with a nominal active diameter of 1 mm were circulated during this comparison and they were measured by interferometry. A description of the method, the final results, and uncertainties are reported in detail.

Contents

1 Introduction

This report summarises the calibration activities carried out in the Sound Department of PTB during measurements of the CIPM/BIPM key comparison CCAUV.U-K4. Two membrane hydrophones with an active spot diameter of 1 mm had to be primarily calibrated for comparison with three other laboratories.

All measurements rely on an interferometric calibration technique. It relates the acoustic displacement in a sound field directly to the well-known optical wavelength of a He-Ne laser. Pressure values are obtained using time differentiation and the method ensures a primary calibration and yields the open-loop sensitivity of the hydrophones.

This report is organised as follows: This introduction is followed by a section describing the calibration method and details of the set-up. A sub-section contains a detailed description of uncertainties. Appendix A summaries all measurement data and appendix B contains detailed uncertainty budgets.

2 Calibration Method

The interferometric calibration procedure is still based on a method and experimental realisation described in [Koch 99]. Although the principle of measurement has not been changed many technical details have been adapted to new requirements and quality management criteria. For the sake of completeness, a brief description of the method is given in the following.

Calibration is based on an interferometric, i. e. an optical technique. It relates the acoustic displacement in a sound field directly to the well-known optical wavelength of a He-Ne laser, thus ensuring a primary calibration.

The sound field generated by a transducer is measured by an interferometer which detects the displacement of a pellicle mounted on the surface of the tank fluid. The ultrasonic wave is incident from the bottom, whereas the laser beam comes from the air-backed side and is not disturbed by the sound. In a second step the interferometric part is removed and the hydrophone is inserted into the tank. After addition of some water the hydrophone spot is adjusted to exactly the previous position of pellicle and laser beam. The measurement is repeated under equivalent conditions and the hydrophone voltage obtained is used for the determination of the sensitivity.

The sound field was generated by two different transducers depending on the frequency range addressed. The tone bursts used to excite the transducer were generated by an arbitrary waveform generator Tektronix AFG3251 and amplified by an rf power amplifier ENI 350L. A purpose made impedance matching network adapts the transducer impedance to the amplifier output. The settings of the network parameters are specific for the particular transducer and for every frequency setting. They are stored in the control software. Different working distances have been used depending on the transducer and frequency range. They were 5 cm and 10 cm.

To calculate the necessary spatial averaging correction factor F_{sp}, a model using the Rayleigh integral was implemented using software developed in the laboratory. For the focusing transducer the model of O'Neil [O'Neil 49] was used. The calculation for the plane transducer is based on Schoch's notation [Schoch 41]. The numerical model provides the complex-valued sound pressure in any plane of the fields, and integration over the active area of the detector normalised to the peak pressure yields the spatial averaging correction factor. To include the non-ideal behaviour of the transducers, an effective transducer diameter and, in case of focusing transducers, an effective focal length [Adach 90] were determined by fitting the calculated on-axis pressure and two lateral pressure distributions to three-dimensional sound field measurements for every transducer in separated measurements. These fitting processes were carried out at different frequencies (0.5, 1, 3, 5, 10, 15, 20 MHz) and on each (lateral) side of the field separately. The difference in effective parameters is used for an estimation of asymmetry of the sound field and a model calculation yields an uncertainty contribution for this effect.

An important point of the calibration procedure is the determination of the photodetector frequency response. It was determined using a method described in [Koch 10]. For the low frequency part down to 0.5 MHz an additional check measurement using a modulated high-speed LED was made.

During the measurements the NPL-amplifier No. 5564166LF was used and the open-circuit correction was carried out by multiplying the loaded sensitivity by the factors given in table 1 of the protocol document. These factors were interpreted to be the impedance quotient of Eq. (3) in [Koch 99].

3 Measurements

3.1 Preparation of measurement

The tank used consisted of PMMA and had an inner diameter of 19 cm. The tank was filled with water deionised using equipment commonly used for the preparation of distilled water. The conductivity was below 1.7 µS/cm. After manual insertion of the hydrophone, it increased to typically 2.6 µS/cm because it was not possible to avoid contact between hand and water. The filling height depended on the distance between transducer and pellicle (see below). For the hydrophone part some water was added.

The water was degassed by a vacuum technique. It spouted into an evacuated vessel and stayed there under vacuum for days. The tank was filled immediately before the measurement and emptied completely afterwards.

Prior to use, the hydrophones were soaked for half an hour in degassed water. After the measurement cycle had been finished they were immediately removed from the tank and stored in air in a container.

3.2 Performance of measurement

One measurement cycle was carried out per day. One cycle covered the determination of one value of the displacement or of the hydrophone voltage in either the interferometric or the hydrophone measurement part at every frequency point. This procedure ensured independent measurements of all quantities.

The sound field used during the calibration process was generated by two different transducers: Karl Deutsch GmbH TS12PB (nominal radius: 6.0 mm; nominal focal length: 50 mm) and Karl Deutsch GmbH STS6WB (nominal radius: 3.0 mm; not focusing)

Typical values of sound pressure and propagation distances are given in Table 1.

Frequency	Sound pressure in kPa	Propagation distance in mm
1	1.6	100
2	6.4	100
5	39.4	100
10	147.0	100
15	281.0	100

Table 1: Typical values of sound pressure amplitude and propagation distances during interferometric calibration

The NPL amplifier was used during the hydrophone measurement part. The gain of the amplifier was determined with the aid of a signal generator HP ESG 1000A and a digital scope Tektronix TDS 3032B. At first the output signal of the generator was directly led into the scope input via a 50 Ω resistor to measure its voltage. After that the signal was fed into the amplifier via a 50 Ω resistor and its output voltage was measured by the scope via a 50 Ω resistor.

3.3 Results

The sensitivity was determined according to Eqs. (2) and (3) in [Koch 99]. Four independent measurements were documented using the protocol sheets of NPL. The data have been summarised in Appendix A.

4 Uncertainties

The calibration is affected by several uncertainties. In the following their estimation is described in detail. The data for every frequency point are given in Appendix B.

4.1 Standard uncertainty of type B (systematic)

The contributions to the standard uncertainty are described in the following:

a) Signal-to-noise-ratio
The signal-to-noise-ratio of the measurement and the corresponding uncertainties δU_I and δU_U of the voltages U_I and U_H are determined from signal and noise measurements using FFT spectra. The signal amplitude is determined from regular measurements and the values U_I^2 and U_H^2 at the frequency f_{fund} are calculated. The noise spectral density is determined from separately acquired data evaluating small frequency ranges around *f*. The statistical processes of single noise contributions are different (for instance: shot noise: Poisson statistics, thermal noise: Gaussian statistics). For simplification it is assumed, that a normal distribution description is appropriate. The rms-value of the noise voltage is:

$$\delta U_{\mathrm{I,H,rms}}^2 \cong S_{U_{\mathrm{I,H}}} \cdot BW \quad (1)$$

BW denoting the bandwidth of the measurement ($BW = 1.5 f_{fund}$). The rms-values are identified with the standard uncertainties and the relative standard uncertainties are given by:

$$\frac{\delta U_{\mathrm{I,H}}}{U_{\mathrm{I,H}}} = \sqrt{\frac{S_{U_{\mathrm{I,H}}} \cdot BW}{U_{\mathrm{I,H}}^2}} \quad (2)$$

The signal-to-noise ratio is determined for all frequency points.

b) Resolution of the oscilloscope O_I, O_H
The resolution of the oscilloscope depends on the accuracy of the gain and the vertical resolution [Koch 99]. For the device used, values from the manual were applied for both parameters. There is no additional knowledge about the statistics and according to the Guide of Expression of Uncertainties in Measurement a rectangular distribution is assumed.

c) Determination of amplitudes from FFT-spectra
The amplitude of signals is determined from FFT-spectra. To do so, a flat-top window is applied to reduce scalloping losses. Additional investigations have shown that deviations up to 0.4% can occur nevertheless. Therefore, this uncertainty is added to the budget.

d) Measurement of voltage at the transducer T_r
The substantial source of error is the uncertainty of digitizing. For the used 8-bit device an upper limit of 1/256 is given. Additional experiments have shown that the reproducibility of the setting was better than the uncertainty of the voltage measurement estimated this way which serves as a conservative estimate here.

e) Uncertainty of the determination of the photodetector frequency response $A_Z(f)$
The procedure of determination of the photodetector frequency response is described in [Koch 10] including the determination of uncertainties of this procedure.

f) Temperature dependence of the sensitivity J_T
During measurements the ambient and water temperature is measured. Due to the temperature measurement uncertainty and due to variations of the temperature in the laboratory a temperature uncertainty of ±1 K at the location of measurement has to be assumed. The sensitivity of PVDF membrane hydrophones varies typically up to 0.2% / K at maximum. Therefore, an uncertainty contribution of 0.2% is considered for all frequencies.

g) Uncertainty of the determination of the gain V(f)
The substantial source of error is the reading accuracy. A voltage value can be determined with an uncertainty of 1/10 scale division using 8 scale divisions over all.

h) Uncertainty of the transmission coefficient of foil T(f)
For the calculation of the acoustic transmission coefficient of the foil, its thickness, speed of sound, and the density of the material were used. All three parameters were measured with an uncertainty of 10 %. Transmission coefficients were calculated with the measured parameters and with by 10 % increased parameters. From the variations upper limits were derived which serve as uncertainty.

i) Uncertainty due to positioning uncertainty in z-direction J_z
During the adjustment procedure the position of focus can only be found within an uncertainty which depends on the accuracy of the scanning system. In dependence on frequency this uncertainty results in different sound field values which contribute as an uncertainty to the final result. The uncertainty of positioning of the scanning system was determined in a separate experiment. Using a numerical model the sound field is calculated for two positions with a difference in *z*-direction of the positioning uncertainty. The difference in the sound field amplitude is considered as an upper limit of uncertainty and a rectangular distribution is assumed.

j) Uncertainty due to positioning uncertainty in lateral direction J_r
The same procedure as in section i) was applied for the uncertainty by positioning in both lateral directions. The result is considered as an upper limit and a rectangular distribution is assumed. A factor of 2 is used to account for the two spatial dimensions.

k) Uncertainty of the correction for spatial averaging F_{sp}
The dependence of the correction factor for spatial averaging on the effective source transducer parameters and the uncertainty of the effective hydrophone diameter are taken into account by parameter variation calculations using a numerical model. The result is considered as an upper limit and a rectangular distribution is assumed.

l) Uncertainty of the effective hydrophone diameter $F_{d,H}$
The effective diameter data used were provided in the technical protocol document. There were no uncertainties or details on the measurement procedures used to obtain the data available. Therefore, typical uncertainties for the determination of the effective diameter for a nominal 1 mm hydrophone following the PTB procedures were used. Here, the effective diameter of the hydrophone is determined by measurements of the directional response in two perpendicular directions. The overall uncertainty of the diameter determination is used to calculate upper and lower limits of the spatial averaging correction factor of the hydrophone. The result is considered as an upper limit and a rectangular distribution is assumed.

m) Inhomogeneity of the sound field I_h
The impact of sound field inhomogeneities on specifically the correction factor for spatial averaging is estimated by a single-sided fit procedure. During the determination of the effective transducer parameters the left and the right side lobe of fitted sound fields were accounted for separately by defining a left and right wing parameter set. The use of these different sets results in two slightly different correction factors. The differences between the factors were used as an upper limit and a rectangular distribution is assumed.

n) Uncertainty of open circuit correction factor L
The open circuit correction factor data were provided in the technical protocol document. Since there were no uncertainties specified and no details on the measurement technique used to obtain the data, the factors were considered here as given numbers without uncertainty contribution to be considered in the uncertainty budget of the key comparison. For regular calibrations, the uncertainty of the open circuit correction factor is determined by the uncertainty of the impedance measurements at the hydrophone and preamplifier. The differences between the factors calculated using the measured impedance plus and minus its uncertainty are used as an upper limit and a rectangular distribution is assumed.

o) Uncertainty due to variation of laser intensity I_L
The impact of varying laser intensity on calibration results was investigated by repetitive calibrations using different optical attenuators in the optical path. A slight change in the final results was determined. Using worst case changes in the laser intensity during one measurement cycle an overall maximum uncertainty was estimated.

p) Uncertainty due to use of relay and high pass filter Hpf
The measurement of elongation requires a low-frequency measurement for determination of the whole fringe and a measurement at rf frequencies in the stabilized configuration. The measurement uses slightly different signal paths which were addressed by a relay switch introducing a slight systematic uncertainty.

4.2 Standard uncertainty of type A

The standard uncertainty of type A is given by the empirical standard deviation of the four measurements at every measurement point as. The data has been summarised in Appendix B.

4.3 Overall uncertainty

The overall relative uncertainty $\delta M_{oc}/M_{oc}$ is calculated from the contributions δu_i by:

$$\frac{\delta M_{oc}}{M_{oc}} = \sqrt{\sum_i c_i^2 \frac{\delta u_i^2}{u_i^2}}, \quad u = U_1, U_H \ldots \tag{4}$$

The expanded uncertainty ($k = 2$) is determined from the overall standard uncertainty by multiplication with the coverage factor $k = 2$ and is given in Appendix B.

The effective degrees of freedom ν_{eff} were calculated for all frequency points, and the values were between 12 and 16. Following table G.2 in the Guide of Expression of Uncertainties in Measurement in the version of document JCGM 100:2008 this numbers require an extension value of $k = 2.16$ for an interval with a level of confidence of 95%. Most contributions to the Type B uncertainties follow, however, a rectangular statistic which is "narrower" than the normal distribution which is the basis of the common extensions values. This justifies the choice of the common extension factor of $k = 2$ which was applied to all single measurements.

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Appendix A

This Appendix indicates the results of the interferometric calibration. Tables A1 to Table A16 list the data with respect to the single frequency point using the calibration report sheet of the protocol document. Tables A17 and A18 summarise the results using the summary sheet.

Table A1: Results for 0.5 MHz, Hydrophone ER070

Participating Laboratory: PTB			**Calibration method:** interferometry	
Date(s) of calibrations: see below			**Hydrophone serial number:** ER070	
Nominal frequency (MHz): 0.5				
Measurement number	**1**	**2**	**3**	**4**
Actual frequency (MHz)	0.5	0.5	0.5	0.5
Date(s)	05.08.14	07.08.14	11.08.14	13.08.14
Temperature, *T* (°C)	20.29	20.35	20.23	20.26
Open-circuit correction	1.0519	1.0519	1.0519	1.0519
Water conductivity (µS/cm)	0.9	1.0	1.2	0.9
Oxygen content (mg/l), or alternative (ppm or % saturation)	4.36	4.40	8.94	4.24
Amplifier gain (dB)	13.29	13.29	13.29	13.29
Measured sensitivity (nV/Pa)	115.35	113.17	113.48	112.50
Open-circuit sensitivity at T °C (nV/Pa) .	121.34	119.04	119.37	118.34
Notes (e.g. of any unusual difficulties)				

Table A2: Results for 1 MHz, Hydrophone ER070

Participating Laboratory: PTB		**Calibration method:** interferometry		
Date(s) of calibrations: see below		**Hydrophone serial number:** ER070		
Nominal frequency (MHz): 1				
Measurement number	**1**	**2**	**3**	**4**
Actual frequency (MHz)	1	1	1	1
Date(s)	08.07.14	16.07.14	23.07.14	28.07.14
Temperature, *T* (°C)	20.16	20.42	20.40	20.49
Open-circuit correction	1.0545	1.0545	1.0545	1.0545
Water conductivity (µS/cm)	1.1	0.8	1.6	1.4
Oxygen content (mg/l), or alternative (ppm or % saturation)	3.69	3.55	3.62	3.93
Amplifier gain (dB)	13.25	13.25	13.25	13.25
Measured sensitivity (nV/Pa)	119.62	116.80	117.18	115.98
Open-circuit sensitivity at T °C (nV/Pa) .	126.14	123.17	123.57	122.30
Notes (e.g. of any unusual difficulties)				

Table A3: Results for 2.25 MHz, Hydrophone ER070

Participating Laboratory: PTB		**Calibration method:** interferometry		
Date(s) of calibrations: see below		**Hydrophone serial number:** ER070		
Nominal frequency (MHz): 2.25				
Measurement number	**1**	**2**	**3**	**4**
Actual frequency (MHz)	2.25	2.25	2.25	2.25
Date(s)	08.07.14	16.07.14	23.07.14	28.07.14
Temperature, *T* (°C)	20.15	20.41	20.42	20.49
Open-circuit correction	1.0584	1.0584	1.0584	1.0584
Water conductivity (µS/cm)	1.1	0.8	1.6	1.4
Oxygen content (mg/l), or alternative (ppm or % saturation)	3.69	3.55	3.62	3.93
Amplifier gain (dB)	13.13	13.13	13.13	13.13
Measured sensitivity (nV/Pa)	124.98	125.43	125.32	126.73
Open-circuit sensitivity at T °C (nV/Pa) .	132.28	132.76	132.64	134.13
Notes (e.g. of any unusual difficulties)				

Table A4: Results for 3.5 MHz, Hydrophone ER070

Participating Laboratory: PTB		**Calibration method:** interferometry		
Date(s) of calibrations: see below		**Hydrophone serial number:** ER070		
Nominal frequency (MHz): 3.5				
Measurement number	**1**	**2**	**3**	**4**
Actual frequency (MHz)	3.5	3.5	3.5	3.5
Date(s)	08.07.14	16.07.14	23.07.14	28.07.14
Temperature, *T* (°C)	20.14	20.41	20.42	20.48
Open-circuit correction	1.0603	1.0603	1.0603	1.0603
Water conductivity (µS/cm)	1.1	0.8	1.6	1.4
Oxygen content (mg/l), or alternative (ppm or % saturation)	3.69	3.55	3.62	3.93
Amplifier gain (dB)	12.98	12.98	12.98	12.98
Measured sensitivity (nV/Pa)	130.05	130.34	130.48	130.63
Open-circuit sensitivity at T °C (nV/Pa) .	137.89	138.20	138.35	138.51
Notes (e.g. of any unusual difficulties)				

Table A5: Results for 5 MHz, Hydrophone ER070

Participating Laboratory: PTB		**Calibration method:** interferometry		
Date(s) of calibrations: see below		**Hydrophone serial number:** ER070		
Nominal frequency (MHz): 5				
Measurement number	**1**	**2**	**3**	**4**
Actual frequency (MHz)	5	5	5	5
Date(s)	08.07.14	16.07.14	23.07.14	28.07.14
Temperature, *T* (°C)	20.18	20.42	20.41	20.48
Open-circuit correction	1.0620	1.0620	1.0620	1.0620
Water conductivity (µS/cm)	1.1	0.8	1.6	1.4
Oxygen content (mg/l), or alternative (ppm or % saturation)	3.69	3.55	3.62	3.93
Amplifier gain (dB)	12.72	12.72	12.72	12.72
Measured sensitivity (nV/Pa)	136.56	137.05	137.55	137.64
Open-circuit sensitivity at T °C (nV/Pa) .	145.03	145.55	146.08	146.17
Notes (e.g. of any unusual difficulties)				

Table A6: Results for 10 MHz, Hydrophone ER070

Participating Laboratory: PTB		**Calibration method:** interferometry		
Date(s) of calibrations: see below		**Hydrophone serial number:** ER070		
Nominal frequency (MHz): 10				
Measurement number	**1**	**2**	**3**	**4**
Actual frequency (MHz)	10	10	10	10
Date(s)	08.07.14	16.07.14	23.07.14	28.07.14
Temperature, *T* (°C)	20.14	20.41	20.42	20.48
Open-circuit correction	1.0641	1.0641	1.0641	1.0641
Water conductivity (µS/cm)	1.1	0.8	1.6	1.4
Oxygen content (mg/l), or alternative (ppm or % saturation)	3.69	3.55	3.62	3.93
Amplifier gain (dB)	11.31	11.31	11.31	11.31
Measured sensitivity (nV/Pa)	166.91	167.76	168.05	167.03
Open-circuit sensitivity at T °C (nV/Pa) .	177.61	178.51	178.82	177.74
Notes (e.g. of any unusual difficulties)				

Table A7: Results for 15 MHz, Hydrophone ER070

Participating Laboratory: PTB		**Calibration method:** interferometry		
Date(s) of calibrations: see below		**Hydrophone serial number:** ER070		
Nominal frequency (MHz): 15				
Measurement number	**1**	**2**	**3**	**4**
Actual frequency (MHz)	15	15	15	15
Date(s)	08.07.14	16.07.14	23.07.14	28.07.14
Temperature, *T* (°C)	20.15	20.41	20.40	20.49
Open-circuit correction	1.0627	1.0627	1.0627	1.0627
Water conductivity (µS/cm)	1.1	0.8	1.6	1.4
Oxygen content (mg/l), or alternative (ppm or % saturation)	3.69	3.55	3.62	3.93
Amplifier gain (dB)	9.28	9.28	9.28	9.28
Measured sensitivity (nV/Pa)	219.70	223.11	219.50	220.04
Open-circuit sensitivity at T °C (nV/Pa) .	233.48	237.10	233.26	233.84
Notes (e.g. of any unusual difficulties)				

Table A8: Results for 20 MHz, Hydrophone ER070

Participating Laboratory: PTB		**Calibration method:** interferometry		
Date(s) of calibrations: see below		**Hydrophone serial number:** ER070		
Nominal frequency (MHz): 20				
Measurement number	**1**	**2**	**3**	**4**
Actual frequency (MHz)	20	20	20	20
Date(s)	08.07.14	16.07.14	23.07.14	28.07.14
Temperature, *T* (°C)	20.15	20.42	20.40	20.49
Open-circuit correction	1.0578	1.0578	1.0578	1.0578
Water conductivity (µS/cm)	1.1	0.8	1.6	1.4
Oxygen content (mg/l), or alternative (ppm or % saturation)	3.69	3.55	3.62	3.93
Amplifier gain (dB)	6.72	6.72	6.72	6.72
Measured sensitivity (nV/Pa)	205.96	213.37	208.71	207.56
Open-circuit sensitivity at T °C (nV/Pa) .	217.86	225.70	220.77	219.56
Notes (e.g. of any unusual difficulties)				

Table A9: Results for 0.5 MHz, Hydrophone IP999

Participating Laboratory: PTB		**Calibration method:** interferometry		
Date(s) of calibrations: see below		**Hydrophone serial number:** IP999		
Nominal frequency (MHz): 0.5				
Measurement number	**1**	**2**	**3**	**4**
Actual frequency (MHz)	0.5	0.5	0.5	0.5
Date(s)	05.08.14	07.08.14	11.08.14	13.08.14
Temperature, *T* (°C)	20.31	20.19	20.32	20.12
Open-circuit correction	1.0722	1.0722	1.0722	1.0722
Water conductivity (µS/cm)	1.0	0.9	0.9	1.2
Oxygen content (mg/l), or alternative (ppm or % saturation)	4.48	8.98	4.12	8.87
Amplifier gain (dB)	13.29	13.29	13.29	13.29
Measured sensitivity (nV/Pa)	196.97	192.34	194.13	192.05
Open-circuit sensitivity at T °C (nV/Pa) .	211.19	206.23	208.15	205.92
Notes (e.g. of any unusual difficulties)				

Table A10: Results for 1 MHz, Hydrophone IP999

Participating Laboratory: PTB		**Calibration method:** interferometry		
Date(s) of calibrations: see below		**Hydrophone serial number:** IP999		
Nominal frequency (MHz): 1				
Measurement number	**1**	**2**	**3**	**4**
Actual frequency (MHz)	1	1	1	1
Date(s)	09.07.14	17.07.14	21.07.14	29.07.14
Temperature, *T* (°C)	20.85	20.37	20.34	20.47
Open-circuit correction	1.0748	1.0748	1.0748	1.0748
Water conductivity (µS/cm)	0.8	1.0	1.2	0.8
Oxygen content (mg/l), or alternative (ppm or % saturation)	3.72	8.78	4.11	4.14
Amplifier gain (dB)	13.25	13.25	13.25	13.25
Measured sensitivity (nV/Pa)	198.37	192.89	192.96	198.09
Open-circuit sensitivity at T °C (nV/Pa) .	213.21	207.32	207.39	212.91
Notes (e.g. of any unusual difficulties)				

Table A11: Results for 2.25 MHz, Hydrophone IP999

Participating Laboratory: PTB		**Calibration method:** interferometry		
Date(s) of calibrations: see below		**Hydrophone serial number:** IP999		
Nominal frequency (MHz): 2.25				
Measurement number	**1**	**2**	**3**	**4**
Actual frequency (MHz)	2.25	2.25	2.25	2.25
Date(s)	09.07.14	17.07.14	21.07.14	29.07.14
Temperature, *T* (°C)	20.83	20.37	20.36	20.46
Open-circuit correction	1.0787	1.0787	1.0787	1.0787
Water conductivity (µS/cm)	0.8	1.0	1.2	0.8
Oxygen content (mg/l), or alternative (ppm or % saturation)	3.72	8.78	4.11	4.14
Amplifier gain (dB)	13.13	13.13	13.13	13.13
Measured sensitivity (nV/Pa)	197.34	197.47	197.04	199.92
Open-circuit sensitivity at T °C (nV/Pa) .	212.87	213.01	212.55	215.65
Notes (e.g. of any unusual difficulties)				

Table A12: Results for 3.5 MHz, Hydrophone IP999

Participating Laboratory: PTB		**Calibration method:** interferometry		
Date(s) of calibrations: see below		**Hydrophone serial number:** IP999		
Nominal frequency (MHz): 3.5				
Measurement number	**1**	**2**	**3**	**4**
Actual frequency (MHz)	3.5	3.5	3.5	3.5
Date(s)	09.07.14	17.07.14	21.07.14	29.07.14
Temperature, *T* (°C)	20.82	20.36	20.36	20.46
Open-circuit correction	1.0805	1.0805	1.0805	1.0805
Water conductivity (µS/cm)	0.8	1.0	1.2	0.8
Oxygen content (mg/l), or alternative (ppm or % saturation)	3.72	8.78	4.11	4.14
Amplifier gain (dB)	12.98	12.98	12.98	12.98
Measured sensitivity (nV/Pa)	197.16	197.40	197.69	197.77
Open-circuit sensitivity at T °C (nV/Pa) .	213.03	213.29	213.60	213.69
Notes (e.g. of any unusual difficulties)				

Table A13: Results for 5 MHz, Hydrophone IP999

Participating Laboratory: PTB			**Calibration method:** interferometry	
Date(s) of calibrations: see below			**Hydrophone serial number:** IP999	
Nominal frequency (MHz): 5				
Measurement number	**1**	**2**	**3**	**4**
Actual frequency (MHz)	5	5	5	5
Date(s)	09.07.14	17.07.14	21.07.14	29.07.14
Temperature, *T* (°C)	20.88	20.38	20.35	20.46
Open-circuit correction	1.0823	1.0823	1.0823	1.0823
Water conductivity (µS/cm)	0.8	1.0	1.2	0.8
Oxygen content (mg/l), or alternative (ppm or % saturation)	3.72	8.78	4.11	4.14
Amplifier gain (dB)	12.72	12.72	12.72	12.72
Measured sensitivity (nV/Pa)	198.39	198.43	198.68	198.56
Open-circuit sensitivity at T °C (nV/Pa) .	214.72	214.76	215.03	214.90
Notes (e.g. of any unusual difficulties)				

Table A14: Results for 10 MHz, Hydrophone IP999

Participating Laboratory: PTB		**Calibration method:** interferometry		
Date(s) of calibrations: see below		**Hydrophone serial number:** IP999		
Nominal frequency (MHz): 10				
Measurement number	**1**	**2**	**3**	**4**
Actual frequency (MHz)	10	10	10	10
Date(s)	09.07.14	17.07.14	21.07.14	29.07.14
Temperature, *T* (°C)	20.82	20.36	20.35	20.46
Open-circuit correction	1.0854	1.0854	1.0854	1.0854
Water conductivity (µS/cm)	0.8	1.0	1.2	0.8
Oxygen content (mg/l), or alternative (ppm or % saturation)	3.72	8.78	4.11	4.14
Amplifier gain (dB)	11.31	11.31	11.31	11.31
Measured sensitivity (nV/Pa)	221.22	220.60	219.32	219.00
Open-circuit sensitivity at T °C (nV/Pa) .	240.11	239.44	238.05	237.70
Notes (e.g. of any unusual difficulties)				

Table A15: Results for 15 MHz, Hydrophone IP999

Participating Laboratory: PTB		**Calibration method:** interferometry		
Date(s) of calibrations: see below		**Hydrophone serial number:** IP999		
Nominal frequency (MHz): 15				
Measurement number	**1**	**2**	**3**	**4**
Actual frequency (MHz)	15	15	15	15
Date(s)	09.07.14	17.07.14	21.07.14	29.07.14
Temperature, *T* (°C)	20.83	20.37	20.33	20.47
Open-circuit correction	1.0858	1.0858	1.0858	1.0858
Water conductivity (µS/cm)	0.8	1.0	1.2	0.8
Oxygen content (mg/l), or alternative (ppm or % saturation)	3.72	8.78	4.11	4.14
Amplifier gain (dB)	9.28	9.28	9.28	9.28
Measured sensitivity (nV/Pa)	274.42	274.94	268.24	265.85
Open-circuit sensitivity at T °C (nV/Pa) .	297.97	298.53	291.26	288.66
Notes (e.g. of any unusual difficulties)				

Table A16: Results for 20 MHz, Hydrophone IP999

Participating Laboratory: PTB		**Calibration method:** interferometry		
Date(s) of calibrations: see below		**Hydrophone serial number:** IP999		
Nominal frequency (MHz): 20				
Measurement number	**1**	**2**	**3**	**4**
Actual frequency (MHz)	20	20	20	20
Date(s)	09.07.14	17.07.14	21.07.14	29.07.14
Temperature, *T* (°C)	20.83	20.38	20.33	20.47
Open-circuit correction	1.0835	1.0835	1.0835	1.0835
Water conductivity (µS/cm)	0.8	1.0	1.2	0.8
Oxygen content (mg/l), or alternative (ppm or % saturation)	3.72	8.78	4.11	4.14
Amplifier gain (dB)	6.72	6.72	6.72	6.72
Measured sensitivity (nV/Pa)	319.12	320.88	310.22	303.12
Open-circuit sensitivity at T °C (nV/Pa) .	345.77	347.67	336.12	328.43
Notes (e.g. of any unusual difficulties)				

Table A17: Summary of results for hydrophone ER070

Participating laboratory: PTB					**Method:** interferometry			
Dates:	**Hydrophone serial number:** ER070							
Nominal frequency (MHz)	0.5	1	2.25	3.5	5	10	15	20
Actual frequency (MHz)	0.5	1	2.25	3.5	5	10	15	20
Mean open-circuit sensitivity at *T* °C (nV/Pa)	119.52	123.79	132.95	138.24	145.71	178.17	234.42	220.98
Type A (random) standard uncertainty (%)	0.93	1.16	0.53	0.17	0.31	0.29	0.67	1.32
Type B (systematic) standard uncertainty (%)	2.77	3.05	3.02	2.99	2.92	2.86	2,86	2.89
Coverage factor (*k*)	2	2	2	2	2	2	2	2
Expanded uncertainty (%)	5.85	6.54	6.14	5.99	5.88	5.74	5.87	6.36

Table A18: Summary of results for hydrophone IP999

Participating laboratory: PTB						**Method:** interferometry		
Dates:	**Hydrophone serial number:** IP999							
Nominal frequency (MHz)	0.5	1	2.25	3.5	5	10	15	20
Actual frequency (MHz)	0.5	1	2.25	3.5	5	10	15	20
Mean open-circuit sensitivity at *T* °C (nV/Pa)	207.87	210.21	213.52	213.40	214.85	238.83	294.11	339.50
Type A (random) standard uncertainty (%)	1.01	1.36	0.58	0.12	0.06	0.41	1.45	2.28
Type B (systematic) standard uncertainty (%)	2.77	3.43	3.36	3.29	3.21	3.00	2.90	2.89
Coverage factor (*k*)	2	2	2	2	2	2	2	2
Expanded uncertainty (%)	5.90	7.38	6.82	6.58	6.43	6.06	6.48	7.37

Appendix B

This Appendix states the uncertainties of the interferometric calibration. The type B uncertainty contributions for every frequency point are listed in Tables B1 to B8 for the hydrophone ER070 and in Tables B9 to B16 for the hydrophone IP999. The summary document sheet in Appendix A gives all results, type A and type B overall uncertainties and the expanded uncertainty for all measurements.

Table B1: Uncertainty contributions in % for ER070 at $f = 0.5$ MHz

clause	contribution	symbol	coefficient	distribution	standard uncertainty
4.1.a)	s/n interferometer	U_I	1	Gaussian	0,07
4.1.a)	s/n hydrophone	U_H	1	Gaussian	0,04
4.1.b)	resolution of the oscilloscope	O_H	1	rectangular	1,00
4.1.b)	resolution of the oscilloscope	O_I	1	rectangular	1,00
4.1.c)	determination of amplitudes	$U_{A,H}$	1	rectangular	0,24
4.1.c)	determination of amplitudes	$U_{A,I}$	1	rectangular	0,24
4.1.d)	voltage at the transducer	T_r	1	rectangular	0,74
4.1.e)	pd frequency response	A_Z	1	Gaussian	2,00
4.1.f)	temperature	J_T	1	Gaussian	0,12
4.1.g)	gain	V	1	Gaussian	0,80
4.1.h)	transmission of foil	Tr	1	rectangular	0,02
4.1.i)	positioning *z* interferometer	$J_{z,I}$	1	rectangular	0,12
4.1.i)	positioning *z* hydrophone	$J_{z,H}$	1	rectangular	0,12
4.1.j)	positioning *r* interferometer	$J_{r,I}$	2	rectangular	0,00
4.1.j)	positioning *r* hydrophone	$J_{r,H}$	2	rectangular	0,00
4.1.k)	spatial aver. interferometer	$F_{sp,I}$	1	rectangular	0,00
4.1.k)	spatial aver. hydrophone	$F_{sp,H}$	1	rectangular	0,02
4.1.l)	effective diameter hydrophone	$F_{d,H}$	1	rectangular	0,02
4.1.m)	inhomogeneity sound field	I_h	1	rectangular	0,00
4.1.n)	open circuit correction	L	1	rectangular	0,00
4.1.o)	laser intensity	I_L	1	rectangular	0,58
4.1.p)	relais and highpass filter	Hpf	1	Gaussian	0,11
4.3	Pythagorean sum type B				2.77
4.2	type A				0.93
4.3	standard uncertainty				2.93
4.3	expanded uncertainty				5.85

Table B2: Uncertainty contributions in % for ER070 at f = 1 MHz

clause	contribution	symbol	coefficient	distribution	standard uncertainty
4.1.a)	s/n interferometer	*UI*	1	Gaussian	1,23
4.1.a)	s/n hydrophone	*UH*	1	Gaussian	0,38
4.1.b)	resolution of the oscilloscope	*OH*	1	rectangular	1,00
4.1.b)	resolution of the oscilloscope	*OI*	1	rectangular	1,00
4.1.c)	determination of amplitudes	*UA,H*	1	rectangular	0,24
4.1.c)	determination of amplitudes	*UA,I*	1	rectangular	0,24
4.1.d)	voltage at the transducer	*Tr*	1	rectangular	0,74
4.1.e)	pd frequency response	*AZ*	1	Gaussian	2,00
4.1.f)	temperature	*JT*	1	Gaussian	0,12
4.1.g)	gain	*V*	1	Gaussian	0,80
4.1.h)	transmission of foil	*Tr*	1	rectangular	0,03
4.1.i)	positioning *z* interferometer	*Jz,I*	1	rectangular	0,06
4.1.i)	positioning *z* hydrophone	*Jz,H*	1	rectangular	0,06
4.1.j)	positioning *r* interferometer	*Jr,I*	2	rectangular	0,00
4.1.j)	positioning *r* hydrophone	*Jr,H*	2	rectangular	0,00
4.1.k)	spatial aver. interferometer	*Fsp,I*	1	rectangular	0,00
4.1.k)	spatial aver. hydrophone	*Fsp,H*	1	rectangular	0,00
4.1.l)	effective diameter hydrophone	*Fd,H*	1	rectangular	0,00
4.1.m)	inhomogeneity sound field	*Ih*	1	rectangular	0,00
4.1.n)	open circuit correction	*L*	1	rectangular	0,00
4.1.o)	laser intensity	*IL*	1	rectangular	0,58
4.1.p)	relais and highpass filter	*Hpf*	1	Gaussian	0,11
4.3	Pythagorean sum type B				3.05
4.2	type A				1.16
4.3	standard uncertainty				3.27
4.3	expanded uncertainty				6.54

Table B3: Uncertainty contributions in % for ER070 at f = 2.25 MHz

clause	contribution	symbol	coefficient	distribution	standard uncertainty
4.1.a)	s/n interferometer	U_I	1	Gaussian	1,16
4.1.a)	s/n hydrophone	U_H	1	Gaussian	0,36
4.1.b)	resolution of the oscilloscope	O_H	1	rectangular	1,00
4.1.b)	resolution of the oscilloscope	O_I	1	rectangular	1,00
4.1.c)	determination of amplitudes	$U_{A,H}$	1	rectangular	0,24
4.1.c)	determination of amplitudes	$U_{A,I}$	1	rectangular	0,24
4.1.d)	voltage at the transducer	T_r	1	rectangular	0,74
4.1.e)	pd frequency response	A_Z	1	Gaussian	2,00
4.1.f)	temperature	J_T	1	Gaussian	0,12
4.1.g)	gain	V	1	Gaussian	0,80
4.1.h)	transmission of foil	Tr	1	rectangular	0,06
4.1.i)	positioning z interferometer	$J_{z,I}$	1	rectangular	0,06
4.1.i)	positioning z hydrophone	$J_{z,H}$	1	rectangular	0,06
4.1.j)	positioning r interferometer	$J_{r,I}$	2	rectangular	0,00
4.1.j)	positioning r hydrophone	$J_{r,H}$	2	rectangular	0,00
4.1.k)	spatial aver. interferometer	$F_{sp,I}$	1	rectangular	0,00
4.1.k)	spatial aver. hydrophone	$F_{sp,H}$	1	rectangular	0,00
4.1.l)	effective diameter hydrophone	$F_{d,H}$	1	rectangular	0,01
4.1.m)	inhomogeneity sound field	I_h	1	rectangular	0,00
4.1.n)	open circuit correction	L	1	rectangular	0,00
4.1.o)	laser intensity	I_L	1	rectangular	0,58
4.1.p)	relais and highpass filter	Hpf	1	Gaussian	0,11
4.3	Pythagorean sum type B				3.02
4.2	type A				0.53
4.3	standard uncertainty				3.07
4.3	expanded uncertainty				6.14

Table B4: Uncertainty contributions in % for ER070 at f = 3.5 MHz

clause	contribution	symbol	coefficient	distribution	standard uncertainty
4.1.a)	s/n interferometer	U_I	1	Gaussian	1,08
4.1.a)	s/n hydrophone	U_H	1	Gaussian	0,33
4.1.b)	resolution of the oscilloscope	O_H	1	rectangular	1,00
4.1.b)	resolution of the oscilloscope	O_I	1	rectangular	1,00
4.1.c)	determination of amplitudes	$U_{A,H}$	1	rectangular	0,24
4.1.c)	determination of amplitudes	$U_{A,I}$	1	rectangular	0,24
4.1.d)	voltage at the transducer	T_r	1	rectangular	0,74
4.1.e)	pd frequency response	A_Z	1	Gaussian	2,00
4.1.f)	temperature	J_T	1	Gaussian	0,12
4.1.g)	gain	V	1	Gaussian	0,80
4.1.h)	transmission of foil	Tr	1	rectangular	0,10
4.1.i)	positioning z interferometer	$J_{z,I}$	1	rectangular	0,06
4.1.i)	positioning z hydrophone	$J_{z,H}$	1	rectangular	0,06
4.1.j)	positioning r interferometer	$J_{r,I}$	2	rectangular	0,00
4.1.j)	positioning r hydrophone	$J_{r,H}$	2	rectangular	0,00
4.1.k)	spatial aver. interferometer	$F_{sp,I}$	1	rectangular	0,00
4.1.k)	spatial aver. hydrophone	$F_{sp,H}$	1	rectangular	0,01
4.1.l)	effective diameter hydrophone	$F_{d,H}$	1	rectangular	0,01
4.1.m)	inhomogeneity sound field	I_h	1	rectangular	0,00
4.1.n)	open circuit correction	L	1	rectangular	0,00
4.1.o)	laser intensity	I_L	1	rectangular	0,58
4.1.p)	relais and highpass filter	Hpf	1	Gaussian	0,07
4.3	Pythagorean sum type B				2.99
4.2	type A				0.17
4.3	standard uncertainty				3.00
4.3	expanded uncertainty				5.99

Table B5: Uncertainty contributions in % for ER070 at f = 5 MHz

clause	contribution	symbol	coefficient	distribution	standard uncertainty
4.1.a)	s/n interferometer	U_I	1	Gaussian	0,86
4.1.a)	s/n hydrophone	U_H	1	Gaussian	0,34
4.1.b)	resolution of the oscilloscope	O_H	1	rectangular	1,00
4.1.b)	resolution of the oscilloscope	O_I	1	rectangular	1,00
4.1.c)	determination of amplitudes	$U_{A,H}$	1	rectangular	0,24
4.1.c)	determination of amplitudes	$U_{A,I}$	1	rectangular	0,24
4.1.d)	voltage at the transducer	T_r	1	rectangular	0,74
4.1.e)	pd frequency response	A_Z	1	Gaussian	2,00
4.1.f)	temperature	J_T	1	Gaussian	0,12
4.1.g)	gain	V	1	Gaussian	0,80
4.1.h)	transmission of foil	Tr	1	rectangular	0,14
4.1.i)	positioning z interferometer	$J_{z,I}$	1	rectangular	0,06
4.1.i)	positioning z hydrophone	$J_{z,H}$	1	rectangular	0,06
4.1.j)	positioning r interferometer	$J_{r,I}$	2	rectangular	0,00
4.1.j)	positioning r hydrophone	$J_{r,H}$	2	rectangular	0,00
4.1.k)	spatial aver. interferometer	$F_{sp,I}$	1	rectangular	0,00
4.1.k)	spatial aver. hydrophone	$F_{sp,H}$	1	rectangular	0,01
4.1.l)	effective diameter hydrophone	$F_{d,H}$	1	rectangular	0,03
4.1.m)	inhomogeneity sound field	I_h	1	rectangular	0,00
4.1.n)	open circuit correction	L	1	rectangular	0,00
4.1.o)	laser intensity	I_L	1	rectangular	0,58
4.1.p)	relais and highpass filter	Hpf	1	Gaussian	0,07
4.3	Pythagorean sum type B				2,92
4.2	type A				0.31
4.3	standard uncertainty				2.94
4.3	expanded uncertainty				5.88

Table B6: Uncertainty contributions in % for ER070 at f = 10 MHz

clause	contribution	symbol	coefficient	distribution	standard uncertainty
4.1.a)	s/n interferometer	U_I	1	Gaussian	0,59
4.1.a)	s/n hydrophone	U_H	1	Gaussian	0,23
4.1.b)	resolution of the oscilloscope	O_H	1	rectangular	1,00
4.1.b)	resolution of the oscilloscope	O_I	1	rectangular	1,00
4.1.c)	determination of amplitudes	$U_{A,H}$	1	rectangular	0,24
4.1.c)	determination of amplitudes	$U_{A,I}$	1	rectangular	0,24
4.1.d)	voltage at the transducer	T_r	1	rectangular	0,74
4.1.e)	pd frequency response	A_Z	1	Gaussian	2,00
4.1.f)	temperature	J_T	1	Gaussian	0,12
4.1.g)	gain	V	1	Gaussian	0,80
4.1.h)	transmission of foil	Tr	1	rectangular	0,30
4.1.i)	positioning z interferometer	$J_{z,I}$	1	rectangular	0,06
4.1.i)	positioning z hydrophone	$J_{z,H}$	1	rectangular	0,05
4.1.j)	positioning r interferometer	$J_{r,I}$	2	rectangular	0,01
4.1.j)	positioning r hydrophone	$J_{r,H}$	2	rectangular	0,01
4.1.k)	spatial aver. interferometer	$F_{sp,I}$	1	rectangular	0,00
4.1.k)	spatial aver. hydrophone	$F_{sp,H}$	1	rectangular	0,05
4.1.l)	effective diameter hydrophone	$F_{d,H}$	1	rectangular	0,10
4.1.m)	inhomogeneity sound field	I_h	1	rectangular	0,01
4.1.n)	open circuit correction	L	1	rectangular	0,00
4.1.o)	laser intensity	I_L	1	rectangular	0,58
4.1.p)	relais and highpass filter	Hpf	1	Gaussian	0,07
4.3	Pythagorean sum type B				2.86
4.2	type A				0.29
4.3	standard uncertainty				2.87
4.3	expanded uncertainty				5.74

Table B7: Uncertainty contributions in % for ER070 at f = 15 MHz

clause	contribution	symbol	coefficient	distribution	standard uncertainty
4.1.a)	s/n interferometer	U_I	1	Gaussian	0,32
4.1.a)	s/n hydrophone	U_H	1	Gaussian	0,12
4.1.b)	resolution of the oscilloscope	O_H	1	rectangular	1,00
4.1.b)	resolution of the oscilloscope	O_I	1	rectangular	1,00
4.1.c)	determination of amplitudes	$U_{A,H}$	1	rectangular	0,24
4.1.c)	determination of amplitudes	$U_{A,I}$	1	rectangular	0,24
4.1.d)	voltage at the transducer	T_r	1	rectangular	0,74
4.1.e)	pd frequency response	A_Z	1	Gaussian	2,00
4.1.f)	temperature	J_T	1	Gaussian	0,12
4.1.g)	gain	V	1	Gaussian	0,80
4.1.h)	transmission of foil	Tr	1	rectangular	0,50
4.1.i)	positioning *z* interferometer	$J_{z,I}$	1	rectangular	0,03
4.1.i)	positioning *z* hydrophone	$J_{z,H}$	1	rectangular	0,02
4.1.j)	positioning *r* interferometer	$J_{r,I}$	2	rectangular	0,04
4.1.j)	positioning *r* hydrophone	$J_{r,H}$	2	rectangular	0,03
4.1.k)	spatial aver. interferometer	$F_{sp,I}$	1	rectangular	0,00
4.1.k)	spatial aver. hydrophone	$F_{sp,H}$	1	rectangular	0,25
4.1.l)	effective diameter hydrophone	$F_{d,H}$	1	rectangular	0,25
4.1.m)	inhomogeneity sound field	I_h	1	rectangular	0,10
4.1.n)	open circuit correction	L	1	rectangular	0,00
4.1.o)	laser intensity	I_L	1	rectangular	0,58
4.1.p)	relais and highpass filter	Hpf	1	Gaussian	0,07
4.3	Pythagorean sum type B				2.86
4.2	type A				0.67
4.3	standard uncertainty				2.93
4.3	expanded uncertainty				5.87

Table B8: Uncertainty contributions in % for ER070 at f = 20 MHz

clause	contribution	symbol	coefficient	distribution	standard uncertainty
4.1.a)	s/n interferometer	U_I	1	Gaussian	0,08
4.1.a)	s/n hydrophone	U_H	1	Gaussian	0,01
4.1.b)	resolution of the oscilloscope	O_H	1	rectangular	1,00
4.1.b)	resolution of the oscilloscope	O_I	1	rectangular	1,00
4.1.c)	determination of amplitudes	$U_{A,H}$	1	rectangular	0,24
4.1.c)	determination of amplitudes	$U_{A,I}$	1	rectangular	0,24
4.1.d)	voltage at the transducer	T_r	1	rectangular	0,74
4.1.e)	pd frequency response	A_Z	1	Gaussian	2,00
4.1.f)	temperature	J_T	1	Gaussian	0,12
4.1.g)	gain	V	1	Gaussian	0,80
4.1.h)	transmission of foil	Tr	1	rectangular	0,71
4.1.i)	positioning z interferometer	$J_{z,I}$	1	rectangular	0,02
4.1.i)	positioning z hydrophone	$J_{z,H}$	1	rectangular	0,01
4.1.j)	positioning r interferometer	$J_{r,I}$	2	rectangular	0,06
4.1.j)	positioning r hydrophone	$J_{r,H}$	2	rectangular	0,05
4.1.k)	spatial aver. interferometer	$F_{sp,I}$	1	rectangular	0,00
4.1.k)	spatial aver. hydrophone	$F_{sp,H}$	1	rectangular	0,15
4.1.l)	effective diameter hydrophone	$F_{d,H}$	1	rectangular	0,38
4.1.m)	inhomogeneity sound field	I_h	1	rectangular	0,19
4.1.n)	open circuit correction	L	1	rectangular	0,00
4.1.o)	laser intensity	I_L	1	rectangular	0,58
4.1.p)	relais and highpass filter	Hpf	1	Gaussian	0,07
4.3	Pythagorean sum type B				2.89
4.2	type A				1.32
4.3	standard uncertainty				3.18
4.3	expanded uncertainty				6.36

Table B9: Uncertainty contributions in % for IP999 at f = 0.5 MHz

clause	contribution	symbol	coefficient	distribution	standard uncertainty
4.1.a)	s/n interferometer	U_I	1	Gaussian	0,08
4.1.a)	s/n hydrophone	U_H	1	Gaussian	0,03
4.1.b)	resolution of the oscilloscope	O_H	1	rectangular	1,00
4.1.b)	resolution of the oscilloscope	O_I	1	rectangular	1,00
4.1.c)	determination of amplitudes	$U_{A,H}$	1	rectangular	0,24
4.1.c)	determination of amplitudes	$U_{A,I}$	1	rectangular	0,24
4.1.d)	voltage at the transducer	T_r	1	rectangular	0,74
4.1.e)	pd frequency response	A_Z	1	Gaussian	2,00
4.1.f)	temperature	J_T	1	Gaussian	0,12
4.1.g)	gain	V	1	Gaussian	0,80
4.1.h)	transmission of foil	Tr	1	rectangular	0,02
4.1.i)	positioning z interferometer	$J_{z,I}$	1	rectangular	0,12
4.1.i)	positioning z hydrophone	$J_{z,H}$	1	rectangular	0,12
4.1.j)	positioning r interferometer	$J_{r,I}$	2	rectangular	0,00
4.1.j)	positioning r hydrophone	$J_{r,H}$	2	rectangular	0,00
4.1.k)	spatial aver. interferometer	$F_{sp,I}$	1	rectangular	0,00
4.1.k)	spatial aver. hydrophone	$F_{sp,H}$	1	rectangular	0,02
4.1.l)	effective diameter hydrophone	$F_{d,H}$	1	rectangular	0,02
4.1.m)	inhomogeneity sound field	I_h	1	rectangular	0,00
4.1.n)	open circuit correction	L	1	rectangular	0,00
4.1.o)	laser intensity	I_L	1	rectangular	0,58
4.1.p)	relais and highpass filter	Hpf	1	Gaussian	0,11
4.3	Pythagorean sum type B				2.77
4.2	type A				1.01
4.3	standard uncertainty				2.95
4.3	expanded uncertainty				5.90

Table B10: Uncertainty contributions in % for IP999 at $f = 1$ MHz

clause	contribution	symbol	coefficient	distribution	standard uncertainty
4.1.a)	s/n interferometer	U_I	1	Gaussian	2,01
4.1.a)	s/n hydrophone	U_H	1	Gaussian	0,23
4.1.b)	resolution of the oscilloscope	O_H	1	rectangular	1,00
4.1.b)	resolution of the oscilloscope	O_I	1	rectangular	1,00
4.1.c)	determination of amplitudes	$U_{A,H}$	1	rectangular	0,24
4.1.c)	determination of amplitudes	$U_{A,I}$	1	rectangular	0,24
4.1.d)	voltage at the transducer	T_r	1	rectangular	0,74
4.1.e)	pd frequency response	A_Z	1	Gaussian	2,00
4.1.f)	temperature	J_T	1	Gaussian	0,12
4.1.g)	gain	V	1	Gaussian	0,80
4.1.h)	transmission of foil	Tr	1	rectangular	0,03
4.1.i)	positioning *z* interferometer	$J_{z,I}$	1	rectangular	0,06
4.1.i)	positioning *z* hydrophone	$J_{z,H}$	1	rectangular	0,06
4.1.j)	positioning *r* interferometer	$J_{r,I}$	2	rectangular	0,00
4.1.j)	positioning *r* hydrophone	$J_{r,H}$	2	rectangular	0,00
4.1.k)	spatial aver. interferometer	$F_{sp,I}$	1	rectangular	0,00
4.1.k)	spatial aver. hydrophone	$F_{sp,H}$	1	rectangular	0,00
4.1.l)	effective diameter hydrophone	$F_{d,H}$	1	rectangular	0,00
4.1.m)	inhomogeneity sound field	I_h	1	rectangular	0,00
4.1.n)	open circuit correction	L	1	rectangular	0,00
4.1.o)	laser intensity	I_L	1	rectangular	0,58
4.1.p)	relais and highpass filter	Hpf	1	Gaussian	0,11
4.3	Pythagorean sum type B				3.43
4.2	type A				1.36
4.3	standard uncertainty				3.69
4.3	expanded uncertainty				7.38

Table B11: Uncertainty contributions in % for IP999 at $f = 2.25$ MHz

clause	contribution	symbol	coefficient	distribution	standard uncertainty
4.1.a)	s/n interferometer	U_I	1	Gaussian	1,89
4.1.a)	s/n hydrophone	U_H	1	Gaussian	0,22
4.1.b)	resolution of the oscilloscope	O_H	1	rectangular	1,00
4.1.b)	resolution of the oscilloscope	O_I	1	rectangular	1,00
4.1.c)	determination of amplitudes	$U_{A,H}$	1	rectangular	0,24
4.1.c)	determination of amplitudes	$U_{A,I}$	1	rectangular	0,24
4.1.d)	voltage at the transducer	T_r	1	rectangular	0,74
4.1.e)	pd frequency response	A_Z	1	Gaussian	2,00
4.1.f)	temperature	J_T	1	Gaussian	0,12
4.1.g)	gain	V	1	Gaussian	0,80
4.1.h)	transmission of foil	Tr	1	rectangular	0,06
4.1.i)	positioning *z* interferometer	$J_{z,I}$	1	rectangular	0,06
4.1.i)	positioning *z* hydrophone	$J_{z,H}$	1	rectangular	0,06
4.1.j)	positioning *r* interferometer	$J_{r,I}$	2	rectangular	0,00
4.1.j)	positioning *r* hydrophone	$J_{r,H}$	2	rectangular	0,00
4.1.k)	spatial aver. interferometer	$F_{sp,I}$	1	rectangular	0,00
4.1.k)	spatial aver. hydrophone	$F_{sp,H}$	1	rectangular	0,00
4.1.l)	effective diameter hydrophone	$F_{d,H}$	1	rectangular	0,01
4.1.m)	inhomogeneity sound field	I_h	1	rectangular	0,00
4.1.n)	open circuit correction	L	1	rectangular	0,00
4.1.o)	laser intensity	I_L	1	rectangular	0,58
4.1.p)	relais and highpass filter	Hpf	1	Gaussian	0,11
4.3	Pythagorean sum type B				3.36
4.2	type A				0.58
4.3	standard uncertainty				3.41
4.3	expanded uncertainty				6.82

Table B12: Uncertainty contributions in % for IP999 at f = 3.5 MHz

clause	contribution	symbol	coefficient	distribution	standard uncertainty
4.1.a)	s/n interferometer	U_I	1	Gaussian	1,76
4.1.a)	s/n hydrophone	U_H	1	Gaussian	0,20
4.1.b)	resolution of the oscilloscope	O_H	1	rectangular	1,00
4.1.b)	resolution of the oscilloscope	O_I	1	rectangular	1,00
4.1.c)	determination of amplitudes	$U_{A,H}$	1	rectangular	0,24
4.1.c)	determination of amplitudes	$U_{A,I}$	1	rectangular	0,24
4.1.d)	voltage at the transducer	T_r	1	rectangular	0,74
4.1.e)	pd frequency response	A_Z	1	Gaussian	2,00
4.1.f)	temperature	J_T	1	Gaussian	0,12
4.1.g)	gain	V	1	Gaussian	0,80
4.1.h)	transmission of foil	Tr	1	rectangular	0,10
4.1.i)	positioning z interferometer	$J_{z,I}$	1	rectangular	0,06
4.1.i)	positioning z hydrophone	$J_{z,H}$	1	rectangular	0,06
4.1.j)	positioning r interferometer	$J_{r,I}$	2	rectangular	0,00
4.1.j)	positioning r hydrophone	$J_{r,H}$	2	rectangular	0,00
4.1.k)	spatial aver. interferometer	$F_{sp,I}$	1	rectangular	0,00
4.1.k)	spatial aver. hydrophone	$F_{sp,H}$	1	rectangular	0,01
4.1.l)	effective diameter hydrophone	$F_{d,H}$	1	rectangular	0,01
4.1.m)	inhomogeneity sound field	I_h	1	rectangular	0,00
4.1.n)	open circuit correction	L	1	rectangular	0,00
4.1.o)	laser intensity	I_L	1	rectangular	0,58
4.1.p)	relais and highpass filter	Hpf	1	Gaussian	0,07
4.3	Pythagorean sum type B				3.29
4.2	type A				0.12
4.3	standard uncertainty				3.29
4.3	expanded uncertainty				6.58

Table B13: Uncertainty contributions in % for IP999 at f = 5 MHz

clause	contribution	symbol	coefficient	distribution	standard uncertainty
4.1.a)	s/n interferometer	U_I	1	Gaussian	1,61
4.1.a)	s/n hydrophone	U_H	1	Gaussian	0,19
4.1.b)	resolution of the oscilloscope	O_H	1	rectangular	1,00
4.1.b)	resolution of the oscilloscope	O_I	1	rectangular	1,00
4.1.c)	determination of amplitudes	$U_{A,H}$	1	rectangular	0,24
4.1.c)	determination of amplitudes	$U_{A,I}$	1	rectangular	0,24
4.1.d)	voltage at the transducer	T_r	1	rectangular	0,74
4.1.e)	pd frequency response	A_Z	1	Gaussian	2,00
4.1.f)	temperature	J_T	1	Gaussian	0,12
4.1.g)	gain	V	1	Gaussian	0,80
4.1.h)	transmission of foil	Tr	1	rectangular	0,14
4.1.i)	positioning z interferometer	$J_{z,I}$	1	rectangular	0,06
4.1.i)	positioning z hydrophone	$J_{z,H}$	1	rectangular	0,06
4.1.j)	positioning r interferometer	$J_{r,I}$	2	rectangular	0,00
4.1.j)	positioning r hydrophone	$J_{r,H}$	2	rectangular	0,00
4.1.k)	spatial aver. interferometer	$F_{sp,I}$	1	rectangular	0,00
4.1.k)	spatial aver. hydrophone	$F_{sp,H}$	1	rectangular	0,01
4.1.l)	effective diameter hydrophone	$F_{d,H}$	1	rectangular	0,02
4.1.m)	inhomogeneity sound field	I_h	1	rectangular	0,00
4.1.n)	open circuit correction	L	1	rectangular	0,00
4.1.o)	laser intensity	I_L	1	rectangular	0,58
4.1.p)	relais and highpass filter	Hpf	1	Gaussian	0,07
4.3	Pythagorean sum type B				3.21
4.2	type A				0.06
4.3	standard uncertainty				3.21
4.3	expanded uncertainty				6.43

Table B14: Uncertainty contributions in % for IP999 at f = 10 MHz

clause	contribution	symbol	coefficient	distribution	standard uncertainty
4.1.a)	s/n interferometer	U_I	1	Gaussian	1,11
4.1.a)	s/n hydrophone	U_H	1	Gaussian	0,13
4.1.b)	resolution of the oscilloscope	O_H	1	rectangular	1,00
4.1.b)	resolution of the oscilloscope	O_I	1	rectangular	1,00
4.1.c)	determination of amplitudes	$U_{A,H}$	1	rectangular	0,24
4.1.c)	determination of amplitudes	$U_{A,I}$	1	rectangular	0,24
4.1.d)	voltage at the transducer	T_r	1	rectangular	0,74
4.1.e)	pd frequency response	A_Z	1	Gaussian	2,00
4.1.f)	temperature	J_T	1	Gaussian	0,12
4.1.g)	gain	V	1	Gaussian	0,80
4.1.h)	transmission of foil	Tr	1	rectangular	0,30
4.1.i)	positioning z interferometer	$J_{z,I}$	1	rectangular	0,06
4.1.i)	positioning z hydrophone	$J_{z,H}$	1	rectangular	0,05
4.1.j)	positioning r interferometer	$J_{r,I}$	2	rectangular	0,01
4.1.j)	positioning r hydrophone	$J_{r,H}$	2	rectangular	0,01
4.1.k)	spatial aver. interferometer	$F_{sp,I}$	1	rectangular	0,00
4.1.k)	spatial aver. hydrophone	$F_{sp,H}$	1	rectangular	0,05
4.1.l)	effective diameter hydrophone	$F_{d,H}$	1	rectangular	0,09
4.1.m)	inhomogeneity sound field	I_h	1	rectangular	0,00
4.1.n)	open circuit correction	L	1	rectangular	0,00
4.1.o)	laser intensity	I_L	1	rectangular	0,58
4.1.p)	relais and highpass filter	Hpf	1	Gaussian	0,07
4.3	Pythagorean sum type B				3.00
4.2	type A				0.41
4.3	standard uncertainty				3.03
4.3	expanded uncertainty				6.06

Table B15: Uncertainty contributions in % for IP999 at f = 15 MHz

clause	contribution	symbol	coefficient	distribution	standard uncertainty
4.1.a)	s/n interferometer	U_I	1	Gaussian	0,61
4.1.a)	s/n hydrophone	U_H	1	Gaussian	0,07
4.1.b)	resolution of the oscilloscope	O_H	1	rectangular	1,00
4.1.b)	resolution of the oscilloscope	O_I	1	rectangular	1,00
4.1.c)	determination of amplitudes	$U_{A,H}$	1	rectangular	0,24
4.1.c)	determination of amplitudes	$U_{A,I}$	1	rectangular	0,24
4.1.d)	voltage at the transducer	T_r	1	rectangular	0,74
4.1.e)	pd frequency response	A_Z	1	Gaussian	2,00
4.1.f)	temperature	J_T	1	Gaussian	0,12
4.1.g)	gain	V	1	Gaussian	0,80
4.1.h)	transmission of foil	Tr	1	rectangular	0,50
4.1.i)	positioning z interferometer	$J_{z,I}$	1	rectangular	0,03
4.1.i)	positioning z hydrophone	$J_{z,H}$	1	rectangular	0,02
4.1.j)	positioning r interferometer	$J_{r,I}$	2	rectangular	0,04
4.1.j)	positioning r hydrophone	$J_{r,H}$	2	rectangular	0,03
4.1.k)	spatial aver. interferometer	$F_{sp,I}$	1	rectangular	0,00
4.1.k)	spatial aver. hydrophone	$F_{sp,H}$	1	rectangular	0,23
4.1.l)	effective diameter hydrophone	$F_{d,H}$	1	rectangular	0,23
4.1.m)	inhomogeneity sound field	I_h	1	rectangular	0,10
4.1.n)	open circuit correction	L	1	rectangular	0,00
4.1.o)	laser intensity	I_L	1	rectangular	0,58
4.1.p)	relais and highpass filter	Hpf	1	Gaussian	0,07
4.3	Pythagorean sum type B				2.90
4.2	type A				1.45
4.3	standard uncertainty				3.24
4.3	expanded uncertainty				6.48

Table B16: Uncertainty contributions in % for IP999 at $f = 20$ MHz

clause	contribution	symbol	coefficient	distribution	standard uncertainty
4.1.a)	s/n interferometer	U_I	1	Gaussian	0,11
4.1.a)	s/n hydrophone	U_H	1	Gaussian	0,01
4.1.b)	resolution of the oscilloscope	O_H	1	rectangular	1,00
4.1.b)	resolution of the oscilloscope	O_I	1	rectangular	1,00
4.1.c)	determination of amplitudes	$U_{A,H}$	1	rectangular	0,24
4.1.c)	determination of amplitudes	$U_{A,I}$	1	rectangular	0,24
4.1.d)	voltage at the transducer	T_r	1	rectangular	0,74
4.1.e)	pd frequency response	A_Z	1	Gaussian	2,00
4.1.f)	temperature	J_T	1	Gaussian	0,12
4.1.g)	gain	V	1	Gaussian	0,80
4.1.h)	transmission of foil	Tr	1	rectangular	0,71
4.1.i)	positioning *z* interferometer	$J_{z,I}$	1	rectangular	0,02
4.1.i)	positioning *z* hydrophone	$J_{z,H}$	1	rectangular	0,01
4.1.j)	positioning *r* interferometer	$J_{r,I}$	2	rectangular	0,06
4.1.j)	positioning *r* hydrophone	$J_{r,H}$	2	rectangular	0,05
4.1.k)	spatial aver. interferometer	$F_{sp,I}$	1	rectangular	0,00
4.1.k)	spatial aver. hydrophone	$F_{sp,H}$	1	rectangular	0,14
4.1.l)	effective diameter hydrophone	$F_{d,H}$	1	rectangular	0,35
4.1.m)	inhomogeneity sound field	I_h	1	rectangular	0,18
4.1.n)	open circuit correction	L	1	rectangular	0,00
4.1.o)	laser intensity	I_L	1	rectangular	0,58
4.1.p)	relais and highpass filter	Hpf	1	Gaussian	0,07
4.3	Pythagorean sum type B				2.89
4.2	type A				2.28
4.3	standard uncertainty				3.68
4.3	expanded uncertainty				7.37

APPENDIX D: REPORT SUBMITTED BY NATIONAL METROLOGY INSTITUTE, JAPAN.

Comparison of ultrasonic hydrophone calibrations in the frequency range 0.5 MHz to 20 MHz

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Abstract

This report describes the absolute calibrations of two 1 mm membrane hydrophones carried out by the National Metrology Institute of Japan (NMIJ) as a part of the CIPM/BIPM key comparison CCAUV.U-K4. The calibration method, the calibration results, and measurement uncertainties are reported.

November 2014

1. Introduction

This report describes the absolute calibrations of two 1 mm membrane hydrophones carried out by NMIJ in the CIPM/BIPM key comparison CCAUV.U-K4. The key comparison was coordinated by the National Physical Laboratory (NPL) in compliance with the technical protocol document [1].

NMIJ participated in this key comparison and calibrated the two membrane hydrophones (Serial number: IP999 and ER070) using optical interferometry and the NPL amplifier (Serial number: 5564166LF).

Four independent calibrations were carried out for each hydrophone at 8 nominal frequencies of 0.5 MHz, 1 MHz, 2.25 MHz, 3.5 MHz, 5 MHz, 10 MHz, 15 MHz, and 20 MHz. The calibrations were performed from September 2014 to October 2014.

2. Calibration using optical interferometry

2.1 Calibration method

The hydrophones are absolutely calibrated using optical interferometry in accordance with IEC 62127-2:2013 by [2, 3, and 4]. They are calibrated four times on different days and different alignment. Fig. 1 portrays a block diagram of our hydrophone calibration system [5]. Tone-burst ultrasound is generated from a transducer and alternately observed using a stabilized Michelson interferometer and the hydrophone to be calibrated. The amplitude of the hydrophone sensitivity $M(f)$ is given as

$$M(f) = \frac{V_{\mathrm{h}}(f)}{p(f)} = \frac{V_{\mathrm{h}}(f)}{2\pi f \rho c U(f)}, \qquad (1)$$

where f is the ultrasound frequency [5]. $p(f)$ is sound-pressure amplitude of the incident plane wave and $V_{\mathrm{h}}(f)$ is the hydrophone output voltage amplitude. $U(f)$ is ultrasound displacement amplitude of the incident plane wave and is measured using the interferometer. ρ is the water density and c is the sound velocity in water. The water temperature is measured using a thermometer (TECHNOL SEVEN, D641) with a 0.1 °C accuracy and is used to calculate ρ and c. The room temperature is controlled at 21 °C ± 0.5 °C to stabilize the water temperature. Then, $U(f)$ is given as

$$U(f) = \frac{OP_{\mathrm{T}}(f)}{n^* \times t_{\mathrm{T}}(f) \times K(f)}, \qquad (2)$$

where $OP_{\mathrm{T}}(f)$ is the optical path length change measured using the interferometer. n^* is the effective refractive index of water [2, 3, and 4]. The pellicle transmission coefficient [2, 3, and 4] $t_{\mathrm{T}}(f)$ is experimentally determined and is defined as the ratio of the ultrasound displacement amplitude in the interferometer side of pellicle surface to that in the absence of the pellicle. The twice-modulated light system [6] is used to measure the frequency response of the photo detector, $K(f)$.

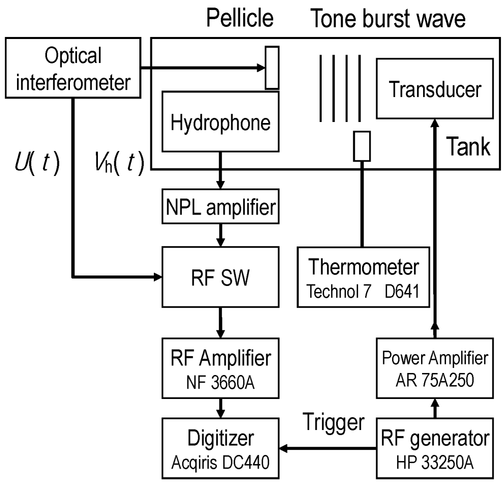

Figure 1 The block diagram of the NMIJ hydrophone calibration system

Signals from the interferometer and the NPL amplifier (Serial number 5564166LF) are amplified using an RF amplifier (NF Corporation, 3660A) and are averaged 2560 times to increase the signal-to-noise ratio. They are recorded using a 12-bit digitizer (Aqiris, DC440) with the external clock mode of 102.4 MHz. For data acquisition, the record length and the type of the time window are 1024 points and flat, respectively. The signal amplitude is calculated using the fast Fourier transformation (FFT). The frequency interval for the FFT of the signals is fixed to 100 kHz in our system. Thus hydrophones are calibrated at 2.2 MHz instead of 2.25 MHz. Hydrophones are also calibrated at 2.3 MHz. It was confirmed that the difference between the hydrophones calibration results at those two frequencies is negligible.

The transducer generates tone-burst ultrasound with 20 µs pulse duration. The two lateral positions and the two rotation angles of the transducer are controlled accurately to maximize the hydrophone output voltage amplitude. The propagation distance between the transducer and the detection point is adjusted using the ultrasound propagation time.

A 1 mW frequency-stabilized He–Ne laser is used as the interferometer probe laser, which is operated at the wavelength of 633 nm. A 5-µm-thick polyethylene terephthalate (PET) film with a 300 nm gold coating on the surface of interferometer side is used as a pellicle. This pellicle is acoustically transparent and optically reflective. The pellicle is stretched over a circular frame. Inner and outer diameter of the frame is 80 mm and 100 mm, respectively. The direct waves from the transducer and the reflected waves from the frame are separated using the arrival time difference. The frame and the hydrophone are alternately set to the common holder. Therefore, the interferometer and the hydrophone can observe the ultrasonic wave at almost the same positions.

2.2 Information on calibration

The water tank is filled with distilled water. Water is circulated in a deionizer and a degassing apparatus (ERC, 3702W) before calibrations. The dissolved oxygen level is measured using a DO level meter (Iijima, ID-100) and is kept below 4 mg/L. The electrical conductivity is measured using a hand-held conductivity meter (Eutech instruments, CON400) and is kept below 0.8 µS.

The hydrophone is soaked in degassed water at least one hour before measurements. The measurement apparatus is also switched on at least one hour before uses for warming up.

The gain switch of the NPL amplifier is set to the mode x5 for the calibration at 1 MHz and is set to the mode x1 at the other frequencies. The measured sensitivity is corrected to calibrate the open-circuit sensitivity by multiplying the open-circuit factor on the Table 1 of the protocol.

Figure 2 shows a block diagram to determine the NPL amplifier gain. The output impedance of the RF generator and the input impedance of the digitizer are set to 50 Ω. The input of the NPL amplifier is terminated using a 50 Ω resistance. Tone burst wave is generated from the RF generator (Agilent Technologies, 33250A) and fed into the digitizer. The amplifier gain is measured by comparing the voltage amplitude with and without the NPL amplifier. The amplifier gain at each frequency is determined by averaging the measured values for the input voltage amplitude of 2.5 mV, 5 mV and 10 mV.

Our acrylic water tank has inner dimensions of 0.4 m in height, 0.8 m in width and 0.3 m in length. The water depth is 0.3 m. The hydrophone earth pin is connected to the metal optical table where the water tank and the optical interferometer are placed.

The spatial-averaging effect at the hydrophone is corrected using the equation (11) by Bacon [2]. The effective radius of hydrophones on the Table 3 in the protocol is used for the calculation.

Three types of piezoelectric zirconate titanate (PZT) transducers are used to cover the whole frequency range. Table 1 shows the specifications of these transducers.

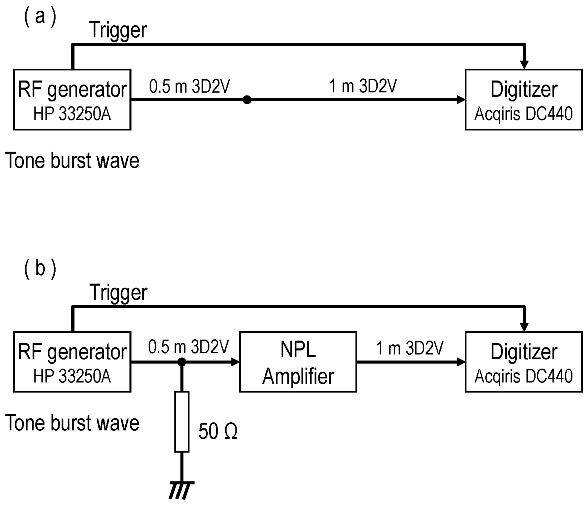

Figure 2 The block diagram to determine the NPL amplifier gain; (a) Reference measurement, (b) Gain measurement.

Table 1 Propagation parameters of the sound source transducers.

Ultrasound nominal frequency (MHz)	Transducer type / manufacturer	Transducer active element diameter (mm)	Typical sound pressure (kPa)	Propagation distance (mm)
0.5	V301 / Olympus	25.4	36.7	100
1	V309 / Olympus	12.7	5.6	370
2.25			29.7	
3.5			61.8	
5			78.3	
10	V313 / Olympus	6.35	25.9	270
15			24.9	
20			6.8	

3. Results

3.1 IP999

Calibration results of hydrophone IP999 for each frequency are shown in Table 2-9 and summarized in Table 10.

Table 2 Calibration report table for hydrophone IP999 at 0.5 MHz

Participating Laboratory: NMIJ		Calibration method: Optical interferometry		
Date (s) of calibrations: 21, 22, 23, and 24 September 2014		Hydrophone serial number: IP999		
Nominal frequency (MHz): 0.5				
Measurement Number	1	2	3	4
Date of calibration	21 Sep. 2014	22 Sep. 2014	23 Sep. 2014	24 Sep. 2014
Actual frequency (MHz)	0.5	0.5	0.5	0.5
Temperature, T (℃)	20.5	20.5	20.4	20.5
Open-circuit correction	1.0722	1.0722	1.0722	1.0722
Water conductivity (μS)	< 0.8	< 0.8	< 0.8	< 0.8
Oxgen content (mg/l)	< 4.0	< 4.0	< 4.0	< 4.0
Amplifier gain (dB)	-0.62	-0.62	-0.62	-0.62
Measured sensitivity (nV/Pa)	184.6	182.6	184.1	183.8
Open-circuit sensitivity at T ℃ (nV/Pa)	212.7	210.4	212.1	211.8
Notes (e.g. of any unusual difficulties)				

Table 3 Calibration report table for hydrophone IP999 at 1 MHz

Participating Laboratory: NMIJ		Calibration method: Optical interferometry		
Date (s) of calibrations: 21, 22, 23, and 24 September 2014		Hydrophone serial number: IP999		
Nominal frequency (MHz): 1				
Measurement Number	1	2	3	4
Date of calibration	21 Sep. 2014	22 Sep. 2014	23 Sep. 2014	24 Sep. 2014
Actual frequency (MHz)	1	1	1	1
Temperature, T (℃)	20.5	20.5	20.5	20.6
Open-circuit correction	1.0748	1.0748	1.0748	1.0748
Water conductivity (μS)	< 0.8	< 0.8	< 0.8	< 0.8
Oxgen content (mg/l)	< 4.0	< 4.0	< 4.0	< 4.0
Amplifier gain (dB)	13.26	13.26	13.26	13.26
Measured sensitivity (nV/Pa)	901.3	903.0	897.9	904.1
Open-circuit sensitivity at T ℃ (nV/Pa)	210.5	210.9	209.7	211.2
Notes (e.g. of any unusual difficulties)				

Table 4 Calibration report table for hydrophone IP999 at 2.25 MHz

Participating Laboratory: NMIJ		Calibration method: Optical interferometry		
Date (s) of calibrations: 21, 22, 23, and 24 September 2014		Hydrophone serial number: IP999		
Nominal frequency (MHz): 2.25				
Measurement Number	1	2	3	4
Date of calibration	21 Sep. 2014	22 Sep. 2014	23 Sep. 2014	24 Sep. 2014
Actual frequency (MHz)	2.2	2.2	2.2	2.2
Temperature, T (℃)	20.5	20.5	20.5	20.6
Open-circuit correction	1.0787	1.0787	1.0787	1.0787
Water conductivity (μS)	< 0.8	< 0.8	< 0.8	< 0.8
Oxgen content (mg/l)	< 4.0	< 4.0	< 4.0	< 4.0
Amplifier gain (dB)	-0.76	-0.76	-0.76	-0.76
Measured sensitivity (nV/Pa)	180.3	181.4	181.4	180.7
Open-circuit sensitivity at T ℃ (nV/Pa)	212.2	213.6	213.6	212.7
Notes (e.g. of any unusual difficulties)				

Table 5 Calibration report table for hydrophone IP999 at 3.5 MHz

Participating Laboratory: NMIJ		Calibration method: Optical interferometry		
Date (s) of calibrations: 21, 22, 23, and 24 September 2014		Hydrophone serial number: IP999		
Nominal frequency (MHz): 3.5				
Measurement Number	1	2	3	4
Date of calibration	21 Sep. 2014	22 Sep. 2014	23 Sep. 2014	24 Sep. 2014
Actual frequency (MHz)	3.5	3.5	3.5	3.5
Temperature, T (℃)	20.5	20.5	20.5	20.6
Open-circuit correction	1.0805	1.0805	1.0805	1.0805
Water conductivity (μS)	< 0.8	< 0.8	< 0.8	< 0.8
Oxgen content (mg/l)	< 4.0	< 4.0	< 4.0	< 4.0
Amplifier gain (dB)	-0.92	-0.92	-0.92	-0.92
Measured sensitivity (nV/Pa)	179.4	179.0	178.8	178.9
Open-circuit sensitivity at T ℃ (nV/Pa)	215.4	214.9	214.7	214.8
Notes (e.g. of any unusual difficulties)				

Table 6 Calibration report table for hydrophone IP999 at 5 MHz

Participating Laboratory: NMIJ		Calibration method: Optical interferometry		
Date (s) of calibrations: 21, 22, 23, and 24 September 2014		Hydrophone serial number: IP999		
Nominal frequency (MHz): 5				
Measurement Number	1	2	3	4
Date of calibration	21 Sep. 2014	22 Sep. 2014	23 Sep. 2014	24 Sep. 2014
Actual frequency (MHz)	5	5	5	5
Temperature, T (℃)	20.5	20.5	20.5	20.6
Open-circuit correction	1.0823	1.0823	1.0823	1.0823
Water conductivity (μS)	< 0.8	< 0.8	< 0.8	< 0.8
Oxgen content (mg/l)	< 4.0	< 4.0	< 4.0	< 4.0
Amplifier gain (dB)	-1.15	-1.15	-1.15	-1.15
Measured sensitivity (nV/Pa)	178.1	176.0	177.2	177.1
Open-circuit sensitivity at T ℃ (nV/Pa)	220.1	217.5	218.9	218.8
Notes (e.g. of any unusual difficulties)				

Table 7 Calibration report table for hydrophone IP999 at 10 MHz

Participating Laboratory: NMIJ		Calibration method: Optical interferometry		
Date (s) of calibrations: 21, 22, 23, and 24 September 2014		Hydrophone serial number: IP999		
Nominal frequency (MHz): 10				
Measurement Number	1	2	3	4
Date of calibration	21 Sep. 2014	22 Sep. 2014	23 Sep. 2014	24 Sep. 2014
Actual frequency (MHz)	10	10	10	10
Temperature, T (℃)	20.6	20.5	20.5	20.6
Open-circuit correction	1.0854	1.0854	1.0854	1.0854
Water conductivity (μS)	< 0.8	< 0.8	< 0.8	< 0.8
Oxgen content (mg/l)	< 4.0	< 4.0	< 4.0	< 4.0
Amplifier gain (dB)	-2.38	-2.38	-2.38	-2.38
Measured sensitivity (nV/Pa)	172.4	168.9	166.3	167.9
Open-circuit sensitivity at T ℃ (nV/Pa)	246.1	241.1	237.4	239.7
Notes (e.g. of any unusual difficulties)				

Table 8 Calibration report table for hydrophone IP999 at 15 MHz

Participating Laboratory: NMIJ			Calibration method: Optical interferometry	
Date (s) of calibrations: 21, 22, 23, and 24 September 2014			Hydrophone serial number: IP999	
Nominal frequency (MHz): 15				
Measurement Number	1	2	3	4
Date of calibration	21 Sep. 2014	22 Sep. 2014	23 Sep. 2014	24 Sep. 2014
Actual frequency (MHz)	15	15	15	15
Temperature, T (℃)	20.6	20.5	20.5	20.6
Open-circuit correction	1.0858	1.0858	1.0858	1.0858
Water conductivity (μS)	< 0.8	< 0.8	< 0.8	< 0.8
Oxgen content (mg/l)	< 4.0	< 4.0	< 4.0	< 4.0
Amplifier gain (dB)	-4.03	-4.03	-4.03	-4.03
Measured sensitivity (nV/Pa)	173.8	172.8	172.3	170.9
Open-circuit sensitivity at T ℃ (nV/Pa)	300.1	298.3	297.5	295.0
Notes (e.g. of any unusual difficulties)				

Table 9 Calibration report table for hydrophone IP999 at 20 MHz

Participating Laboratory: NMIJ			Calibration method: Optical interferometry	
Date (s) of calibrations: 21, 22, 23, and 24 September 2014			Hydrophone serial number: IP999	
Nominal frequency (MHz): 20				
Measurement Number	1	2	3	4
Date of calibration	21 Sep. 2014	22 Sep. 2014	23 Sep. 2014	24 Sep. 2014
Actual frequency (MHz)	20	20	20	20
Temperature, T (℃)	20.6	20.5	20.5	20.6
Open-circuit correction	1.0853	1.0853	1.0853	1.0853
Water conductivity (μS)	< 0.8	< 0.8	< 0.8	< 0.8
Oxgen content (mg/l)	< 4.0	< 4.0	< 4.0	< 4.0
Amplifier gain (dB)	-5.93	-5.93	-5.93	-5.93
Measured sensitivity (nV/Pa)	163.1	166.0	163.3	167.7
Open-circuit sensitivity at T ℃ (nV/Pa)	350.1	356.4	350.6	360.1
Notes (e.g. of any unusual difficulties)				

Table 10 Calibration report table for hydrophone IP999

Participating Laboratory: NMIJ			Method: Optical interferometry					
Dates: 21 to 24 September 2014	Hydrophone serial number: IP999							
Nominal frequency (MHz):	0.5	1	2.25	3.5	5	10	15	20
Actual frequency (MHz)	0.5	1	2.2	3.5	5	10	15	20
Mean open-circuit sensitivity at T ℃ (nV/Pa)	211.8	210.6	213.0	214.9	218.8	241.1	297.7	354.3
Type A standard uncertainty (%)	0.23	0.15	0.16	0.08	0.24	0.77	0.36	0.68
Type B standard uncertainty (%)	2.00	2.00	2.00	2.00	2.00	2.40	2.70	3.50
Coverage factor (*k*)	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Expanded uncertainty (%)	4.0	4.0	4.0	4.0	4.0	5.0	5.4	7.1

3.2 ER070

Calibration results of hydrophone ER070 for each frequency are shown in Table 11-18 and summarized in Table 19.

Table 11 Calibration report table for hydrophone ER070 at 0.5 MHz

Participating Laboratory: NMIJ		Calibration method: Optical interferometry		
Date (s) of calibrations: 25, 26, 27, and 28 September 2014		Hydrophone serial number: ER070		
Nominal frequency (MHz): 0.5				
Measurement Number	1	2	3	4
Date of calibration	25 Sep. 2014	26 Sep. 2014	27 Sep. 2014	28 Sep. 2014
Actual frequency (MHz)	0.5	0.5	0.5	0.5
Temperature, T (℃)	20.5	20.4	20.4	20.5
Open-circuit correction	1.0519	1.0519	1.0519	1.0519
Water conductivity (μS)	< 0.8	< 0.8	< 0.8	< 0.8
Oxgen content (mg/l)	< 4.0	< 4.0	< 4.0	< 4.0
Amplifier gain (dB)	-0.62	-0.62	-0.62	-0.62
Measured sensitivity (nV/Pa)	108.0	108.5	107.3	108.4
Open-circuit sensitivity at T ℃ (nV/Pa)	122.1	122.6	121.3	122.5
Notes (e.g. of any unusual difficulties)				

Table 12 Calibration report table for hydrophone ER070 at 1 MHz

Participating Laboratory: NMIJ		Calibration method: Optical interferometry		
Date (s) of calibrations: 25, 26, 27, and 28 September 2014		Hydrophone serial number: ER070		
Nominal frequency (MHz): 1				
Measurement Number	1	2	3	4
Date of calibration	25 Sep. 2014	26 Sep. 2014	27 Sep. 2014	28 Sep. 2014
Actual frequency (MHz)	1	1	1	1
Temperature, T (℃)	20.5	20.4	20.5	20.6
Open-circuit correction	1.0545	1.0545	1.0545	1.0545
Water conductivity (μS)	< 0.8	< 0.8	< 0.8	< 0.8
Oxgen content (mg/l)	< 4.0	< 4.0	< 4.0	< 4.0
Amplifier gain (dB)	13.26	13.26	13.26	13.26
Measured sensitivity (nV/Pa)	547.5	544.3	543.8	546.4
Open-circuit sensitivity at T ℃ (nV/Pa)	125.5	124.7	124.6	125.2
Notes (e.g. of any unusual difficulties)				

Table 13 Calibration report table for hydrophone ER070 at 2.25 MHz

Participating Laboratory: NMIJ		Calibration method: Optical interferometry		
Date (s) of calibrations: 25, 26, 27, and 28 September 2014		Hydrophone serial number: ER070		
Nominal frequency (MHz): 2.25				
Measurement Number	1	2	3	4
Date of calibration	25 Sep. 2014	26 Sep. 2014	27 Sep. 2014	28 Sep. 2014
Actual frequency (MHz)	2.2	2.2	2.2	2.2
Temperature, T (℃)	20.5	20.4	20.5	20.6
Open-circuit correction	1.0584	1.0584	1.0584	1.0584
Water conductivity (μS)	< 0.8	< 0.8	< 0.8	< 0.8
Oxgen content (mg/l)	< 4.0	< 4.0	< 4.0	< 4.0
Amplifier gain (dB)	-0.76	-0.76	-0.76	-0.76
Measured sensitivity (nV/Pa)	113.8	113.7	114.2	114.1
Open-circuit sensitivity at T ℃ (nV/Pa)	131.4	131.3	131.9	131.8
Notes (e.g. of any unusual difficulties)				

Table 14 Calibration report table for hydrophone ER070 at 3.5 MHz

Participating Laboratory: NMIJ		Calibration method: Optical interferometry		
Date (s) of calibrations: 25, 26, 27, and 28 September 2014		Hydrophone serial number: ER070		
Nominal frequency (MHz): 3.5				
Measurement Number	1	2	3	4
Date of calibration	25 Sep. 2014	26 Sep. 2014	27 Sep. 2014	28 Sep. 2014
Actual frequency (MHz)	3.5	3.5	3.5	3.5
Temperature, T (℃)	20.5	20.4	20.5	20.5
Open-circuit correction	1.0603	1.0603	1.0603	1.0603
Water conductivity (μS)	< 0.8	< 0.8	< 0.8	< 0.8
Oxgen content (mg/l)	< 4.0	< 4.0	< 4.0	< 4.0
Amplifier gain (dB)	-0.92	-0.92	-0.92	-0.92
Measured sensitivity (nV/Pa)	118.4	117.9	117.8	117.9
Open-circuit sensitivity at T ℃ (nV/Pa)	139.5	138.9	138.8	138.9
Notes (e.g. of any unusual difficulties)				

Table 15 Calibration report table for hydrophone ER070 at 5 MHz

Participating Laboratory: NMIJ			Calibration method: Optical interferometry	
Date (s) of calibrations: 25, 26, 27, and 28 September 2014			Hydrophone serial number: ER070	
Nominal frequency (MHz): 5				
Measurement Number	1	2	3	4
Date of calibration	25 Sep. 2014	26 Sep. 2014	27 Sep. 2014	28 Sep. 2014
Actual frequency (MHz)	5	5	5	5
Temperature, T (℃)	20.5	20.4	20.5	20.5
Open-circuit correction	1.062	1.062	1.062	1.062
Water conductivity (μS)	< 0.8	< 0.8	< 0.8	< 0.8
Oxgen content (mg/l)	< 4.0	< 4.0	< 4.0	< 4.0
Amplifier gain (dB)	-1.15	-1.15	-1.15	-1.15
Measured sensitivity (nV/Pa)	121.3	122.3	121.3	121.0
Open-circuit sensitivity at T ℃ (nV/Pa)	147.1	148.3	147.0	146.7
Notes (e.g. of any unusual difficulties)				

Table 16 Calibration report table for hydrophone ER070 at 10 MHz

Participating Laboratory: NMIJ		Calibration method: Optical interferometry		
Date (s) of calibrations: 25, 26, 27, and 28 September 2014		Hydrophone serial number: ER070		
Nominal frequency (MHz): 10				
Measurement Number	1	2	3	4
Date of calibration	25 Sep. 2014	26 Sep. 2014	27 Sep. 2014	28 Sep. 2014
Actual frequency (MHz)	10	10	10	10
Temperature, T (℃)	20.6	20.5	20.5	20.6
Open-circuit correction	1.0641	1.0641	1.0641	1.0641
Water conductivity (μS)	< 0.8	< 0.8	< 0.8	< 0.8
Oxgen content (mg/l)	< 4.0	< 4.0	< 4.0	< 4.0
Amplifier gain (dB)	-2.38	-2.38	-2.38	-2.38
Measured sensitivity (nV/Pa)	127.9	133.9	129.6	127.8
Open-circuit sensitivity at T ℃ (nV/Pa)	179.0	187.4	181.4	178.9
Notes (e.g. of any unusual difficulties)				

Table 17 Calibration report table for hydrophone ER070 at 15 MHz

<table>
<tr><td colspan="2">Participating Laboratory:

NMIJ</td><td colspan="3">Calibration method:

Optical interferometry</td></tr>
<tr><td colspan="2">Date (s) of calibrations:

25, 26, 27, and 28 September 2014</td><td colspan="3">Hydrophone serial number:

ER070</td></tr>
<tr><td colspan="5">Nominal frequency (MHz): 15</td></tr>
<tr><td>Measurement

Number</td><td>1</td><td>2</td><td>3</td><td>4</td></tr>
<tr><td>Date of calibration</td><td>25 Sep. 2014</td><td>26 Sep. 2014</td><td>27 Sep. 2014</td><td>28 Sep. 2014</td></tr>
<tr><td>Actual frequency (MHz)</td><td>15</td><td>15</td><td>15</td><td>15</td></tr>
<tr><td>Temperature, T (℃)</td><td>20.6</td><td>20.5</td><td>20.5</td><td>20.6</td></tr>
<tr><td>Open-circuit correction</td><td>1.0627</td><td>1.0627</td><td>1.0627</td><td>1.0627</td></tr>
<tr><td>Water conductivity (μS)</td><td>< 0.8</td><td>< 0.8</td><td>< 0.8</td><td>< 0.8</td></tr>
<tr><td>Oxgen content (mg/l)</td><td>< 4.0</td><td>< 4.0</td><td>< 4.0</td><td>< 4.0</td></tr>
<tr><td>Amplifier gain (dB)</td><td>-4.03</td><td>-4.03</td><td>-4.03</td><td>-4.03</td></tr>
<tr><td>Measured sensitivity (nV/Pa)</td><td>138.7</td><td>140.1</td><td>140.5</td><td>140.1</td></tr>
<tr><td>Open-circuit sensitivity at T ℃ (nV/Pa)</td><td>234.3</td><td>236.6</td><td>237.4</td><td>236.7</td></tr>
<tr><td>Notes (e.g. of any unusual difficulties)</td><td></td><td></td><td></td><td></td></tr>
</table>

Table 18 Calibration report table for hydrophone ER070 at 20 MHz

Participating Laboratory: NMIJ			Calibration method: Optical interferometry	
Date (s) of calibrations: 25, 26, 27, and 28 September 2014			Hydrophone serial number: ER070	
Nominal frequency (MHz): 20				
Measurement Number	1	2	3	4
Date of calibration	25 Sep. 2014	26 Sep. 2014	27 Sep. 2014	28 Sep. 2014
Actual frequency (MHz)	20	20	20	20
Temperature, T (℃)	20.6	20.5	20.5	20.6
Open-circuit correction	1.0578	1.0578	1.0578	1.0578
Water conductivity (μS)	< 0.8	< 0.8	< 0.8	< 0.8
Oxgen content (mg/l)	< 4.0	< 4.0	< 4.0	< 4.0
Amplifier gain (dB)	-5.93	-5.93	-5.93	-5.93
Measured sensitivity (nV/Pa)	110.0	113.0	110.9	112.2
Open-circuit sensitivity at T ℃ (nV/Pa)	230.3	236.5	232.0	234.9
Notes (e.g. of any unusual difficulties)				

Table 19 Calibration report table for hydrophone ER070

Participating Laboratory: NMIJ			Method: Optical interferometry					
Dates: 25 to 28 September 2014	Hydrophone serial number: ER070							
Nominal frequency (MHz):	0.5	1	2.25	3.5	5	10	15	20
Actual frequency (MHz)	0.5	1	2.2	3.5	5	10	15	20
Mean open-circuit sensitivity at T ℃ (nV/Pa)	122.1	125.0	131.6	139.0	147.3	181.6	236.2	233.4
Type A standard uncertainty (%)	0.26	0.16	0.10	0.12	0.23	1.10	0.29	0.60
Type B standard uncertainty (%)	2.00	2.00	2.00	2.00	2.00	2.40	2.70	3.50
Coverage factor (*k*)	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Expanded uncertainty (%)	4.0	4.0	4.0	4.0	4.0	5.3	5.4	7.1

4. Uncertainties

4.1 Type B standard uncertainties

Type B standard uncertainties for the calibration at NMIJ is shown in Table 20. The factors of the uncertainties are briefed below.

Table 20 Type B standard uncertainties at each calibration frequency

Symbol	Source of uncertainty	Nominal frequency (MHz)							
		0.5	1	2.25	3.5	5	10	15	20
u1	Signal voltage amplitude (%)	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04
u2	Ultrasound propagation distance (%)	0.29	0.08	0.08	0.08	0.08	0.11	0.11	0.11
u3	Hydrophone orientation (%)	0.00	0.01	0.03	0.06	0.11	0.41	0.91	1.62
u4	Hydrophone spatial averaging (%)	0.43	0.02	0.06	0.13	0.25	0.45	1.00	1.77
u5	Photo-detector frequency response (%)	1.09	1.09	1.09	1.09	1.09	1.48	1.48	1.48
u6	Effective refractive index (%)	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58
u7	Pellicle transmission coefficient (%)	0.30	0.30	0.30	0.30	0.30	0.60	0.80	1.30
u8	Specific acoustic impedance of water ρc (%)	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
u9	Hydrophone pre-amplifier gain (%)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Type B combined standard uncertainty u_B (%)		2.0	2.0	2.0	2.0	2.0	2.4	2.7	3.5

a) Signal voltage amplitude (u1)

The uncertainty is mainly caused by the impedance mismatching, nonlinear error, and quantization error at the digitizer. The uncertainty is estimated to be 1.04 %.

b) Ultrasound propagation distance (u2)

The uncertainty is caused by the difference of the propagation distance between the measurements using the hydrophone and the optical interferometer. The maximum deviation is estimated to be 0.5 mm. The sound-pressure amplitude of the incident wave is assumed to be inversely proportionate to the propagation distance.

c) Hydrophone orientation (u3)

The uncertainty is caused by the misalignment of the two lateral positions between the hydrophone and the transducer. The uncertainty is estimated using the normalized directivity function of the circular piston [7].

d) Hydrophone spatial averaging (u4)

The uncertainty is estimated using the equation (11) by Bacon [2]. The effective radius of hydrophones in the Table 3 of the protocol is used for estimation.

e) Photo-detector frequency response (u5)

The photo detector frequency response is calibrated using the twice-modulated light system [6]. The uncertainty is ranged from 1.09 % to 1.48 %.

f) Effective refractive index (u6)

The uncertainty is caused by the imperfection of the effective refractive index of water and is estimated to be 0.58 %.

g) Pellicle transmission coefficient (u7)

The pellicle transmission coefficient is experimentally determined. The uncertainty is estimated to be from 0.3 % to 1.3 %.

h) Specific acoustic impedance of water *ρc* (u8)

The uncertainty is caused by the water temperature uncertainty and is estimated to be 0.1 %.

i) Hydrophone pre-amplifier gain (u9)

The amplifier gain is experimentally determined. The uncertainty is estimated to be 1 %.

4.2 Type A standard uncertainty

The type A standard uncertainty for each hydrophone is calculated using the standard deviation of four independent calibrations at each frequency.

4.3 Combined and expanded uncertainty

The combined standard uncertainty u_C for each hydrophone at each calibration frequency is given as

$$u_C = \sqrt{u_A{}^2 + u_B{}^2},$$

where u_A and u_B are the type A standard uncertainty and the type B combined standard uncertainty, respectively.

The expanded uncertainty U for each hydrophone at each calibration frequency is given as

$$U = k \cdot u_C,$$

where k is the coverage factor which corresponds to a 95 % of confidence and is determined using effective degrees of freedom [8]. More detailed uncertainty estimation can be referred to the paper [9].

5. References

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APPENDIX E: ORIGINAL REPORT SUBMITTED BY NATIONAL INSTITUTE OF METROLOGY, CHINA.

Laboratory Report from NIM

for CCAUV.U-K4

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2015-3-10

Contents

1. Introduction

The calibration method used by NIM, is based on the Chinese National standard GB/T 15611-1995 <Acoustics – Calibration of high frequency hydrophone> which is a modified version of the IEC Standard 60866 (1987) <Characteristics and calibration of hydrophones for operation in the frequency range 0.5 to 15 MHz>, We completed the measurements of 2 PVDF membrane hydrophones from 16th Nov. 2014 to 31st Jan. 2015.

2. Methods

2.1Description of the Reciprocity Calibration Set-up

The calibration procedure is based on the two-transducer reciprocity method. The systematic diagram of the experimental set-up is shown in Fig. 1. The reciprocal transducer radiates repetitive acoustic tone bursts into a tank filled with water. The duty cycles are well chosen to ensure there are no interferences. Those tone bursts signals are either reflected by a thick stainless steel reflector or directed to the hydrophone to be calibrated. For the self-reciprocity calibration of the transmitter [1], the transducer is adjusted to a position in which the axis of the ultrasonic beam is perpendicular to the surface of the reflector, position 1 in Fig. 1. For the calibration of the hydrophone, the reciprocal transducer is displaced to bring the ultrasonic field in front of the hydrophone, position 2. The alignment device positions the hydrophone to make sure it is in the centre of the ultrasonic beam.

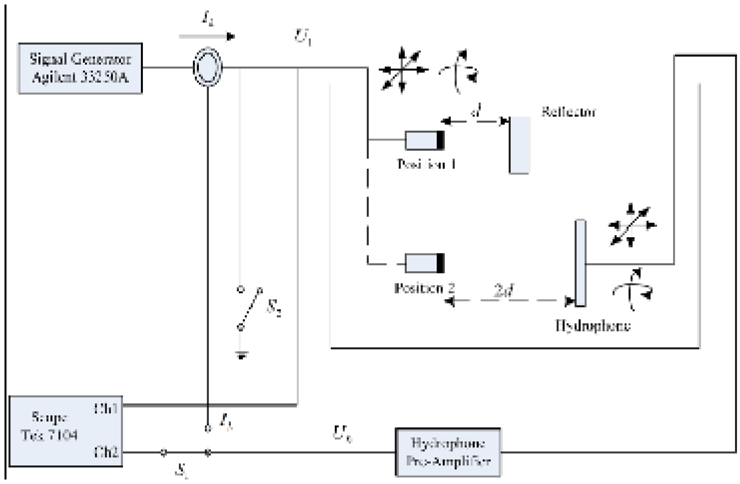

Fig. 1 Schematic diagram of the two-transducer reciprocity calibration method

Furthermore, the distance between the transmitter and the hydrophone is twice to the distance between the transmitter and the reflector. For this calibration set-up the expression for the hydrophone sensitivity is derived as

$$M = \sqrt{\frac{U_k^2}{U_1 I_k}} \cdot \sqrt{\frac{2A_1 r}{\rho c}} \cdot \frac{\sqrt{G_1}}{G_2} e^{\alpha d}$$

In which:

U_k Free field voltage of hydrophone

U_1 Apparent voltage of the reciprocal transducer during receiving of the tone burst

I_k Current through short-circuit introduced in place of the source transducer

A_1 Effective area of the reciprocal transducer

r Pressure reflection coefficient of reflector

ρ Density

c Velocity of sound in water

G_1 Factor for the diffraction loss of the reciprocal transducer

G_2 Factor for the averaging effect of the hydrophone

α Amplitude attenuation coefficient for water

d Distance between transmitter and reflector

2.2 Some Operation Details

1) How was the water prepared for the calibration?

The water was degassed and de-ionized. The conductivity of water was below 0.3 uS. The oxygen content of water was below 6 mg/L.

2) Was the hydrophone soaked in degassed water before use, and for how long?

The hydrophone was soaked in degassed water for about 1 hour.

3) Was the NPL preamplifier used? If not, describe how the open-circuit correction was obtained.

The NPL preamplifier was used.

4) Was it necessary to determine the gain of the preamplifier? If so, describe the method, and estimate its accuracy.

All measurements were included with the NPL preamplifier. It was necessary to determine the gain of the preamplifier. The gain of the preamplifier was determined separately as shown in Fig. 2. The output impedance of signal generator is 50Ω, the coupled impedance of the scope is chosen to be 50Ω. The preamplifier $X5$ gear was used and the gain could be measured through turning the switch to position 1 and position 2. The calibrations of the preamplifier have been calibrated six times and the uncertainty was estimated to be 0.3%.

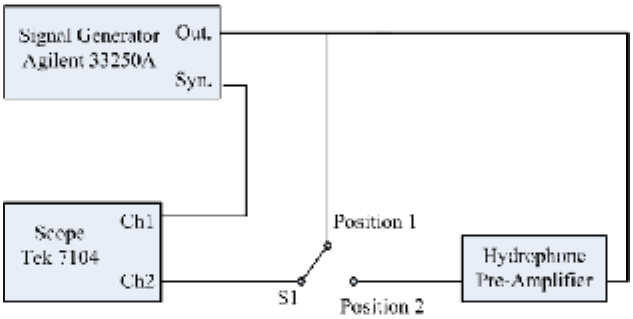

Fig. 2 Schematic diagram of the preamplifier calibration set-up

5) What type of tank was used (give the size and material used in construction) and how were any earth or shielding connections made?

The water tank is made of glass. The size is 900 mm (length)$\times$500 mm (width) $\times$500 mm (height). The aluminum shelf of the water tank is connected to the measuring electronic equipment.

6) How were any corrections for spatial-averaging obtained?

In self-reciprocity calibration of the transmitters, a correction must be applied for the diffraction loss of the transmitted ultrasonic beam. In the experiment, the diffraction loss coefficient G_1 was numerically calculated according to ref [2,3]. Similarly, the spatial averaging effect of the hydrophone was numerically calculated [3] using the effective diameter delivered by NPL.

7) What acoustic pressure was used at each frequency of calibration?

The acoustic pressure used was shown in table 1.

Table-1

Frequency (MHz)	Acoustic Pressure (kPa)
0.5	9.0
1	57.1
2.25	35.2
3.5	50.4
5	27.4
10	42.0
15	16.6
20	35.6

8) What propagation distance(s) was (were) used at each calibration frequency?

The normalized distance was given at each calibration frequency is given in table 2.

Table-2

Frequency (MHz)	Normalized Distance
0.5	1.566
1	1.562
2.25	1.556
3.5	1.557
5	1.557
10	1.570
15	1.565
20	1.563

3. Uncertainties

3.1 Type A Standard Uncertainty

Type A standard uncertainty is evaluated by the statistic method.

$$u_A = \frac{s}{\sqrt{n}} = \frac{\sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}}}{\sqrt{n}}$$

where $\bar{x}$ is the mean value of the sensitivities, n is the number of measurements.

3.2 Type B Standard Uncertainty

The total Type B standard uncertainty in the open-circuit hydrophone sensitivity M_0 is estimated by considering the systematic uncertainty contributions of each component in the expression:

$$M_0 = \sqrt{\frac{U_h^2}{U_1 I_k}} \cdot a \cdot \sqrt{\frac{2\pi}{\rho c}} \cdot \sqrt{r} \cdot \sqrt{G_1} \cdot \frac{1}{G_2} \cdot e^{\alpha d} \cdot k_c$$

Factor: A B C D E F G H

Factor A: Electrical quantities. The electrical quantities U_h, U_1 and I_k are all measured by Tektronix oscilloscope TEK 7104. Current is measured through TCP 0030 connected to the scope. The calibrations are performed at the frequencies and settings of the oscilloscope are identical to those during the hydrophone calibration process. In addition, an impedance uncertainty (0.5 % for each 50Ω impedance) remains. The uncertainty for the electrical quantities is estimated to be 1.

Factor B: Effective radius of the reciprocal transducer. The uncertainty is estimated to be 2%.

Factor C: Due to ρc. As ρc is dependent on temperature and calculated. The uncertainty is estimated to be 0.1%.

Factor D: Reflection coefficient: The value of the reflection coefficient is stated in IEC 62127-2. The uncertainty is small and neglected.

Factor E: Diffraction loss of the reciprocal transducer. Using the results given in reference [2,3] the uncertainty of factor E is estimated to be 2.5%.

Factor F: Averaging effect of the hydrophone. The correction factors G_1 is obtained by interpolation of the table given in [3] . The uncertainty is estimated to be 4%.

Factor G: Attenuation of water path. The attenuation coefficeint dependent on temperature and frequency can be derived from IEC 62127-2. The transition time is measured by oscilloscope. The uncertainty due to attenuation is negligible.

Factor H: Open-circuit correction factor. The open-circuit correction factors are submitted by NPL and are considered as values with a negligible uncertainty.

Factor I: Gain of the preamplifier. The measurement of preamplifer gain is a relative measurement, its uncertainty is based on the accuracy of readings and differences in load impedances. The uncertainty is estimated to be 0.3%.

Factor G: Non-ideal reciprocal transducer. Although the transmitter should be firstly checked for its reciprocity, the calibraiton results can be different using different transducers. We assume the transducers are not ideal reciprocal transducers. The uncertainty is estimated to be 3%.

Table-3 List of Type B relative standard uncertainties (u_i)

Source of measurement Uncertainty	Distribution	Coverage Factor	Value	Relative standard uncertainty /%
Factor A: Electrical Quantities	rect.	1.73	1.0	0.578
Factor B: Effective radius of transducer	Norm	1.96	2.0	1.020
Factor C: due to c	Norm	1.96	0.1	0.051
Factor D: Reflection coefficient			negl.	
Factor E: Diffraction loss of transducer	rect.	1.73	2.5	1.45
Factor F: Averaging effect of hydrophone	rect.	1.73	4.0	2.31
Factor G: Attenuation of water path			negl.	
Factor H: Open-circuit correction			negl.	
Factor I: Gain of the preamplifier	rect.	1.73	0.3	0.173
Factor G: Non-ideal reciprocal transducer	rect.	1.73	3.0	1.734
Total Type B Standard Uncertainty				3.44

3.3 Expanded Uncertainty

The combined standard uncertainty, u_c is calculated by combining the Type A and Type B uncertainties, standard uncertainties according to the procedures

$$u_C = \sqrt{u_A^2 + u_B^2}$$

Finally, the expected uncertainty is calculated using a coverage factor $k = 2$.

$$U = 2 \cdot u_C$$

Which corresponds to a 95% level of confidence if the results are normally distributed.

4. Results

Table-4 Calibration results of IP999

Frequency (MHz)	**0.5**	**1.0**	**2.25**	**3.5**	**5.0**	**10.0**	**15.0**	**20.0**
Mean open-circuit sensitivity (nV/Pa)	101.8	102.8	104.6	106.2	108.5	124.4	141.0	172.2
Type A standard uncertainty (%)	0.44	0.50	0.30	0.16	0.15	0.54	0.51	1.62
Type B standard uncertainty (%)	3.44	3.44	3.44	3.44	3.44	3.44	3.44	3.44
Expanded uncertainty (%) *U* (*k*=2)	6.94	6.96	6.91	6.89	6.89	6.96	6.96	7.61

Table-5 Calibration results of ER070

Frequency (MHz)	**0.5**	**1.0**	**2.25**	**3.5**	**5.0**	**10.0**	**15.0**	**20.0**
Mean open-circuit sensitivity (nV/Pa)	59.1	61.9	64.5	68.6	74.3	91.6	111.9	112.3
Type A standard uncertainty (%)	0.74	0.63	0.34	0.22	0.43	1.53	1.01	0.95
Type B standard uncertainty (%)	3.44	3.44	3.44	3.44	3.44	3.44	3.44	3.44
Expanded uncertainty (%) *U* (*k*=2)	7.04	7.00	6.91	6.89	6.93	7.53	7.18	7.14

Participating laboratory: NIM	Calibration method : Two-transducer reciprocity			
Dates of calibration: 12.22-1.15	Hydrophone serial number: IP999			
Nominal frequency(MHz):	0.5 MHz			
Measurement number	1	2	3	4
Actual frequency (MHz)	0.50	0.50	0.50	0.50
Temperature, T(°C)	19.3	22	21.8	22.2
Open-circuit correction	1.0722	1.0722	1.0722	1.0722
Water conductivity (uS)	0.3	0.1	0.1	0.1
Oxygen content (mgL^{-1})	3.5	3.5	4.2	4.2
Amplifier gain (dB)	19.2897	19.2897	19.2897	19.2897
Measured sensitivity (nV/Pa)	94.2	95.9	95.4	94.3
Open-circuit sensitivity at T °C (nV/Pa)	100.9	102.8	102.3	101.2
Notes (e.g. of any unuaual difficulties)				

Participating laboratory: NIM	Calibration method : Two-transducer reciprocity			
Dates of calibration: 12.22-1.15	Hydrophone serial number: IP999			
Nominal frequency(MHz):	1.0 MHz			
Measurement number	1	2	3	4
Actual frequency (MHz)	1.00	1.00	1.00	1.00
Temperature, T(°C)	19.5	21.6	21.4	21.8
Open-circuit correction	1.0748	1.0748	1.0748	1.0748
Water conductivity (uS)	0.3	0.1	0.1	0.1
Oxygen content (mgL^{-1})	3.5	3.5	4.2	4.2
Amplifier gain (dB)	19.2827	19.2827	19.2827	19.2827
Measured sensitivity (nV/Pa)	94.5	95.6	96.9	95.5
Open-circuit sensitivity at T °C (nV/Pa)	101.6	102.8	104.1	102.6
Notes (e.g. of any unuaual difficulties)				

Participating laboratory: NIM	Calibration method : Two-transducer reciprocity			
Dates of calibration: 12.22-1.15	Hydrophone serial number: IP999			
Nominal frequency(MHz):	2.25 MHz			
Measurement number	1	2	3	4
Actual frequency (MHz)	2.25	2.25	2.25	2.25
Temperature, T(°C)	20.8	21.7	21.3	21.8
Open-circuit correction	1.0787	1.0787	1.0787	1.0787
Water conductivity (uS)	0.3	0.1	0.1	0.1
Oxygen content (mgL^{-1})	3.5	3.5	4.2	4.2
Amplifier gain (dB)	19.2444	19.2444	19.2444	19.2444
Measured sensitivity (nV/Pa)	96.6	97.2	96.3	97.5
Open-circuit sensitivity at T °C (nV/Pa)	104.1	104.9	103.9	105.2
Notes (e.g. of any unuaual difficulties)				

Participating laboratory: NIM	Calibration method : Two-transducer reciprocity			
Dates of calibration: 12.22-1.15	Hydrophone serial number: IP999			
Nominal frequency(MHz):	3.5 MHz			
Measurement number	1	2	3	4
Actual frequency (MHz)	3.50	3.50	3.50	3.50
Temperature, T(°C)	20.8	22	21.5	21.9
Open-circuit correction	1.0805	1.0805	1.0805	1.0805
Water conductivity (uS)	0.3	0.1	0.1	0.1
Oxygen content (mgL^{-1})	3.5	3.5	4.2	4.2
Amplifier gain (dB)	19.0942	19.0942	19.0942	19.0942
Measured sensitivity (nV/Pa)	98.7	98.0	98.0	98.4
Open-circuit sensitivity at T °C (nV/Pa)	106.6	105.9	105.9	106.3
Notes (e.g. of any unuaual difficulties)				

Participating laboratory: NIM	Calibration method : Two-transducer reciprocity			
Dates of calibration: 12.22-1.15	Hydrophone serial number: IP999			
Nominal frequency(MHz):	5 MHz			
Measurement number	1	2	3	4
Actual frequency (MHz)	5.00	5.00	5.00	5.00
Temperature, T(°C)	20.8	22	21.5	21.9
Open-circuit correction	1.0823	1.0823	1.0823	1.0823
Water conductivity (uS)	0.3	0.1	0.1	0.1
Oxygen content (mgL^{-1})	3.5	3.5	4.2	4.2
Amplifier gain (dB)	18.8604	18.8604	18.8604	18.8604
Measured sensitivity (nV/Pa)	100.6	100.1	100.0	100.2
Open-circuit sensitivity at T °C (nV/Pa)	108.9	108.3	108.2	108.4
Notes (e.g. of any unuaual difficulties)				

Participating laboratory: NIM	Calibration method : Two-transducer reciprocity			
Dates of calibration: 12.22-1.15	Hydrophone serial number: IP999			
Nominal frequency(MHz):	10 MHz			
Measurement number	1	2	3	4
Actual frequency (MHz)	10.00	10.00	10.00	10.00
Temperature, T(°C)	19.6	22	21.8	22.2
Open-circuit correction	1.0854	1.0854	1.0854	1.0854
Water conductivity (uS)	0.3	0.1	0.1	0.1
Oxygen content (mgL^{-1})	3.5	3.5	4.2	4.2
Amplifier gain (dB)	17.4970	17.4970	17.4970	17.4970
Measured sensitivity (nV/Pa)	114.4	115.3	115.6	112.8
Open-circuit sensitivity at T °C (nV/Pa)	124.2	125.1	125.5	122.5
Notes (e.g. of any unuaual difficulties)				

Participating laboratory: NIM	Calibration method : Two-transducer reciprocity			
Dates of calibration: 12.22-1.15	Hydrophone serial number: IP999			
Nominal frequency(MHz):	15 MHz			
Measurement number	1	2	3	4
Actual frequency (MHz)	15.00	15.00	15.00	15.00
Temperature, T(°C)	20.1	22	21.6	22.1
Open-circuit correction	1.0858	1.0858	1.0858	1.0858
Water conductivity (uS)	0.3	0.1	0.1	0.1
Oxygen content (mgL^{-1})	3.5	3.5	4.2	4.2
Amplifier gain (dB)	15.2819	15.2819	15.2819	15.2819
Measured sensitivity (nV/Pa)	131.8	129.0	129.0	129.6
Open-circuit sensitivity at T °C (nV/Pa)	143.1	140.1	140.1	140.7
Notes (e.g. of any unuaual difficulties)				

Participating laboratory: NIM	Calibration method : Two-transducer reciprocity			
Dates of calibration: 12.22-1.15	Hydrophone serial number: IP999			
Nominal frequency(MHz):	20 MHz			
Measurement number	1	2	3	4
Actual frequency (MHz)	20.00	20.00	20.00	20.00
Temperature, T(°C)	20	22	21.7	22.2
Open-circuit correction	1.0835	1.0835	1.0835	1.0835
Water conductivity (uS)	0.3	0.1	0.1	0.1
Oxygen content (mgL^{-1})	3.5	3.5	4.2	4.2
Amplifier gain (dB)	12.6856	12.6856	12.6856	12.6856
Measured sensitivity (nV/Pa)	165.9	159.1	156.8	153.8
Open-circuit sensitivity at T °C (nV/Pa)	179.7	172.4	169.9	166.6
Notes (e.g. of any unuaual difficulties)				

Participating laboratory: NIM	Calibration method : Two-transducer reciprocity			
Dates of calibration: 12.22-1.15	Hydrophone serial number: ER070			
Nominal frequency(MHz):	0.5 MHz			
Measurement number	1	2	3	4
Actual frequency (MHz)	0.50	0.50	0.50	0.50
Temperature, T(°C)	19.3	22	21.6	22.5
Open-circuit correction	1.0519	1.0519	1.0519	1.0519
Water conductivity (uS)	0.2	0.1	0.1	0.2
Oxygen content (mgL^{-1})	3.5	4.2	5.5	3.7
Amplifier gain (dB)	19.2897	19.2897	19.2897	19.2897
Measured sensitivity (nV/Pa)	55.3	56.0	56.0	57.2
Open-circuit sensitivity at T °C (nV/Pa)	58.1	58.9	58.9	60.2
Notes (e.g. of any unuaual difficulties)				

Participating laboratory: NIM	Calibration method : Two-transducer reciprocity			
Dates of calibration: 12.22-1.15	Hydrophone serial number: ER070			
Nominal frequency(MHz):	1.0 MHz			
Measurement number	1	2	3	4
Actual frequency (MHz)	1.00	1.00	1.00	1.00
Temperature, T(°C)	19.5	22	21.6	22.1
Open-circuit correction	1.0545	1.0545	1.0545	1.0545
Water conductivity (uS)	0.2	0.1	0.1	0.2
Oxygen content (mgL^{-1})	3.5	4.2	5.5	3.7
Amplifier gain (dB)	19.2827	19.2827	19.2827	19.2827
Measured sensitivity (nV/Pa)	59.5	57.8	59.1	58.2
Open-circuit sensitivity at T °C (nV/Pa)	62.7	61.0	62.3	61.4
Notes (e.g. of any unuaual difficulties)				

Participating laboratory: NIM	Calibration method : Two-transducer reciprocity			
Dates of calibration: 12.22-1.15	Hydrophone serial number: ER070			
Nominal frequency(MHz):	2.25 MHz			
Measurement number	1	2	3	4
Actual frequency (MHz)	2.25	2.25	2.25	2.25
Temperature, T(°C)	20.8	22	21.6	22.2
Open-circuit correction	1.0584	1.0584	1.0584	1.0584
Water conductivity (uS)	0.2	0.1	0.1	0.2
Oxygen content (mgL^{-1})	3.5	4.2	5.5	3.7
Amplifier gain (dB)	19.2444	19.2444	19.2444	19.2444
Measured sensitivity (nV/Pa)	60.7	60.7	61.5	60.6
Open-circuit sensitivity at T °C (nV/Pa)	64.2	64.3	65.1	64.2
Notes (e.g. of any unuaual difficulties)				

Participating laboratory: NIM	Calibration method : Two-transducer reciprocity			
Dates of calibration: 12.22-1.15	Hydrophone serial number: ER070			
Nominal frequency(MHz):	3.5 MHz			
Measurement number	1	2	3	4
Actual frequency (MHz)	3.50	3.50	3.50	3.50
Temperature, T(°C)	20.8	22	21.6	22.3
Open-circuit correction	1.0603	1.0603	1.0603	1.0603
Water conductivity (uS)	0.2	0.1	0.1	0.2
Oxygen content (mgL^{-1})	3.5	4.2	5.5	3.7
Amplifier gain (dB)	19.0942	19.0942	19.0942	19.0942
Measured sensitivity (nV/Pa)	64.3	64.9	64.8	64.7
Open-circuit sensitivity at T °C (nV/Pa)	68.2	68.9	68.7	68.6
Notes (e.g. of any unuaual difficulties)				

Participating laboratory: NIM	Calibration method : Two-transducer reciprocity
Dates of calibration: 12.22-1.15	Hydrophone serial number: ER070

Nominal frequency(MHz):	5 MHz			
Measurement number	1	2	3	4
Actual frequency (MHz)	5.00	5.00	5.00	5.00
Temperature, T(℃)	20.8	21.9	21.5	22.3
Open-circuit correction	1.0620	1.0620	1.0620	1.0620
Water conductivity (uS)	0.2	0.1	0.1	0.2
Oxygen content (mgL^{-1})	3.5	4.2	5.5	3.7
Amplifier gain (dB)	18.8604	18.8604	18.8604	18.8604
Measured sensitivity (nV/Pa)	70.3	69.1	70.5	69.8
Open-circuit sensitivity at T ℃ (nV/Pa)	74.6	73.4	74.8	74.1
Notes (e.g. of any unuaual difficulties)				

Participating laboratory: NIM	Calibration method : Two-transducer reciprocity
Dates of calibration: 12.22-1.15	Hydrophone serial number: ER070

Nominal frequency(MHz):	10 MHz			
Measurement number	1	2	3	4
Actual frequency (MHz)	10.00	10.00	10.00	10.00
Temperature, T(℃)	19.6	21.6	21.5	22.4
Open-circuit correction	1.0620	1.0620	1.0620	1.0620
Water conductivity (uS)	0.2	0.1	0.1	0.2
Oxygen content (mgL^{-1})	3.5	4.2	5.5	3.7
Amplifier gain (dB)	17.4970	17.4970	17.4970	17.4970
Measured sensitivity (nV/Pa)	87.6	88.8	83.1	84.8
Open-circuit sensitivity at T ℃ (nV/Pa)	93.2	94.4	88.3	90.2
Notes (e.g. of any unuaual difficulties)				

Participating laboratory: NIM		Calibration method : Two-transducer reciprocity		
Dates of calibration: 12.22-1.15		Hydrophone serial number: ER070		
Nominal frequency(MHz):	15 MHz			
Measurement number	1	2	3	4
Actual frequency (MHz)	15.00	15.00	15.00	15.00
Temperature, T(℃)	20.1	21.6	21.4	22.4
Open-circuit correction	1.0627	1.0627	1.0627	1.0627
Water conductivity (uS)	0.2	0.1	0.1	0.2
Oxygen content (mgL^{-1})	3.5	4.2	5.5	3.7
Amplifier gain (dB)	15.2819	15.2819	15.2819	15.2819
Measured sensitivity (nV/Pa)	105.6	104.9	102.8	107.9
Open-circuit sensitivity at T ℃ (nV/Pa)	112.2	111.5	109.2	114.7
Notes (e.g. of any unuaual difficulties)				

Participating laboratory: NIM		Calibration method : Two-transducer reciprocity		
Dates of calibration: 12.22-1.15		Hydrophone serial number: ER070		
Nominal frequency(MHz):	20 MHz			
Measurement number	1	2	3	4
Actual frequency (MHz)	20.00	20.00	20.00	20.00
Temperature, T(℃)	20	21.5	21.3	22.4
Open-circuit correction	1.0578	1.0578	1.0578	1.0578
Water conductivity (uS)	0.2	0.1	0.1	0.2
Oxygen content (mgL^{-1})	3.5	4.2	5.5	3.7
Amplifier gain (dB)	12.6856	12.6856	12.6856	12.6856
Measured sensitivity (nV/Pa)	104.8	105.9	104.9	109.1
Open-circuit sensitivity at T ℃ (nV/Pa)	110.9	112.0	110.9	115.4
Notes (e.g. of any unuaual difficulties)				

5. References

[1] IEC Standard 62127-2, *Calibration for ultrasonic fields up to 40 MHz,* 2007.

[2] Brendel, K., Ludwig, G, *Measurement of ultrasonic diffraction loss for circular transducers,* Acsutica, 32，(1975), 110.

[3] Fay, B. *Numerische Berchnung der Beugungsverluste im Schallfeld von Ultraschallwandlern*, Acustica, 36, (1976), 209.

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2015-3-10

APPENDIX F: REVISED REPORT SUBMITTED BY NATIONAL INSTITUTE OF METROLOGY, CHINA.

Laboratory Report from NIM for CCAUV.U-K4

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Contents

1. Introduction

The calibration method used by NIM, is based on the Chinese National standard GB/T 15611-1995 <Acoustics – Calibration of high frequency hydrophone> which is a modified version of the IEC Standard 60866 (1987) <Characteristics and calibration of hydrophones for operation in the frequency range 0.5 to 15 MHz>, We completed the measurements of 2 PVDF membrane hydrophones from 16th Nov. 2014 to 31st Jan. 2015.

2. Methods

2.1Description of the Reciprocity Calibration Set-up

The calibration procedure is based on the two-transducer reciprocity method. The systematic diagram of the experimental set-up is shown in Fig. 1. The reciprocal transducer radiates repetitive acoustic tone bursts into a tank filled with water. The duty cycles are well chosen to ensure there are no interferences. Those tone bursts signals are either reflected by a thick stainless steel reflector or directed to the hydrophone to be calibrated. For the self-reciprocity calibration of the transmitter [1], the transducer is adjusted to a position in which the axis of the ultrasonic beam is perpendicular to the surface of the reflector, position 1 in Fig. 1. For the calibration of the hydrophone, the reciprocal transducer is displaced to bring the ultrasonic field in front of the hydrophone, position 2. The alignment device positions the hydrophone to make sure it is in the centre of the ultrasonic beam.

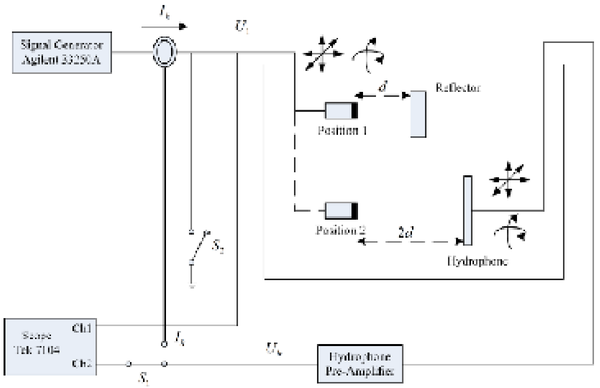

Fig. 1 Schematic diagram of the two-transducer reciprocity calibration method

Furthermore, the distance between the transmitter and the hydrophone is twice to the distance between the transmitter and the reflector. For this calibration set-up the expression for the hydrophone sensitivity is derived as

$$M = \sqrt{\frac{U_h^2}{U_1 I_k}} \cdot \sqrt{\frac{2A_1 r}{\rho c}} \cdot \frac{\sqrt{G_1}}{G_2} e^{\alpha d}$$

In which:

U_h Free field voltage of hydrophone

U_1 Apparent voltage of the reciprocal transducer during receiving of the tone burst

I_k Current through short-circuit introduced in place of the source transducer

A_1 Effective area of the reciprocal transducer

r Pressure reflection coefficient of reflector

ρ Density

c Velocity of sound in water

G_1 Factor for the diffraction loss of the reciprocal transducer

G_2 Factor for the averaging effect of the hydrophone

α Amplitude attenuation coefficient for water

d Distance between transmitter and reflector

2.2 Some Operation Details

1) How was the water prepared for the calibration?

The water was degassed and de-ionized. The conductivity of water was below 0.3 uS. The oxygen content of water was below 6 mg/L.

2) Was the hydrophone soaked in degassed water before use, and for how long?

The hydrophone was soaked in degassed water for about 1 hour.

3) Was the NPL preamplifier used? If not, describe how the open-circuit correction was obtained.

The NPL preamplifier was used.

4) Was it necessary to determine the gain of the preamplifier? If so, describe the method, and estimate its accuracy.

All measurements were included with the NPL preamplifier. It was necessary to determine the gain of the preamplifier. The amplifier *X5* gear was used and the gain was determined separately as shown in Fig. 2. The output impedance of signal generator is 50 Ω. The gain has been measured in the following two configurations. The oscilloscope was set to 1 MΩ input impedance at the amplifier input and to 50 Ω at the output. Excellent agreement within the uncertainty range was found in the two configurations. The calibrations of the preamplifier have been calibrated six times and the uncertainty was estimated to be 2.0%.

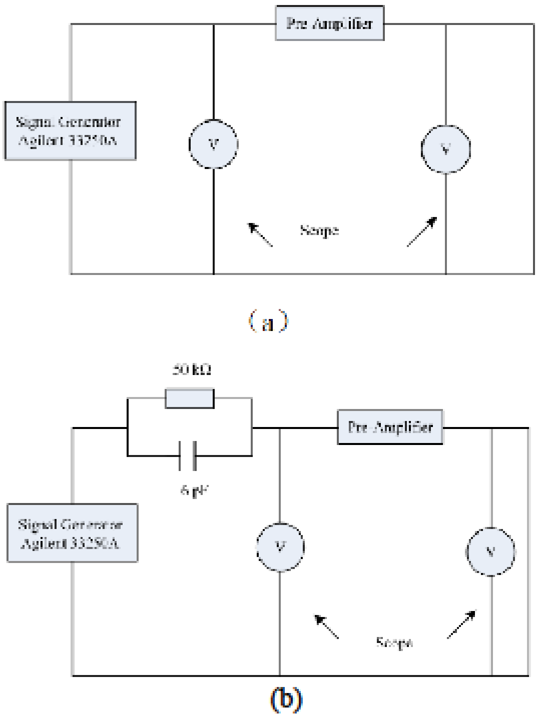

Fig. 2 Schematic diagram of the preamplifier calibration set-up

5) What type of tank was used (give the size and material used in construction) and how were any earth or shielding connections made?

The water tank is made of glass. The size is 900 mm (length) × 500 mm (width) $\times$500 mm (height). The aluminum shelf of the water tank is connected to the measuring electronic equipment.

6) How were any corrections for spatial-averaging obtained?

In self-reciprocity calibration of the transmitters, a correction must be applied for the diffraction loss of the transmitted ultrasonic beam. In the experiment, the diffraction loss coefficient G_1 was numerically calculated according to ref [2,3]. Similarly, the spatial averaging effect of the hydrophone was numerically calculated [3] using the effective diameter delivered by NPL.

7) What acoustic pressure was used at each frequency of calibration?

The acoustic pressure used was shown in table 1.

Table-1

Frequency (MHz)	Acoustic Pressure (kPa)
0.5	9.0
1	57.1
2.25	35.2
3.5	50.4
5	27.4
10	42.0
15	16.6
20	35.6

8) What propagation distance(s) was (were) used at each calibration frequency?

The normalized distance was given at each calibration frequency is given in table 2.

Table-2

Frequency (MHz)	Normalized Distance
0.5	1.566
1	1.562
2.25	1.556
3.5	1.557
5	1.557
10	1.570
15	1.565
20	1.563

3. Uncertainties

3.1 Type A Standard Uncertainty

Type A standard uncertainty is evaluated by the statistic method.

$$u_A = \frac{s}{\sqrt{n}} = \frac{\sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}}}{\sqrt{n}}$$

where $\bar{x}$ is the mean value of the sensitivities, n is the number of measurements.

3.2 Type B Standard Uncertainty

The total Type B standard uncertainty in the open-circuit hydrophone sensitivity M_0 is estimated by considering the systematic uncertainty contributions of each component in the expression:

$$M_0 = \sqrt{\frac{U_h^2}{U_1 I_k}} \cdot a \cdot \sqrt{\frac{2\pi}{\rho c}} \cdot \sqrt{r} \cdot \sqrt{G_1} \cdot \frac{1}{G_2} \cdot e^{\alpha d} \cdot k_c$$

Factor: A B C D E F G H

Factor A: Electrical quantities. The electrical quantities U_h, U_1 and I_k are all measured by Tektronix oscilloscope TEK 7104. Current is measured through TCP 0030 connected to the scope. The calibrations are performed at the frequencies and settings of the oscilloscope are identical to those during the hydrophone calibration process. In addition, an impedance uncertainty (0.5 % for each 50 Ω impedance) remains. The uncertainty for the electrical quantities is estimated to be 2.0%.

Factor B: Effective radius of the reciprocal transducer. The uncertainty is estimated to be 2.0%.

Factor C: Due to ρc. As ρc is dependent on temperature and calculated. The uncertainty is estimated to be 0.1%.

Factor D: Reflection coefficient: The value of the reflection coefficient is stated in IEC 62127-2. The uncertainty is small and neglected.

Factor E: Diffraction loss of the reciprocal transducer. Using the results given in reference [2,3] the uncertainty of factor E is estimated to be 2.5%.

Factor F: Averaging effect of the hydrophone. The correction factors G_s is obtained by interpolation of the table given in [3] . The uncertainty is estimated to be 4.0%.

Factor G: Attenuation of water path. The attenuation coefficeint dependent on temperature and frequency can be derived from IEC 62127-2. The transition time is measured by oscilloscope. The uncertainty due to attenuation is negligible.

Factor H: Open-circuit correction factor. The open-circuit correction factors are submitted by NPL and are considered as values with a negligible uncertainty.

Factor I: Gain of the preamplifier. The measurement of preamplifer gain is a relative measurement, its uncertainty is based on the accuracy of readings and differences in load impedances. The uncertainty is estimated to be 2.0 %.

Factor G: Non-ideal reciprocal transducer. Although the transmitter should be firstly checked for its reciprocity, the calibraiton results can be different using different transducers. We assume the transducers are not ideal reciprocal transducers. The uncertainty is estimated to be 1.5%.

Table-3 List of Type B relative standard uncertainties (u_i)

Source of measurement Uncertainty	Distribution	Coverage Factor	Value	Relative standard uncertainty /%
Factor A: Electrical Quantities	rect.	1.73	2.0	1.156
Factor B: Effective radius of transducer	Norm	1.96	2.0	1.020
Factor C: due to c	Norm	1.96	0.1	0.051
Factor D: Reflection coefficient			negl.	
Factor E: Diffraction loss of transducer	rect.	1.73	2.5	1.445
Factor F: Averaging effect of hydrophone	rect.	1.73	4.0	2.312
Factor G: Attenuation of water path			negl.	
Factor H: Open-circuit correction			negl.	
Factor I: Gain of the preamplifier	rect.	1.73	2.0	1.156
Factor G: Non-ideal reciprocal transducer	rect.	1.73	1.5	0.867
Total Type B Standard Uncertainty				3.45

3.3 Expanded Uncertainty

The combined standard uncertainty, u_c is calculated by combining the Type A and Type B uncertainties, standard uncertainties according to the procedures:

$$u_C = \sqrt{u_A^2 + u_B^2}$$

Finally, the expected uncertainty is calculated using a coverage factor $k = 2$.

$$U = 2 \cdot u_C$$

Which corresponds to a 95% level of confidence if the results are normally distributed.

4. Results

Table-4 Calibration results of IP999

Frequency (MHz)	**0.5**	**1.0**	**2.25**	**3.5**	**5.0**	**10.0**	**15.0**	**20.0**
Mean open-circuit sensitivity (nV/Pa)	205.0	207.2	211.6	215.3	220.2	251.1	279.8	344.1
Type A standard uncertainty (%)	0.44	0.52	0.29	0.18	0.14	0.55	0.52	1.62
Type B standard uncertainty (%)	3.45	3.45	3.45	3.45	3.45	3.45	3.45	3.45
Expanded uncertainty (%) U (k=2)	6.96	6.98	6.93	6.91	6.91	6.99	6.98	7.63

Table-5 Calibration results of ER070

Frequency (MHz)	**0.5**	**1.0**	**2.25**	**3.5**	**5.0**	**10.0**	**15.0**	**20.0**
Mean open-circuit sensitivity (nV/Pa)	118.9	124.7	130.5	139.0	150.8	185.0	222.1	224.5
Type A standard uncertainty (%)	0.71	0.67	0.35	0.21	0.45	1.51	1.00	0.95
Type B standard uncertainty (%)	3.45	3.45	3.45	3.45	3.45	3.45	3.45	3.45
Expanded uncertainty (%) U (k=2)	7.05	7.03	6.94	6.92	6.96	7.54	7.19	7.16

Participating laboratory: NIM		Calibration method : Two-transducer reciprocity		
Dates of calibration: 12.22-1.15		Hydrophone serial number: IP999		
Nominal frequency(MHz):	0.5 MHz			
Measurement number	1	2	3	4
Actual frequency (MHz)	0.50	0.50	0.50	0.50
Temperature, T(°C)	19.3	22	21.8	22.2
Open-circuit correction	1.0722	1.0722	1.0722	1.0722
Water conductivity (uS)	0.3	0.1	0.1	0.1
Oxygen content (mgL^{-1})	3.5	3.5	4.2	4.2
Amplifier gain (dB)	13.2117	13.2117	13.2117	13.2117
Measured sensitivity (nV/Pa)	189.6	193.1	192.1	189.9
Open-circuit sensitivity at T °C (nV/Pa)	203.3	207.0	205.9	203.6
Notes (e.g. of any unuaual difficulties)				

Participating laboratory: NIM		Calibration method : Two-transducer reciprocity		
Dates of calibration: 12.22-1.15		Hydrophone serial number: IP999		
Nominal frequency(MHz):	1.0 MHz			
Measurement number	1	2	3	4
Actual frequency (MHz)	1.00	1.00	1.00	1.00
Temperature, T(°C)	19.5	21.6	21.4	21.8
Open-circuit correction	1.0748	1.0748	1.0748	1.0748
Water conductivity (uS)	0.3	0.1	0.1	0.1
Oxygen content (mgL^{-1})	3.5	3.5	4.2	4.2
Amplifier gain (dB)	13.1940	13.1940	13.1940	13.1940
Measured sensitivity (nV/Pa)	190.5	192.7	195.3	192.5
Open-circuit sensitivity at T °C (nV/Pa)	204.8	207.1	209.9	206.9
Notes (e.g. of any unuaual difficulties)				

Participating laboratory: NIM	Calibration method : Two-transducer reciprocity
Dates of calibration: 12.22-1.15	Hydrophone serial number: IP999

Nominal frequency(MHz):	2.25 MHz			
Measurement number	1	2	3	4
Actual frequency (MHz)	2.25	2.25	2.25	2.25
Temperature, T(°C)	20.8	21.7	21.3	21.8
Open-circuit correction	1.0787	1.0787	1.0787	1.0787
Water conductivity (uS)	0.3	0.1	0.1	0.1
Oxygen content (mgL^{-1})	3.5	3.5	4.2	4.2
Amplifier gain (dB)	13.1171	13.1171	13.1171	13.1171
Measured sensitivity (nV/Pa)	195.6	196.8	195.0	197.4
Open-circuit sensitivity at T °C (nV/Pa)	211.0	212.3	210.3	212.9
Notes (e.g. of any unuaual difficulties)				

Participating laboratory: NIM	Calibration method : Two-transducer reciprocity
Dates of calibration: 12.22-1.15	Hydrophone serial number: IP999

Nominal frequency(MHz):	3.5 MHz			
Measurement number	1	2	3	4
Actual frequency (MHz)	3.50	3.50	3.50	3.50
Temperature, T(°C)	20.8	22	21.5	21.9
Open-circuit correction	1.0805	1.0805	1.0805	1.0805
Water conductivity (uS)	0.3	0.1	0.1	0.1
Oxygen content (mgL^{-1})	3.5	3.5	4.2	4.2
Amplifier gain (dB)	12.9553	12.9553	12.9553	12.9553
Measured sensitivity (nV/Pa)	200.1	198.7	198.7	199.5
Open-circuit sensitivity at T °C (nV/Pa)	216.2	214.7	214.7	215.6
Notes (e.g. of any unuaual difficulties)				

Participating laboratory: NIM	Calibration method : Two-transducer reciprocity			
Dates of calibration: 12.22-1.15	Hydrophone serial number: IP999			
Nominal frequency(MHz):	5 MHz			
Measurement number	1	2	3	4
Actual frequency (MHz)	5.00	5.00	5.00	5.00
Temperature, T(℃)	20.8	22	21.5	21.9
Open-circuit correction	1.0823	1.0823	1.0823	1.0823
Water conductivity (uS)	0.3	0.1	0.1	0.1
Oxygen content (mgL^{-1})	3.5	3.5	4.2	4.2
Amplifier gain (dB)	12.7094	12.7094	12.7094	12.7094
Measured sensitivity (nV/Pa)	204.2	203.2	203.0	203.4
Open-circuit sensitivity at T ℃ (nV/Pa)	221.1	220.0	219.7	220.2
Notes (e.g. of any unuaual difficulties)				

Participating laboratory: NIM	Calibration method : Two-transducer reciprocity			
Dates of calibration: 12.22-1.15	Hydrophone serial number: IP999			
Nominal frequency(MHz):	10 MHz			
Measurement number	1	2	3	4
Actual frequency (MHz)	10.00	10.00	10.00	10.00
Temperature, T(℃)	19.6	22	21.8	22.2
Open-circuit correction	1.0854	1.0854	1.0854	1.0854
Water conductivity (uS)	0.3	0.1	0.1	0.1
Oxygen content (mgL^{-1})	3.5	3.5	4.2	4.2
Amplifier gain (dB)	11.3917	11.3917	11.3917	11.3917
Measured sensitivity (nV/Pa)	231.1	232.9	233.5	227.8
Open-circuit sensitivity at T ℃ (nV/Pa)	250.8	252.8	253.4	247.3
Notes (e.g. of any unuaual difficulties)				

Participating laboratory: NIM	Calibration method : Two-transducer reciprocity			
Dates of calibration: 12.22-1.15	Hydrophone serial number: IP999			
Nominal frequency(MHz):	15 MHz			
Measurement number	1	2	3	4
Actual frequency (MHz)	15.00	15.00	15.00	15.00
Temperature, T(°C)	20.1	22	21.6	22.1
Open-circuit correction	1.0858	1.0858	1.0858	1.0858
Water conductivity (uS)	0.3	0.1	0.1	0.1
Oxygen content (mgL^{-1})	3.5	3.5	4.2	4.2
Amplifier gain (dB)	9.3289	9.3289	9.3289	9.3289
Measured sensitivity (nV/Pa)	261.6	256.0	256.0	257.2
Open-circuit sensitivity at T °C (nV/Pa)	284.0	278.0	278.0	279.3
Notes (e.g. of any unuaual difficulties)				

Participating laboratory: NIM	Calibration method : Two-transducer reciprocity			
Dates of calibration: 12.22-1.15	Hydrophone serial number: IP999			
Nominal frequency(MHz):	20 MHz			
Measurement number	1	2	3	4
Actual frequency (MHz)	20.00	20.00	20.00	20.00
Temperature, T(°C)	20	22	21.7	22.2
Open-circuit correction	1.0835	1.0835	1.0835	1.0835
Water conductivity (uS)	0.3	0.1	0.1	0.1
Oxygen content (mgL^{-1})	3.5	3.5	4.2	4.2
Amplifier gain (dB)	6.6708	6.6708	6.6708	6.6708
Measured sensitivity (nV/Pa)	331.6	318.0	313.4	307.4
Open-circuit sensitivity at T °C (nV/Pa)	359.3	344.6	339.6	333.1
Notes (e.g. of any unuaual difficulties)				

Participating laboratory: NIM		Calibration method : Two-transducer reciprocity		
Dates of calibration: 12.22-1.15		Hydrophone serial number: ER070		
Nominal frequency(MHz):	0.5 MHz			
Measurement number	1	2	3	4
Actual frequency (MHz)	0.50	0.50	0.50	0.50
Temperature, T(°C)	19.3	22	21.6	22.5
Open-circuit correction	1.0519	1.0519	1.0519	1.0519
Water conductivity (uS)	0.2	0.1	0.1	0.2
Oxygen content (mgL^{-1})	3.5	4.2	5.5	3.7
Amplifier gain (dB)	13.2117	13.2117	13.2117	13.2117
Measured sensitivity (nV/Pa)	111.3	112.7	112.7	115.2
Open-circuit sensitivity at T °C (nV/Pa)	117.1	118.6	118.6	121.2
Notes (e.g. of any unuaual difficulties)				

Participating laboratory: NIM		Calibration method : Two-transducer reciprocity		
Dates of calibration: 12.22-1.15		Hydrophone serial number: ER070		
Nominal frequency(MHz):	1.0 MHz			
Measurement number	1	2	3	4
Actual frequency (MHz)	1.00	1.00	1.00	1.00
Temperature, T(°C)	19.5	22	21.6	22.1
Open-circuit correction	1.0545	1.0545	1.0545	1.0545
Water conductivity (uS)	0.2	0.1	0.1	0.2
Oxygen content (mgL^{-1})	3.5	4.2	5.5	3.7
Amplifier gain (dB)	13.1940	13.1940	13.1940	13.1940
Measured sensitivity (nV/Pa)	119.9	116.5	119.1	117.3
Open-circuit sensitivity at T °C (nV/Pa)	126.5	122.9	125.6	123.7
Notes (e.g. of any unuaual difficulties)				

Participating laboratory: NIM	Calibration method : Two-transducer reciprocity			
Dates of calibration: 12.22-1.15	Hydrophone serial number: ER070			
Nominal frequency(MHz):	2.25 MHz			
Measurement number	1	2	3	4
Actual frequency (MHz)	2.25	2.25	2.25	2.25
Temperature, T(℃)	20.8	22	21.6	22.2
Open-circuit correction	1.0584	1.0584	1.0584	1.0584
Water conductivity (uS)	0.2	0.1	0.1	0.2
Oxygen content (mgL^{-1})	3.5	4.2	5.5	3.7
Amplifier gain (dB)	13.1171	13.1171	13.1171	13.1171
Measured sensitivity (nV/Pa)	122.9	122.9	124.5	122.7
Open-circuit sensitivity at T ℃ (nV/Pa)	130.1	130.1	131.8	129.9
Notes (e.g. of any unuaual difficulties)				

Participating laboratory: NIM	Calibration method : Two-transducer reciprocity			
Dates of calibration: 12.22-1.15	Hydrophone serial number: ER070			
Nominal frequency(MHz):	3.5 MHz			
Measurement number	1	2	3	4
Actual frequency (MHz)	3.50	3.50	3.50	3.50
Temperature, T(℃)	20.8	22	21.6	22.3
Open-circuit correction	1.0603	1.0603	1.0603	1.0603
Water conductivity (uS)	0.2	0.1	0.1	0.2
Oxygen content (mgL^{-1})	3.5	4.2	5.5	3.7
Amplifier gain (dB)	12.9553	12.9553	12.9553	12.9553
Measured sensitivity (nV/Pa)	130.4	131.6	131.4	131.2
Open-circuit sensitivity at T ℃ (nV/Pa)	138.2	139.5	139.3	139.1
Notes (e.g. of any unuaual difficulties)				

Participating laboratory: NIM	Calibration method : Two-transducer reciprocity			
Dates of calibration: 12.22-1.15	Hydrophone serial number: ER070			
Nominal frequency(MHz):	5 MHz			
Measurement number	1	2	3	4
Actual frequency (MHz)	5.00	5.00	5.00	5.00
Temperature, T(℃)	20.8	21.9	21.5	22.3
Open-circuit correction	1.0620	1.0620	1.0620	1.0620
Water conductivity (uS)	0.2	0.1	0.1	0.2
Oxygen content (mgL^{-1})	3.5	4.2	5.5	3.7
Amplifier gain (dB)	12.7094	12.7094	12.7094	12.7094
Measured sensitivity (nV/Pa)	142.7	140.3	143.1	141.7
Open-circuit sensitivity at T ℃ (nV/Pa)	151.6	149.0	152.0	150.5
Notes (e.g. of any unuaual difficulties)				

Participating laboratory: NIM	Calibration method : Two-transducer reciprocity			
Dates of calibration: 12.22-1.15	Hydrophone serial number: ER070			
Nominal frequency(MHz):	10 MHz			
Measurement number	1	2	3	4
Actual frequency (MHz)	10.00	10.00	10.00	10.00
Temperature, T(℃)	19.6	21.6	21.5	22.4
Open-circuit correction	1.0620	1.0620	1.0620	1.0620
Water conductivity (uS)	0.2	0.1	0.1	0.2
Oxygen content (mgL^{-1})	3.5	4.2	5.5	3.7
Amplifier gain (dB)	11.3917	11.3917	11.3917	11.3917
Measured sensitivity (nV/Pa)	176.9	179.3	167.8	171.3
Open-circuit sensitivity at T ℃ (nV/Pa)	188.3	190.8	178.6	182.2
Notes (e.g. of any unuaual difficulties)				

Participating laboratory: NIM		Calibration method : Two-transducer reciprocity		
Dates of calibration: 12.22-1.15		Hydrophone serial number: ER070		
Nominal frequency(MHz):	15 MHz			
Measurement number	1	2	3	4
Actual frequency (MHz)	15.00	15.00	15.00	15.00
Temperature, T(°C)	20.1	21.6	21.4	22.4
Open-circuit correction	1.0627	1.0627	1.0627	1.0627
Water conductivity (uS)	0.2	0.1	0.1	0.2
Oxygen content (mgL^{-1})	3.5	4.2	5.5	3.7
Amplifier gain (dB)	9.3289	9.3289	9.3289	9.3289
Measured sensitivity (nV/Pa)	209.6	208.2	204.0	214.1
Open-circuit sensitivity at T °C (nV/Pa)	222.7	221.2	216.8	227.6
Notes (e.g. of any unuaual difficulties)				

Participating laboratory: NIM		Calibration method : Two-transducer reciprocity		
Dates of calibration: 12.22-1.15		Hydrophone serial number: ER070		
Nominal frequency(MHz):	20 MHz			
Measurement number	1	2	3	4
Actual frequency (MHz)	20.00	20.00	20.00	20.00
Temperature, T(°C)	20	21.5	21.3	22.4
Open-circuit correction	1.0578	1.0578	1.0578	1.0578
Water conductivity (uS)	0.2	0.1	0.1	0.2
Oxygen content (mgL^{-1})	3.5	4.2	5.5	3.7
Amplifier gain (dB)	6.6708	6.6708	6.6708	6.6708
Measured sensitivity (nV/Pa)	209.5	211.7	209.7	218.1
Open-circuit sensitivity at T °C (nV/Pa)	221.6	223.9	221.8	230.7
Notes (e.g. of any unuaual difficulties)				

5. References

[1] IEC Standard 62127-2, *Calibration for ultrasonic fields up to 40 MHz,* 2007.

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APPENDIX G: REPORT SUBMITTED BY NATIONAL INSTITUTE OF METROLOGY, QUALITY AND TECHNOLOGY, BRAZIL.

CIPM/BIPM CCAUV.U-K4

COMPARISON OF ULTRASONIC HYDROPHONE CALIBRATIONS IN THE FREQUENCY RANGE 0.5 MHz to 20 MHz

INMETRO – 16th Feb to 15th Apr 2015

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Annex B: Contents of the final calibration report

Answer to checklist of the information required for the final report supplied to NPL which describes the hydrophone calibrations carried out by Inmetro.

1. How was the water prepared for the calibration?

The water used for the calibration was not changed during the measuring period. The water was taken from the de-ionising equipment. The calibration tank is made of PVC filled with fresh deionized water. The conductivity of water is less than 1 µs. The oxygen content of the water is less than 5 ppm.

2. Was the hydrophone soaked in degassed water before use, and for how long?

The hydrophones were soaked in water at the beginning of each working day. The hydrophones were soaked at least 1 hour before the measurement started. At the end of day they were stored in air in a container.

3. Was the NPL preamplifier used? If not, describe how the open-circuit correction was obtained.

All measurements were carried out including the pre-amplifier supplied by NPL serial number 5564166LF.

4. Was it necessary to determine the gain of the preamplifier? If so, describe the method, and estimate its accuracy.

The gain of preamplifier was performed using 4 measurements in repeatability conditions of the output voltage level of the arbitrary waveform generator connected to oscilloscope, divided by the output voltage level of the preamplifier with a shunt in line connected to arbitrary waveform generator. All connectors used are BNC. The NPL preamplifier is related to end-of-cable open-circuit sensitivity by using the expression below:

$$M_0 = \frac{M_L}{G} k_c$$

Where: M_0 end-of-cable open-circuit sensitivity, M_L end-of-cable loaded sensitivity of the hydrophone, k_c open-circuit correction factor as given by NPL.

The estimated accuracy of amplifier gain is 2.4%.

5. What type of tank was used (give the size and material used in construction) and how were any earth or shielding connections made?

The calibration tank is made of PVC. The size is 450 mm length, 450 mm depth, 450 mm width. It was filled with fresh water deionized water. The aluminum holder of steel target reflector immersed in water is connect electrically to the earth of measuring electronic equipment.

6. How were any corrections for spatial-averaging obtained?

The spatial averaging correction procedure follows the paper by Fay [1]. The calculation of the diffraction loss of the sound field propagation from the transmitter to the receiver. The acoustic field was modeled using the Rayleigh integral. For a reciprocal transducer the correction factor DS_u is related to diffraction, due to the auxiliary transducer finite aperture during transmission, and to spatial averaging, due to the auxiliary transducer finite aperture receiving an acoustic wave. In the case of hydrophone the term DS_{uh} is related do diffraction, due to the finite aperture of auxiliary transducer (transmitter) and to the spatial averaging owing to an acoustic wave incident upon the hydrophone finite aperture.

7. What acoustic pressure was used at each frequency of calibration?

Typical values of sound pressure amplitude:

F(MHz)	Typical acoustic pressure (kPa)
0.5	6.12 – 6.13
1.0	33.8 – 34.0
2.25	53.1 – 53.4
3.5	67.4 – 67.8
5	48.9 – 49.9
10	16.5 – 17.5
15	69.2 – 69.3

8. What propagation distance(s) was (were) used at each calibration frequency?

Typical values of propagation distances.

F(MHz)	Propagation distance (mm)
0.5	114.8
1.0	97.0
2.25	59.2
3.5	103.6
5	126.3
10	256.4
15	232.6

CALIBRATION BY TWO TRANSDUCER RECIPROCITY

The starting point for the approach used in the present work considers determining the complex transmit transfer function, T_t, of an auxiliary ultrasonic transducer, based on the setup depicted in Fig. 1 and defined in van Neer *et al.* [2] as:

$$T_t(\omega) = \frac{p_{tx}(\omega)}{V(\omega)}, \tag{1}$$

with $\omega = 2\pi f$, f is the ultrasound frequency, p_{tx} = the average pressure generated on the emitting surface of the transducer when excited with the electrical signal V.

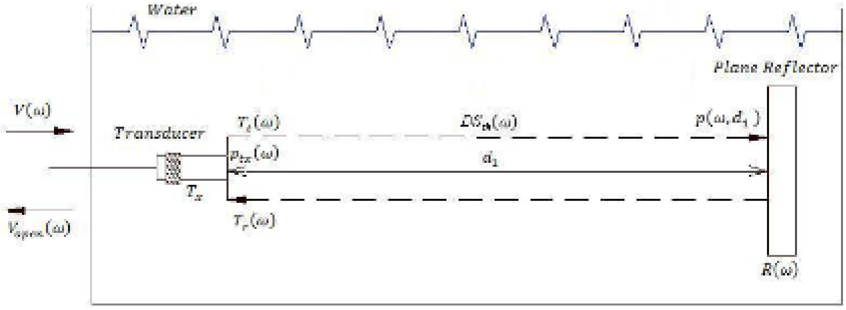

Fig. 1. Diagram of the pulse-echo setup used to determine the complex transmit transfer function of the auxiliary ultrasonic transducer, T_x, based on the echo from the reflector, immersed in water. The variables V, T_t, DS_u, R, T_r and V_{open} are phasors and function of angular frequency, ω, and corresponding to the excitation signal of T_x, the complex transmit transfer function of T_x, the one-way diffraction term, the reflector reflection coefficient, the complex receive transfer function of T_x and the electrical signal output of the transducer, loaded with an infinite electrical impedance and upon arrival of the echo, respectively.

Considering the auxiliary transducer to be a reciprocal flat circularly symmetric piston, with effective radius a, and d_1 the distance between transducer and reflector, then T_t becomes expressed [3] by:

$$T_t(\omega,d_1)=\sqrt{\frac{i\omega\rho_0 V_{open}(\omega,d_1)}{8\pi d_1 Z(\omega)V(\omega)}\frac{1}{\exp[-2\alpha(\omega)d_1]\exp(-i2kd_1)\left[1-\exp\left(-ika^2/4d_1\right)\right]DS_u(\omega,d_1)R(\omega)}} \tag{2}$$

where ρ_0 = the density of the medium between transducer and reflector, V_{open} = the output signal of the transducer, loaded by an infinite electrical impedance, upon arrival of the echo from the reflector, Z = the transducer electrical input impedance, α = the acoustic wave attenuation coefficient of the medium between transducer and reflector, $\exp(-ik2d_1)$ = the phase variation due to the distance traveled by the wave front, with $k=2\pi/\lambda$ and λ = acoustic wavelength, DS_u = the term related to diffraction, due to the auxiliary transducer finite aperture during transmission, and also to spatial averaging, due to the auxiliary transducer finite aperture receiving a non-planar acoustic wave, and

$R(\omega)$ = the reflection coefficient of the plane reflector. For general representation, R is a function of ω, but in practice the magnitude and phase influence of the reflection coefficient is considered frequency independent.

The voltage, V_k, over the impedance, Z_k, with the transducer input short-circuited [3]. e reflected signal is measureable and V_{open}^{*} is the apparent open circuit reflected voltage. V_{open}, was calculated as follows:

$$V_{open} = \frac{I_k}{I} V_{open}^{*}, \qquad (3)$$

where $I_k = V_k / Z_k$ = the current through Z_k with the transducer input short-circuited, I = the current passing through the transducer when driven by V (as $V = Z \cdot I$)..

Replacing the reflector replaced by a hydrophone positioned aligned with the transducer axis of symmetry and distant d_1 from the transducer face, then the hydrophone electrical output signal, V_h, is expressed [2] by:

$$V_h(\omega, d_1) = T_h(\omega)[V(\omega)T_t(\omega, d_1)\exp(-\alpha d_1)\exp(-ikd_1)DS_{th}(\omega, d_1)], \qquad (4)$$

considering T_h = the hydrophone receive transfer function and DS_{th} = the term related to diffraction, due to the finite aperture of auxiliary transducer (transmitter) and to the spatial averaging owing to a non-planar acoustic wave incident upon the hydrophone finite aperture.

The hydrophone sensitivity, M_h, is defined as:

$$M_h(\omega) = \frac{V_h(\omega, d_1)}{p(\omega, d_1)}, \qquad (5)$$

with $p(\omega, d_1)$ = the average acoustic pressure incident upon the hydrophone face, which is the term inside the brackets in (3).

Therefore, from (3) and (4) comes:

$$M_h(\omega) = T_h(\omega). \tag{6}$$

Combining (1)-(7) results in the expressions for magnitude sensitivity $|M_h|$.

$$|M_h(\omega)| = \frac{|V_h(\omega, d_1)|}{|V(\omega) T_t(\omega, d_1) \exp(-\alpha d_1) DS_{th}(\omega, d_1)|} \tag{7}$$

TYPE A RANDOM UNCERTAINTIES

The type A uncertainties (u_{typeA}) for each hydrophone are presented in table 5, and have been calculated from four independent measurements.

COMBINED AND EXPANDED UNCERTAINTIES

The combined uncertainty [4] is obtained by:

$$u_c = \sqrt{(u_{typeA})^2 + (u_{typeB})^2}, \tag{8}$$

The method for calculating the uncertainty of the type B is shown in [3].

The expanded uncertainty [4], with equivalent coverage factor, is obtained by

$$U = ku_c, \tag{9}$$

REFERENCES

[1] FAY, B. "Numerische Berechnung der Beugungsverluste im Schallfeld von Ultraschallwandlern", *Acustica*, v. 36, n.4, pp. 209-213, 1976.

[2] P.L.M.J.V. Neer, H.J. Vos, N.D. Jong, Reflector-based phase calibration of ultrasound transducers, Ultrasonics 51 (2011) 1-6.

[3] E.G.Oliveira, R.P.B. Costa-Felix, J.C. Machado, Primary reciprocity-based method for calibration of hydrophone magnitude and phase sensitivity: Complete tests at frequencies from 1 to 7 MHz., Ultrasonics 58 (2015) 87-95.

[4] BIPM, IEC, IFCC, ISO, IUPAC, OIML, JCGM 100:2008, Evaluation of measurement data Guide to the Expression of Uncertainty in Measurement. Joint Committee for Guides in Metrology, First Edition, September 2008.

Table 4: Calibration report Sheet.

Participating Laboratory: Inmetro		Calibration method: Two-Transducer Reciprocity		
Date(s) of Calibrations: 9 to 12 February 2015		Hydrophone serial number: ER070		
Nominal frequency (MHz): 0.5 MHz				
Measurement number	1	2	3	4
Actual frequency (MHz)	0.5	0.5	0.5	0.5
Temperature, T (°C)	19.3	19.3	19.3	19.3
Open-circuit correction	1.0519	1.0519	1.0519	1.0519
Water conductivity (µS)	<1 µS	<1 µS	<1 µS	<1 µS
Oxigen content (ppm)	<10 ppm	<10 ppm	<10 ppm	<10 ppm
Amplifier gain (dB)	13.29	13.29	13.29	13.29
Measured sensitivity (nV/Pa)	478.6	476.9	478.2	479.9
Open-circuit sensitivity at T (°C) (nV/Pa)	109	108.6	108.9	109.3
Notes (e.g. of any unusual difficulties)				

Participating Laboratory: Inmetro		Calibration method: Two-Transducer Reciprocity		
Date(s) of Calibrations: 9 to 12 February 2015		Hydrophone serial number: IP999		
Nominal frequency (MHz): 0.5 MHz				
Measurement number	1	2	3	4
Actual frequency (MHz)	0.5	0.5	0.5	0.5
Temperature, T (°C)	19.4	19.4	19.4	19.4
Open circuit correction	1.0722	1.0722	1.0722	1.0722
Water conductivity (µS)	<1 µS	<1 µS	<1 µS	<1 µS
Oxigen content (ppm)	<10 ppm	<10 ppm	<10 ppm	<10 ppm
Amplifier gain (dB)	13.29	13.29	13.29	13.29
Measured sensitivity (nV/Pa)	811.6	815.9	842.2	821.1
Open-circuit sensitivity at T (°C) (nV/Pa)	188.4	189.4	195.5	190.6
Notes (e.g. of any unusual difficulties)				

Participating Laboratory: Inmetro		Calibration method: Two-Transducer Reciprocity		
Date(s) of Calibrations: 23 to 26 February 2015		Hydrophone serial number: ER070		
Nominal frequency (MHz): 1.0 MHz				
Measurement number	1	2	3	4
Actual frequency (MHz)	1.0	1.0	1.0	1.0
Temperature, T (°C)	19.3	19.3	19.4	19.2
Open-circuit correction	1.0545	1.0545	1.0545	1.0545
Water conductivity (µS)	<1 µS	<1 µS	<1 µS	<1 µS
Oxigen content (ppm)	<10 ppm	<10 ppm	<10 ppm	<10 ppm
Amplifier gain (dB)	13.26	13.26	13.26	13.26
Measured sensitivity (nV/Pa)	476.2	502.4	482.3	480.6
Open-circuit sensitivity at T (°C) (nV/Pa)	109.1	115.1	110.5	110.1
Notes (e.g. of any unusual difficulties)				

Participating Laboratory: Inmetro		Calibration Method: Two-Transducer Reciprocity		
Date(s) of Calibrations: 23 to 26 February 2015		Hydrophone serial number: IP999		
Nominal Frequency (MHz): 1.0 MHz				
Measurement number	1	2	3	4
Actual frequency (MHz)	1.0	1.0	1.0	1.0
Temperature, T (°C)	19.5	19.3	19.4	19.4
Open-circuit correction	1.0748	1.0748	1.0748	1.0748
Water conductivity (µS)	<1 µS	<1 µS	<1 µS	<1 µS
Oxigen content (ppm)	<10 ppm	<10 ppm	<10 ppm	<10 ppm
Amplifier gain (dB)	13.26	13.26	13.26	13.26
Measured sensitivity (nV/Pa)	803.4	773.0	796.5	790.5
Open-circuit sensitivity at T (°C) (nV/Pa)	187.6	180.5	186.0	184.6
Notes (e.g. of any unusual difficulties)				

Participating Laboratory: Inmetro		Calibration Method: Two-Transducer Reciprocity		
Date(s) of Calibrations: 2 to 5 March 2015		Hydrophone serial number: ER070		
Nominal Frequency (MHz): 2.25 MHz				
Measurement number	1	2	3	4
Actual frequency (MHz)	2.25	2.25	2.25	2.25
Temperature, T (°C)	18.8	18.8	18.8	18.8
Open-circuit correction	1.0584	1.0584	1.0584	1.0584
Water conductivity (µS)	<1 µS	<1 µS	<1 µS	<1 µS
Oxigen content (ppm)	<5 ppm	<5 ppm	<5 ppm	<5 ppm
Amplifier gain (dB)	13.18	13.18	13.18	13.18
Measured sensitivity (nV/Pa)	503.9	505.6	505.6	503.9
Open-circuit sensitivity at T (°C) (nV/Pa)	117	117.4	117.4	117
Notes (e.g. of any unusual difficulties)				

Participating Laboratory: Inmetro		Calibration Method: Two-Transducer Reciprocity		
Date(s) of Calibrations: 2 to 5 March 2015		Hydrophone serial number: IP999		
Nominal Frequency (MHz): 2.25 MHz				
Measurement number	1	2	3	4
Actual frequency (MHz)	2.25	2.25	2.25	2.25
Temperature, T (°C)	19.0	19.0	19.0	19.0
Open-circuit correction	1.0787	1.0787	1.0787	1.0787
Water conductivity (µS)	<1 µS	<1 µS	<1 µS	<1 µS
Oxigen content (ppm)	<5 ppm	<5 ppm	<5 ppm	<5 ppm
Amplifier gain (dB)	13.18	13.18	13.18	13.18
Measured sensitivity (nV/Pa)	794,8	793,5	794	793,5
Open-circuit sensitivity at T (°C) (nV/Pa)	188,1	187,8	187,9	187,8
Notes (e.g. of any unusual difficulties)				

Participating Laboratory: Inmetro		Calibration Method: Two-Transducer Reciprocity		
Date(s) of Calibrations: 9 to 12 March 2015		Hydrophone serial number: ER070		
Nominal Frequency (MHz): 3.5 MHz				
Measurement number	1	2	3	4
Actual frequency (MHz)	3.5	3.5	3.5	3.5
Temperature, T (°C)	19.1	19.1	19.1	18.7
Open-circuit correction	1.0603	1.0603	1.0603	1.0603
Water conductivity (µS)	<1 µS	<1 µS	<1 µS	<1 µS
Oxigen content (ppm)	<5 ppm	<5 ppm	<5 ppm	<5 ppm
Amplifier gain (dB)	13.02	13.02	13.02	13.02
Measured sensitivity (nV/Pa)	529.4	532.8	523.5	532.8
Open-circuit sensitivity at T (°C) (nV/Pa)	125.4	126.2	124	126.2
Notes (e.g. of any unusual difficulties)				

Participating Laboratory: Inmetro		Calibration Method: Two-Transducer Reciprocity		
Date(s) of Calibrations: 9 to 12 March 2015		Hydrophone serial number: IP999		
Nominal Frequency (MHz): 3.5 MHz				
Measurement number	1	2	3	4
Actual frequency (MHz)	3.5	3.5	3.5	3.5
Temperature, T (°C)	19.1	19.1	19.2	18.9
Open-circuit correction	1.0805	1.0805	1.0805	1.0805
Water conductivity (µS)	<1 µS	<1 µS	<1 µS	<1 µS
Oxigen content (ppm)	<5 ppm	<5 ppm	<5 ppm	<5 ppm
Amplifier gain (dB)	13.02	13.02	13.02	13.02
Measured sensitivity (nV/Pa)	795.5	800.0	799.6	795.9
Open-circuit sensitivity at T (°C) (nV/Pa)	192	193.1	193	192.1
Notes (e.g. of any unusual difficulties)				

Participating Laboratory: Inmetro		Calibration Method: Two-Transducer Reciprocity		
Date(s) of Calibrations: 16 to 19 March 2015		Hydrophone serial number: ER070		
Nominal Frequency (MHz): 5 MHz				
Measurement number	1	2	3	4
Actual frequency (MHz)	5	5	5	5
Temperature, T (°C)	19.1	19.2	19.0	19.1
Open-circuit correction	1.0620	1.0620	1.0620	1.0620
Water conductivity (µS)	<1 µS	<1 µS	<1 µS	<1 µS
Oxigen content (ppm)	<5 ppm	<5 ppm	<5 ppm	<5 ppm
Amplifier gain (dB)	12.89	12.89	12.89	12.89
Measured sensitivity (nV/Pa)	575.0	581.6	569.8	574.1
Open-circuit sensitivity at T (°C) (nV/Pa)	138.4	140	137.2	138.2
Notes (e.g. of any unusual difficulties)				

Participating Laboratory: Inmetro		Calibration Method: Two-Transducer Reciprocity		
Date(s) of Calibrations: 16 to 19 March 2015		Hydrophone serial number: IP999		
Nominal Frequency (MHz): 5 MHz				
Measurement number	1	2	3	4
Actual frequency (MHz)	5	5	5	5
Temperature, T (°C)	19.3	19.4	19.0	19.1
Open-circuit correction	1.0823	1.0823	1.0823	1.0823
Water conductivity (µS)	<1 µS	<1 µS	<1 µS	<1 µS
Oxigen content (ppm)	<5 ppm	<5 ppm	<5 ppm	<5 ppm
Amplifier gain (dB)	12.89	12.89	12.89	12.89
Measured sensitivity (nV/Pa)	836.5	836.5	832.4	836.1
Open-circuit sensitivity at T (°C) (nV/Pa)	205.2	205.2	204.2	205.1
Notes (e.g. of any unusual difficulties)				

Participating Laboratory: Inmetro		Calibration Method: Two-Transducer Reciprocity		
Date(s) of Calibrations: 23 to 26 March 2015		Hydrophone serial number: ER070		
Nominal Frequency (MHz): 10 MHz				
Measurement number	1	2	3	4
Actual frequency (MHz)	10	10	10	10
Temperature, T (°C)	19,8	19,8	19,8	19,8
Open-circuit correction	1.0641	1.0641	1.0641	1.0641
Water conductivity (µS)	<1 µS	<1 µS	<1 µS	<1 µS
Oxigen content (ppm)	<5 ppm	<5 ppm	<5 ppm	<5 ppm
Amplifier gain (dB)	12.53	12.53	12.53	12.53
Measured sensitivity (nV/Pa)	582.4	583.8	594.3	570.5
Open-circuit sensitivity at T (°C) (nV/Pa)	146.4	146.8	149.4	143.4
Notes (e.g. of any unusual difficulties)				

Participating Laboratory: Inmetro		Calibration Method: Two-Transducer Reciprocity		
Date(s) of Calibrations: 23 to 26 March 2015		Hydrophone serial number: IP999		
Nominal Frequency (MHz): 10 MHz				
Measurement number	1	2	3	4
Actual frequency (MHz)	10	10	10	10
Temperature, T (°C)	20	20	20	20
Open-circuit correction	1.0854	1.0854	1.0854	1.0854
Water conductivity (µS)	<1 µS	<1 µS	<1 µS	<1 µS
Oxigen content (ppm)	<5 ppm	<5 ppm	<5 ppm	<5 ppm
Amplifier gain (dB)	12.53	12.53	12.53	12.53
Measured sensitivity (nV/Pa)	739.4	725.5	728.9	726.4
Open-circuit sensitivity at T (°C) (nV/Pa)	189.6	186.0	186.9	186.2
Notes (e.g. of any unusual difficulties)				

Participating Laboratory: Inmetro		Calibration Method: Two-Transducer Reciprocity		
Date(s) of Calibrations: 30 March 2015 to 2 April 2015		Hydrophone serial number: ER070		
Nominal Frequency (MHz): 15 MHz				
Measurement number	1	2	3	4
Actual frequency (MHz)	15	15	15	15
Temperature, T (°C)	19,4	19,4	19,4	19,4
Open-circuit correction	1.0627	1.0627	1.0627	1.0627
Water conductivity (µS)	<1 µS	<1 µS	<1 µS	<1 µS
Oxigen content (ppm)	<5 ppm	<5 ppm	<5 ppm	<5 ppm
Amplifier gain (dB)	12.08	12.08	12.08	12.08
Measured sensitivity (nV/Pa)	502.9	503.5	505.5	501.8
Open-circuit sensitivity at T (°C) (nV/Pa)	133.0	133.2	133.7	132.7
Notes (e.g. of any unusual difficulties)				

Participating Laboratory: Inmetro		Calibration Method: Two-Transducer Reciprocity		
Date(s) of Calibrations: 30 March 2015 to 2 April 2015		Hydrophone serial number: IP999		
Nominal Frequency (MHz): 15 MHz				
Measurement number	1	2	3	4
Actual frequency (MHz)	15	15	15	15
Temperature, T (°C)	19,4	19,4	19,4	19,5
Open-circuit correction	1.0858	1.0858	1.0858	1.0858
Water conductivity (µS)	<1 µS	<1 µS	<1 µS	<1 µS
Oxigen content (ppm)	<5 ppm	<5 ppm	<5 ppm	<5 ppm
Amplifier gain (dB)	12.08	12.08	12.08	12.08
Measured sensitivity (nV/Pa)	583.6	611.4	578.1	612.7
Open-circuit sensitivity at T (°C) (nV/Pa)	157.7	165.2	156.2	165.6
Notes (e.g. of any unusual difficulties)				

Table 5: Summary sheet.

Participating Laboratory: Inmetro			Method: Two-Transducer Reciprocity					
Dates: 9-2-2015 to 2-4-2015	Hydrophone serial number: ER070							
Nominal Frequency (MHz)	0.5	1	2.25	3.5	5	10	15	20
Actual frequency (MHz)	0.5	1	2.25	3.5	5	10	15	n.a.
Mean open-circuit sensitivity at T ℃ (nV/Pa)	109.0 at 19.3	111.2 at 19.3	117.2 at 18.8	125.5 at 19.0	138.4 at 19.1	146.5 at 19.8	133.1 at 19.4	n.a.
Type A (random) Standard Uncertainty (%)	0.13	1.20	0.10	0.41	0.42	0.84	0.16	n.a.
Type B (systematic) standard uncertainty (%)	3.25	3.35	3.25	3.27	3.25	3.26	3.22	n.a.
Coverage fator (*k*)	2	2	2	2	2	2	2	n.a.
Expanded uncertainty (%)	6.5	7.1	6.5	6.6	6.6	6.7	6.4	n.a.

Participating Laboratory: Inmetro			Method: Two-Transducer Reciprocity					
Dates: 9-2-2015 to 2-4-2015	Hydrophone serial number: IP999							
Nominal Frequency (MHz)	0.5	1	2.25	3.5	5	10	15	20
Actual frequency (MHz)	0.5	1	2.25	3.5	5	10	15	n.a.
Mean open-circuit sensitivity at T ℃ (nV/Pa)	191.0 at 19.4	184.7 at 19.4	187.9 at 19	192.6 at 19.1	204.9 at 19.1	187.2 at 20.0	161.2 at 19.4	n.a.
Type A (random) Standard Uncertainty (%)	0.82	0.82	0.04	0.15	0.12	0.44	1.52	n.a.
Type B (systematic) standard uncertainty (%)	3.25	3.23	3.19	3.17	3.17	3.18	3.23	n.a.
Coverage fator (*k*)	2	2	2	2	2	2	2	n.a.
Expanded uncertainty (%)	6.7	6.7	6.4	6.3	6.4	6.4	7.1	n.a.