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BIPM/CIPM Key Comparison CCAUV.U-K2:

Comparison of 1 mm hydrophone calibrations in the frequency range 1 MHz to 15 MHz

Final Report

Bajram Zeqiri and Nigel D Lee

September 2005

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BIPM/CIPM Key Comparison CCAUV.U-K2: Comparison of 1 mm hydrophone calibrations in the frequency range 1 MHz to 15 MHz

Final Report

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ABSTRACT

This is the Final Report describing BIPM/CIPM Key comparison CCAUV.U-K2, involving the comparison of 1 mm active element hydrophone calibrations at ultrasonic frequencies over the range 1 MHz to 15 MHz. The report summarises the results of the participants: TNO (The Netherlands), PTB (Germany), NIM (China), FORCE Institute (Denmark) and NPL (The United Kingdom). It also provides proposals for deriving the key comparison reference values (KCRVs) and their associated uncertainties as well as the degrees of equivalence between participant laboratories. Over the frequency range 1 MHz to 5 MHz, agreement between the four laboratories providing independent absolute calibrations of the hydrophones was within the quoted individual uncertainties. However, at both 10 MHz and 15 MHz, one of the laboratories provided values for the open-circuit free-field sensitivity that were significantly discrepant. Following a meeting at BIPM in October 2002, it was suggested the origin of the discrepant results should be investigated through a bilateral comparison between the laboratory involved and NPL. The revised results obtained from this bilateral comparison are also presented in this report and, along with the results originally submitted by three of the other laboratories, are used to evaluate the key comparison reference values (KCRVs) and the resultant degrees of equivalence between the participating laboratories.

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Approved on behalf of the Managing Director, NPL,
by Dr Martin Milton, authorised by Director for Quality of Life Division

CONTENTS

1 INTRODUCTION

A central objective of the Mutual Recognition Arrangement (MRA), signed by national measurement institute (NMI) directors in 1999, is the establishment of the degrees of equivalence of national measurement standards held by each institute. International comparisons, known as key comparisons, represent the sole mechanism for establishing these degrees of equivalence.

This document constitutes the Final Report of the key comparison CCAUV.U-K2, undertaken under the auspices of the BIPM/CIPM Consultative Committee for Acoustics, Ultrasound and Vibration. The key comparison relates to the realisation of the acoustic pascal in water at ultrasonic frequencies. 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;

- degrees of equivalence between participant laboratories and the associated uncertainties.

The individual reports supplied by the measurement institutions taking part in the key comparison are presented in Appendices C (NIM), E (FORCE Institute), F (PTB), G (TNO) and J (NPL). Supplementary reports submitted by TNO and NIM are presented in appendices D and H respectively. These Appendices give uncertainty budgets for the calibration results provided by the participants.

This Report B is circulated as a confidential report although the ultimate intention is to publish the results of the key comparison more widely within the open literature, following the agreement of the laboratories participating in the key comparison.

2 BACKGROUND TO COMPARISON

The realisation of the acoustic pascal is most appropriately achieved through a comparison of calibrations carried out on stable transfer standard hydrophones; 1 mm active element bilaminar membrane hydrophones, being chosen for this purpose (Preston et al. 1981). The detailed protocol of the comparison is described in the associated earlier report (Lee and Zeqiri 2001) and only the key aspects will be dealt with here. With NPL acting as the pilot laboratory, two hydrophones were calibrated using the NPL primary standard laser interferometer and circulated sequentially to participant NMI laboratories in Germany, China, The Netherlands and Denmark. Laboratories were asked to report values for the hydrophone open-circuit free-field sensitivity over the frequency range 1 MHz to 15 MHz. The principal calibration methods used by the NMIs were optical interferometry and/or two-transducer reciprocity. The sequence of calibrations was as follows:-

NPL (initial calibration)	May 1999
TNO	January – February 2000
PTB	April- May 2000
NIM	June-August 2000
FORCE Institute	September – November 2000
NPL (final calibration)	August 2001.
NIM	May 2003 - August: Bilateral comparison. NIM Report received November 2003.
NPL	August 2003: Final stability checks at NPL.

The first report was circulated in February 2002 as an In-confidence Report to participants for comment. Following receipt of these comments, a number of key decisions were made by the participants which affected the declared comparison values used within the current Report to derive the KCRVs. These decisions are summarised as follows:-

• due to the limited availability of temperature coefficient data for the hydrophones at the specific frequencies of interest, it was decided not to correct any measurement data for differences in temperature between the laboratories. The majority of participant laboratories completed measurements within the temperature range 20°C – 21.5°C and for these the ensuing corrections for the generic type of hydrophone used in the comparison are negligible (< 0.3%);

• one of the NMIs involved in the key comparison, the FORCE Institute of Denmark, supplied calibration values which had been derived through a relative method traceable to both PTB and NPL. Due to this correlation in results, it was agreed that FORCE's results would not be used in deriving KCRVs. However, for completeness, the FORCE results will be presented within the tables describing the KCRVs and the degrees of equivalence;

• from the results presented in the first report, the TNO (The Netherlands) concluded that their results showed a consequent underestimate compared to the results of other participants. Although the difference was within the measurement uncertainty, TNO wished to investigate the origin of the difference. They therefore requested that they should be able to repeat calibrations on one of the reference hydrophones used during the comparison, IP027. Once the hydrophone had been returned by NPL, calibrations were repeated using an identical set-up and the results were within ±2% of the initial value, indicating a possible systematic effect. The only part of their measurement system TNO judged to be responsible was the source transducer used. A thorough beam characterisation established an asymmetrical beam. The acoustic beam characterisation was repeated for another, identical, source transducer that exhibited a more predictable behaviour. Calibrations of hydrophone IP027 were then repeated with this source transducer and TNO requested that the data presented in the first report be corrected to revised values of the open-circuit sensitivity presented in the revised Report. This approach was agreed by all participants. The original TNO values for the hydrophone IP027 along with the revised sensitivities are summarised in Section 3. A Supplementary report from TNO describing these calibrations is given in Appendix H.

• NIM (China) reported an error in their analysis of sensitivity values during the correction for attenuation through the water path. They requested that the data presented in the first report be corrected with revised values of the open-circuit sensitivity being presented in the revisd Report. This was subsequently agreed by all participants, and the original NIM values along with the revised data are summarised in Section 3. A Supplementary report from NIM describing these calibrations is given in Appendix D.

An advanced version of the revised report was presented to the CCAUV at a meeting at BIPM in October 2002 as an In-confidence Report to participants for comment. Following receipt of these comments, the participant NMIs agreed further investigation into the reasons for the discrepant results at 10 and 15 MHz should be carried out in the form of a bilateral comparison between NIM (China) and NPL. Hydrophone IP027 was consequently returned to NIM during May 2003, and the measurements completed, with the hydrophone being sent back to NPL during August 2003. NIM attributed their discrepant results to issues related to measuring transducer transmitting current, and for the bilateral comparison they used a new current probe. Upon return to NPL, a further check on the stability of the hydrophone frequency response was carried out.

It should be noted that TNO and NIM were only able to complete repeat measurements on the hydrophone IP027. Consequently, it is only results for this hydrophone which will be used the KCRV analysis described in Section 5.

3 FINAL DECLARED PARTICIPANT VALUES USED WITHIN THE KCRV ANALYSIS

Tables 3.1 and 3.2 represent a summary of the open-circuit free-field sensitivity values declared by TNO, PTB, NIM, FORCE and NPL. The Tables include the original data provided by the NIM and TNO along with their amended measurements. There were no changes to the uncertainty figures declared by these two laboratories. Although only results for hydrophone IP027 will be used in the KCRV analysis presented in Section 5, data for IP039 are also presented because this hydrophone has been used to assess the stability of the hydrophone IP027, during the course of the key comparison (see Section 4).

Table 3.1: Summary of end-of-cable open-circuit sensitivities, expressed in nV Pa^{-1}, for the hydrophone IP039 derived by the five participant laboratories taking part in this key comparison. Revised and original values are presented for the TNO (The Netherlands) and the NIM (China). It should be noted that the values submitted by FORCE are obtained from a relative method of calibration. Declared values of the expanded uncertainty, given in nV Pa^{-1}, have been derived using a coverage factor, *k*, equal to 2.

Participant	**(MHz)**				
	1	**2**	**5**	**10**	**15**
NPL (original)	169.5 (±4.1)	170.7 (±4.3)	177 (±4.4)	200.8 (±5.2)	258.7 (±10.3)
PTB (original)	170.6 (±14.3)	170.9 (±14.0)	176.8 (±14.1)	202.1 (±17.0)	265.2 (±22.8)
TNO (original)	167.6 (±10.1)	173.2 (±10.2)	177.1 (±10.8)	185.8 (±11.1)	232.6 (±14.9)
NIM (revised after circulation of original)	174 (±13.7)	181 (±13.6)	181 (±13.0)	186 (±19.2)	259 (±24.1)
NIM (original)	174 (±13.7)	181 (±13.6)	179 (±12.9)	178 (±18.3)	169 (±15.7)
FORCE (original)	175 (±13.8)	174 (±13.8)	185 (±14.6)	214 (±18.6)	261 (±25.6)

Table 3.2: Summary of end-of-cable open-circuit sensitivities, expressed in nV Pa^{-1}, for the hydrophone IP027 derived by the five participant laboratories taking part in this key comparison. Revised and original values are presented for the TNO (The Netherlands) and the NIM (China). Also values obtained by the NIM from the bilateral comparison are presented. It should be noted that the values submitted by FORCE are obtained from a relative method of calibration. Declared values of the expanded uncertainty, given in nV Pa^{-1}, have been derived using a coverage factor, *k*, equal to 2. Laboratory results identified with the asterisk (*) have been used in the KCRV analysis.

Participant	**Frequency (MHz)**				
	1	**2**	**5**	**10**	**15**
NPL* (original)	157.5 (±4.9)	158 (±4.0)	170.9 (±4.4)	194.5 (±5.1)	244.6 (±7.6)
PTB * (original)	158.1 (±13.3)	161.4 (±13.6)	171.6 (±14.1)	199.1 (±16.7)	252.8 (±22.8)
TNO * (revised after circulation of original)	155.1 (±9.3)	163.5 (±9.6)	169.3 (±10.2)	207.8 (±12.3)	237.7 (±14.3)
TNO (original)	155.1 (±9.3)	163.5 (±9.6)	169.3 (±10.2)	180.4 (±12.3)	224.3 (±14.3)
NIM * (Results obtained from Bilateral comparison)	156.3 (±11.4)	164.3 (±11.9)	172.9 (±12.6)	191.5 (±13.8)	244.9 (±18.2)
NIM (revised after circulation of original)	150 (±11.4)	163 (±12.1)	162 (±11.3)	165 (±19.8)	213 (±20.9)
NIM (original)	150 (±11.4)	163 (±12.1)	160 (±11.2)	158 (±19.0)	139 (±13.6)
FORCE (original)	166 (±13.8)	164 (±13.1)	177 (±14.0)	205 (±18.0)	246 (±24.4)

4 STABILITY OF REFERENCE HYDROPHONES

As described in the first Report (Lee and Zeqiri 2002), intermediate checks of the stability of the two key comparison hydrophones were completed whenever the devices were returned to NPL. This occurred when a NMI laboratory had completed their measurements. The technique used to calibrate the hydrophones is commonly referred to as the ‘nonlinear’ method, and is a comparison method utilizing a distorted 1 MHz fundamental waveform containing frequency components well beyond the 15 MHz limit of the key comparison. The response of the hydrophone within this acoustic field is compared to that of a secondary standard hydrophone which has itself been previously calibrated using the NPL primary standard. Throughout the course of the key comparison, this technique was used to monitor the stability of both of the hydrophones IP039 and IP027.

This Section presents the results of these stability checks in a primarily graphical format. Additionally, it provides values for the ratio’s of the derived sensitivities of the two hydrophones – IP039/IP027. This quantity represents a much better test of the stability of the hydrophones as the ratio will be relatively insensitive to slight drifts in the measurement system which occur over a period of time.

4.1 1 MHz

Figure 4.1 illustrates the variation in the measured sensitivity of the two reference hydrophones, IP027 and IP039, during the course of the key comparison. Checks on the stability of the devices are shown at the beginning (May 1999) and end (August 2003) of the comparison. Results for both hydrophones appear to indicate a similar drop in sensitivity during the course of the comparison, relative to the sensitivity at the beginning and end, arising from a slight drift in the measurement system. This is demonstrated in Figure 4.2, where the ratio of the derived open-circuit sensitivities of the hydrophones is presented over the same time-period. This latter figure indicates that the sensitivities of the hydrophone have remained stable to well within the random uncertainties in the measurements. The derived ratio is 1.0630 ± 0.0100, where the standard uncertainty is given derived from the 7 measurements.

4.2 2 MHz

Figures 4.3 and 4.4 present stability checks carried out at a frequency of 2 MHz, for values of absolute sensitivity and the sensitivity ratio of the two hydrophones, respectively. From Figure 4.4, the mean value of the sensitivity ratio is 1.0509 ± 0.0097, where the standard uncertainty is given derived from the 7 measurements.

4.3 5 MHz

Figures 4.5 and 4.6 present stability checks carried out at a frequency of 5 MHz, for values of absolute sensitivity and the sensitivity ratio of the two hydrophones, respectively. From Figure 4.6, the mean value of the sensitivity ratio is 1.0353 ± 0.0062, where the standard uncertainty is given derived from the 7 measurements.

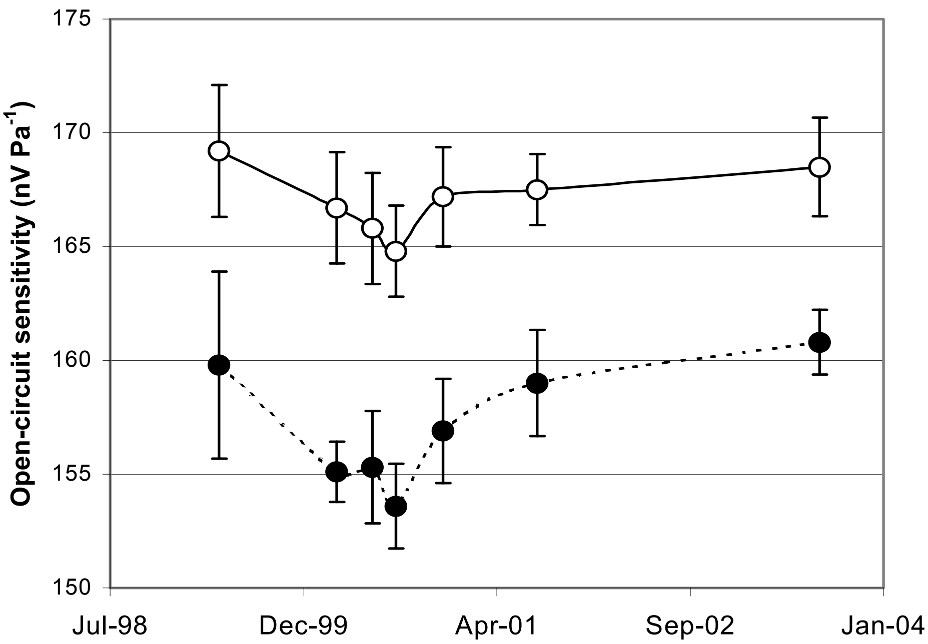

Figure 4.1: Stability checks carried out at NPL during the course of the key comparison. Values of the end-of-cable open-circuit sensitivities of the two hydrophones used, IP027 (•) and IP039 (o), are presented at a frequency of 1 MHz. Values for the standard uncertainty are given which in each case has been derived from four repeat measurements.

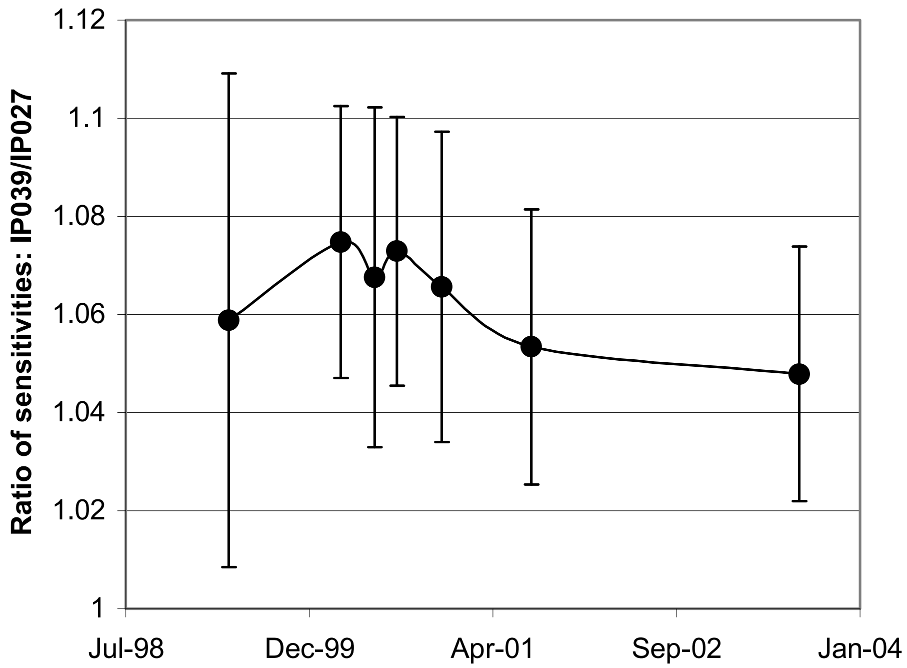

Figure 4.2: Stability checks carried out at NPL during the course of the key comparison. Values of the ratio of the end-of-cable open-circuit sensitivities of the two hydrophones used, IP027 and IP039, are given derived at a frequency of 1 MHz. Standard uncertainties are presented for the ratio.

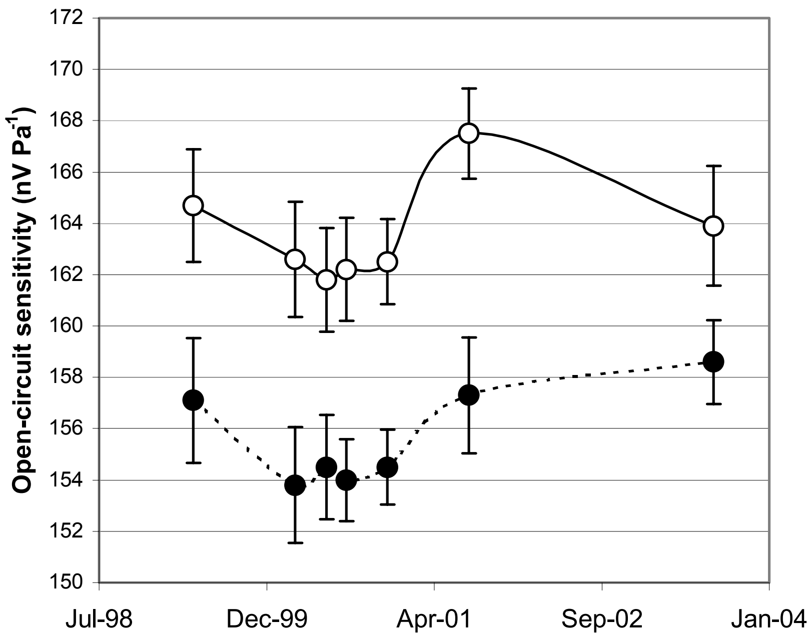

Figure 4.3: Stability checks carried out at NPL during the course of the key comparison. Values of the end-of-cable open-circuit sensitivities of the two hydrophones used, IP027 (•) and IP039 (o), are given derived at a frequency of 2 MHz. The standard uncertainties are presented derived in each instance from four repeat measurements.

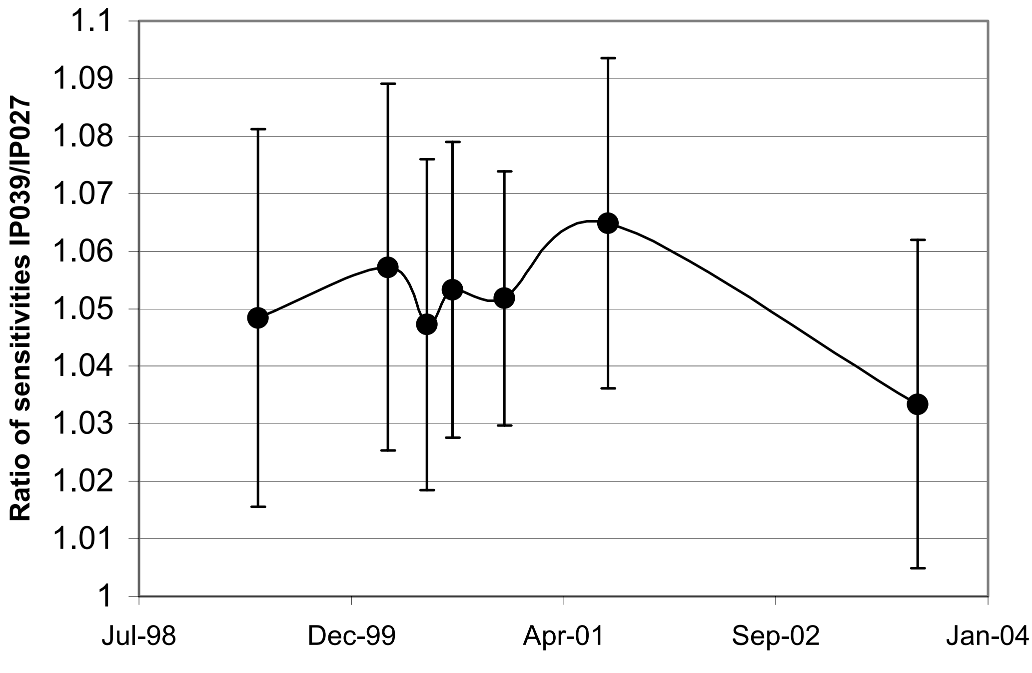

Figure 4.4: Stability checks carried out at NPL during the course of the key comparison. Values of the ratio of the end-of-cable open-circuit sensitivities of the two hydrophones used, IP027 and IP039, are given derived at a frequency of 2 MHz. Standard uncertainties are presented for the ratio.

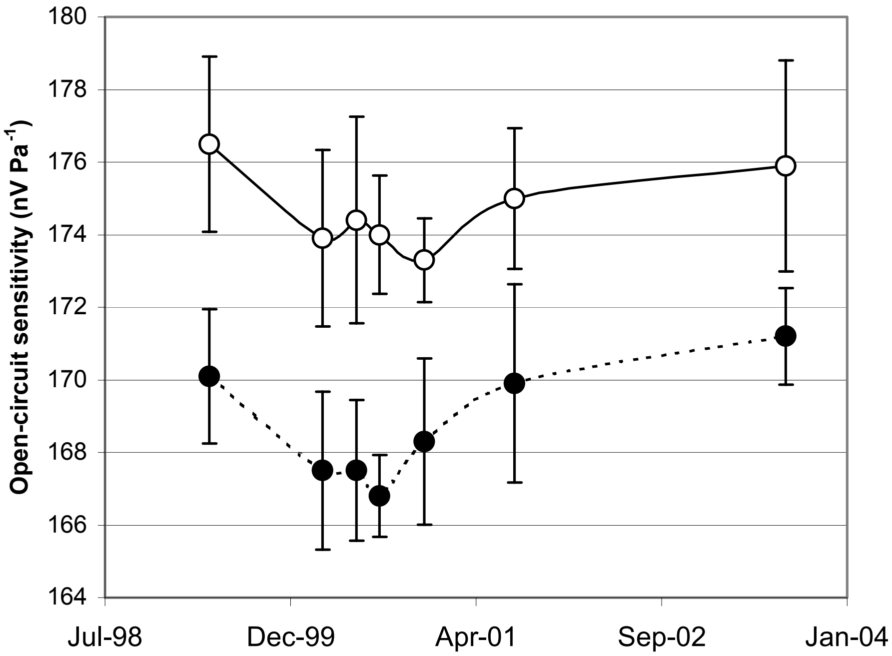

Figure 4.5: Stability checks carried out at NPL during the course of the key comparison. Values of the end-of-cable open-circuit sensitivities of the two hydrophones used, IP027 (•) and IP039 (o), are given derived at a frequency of 5 MHz. The standard uncertainties are presented derived in each instance from four repeat measurements.

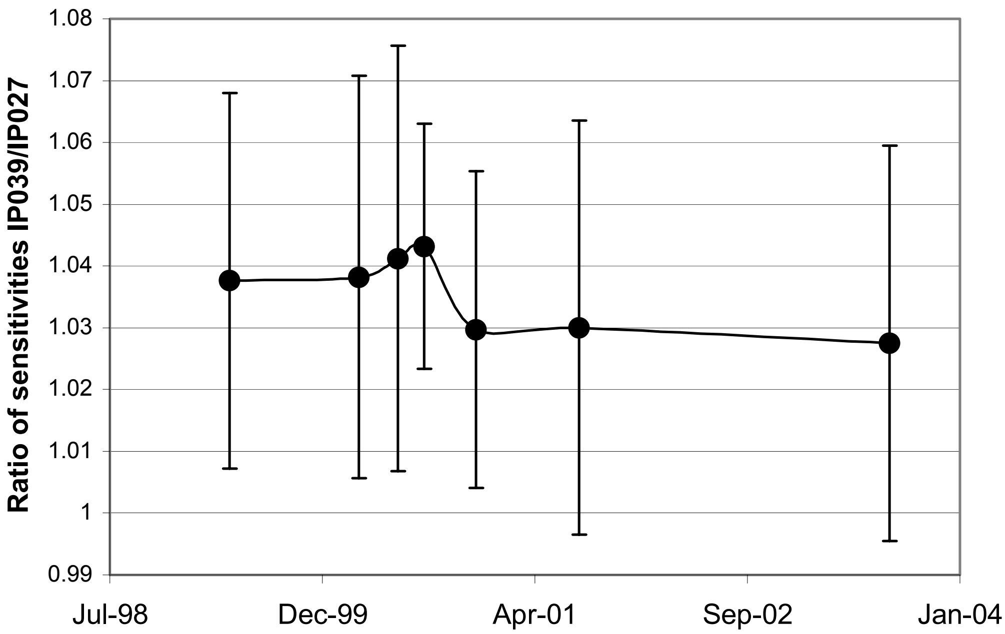

Figure 4.6: Stability checks carried out at NPL during the course of the key comparison. Values of the ratio of the end-of-cable open-circuit sensitivities of the two hydrophones used, IP027 and IP039, are given derived at a frequency of 5 MHz. Standard uncertainties are presented for the ratio.

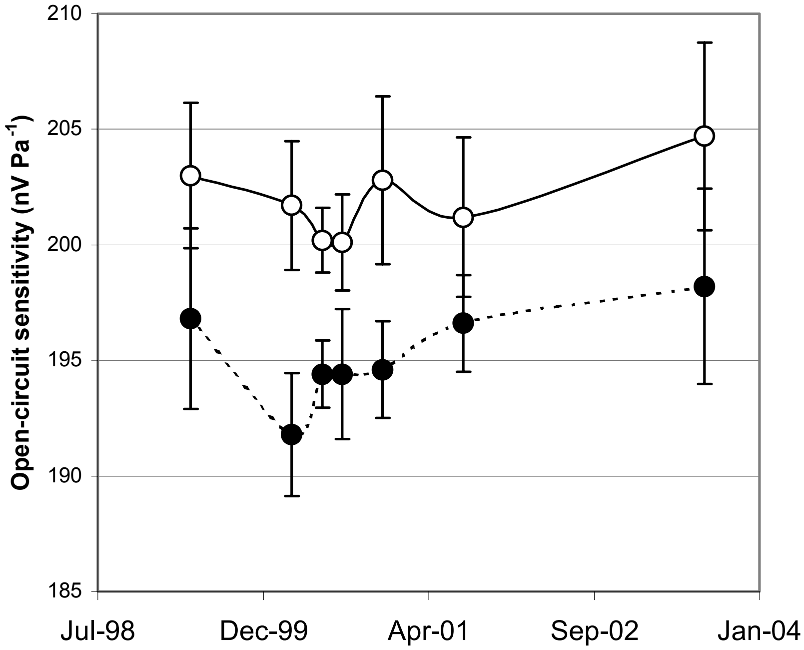

Figure 4.7: Stability checks carried out at NPL during the course of the key comparison. Values of the end-of-cable open-circuit sensitivities of the two hydrophones used, IP027 (•) and IP039 (o), are given derived at a frequency of 10 MHz. The standard uncertainties are presented derived in each instance from four repeat measurements.

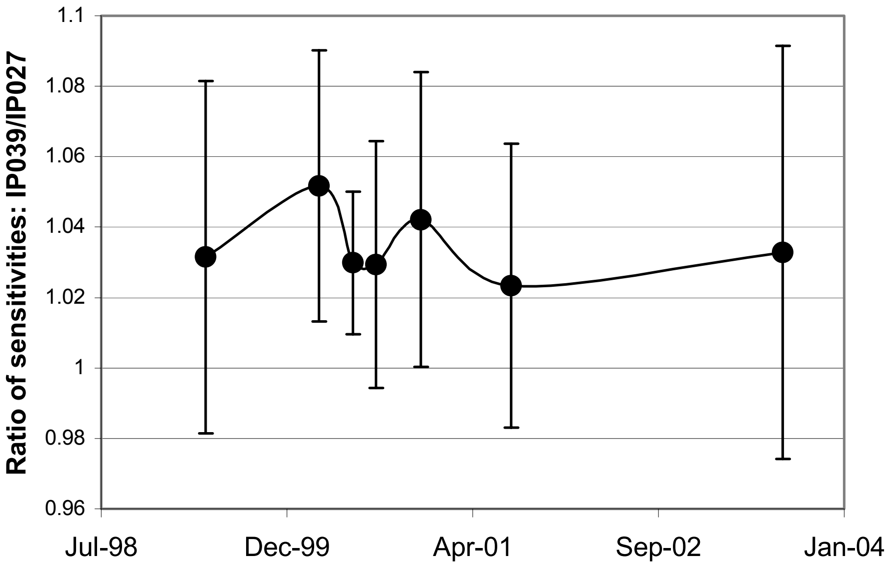

Figure 4.8: Stability checks carried out NPL during the key comparison. Values of the ratio of the end-of-cable open-circuit sensitivities of the two hydrophones used, IP027 and IP039, are given derived at a frequency of 10 MHz. Standard uncertainties are presented for the ratio.

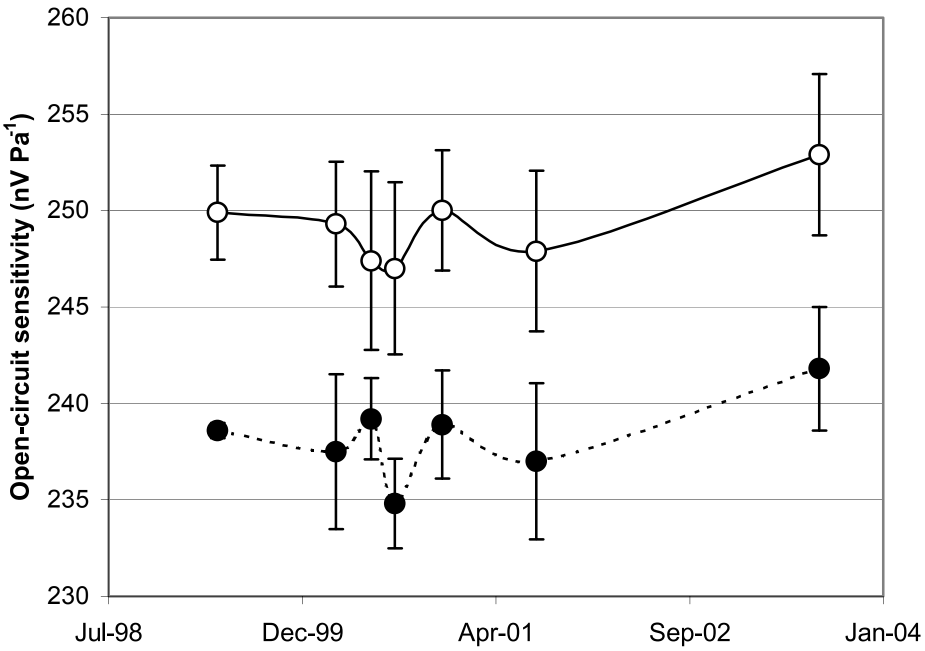

Figure 4.9: Stability checks carried out at NPL during the course of the key comparison. Values of the end-of-cable open-circuit sensitivities of the two hydrophones used, IP027 (•) and IP039 (o), are given derived at a frequency of 15 MHz. The standard uncertainties are presented derived in each instance from four repeat measurements.

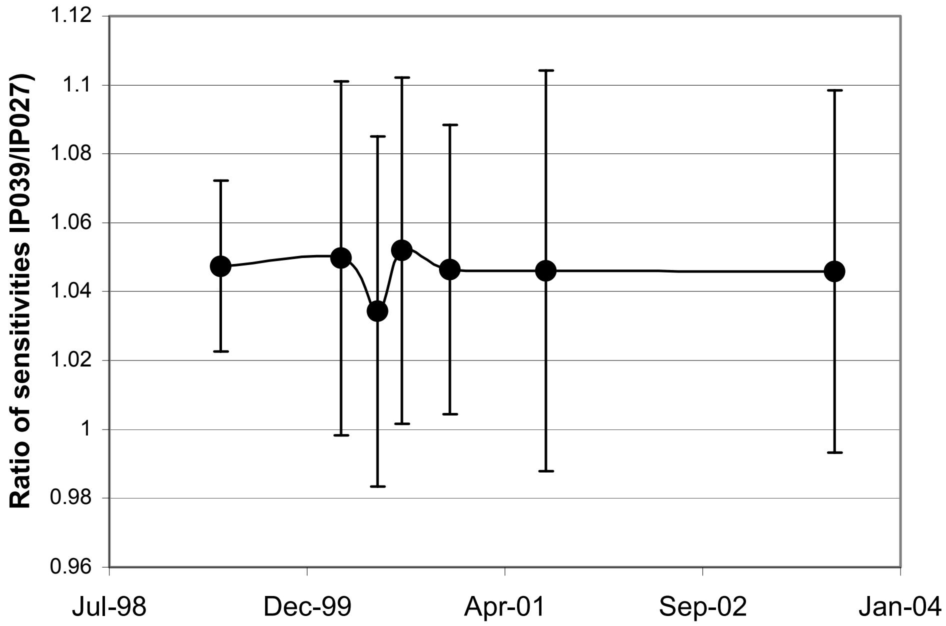

Figure 4.10: Stability checks carried out at NPL during the course of the key comparison. Values of the ratio of the end-of-cable open-circuit sensitivities of the two hydrophones used, IP027 and IP039, are given derived at a frequency of 15 MHz. Standard uncertainties are presented for the ratio.

4.4 10 MHz

Figures 4.7 and 4.8 present stability checks carried out at a frequency of 10 MHz, for values of absolute sensitivity and the sensitivity ratios of the two hydrophones, respectively. From Figure 4.8, the mean values of the sensitivity ratio are 1.0344 ± 0.0094, where the standard uncertainty is given derived from the 6 measurements.

4.5 15 MHz

Figures 4.9 and 4.10 present stability checks carried out at a frequency of 15 MHz, for values of absolute sensitivity and the sensitivity ratios of the two hydrophones, respectively. From Figure 4.10, the mean values of the sensitivity ratio are 1.0459 ± 0.0056, where the standard uncertainty is given derived from the 6 measurements.

4.6 CONCLUSIONS

The reference checks carried out on the two hydrophones indicate that each hydrophone was stable during the course of the comparison. There is no evidence of a systematic drift of the sensitivity of the either of the hydrophones during the course of the key comparison. These findings are entirely in line with previously documentary evidence (Preston et al. 1999) that this type of hydrophone exhibits excellent temporal stability, with no evidence for long-term variation of the sensitivity of the bilaminar hydrophone by more than +0.0013 per annum. Furthermore, by following the ratio of the sensitivity of two secondary standard hydrophones over more then ten years at NPL, the observed systematic trend exhibits a relative increase of no more than +0.0025 per annum.

5 ANALYSIS OF KEY COMPARISON REFERENCE VALUES (KCRVs)

5.1 PHILOSOPHY

In carrying out the KCRV analysis, known correlations between uncertainty contributions declared by the participant laboratories have been removed. The only relevant component involved was the loading correction of the hydrophone when used in conjunction with the amplifier circulated (Lee and Zeqiri 2002). As the uncertainty associated with this correction is potentially common to all uncertainty budgets, it has been removed from the participant uncertainty budgets, where appropriate.

The data for this key comparison presented in Section 5 has been analysed the BIPM guidelines (Cox, M.G., The evaluation of key comparison data, 2002, Metrologia, 39, 589 – 595). This publication sets out procedures for:

- deriving the key comparison reference values (KCRVs);
- deriving the uncertainty in the KCRV values;
- checking the consistency of data;
- establishing the degrees of equivalence of participant laboratories.

The equations and approach used will now be described.

5.2 KEY FORMULAE

5.2.1 Deriving the KCRV from the weighted mean

As proposed within the BIPM procedures, KCRVs for this key comparison have been derived using a *weighted* mean analysis. From Cox (1999), the weighted mean, x_{KCRV}, is given by:

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

where N is the number of values in the comparison, and x_j is the jth comparison value.

5.2.2 The uncertainty in the KCRV value

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

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

where u_j is the standard uncertainty of the key comparison value provided by the jth participant.

5.2.3 Consistency checks

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

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

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:

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

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

A point of interest for key comparison lies in the methods used to identify discrepant laboratories (BIPM 2001; Beissner 2001). The BIPM procedures (BIPM 2001) provide guidance on identifying discrepant laboratories, and, for information, the main features of the analysis will be presented.

From the KCRV vales calculated in Section 6.2.1, and the individual values of the participant laboratories (x_j), the degree of equivalence of the laboratory may be described by the pair of values (d_j, $U(d_j)$) given by the pair of equations:

$$d_j = x_j - x_{KCRV}$$

and

$$U(d_i) = 1.96u(d_i)$$

where the uncertainty in the degree of equivalence, or the deviation from the KCRV, is given by the expression:

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

A discrepant laboratory is identified as one for which:

$$\left|d_j\right| > 1.96\,u(d_j).$$

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

Note: the BIPM procedures deal with a confidence level of 95%. In many parts of this report, a coverage factor of k=2 is used corresponding to a confidence level of 95.45%.

5.3 KEY COMPARISON REFERENCE VALUES

5.3.1 1 MHz

Figure 5.1 shows the key comparison results derived at a frequency of 1 MHz. The KCRV is 157.0 nV Pa^{-1} ± 3.9 nV Pa^{-1}, where the expanded uncertainty and has been calculated using a coverage factor equal to 2. From the data set, the value of $\chi_{obs}^2(3) = 0.25$, indicating that the results are consistent.

5.3.2 2 MHz

Figure 5.2 shows the key comparison results derived at a frequency of 2 MHz. The KCRV is 159.4 nV Pa^{-1} ± 3.4 nV Pa^{-1}, where the expanded uncertainty is given and has been calculated using a coverage factor equal to 2. From the data set, the value of $\chi_{obs}^2(3) = 2.0$, indicating that the results are consistent.

5.3.3 5 MHz

Figure 5.3 shows the key comparison results derived at a frequency of 5 MHz. The KCRV is 171.0 nV Pa^{-1} ± 3.7 nV Pa^{-1}, where the expanded uncertainty is given calculated using a coverage factor equal to 2. From the data set, the value of $\chi_{obs}^2(3) = 0.21$, indicating that the results are consistent.

5.3.4 10 MHz

Figure 5.4 shows the key comparison results derived at a frequency of 10 MHz. The derived KCRV is 196.1 nV Pa^{-1} ± 4.3 nV Pa^{-1}, where the expanded uncertainty is given calculated using a coverage factor equal to 2. From the data set, the value of $\chi_{obs}^2(3) = 4.4$, indicating that the results are consistent.

5.3.5 15 MHz

Figure 5.5 shows the key comparison results derived at a frequency of 15 MHz. The KCRV is 243.9 nV Pa^{-1} ± 6.1 nV Pa^{-1}, where the expanded uncertainty is given calculated using a coverage factor equal to 2. From the data set, the value of $\chi_{obs}^2(3) = 1.4$, again indicating that the results are consistent.

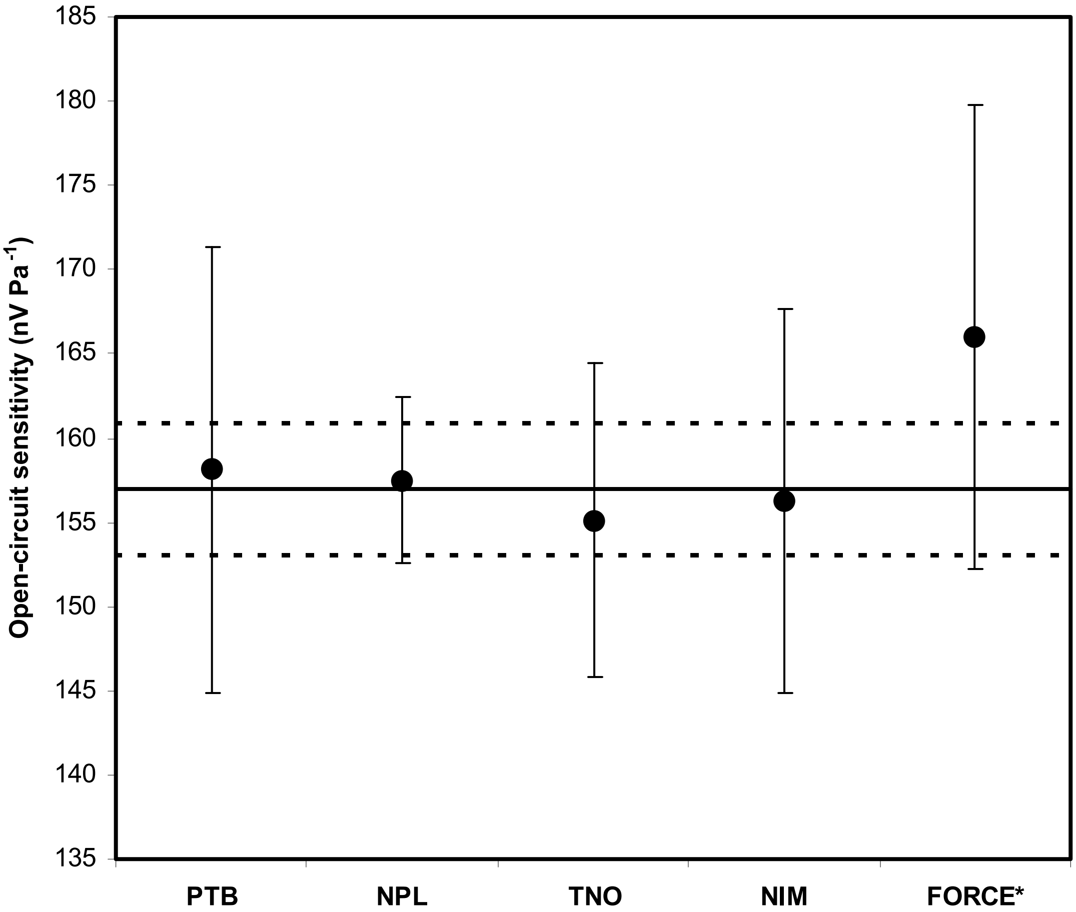

Figure 5.1: Summary of key comparison results obtained at a frequency of 1 MHz for the five laboratories. The results of individual participants are shown along with the expanded uncertainties derived using a coverage, *k*, equal to 2. The KCRV value derived from the set of data is depicted by the bold horizontal line, with the uncertainty limits of the value, again calculated using a coverage factor of 2, being given by the two horizontal broken lines. In this figure and in the subsequent ones 5.2 to 5.5, the value obtained by the FORCE Institute, identified by *, were obtained using a relative method. It should be noted that the FORCE results were not used in the KCRV analysis described in Appendix A.

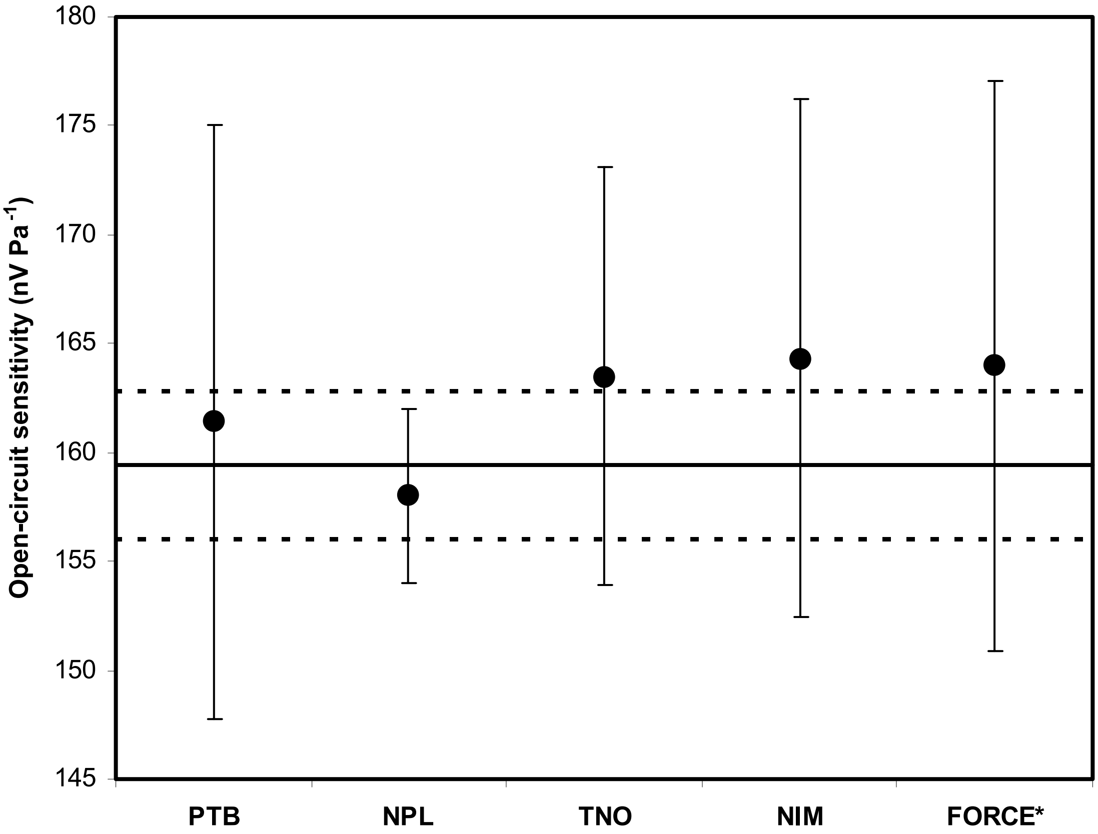

Figure 5.2: Summary of key comparison results obtained at a frequency of 2 MHz for the five laboratories. The results of individual participants are shown along with the expanded uncertainties derived using a coverage factor, *k*, equal to 2. The KCRV value derived from the set of data is depicted by the bold horizontal line, with the uncertainty limits of the value, again calculated using a coverage factor of 2, being given by the two horizontal broken lines.

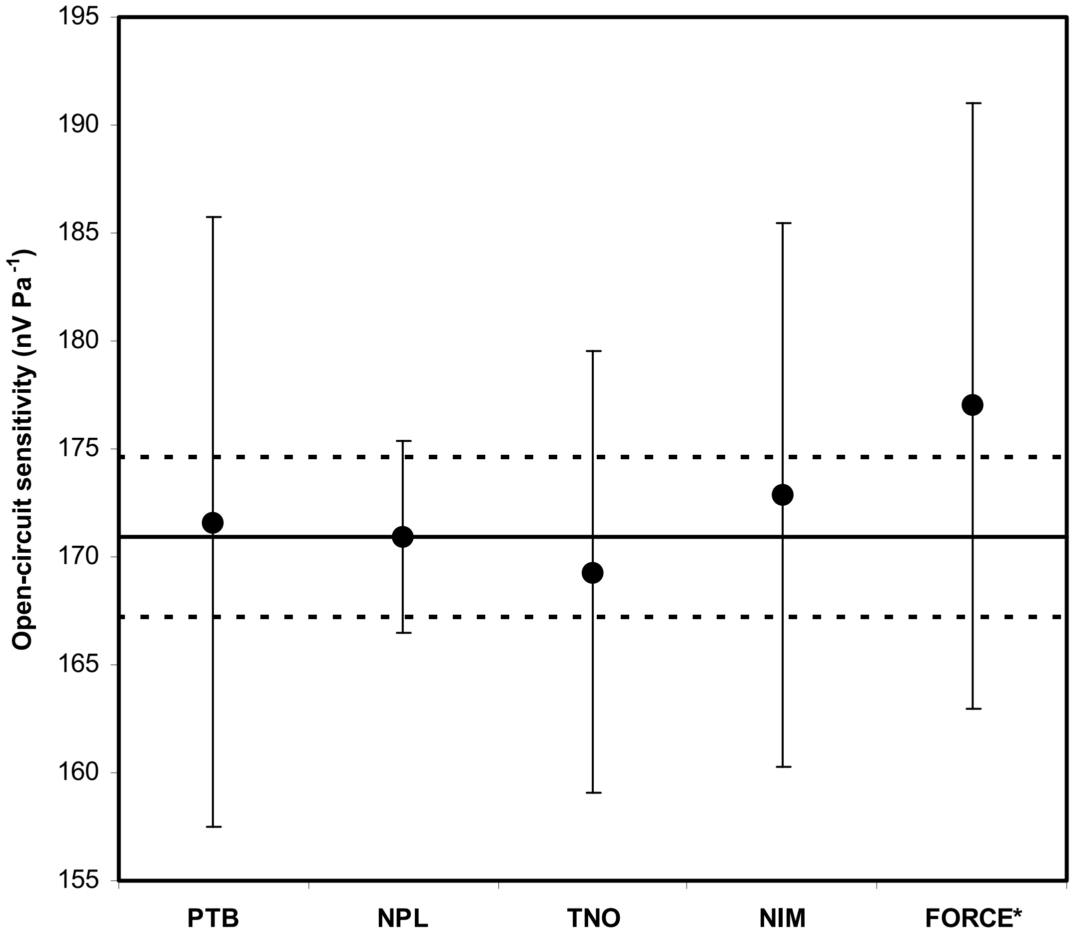

Figure 5.3: Summary of key comparison results obtained at a frequency of 5 MHz for the five laboratories. The results of individual participants are shown along with the expanded uncertainties derived using a coverage, *k*, equal to 2. The KCRV value derived from the set of data is depicted by the bold horizontal line, with the uncertainty limits of the value, again calculated using a coverage factor of 2, being given by the two horizontal broken lines.

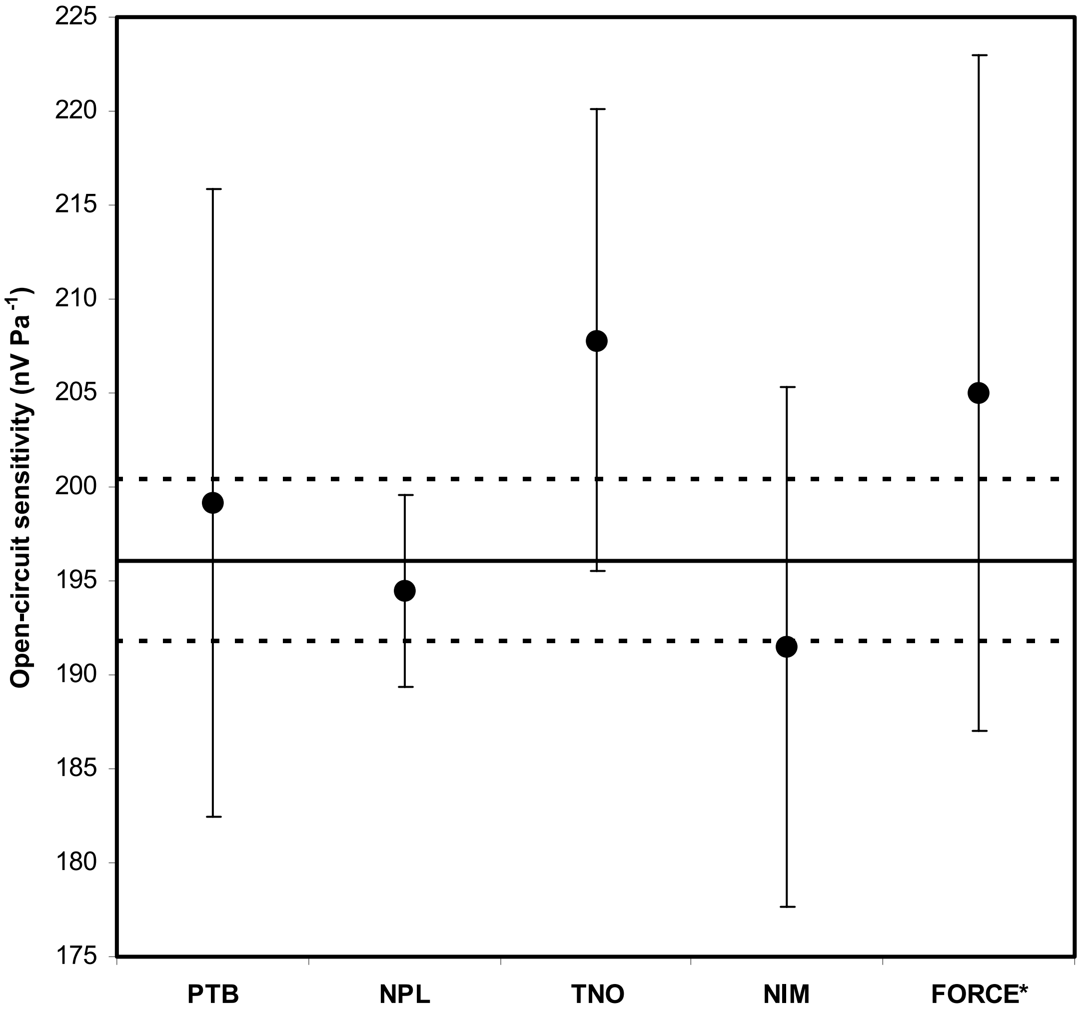

Figure 5.4: Summary of key comparison results obtained at a frequency of 10 MHz for the five laboratories. The results of individual participants are shown along with the expanded uncertainties derived using a coverage, *k*, equal to 2. The KCRV value derived from the set of data is depicted by the bold horizontal line, with the uncertainty limits of the value, again calculated using a coverage factor of 2, being given by the two horizontal broken lines.

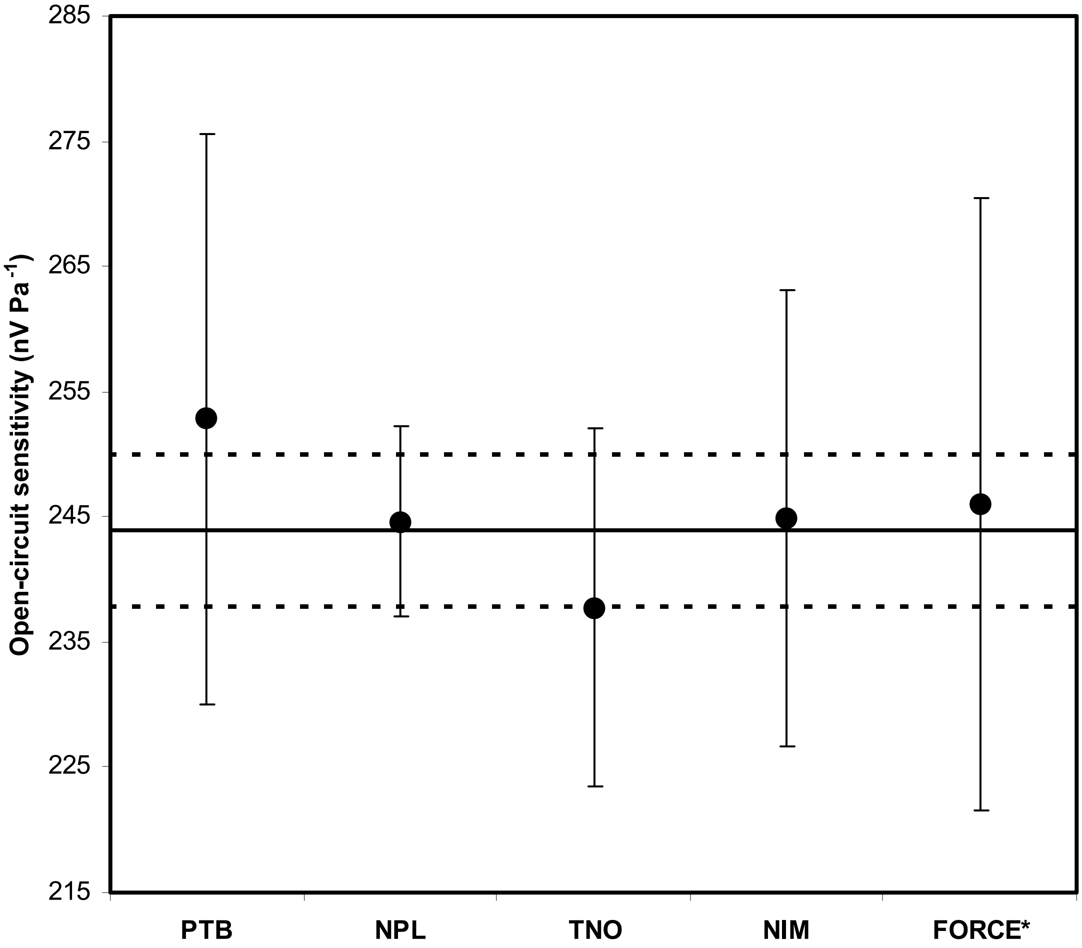

Figure 5.5: Summary of key comparison results obtained at a frequency of 15 MHz for the five laboratories. The results of individual participants are shown along with the expanded uncertainties derived using a coverage, *k*, equal to 2. The KCRV value derived from the set of data is depicted by the bold horizontal line, with the uncertainty limits of the value, again calculated using a coverage factor of 2, being given by the two horizontal broken lines.

The previous Section has presented a description of the how the KCRV values were derived at each of the acoustic frequencies used within this comparison. For ease of reference, these are now summarised in Table 5.1.

Table 5.1: Summary of key comparison reference values derived from the key comparison CCAUV.U-K2. Values of expanded uncertainty are presented derived from the comparison.

Frequency (MHz)	**Key comparison reference (KCRV) (nV Pa^{-1})**	**KCRV expanded uncertainty (*k*=2) (nV Pa^{-1})**
1	157.0	3.9
2	159.4	3.4
5	170.9	3.7
10	196.1	4.3
15	244.0	6.1

5.4 DEVIATIONS FROM KCRV VALUES AND DEGREES OF EQUIVALENCE

Proposals for the parameters are made in the attached Appendices. Appendix A deals with the deviations of the participant results from the KCRV values. Appendix B presents Tables providing degrees of equivalence for the laboratories.

6 SUMMARY

A number of points may be made to summarise the findings of the completed Key Comparison CCAUV.U-K2:

• due a variety of reasons, the number of NMIs completing absolute measurements on the circulated reference hydrophones was restricted to only four;

• three of the NMIs were from Europe (NPL - United Kingdom; PTB - Germany; TNO - The Netherlands) along with NIM (China);

• the expanded uncertainties declared by the laboratories showed a significant variation, typically by a factor as high as 2 or 3, with NPL providing lowest uncertainties;

• the KCRV values at the five frequencies of interest have been calculated using the weighted mean;

• at the three lowest frequencies, 1 MHz, 2 MHz and 5 MHz, agreement between the four laboratories was good, within quoted expanded measurement uncertainties;

• at 10 MHz and 15 MHz, the results of NIM were considered to be discrepant;

• through a bilateral comparison, NIM traced the origin of their discrepant results and submitted new values for the open-circuit sensitivity of one of the hydrophones. These values have been fed into the KCRV analysis;

• tabulations of deviations from the KCRV values for the individual laboratories and the degrees of equivalence between NMIs are presented in two Appendices.

7 ACKNOWLEDGEMENTS

The authors acknowledge the financial support of the UK Department of Trade and Industry National Measurement System Directorate.

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APPENDIX A: DEVIATIONS OF INDIVIDUAL PARTICIPANT VALUES FROM THE DERIVED KCRV's

This Appendix provides tables for the deviations of the individual participant results from the KCRV values derived in Section 5. Tables A1 to A5 cover each of the frequencies over the range 1 to 15 MHz. Within these Tables, the deviation is calculated relative the magnitude of the derived KCRV value, using the expression:-

$$d_{i,R} = \frac{x_i - x_{KCRV}}{x_{KCRV}}$$

where x_i is the value provided by the *i*th participant and x_{KCRV} is the relevant KCRV. Expressions for the derivation of the uncertainty in the deviation have been presented Section 5. Within Tables A1 to A5, the relative expanded uncertainties in the deviation are given using k=2. These deviations have been normalised to the KCRV using:-

$$U(d_{i,R}) = \frac{U(d_i)}{x_{KCRV}}.$$

Table A.1: Table summarising deviations of the individual participant results from the derived KCRV values at a frequency of 1 MHz. Values for the relative expanded uncertainty (k=2) in the deviations are also given.

Participant Laboratory	Relative deviation from KCRV ($d_{i,R}$)	Uncertainty in relative deviation from KCRV ($U(d_{i,R})$)
TNO	-0.012	0.053
NPL	0.003	0.019
PTB	0.007	0.079
NIM	-0.004	0.067
FORCE	0.057	0.083

Table A.2: Table summarising deviations of the individual participant results from the derived KCRV values at a frequency of 2 MHz. Values for the relative expanded uncertainty (*k*=2) in the deviations are also given.

Participant Laboratory	**Relative deviation from KCRV ($d_{i,\mathrm{R}}$)**	**Uncertainty in relative deviation from KCRV ($U(d_{i,\mathrm{R}})$)**
TNO	0.026	0.056
NPL	-0.009	0.013
PTB	0.012	0.081
NIM	0.031	0.070
FORCE	0.029	0.078

Table A.3: Table summarising deviations of the individual participant results from the derived KCRV values at a frequency of 5 MHz. Values for the relative expanded uncertainty (*k*=2) in the deviations are also given.

Participant laboratory	**Relative deviation from KCRV ($d_{i,\mathrm{R}}$)**	**Uncertainty in relative deviation from KCRV ($U(d_{i,\mathrm{R}})$)**
TNO	-0.009	0.054
NPL	0.000	0.014
PTB	0.004	0.078
NIM	0.012	0.069
FORCE	0.036	0.077

Table A.4: Table summarising deviations of the individual participant results from the derived KCRV values at a frequency of 10 MHz. Values for the relative expanded uncertainty (*k*=2) in the deviations are also given..

Participant laboratory	**Relative deviation from KCRV ($d_{i,\mathrm{R}}$)**	**Uncertainty in relative deviation from KCRV ($U(d_{i,\mathrm{R}})$)**
TNO	0.059	0.058
NPL	-0.008	0.014
PTB	0.015	0.081
NIM	-0.024	0.066
FORCE	0.045	0.087

Table A.5: Table summarising deviations of the individual participant results from the derived KCRV values at a frequency of 15 MHz. Values for the relative expanded uncertainty (k=2) in the deviations are also given.

Participant laboratory	Relative deviation from KCRV ($d_{i,\mathrm{R}}$)	Uncertainty in relative deviation from KCRV ($U(d_{i,\mathrm{R}})$)
TNO	-0.026	0.052
NPL	0.003	0.018
PTB	0.036	0.088
NIM	0.004	0.069
FORCE	0.008	0.095

APPENDIX B: DEGREES OF EQUIVALENCE BETWEEN PARTICIPANT LABORATORIES

The relative deviation of two participant laboratories, i and j, is defined by the expression:-

$$d_{ij,R} = \frac{x_i - x_j}{x_{KCRV}}$$

where x_i and x_j are the respective values of the measurand provided by the two laboratories, and x_{KCRV} is the relevant KCRV.

The relative expanded uncertainty in the deviation, $U_{ij,R}$, is evaluated using the expression:-

$$U_{ij,R} = \frac{k\,(u_i^2 + u_j^2)^{0.5}}{x_{KCRV}}$$

where u_i and u_j are the respective standard uncertainty values of the two key comparison results. k is the coverage factor, which is equal to 2. Degrees of equivalence between laboratories and the corresponding uncertainties, expressed in a relative sense, are presented in Tables B.1 to B.5.

It should be noted that in Tables B.1 to B.5, correlations between the FORCE results and those of PTB and NPL, have not been taken into account.

Table B.1: The degrees of equivalence between two participants within this key comparison, determined at a frequency of 1 MHz. The relative expanded uncertainty in the difference between any two laboratories has been calculated using a coverage factor of 2.

	TNO		NPL		PTB		NIM		FORCE	
	$d_{ij,R}$	$U_{ij,R}$	$d_{ij,R}$	$U_{ij,R}$	$d_{ij,R}$	$U_{ij,R}$	$d_{ij,R}$	$U_{ij,R}$	$d_{ij,R}$	$U_{ij,R}$
TNO			-0.015	0.067	-0.019	0.103	-0.008	0.094	-0.069	0.11
NPL	0.015	0.067			-0.004	0.09	0.008	0.079	-0.054	0.093
PTB	0.019	0.103	0.004	0.09			0.011	0.11	-0.050	0.12
NIM	0.008	0.094	-0.008	0.079	-0.011	0.11			-0.062	0.11
FORCE	0.069	0.11	0.054	0.093	0.050	0.12	0.062	0.11		

Table B.2: The degrees of equivalence between two participants within this key comparison, determined at a frequency of 2 MHz. The relative expanded uncertainty in the difference between any two laboratories has been calculated using a coverage factor of 2.

	TNO		**NPL**		**PTB**		**NIM**		**FORCE**	
	$d_{ij,R}$	$U_{ij,R}$	$d_{ij,R}$	$U_{ij,R}$	$d_{ij,R}$	$U_{ij,R}$	$d_{ij,R}$	$U_{ij,R}$	$d_{ij,R}$	$U_{ij,R}$
TNO			0.034	0.065	0.013	0.104	-0.005	0.096	-0.003	0.102
NPL	-0.034	0.065			-0.021	0.089	-0.040	0.079	-0.038	0.086
PTB	-0.013	0.104	0.021	0.089			-0.018	0.11	-0.016	0.12
NIM	0.005	0.096	0.040	0.079	0.018	0.11			0.002	0.11
FORCE	0.003	0.102	0.038	0.086	0.016	0.12	-0.002	0.11		

Table B.3: The degrees of equivalence between two participants within this key comparison, determined at a frequency of 5 MHz. The relative expanded uncertainty in the difference between any two laboratories has been calculated using a coverage factor of 2.

	TNO		NPL		PTB		NIM		FORCE	
	$d_{ij,R}$	$U_{ij,R}$	$d_{ij,R}$	$U_{ij,R}$	$d_{ij,R}$	$U_{ij,R}$	$d_{ij,R}$	$U_{ij,R}$	$d_{ij,R}$	$U_{ij,R}$
TNO			-0.009	0.065	-0.013	0.102	-0.021	0.095	-0.045	0.10
NPL	0.009	0.065			-0.004	0.086	-0.012	0.078	-0.036	0.086
PTB	0.013	0.102	0.004	0.086			-0.008	0.11	-0.032	0.12
NIM	0.021	0.095	0.012	0.078	0.008	0.11			-0.024	0.11
FORCE	0.045	0.10	0.036	0.086	0.032	0.12	0.024	0.11		

Table B.4: The degrees of equivalence between two participants within this key comparison, determined at a frequency of 10 MHz. The relative expanded uncertainty in the difference between any two laboratories has been calculated using a coverage factor of 2.

	TNO		NPL		PTB		NIM		FORCE	
	$d_{ij,R}$	$U_{ij,R}$	$d_{ij,R}$	$U_{ij,R}$	$d_{ij,R}$	$U_{ij,R}$	$d_{ij,R}$	$U_{ij,R}$	$d_{ij,R}$	$U_{ij,R}$
TNO			0.068	0.068	0.044	0.106	0.083	0.094	0.014	0.11
NPL	-0.068	0.068			-0.023	0.089	0.015	0.075	-0.054	0.095
PTB	-0.044	0.106	0.023	0.089			0.039	0.11	-0.03	0.125
NIM	-0.083	0.094	-0.015	0.075	-0.039	0.11			-0.069	0.12
FORCE	-0.014	0.11	0.054	0.095	0.03	0.125	0.069	0.12		

Table B.5: The degrees of equivalence between two participants within this key comparison, determined at a frequency of 15 MHz. The relative expanded uncertainty in the difference between any two laboratories has been calculated using a coverage factor of 2.

	TNO		NPL		PTB		NIM		FORCE	
	$d_{ij,R}$	$U_{ij,R}$	$d_{ij,R}$	$U_{ij,R}$	$d_{ij,R}$	$U_{ij,R}$	$d_{ij,R}$	$U_{ij,R}$	$d_{ij,R}$	$U_{ij,R}$
TNO			-0.028	0.066	-0.062	0.11	-0.030	0.095	-0.034	0.12
NPL	0.028	0.066			-0.034	0.099	-0.001	0.081	-0.006	0.10
PTB	0.062	0.11	0.034	0.099			0.032	0.12	0.028	0.14
NIM	0.030	0.095	0.001	0.081	-0.032	0.12			-0.005	0.12
FORCE	0.034	0.12	0.006	0.10	-0.028	0.14	0.005	0.12		

APPENDIX C: REPORT SUBMITTED BY NATIONAL INSTITUTE OF METROLOGY, CHINA

Final Calibration Report
Of the CIPM/BIPM Key Comparison CCAUV-U-K2

(Comparison of 1 mm hydrophone calibrations in the frequency range 1 to 15 MHz)

National Institute of Metrology
No. 18 Bei San Huan Dong Lu
Beijing 100013
China

2000. 10. 12

1 INTRODUCTION

According to the Chinese National Standard GB/T15611-1995 <Acoustics-Calibration of high frequency hydrophone > which is equivalent to the IEC Publication 866(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 in this August and returned these 2 hydrophones to NPL on August 15. 2000.

2 CALIBRATION METHOD

2.1 Two-transducer method

The calibration procedure is based on the two-transducer method . The block diagram of the electrical circuit for this method is shown as Fig. 1:

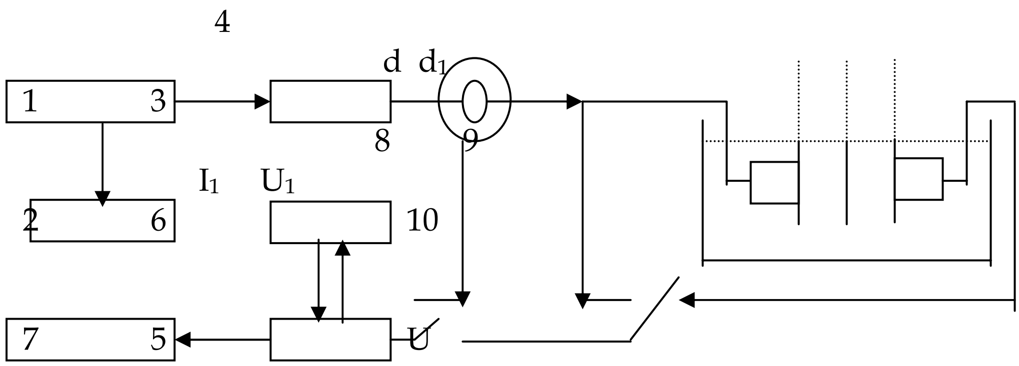

Fig.1 Block diagram of the electrical circuit for the two-transducer reciprocity calibration method.

1.tone-burst generator 2. Frequency counter 3. Matching network
4. current transformer 5. Preamplifier 6. Filter 7. Digital oscilloscope
8. auxiliary transducer 9. Hydrophone 10. reflector

Fig. 1 illustrates the experimental arrangement and shows the associated electrical circuit. The auxiliary transducer 8 radiates repetitive tone bursts by tone burst generator 1 into the water tank where they are reflected by a thick stainless steel reflector 10. For the self-reciprocity calibration of the auxiliary transducer, the transducer is adjusted to the axis of the emitted ultrasonic beams perpendicular to the reflecting surface. The apparent transmitting current response S* is determined by measuring the transmitting current I1 and the receiving signal U1.

$$S^* = P_1 / I_1 = (U_1 / I_1 \cdot J_P)^{1/2} \quad , \quad J_P = 2A/ \rho c$$

Where:

P_1 is acoustic pressure in the plane wave emitted by transducer;

J_P is the reciprocity coefficient for plane wave;
A is the effect area of the surface of transducer 8;
ρ is the density of the propagation medium (water)
c is the speed of sound in the water.

For the second stage, the calibration of the hydrophone, the reflector is removed and the hydrophone is aligned at the axis of the same emitted ultrasonic beam and the distance is $d_1 = d$. The apparent free field receiving sensitivity M* of the hydrophone is:

$$M^* = U / P_1 = U/I_1 \cdot 1/S^*$$

For the third stage, the calibration of the hydrophone, the free-field open circuit voltage sensitivity M of the hydrophone can be calculated:

$$M = M^* \cdot k$$

Where k is the correction factor which is related to the tone burst non-plane wave condition, acoustic absorption in water and tone burst generator output impedance, etc.

$$K = (k_{u1})^{1/2} \cdot G_c \cdot \gamma^{-1/2} \cdot e^{\square' d}$$

(IEC 866-1987, Sub-clause 7.5)

2.2 The water tank

The water tank is made of glass. The size is 800 mm (length)×500 mm(depth) ×500 mm(width). The aluminium shelf of the water tank is connected electrically to the measuring electronic equipment. The water tank is filled with the cooling water of boiled water (degas water). The conductivity of the water is about 150μs (we do not use the de-ion water). The oxygen content of the water is about 1 mg/L.

2.3 The auxiliary transducer

The active elements of 5 auxiliary transducers (made by out Lab.) are PZT-4. The diameters of these elements and the measuring distances are in the table 1.

Table 1: Diameter of active element and measuring distance

f(MHz)	diameter(mm)	Measuring distance (mm) ($d_1+d = 2d$)
1.0	20	133.34
2.0	20	266.66
5.0	5.0	62.49
10.0	3.8	72.20
15.0	6.0	188.00

2.4 The reflector

The diameter of the stainless steel reflector is 120 mm and its thickness is 23 mm.

2.5 The open circuit voltage correction

In out calibration, the NPL preamplifier war not used. According to the impedance R+jX of hydrophones and the input impedance □R_L+jX_L□of the oscilloscope, the open circuit voltage correction is obtained:

Table 2. Open circuit voltage correction C

$$C = \left[\frac{(R+R_L)^2 + (X+X_L)^2}{R_L^2 + X_L^2} \right]^{\frac{1}{2}}$$

f(MHz)	IP027	IP039
1.0	1.256	1.286
2.0	1.271	1.300
5.0	1.288	1.314
10.0	1.291	1.316
15.0	1.283	1.307

3 IP027 calibration report sheet

3.1 1 **MHz**

Version 1.0
CIPM/BIPM Protocol Document CCAUV-U-K2

Table 3: Calibration report Sheet

Institution: NIM		**Calibration method:** IEC 866		
Date(s) of calibrations: 15.07.2000 16.07.2000		**Hydrophone serial number:** IP027		
Nominal frequency (MHz): 1				
Measurement Number	**1**	**2**	**3**	**4**
Actual frequency (MHz)	1.00	1.00	1.00	1.00
Temperature, T (℃)	28.0	28.0	28.0	28.0
Open-circuit correction	1.256	1.256	1.256	1.256
Water conductivity (μS)	150	150	150	150
Oxygen content (mg l^{-1})	1.0	1.0	1.0	1.0
Amplifier gain (dB)	/	/	/	/
Measured sensitivity (nV/Pa)	114	117	126	120
Open-circuit sensitivity at T ℃ (nV/Pa)	143	147	158	151
Notes (e.g. of any unusual difficulties)				

3.2 2 **MHz**

Version 1.0
CIPM/BIPM Protocol Document CCAUV-U-K2

Table 3: Calibration report Sheet

Institution: NIM			**Calibration method:** IEC 866	
Date(s) of calibrations: 15.07.2000 16.07.2000			**Hydrophone serial number:** IP027	
Nominal frequency (MHz): 2				
Measurement Number	**1**	**2**	**3**	**4**
Actual frequency (MHz)	2.00	2.00	2.00	2.00
Temperature, T (℃)	28.0	28.0	28.0	28.0
Open-circuit correction	1.271	1.271	1.271	1.271
Water conductivity (μS)	150	150	150	150
Oxygen content (mg l^{-1})	1.0	1.0	1.0	1.0
Amplifier gain (dB)	/	/	/	/
Measured sensitivity (nV/Pa)	129	122	130	132
Open-circuit sensitivity at T ℃ (nV/Pa)	164	155	165	168
Notes (e.g. of any unusual difficulties)				

3.3 5 **MHz**

Version 1.0
CIPM/BIPM Protocol Document CCAUV-U-K2

Table 3: Calibration report Sheet

Institution: NIM		**Calibration method:** IEC 866		
Date(s) of calibrations: 15.07.2000 16.07.2000		**Hydrophone serial number:** IP027		
Nominal frequency (MHz): 5				
Measurement Number	**1**	**2**	**3**	**4**
Actual frequency (MHz)	5.00	5.00	5.00	5.00
Temperature, T (℃)	28.0	28.0	28.0	28.0
Open-circuit correction	1.288	1.288	1.288	1.288
Water conductivity (μS)	150	150	150	150
Oxygen content (mg l^{-1})	1.0	1.0	1.0	1.0
Amplifier gain (dB)	/	/	/	/
Measured sensitivity (nV/Pa)	127	124	124	122
Open-circuit sensitivity at T ℃ (nV/Pa)	164	160	160	157
Notes (e.g. of any unusual difficulties)				

3.4 10 **MHz**

Version 1.0
CIPM/BIPM Protocol Document CCAUV-U-K2

Table 3: Calibration report Sheet

Institution: NIM			**Calibration method:** IEC 866	
Date(s) of calibrations: 15.07.2000 16.07.2000			**Hydrophone serial number:** IP027	
Nominal frequency (MHz): 10				
Measurement Number	**1**	**2**	**3**	**4**
Actual frequency (MHz)	10.00	10.00	10.00	10.00
Temperature, T (℃)	28.0	28.0	28.0	28.0
Open-circuit correction	1.291	1.291	1.291	1.291
Water conductivity (μ S)	150	150	150	150
Oxygen content (mg l^{-1})	1.0	1.0	1.0	1.0
Amplifier gain (dB)	/	/	/	/
Measured sensitivity (nV/Pa)	130	107	116	133
Open-circuit sensitivity at T ℃ (nV/Pa)	168	138	150	172
Notes (e.g. of any unusual difficulties)				

3.5 15 **MHz**

Version 1.0
CIPM/BIPM Protocol Document CCAUV-U-K2

Table 3: Calibration report Sheet

Institution: NIM		**Calibration method:** IEC 866		
Date(s) of calibrations: 04.08.2000		**Hydrophone serial number:** IP027		
Nominal frequency (MHz): 15				
Measurement Number	**1**	**2**	**3**	**4**
Actual frequency (MHz)	15.00	15.00	15.00	15.00
Temperature, T (℃)	28.0	28.0	28.0	28.0
Open-circuit correction	1.283	1.283	1.283	1.283
Water conductivity (μS)	150	150	150	150
Oxygen content (mg l^{-1})	1.0	1.0	1.0	1.0
Amplifier gain (dB)	/	/	/	/
Measured sensitivity (nV/Pa)	111	100	102	120
Open-circuit sensitivity at T ℃ (nV/Pa)	142	128	131	154
Notes (e.g. of any unusual difficulties)				

4 IP039 calibration report sheet
4.1 1 **MHz**

Version 1.0
CIPM/BIPM Protocol Document CCAUV-U-K2

Table 3: Calibration report Sheet

Institution: NIM		**Calibration method:** IEC 866		
Date(s) of calibrations: 11.07.2000 12.07.2000		**Hydrophone serial number:** IP039		
Nominal frequency (MHz): 1				
Measurement Number	**1**	**2**	**3**	**4**
Actual frequency (MHz)	1.00	1.00	1.00	1.00
Temperature, T (℃)	28.0	28.0	28.0	28.0
Open-circuit correction	1.286	1.286	1.286	1.286
Water conductivity (μ S)	150	150	150	150
Oxygen content (mg l^{-1})	1.0	1.0	1.0	1.0
Amplifier gain (dB)	/	/	/	/
Measured sensitivity (nV/Pa)	133	144	132	131
Open-circuit sensitivity at T ℃ (nV/Pa)	171	185	170	168
Notes (e.g. of any unusual difficulties)				

4.2 2 **MHz**

Version 1.0
CIPM/BIPM Protocol Document CCAUV-U-K2

Table 3: Calibration report Sheet

Institution: NIM		**Calibration method:** IEC 866		
Date(s) of calibrations: 11.07.2000, 12.07.2000		**Hydrophone serial number:** IP039		
Nominal frequency (MHz): 2				
Measurement Number	**1**	**2**	**3**	**4**
Actual frequency (MHz)	2.00	2.00	2.00	2.00
Temperature, T (℃)	28.0	28.0	28.0	28.0
Open-circuit correction	1.300	1.300	1.300	1.300
Water conductivity (μ S)	150	150	150	150
Oxygen content (mg l^{-1})	1.0	1.0	1.0	1.0
Amplifier gain (dB)	/	/	/	/
Measured sensitivity (nV/Pa)	142	143	140	130
Open-circuit sensitivity at T ℃ (nV/Pa)	185	186	182	169
Notes (e.g. of any unusual difficulties)				

4.3 5 **MHz**

Version 1.0
CIPM/BIPM Protocol Document CCAUV-U-K2

Table 3: Calibration report Sheet

Institution: NIM		**Calibration method:** IEC 866		
Date(s) of calibrations: 11.07.2000 12.07.2000		**Hydrophone serial number:** IP039		
Nominal frequency (MHz): 5				
Measurement Number	**1**	**2**	**3**	**4**
Actual frequency (MHz)	5.00	5.00	5.00	5.00
Temperature, T (℃)	28.0	28.0	28.0	28.0
Open-circuit correction	1.314	1.314	1.314	1.314
Water conductivity (μS)	150	150	150	150
Oxygen content (mg l^{-1})	1.0	1.0	1.0	1.0
Amplifier gain (dB)	/	/	/	/
Measured sensitivity (nV/Pa)	139	139	131	133
Open-circuit sensitivity at T ℃ (nV/Pa)	183	183	172	175
Notes (e.g. of any unusual difficulties)				

4.4 10 **MHz**

Version 1.0
CIPM/BIPM Protocol Document CCAUV-U-K2

Table 3: Calibration report Sheet

Institution: NIM	**Calibration method:** IEC 866			
Date(s) of calibrations: 11.07.2000 12.07.2000	**Hydrophone serial number:** IP039			
Nominal frequency (MHz): 10				
Measurement Number	**1**	**2**	**3**	**4**
Actual frequency (MHz)	10.00	10.00	10.00	10.00
Temperature, T (℃)	28.0	28.0	28.0	28.0
Open-circuit correction	1.316	1.316	1.316	1.316
Water conductivity (μS)	150	150	150	150
Oxygen content (mg l^{-1})	1.0	1.0	1.0	1.0
Amplifier gain (dB)	/	/	/	/
Measured sensitivity (nV/Pa)	126	137	144	134
Open-circuit sensitivity at T ℃ (nV/Pa)	166	180	190	176
Notes (e.g. of any unusual difficulties)				

4.5 15 **MHz**

Version 1.0
CIPM/BIPM Protocol Document CCAUV-U-K2

Table 3: Calibration report Sheet

Institution: NIM		**Calibration method:** IEC 866		
Date(s) of calibrations: 04.08.2000		**Hydrophone serial number:** IP039		
Nominal frequency (MHz): 15				
Measurement Number	**1**	**2**	**3**	**4**
Actual frequency (MHz)	15.00	15.00	15.00	15.00
Temperature, T (℃)	28.0	28.0	28.0	28.0
Open-circuit correction	1.307	1.307	1.307	1.307
Water conductivity (μ S)	150	150	150	150
Oxygen content (mg l^{-1})	1.0	1.0	1.0	1.0
Amplifier gain (dB)	/	/	/	/
Measured sensitivity (nV/Pa)	139	128	129	119
Open-circuit sensitivity at T ℃ (nV/Pa)	182	167	169	156
Notes (e.g. of any unusual difficulties)				

5 Summary sheet
5.1 IP027 hydrophone
Version 1.0
CIPM/BIPM Protocol Document CCAUV-U-K2

Table 4: Summary Sheet.

Institution: NIM			**Method:** IEC 866		
Dates: 15.07.2000, 16.07.2000, 04.08.2000		**Hydrophone Serial Number:** IP027			
Nominal frequency (MHz)	**1**	**2**	**5**	**10**	**15**
Actual frequency (MHz)	1.00	2.00	5.00	10.00	15.00
Mean open-circuit sensitivity at T ℃ (nV/Pa) (28 ℃)	150	163	160	158	139
Type A standard Uncertainty (%)	1.7	1.5	0.7	5	3.5
Type B standard Uncertainty (%)	3.4	3.4	3.4	3.4	3.4
Expanded uncertainty (%) (k=2)	7.6	7.4	7.0	12.0	9.8

5.1 **IP039 hydrophone**
Version 1.0
CIPM/BIPM Protocol Document CCAUV-U-K2

Table 4: Summary Sheet.

Institution: NIM			**Method:** IEC 866		
Dates: 11.07.2000, 12.07.2000, 04.08.2000			**Hydrophone Serial Number:** IP039		
Nominal frequency (MHz)	**1**	**2**	**5**	**10**	**15**
Actual frequency (MHz)	1.00	2.00	5.00	10.00	15.00
Mean open-circuit sensitivity at T ℃ (nV/Pa) (28 ℃)	174	181	179	178	169
Type A standard Uncertainty (%)	2.0	1.6	1.2	3.9	3.2
Type B standard Uncertainty (%)	3.4	3.4	3.4	3.4	3.4
Expanded uncertainty (%) (k=2)	7.9	7.5	7.2	10.3	9.3

6. Treatments of uncertainties

6.1 Type A standard uncertainty

Type A standard uncertainty is evaluated by the statistical method. Because measurements are in the same accurate and independent measuring condition, Type A standard uncertainty is evaluated by experimental standard deviation s.

$$u_A = s / \sqrt{n}$$

Where: n is number of measurements. The experimental standard deviation is evaluated by the Bessel method, i.e.

$$S = \sqrt{\frac{\sum_{i=1}^{n}(M_i - \overline{M})^2}{n-1}}$$

Where: $\overline{M}$ is mean of the sensitivity. The type A standard uncertainty is shown in the summary sheet in the frequency range 1 to 15 MHz. In general speaking, the type A standard uncertainty of our calibration is less than 5.0%.

6.2 Type B standard uncertainty

Type B standard uncertainty is evaluated by the measuring equipment and the measuring method. In our calibration, the accuracy of the digital oscilloscope and the current transformer is 1.0 %(rectangular distribution):

(1)

$$S* = (\frac{U_1}{I_1} \cdot \frac{1}{J_P})^{1/2}$$

$$\frac{\Delta S*}{S*} = \frac{1}{2}\left[\left(\frac{\Delta U_1}{U_1}\right)^2 + \left(\frac{\Delta I_1}{I_1}\right)^2 + \left(\frac{\Delta J_P}{J_P}\right)^2\right]^{1/2}$$

$$\frac{\Delta U_1}{U_1} = 1.0\%, \frac{\Delta I_1}{I_1} = 1.0\%$$

$$J_P = \frac{2A}{\rho c}, \frac{\Delta J_P}{J_P} = \left[\left(\frac{\Delta A}{A}\right)^2 + \left(\frac{\Delta \rho}{\rho}\right)^2 + \left(\frac{\Delta c}{c}\right)^2\right]^{1/2}$$

$$\frac{\Delta A}{A} = 2.0\%, \frac{\Delta \rho}{\rho} = 0.5\%, \frac{\Delta c}{c} = 1.5\%, \frac{\Delta J_P}{J_P} = 2.5\%$$

$$\frac{\Delta S*}{S*} = 1.4\%$$

(2)

$$M^* = \frac{U}{I_1} \cdot \frac{1}{S^*}$$

$$\frac{\Delta M^*}{M^*} = \left[\left(\frac{\Delta U}{U} \right)^2 + \left(\frac{\Delta I_1}{I_1} \right)^2 + \left(\frac{\Delta S^*}{S^*} \right)^2 \right]^{1/2}$$

$$\left(\frac{\Delta U}{U} \right) = 1.0\%, \left(\frac{\Delta I_1}{I_1} \right) = 1.0\%, \left(\frac{\Delta S^*}{S^*} \right) = 1.4\%, \frac{\Delta M^*}{M^*} = 2.0\%$$

$$M = M^* \cdot K$$

$$\frac{\Delta M}{M} = \left[\left(\frac{\Delta M^*}{M^*} \right)^2 + \left(\frac{\Delta K}{K} \right)^2 \right]^{1/2}$$

$$K = K_{u1}^{1/2} \cdot G_c \cdot \gamma^{1/2} \cdot e^{a'd}$$

$$\frac{\Delta K}{K} = \left[\frac{1}{2} \left(\frac{\Delta k_{u1}}{k_{u1}} \right)^2 + \left(\frac{\Delta G_c}{G_c} \right)^2 + \frac{1}{2} \left(\frac{\Delta \gamma}{\gamma} \right)^2 + \left(\frac{\Delta a'}{a'} \right)^2 + \left(\frac{\Delta d}{d} \right)^2 \right]^{1/2}$$

$$\frac{\Delta k_{u1}}{k_{u1}} = \left[\left(\frac{\Delta I_1}{I_1} \right)^2 + \left(\frac{\Delta I_k}{I_k} \right)^2 \right]^{1/2} = 1.4\%$$

$$\frac{\Delta G_C}{G} = 2.0\%, \frac{\Delta \gamma}{\gamma} = 1.0\%, \frac{\Delta a'}{a'} = 1.0\%, \frac{\Delta d}{d} = 1.0\%, \frac{\Delta K}{K} = 2.7\%$$

Then the type B standard uncertainty is:

$$\frac{\Delta M}{M} = \sqrt{(2.0\%)^2 + (2.7\%)^2} = 3.4\%$$

Now we can get the combined standard uncertainty is:

$$u_c = \sqrt{u_A{}^2 + u_B^2} = \sqrt{(5.0\%)^2 + (3.4\%)^2} = 6.0\%$$

And the expanded standard uncertainty u =2u_c=12.0 % (k=2)

7. Discussion

(1) During the measurements, the acoustic pressure is about:

F(MHz)	p
1.0	(1～3)• 10^4 Pa
2.0	(1～3)• 10^4 Pa
5.0	(1～3)• 10^4 Pa
10.0	(3 • 10^3～2 •10^4)Pa
15.0	About 2 •10^3 Pa

(2) According to the specifications of the digital oscilloscope and current transformer provided by manufacturer, we evaluated the type B standard uncertainty.

(3) Using the IEC866 calibration method, It is little difficult to calculate the accuracy of correction factor k.

(4) Doing the International Comparison of the hydrophone calibration, It is very worth and beneficial to us.

APPENDIX D SUPPLEMENTARY REPORT SUBMITTED BY NATIONAL INSTITUTE OF METROLOGY, CHINA

RE-CALIBRATION

Report of 1mm Membrane Hydrophone in the Frequency Range 1-15 MHz
(CIPM/BIPM key comparison CCAUV-U-K2)

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1 INTRODUCTION

According to the summary of the revised Report (August 2002) of BIPM/CIPM Key Comparison CCAUV-U-K2: **" at 10 MHz and 15 MHz the results of NIM were considered to be discrepant and it is suggested that origin of the discrepant results be investigated through a bilateral arrangement between NIM and NPL".**
In May of this year (2003), NIM received the 1 mm membrane hydrophone (IP027) from NPL. NIM has got the help from NPL and TNO. NIM carried out the re-calibration and finished the re-calibration work in this August. **In this report, the origin of the discrepant results and the new results of this re-calibration are presented.**

2 ORIGIN OF DISCREPANT RESULTS AND RE-CALIBRATION

2.1 Calibration method

Originally we used the IEC 60866 method to calibrate the 1 mm membrane hydrophone. This method needs a correction factor of ultrasonic attenuation in water. **For this re-calibration, we use the calibration method as used by Dr. R.T.Hekkenberg of TNO PG**. In this way the hydrophone receives the sound pressure directly from the source transducer, instead of after reflection by the stainless steel reflector as given in the IEC 60866. Furthermore if the distance between the source transducer and the hydrophone is made just equal to the distance between source transducer and reflector, not only for the attenuation of ultrasound in water is cancelled out, and the correction for this is not needed, but also for the receiving voltage of the hydrophone is higher.

2.2 Current transformer

Originally we used the Current Monitor for measuring the transmitting current. The Current Monitor is made in USA, PEARSON ELECTRONICS, INC. Its type is 411.Its output is
0.1 Volt /amp. We did not check its accuracy and frequency response. For this re-calibration, we
use the Current Probe, Type TCP202, made in Tektronix . We compared the Current Monitor 411 with Current Probe TCP 202 to measure same current We found the frequency response of Current Monitor PEARSON 411 is not so good and higher 3 dB than the frequency response of TEK Current Probe TCP 202 on the frequency 15 MHz. **Therefore we use the Current Probe TCP 202 for measuring the transducer transmitting current in this re-calibration. We consider the current transformer used in the first calibration is the main origin of the discrepant results.**

2.3 Correction factor G1 and G2

Originally we got the correction factor G_c from the Fig. 5 in the IEC 60866. I feel it is very difficult to get the accurate value of this correction factor. **For this re-calibration, I have got the great help from Dr. R.T.Hekkenberg (TNO). He gave me a file and told me how to calculate the correction factor G1 and G2. I think Gc got from the Fig.5 in the IEC 60866 is the second main origin of the discrepant results.**

2.4 Tone-burst generator

Originally we used the old type function generator (H.P.) as the Tone-Burst Generator. **For this re-calibration, we use the Agilent 33250A function generator as the Tone-Burst Generator. The frequency and amplitude of Agilent 33250A are more stable and more accurate.**

2.5 Auxiliary transducer

In this re-calibration, we use the new 5 Auxiliary transducers made by us. We have got the higher ratio of signal to noise. The hydrophone receiving voltage is more than 15 mV.

3 RESULTS

The new results of re-calibration on the frequency 1,2,5,10,15 MHz and the uncertainties are listed in the Table 1 to Table 6.

Table1. Calibration results of hydrophone IP027

Institution NIM			Method: Reciprocity method		
Dates: 22 July –1 August 2003	Hydrophone Serial Number: IP027				
Nominal frequency (MHz)	1	2	5	10	15
Actual frequency (MHz)	1.000	2.000	5.000	10.000	15.000
Mean open-circuit sensitivity at T □ (nV/Pa) 25.0□	156.3	164.3	172.9	191.5	243.9
Type A standard Uncertainty (%)	0.86	0.74	0.80	0.51	1.08
Type B standard uncertainty (%)	3.00	3.00	3.00	3.00	3.00
Expanded uncertainty (%) U(k=2)	6.2	6.2	6.2	6.1	6.4

Table2. Calibration results at 1 MHz

Institution NIM			Calibration method: Reciprocity method			
Dates(s) of calibrations: 22 July –1 August 2003			Hydrophone Serial Number: IP027			
Nominal frequency (MHz): **1**						
Measurement number	1	2	3	4	5	6
Actual frequency (MHz)	1.000	1.000	1.000	1.000	1.000	1.000
Temperature, T □	25.0	25.0	25.0	25.0	25.0	25.0
Open-circuit correction	1.133	1.133	1.133	1.133	1.133	1.133
Water conductivity(μS)	150	150	150	150	150	150
Oxygen content (mg l^{-1}), or alternative (ppm of % saturation)	<10 ppm	<10 ppm	<10 ppm	<10 ppm	<10 ppm	<10 ppm
Amplifier gain (dB)						
Measured sensitivity (nV/Pa)	133.5	138.0	136.7	140.4	141.7	137.2
Open-circuit sensitivity at T □ (nV/Pa)	151.2	156.4	154.9	159.1	160.5	155.4
Notes (e.g. of any unusual Difficulties)						

Table 3. Calibration results at 2 MHz

Institution NIM			Calibration method: Reciprocity method			
Dates(s) of calibrations: 22 July –1 August 2003			Hydrophone Serial Number: IP027			
Nominal frequency (MHz): **2**						
Measurement number	1	2	3	4	5	6
Actual frequency (MHz)	2.000	2.000	2.000	2.000	2.000	2.000
Temperature, T 	25.0	25.0	25.0	25.0	25.0	25.0
Open-circuit correction	1.140	1.140	1.140	1.140	1.140	1.140
Water conductivity(µS)	150	150	150	150	150	150
Oxygen content (mg 1^{-1}), or alternative (ppm of % saturation)	<10 ppm	<10 ppm	<10 ppm	<10 ppm	<10 ppm	<10 ppm
Amplifier gain (dB)						
Measured sensitivity (nV/Pa)	146.0	140.5	143.4	142.2	147.8	144.6
Open-circuit sensitivity at T (nV/Pa)	166.4	160.2	163.5	162.1	168.5	164.9
Notes (e.g. of any unusual Difficulties)						

Table4. Calibration results at 5 MHz

Institution NIM			Calibration method: Reciprocity method			
Dates(s) of calibrations: 22 July –1 August 2003			Hydrophone Serial Number: IP027			
Nominal frequency (MHz): **5**						
Measurement number	1	2	3	4	5	6
Actual frequency (MHz)	5.000	5.000	5.000	5.000	5.000	5.000
Temperature, T □	25.0	25.0	25.0	25.0	25.0	25.0
Open-circuit correction	1.150	1.150	1.150	1.150	1.150	1.150
Water conductivity(μS)	150	150	150	150	150	150
Oxygen content (mg l^{-1}), or alternative (ppm of % saturation)	<10 ppm	<10 ppm	<10 ppm	<10 ppm	<10 ppm	<10 ppm
Amplifier gain (dB)						
Measured sensitivity (nV/Pa)	149.9	147.4	152.4	155.7	148.5	149.3
Open-circuit sensitivity at T □ (nV/Pa)	172.4	169.5	174.1	179.1	170.8	171.7
Notes (e.g. of any unusual Difficulties)						

Table 5. Calibration results at 10 MHz

Institution: NIM				Calibration method: Reciprocity method		
Dates(s) of calibrations: 22 July –1 August 2003				Hydrophone Serial Number: IP027		
Nominal frequency (MHz): **10**						
Measurement number	1	2	3	4	5	6
Actual frequency (MHz)	10.000	10.000	10.000	10.000	10.000	10.000
Temperature, T □	25.0	25.0	25.0	25.0	25.0	25.0
Open-circuit correction	1.151	1.151	1.151	1.151	1.151	1.151
Water conductivity(μS)	150	150	150	150	150	150
Oxygen content (mg l^{-1}), or alternative (ppm of % saturation)	<10 ppm	<10 ppm	<10 ppm	<10 ppm	<10 ppm	<10 ppm
Amplifier gain (dB)						
Measured sensitivity (nV/Pa)	146.0	140.5	143.4	142.2	147.8	144.6
Open-circuit sensitivity at T □ (nV/Pa)	193.9	193.2	190.9	190.9	186.6	187.9
Notes (e.g. of any unusual Difficulties)						

Table 6. Calibration results at 15 MHz

Institution NIM			Calibration method: Reciprocity method			
Dates(s) of calibrations: 22 July –1 August 2003			Hydrophone Serial Number: IP027			
Nominal frequency (MHz): **15**						
Measurement number	1	2	3	4	5	6
Actual frequency (MHz)	15.000	15.000	15.000	15.000	15.000	15.000
Temperature, T □	25.0	25.0	25.0	25.0	25.0	25.0
Open-circuit correction	1.147	1.147	1.147	1.147	1.147	1.147
Water conducticity(µS)	150	150	150	150	150	150
Oxygen content (mg 1^{-1}), or alternative (ppm of % saturation)	<10 ppm	<10 ppm	<10 ppm	<10 ppm	<10 ppm	<10 ppm
Amplifier gain (dB)						
Measured sensitivity (nV/Pa)	205.6	213.9	221.4	212.7	209.4	217.8
Open-circuit sensitivity at T □ (nV/Pa)	235.8	245.4	253.9	244.0	240.2	249.8
Notes (e.g. of any unusual Difficulties)						

4 UNCERTAINTY

4.1 Type A standard uncertainty

Type A standard uncertainty is evaluated by the statistic method. Because measurements are in the same accurate and independent measuring condition, Type A standard uncertainty u_A is evaluated by experimental standard deviation s

$$. \quad u_A = \frac{s}{\sqrt{n}} = \frac{\sqrt{\dfrac{\sum_{i=1}^{n} \Delta M_i^2}{n-1}}}{\sqrt{n}}$$

Where

$\Delta M = M_i - \overline{M}$, $\overline{M}$ is the mean value of the sensitivities

n is the number of measurements, n=6

Type A standard uncertainty are shown in the results for frequency 1,2,5,10 and 15 MHz in the Table 1

4.2 Estimation of type B standard uncertainty

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

$$M = \frac{e_{oc}}{\sqrt{V_1 I_K}} \cdot a \cdot \sqrt{\frac{2\pi}{\rho c}} \cdot \sqrt{\gamma} \cdot \sqrt{G_1} \cdot \frac{1}{G_2} \cdot k_c$$

Factor A B C D E F G

-Factor A: e_{oc}, V_1, and I_K all electrical quantities are measured by TEK TDS 3012 oscilloscope . Current probe TCP 202 is in connection with the CH.2 of TEK TDS 3012. The accuracy of current probe is 3% .

-Factor B: The certainty of radius a is estimated to be 2 %.

-Factor C: c of water is calculated. Its uncertainty is small and estimated to be 0.2%.

-Factor D: The value of the reflection coefficient of stainless steel is stated in IEC 60866. The uncertainty of is small and is estimated to be 0.2%.

-Factor E: Diffraction loss of the source transducer. By varying the distance used in the calculation of G1 and the uncertainty of factor E is estimated to be 2.5% (TNO R.T.Hekkenberg).

-Factor F: Averaging effect of the hydrophone: The uncertainty of G2 is estimated to be 4% (TNO R.T.Hekkenberg).

-Factor G: Open-circuit correction factor. The open-circuit correction factors k_c are calculated and its uncertainty is estimated to be 1%.

Above systematic uncertainty contributions of each component and total Type B standard uncertainty u_B are listed in Table 7.

Table7. List of Type B standard uncertainties

Source of measurement uncertainty	Distr.	Coverage factor K	Value %	Relative standard uncertainty %
-Factor A: Electrical quantities.	rect.	1.73	3.24	1.87
-Factor B: Effective radius of the source transducer.	rect.	1.73	2.0	1.16
-Factor C: Due to □c.	rect.	1.73	0.2	0.12
-Factor D: Reflection coefficient.	rect.	1.73	0.2	0.12
-Factor E: Diffraction loss of the source transducer.	rect.	1.73	2.5	1.45
-Factor F: Averaging effect of the hydrophone.	rect.	1.73	4.0	2.31
-Factor G: Open-circuit correction factor	rect.	1.73	1.0	0.58
Total Type B standard uncertainty U_B		3%		

4.3 Expanded uncertainty

The combined standard uncertainty u_c is calculated by combining the Type A uncertainty (u_A) and Type B uncertainty (u_B) . The standard uncertainty is

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

Using a coverage factor k=2, the expanded uncertainty is calculated $U=2u_c$ and is listed in Table 1.

5 ACKNOWLEDGEMENTS

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APPENDIX E REPORT SUBMITTED BY FORCE INSTITUTE, DENMARK

Comments on the calibration procedure used by FORCE Institute for the CIPM key comparison.

The water used for the calibration was not changed during the measurement period. The water was taken from the de-ionising apparatus. The initial conductivity was approximately 1 µS/cm. During the measurements, the conductivity increased to a level of 11 µS/cm. The used filter probably causes the relatively high value. The calibration measurements were carried out without recording the conductivity each day. The water was not degassed prior to the measurements. The Oxygen content was 9 ppm at the end of the measuring period. The temperature of the water was controlled with an electronic thermostat. The temperature was 20.0 °C ± 0.1 °C with uncertainty below 0.5 °C.

The hydrophones were soaked in water at the beginning of each working day. The hydrophones soaked at least 1 hour before the measurements started. The amplifier 56055 was used for all the measurements. The gain was determined by measuring the output from a 50-Ohm generator and the output from the amplifier when fed with the same generator. The gain was calculated as the quotient of these two figures. The estimated uncertainty is A: 0.8%, B: 2.2% and expanded 2.4%. The measurements were done in a tank with glass walls measuring 0.4*0.4*0.7 m^3. The positioning of the transducers is done with stepper motors. The motors are mounted on metallic parts, and one of the axes is immersed in the water. This metallic part is grounded. No difference could be observed with the earthing pin on the hydrophones grounded. No correction for spatial averaging was used. The acoustic pressure was approximately:

Frequency, MHz	1	2	5	10	15
Pressure, Pa	0.6k	2.2k	3.2k	3.6k	2.7k

The measuring distance was 84 mm for all the measurements.

The calibrations are done by measuring the pressure at a specific point in the field from an acoustic source. This is done with a hydrophone with known sensitivity and with the unknown hydrophone. The sensitivity of the unknown is calculated using these figures. More than one reference hydrophone was used for this work. Although there are differences between the measurements they are small compared to the overall uncertainty. However, the calibration results given are the mean between calibrations made with the same reference hydrophone (Mi2165) but with original data from NPL and from PTB.

The 95% confidence level systematic uncertainties used in calculation of the overall uncertainty are listed in the table below. The major component is the uncertainty of the reference hydrophone. The figures from NPL are used because they are largest.

Frequency, MHz	1	2	5	10	15
Reference uncertainty (NPL)	7%	7%	7%	8%	9%
Reference uncertainty (PTB)	6%	6%	6%	7%	8%
Amplifier gain	2.4%	2.4%	2.4%	2.4%	2.4%
Spectrum Analyser nonlinearity	2.3%	2.3%	2.3%	2.3%	2.3%
Spectrum Analyser A/D uncertainty (2 readings)	1%	1%	1%	1%	1%
Systematic uncertainty	7.8%	7.8%	7.8%	8.7%	9.7%

Calibration results

13. 14. 15. 16. 20. 21. 22. November 2000			Hydrophone serial number: IP027		
Frequency MHz	1	2	5	10	15
Mean open-circuit sensitivity at 20 °C (nV/Pa)	166	164	177	205	246
Type A (random) uncertainty	2.86%	1.80%	0.96%	1.34%	1.08%
Type B (systematic) uncertainty	7.8%	7.8%	7.8%	8.7%	9.7%
Expanded uncertainty	8.3%	8.0%	7.9%	8.8%	9.9%

13. 14. 15. 16. 20. 21. 22. November 2000			Hydrophone serial number: IP039		
Frequency MHz	1	2	5	10	15
Mean open-circuit sensitivity at 20 °C (nV/Pa)	175	174	185	214	261
Type A (random) uncertainty	1.48%	0.83%	1.08%	0.84%	1.18%
Type B (systematic) uncertainty	7.8%	7.8%	7.8%	8.7%	9.7%
Expanded uncertainty	7.9%	7.9%	7.9%	8.7%	9.8%

FORCE Institute				Substitution with reference hydrophone		
13. 14. 15. 16. 20. 21. 22. November 2000				Hydrophone serial number: IP027		
Nominal Frequency 1 MHz						
Measurement Number	1	2	3	4	5	6
Frequency MHz	1.000					
Temperature, T (°C)	20 ± 0.5					
Open-circuit correction	1,0526					
Water conductivity						
Oxygen content						
Amplifier gain (dB)	22,65					
Measured sensitivity (µV/Pa)N2165	0,170	0,170	0,172	0,171	0,172	0,170
Measured sensitivity (µV/Pa)P2165	0,169	0,158	0,164	0,157	0,159	
Open-circuit sensitivity at T °C (µV/Pa)	0,169	0,164	0,168	0,164	0,165	
Notes						

FORCE Institute				Substitution with reference hydrophone		
13. 14. 15. 16. 20. 21. 22. November 2000				Hydrophone serial number: IP027		
Nominal Frequency 2 MHz						
Measurement Number	1	2	3	4	5	6
Frequency MHz	2.000					
Temperature, T (°C)	20 ± 0.5					
Open-circuit correction	1,0573					
Water conductivity						
Oxygen content						
Amplifier gain (dB)	22,725					
Measured sensitivity (µV/Pa)N2165	0,166	0,166	0,163	0,164	0,162	
Measured sensitivity (µV/Pa)P2165	0,166	0,160	0,163	0,162	0,162	
Open-circuit sensitivity at T °C (µV/Pa)	0,166	0,163	0,163	0,163	0,162	
Notes						

FORCE Institute				Substitution with reference hydrophone		
13. 14. 15. 16. 20. 21. 22. November 2000				Hydrophone serial number: IP027		
Nominal Frequency 5 MHz						
Measurement Number	1	2	3	4	5	6
Frequency MHz	5.000					
Temperature, T (°C)	20 ± 0.5					
Open-circuit correction	1,0573					
Water conductivity						
Oxygen content						
Amplifier gain (dB)	22,6425					
Measured sensitivity (µV/Pa)N2165	0,179	0,179	0,179	0,178	0,180	0,178
Measured sensitivity (µV/Pa)P2165	0,177	0,174	0,174	0,175	0,176	
Open-circuit sensitivity at T °C (µV/Pa)	0,178	0,176	0,176	0,177	0,178	
Notes						

FORCE Institute				Substitution with reference hydrophone		
13. 14. 15. 16. 20. 21. 22. November 2000				Hydrophone serial number: IP027		
Nominal Frequency 10 MHz						
Measurement Number	1	2	3	4	5	6
Frequency MHz	10.000					
Temperature, T (°C)	20 ± 0.5					
Open-circuit correction	1,0589					
Water conductivity						
Oxygen content						
Amplifier gain (dB)	22,1025					
Measured sensitivity (µV/Pa)N2165	0,213	0,213	0,212	0,212	0,213	0,212
Measured sensitivity (µV/Pa)P2165	0,201	0,195	0,199	0,198	0,199	
Open-circuit sensitivity at T °C (µV/Pa)	0,207	0,204	0,204	0,205	0,206	
Notes						

FORCE Institute			Substitution with reference hydrophone			
13. 14. 15. 16. 20. 21. 22. November 2000			Hydrophone serial number: IP027			
Nominal Frequency 15 MHz						
Measurement Number	1	2	3	4	5	6
Frequency MHz	15.000					
Temperature, T (°C)	20 ± 0.5					
Open-circuit correction						
Water conductivity						
Oxygen content						
Amplifier gain (dB)						
Measured sensitivity (µV/Pa)N2165	0,260	0,259	0,257	0,256	0,257	0,257
Measured sensitivity (µV/Pa)P2165	0,237	0,231	0,234	0,236	0,236	
Open-circuit sensitivity at T °C (µV/Pa)	0,249	0,245	0,246	0,246	0,247	
Notes						

FORCE Institute				Substitution with reference hydrophone		
13. 14. 15. 16. 20. 21. 22. November 2000				Hydrophone serial number: IP039		
Nominal Frequency 1 MHz						
Measurement Number	1	2	3	4	5	6
Frequency MHz	1.000					
Temperature, T (°C)	20 ± 0.5					
Open-circuit correction	1,0582					
Water conductivity						
Oxygen content						
Amplifier gain (dB)	22,65					
Measured sensitivity (µV/Pa)N2165	0,184	0,184	0,180	0,173	0,183	0,183
Measured sensitivity (µV/Pa)P2165	0,165	0,168	0,166	0,179	0,168	
Open-circuit sensitivity at T °C (µV/Pa)	0,175	0,176	0,173	0,176	0,176	
Notes						

FORCE Institute				Substitution with reference hydrophone		
13. 14. 15. 16. 20. 21. 22. November 2000				Hydrophone serial number: IP039		
Nominal Frequency 2 MHz						
Measurement Number	1	2	3	4	5	6
Frequency MHz	2.000					
Temperature, T (°C)	20 ± 0.5					
Open-circuit correction	1,0633					
Water conductivity						
Oxygen content						
Amplifier gain (dB)	22,725					
Measured sensitivity (µV/Pa)N2165	0,176	0,178	0,175	0,174	0,174	0,174
Measured sensitivity (µV/Pa)P2165	0,173	0,169	0,172	0,176	0,172	
Open-circuit sensitivity at T °C (µV/Pa)	0,175	0,174	0,173	0,175	0,173	
Notes						

FORCE Institute				Substitution with reference hydrophone		
13. 14. 15. 16. 20. 21. 22. November 2000				Hydrophone serial number: IP039		
Nominal Frequency 5 MHz						
Measurement Number	1	2	3	4	5	6
Frequency MHz	5.000					
Temperature, T (°C)	20 ± 0.5					
Open-circuit correction	1,0625					
Water conductivity						
Oxygen content						
Amplifier gain (dB)	0,186					
Measured sensitivity (µV/Pa)N2165	0,187	0,187	0,187	0,186	0,188	0,187
Measured sensitivity (µV/Pa)P2165	0,184	0,180	0,183	0,186	0,184	
Open-circuit sensitivity at T °C (µV/Pa)	0,186	0,184	0,185	0,186	0,186	
Notes						

FORCE Institute				Substitution with reference hydrophone		
13. 14. 15. 16. 20. 21. 22. November 2000				Hydrophone serial number: IP039		
Nominal Frequency 10 MHz						
Measurement Number	1	2	3	4	5	6
Frequency MHz	10.000					
Temperature, T (°C)	20 ± 0.5					
Open-circuit correction	1,064					
Water conductivity						
Oxygen content						
Amplifier gain (dB)	22,1025					
Measured sensitivity (µV/Pa)N2165	0,223	0,223	0,223	0,220	0,222	0,222
Measured sensitivity (µV/Pa)P2165	0,207	0,203	0,207	0,210	0,207	
Open-circuit sensitivity at T °C (µV/Pa)	0,215	0,213	0,215	0,215	0,214	
Notes						

FORCE Institute				Substitution with reference hydrophone		
13. 14. 15. 16. 20. 21. 22. November 2000				Hydrophone serial number: IP039		
Nominal Frequency 15 MHz						
Measurement Number	1	2	3	4	5	6
Frequency MHz	15.000					
Temperature, T (°C)	20 ± 0.5					
Open-circuit correction	1,0639					
Water conductivity						
Oxygen content						
Amplifier gain (dB)	21,38					
Measured sensitivity (µV/Pa)N2165	0,274	0,272	0,272	0,274	0,274	0,272
Measured sensitivity (µV/Pa)P2165	0,251	0,244	0,250	0,250	0,248	
Open-circuit sensitivity at T °C (µV/Pa)	0,262	0,258	0,261	0,262	0,261	
Notes						

APPENDIX F REPORT SUBMITTED BY PHYSIKALISCH-TECHNISCHE BUNDESANSTALT, GERMANY

Physikalisch-Technische Bundesanstalt
Braunschweig und Berlin

Report

Calibration of 1 mm Membrane Hydrophones in the Frequency Range 1 – 15 MHz

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Abstract: The report covers the calibration measurements carried out in the Ultrasonics Section of the Physikalisch-Technische Bundesanstalt on the occasion of the CIPM/BIPM key comparison CCAUV-U-K2. Two 1 mm membrane hydrophones were calibrated by two-transducer reciprocity and interferometry; the results and uncertainties are reported in detail.

Contents

1. Introduction

This report summarises the calibration activities carried out in the Ultrasonics Section of PTB on the occasion of the CIPM/BIPM key comparison CCAUV-U-K2. Two membrane hydrophones with an active spot diameter of 1 mm had to be primarily calibrated for comparison with five other laboratories.

Two different calibration methods were applied at PTB: two-transducer reciprocity relates the acoustic quantities to purely electrical measurement values. Interferometric calibration is based on an optical technique. It relates the acoustic displacement in a sound field directly to the well-known optical wavelength of an He-Ne laser. Both techniques ensure absolute calibration and furnish the open-loop sensitivity. Although both techniques yielded reliable results, interferometric calibration was considered the primary technique.

The report is organised as follows: This Introduction is followed by section 2 which covers all details of the two-transducer reciprocity, and section 3 which gives the details of the interferometric technique. Both sections contain a description of the method, details of the measurements carried out, and a description of uncertainties. All data have been compiled in the appendices. Appendices A – C contain the results, details of the transducers and the uncertainties of reciprocity calibration, whereas Appendices D and E contain the results and uncertainties of the interferometric part.

2. Calibration using two-transducer reciprocity

2.1 Calibration method

In the first experiment the hydrophone sensitivity was determined by the method of two-transducer reciprocity. The technique is described in Ref. [Ludwig 76, 88] enclosed to this report. Calibration was carried out as discribed in the two references; for completeness, a brief description is given in the following.

The sound field generated by a reciprocal transducer is reflected back to the transducer and the transmitting current and the receiving voltage are measured. This self-reciprocity procedure allows the sound field to be characterised using the reciprocity parameter $J_p=2A/\rho c$, where A is the transducer area. Then the reflector is turned and the sound field is directed to the hydrophone. The voltage generated is measured and the sensitivity can be calculated (see Ref. [Ludwig 88] and Eq. (1) below) for the actual transmitting current. Because of the self-reciprocity principle the method relates the acoustic sound pressure to purely electrical quantities and the calibration is a primary one.

Several corrections have to be applied to obtain the open-circuit sensitivity M (see Eq. (1) below and Eqs. (4), (5) in Ref. [Ludwig 88]). The open-circuit correction of the transducer (correction factor k_{U01}) was carried out by measuring the short-circuit current at the output of the driving amplifier.

The spatial averaging correction procedure follows the papers by Fay and Beissner [Fay 76, Beissner 81]. It is accompanied by the calculation of the diffraction loss of the sound field propagating from the transmitter to the receiver. The acoustic field is modelled using the Rayleigh integral, and the numerical calculation yields the sound pressure in the detection plane. Integration over the active area of the detector provides the correction factor. If the detector is the reciprocal transducer itself, the correction factor (G_1) represents the diffraction losses of the propagation path. In the case of the hydrophone the integral is taken over the hydrophone's active area, and the spatial averaging correction factor (G_2) is obtained by normalising to the pressure at the transmitter. At 2-15 MHz the nominal transducer diameters were used as input parameters in the calculation. In the low-frequency case effective diameters were determined from the directivity response of each transducer.

The open-circuit correction was carried out as described in [Ludwig 88] chapter II. The hydrophone was assumed to be a purely capacitive source to the preamplifier, and the hydrophone capacity was obtained from the impedances Z_H given in tab. 2 of the protocol document. The preamplifier was described as a purely capacitive load to the hydrophone, and its capacity was derived from an impedance measurement. The correction factor (k_{U02}) is the ratio between the hydrophone capacity and the overall capacity.

The assumption of purely capacitive impedances is an approximation. To estimate the deviations from the fully complex calculation the correction factor was calculated as the ratio $Z_L/(Z_H+Z_L)$, where Z_H is the given hydrophone impedance and Z_L the load impedance measured. The differences between both correction factors amounted to less than 0.02 dB.

In the PTB set-up, the relevant electrical quantities are determined in relation to a reference [Ludwig 76] using a precision attenuator. This reduces the number of critical current and voltage measurements, and since signal and reference use the same path the method avoids the determination of the frequency response of the signal line. The receiving voltages of reciprocal transducer and hydrophone were observed on a scope together with the delayed and attenuated transmitting pulse. Both signals were set to equal values and the attenuator read a voltage ratio. In the same manner the transmitting currents were compared with a reference current generated by a reference line in the current-voltage transformer, with the reference impedance Z = 50 Ω. In the calculation of the sensitivity the reference voltage cancels out and only the step attenuator (Rohde & Schwarz RSP) makes the main contribution to the uncertainty budget. The corresponding amplitude ratios determined using the attenuator are referred to as a_{U1} etc. in Eq. (1) below.

2.2 Measurements

2.2.1 Preparation of measurement

The tank used was of rectangular shape (0.55 m×0.4 m×0.4 m) and consisted of glass walls mounted in a steel frame. Standard shielding connections were made. The tank was filled with water deionised using equipment commonly used for the preparation of distilled water. The conductivity was below 2 µS/cm.

The water was degassed by a vacuum technique. It stayed under vacuum for more than 12 hours. The tank was filled immediately before the measurement and emptied of half of the water at the end of the day.

Prior to use, the hydrophones were soaked for 1 hour in degassed water before using. After the measurement cycle had been finished, they were stored in a separate vessel containing degassed water. At the end of day they were stored in air in a container.

2.2.2 Performance of measurement

After installation of the transducer the tank was filled and the hydrophone was adjusted. All necessary measurements were carried out at those frequency points at which the transducer generated a suitable sound field. After the measurement cycle the hydrophone was removed and the transducer was changed. In the majority of cases only one measurement cycle was carried out per day.

The sound field used during the calibration procedure was generated by different plane transducers. Since all electrical quantities were determined in relation to a reference, the sound pressure was not specially measured. Typical values amounted to between 1 kPa and 100 kPa. Care was taken to avoid non-linear distortion of the sound field.

The distance between transducer and hydrophone depended on the frequency and the diameter of the transducer used. With some exceptions in the high-frequency range the distances were larger than $4a^2/\Lambda$, where a is the transducer radius and Λ the wavelength of the sound field. The transducers used and the distances between hydrophone and transducer have been listed in Appendix B.

The NPL amplifier was not used during calibration. The gain of all amplifiers had not to be determined because the signal path of all measurements and the reference path were the same.

2.2.3 Results

The sensitivity M was determined according to

$$M = \frac{a_{U2}}{a_{I12}} \sqrt{\frac{a_{I1}}{a_{U1}}} \sqrt{Z} \sqrt{\frac{2A}{\rho c}} \frac{\sqrt{k_{U01}}}{k_{U02}} \frac{\sqrt{G_1}}{G_2} \sqrt{r}\, e^{\frac{\alpha d}{2}} , \qquad (1)$$

see also Eqs. (3) - (5) in [Ludwig 88]. Four independent measurements were documented using the protocol sheets of NPL. The data have been summarised in Appendix A. The single measurements correspond to the four columns in the table of Appendix B, where four transducer/distance combinations are given at each frequency. The only exception is at 2 MHz, where the third configuration was used twice.

Since the correction factor k_{U01} is given by a_{I1}/a_{Ik1}, where a_{Ik1} refers to the short-circuit current, Eq. (1) can be modified to

$$M = \frac{a_{U2}}{a_{I12}} \frac{a_{I1}}{\sqrt{a_{U1} \, a_{Ik1}}} \sqrt{Z} \sqrt{\frac{2A}{\rho c}} \frac{1}{k_{U02}} \frac{\sqrt{G_1}}{G_2} \sqrt{r} \, e^{\frac{\alpha d}{2}} \quad . \tag{2}$$

2.3 Uncertainties

Calibration is affected by several uncertainties. In the following their estimation is justified in detail. The data for every frequency point are given in Appendix C. Uncertainties below 0.1 % are considered negligible.

2.3.1 Standard uncertainty of Type B

a) Amplitude ratios obtained using the precision attenuator

The uncertainty of a_{U1}, a_{U2}, a_{I1}, a_{Ik1} and a_{I12} is due to the following effects: resolution of the attenuator (0,1 dB), accuracy of the attenuator as calibrated (0.1 dB), resolution of the scope and temporal stability of the signal displayed by the scope (0.2 dB), electromagnetic interference (1% to 3% depending on the frequency).

b) Reference impedance Z

Uncertainties are given in Appendix C.

c) Diffraction loss and alignment of the transducer in self-reciprocity

Uncertainties of the field factor G_1 are given in Appendix C. They cover the uncertainty with which the relevant geometric quantities are known and the uncertainty of transducer alignment.

d) Field factor for the hydrophone and alignment of the hydrophone

Uncertainties of the field factor G_2 are given in Appendix C. They cover the uncertainty with which the relevant geometric quantities are known and the uncertainty of the alignment of the hydrophone.

e) Reflection factor r

The reflectivity of the ultrasonic reflector depends slightly on the temperature, but the effect proved to be negligible.

f) Characteristic acoustic impedance ρc

The characteristic acoustic impedance depends slightly on temperature, but the effect proved to be negligible.

g) Transducer radius

The uncertainty with which the transducer radius is known is estimated to be 1% for the measurements at 1 MHz and 5 % in all other cases. This leads to the uncertainty of the transducer area *A* as given in Appendix C.

h) Open-circuit correction factor k_{U02}

The hydrophone impedance was given by the pilot laboratory. The input impedance of the amplifier used was measured; it was affected by an uncertainty, particularly at 10 and 15 MHz. The values are given in Appendix C.

i) Ultrasonic attenuation in water

This effect is covered by the last term of Eqs. (1) and (2). Values for α as a function of temperature and frequency have been taken from the literature ([Pinkerton], interpolated), but it is assumed here that α is uncertain by 1%. The resulting uncertainty is listed in Appendix C.

2.3.2 Standard uncertainty of Type A

The empirical standard deviation of the four *M* results at every measurement point is calculated. The data are summarised in Appendix C.

2.3.3 Overall uncertainty

The overall uncertainty is obtained by summation in quadrature. The respective values and values of the expanded uncertainty with k=2 are given in Appendix C. Values of the effective degrees of freedom are also given there. They have been obtained according to Appendix E of Document EA-4/02 of the European co-operation for Accreditation. These values proved to be large enough not to affect the calculation of the expanded uncertainty.

3. Calibration using optical interferometry

3.1 Calibration method

This section describes the calibration measurements carried out using optical interferometry. The set-up and the calibration procedure are equal to the high-frequency arrangement recently described in detail in [Koch 99]. Only the transducer, the working distances, and the spatial averaging correction procedure were adapted to the needs of the low-frequency MHz range. 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 an He-Ne laser, thus ensuring a primary calibration.

The sound field generated by a focussing transducer is measured by an interferometer which serves to detect the displacement of a pellicle arranged 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 the second step the interferometric part is removed and the hydrophone is inserted. 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 determining of the sensitivity.

The sound field was generated by a focussing transducer. The tone bursts used to excite the transducer were generated by a function generator whose frequency was controlled by a frequency counter (HP 53131A). In contrast to the high-frequency case, a longer focal length was used (see below) to obtain a sufficiently large spot for the 1 mm diameter hydrophones. The longer focal length led to a longer working distance between hydrophone and transducer. Because of the strong dependence of the on-axis pressure on frequency in a focussed field in the low MHz frequency range, two different working distances (see below) were necessary to ensure sufficient signal strength. They were chosen so that, in the two frequency ranges 1 - 4 MHz and 5 – 15 MHz, the pellicle and the hydrophone, were situated near the maximum on-axis pressure point.

Because of the longer focal length of the transducer, the hydrophone and the pellicle could not be mounted in the geometric focus of the transducer. To calculate the spatial averaging correction factor F_{sp} a model using the Rayleigh integral was implemented as given in the paper by O'Neil [O'Neil 49]. The numerical model provides the complex-valued sound pressure in any plane of the field, 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 transducer, an effective transducer diameter and an effective focal length [Adach 70] were determined by fitting the calculated on-axis pressure and two lateral pressure distributions to three-dimensional interferometer measurements. These fitting processes were carried out at different frequencies (1, 5, 15 MHz).

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].

3.2 Measurements

3.2.1 Preparation of measurement

The tank used consisted of PMMA and had an inner diameter of 30 cm. The tank was filled with water deionised using equipment commonly used for the preparation of distilled water. The conductivity was below 1 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. In the case of the interferometric measurement 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 several hours. The tank was filled immediately before the measurement and emptied completely afterwards.

Prior to use, the hydrophones were soaked for 1 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.

3.2.2 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 a focussing transducer (nominal diameter: 12 mm; nominal focal length: 75 mm; effective diameter: 12.1 mm; effective focal length: 112 mm). Typical values of sound pressure and propagation distances are given in Table 1.

Frequency	Sound pressure in kPa	Propagation distance in mm
1	19.7	50
2	67.6	50
5	72.4	100
10	260	100
15	420	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 two rf-level meters (RACAL DANA 9303, 50 Ω-measurement head) as shown in Fig. 1. A continuous-wave input signal generated by a synthesizer was fed into the amplifier and the output signal as well as the input voltage were measured by two equal rf-level meters (Fig. 1a). To reduce the uncertainty, a calibration was carried out by removing the amplifier (Fig. 1b). The input signal was fed via a 25 Ω resistor directly into the level meters and the deviations from one were recorded. The 25 Ω resistor was necessary to ensure 50 Ω conditions in this part of the measurement.

In contrast to the synthesiser, a hydrophone is far from being a pure 50 Ω source to the amplifier. A test was therefore carried out to estimate changes in the amplifier gain due to different source conditions. The hydrophone was simulated by a 3 kΩ resistor and a 91 pF capacitance. Both values were roughly extracted from the impedance data in the protocol document. The rf-level meters were replaced by a two-channel scope set to 1 MΩ input impedance at the amplifier input and to 50 Ω at the output. The gain was determined for this configuration and compared with the values obtained under pure 50 Ω source conditions. Excellent agreement within the uncertainty range was found.

The input voltage during the gain measurement was adapted to the voltages occurring during calibration. Furthermore, a linearity check was carried out; significant deviations could not be found in the voltage range used during calibration.

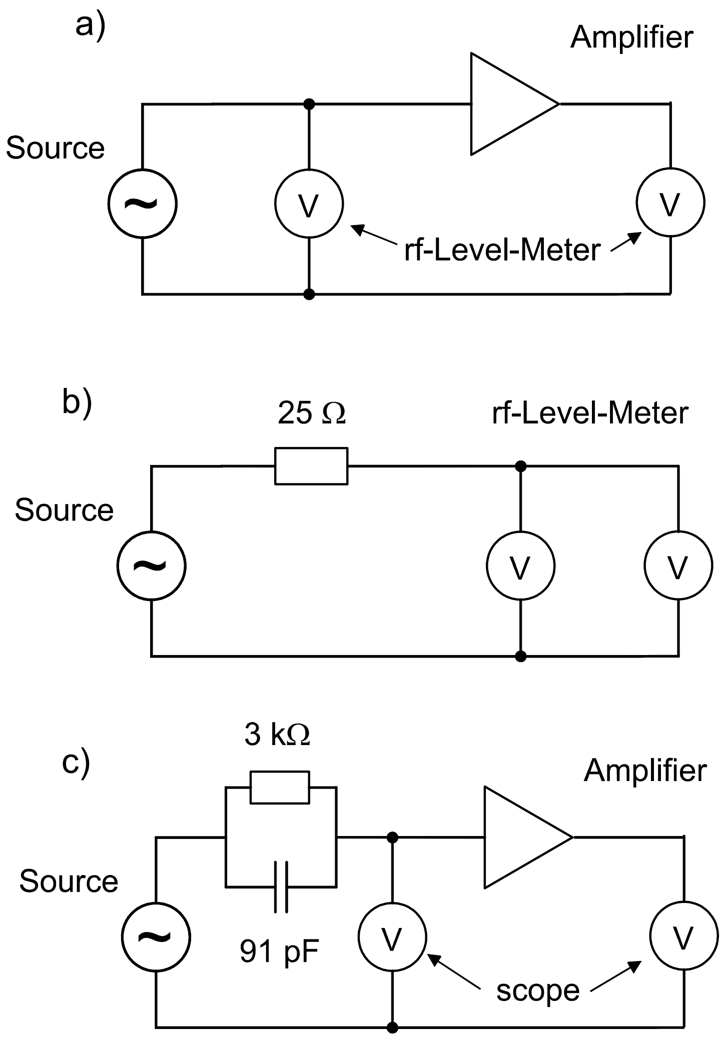

Fig. 1: Set-up for the determination of preamplifier gain; a) gain measurement, b) reference measurement, c) test using complex impedance as a source

3.2.3 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 D.

Although both the two-transducer reciprocity and the interferometric technique provided reliable results, interferometric calibration was considered to be the primary calibration. The main reason for this choice is the lower measurement uncertainty at the higher frequency end of the measurement range. In addition, because of technical problems which could not be solved during the time the hydrophones were at PTB, results for only a single hydrophone were obtained by two-transducer reciprocity. To ensure complete comparison with other participants, the interferometric technique was chosen to be the primary calibration method.

3.3 Uncertainties

Calibration is affected by several uncertainties. In the following, their estimation is justified in detail. The data for every frequency point are given in Appendix E.

3.3.1 Standard uncertainty of Type B

a) Signal-to-noise ratio

The signal-to-noise ratio (SNR) of the measurement and the resulting uncertainty were obtained from the FFT calculation necessary to determine the hydrophone voltage and, the displacement amplitude. The FFT provides the power of both the signal and the noise, and the quotient is the signal-to-noise ratio under current conditions. Although the noise is of a very different nature (amplifier noise and photon shot noise), it may be assumed that a normal distribution is given and that the rms-value of the noise power is identified with standard uncertainty. The uncertainty of the measured hydrophone U_H and photodetector output voltage U_I can be written as follows:

$$\frac{\delta U_{\mathrm{I,H}}}{U_{\mathrm{I,H}}} = 10^{\frac{\mathrm{SNR/dB}}{-20}} \tag{3}$$

Note that this expression is specific for every measurement situation, in particular, the sampling rate and the bandwidth.

b) Resolution of the scope $\delta U_{I,Osc}$, $\delta U_{H,Osc}$

The resolution of the scope has been taken from the manual and covers the sampling uncertainty and linearity errors. Nothing is known about the statistics, and rectangular statistics are assumed.

c) Uncertainty of voltage measurement at transducer T_r

The voltage measurement at the transducer is critical only with respect to the reproducibility which is mainly influenced by the reading error. The voltage value could be read out with an uncertainty of 1/10 of one division and the full screen had eight divisions.

d) Uncertainty of the determination of transimpedance gain $A_Z(f)$

The main uncertainty contributions result from photon detection noise and the slightly unstable laser power during the optical mixing experiment. A normal distribution is used.

e) Uncertainty of determination of $V(f)$

Because of the reference measurement the main contribution to the uncertainty is caused by the non-linearity of the level meter at the amplifier output. It was estimated by comparison with a highly precise step attenuator. Added to this are the uncertainties arising from the display accuracy and from necessary changes in the voltage ranges.

f) Uncertainty of pellicle transmission coefficient

The pellicle transmission coefficient is influenced by the density, the thickness, and the sound velocity of the foil material. All three parameters were measured [Koch 97] with an estimated uncertainty of 10%. Transmission coefficients were determined for each parameter using the measured value and a value higher by 10%. The differences were assumed to be upper limits, and an overall standard uncertainty was calculated.

g) Adjustment uncertainty in the z-direction

The influence of the adjustment uncertainty in the *z*-direction was estimated using the numerical model. The sound field pressure on the axis was calculated for a detector with an active area of 0.5 $mm^2 \times \pi$ at two positions z_1 and z_2 (z_2-z_1: adjustment accuracy). The term $|(p(z_2)-p(z_1)) / p(z_1)|$ defines an upper limit, and rectangular distribution is assumed.

h) Adjustment uncertainty in the lateral direction

The influence of the adjustment uncertainty in the lateral direction was also estimated using the numerical model. The sound field pressure was calculated for a detector with an active area of 0.5 $mm^2 \times \pi$ at the positions r_1=0 and $r_2=\Delta r$ (Δr: adjustment accuracy). The term $|(p(r_2)-p(r_1)) / p(r_1)|$ defines an upper limit, and rectangular distribution is assumed.

i) Uncertainty of spatial averaging correction factor F_{sp}

The spatial averaging correction factor was calculated for effective transducer parameters differing by the estimated uncertainty of the determination of the effective parameters. The values obtained define upper limits, and rectangular distribution is assumed.

j) Sound field inhomogeneities I_h

The influence of sound field inhomogeneities was only roughly estimated using two-dimensional sound field plots. An integration of the experimental values over the active detector area allows the influence of inhomogeneities to be estimated.

3.3.2 Standard uncertainty of Type A

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

3.3.3 Overall uncertainty

The overall uncertainty $\delta M_{oc}/M_{oc}$ is obtained by:

$$\frac{\delta M_{\text{oc}}}{M_{\text{oc}}} = \sqrt{\sum_i c_i^2 \frac{\delta u_i^2}{u_i^2}}, \quad u = U_{\text{I}}, U_{\text{H}} \ldots . \tag{4}$$

Finally, the expanded uncertainty (k=2) is given in Appendix E. The effective degrees of freedom ν_{eff} were calculated for all frequency points, and the values were far from 100 with a single exception which justified the choice of k=2. In the case of IP027 at 15 MHz, ν_{eff} was calculated to be 63. Although this value corresponds to k=2.04, the common factor of k=2 was used.

4. References

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Appendix A

This Appendix gives the results of the two-transducer reciprocity calibration. Tables A1 to A5 list the data with respect to the single frequency point using the calibration report sheet of the protocol document. Table A6 summarises the results using the summary sheet.

Table A1: Results for 1 MHz, IP039

Institution: Physikalisch-Technische Bundesanstalt		Calibration method: Two-transducer reciprocity		
Date(s) of calibrations: 11.4.00; 18.4.00; 19.4.00; 20.4.00		Hydrophone serial number: IP039		
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)	21,2	21,0	21,0	20,4
Open-circuit correction	1,092	1,092	1,092	1,092
Water conductivity (µS/cm)	0,55 – 1,0	0,55 – 1,0	0,55 – 1,0	0,55 – 1,0
Oxygen content (mg/l), or Alternative (ppm or % saturation)	54% - 63%	54% - 63%	54% - 63%	54% - 63%
Amplifier gain (dB)	-	-	-	-
Measured sensitivity (nV/Pa)	155,3	158,9	153,3	158,4
Open-circuit sensitivity at T °C (nV/Pa) .	169,7	173,6	167,5	173,1
Notes (e.g. of any unusual Difficulties)				

Table A2: Results for 2 MHz, IP039

Institution: Physikalisch-Technische Bundesanstalt		Calibration method: Two-transducer reciprocity		
Date(s) of calibrations: 6.4.00; 7..4.00; 14.4.00; 17.4.00		Hydrophone serial number: IP039		
Nominal frequency (MHz): 2,0 MHz				
Measurement number	1	2	3	4
Actual frequency (MHz)	2,0	2,0	2,0	2,0
Temperature, T (°C)	20,9	20,9	19,5	20,3
Open-circuit correction	1,096	1,096	1,096	1,096
Water conductivity (µS/cm)	0,55 – 1,0	0,55 – 1,0	0,55 – 1,0	0,55 – 1,0
Oxygen content (mg/l), or alternative (ppm or % saturation)	54% - 63%	54% - 63%	54% - 63%	54% - 63%
Amplifier gain (dB)	-	-	-	-
Measured sensitivity (nV/Pa)	158,5	151,5	158,8	150,4
Open-circuit sensitivity at T °C (nV/Pa) .	173,7	166,1	174,1	164,9
Notes (e.g. of any unusual difficulties)				

Table A3: Results for 5 MHz, IP039

Institution: Physikalisch-Technische Bundesanstalt			Calibration method: Two-transducer reciprocity	
Date(s) of calibrations: 31.3.00; 6.4.00; 12.4.00; 12.4.00			Hydrophone serial number: IP039	
Nominal frequency (MHz): 5,0 MHz				
Measurement number	1	2	3	4
Actual frequency (MHz)	5,0	5,0	5,0	5,0
Temperature, T (°C)	20,7	20,9	21,0	21,0
Open-circuit correction	1,099	1,099	1,099	1,099
Water conductivity (µS/cm)	0,55 – 1,0	0,55 – 1,0	0,55 – 1,0	0,55 – 1,0
Oxygen content (mg/l), or alternative (ppm or % saturation)	54% - 63%	54% - 63%	54% - 63%	54% - 63%
Amplifier gain (dB)	-	-	-	-
Measured sensitivity (nV/Pa)	166,4	165,0	167,0	168,4
Open-circuit sensitivity at T °C (nV/Pa) .	182,7	181,2	183,4	185,0
Notes (e.g. of any unusual difficulties)				

Table A4: Results for 10 MHz, IP039

Institution: Physikalisch-Technische Bundesanstalt			Calibration method: Two-transducer reciprocity	
Date(s) of calibrations: 4.4.00; 5.4,00;2 5.4.00; 26.4.00			Hydrophone serial number: IP039	
Nominal frequency (MHz): 10 MHz				
Measurement number	1	2	3	4
Actual frequency (MHz)	10,0	10,0	10,0	10,0
Temperature, T (°C)	20,5	20,5	19,6	20,1
Open-circuit correction	1,098	1,098	1,098	1,098
Water conductivity (µS/cm)	0,6 – 1,0	0,6 – 1,0	0,6 – 1,0	0,6 – 1,0
Oxygen content (mg/l), or alternative (ppm or % saturation)	54 - 63	54 – 63	54 – 63	54 - 63
Amplifier gain (dB)	-	-	-	-
Measured sensitivity (nV/Pa)	185,0	197,6	175,2	179,0
Open-circuit sensitivity at T °C (nV/Pa) .	203,1	216,8	192,3	196,4
Notes (e.g. of any unusual difficulties)				

Table A5: Results for 15 MHz, IP039

Institution: Physikalisch-Technische Bundesanstalt	Calibration method: Two-transducer reciprocity			
Date(s) of calibrations: 4.4.00; 25.4.00; 25.4.00; 26.4.00	Hydrophone serial number: IP039			
Nominal frequency (MHz): 15,0 MHz				
Measurement number	1	2	3	4
Actual frequency (MHz)	15,0	15,0	15,0	15,0
Temperature, T (°C)	20,5	19,6	19,6	20,0
Open-circuit correction	1,0995	1,0995	1,0995	1,0995
Water conductivity (µS/cm)	0,55 – 1,0	0,55 – 1,0	0,55 – 1,0	0,55 – 1,0
Oxygen content (mg/l), or alternative (ppm or % saturation)	54% - 63%	54% - 63%	54% - 63%	54% - 63%
Amplifier gain (dB)	-	-	-	-
Measured sensitivity (nV/Pa)	221,6	243,3	230,0	247,0
Open-circuit sensitivity at T °C (nV/Pa) .	243,7	267,5	252,9	271,6
Notes (e.g. of any unusual difficulties)				

Table A6: Summary of results for IP039

Institution: Physikalisch-Technische Bundesanstalt			Method: **Two-transducer reciprocity**		
Dates:	Hydrophone Serial Number: IP039				
Nominal frequency (MHz)	1	2	5	10	15
Actual frequency (MHz)	1,0	2,0	5,0	10,0	15,0
Mean open-circuit sensitivity at T °C (nV/Pa) 20°±1°C	170,9	169,7	183,1	202,1	258,9
Type A (random) standard uncertainty (%)	0,8	1,4	0,4	2,7	2,5
Type B (systematic) standard uncertainty (%)	4,4	5,0	5,0	6,2	7,2
Expanded uncertainty (%)	9,0	10,4	10,0	13,6	15,4

Appendix B

This Appendix gives the list of the transducers and the distances between transducer and hydrophone used in the two-transducer reciprocity method.

Table B1: Transducers and distances used during two-transducer reciprocity calibration

Frequency	Parameters of transducers used				
1	Nom. frequ. / MHz	1.0	1.0	2.25	2.25
	Nom. diam. / mm	19	19	19	19
	Distance / cm	36.02	22.85	34.83	27.19
2	Nom. frequ. / MHz	2.25	3.5	5.0	
	Nom. diam. / mm	19	12.7	6.3	
	Distance / cm	32.41	16.21	11.06	
5	Nom. frequ. / MHz	2-7	6-12	5.0	15.0
	Nom. diam. / mm	6	6	6.3	6.3
	Distance / cm	17.73	16.53	18.19	16.34
10	Nom. frequ. / MHz	6-12	4-20	15.0	20.0
	Nom. diam. / mm	6	6	6.3	6.3
	Distance / cm	22.18	22.88	23.80	29.16
15	Nom. frequ. / MHz	6-12	4-20	15.0	20.0
	Nom. diam. / mm	6	6	6.3	6.3
	Distance / cm	32.94	30.72	33.71	27.95

Appendix C

This Appendix indicates the uncertainties of the reciprocity calibration. Tables C1 to C5 list the Type B uncertainty contributions for every frequency point, the Type A uncertainty and the overall and expanded uncertainties.

Table C1: Uncertainties at 1 MHz

Section	Quantity	Limit	Distribution	Standard uncertainty	Sensitivity coefficient	Uncertainty
2.3.1.a)	$\frac{\delta a_{U1}}{a_{U1}}$	0.2 dB + 0.2 dB + 2 %	rectangular	2.2 %	0.5	1.1 %
a)	$\frac{\delta a_{U2}}{a_{U2}}$	0.2 dB + 0.2 dB + 2 %	rectangular	2.2 %	1	2.2 %
a)	$\frac{\delta a_{I1}}{a_{I1}}$	0.2 dB + 0.2 dB + 2 %	rectangular	2.2 %	1	2.2 %
a)	$\frac{\delta a_{Ik1}}{a_{Ik1}}$	0.2 dB + 0.2 dB + 2 %	rectangular	2.2 %	0.5	1.1 %
a)	$\frac{\delta a_{I12}}{a_{I12}}$	0.2 dB + 0.2 dB + 2 %	rectangular	2.2 %	1	2.2 %
b)	$\frac{\delta Z}{Z}$	1.2 %	rectangular	0.7 %	0.5	0.3 %
c)	$\frac{\delta G_1}{G_1}$	2.1 %	rectangular	1.2 %	0.5	0.6 %
d)	$\frac{\delta G_2}{G_2}$	2.1 %	rectangular	1.2 %	1	1.2 %
e)	$\frac{\delta r}{r}$	0.1 %	rectangular	0.07 %	0.5	negligible
f)	$\frac{\delta(\rho c)}{\rho c}$	0.2 %	rectangular	0.1 %	0.5	negligible
g)	$\frac{\delta A}{A}$	2.0 %	rectangular	1.2 %	0.5	0.6 %
h)	$\frac{\delta k_{U02}}{k_{U02}}$	1.2 %	rectangular	0.7 %	1	0.7 %
i)	$\frac{\delta e^{\alpha d/2}}{e^{\alpha d/2}}$	0.004 %			1	negligible
Type B	Combined					4.4 %
2.3.2 Type A	$\frac{\delta M}{M}$		normal	0.8 %	1	0.8 %
2.3.3	Overall					4.5 %
2.3.3	Expanded		(k=2)			9.0 %

The effective degrees of freedom are ν_{eff} = 3003.

Table C2: Uncertainties at 2 MHz

Section	Quantity	Limit	Distribution	Standard uncertainty	Sensitivity coefficient	Uncertainty
2.3.1.a)	$\frac{\delta a_{U1}}{a_{U1}}$	0.2 dB + 0.2 dB + 1 %	rectangular	2.0 %	0.5	1.0 %
a)	$\frac{\delta a_{U2}}{a_{U2}}$	0.2 dB + 0.2 dB + 1 %	rectangular	2.0 %	1	2.0 %
a)	$\frac{\delta a_{I1}}{a_{I1}}$	0.2 dB + 0.2 dB + 1 %	rectangular	2.0 %	1	2.0 %
a)	$\frac{\delta a_{Ik1}}{a_{Ik1}}$	0.2 dB + 0.2 dB + 1 %	rectangular	2.0 %	0.5	1.0 %
a)	$\frac{\delta a_{I12}}{a_{I12}}$	0.2 dB + 0.2 dB + 1 %	rectangular	2.0 %	1	2.0 %
b)	$\frac{\delta Z}{Z}$	1.2 %	rectangular	0.7 %	0.5	0.3 %
c)	$\frac{\delta G_1}{G_1}$	2.1 %	rectangular	1.2 %	0.5	0.6 %
d)	$\frac{\delta G_2}{G_2}$	2.1 %	rectangular	1.2 %	1	1.2 %
e)	$\frac{\delta r}{r}$	0.1 %	rectangular	0.07 %	0.5	negligible
f)	$\frac{\delta(\rho c)}{\rho c}$	0.2 %	rectangular	0.1 %	0.5	negligible
g)	$\frac{\delta A}{A}$	10.0 %	rectangular	5.7 %	0.5	2.9 %
h)	$\frac{\delta k_{U02}}{k_{U02}}$	1.2 %	rectangular	0.7 %	1	0.7 %
i)	$\frac{\delta e^{\alpha d/2}}{e^{\alpha d/2}}$	0.009 %			1	negligible
Type B	Combined					5.0 %
2.3.2 Type A	$\frac{\delta M}{M}$		normal	1.4 %	1	1.4 %
2.3.3	Overall					5.2 %
2.3.3	Expanded		(*k*=2)			10.4 %

The effective degrees of freedom are ν_{eff} = 570.

Table C3: Uncertainties at 5 MHz

Section	Quantity	Limit	Distribution	Standard uncertainty	Sensitivity coefficient	Uncertainty
2.3.1.a)	$\frac{\delta a_{U1}}{a_{U1}}$	0.2 dB + 0.2 dB + 1 %	rectangular	2.0 %	0.5	1.0 %
a)	$\frac{\delta a_{U2}}{a_{U2}}$	0.2 dB + 0.2 dB + 1 %	rectangular	2.0 %	1	2.0 %
a)	$\frac{\delta a_{I1}}{a_{I1}}$	0.2 dB + 0.2 dB + 1 %	rectangular	2.0 %	1	2.0 %
a)	$\frac{\delta a_{Ik1}}{a_{Ik1}}$	0.2 dB + 0.2 dB + 1 %	rectangular	2.0 %	0.5	1.0 %
a)	$\frac{\delta a_{I12}}{a_{I12}}$	0.2 dB + 0.2 dB + 1 %	rectangular	2.0 %	1	2.0 %
b)	$\frac{\delta Z}{Z}$	1.2 %	rectangular	0.7 %	0.5	0.3 %
c)	$\frac{\delta G_1}{G_1}$	2.1 %	rectangular	1.2 %	0.5	0.6 %
d)	$\frac{\delta G_2}{G_2}$	2.1 %	rectangular	1.2 %	1	1.2 %
e)	$\frac{\delta r}{r}$	0.1 %	rectangular	0.07 %	0.5	negligible
f)	$\frac{\delta(\rho c)}{\rho c}$	0.2 %	rectangular	0.1 %	0.5	negligible
g)	$\frac{\delta A}{A}$	10.0 %	rectangular	5.7 %	0.5	2.9 %
h)	$\frac{\delta k_{U02}}{k_{U02}}$	1.2 %	rectangular	0.7 %	1	0.7 %
i)	$\frac{\delta e^{\alpha d/2}}{e^{\alpha d/2}}$	0.05 %			1	negligible
Type B	Combined					5.0 %
2.3.2 Type A	$\frac{\delta M}{M}$		normal	0.4 %	1	0.4 %
2.3.3	Overall					5.0 %
2.3.3	Expanded		(k=2)			10.0 %

The effective degrees of freedom are ν_{eff} = 73242.

Table C4: Uncertainties at 10 MHz

Section	Quantity	Limit	Distribution	Standard uncertainty	Sensitivity coefficient	Uncertainty
2.3.1.a)	$\frac{\delta a_{U1}}{a_{U1}}$	0.2 dB + 0.2 dB + 2 %	rectangular	2.2 %	0.5	1.1 %
a)	$\frac{\delta a_{U2}}{a_{U2}}$	0.2 dB + 0.2 dB + 2 %	rectangular	2.2 %	1	2.2 %
a)	$\frac{\delta a_{I1}}{a_{I1}}$	0.2 dB + 0.2 dB + 2 %	rectangular	2.2 %	1	2.2 %
a)	$\frac{\delta a_{Ik1}}{a_{Ik1}}$	0.2 dB + 0.2 dB + 2 %	rectangular	2.2 %	0.5	1.1 %
a)	$\frac{\delta a_{I12}}{a_{I12}}$	0.2 dB + 0.2 dB + 2 %	rectangular	2.2 %	1	2.2 %
b)	$\frac{\delta Z}{Z}$	1.2 %	rectangular	0.7 %	0.5	0.3 %
c)	$\frac{\delta G_1}{G_1}$	2.1 %	rectangular	1.2 %	0.5	0.6 %
d)	$\frac{\delta G_2}{G_2}$	2.1 %	rectangular	1.2 %	1	1.2 %
e)	$\frac{\delta r}{r}$	0.1 %	rectangular	0.07 %	0.5	negligible
f)	$\frac{\delta(\rho c)}{\rho c}$	0.2 %	rectangular	0.1 %	0.5	negligible
g)	$\frac{\delta A}{A}$	10.0 %	rectangular	5.7 %	0.5	2.9 %
h)	$\frac{\delta k_{U02}}{k_{U02}}$	5.9 %	rectangular	3.4 %	1	3.4 %
i)	$\frac{\delta e^{\alpha d/2}}{e^{\alpha d/2}}$	0.3 %	rectangular	0.2 %	1	0.2 %
Type B	Combined					6.2 %
2.3.2 Type A	$\frac{\delta M}{M}$		normal	2.7 %	1	2.7 %
2.3.3	Overall					6.8 %
2.3.3	Expanded		(k=2)			13.6 %

The effective degrees of freedom are ν_{eff} = 120.

Table C5: Uncertainties at 15 MHz

Section	Quantity	Limit	Distribution	Standard uncertainty	Sensitivity coefficient	Uncertainty
2.3.1.a)	$\frac{\delta a_{U1}}{a_{U1}}$	0.2 dB + 0.2 dB + 3 %	rectangular	2.9 %	0.5	1.5 %
a)	$\frac{\delta a_{U2}}{a_{U2}}$	0.2 dB + 0.2 dB + 3 %	rectangular	2.9 %	1	2.9 %
a)	$\frac{\delta a_{I1}}{a_{I1}}$	0.2 dB + 0.2 dB + 3 %	rectangular	2.9 %	1	2.9 %
a)	$\frac{\delta a_{Ik1}}{a_{Ik1}}$	0.2 dB + 0.2 dB + 3 %	rectangular	2.9 %	0.5	1.5 %
a)	$\frac{\delta a_{I12}}{a_{I12}}$	0.2 dB + 0.2 dB + 3 %	rectangular	2.9 %	1	2.9 %
b)	$\frac{\delta Z}{Z}$	2.3 %	rectangular	1.3 %	0.5	0.7 %
c)	$\frac{\delta G_1}{G_1}$	2.1 %	rectangular	1.2 %	0.5	0.6 %
d)	$\frac{\delta G_2}{G_2}$	2.1 %	rectangular	1.2 %	1	1.2 %
e)	$\frac{\delta r}{r}$	0.1 %	rectangular	0.07 %	0.5	negligible
f)	$\frac{\delta(\rho c)}{\rho c}$	0.2 %	rectangular	0.1 %	0.5	negligible
g)	$\frac{\delta A}{A}$	10.0 %	rectangular	5.7 %	0.5	2.9 %
h)	$\frac{\delta k_{U02}}{k_{U02}}$	5.9 %	rectangular	3.4 %	1	3.4 %
i)	$\frac{\delta e^{\alpha d/2}}{e^{\alpha d/2}}$	0.9 %	rectangular	0.5 %	1	0.5 %
Type B	Combined					7.2 %
2.3.2 Type A	$\frac{\delta M}{M}$		normal	2.5 %	1	2.5 %
2.3.3	Overall					7.7 %
2.3.3	Expanded		(k=2)			15.4 %

The effective degrees of freedom are ν_{eff} = 269.

Appendix D

This Appendix indicates the results of the interferometric calibration. Tables D1 to Table D10 list the data with respect to the single frequency point using the calibration report sheet of the protocol document. Tables D11 and D12 summarise the results using the summary sheet.

Table D1: Results for 1 MHz, IP027

Institution: PTB		Calibration method: interferometry		
Date(s) of calibrations: see below		Hydrophone serial number: IP027		
Nominal frequency (MHz): 1				
Measurement number	1	2	3	4
Actual frequency (MHz)	1.0	1.0	1.0	1.0
Date(s)	22/3, 24/3	30/3, 31/3	7/4, 3/4	18/4, 19/4
Temperature, T (°C)	21.0	21.2	21.2	21.1
Open-circuit correction	1.0526	1.0526	1.0526	1.0526
Water conductivity (µS/cm)	1.9	2	1.8	1.7
Oxygen content (mg/l), or alternative (ppm or % saturation)	68 %	68 %	55 %	60 %
Amplifier gain (dB) (50 Ohm load)	16.23	16.23	16.23	16.23
Measured sensitivity (nV/Pa)	147.4	150.5	150.6	152.4
Open-circuit sensitivity at T °C (nV/Pa) .	155.1	158.4	158.5	160.4
Notes (e.g. of any unusual difficulties)				

Table D2: Results for 2 MHz, IP027

Institution: PTB				Calibration method: interferometry
Date(s) of calibrations: see below				Hydrophone serial number: IP027
Nominal frequency (MHz): 2				
Measurement number	1	2	3	4
Actual frequency (MHz)	2.0	2.0	2.0	2.0
Date(s)	22/3, 24/3	30/3, 31/3	7/4, 3/4	18/4, 19/4
Temperature, T (°C)	21.0	21.2	21.2	21.1
Open-circuit correction	1.0573	1.0573	1.0573	1.0573
Water conductivity (µS/cm)	1.9	2	1.8	1.7
Oxygen content (mg/l), or alternative (ppm or % saturation)	68 %	68 %	55 %	60 %
Amplifier gain (dB) (50 Ohm load)	16.3	16.3	16.3	16.3
Measured sensitivity (nV/Pa)	151.7	154.6	154.1	150.3
Open-circuit sensitivity at T °C (nV/Pa) .	160.4	163.4	162.9	158.9
Notes (e.g. of any unusual difficulties)				

Table D3: Results for 5 MHz, IP027

Institution: PTB		Calibration method: interferometry		
Date(s) of calibrations: see below		Hydrophone serial number: IP027		
Nominal frequency (MHz): 5				
Measurement number	1	2	3	4
Actual frequency (MHz)	5.0	5.0	5.0	5.0
Date(s)	22/3, 24/3	30/3, 31/3	7/4, 3/4	18/4, 19/4
Temperature, T (°C)	21.0	21.2	21.2	21.1
Open-circuit correction	1.0573	1.0573	1.0573	1.0573
Water conductivity (µS/cm)	1.9	2	1.8	1.7
Oxygen content (mg/l), or alternative (ppm or % saturation)	68 %	68 %	55 %	60 %
Amplifier gain (dB) (50 Ohm load)	16.19	16.19	16.19	16.19
Measured sensitivity (nV/Pa)	161.3	163.2	160.0	164.6
Open-circuit sensitivity at T °C (nV/Pa) .	170.5	172.6	169.2	174.0
Notes (e.g. of any unusual difficulties)				

Table D4: Results for 10 MHz, IP027

Institution: PTB			Calibration method: interferometry	
Date(s) of calibrations: see below			Hydrophone serial number: IP027	
Nominal frequency (MHz): 10				
Measurement number	1	2	3	4
Actual frequency (MHz)	10.0	10.0	10.0	10.0
Date(s)	22/3, 24/3	30/3, 31/3	7/4, 3/4	18/4, 19/4
Temperature, T (°C)	21.0	21.2	21.2	21.1
Open-circuit correction	1.0589	1.0589	1.0589	1.0589
Water conductivity (µS/cm)	1.9	2	1.8	1.7
Oxygen content (mg/l), or alternative (ppm or % saturation)	68 %	68 %	55 %	60 %
Amplifier gain (dB) (50 Ohm load)	15.64	15.64	15.64	15.64
Measured sensitivity (nV/Pa)	189.4	188.2	189.2	185.3
Open-circuit sensitivity at T °C (nV/Pa) .	200.6	199.3	200.4	196.2
Notes (e.g. of any unusual difficulties)				

Table D5: Results for 15 MHz, IP027

Institution: PTB		Calibration method: interferometry		
Date(s) of calibrations: see below		Hydrophone serial number: IP027		
Nominal frequency (MHz): 15				
Measurement number	1	2	3	4
Actual frequency (MHz)	15.0	15.0	15.0	15.0
Date(s)	22/3, 24/3	30/3, 31/3	7/4, 3/4	18/4, 19/4
Temperature, T (°C)	21.0	21.0	21.1	21.0
Open-circuit correction	1.0587	1.0587	1.0587	1.0587
Water conductivity (µS/cm)	1.9	2	1.8	1.7
Oxygen content (mg/l), or alternative (ppm or % saturation)	68 %	68 %	55 %	60 %
Amplifier gain (dB) (50 Ohm load)	14.7	14.7	14.7	14.7
Measured sensitivity (nV/Pa)	236.6	233.9	245.3	239.7
Open-circuit sensitivity at T °C (nV/Pa) .	250.5	247.6	259.5	253.8
Notes (e.g. of any unusual difficulties)				

Table D6: Results for 1 MHz, IP039

Institution: PTB		Calibration method: interferometry		
Date(s) of calibrations: see below		Hydrophone serial number: IP039		
Nominal frequency (MHz): 1				
Measurement number	1	2	3	4
Actual frequency (MHz)	1.0	1.0	1.0	1.0
Date(s)	5/5, 4/5	8/5, 11/5	17/5, 12/5	25/5, 29/5
Temperature, T (°C)	21.4	21.5	21.2	21.0
Open-circuit correction	1.0582	1.0582	1.0582	1.0582
Water conductivity (µS/cm)	2.3	2.3	2.4	2.6
Oxygen content (mg/l), or alternative (ppm or % saturation)	60 %	61 %	59 %	60 %
Amplifier gain (dB) (50 Ohm load)	16.23	16.23	16.23	16.23
Measured sensitivity (nV/Pa)	160.6	162.3	160.0	165.0
Open-circuit sensitivity at T °C (nV/Pa) .	168.9	171.7	168.4	173.7
Notes (e.g. of any unusual difficulties)				

Table D7: Results for 2 MHz, IP039

Institution: PTB		Calibration method: interferometry		
Date(s) of calibrations: see below		Hydrophone serial number: IP039		
Nominal frequency (MHz): 2				
Measurement number	1	2	3	4
Actual frequency (MHz)	2.0	2.0	2.0	2.0
Date(s)	5/5, 4/5	8/5, 11/5	17/5, 12/5	25/5, 29/5
Temperature, T (°C)	21.4	21.3	21.2	21.1
Open-circuit correction	1.0633	1.0633	1.0633	1.0633
Water conductivity (µS/cm)	2.3	2.3	2.4	2.6
Oxygen content (mg/l), or alternative (ppm or % saturation)	60 %	61 %	59 %	60 %
Amplifier gain (dB) (50 Ohm load)	16.3	16.3	16.3	16.3
Measured sensitivity (nV/Pa)	160.5	162.4	161.1	160.6
Open-circuit sensitivity at T °C (nV/Pa) .	170.7	172.7	170.3	169.8
Notes (e.g. of any unusual difficulties)				

Table D8: Results for 5MHz, IP039

Institution: PTB		Calibration method: interferometry		
Date(s) of calibrations: see below		Hydrophone serial number: IP039		
Nominal frequency (MHz): 5				
Measurement number	1	2	3	4
Actual frequency (MHz)	5.0	5.0	5.0	5.0
Date(s)	5/5, 4/5	8/5, 11/5	17/5, 12/5	25/5, 29/5
Temperature, T (°C)	21.3	21.3	21.2	21.2
Open-circuit correction	1.0625	1.0625	1.0625	1.0625
Water conductivity (µS/cm)	2.3	2.3	2.4	2.6
Oxygen content (mg/l), or alternative (ppm or % saturation)	60 %	61 %	59 %	60 %
Amplifier gain (dB) (50 Ohm load)	16.19	16.19	16.19	16.19
Measured sensitivity (nV/Pa)	168.2	165.6	165.8	167.6
Open-circuit sensitivity at T °C (nV/Pa) .	178.7	176.0	175.3	177.2
Notes (e.g. of any unusual difficulties)				

Table D9: Results for 10 MHz, IP039

Institution: PTB			Calibration method: interferometry	
Date(s) of calibrations: see below			Hydrophone serial number: IP039	
Nominal frequency (MHz): 10				
Measurement number	1	2	3	4
Actual frequency (MHz)	10.0	10.0	10.0	10.0
Date(s)	5/5, 4/5	8/5, 11/5	17/5, 12/5	25/5, 29/5
Temperature, T (°C)	21.3	21.3	21.2	21.2
Open-circuit correction	1.0640	1.0640	1.0640	1.0640
Water conductivity (µS/cm)	2.3	2.3	2.4	2.6
Oxygen content (mg/l), or alternative (ppm or % saturation)	60 %	61 %	59 %	60 %
Amplifier gain (dB) (50 Ohm load)	15.64	15.64	15.64	15.64
Measured sensitivity (nV/Pa)	190.2	193.1	190.8	187.5
Open-circuit sensitivity at T °C (nV/Pa) .	202.4	205.4	202.1	198.5
Notes (e.g. of any unusual difficulties)				

Table D10: Results for 15 MHz, IP039

Institution: PTB		Calibration method: interferometry		
Date(s) of calibrations: see below		Hydrophone serial number: IP039		
Nominal frequency (MHz): 15				
Measurement number	1	2	3	4
Actual frequency (MHz)	15.0	15.0	15.0	15.0
Date(s)	5/5, 4/5	8/5, 11/5	17/5, 12/5	25/5, 29/5
Temperature, T (°C)	21.5	21.3	21.2	21.1
Open-circuit correction	1.0639	1.0639	1.0639	1.0639
Water conductivity (µS/cm)	2.3	2.3	2.4	2.6
Oxygen content (mg/l), or alternative (ppm or % saturation)	60 %	61 %	59 %	60 %
Amplifier gain (dB) (50 Ohm load)	14.7	14.7	14.7	14.7
Measured sensitivity (nV/Pa)	248.1	249.5	250.8	251.1
Open-circuit sensitivity at T °C (nV/Pa) .	264.0	265.5	265.5	265.8
Notes (e.g. of any unusual difficulties)				

Table D11: Summary of results for IP027

Institution: PTB			Method: interferometry		
Dates: 4/5/8/11/12/17/25/26/29 of May	Hydrophone serial number: IP027				
Nominal frequency (MHz)	1	2	5	10	15
Actual frequency (MHz)	1	2	5	10	15
Mean open-circuit sensitivity at T °C (nV/Pa)	158.1 at 21.1	161.4 at 21.1	171.6 at 21.1	199.1 at 21.1	252.8 at 21.1
Type A (random) standard uncertainty (%)	1.4	1.4	1.3	1.2	2.1
Type B (systematic) standard uncertainty (%)	3.9	4.0	3.9	4.0	4.0
Expanded uncertainty (%)	8.4	8.4	8.2	8.4	9.0

Table D12: Summary of results for IP039

Institution: PTB			Method: interferometry		
Dates: 4/5/8/11/12/17/25/26 /29 of May	Hydrophone serial number: IP039				
Nominal frequency (MHz)	1	2	5	10	15
Actual frequency (MHz)	1	2	5	10	15
Mean open-circuit sensitivity at T °C (nV/Pa)	170.6 at 21.3	170.9 at 21.3	176.8 at 21.3	202.1 at 21.4	265.2 at 21.4
Type A (random) standard uncertainty (%)	1.5	1.0	1.0	1.4	1.6
Type B (systematic) standard uncertainty (%)	3.9	4.0	3.9	4.0	4.0
Expanded uncertainty (%)	8.4	8.2	8.0	8.4	8.6

Appendix E

This Appendix states the uncertainties of the interferometric calibration. Tables E1 to Table E5 list the Type B uncertainty contributions for every frequency point. The summary document sheet in Appendix D gives all results, Type A and Type B overall uncertainties and the expanded uncertainty for all measurements.

Table E1: Uncertainty *f*=1 MHz

Section	Quantity	Limit	Standard uncertainty	Distribution	Coefficient	Uncertainty
3.3.1a)	$\frac{\delta U_I}{U_I}$	/	0.2%	normal	1	0.2%
	$\frac{\delta U_H}{U_H}$	/	0.2%	normal	1	0.2%
b)	$\frac{\delta U_{I,Osc}}{U_{I,Osc}}$	1.25%+0.4%	1%	rectangular	1	1%
	$\frac{\delta U_{H,Osc}}{U_{H,Osc}}$	1.25%+0.4%	1%	rectangular	1	1%
c)	T_r	1.25%	0.7%	rectangular	1	0.7%
d)	$\frac{\delta A_Z}{A_Z}$		3.4%	normal	1	3.4%
e)	$\frac{\delta V}{V}$		1.0%	normal	1	1.0%
f)	$\frac{\delta T}{T}$	<0.01	<0.01	rectangular	1	0%
g)	$\left.\frac{\lvert p(z_2)-p(z_1)\rvert}{p(z_1)}\right\rvert_{Hyd}$	<0.01%	<0.01%	rectangular	1	0%
	$\left.\frac{\lvert p(z_2)-p(z_1)\rvert}{p(z_1)}\right\rvert_{Int}$	<0.01%	<0.01%	rectangular	1	0%
h)	$\left.\frac{\lvert p(r_2)-p(r_1)\rvert}{p(r_1)}\right\rvert_{Hyd}$	0.06%	0.04%	rectangular	1	0.04%
	$\left.\frac{\lvert p(r_2)-p(r_1)\rvert}{p(r_1)}\right\rvert_{Int}$	0.17%	0.1%	rectangular	1	0.1%
i)	$\left.\frac{\delta F_{sp}}{F_{sp}}\right\rvert_{f_l,Hyd}$	0.4%	0.23%	rectangular	1	0.23%

	$\left.\frac{\delta F_{sp}}{F_{sp}}\right\|_{f_l,Int}$	<0.01%	<0.01%	rectangular	1	0%
j)	I_h	0.4%	0.23%	rectangular	1	0.23%
	combined					3.9%

Table E2: Uncertainty *f*=2 MHz

Section	Quantity	Limit	Standard uncertainty	Distribution	Coefficient	Uncertainty
3.3.1a)	$\frac{\delta U_I}{U_I}$	/	0.1%	normal	1	0.1%
	$\frac{\delta U_H}{U_H}$	/	0.1%	normal	1	0.1%
b)	$\frac{\delta U_{I,Osc}}{U_{I,Osc}}$	1.25%+0.4%	1%	rectangular	1	1%
	$\frac{\delta U_{H,Osc}}{U_{H,Osc}}$	1.25%+0.4%	1%	rectangular	1	1%
c)	T_r	1.25%	0.7%	rectangular	1	0.7%
d)	$\frac{\delta A_Z}{A_Z}$		3.4%	normal	1	3.4%
e)	$\frac{\delta V}{V}$		1.0%	normal	1	1.0%
f)	$\frac{\delta T}{T}$	<0.01	<0.01	rectangular	1	0%
g)	$\left.\frac{\|p(z_2)-p(z_1)\|}{p(z_1)}\right\|_{Hyd}$	<0.01%	<0.01%	rectangular	1	0%
	$\left.\frac{\|p(z_2)-p(z_1)\|}{p(z_1)}\right\|_{Int}$	<0.01%	<0.01%	rectangular	1	0%
h)	$\left.\frac{\|p(r_2)-p(r_1)\|}{p(r_1)}\right\|_{Hyd}$	0.06%	0.04%	rectangular	1	0.04%
	$\left.\frac{\|p(r_2)-p(r_1)\|}{p(r_1)}\right\|_{Int}$	0.18%	0.1%	rectangular	1	0.1%
i)	$\left.\frac{\delta F_{sp}}{F_{sp}}\right\|_{f_l,Hyd}$	1.7%	1.0%	rectangular	1	1.0%

	$\left.\frac{\delta F_{\mathrm{sp}}}{F_{\mathrm{sp}}}\right\|_{f_l,\mathrm{Int}}$	<0.01%	<0.01%	rectangular	1	0%
i)	I_{h}	0.4%	0.23%	rectangular	1	0.23%
	combined					4.0%

Table E3: Uncertainty f=5 MHz

Section	Quantity	Limit	Standard uncertainty	Distribution	Coefficient	Uncertainty
3.3.1a)	$\frac{\delta U_I}{U_I}$	/	0.1%	normal	1	0.1%
	$\frac{\delta U_H}{U_H}$	/	0.05%	normal	1	0.05%
b)	$\frac{\delta U_{I,Osc}}{U_{I,Osc}}$	1.25%+0.4%	1%	rectangular	1	1%
	$\frac{\delta U_{H,Osc}}{U_{H,Osc}}$	1.25%+0.4%	1%	rectangular	1	1%
c)	T_r	1.25%	0.7%	rectangular	1	0.7%
d)	$\frac{\delta A_Z}{A_Z}$		3.4%	normal	1	3.4%
e)	$\frac{\delta V}{V}$		1.0%	normal	1	1.0%
f)	$\frac{\delta T}{T}$	0.05	0.03	rectangular	1	0.03%
g)	$\left.\frac{\lvert p(z_2)-p(z_1)\rvert}{p(z_1)}\right\rvert_{Hyd}$	<0.01%	<0.01%	rectangular	1	0%
	$\left.\frac{\lvert p(z_2)-p(z_1)\rvert}{p(z_1)}\right\rvert_{Int}$	<0.01%	<0.01%	rectangular	1	0%
h)	$\left.\frac{\lvert p(r_2)-p(r_1)\rvert}{p(r_1)}\right\rvert_{Hyd}$	0.05%	0.03%	rectangular	1	0.03%
	$\left.\frac{\lvert p(r_2)-p(r_1)\rvert}{p(r_1)}\right\rvert_{Int}$	0.18%	0.1%	rectangular	1	0.1%
i)	$\left.\frac{\delta F_{sp}}{F_{sp}}\right\rvert_{f_l,Hyd}$	<0.01%	<0.01%	rectangular	1	0%
	$\left.\frac{\delta F_{sp}}{F_{sp}}\right\rvert_{f_l,Int}$	<0.01%	<0.01%	rectangular	1	0%
j)	I_h	0.5%	0.3%	rectangular	1	0.3%
	combined					3.9%

Table E4: Uncertainty f=10 MHz

Section	Quantity	Limit	Standard uncertainty	Distribution	Coefficient	Uncertainty
3.3.1a)	$\frac{\delta U_I}{U_I}$	/	0.1%	normal	1	0.1%
	$\frac{\delta U_H}{U_H}$	/	0.05%	normal	1	0.05%
b)	$\frac{\delta U_{I,Osc}}{U_{I,Osc}}$	1.25%+0.4%	1%	rectangular	1	1%
	$\frac{\delta U_{H,Osc}}{U_{H,Osc}}$	1.25%+0.4%	1%	rectangular	1	1%
c)	T_r	1.25%	0.7%	rectangular	1	0.7%
d)	$\frac{\delta A_Z}{A_Z}$		3.4%	normal	1	3.4%
e)	$\frac{\delta V}{V}$		1.0%	normal	1	1.0%
f)	$\frac{\delta T}{T}$	0.2	0.12	rectangular	1	0.12%
g)	$\left.\frac{\lvert p(z_2)-p(z_1)\rvert}{p(z_1)}\right\rvert_{Hyd}$	0.02%	0.02%	rectangular	1	0.02%
	$\left.\frac{\lvert p(z_2)-p(z_1)\rvert}{p(z_1)}\right\rvert_{Int}$	<0.01%	<0.01%	rectangular	1	0%
h)	$\left.\frac{\lvert p(r_2)-p(r_1)\rvert}{p(r_1)}\right\rvert_{Hyd}$	0.02%	0.02%	rectangular	1	0.02%
	$\left.\frac{\lvert p(r_2)-p(r_1)\rvert}{p(r_1)}\right\rvert_{Int}$	0.2%	0.14%	rectangular	1	0.14%
i)	$\left.\frac{\delta F_{sp}}{F_{sp}}\right\rvert_{f_i,Hyd}$	0.01%	0.01%	rectangular	1	0.01%
	$\left.\frac{\delta F_{sp}}{F_{sp}}\right\rvert_{f_i,Int}$	<0.01%	<0.01%	rectangular	1	0%
j)	I_h	1.0%	0.6%	rectangular	1	0.6%
	combined					4.0%

Table E5: Uncertainty *f*=15 MHz

Section	Quantity	Limit	Standard uncertainty	Distribution	Coefficient	Uncertainty
3.3.1a)	$\frac{\delta U_{\mathrm{I}}}{U_{\mathrm{I}}}$	/	0.15%	normal	1	0.15%
	$\frac{\delta U_{\mathrm{H}}}{U_{\mathrm{H}}}$	/	0.15%	normal	1	0.15%
b)	$\frac{\delta U_{\mathrm{I,Osc}}}{U_{\mathrm{I,Osc}}}$	1.25%+0.4%	1%	rectangular	1	1%
	$\frac{\delta U_{\mathrm{H,Osc}}}{U_{\mathrm{H,Osc}}}$	1.25%+0.4%	1%	rectangular	1	1%
c)	T_{r}	1.25%	0.7%	rectangular	1	0.7%
d)	$\frac{\delta A_{\mathrm{Z}}}{A_{\mathrm{Z}}}$		3.4%	normal	1	3.4%
e)	$\frac{\delta V}{V}$		1.0%	normal	1	1.0%
f)	$\frac{\delta T}{T}$	0.4	0.25	rectangular	1	0.25%
g)	$\left.\frac{\lvert p(z_2)-p(z_1)\rvert}{p(z_1)}\right\rvert_{\mathrm{Hyd}}$	0.05%	0.03%	rectangular	1	0.03%
	$\left.\frac{\lvert p(z_2)-p(z_1)\rvert}{p(z_1)}\right\rvert_{\mathrm{Int}}$	<0.01%	<0.01%	rectangular	1	0%
h)	$\left.\frac{\lvert p(r_2)-p(r_1)\rvert}{p(r_1)}\right\rvert_{\mathrm{Hyd}}$	0.02%	0.02%	rectangular	1	0.02%
	$\left.\frac{\lvert p(r_2)-p(r_1)\rvert}{p(r_1)}\right\rvert_{\mathrm{Int}}$	0.25%	0.15%	rectangular	1	0.15%
i)	$\left.\frac{\delta F_{\mathrm{sp}}}{F_{\mathrm{sp}}}\right\rvert_{f_i,\mathrm{Hyd}}$	0.12%	0.07%	rectangular	1	0.07%
	$\left.\frac{\delta F_{\mathrm{sp}}}{F_{\mathrm{sp}}}\right\rvert_{f_i,\mathrm{Int}}$	<0.01%	<0.01%	rectangular	1	0%
j)	I_{h}	1.4%	0.9%	rectangular	1	0.9 %
	combined					4.0%

APPENDIX G REPORT SUBMITTED BY TNO PREVENTION AND HEALTH, THE NETHERLANDS

TNO research report
PG/TG/00.029

Hydrophone free-field open-circuit sensitivity contribution of TNO PG to the BIPM/CIPM Key Comparison US2

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20 March 2000

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The Quality System of the TNO Institute Prevention and Health has been certified in accordance with ISO 9001

TNO Prevention and Health contributes to the improvement of quality of life and to an increased healthy human life expectancy. Research and consultancy activities aim at improving health and health care in all stages of life.

Netherlands Organization for Applied Scientific Research (TNO)

Title

Hydrophone free-field open-circuit sensitivity contribution of TNO PG to the BIPM/CIPM Key Comparison US2

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Executive summary

As a part of a BIPM/CIPM Key comparison co-ordinated by NPL (UK), TNO Prevention and Health (NL) has calibrated two Marconi bilaminar membrane hydrophones, each having an active element diameter of nominally 1 mm.

The calibration is performed using a modified configuration of the reciprocity method, at frequencies of 1, 2, 5, 10 and 15 MHz. The acoustic pressures ranged from 20 to 80 kPa.

Four independent calibrations, each consisting of a series of 3 consecutive calibrations are performed in the period between 20 January and 10 February 2000.

The resulting hydrophone open-circuit sensitivity show a reproducibility in the range of 0,2 % to1,2 %. The expanded uncertainty has been estimated to range from 5,9 % to 6,4 %.

Contents

1 Introduction

This report describes the method used and the results obtained from a calibration of 2 membrane hydrophones within the project: "Comparison of 1 mm hydrophone calibrations in the frequency range 1 to 15 MHz".

The project is a contribution to the BIPM/CIPM Key Comparison US2 (hydrophone free-field open-circuit sensitivity in the megahertz frequency range). This Key comparison is co-ordinated by Dr. B. Zeqiri of NPL. The official contacts to BIPM/CIPM are covered by the Dutch National Metrology Institute which contributed financially to the part of the project carried out by TNO Prevention and Health.

The hydrophones calibrated are of the bilaminar design, manufactured by Marconi Technology Centre (Caswell, Northamptonshire, UK).
They were supplied by: National Physical Laboratory (NPL)
Centre for Mechanical and Acoustical Metrology
Teddington
Middlesex TW 11 0LW
UK.

The types calibrated are: Y-33-7611 MRQ serial no.: IP027
Y-33-7611 MRQ serial no.: IP039

The calibration has been performed using a modified configuration of the reciprocity method, at frequencies of 1, 2, 5, 10 and 15 MHz and using the pre-amplifier (serial no: 56055) supplied by NPL.

The measurements have been performed in compliance with the Protocol Document covering the BIPM/CIPM Key Comparison: CCAUV-U-K2 (ref. **1**).

The period of the calibration is: January 2000 – February 2000.

2 Methods

2.1 Description of the Reciprocity Calibration Set-up

The calibration method as used by TNO PG, see Figure 1, is based on a modified configuration of the reciprocity method described in the IEC publication 60866 [ref. **2**].

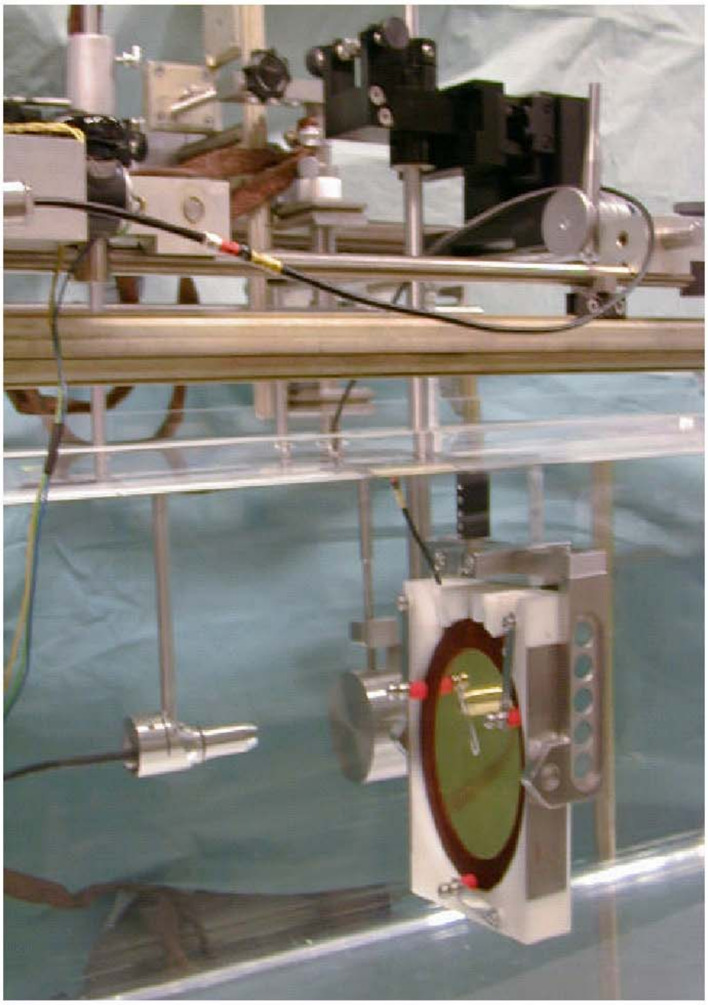

Figure 1. The modified set-up of the reciprocity method used by TNO PG

Figure 2 illustrates the arrangement for the Reciprocity Calibration Set-up. The source transducer radiates repetitive acoustic tone bursts into a tank filled with water. These tone bursts are either reflected by a thick stainless steel reflector or directed to the hydrophone to be calibrated.
For the self-reciprocity calibration of the source transducer, the transducer is adjusted to a position in which the axis of the emitted ultrasonic beam is perpendicular to the reflected surface: position 1 in Figure 2.

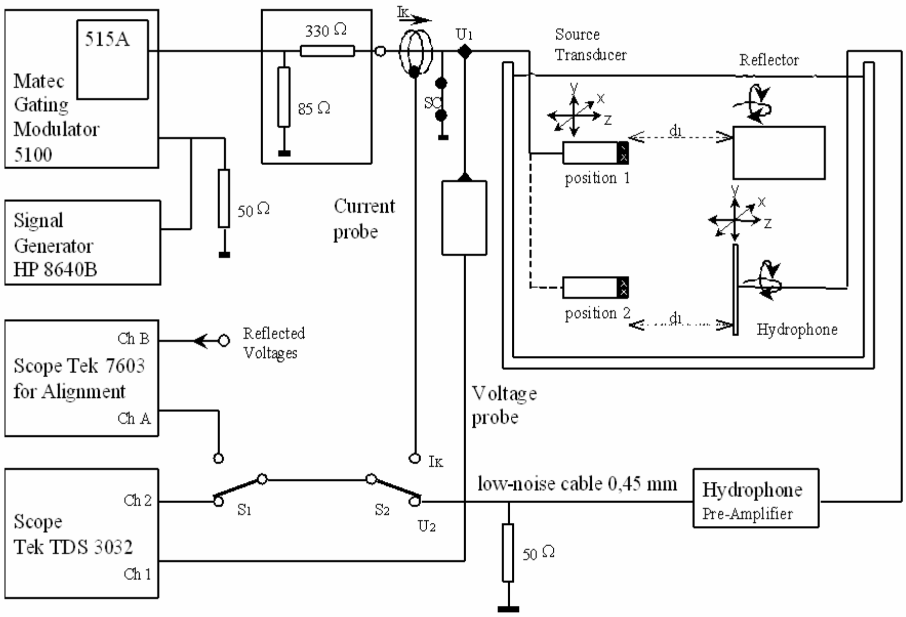

Figure 2. Schematic diagram of the Reciprocity Calibration Set-up in use by TNO PG

For the second stage: i.e., the calibration of the hydrophone, the source transducer is displaced so as to bring its acoustic field in front of the hydrophone: position 2.
The hydrophone is aligned such that the reflected wave from the hydrophone surface as received by the source transducer is at maximum. A second alignment device positions the hydrophone in the centre of the ultrasonic beam so it is in line and collinear with the direction of maximal sensitivity of the hydrophone.
In this way the hydrophone receives the sound pressure directly from the source transducer, instead of after reflection by the stainless steel reflector as given in IEC 60866. Furthermore if the distance between the source transducer and the hydrophone is made just equal to the distance between source transducer and reflector, for the attenuation of the ultrasound in water is cancelled out, and correction for this is not needed.
For this calibration set-up the expression for the hydrophone sensitivity is derived using clause 7.2.1 in the IEC 60866 standard. The transmitting current response of the transducer is:

$$S_1^* = \frac{p_1^*}{I_{0(p)}} = \sqrt{\frac{U_{0(p)}}{I_{0(p)}}} \cdot \sqrt{\frac{\rho \cdot c}{2 \cdot \pi \cdot a_1^2}} \quad (1)$$

and

$$p_1^* = I_{0(p)} \cdot \sqrt{\frac{U_{0(p)}}{I_{0(p)}}} \cdot \frac{1}{a_1}\sqrt{\frac{\rho \cdot c}{2 \cdot \pi}} = \sqrt{I_{0(p)} \cdot U_{0(p)}} \cdot \frac{1}{a_1} \cdot \sqrt{\frac{\rho \cdot c}{2 \cdot \pi}} \quad (2)$$

in which:

$U_{0(p)}$ Open-circuit voltage of source transducer during receiving of the tone burst

$I_{0(p)}$ Current through the source transducer

p_1^* Apparent acoustic pressure at the position of the reflector

a_1 Effective radius of the source transducer

ρ Density

c Velocity of sound in water

The desired open-circuit voltage $U_{0(p)}$ can be inferred from the actual measured voltage $U^*_{1(p)}$ of the source transducer when loaded by a finite electrical impedance. If this electrical load conditions (e.g., tone burst generator output impedance) is unchanged during transmission and reception, the value of $U_{0(p)}$ may be determined by measuring the current, $I_{k(p)}$, trough the circuit when the transducer is replaced or shortened by a short-circuit link ("SC" in Figure 1).

Then it is clear that:

$$U_{0(p)} = \frac{I_{k(p)}}{I_{0(p)}} U^*_{1(p)} \quad (3)$$

in which:

$I_{k(p)}$ Current through short-circuit introduced in place of the source transducer,

$U^*_{1(p)}$ Apparent voltage of source transducer during receiving of the tone burst.

Substitution of (3) in (2) gives:

$$p_1^* = \sqrt{I_{k(p)} \cdot U^*_{1(p)}} \cdot \frac{1}{a_1} \cdot \sqrt{\frac{\rho \cdot c}{2 \cdot \pi}} \quad (4)$$

The following relations takes corrections for reflection loss, diffraction and spatial averaging on the hydrophone into account:

$$U_{1(p)} = k_1 \cdot U^*_{1(p)} \quad \text{and} \quad p_1 = k_2 \cdot p_1^* \tag{5}$$

$$k_1 = \frac{1}{r \cdot G_1} \cdot e^{\alpha \cdot 2 \cdot d_1} \quad \text{and} \quad k_2 = G_2 \tag{6}$$

in which:

k_1 Correction factor for reflection loss and diffraction
k_2 Correction factor for spatial averaging
G_1 Factor for the diffraction loss of the source transducer
G_2 Factor for the averaging effect of the hydrophone
r Amplitude reflection coefficient of the reflector
$e^{\alpha \cdot 2 \cdot d_1}$ Correction factor for attenuation in the sound path from source transducer to reflector and back
d_1 Distance between source transducer and reflector and between source transducer and hydrophone
α Amplitude attenuation coefficient for water

As a result the acoustic pressure in a specific point in the field is:

$$p_1 = \sqrt{I_{k(p)} \cdot U_{1(p)}} \cdot \sqrt{\frac{e^{\alpha \cdot 2 \cdot d_1}}{r \cdot G_1}} \cdot G_2 \cdot \frac{1}{a_1} \cdot \sqrt{\frac{\rho \cdot c}{2 \cdot \pi}} \tag{7}$$

And the expression for the hydrophone sensitivity M is:

$$M = \frac{U^*_{2(p)}}{p_1} = \frac{e^{\alpha \cdot d_1} \cdot U_{2(p)}}{e^{\alpha \cdot d_1} \cdot \sqrt{U_{1(p)} \cdot I_{k(p)}}} \cdot a \cdot \sqrt{\frac{2 \cdot \pi \cdot r}{\rho \cdot c}} \cdot \frac{\sqrt{G_1}}{G_2} =$$

$$M = \frac{U_{2(p)}}{\sqrt{U_{1(p)} \cdot I_{k(p)}}} \cdot a \cdot \sqrt{\frac{2 \cdot \pi \cdot r}{\rho \cdot c}} \cdot \frac{\sqrt{G_1}}{G_2} \tag{8}$$

in which:

$U_{2(p)}$ Free-field voltage of the hydrophone
$U^*_{2(p)}$ Apparent Free-field voltage of the hydrophone
$e^{\alpha \cdot d_1}$ Correction factor for attenuation in the sound path from source transducer to hydrophone

2.2 Source transducers

The calibration of the hydrophones provided has to be performed at nominal frequencies of 1, 2, 5, 10 and 15 MHz. To cover this range 4 transducers with plane, circular active elements and different centre frequencies and diameters are used as sources. They are manufactured by Panametrics. Table 1 presents characteristic parameters of the transducers relevant for the calculation of the acoustic pressure.
The effective radius of the source transducer, a_1, is the radius of the equivalent piston-like source for which the spatial distribution of the acoustic pressure amplitude in the far field most closely resembles that from the transducer itself.
The effective radius is determined from a plot of the acoustic pressure amplitude as a function of the position along the beam axis, obtained by means of hydrophone measurements. Instead of using the last axial *maximum* for the calculation, the last axial *minimum* has been chosen as this position will provide a better spatial definition. The well known analysis [ref. **3**] for the field radiated by a sinusoidal exited plane disk-shaped piston source in an infinite baffle yields an expression for the last axial minimum x_1:

$$x_1 = \frac{a_1^2 - \lambda^2}{2\lambda} \qquad (9)$$

Which yields for the effective radius: $a_1 = \sqrt{\left(2 \cdot \lambda \cdot x_1 + \lambda^2\right)}$ (10)
in which λ is the wavelength of the transmitted signal. The results are given in Table 1.

Table 1. Characteristics of the source transducers (nominal values)

Source Transducer	f (MHz)	T=1/f (µs)	λ (mm)	D/λ	ka	Nominal Radius (mm)	Last axial minimum x_1 (mm)	Calculated Radius a_1 (mm)
V314 1,0/0,75"	1,00000	1	1,482	12,6	39,6	9,35	26,4	8,97
V306 2,25/0,5"	2,00000	0,5	0,7412	17,1	53,8	6,35	25,4	6,17
V310 5,0/0,25"	5,00000	0,2	0,2965	21,4	67,3	3,175	15,9	3,08
V312 10/0,25"	10,0000	0,1	0,1482	42,8	134,6	3,175	34,3	3,18
	15,0000	0,07	0,09882	64,3	201,9	3,175	51,2	3,17

Calculated using sound velocity c: 1482,3 m/s at 20 °C [ref. **4**]
D is the diameter of the source transducer, λ is the wavelength of the transmitted signal and f is the driving frequency. In ka, k is the wavenumber equal to: $2\pi/\lambda$, a is the radius.

2.3 Tone-burst excitation

Each source transducer has been driven by a tone-burst signal and receives its own transmitted field after reflection at the stainless steel-water interface. To accomplish this, an RF signal has been fed to

an RF Gated Amplifier (MATEC Model 515A) to generate tone-burst signals, adjustable in duration by a Gating Modulator (MATEC Model 5100).
To establish a condition for the ultrasonic field which is comparable with a continuous wave excitation, a minimum duration of the tone-burst is required. The minimum duration equals:

$$t_{p(\min)} = \frac{D}{\lambda} \cdot \frac{1}{f} \qquad (11)$$

in which D is the diameter of the source element, λ is the wavelength of the transmitted signal and f is the driving frequency. From this the actual duration of the tone-burst, t_p, has been chosen. The values for the different frequencies are given in Table 2.

Table 2. Timing characteristics of the driving signal (nominal values)

Source transducer	f (MHz)	T=1/f (µs)	λ (mm)	D/λ	Min. Tone-burst duration $t_{p(\min)}$ (µs)	Actual Tone-burst duration t_p (µs)	Number of periods of constant exitation
V314 1,0/0,75"	1,0	1	1,482	12,6	12,6	24	20
V306 2,25/0,5"	2,0	0,5	0,7412	17,1	8,6	20	15
V310 5,0/0,25"	5,0	0,2	0,2965	21,4	4,3	8	25
V312 10/0,25"	10,0	0,1	0,1482	42,8	4,3	5	42
	15,0	0,07	0,0988	64,3	4,5	5	60

Calculated using sound velocity c: 1482,3 m/s at 20 °C [ref. 5]
Burst repetition rate : 200 Hz

To be sure that the field is not non-linearly distorted in the water path, the amplitudes of the derived pressure levels were kept low. A factor to estimate the amount of non-linear distortion, σ_m [ref. 4], is calculated and results are given in the tables in section 4.1. Additionally the level of the second harmonic in the received waveform relative to the fundamental is measured and the result is given in section 4.1. Both results give confidence that the waveform is not non-linearly distorted. The relatively high level of the second harmonic in the 10 MHz signal is due to a small distortion in the driving voltage signal.

2.4 Reflector

The reflector has been made of a stainless steel rod with a diameter of 60 mm to entirely encompass the ultrasonic beams radiated by the source transducers. The length of the rod (100 mm) is sufficiently long to prevent that reflections from the rear surface interfere with those coming from the front. A maximum duration of the tone-burst of approximately 38 μs is allowed to perform proper measurements. The reflector has the surface finished to a roughness within ± 5 μm.

2.5 Alignment

Precise positioning and orientation of the source transducer, the reflector and the hydrophone to be calibrated is a necessity. The source transducer is mounted in an X, Y, Z positioning device to direct the ultrasonic beam correctly with respect to the reflector and the hydrophone. The Z-axis is used to adjust the distance d_1 between the transducer and the reflector or the hydrophone.
Both the reflector and the hydrophone can be rotated in two perpendicular directions. To be able to make small corrections in the position of the hydrophone, the hydrophone support is additionally mounted in a second X, Y, Z positioning device.

2.6 Water tank

The water tank in which the calibrations take place has a dimension of (h,w,l) 30 x 35 x 80 cm. It is made from a high quality Perspex. As no disturbing reflections coming from the walls or the water surface have been observed, the tank is not aligned with absorbent material. The water is degassed and deionised and the temperature of the water is controlled.

2.7 Procedures for the calculation of the hydrophone sensitivity

2.7.1 Measurement of the required electrical quantities

As discussed in section 2.1 three electrical quantities have to be determined:

$I_{o(p)}$: the transmit current of the source transducer

$U_{o(p)}$: the open-circuit voltage during reception of the tone-burst

$U_{2(p)}$: the free-field hydrophone voltage

In practice these quantities are derived from the measurement of $U_{1(p)}$ of the source transducer and by measuring the current $I_{k(p)}$ through the circuit when the source transducer is replaced or shortened by a short-circuit link ("SC" in Figure 1).
The current is measured with a Current probe (HP P6022) to convert the current signal into a proportional voltage signal. The three electrical quantities $I_{k(p)}$, $U_{1(p)}$ and $U_{2(p)}$ are measured with a Digital Phosphor oscilloscope (Tektronix TDS 3032) which performs the peak-to-peak measurements of the tone-burst signals.

2.7.2 Propagation distances

At each frequency point of the calibration measurement the total length of the sound path from the source transducer back to the transducer via the reflector ($2d_1$ in Figure 2) was 1,5 to 2,8 times the near-field distance N of that particular source transducer.
In this position the propagation distance $2d_1$ is adjusted to the desired value by measuring the reflection time t_r on the oscilloscope. The propagation distance $2d_1$ is then equal to:

$$2d_1 = t_r \cdot c \qquad (12)$$

The normalised distance S_1 equals:

$$S_1 = \frac{2d_1}{N} = \frac{2d_1 \cdot \lambda}{a_1^2} = \frac{t_r}{a_1^2} \cdot \frac{c^2}{f} \qquad (13)$$

In position 2 in Figure 2 the propagation distance is the length of the sound path between the source transducer and the hydrophone and equals d_1. This distance is obtained by adjusting the hydrophone position such that the propagation time of the tone burst equals exactly half the value of t_r. The normalised distance S_2, representing the distance between the hydrophone and the source transducer, equals:

$$S_2 = \frac{1}{2} \cdot S_1 \qquad (14)$$

The nominal values are given in Table 3.

Table 3. Propagation parameters source transducers (nominal values)

Source transducer	f (MHz)	t_r (µs)	$2d_1$ (mm)	S_1	S_2	G_1
V314 1,0/0,75"	1,0	80	118,5	2,183	1,091	0,758
V306 2,25/0,5"	2,0	70	103,7	2,018	1,009	0,752
V310 5,0/0,25"	5,0	54	80,0	2,500	1,250	0,760
V312 10/0,25"	10,0	100	148,2	2,171	1,086	0,758
	15,0	140	207,5	2,040	1,020	0,754
Calculated using sound velocities c at the actual measured water temperature.						

2.7.3 Correction factor for the diffraction loss of the source transducer (G_1)

In the calculations of the self-reciprocity of the source transducer a correction must be applied for the diffraction loss of the transmitted ultrasonic beam. According to [ref.6], a constant correction can be made despite the variety of different source transducers with their ka-values of 20 to 200, since the normalised distance for the self-reciprocity of the source transducers is between: $1{,}5 \leq S_1 \leq 2{,}8$. In the present study G_1 has been calculated more accurately using the source transducer as transmitter and receiver [ref. 7]. The results are given in Table 3.

2.7.4 Correction factor for the averaging effect of the hydrophone (G_2)

In order to estimate the pressure averaged over the active surface of the hydrophone, the actual effective radius b of the hydrophone has to be known. The effective radii as given by NPL for two perpendicular directions are averaged and used in the calculation of the correction factor for the averaging effect of the hydrophone (G_2).

Table 4. Effective radius of the hydrophone (nominal: 0,5 mm)						
f (MHz)	IP027 (mm)			IP039 (mm)		
	direction A	direction B	average	direction A	direction B	average
1,0	0,91	0,936	0,923	1,28	1,28	1,280
2,0	0,556	0,573	0,5645	0,662	0,693	0,6775
5,0	0,502	0,512	0,507	0,507	0,582	0,5445
10,0	0,502	0,508	0,505	0,498	0,515	0,5065
15,0	0,499	0,499	0,499	0,494	0,504	0,499

Note: direction B is perpendicular to direction A. No uncertainties of the NPL values were given, but due to averaging an additional uncertainty has been taken into account.

A correction is necessary to take account of the diffraction loss of the transmitted ultrasonic field of the source transducer with regard to the size and position of the hydrophone. The factor G_2 is used to calculate the pressure amplitude averaged over the effective area of the hydrophone in the acoustic field of the source transducer. G_2 is a function of the ratio of the effective radius of the hydrophone to the radius of the source transducer and the normalised distance between the source transducer and the hydrophone during calibration: $G_2 = f(b/a_1, S_2)$. The values of G_2 as used in the present calibration are obtained by interpolating the data given in [ref. 7] for the acoustic parameters $q = 32 \cdot \frac{b}{a_1}$ and S_2.

As S_2 is slightly temperature dependent G_2 has been calculated for each individual measurement. Table 5 presents the nominal values obtained for G_2.

Table 5. Spatial averaging corrections for the hydrophones: G_2 (nominal values)							
f (MHz)	S_2	Hydrophone: IP027			Hydrophone: IP039		
		hydrophone radius b (mm)	q=32b/a	G_2	hydrophone radius b (mm)	q=32b/a	G_2
1,0	1,091	0,923	3,293	1,943	1,28	4,566	1,907
2,0	1,009	0,5645	2,928	1,965	0,6775	3,514	1,950
5,0	1,250	0,507	5,268	1,822	0,5445	5,567	1,811
10,0	1,086	0,505	5,082	1,890	0,5065	5,097	1,890
15,0	1,020	0,499	5,037	1,897	0,499	5,037	1,897

Calculated using sound velocities c at the actual measured water temperature.

2.7.5 The measured and open-circuit hydrophone sensitivity

All measurements are carried out including the pre-amplifier supplied by NPL (serial-no: 56055). To calculate the open-circuit sensitivity of the hydrophone alone, the following expression is used:

$$M_0 = \frac{M_2}{G} \cdot k_c \qquad (15)$$

in which:
M_0 open-circuit sensitivity of the hydrophone alone
M_2 sensitivity of the hydrophone including the pre-amplifier
G gain of the pre-amplifier
k_c open-circuit correction factor as given by NPL

The gain of the pre-amplifier is determined separately using the schematic diagram given in Figure 2. The set-up is identical to the set-up for the hydrophone calibration including the output voltage level. The calibrations of the pre-amplifier have been performed three times. The are given in Table 6.

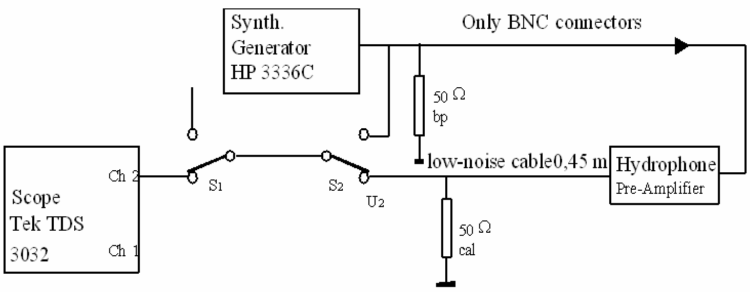

Figure 2. Schematic diagram of the pre-amplifier calibration set-up.

Table 6. Gain G of pre-amplifier serial number 56055					
	Frequency (MHz)				
	1	2	5	10	15
Amplifier gain	6,5678	6,5572	6,4697	6,0822	5,4482
Standard deviation	0,0043	0,0050	0,0131	0,0047	0,0031
Output voltage level (mV_{pp})	176,3	132,0	130,1	122,9	55,8
The ambient temperature during all measurements, including hydrophone calibration: 20 ± 1°C					

The open-circuit sensitivity M_0 is calculated with the open-circuit correction factors k_c provided by NPL and given in Table 7.

Table 7. Open-circuit correction factors, provided by NPL

Hydrophone serial number	Frequency (MHz)				
	1	2	5	10	15
IP027	1,0526	1,0573	1,0573	1,0589	1,0587
IP039	1,0582	1,0633	1,0625	1,0640	1,0639

2.8 Conditions during the calibration process

2.8.1 Preparation of the water

The water in which the measurements have been carried out is prepared to obtain a low gas content and a low electrical conductivity. Distilled water is degassed by exposing it to an ambient pressure of about 25 kPa for at least 16 hours. Just before use the water is fed through a de-ioniser to minimise the electrical conductivity. The water in the measurement tank is refreshed prior to the start of the hydrophone calibration sequence of that day. It was found not to be necessary to refresh the water after the first hydrophone was calibrated.

A Conductance Meter (YSI Model 32) measures the electrical conductivity. During the hydrophone calibration process values below 2 µS/cm are measured.
The gas content is measured periodically using a Dissolved Oxygen meter (YSI Model 57). Mostly values between 3 to 4,5 mg/l dissolved oxygen are measured.

2.8.2 Temperature of the water

The temperature of the water is controlled by an automatic heat source which heats the water homogeneously to a nominal temperature of 20 °C. During the calibration measurements this device is switched off. During the entire hydrophone calibration process the water temperature is measured with a temperature meter (TEMPCONTROL, type 1411) and kept constant to 20,2 ± 0,5 °C.

2.8.3 Time sequence of the measurements

A single calibration of both hydrophones, consisting of a set of 3 consecutive calibrations at frequencies of 1, 2, 5, 10 and 15 MHz, is performed in one day. In between these consecutive calibrations the reflector and hydrophone are aligned again. The particular hydrophone to start with was switched each day. Although the dissolved oxygen content did not vary much over a day it was decided to start the sequence with the calibration at a frequency of 15 MHz and continue respectively with 10, 5, 2, and 1 MHz. After changing the hydrophone the calibration was started again at 15 MHz. The complete calibration of each hydrophone consists of 4 independent single calibration sequences.

2.8.4 Soaking of the hydrophone

Before the calibration process starts, the hydrophone to be calibrated is immersed in the freshly degassed water for at least 1 hour.
During the calibration process the connection cable of the hydrophone is kept in the water to a length of approximately 10 cm.

2.8.5 Soaking of the source transducers

Before the calibration process starts, the source transducers are immersed in distilled water at an ambient temperature of 20 ± 1 °C for at least 1 hour.

2.8.6 Electrical shielding

Some additional protective shielding is applied to eliminate direct electrical interference with the source transducer voltage probe and with environmental high frequency radiation. The entire applied part of the source transducer is shielded.
All metal parts coming into contact with the water are connected with a relative thick Litze to a central protective earthing point. The earthing pin of the hydrophone is not used.

3 Uncertainties

3.1 Estimation of the Type B (systematic) standard uncertainties

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

$$M_0 = \frac{U_{2(p)}}{\sqrt{U_{1(p)} \cdot I_{k(p)}}} \cdot a \cdot \sqrt{\frac{2 \cdot \pi}{\rho \cdot c}} \cdot \sqrt{r} \cdot \sqrt{G_1} \cdot \frac{1}{G_2} \cdot G \cdot k_c$$

Factor: A B C D E F G H

- Factor A: Electrical quantities. Calibrations of the electrical quantities are performed in the same configuration as for the hydrophone calibrations.

- The current $I_{k(p)}$: is calibrated including the transfer of the current-probe P6022 in connection with the reading of Ch.1 of the TEK TDS 3032 oscilloscope and the switch in position I_k;
- The voltage $U_{1(p)}$: is calibrated including the attenuation of the probe in connection with the reading of Ch.2 of the TEK TDS 3032 oscilloscope;
- The reading of $U_{2(p)}$: is calibrated with Ch.1 of the TEK TDS 3032 oscilloscope directly connected with the switch in position U_2.

The results of these calibrations are used to correct the measured values of $I_{k(p)}$, $U_{1(p)}$ and $U_{2(p)}$ and to estimate the residual uncertainty. The calibrations are performed at the frequencies and settings of the oscilloscope identical to those during the hydrophone calibration process.
The uncertainty of each individual quantity is determined to be 0,6% for all frequencies.
Although some of the uncertainties may cancel out, an impedance uncertainty (0,5 % for each 50 Ω impedance) remains. The uncertainty for the expression in factor A is estimated to be: 1%.

- Factor B: Effective radius of the source transducer. The uncertainty in the experimentally determined value of the effective radius is based on:

- effects of the variation in the measurement distance on the calculated radius and
- half the maximum deviation of the above value from the physical radius.

The uncertainty is estimated to be: 2%

- Factor C: Due to ρc. As ρc is calculated taking the actual temperature into account the uncertainty is small. The uncertainty is estimated to be 0,1 %.

- Factor D: Reflection coefficient. The value of the reflection coefficient is stated in IEC 60866 (ref **2**) with an unspecified uncertainty. Due to the notation of 4 significant figures of $\sqrt{r}$ the uncertainty is small and for the purpose of the total estimation neglected.

- Factor E: Diffraction loss of the source transducer. By varying the distance used in the calculation of G_1 and using the results given in [ref. **6**] and [ref **7**] the uncertainty of factor E is estimated to be 2,5 %.

- Factor F: Averaging effect of the hydrophone. As mentioned before the correction factors G_2 are obtained by interpolation of the table given in [ref. 7] for the acoustic parameters q and S_2. Given the uncertainties in the source radius a and the hydrophone radius b the uncertainty in q will be maximal 0,5%. The contribution of this to the uncertainty of G_2 will be negligible. The uncertainty of G_2 is mainly caused by the acoustic parameter S_2 equal to:

$$S_2 = \frac{d_1 \cdot \lambda}{a_1^2} = \frac{t_t}{a_1^2} \cdot \frac{c^2}{f}$$

The uncertainty in S_2 depends heavily on the propagation time t_t of the tone-burst signal from the source transducer to the hydrophone and on the accuracy of the effective radius a of the source transducer. The uncertainty in t_t is determined to be 0,5 %. The uncertainty in a is estimated to be 2 %. The resulting uncertainty in S_2 is then 4 %.
As the variation in G_2 does not vary linearly with variations in S_2 the uncertainty contributions due to G_2 are calculated individually for each situation in the hydrophone calibration process.
Although the uncertainty in G_2 then varies from 0,1% to 1,3 % an additional uncertainty in the theoretical estimation of G_2 is taken into account. As a result a contribution of 4,0 % is taken.

- Factor G: Gain of the pre-amplifier. As the measurement of the gain is a relative measurement, its uncertainty is based on the accuracy of the reading and differences in load impedances. The uncertainty is estimated to be 0,3%.

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

- **Frequency dependence**: The behaviour of the source transducer, the hydrophone and some quantities, are frequency dependent. The driving frequency is accurate and stable within 0,01%. This is negligible, so no uncertainty is added to the list.

Table 8. List of Type B (systematic) relative standard uncertainties (u_i)

Source of measurement uncertainty	Distr.	Coverage factor k	Value %	Relative standard uncertainty %
- Factor A: Electrical quantities.	rect.	1,73	1,0	0,578
- Factor B: Effective radius of the source transducer.	norm	1,96	2,0	1,020
- Factor C: Due to ρc	norm	1,96	0,1	0,051
- Factor D: Reflection coefficient.			negl.	
- Factor E: Diffraction loss of the source transducer.	rect.	1,73	2,5	1,45
- Factor F: Averaging effect of the hydrophone.	rect.	1,73	4,0	2,31
- Factor G: Gain of the pre-amplifier.	rect.	1,73	0,3	0,173
- Factor H: Open-circuit correction factor.			negl.	
Total type B (systematic) standard uncertainty				2,97

Value means: for a rectangular distribution the half width of the distribution
for a normal distribution the uncertainty corresponding to a 95% confidence interval
The total standard uncertainty is calculated as: $Total\ \ u_B = \sqrt{A^2 + ... + H^2}$

3.2 Type A standard uncertainty

The Type A standard uncertainties as a result of the contribution of random components are given in the Summary Sheets 1 and 2 in Section 4.3.

3.3 Expanded uncertainty

The combined standard uncertainty, u_c, is calculated by combining the Type A, referred to as u_A, and Type B, referred to as u_B, standard uncertainties according to the procedures given in [ref. **8**] following:

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

Finally, the expanded uncertainty is calculated using a coverage factor $k = 2$:

$$U = 2 \cdot u_c$$

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

4 Results

The results are presented in 3 types of tables.
The tables in section 4.1 present the basic information used for the calculation of the hydrophone sensitivity including the pre-amplifier.
The tables in section 4.2 present the calibration report sheets in the layout as given in the protocol (ref. **1**).
The summary sheets in section 4.3 present the Mean open circuit sensitivity of the hydrophones including the uncertainty figures in the layout as given in the protocol (ref. **1**).

4.1 Measured quantities

4.1.1 Measured quantities with hydrophone IP027

Table 9. Measured values with hydrophone IP027

	Source Transducer			Hydrophone		Pre-amplifier					
Freq. (MHz)	$I_{K(p\text{-}p)}$ (mA)	$U_{1(p\text{-}p)}$ (mV)	p_p (kPa)	$U_{2(p\text{-}p)}$ (mV)	M (µV/Pa)	G	k_c	M_0 (nV/Pa)	σ_m 1)	2_{nd} harm -dB	Date
1,00000	484,7	3546,4	81,82	159,37	0,9739	6,568	1,0526	156,1	0,02	43	26-1-00
	488,1	3653,9	83,35	160,83	0,9649			154,6			27-1-00
	486,7	3862,1	85,59	165,90	0,9692			155,3			28-1-00
	485,0	3905,7	85,91	165,57	0,9636			154,4			1-2-00
mean	**486,1**	**3742,0**	84,17	**162,9**	**0,9679**			**155,1**			
2,00000	419,4	1248,3	66,69	135,08	1,0128	6,557	1,0573	163,3	0,04	38	26-1-00
	426,4	1218,0	66,43	135,01	1,0162			163,9			27-1-00
	419,4	1193,0	65,18	132,08	1,0131			163,4			28-1-00
	414,4	1196,0	64,87	131,55	1,0140			163,5			1-2-00
mean	**419,9**	**1213,8**	65,79	**133,43**	**1,0140**			**163,5**			
5,00000	214,2	450,46	52,89	109,76	1,0375	6,460	1,0573	169,8	0,06	n.m.	26-1-00
	210,0	450,80	52,38	107,79	1,0290			168,4			27-1-00
	204,7	471,88	52,92	109,29	1,0326			169,0			28-1-00
	206,5	416,99	49,96	103,82	1,0391			170,1			1-2-00
mean	**208,8**	**447,53**	52,04	**107,66**	**1,0346**			**169,3**			
10,0000	548,4	160,55	50,81	104,95	1,0328	6,082	1,0589	179,8	0,23	24	26-1-00
	544,0	160,84	50,69	105,15	1,0372			180,6			27-1-00
	540,9	159,89	50,38	104,35	1,0357			180,3			28-1-00
	536,2	158,57	49,94	103,68	1,0381			180,7			1-2-00
mean	**542,4**	**159,96**	50,45	**104,53**	**1,0359**			**180,4**			
15,0000	450,3	36,19	22,07	50,67	1,1481	5,448	1,0587	223,1	0,21	41	26-1-00
	450,7	37,41	22,46	51,91	1,1555			224,5			27-1-00
	444,8	36,13	21,92	50,61	1,1542			224,3			28-1-00
	456,2	36,89	22,43	52,01	1,1593			225,3			1-2-00
mean	**450,5**	**36,65**	22,22	**51,30**	**1,1543**			**224,3**			

1) rough estimate, see page 11

4.1.2 Measured quantities with hydrophone IP039

Table 10. Measured values with hydrophone IP039

	Source Transducer			Hydrophone		Pre-amplifier					
Freq. (MHz)	$I_{K(p-p)}$ (mA)	$U_{1(p-p)}$ (mV)	p_p (kPa)	$U_{2(p-p)}$ (mV)	M (µV/Pa)	G	k_c	M_0 (nV/Pa)	σ_m 1)	2_{nd} harm -dB	Date
1,00000	481,7	3875,5	83,71	174,97	1,0451	6,568	1,0582	168,4	0,02	43	28-1-00
	483,7	3727,8	82,25	170,90	1,0389			167,4			26-1-00
	486,4	3734,5	82,57	171,47	1,0383			167,3			27-1-00
	491,4	3808,4	83,82	174,30	1,0397			167,5			1-2-00
mean:	**485,8**	**3786,5**	83,09	**172,91**	**1,0405**			**167,6**			
2,00000	417,1	1213,9	65,04	138,61	1,0656	6,557	1,0633	172,8	0,04	38	24-1-00
	418,4	1201,8	64,83	138,21	1,0660			172,9			26-1-00
	419,8	1174,5	64,21	137,48	1,0706			173,6			27-1-00
	424,4	1234,2	66,18	141,81	1,0713			173,7			1-2-00
mean:	**419,9**	**1206,1**	65,06	**139,02**	**1,0684**			**173,2**			
5,00000	201,6	430,72	49,88	107,97	1,0824	6,460	1,0625	178,0	0,06	n.m.	24-1-00
	202,0	417,41	49,13	105,47	1,0735			176,6			26-1-00
	207,2	450,80	51,72	110,36	1,0668			175,5			27-1-00
	205,9	411,47	49,25	106,69	1,0833			178,2			1-2-00
mean:	**204,1**	**427,60**	49,99	**107,62**	**1,0765**			**177,1**			
10,0000	539,9	161,67	50,59	106,58	1,0534	6,082	1,0640	184,3	0,23	24	24-1-00
	545,0	162,46	50,96	108,28	1,0624			185,9			26-1-00
	540,9	160,02	50,37	107,35	1,0656			186,4			27-1-00
	536,6	159,62	50,10	106,85	1,0662			186,5			1-2-00
mean:	**540,6**	**160,94**	50,51	**107,26**	**1,0619**			**185,8**			
15,0000	453,1	36,83	22,34	53,54	1,1986	5,448	1,0639	234,1	0,21	41	28-1-00
	455,8	35,74	22,07	51,64	1,1700			228,5			26-1-00
	449,6	36,83	22,26	53,14	1,1939			233,2			27-1-00
	456,5	37,15	22,52	54,14	1,2020			234,7			1-2-00
mean:	**453,8**	**36,64**	22,30	**53,12**	**1,1911**			**232,6**			

1) rough estimate, see page 11

4.2 Calibration report sheets

4.2.1 Calibration report sheet 1

Institution: TNO Prevention and Health	Calibration method: Reciprocity method
Date(s) of calibrations: 26 January – 1 February	Hydrophone serial number: IP027
Nominal frequency (MHz): 1.0	

Measurement number	1	2	3	4
Actual frequency (MHz)	1.00000	1.00000	1.00000	1.00000
Temperature, T (°C)	19,80	20,46	20,19	20,01
Open-circuit correction	1,0526	1,0526	1,0526	1,0526
Water conductivity (µS)	0,5	1,0	0,5	1,4
Oxygen content (mg/l)	4,5	3,6	4,5	4,2
Amplifier gain (dB)	6,568 ± 0,0043	6,568 ± 0,0043	6,568 ± 0,0043	6,568 ± 0,0043
Measured sensitivity (nV/Pa)	973,9	964,9	969,2	963,6
Open circuit sensitivity at T (nV/Pa)	156,1	154,6	155,3	154,4
Date of calibration	26-01-00	27-01-00	28-01-00	01-02-00
Notes:				

4.2.2 Calibration report sheet 2

Institution: TNO Prevention and Health	Calibration method: Reciprocity method
Date(s) of calibrations: 26 January – 1 February	Hydrophone serial number: IP027
Nominal frequency (MHz): 2.0	

Measurement number	1	2	3	4
Actual frequency (MHz)	2,00000	2,00000	2,00000	2,00000
Temperature, T (°C)	19,80	20,50	20,20	20,02
Open-circuit correction	1,0573	1,0573	1,0573	1,0573
Water conductivity (μS)	0,5	1,0	0,5	1,4
Oxygen content (mg/l)	4,5	3,6	4,5	4,2
Amplifier gain (dB)	6,557 ± 0,0050	6,557 ± 0,0050	6,557 ± 0,0050	6,557 ± 0,0050
Measured sensitivity (nV/Pa)	1012,8	1016,2	1013,1	1014,0
Open circuit sensitivity at T (nV/Pa)	163,3	163,9	163,4	163,5
Date of calibration	26-01-00	27-01-00	28-01-00	01-02-00
Notes:				

4.2.3 Calibration report sheet 3

Institution: TNO Prevention and Health	Calibration method: Reciprocity method
Date(s) of calibrations: 26 January – 1 February	Hydrophone serial number: IP027
Nominal frequency (MHz): 5.0	

Measurement number	1	2	3	4
Actual frequency (MHz)	5,00000	5,00000	5,00000	5,00000
Temperature, T (°C)	19,85	20,56	20,23	20,03
Open-circuit correction	1,0573	1,0573	1,0573	1,0573
Water conductivity (μS)	0,5	1,0	0,5	1,4
Oxygen content (mg/l)	4,4	3,5	4,4	4,1
Amplifier gain (dB)	6,460 ± 0,0131	6,460 ± 0,0131	6,460 ± 0,0131	6,460 ± 0,0131
Measured sensitivity (nV/Pa)	1037,5	1029,0	1032,6	1039,1
Open circuit sensitivity at T (nV/Pa)	169,8	168,4	169,0	170,1
Date of calibration	26-01-00	27-01-00	28-01-00	01-02-00
Notes:				

4.2.4 Calibration report sheet 4

Institution: TNO Prevention and Health	Calibration method: Reciprocity method
Date(s) of calibrations: 26 January – 1 February	Hydrophone serial number: IP027
Nominal frequency (MHz): 10.0	

Measurement number	1	2	3	4
Actual frequency (MHz)	10,0000	10,0000	10,0000	10,0000
Temperature, T (°C)	19,85	20,64	20,25	20,04
Open-circuit correction	1,0589	1,0589	1,0589	1,0589
Water conductivity (μS)	0,5	1,0	0,5	1,4
Oxygen content (mg/l)	4,3	3,4	4,3	4,0
Amplifier gain (dB)	6,082 ± 0,0047	6,082 ± 0,0047	6,082 ± 0,0047	6,082 ± 0,0047
Measured sensitivity (nV/Pa)	1032,8	1037,2	1035,7	1038,1
Open circuit sensitivity at T (nV/Pa)	179,8	180,6	180,3	180,7
Date of calibration	26-01-00	27-01-00	28-01-00	01-02-00
Notes:				

4.2.5 Calibration report sheet 5

Institution: TNO Prevention and Health		Calibration method: Reciprocity method		
Date(s) of calibrations: 26 January – 1 February		Hydrophone serial number: IP027		
Nominal frequency (MHz): 15.0				
Measurement number	1	2	3	4
Actual frequency (MHz)	15,0000	15,0000	15,0000	15,0000
Temperature, T (°C)	19,90	20,61	20.27	20,07
Open-circuit correction	1,0587	1,0587	1,0587	1,0587
Water conductivity (μS)	0,5	1,0	0,5	1,4
Oxygen content (mg/l)	4,3	3,4	4,2	3,9
Amplifier gain (dB)	5,448 ± 0,0031	5,448 ± 0,0031	5,448 ± 0,0031	5,448 ± 0,0031
Measured sensitivity (nV/Pa)	1148,1	1155,5	1154,2	1159,3
Open circuit sensitivity at T (nV/Pa)	223,1	224,5	224,3	225,3
Date of calibration	26-01-00	27-01-00	28-01-00	01-02-00
Notes:				

4.2.6 Calibration report sheet 6

Institution: TNO Prevention and Health	Calibration method: Reciprocity method
Date(s) of calibrations: 26 January – 1 February	Hydrophone serial number: IP039
Nominal frequency (MHz): 1.0	

Measurement number	1	2	3	4
Actual frequency (MHz)	1.00000	1.00000	1.00000	1.00000
Temperature, T (°C)	19,90	20,13	19,86	20,19
Open-circuit correction	1,0582	1,0582	1,0582	1,0582
Water conductivity (µS)	0,5	1,0	0,5	1,4
Oxygen content (mg/l)	4,2	4,2	3,9	3,8
Amplifier gain (dB)	6,568 ± 0,0043	6,568 ± 0,0043	6,568 ± 0,0043	6,568 ± 0,0043
Measured sensitivity (nV/Pa)	1038,9	1038,3	1045,1	1039,7
Open circuit sensitivity at T (nV/Pa)	167,4	167,3	168,4	167,5
Date of calibration	26-01-00	27-01-00	28-01-00	01-02-00
Notes:				

4.2.7 Calibration report sheet 7

Institution: TNO Prevention and Health	Calibration method: Reciprocity method
Date(s) of calibrations: 24 January – 1 February	Hydrophone serial number: IP039
Nominal frequency (MHz): 2.0	

Measurement number	1	2	3	4
Actual frequency (MHz)	2,00000	2,00000	2,00000	2,00000
Temperature, T (°C)	19,70	19,90	20,18	20,19
Open-circuit correction	1,0633	1,0633	1,0633	1,0633
Water conductivity (μS)	1,0	0,5	1,0	1,4
Oxygen content (mg/l)	3,9	4,2	4,1	3,8
Amplifier gain (dB)	6,557 ± 0,0050	6,557 ± 0,0050	6,557 ± 0,0050	6,557 ± 0,0050
Measured sensitivity (nV/Pa)	1065,6	1066,0	1070,6	1071,3
Open circuit sensitivity at T (nV/Pa)	172,8	172,9	173,6	173,7
Date of calibration	24-01-00	26-01-00	27-01-00	01-02-00
Notes:				

4.2.8 Calibration report sheet 8

Institution: TNO Prevention and Health	Calibration method: Reciprocity method
Date(s) of calibrations: 24 January – 1 February	Hydrophone serial number: IP039
Nominal frequency (MHz): 5.0	

Measurement number	1	2	3	4
Actual frequency (MHz)	5,00000	5,00000	5,00000	5,00000
Temperature, T (°C)	19,80	19,97	20,20	20,22
Open-circuit correction	1,0625	1,0625	1,0625	1,0625
Water conductivity (µS)	1,0	0,5	1,0	1,4
Oxygen content (mg/l)	3,9	4,0	4,0	3,6
Amplifier gain (dB)	6,460 ± 0,0131	6,460 ± 0,0131	6,460 ± 0,0131	6,460 ± 0,0131
Measured sensitivity (nV/Pa)	1082,4	1073,5	1066,8	1083,3
Open circuit sensitivity at T (nV/Pa)	178,0	176,6	175,5	178,2
Date of calibration	24-01-00	26-01-00	27-01-00	01-02-00
Notes:				

4.2.9 Calibration report sheet 9

Institution: TNO Prevention and Health	Calibration method: Reciprocity method
Date(s) of calibrations: 24 January – 1 February	Hydrophone serial number: IP039
Nominal frequency (MHz): 10.0	

Measurement number	1	2	3	4
Actual frequency (MHz)	10,0000	10,0000	10,0000	10,0000
Temperature, T (°C)	19,84	19,97	20,23	20,24
Open-circuit correction	1,0640	1,0640	1,0640	1,0640
Water conductivity (µS)	1,0	0,5	1,0	1,4
Oxygen content (mg/l)	3,8	3,6	3,9	3,6
Amplifier gain (dB)	6,082 ± 0,0047	6,082 ± 0,0047	6,082 ± 0,0047	6,082 ± 0,0047
Measured sensitivity (nV/Pa)	1053,4	1062,4	1065,6	1066,2
Open circuit sensitivity at T (nV/Pa)	184,3	185,9	186,4	186,5
Date of calibration	24-01-00	26-01-00	27-01-00	01-02-00
Notes:				

4.2.10 Calibration report sheet 10

Institution: TNO Prevention and Health	Calibration method: Reciprocity method
Date(s) of calibrations: 26 January – 1 February	Hydrophone serial number: IP039
Nominal frequency (MHz): 15.0	

Measurement number	1	2	3	4
Actual frequency (MHz)	15,0000	15,0000	15,0000	15,0000
Temperature, T (°C)	20,03	20,28	20.11	20,28
Open-circuit correction	1,0639	1,0639	1,0639	1,0639
Water conductivity (µS)	0,5	1,0	0,5	1,4
Oxygen content (mg/l)	3,5	3,8	4,5	3,5
Amplifier gain (dB)	5,448 ± 0,0031	5,448 ± 0,0031	5,448 ± 0,0031	5,448 ± 0,0031
Measured sensitivity (nV/Pa)	1170,0	1193,9	1198,6	1202,0
Open circuit sensitivity at T (nV/Pa)	228,5	233,2	234,1	234,7
Date of calibration	26-01-00	27-01-00	28-01-00	01-02-00
Notes:				

4.3 Summary sheets

4.3.1 Summary sheet 1

Institution: TNO Prevention and Health			Calibration method: Reciprocity method		
Date(s) of calibrations: 26 January – 1 February			Hydrophone serial number: IP027		
Nominal frequency (MHz)	1	2	5	10	15
Actual frequency (MHz)	1,00000	2,00000	5,00000	10,0000	15,0000
Mean open circuit sensitivity at T °C (nV/Pa)	155,1	163,5	169,3	180,4	224,3
Type A standard uncertainty (%)	0,48	0,15	0,45	0,22	0,40
Type B standard uncertainty (%)	2,97	2,97	2,97	2,97	2,97
Expanded uncertainty (%)	6,0	5,9	6,0	5,9	6,0

4.3.2 Summary sheet 2

Institution: TNO Prevention and Health			Calibration method: Reciprocity method		
Date(s) of calibrations: 26 January – 1 February			Hydrophone serial number: IP039		
Nominal frequency (MHz)	1	2	5	10	15
Actual frequency (MHz)	1,00000	2,00000	5,00000	10,0000	15,0000
Mean open circuit sensitivity at T °C (nV/Pa)	167,6	173,2	177,1	185,8	232,6
Type A standard uncertainty (%)	0,30	0,28	0,73	0,56	1,21
Type B standard uncertainty (%)	2,97	2,97	2,97	2,97	2,97
Expanded uncertainty (%)	6,0	5,9	6,1	6,0	6,4

5 Signature

Authors	Signature
R.T.Hekkenberg	
Peer Review	Signature
R.A.Bezemer	
Dr. J. v. Boxsel, head of section	

6 References

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3 Chivers, R.C., Bosselaar, L., Filmore, P.R., *Effective area to be used in diffraction correction,* JASA **68(1)**, (1980), 80.

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5 IEC 61102, *Measurement and characterisation of ultrasonic fields using hydrophones in the frequency range 0,5 MHz to 15 MHz,* 1991.

6 Brendel, K., Ludwig, G, *Measurement of ultrasonic diffraction loss for circular transducers,* Acustica, **32**, (1975), 110.

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APPENDIX H SUPPLEMENTARY REPORT SUBMITTED BY TNO PREVENTION AND HEALTH, THE NETHERLANDS

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National Physical Laboratory
Centre for Mechanical and Acoustical Metrology
attn. Nigel Lee
Queensroad
TW11 0LW Teddington
UK

TW110LW

Subject
Re-calibration of hydrophone IP27

Date
8 April 2002

Our reference
PG\TG\02.313\rhg

E-mail
R.T.Hekkenberg@pg.tno.nl

Direct dialing
81242

Dear Nigel,

As promised we have perfomed a re-calibration at 10 and 15 MHz for the IP27 hydrophone. As discussed earlier, we suspected the source transducer (Panametrics V312) not to behave well. (We have repeated the measurements using this V312: the result was within 2% of our previous values). Then we characterised the source for its beam behaviour: it had an asymmetric dip. So we ordered two replacements: Panametrics V312 and V313). Although we did perform beam characterisations for these sources we did use as effective radius the nominal value (3,175 mm). As limited measurements were performed now the uncertainty did increase somewhat. The pre-amp used was a similar type of Marconi that you had provided in the project.

I am much more pleased with the results now.
I hope it is possible to add these results somehow in your report.

Kind regards,

R.T. Hekkenberg

Date
8 April 2002

Our reference
PG\TG\02.313\rhg

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1.1.1 Calibration report sheet 4A

Institution: TNO Prevention and Health	Calibration method: Reciprocity method **Re-calibration using new source transducers**
Date(s) of calibrations: 03 April – 5 April	Hydrophone serial number: IP027
Nominal frequency (MHz): 10.0	

Measurement number	1	2	3	
Actual frequency (MHz)	10,0000	10,0000	10,0000	
Temperature, T (°C)	21,2	20,9	20,6	
Open-circuit correction	1,0567	1,0567	1,0567	
Water conductivity (μS)	n.m.	n.m.	n.m.	
Oxygen content (mg/l) (about)	6	6	6	
Amplifier gain	6,0643	6,0643	6,0643	
Measured sensitivity (nV/Pa)	1181,4	1185,2	1213,5	
Open circuit sensitivity at T (nV/Pa)	205,9	206,5	211,4	
Date of calibration	03-04-02	04-04-02	05-04-02	
Notes: Used source	Panasonic V312	Panasonic V312	Panasonic V312	

Date
8 April 2002

Our reference
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1.1.2 Calibration report sheet 5B

Institution: TNO Prevention and Health	Calibration method: Reciprocity method **Re-calibration using new source transducers**
Date(s) of calibrations: 03 April – 5 April	Hydrophone serial number: IP027
Nominal frequency (MHz): 15.0	

Measurement number	1	2	3	
Actual frequency (MHz)	15,0000	15,0000	15,0000	
Temperature, T (°C)	21,0	21,0	20,5	
Open-circuit correction	1,0554	1,0554	1,0554	
Water conductivity (µS)	n.m.	n.m.	n.m.	
Oxygen content (mg/l) (about)	6	6	6	
Amplifier gain	5,3815	5,3815	5,3815	
Measured sensitivity (nV/Pa)	1215,2	1208,2	1212,0	
Open circuit sensitivity at T (nV/Pa)	238,3	237,0	237,7	
Date of calibration	04-04-02	04-04-02	05-04-02	
Notes: Used source	Panasonic V313	Panasonic V313	Panasonic V313	

Date
8 April 2002

Our reference
PG\TG\02.313\rhg

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1.2 Summary sheets

1.2.1 Summary sheet 1

Institution: TNO Prevention and Health	Calibration method: Reciprocity method
Date(s) of calibrations: 26 January – 1 February	Hydrophone serial number: IP027

Nominal frequency (MHz)				10	15
Actual frequency (MHz)				10,0000	15,0000
Mean open circuit sensitivity at T °C (nV/Pa)				207,8	237,7
Type A standard uncertainty (%)				1,30	0,42
Type B standard uncertainty (%)				3,5	3,50
Expanded uncertainty (%)				7,5	7,1

APPENDIX J REPORT SUBMITTED BY THE NATIONAL PHYSICAL LABORATORY, UNITED KINGDOM

Comparison of 1 mm hydrophone calibrations in the frequency range 1 to 15 MHz

Measurements carried at out at NPL on two membrane hydrophones for CIPM Key Comparison

Nigel Lee, Stephen Robinson
and Bajram Zeqiri

August 1999

RESTRICTED-COMMERCIAL

August 1999

Comparison of 1 mm hydrophone calibrations in the frequency range 1 to 15 MHz

Nigel Lee, Stephen Robinson and Bajram Zeqiri

Centre for Mechanical and Acoustical Metrology
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ABSTRACT

This report describes work undertaken under Milestone (a) of deliverable 4.1.5.1. of the NMS Acoustical Metrology Programme 1998-2001. Under this Milestone, absolute calibrations of two membrane hydrophones used for the BIPM/CIPM key comparison CCAUV-U-K2 (Hydrophone free-field open-circuit sensitivity - Megahertz frequency range) have been completed.

LIST OF CONTENTS

1 INTRODUCTION

This report describes the absolute calibrations of two membrane hydrophones used for the BIPM/CIPM Key Comparison CCAUV-U-K2 (Hydrophone free-field open-circuit sensitivity - Megahertz frequency range). The key comparison involved five laboratories with NPL acting as the coordinating laboratory. As well as organising the key comparison NPL performed reference calibrations as a participant within the key comparison and this report describes the calibrations carried out at NPL.

2 CALIBRATION BY OPTICAL INTERFEROMETRY

2.1 CALIBRATION METHOD

Primary calibration of hydrophones for frequencies greater than 500 kHz is achieved using the NPL laser interferometer. In this method, an ultrasonic transducer produces an acoustic field that is detected by a thin plastic membrane (the pellicle), which is 3.5 or 5 µm thick and coated on one side with 25 nm of gold. The pellicle reflects the optical beam but is effectively transparent to the acoustic beam so that it follows the motion of the wave. The displacement of the pellicle is determined using a specially-designed Michelson interferometer, the output of which, V_I , varies with displacement, a, according to the following relationship [1]:

$$V_I = V_0 \sin(4\pi \, \mu \, a / \lambda) \qquad [1]$$

where λ is the optical wavelength, V_0 is the reference voltage corresponding to the amplitude of the output signal when the displacement exceeds $\lambda/2$, and μ is the 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 at the same point in the field that has been interrogated by the interferometer. The hydrophone output voltage, V_H , corresponding to the known acoustic pressure is then measured, and the hydrophone sensitivity, M_H, derived using the expression:

$$M_H = \frac{V_H V_0}{V_I} \frac{2\mu}{\rho c f \lambda} \qquad [2]$$

where ρ is the water density, c is the speed of sound and f is the acoustic frequency.

Figure 1 shows a schematic diagram of the interferometer, the design being based on the original work of Drain, Speake and Moss [2], and subsequently refined by NPL [3]. The output of a 5 mW HeNe laser is split into the reference and signal beams by use of an electro-optic Pockels cell and a polarising beam splitter. The reference beam is turned back on its original path by use of the corner-cube reflector and the calcite prism, whereas the signal beam is reflected from the pellicle which follows the motion of the ultrasonic wave. The beams are recombined at the avalanche photodiode detectors and the difference in optical phase is detected by the interferometer circuitry. A number of quarter wave plates are used to effect necessary changes in polarisation and prevent light returning to the laser. A second polarising beam splitter at 45° permits interference between the signal and reference beams, providing two interference signals which differ in phase by π. The interferometer output is obtained by taking the difference between these signals, enabling common-mode rejection of fluctuations in light level occurring in both beams due to changes in laser power. A beam displacer (a rotatable glass block) and a translatable lens allow the positioning and focusing of the signal beam on the pellicle so that it may be aligned with the acoustic centre of the hydrophone. The acoustic source transducer (a plane-piston) is driven by tone-burst signals and time-windowing and gating techniques employed to isolate boundary reflections, enabling measurements to be made at frequencies from 200 kHz to 20 MHz in the 1.0 x 0.4 x 0.4 m tank.

The interferometer is mounted on an optical table that is supported by air-operated anti-vibration mounts. However, even with this arrangement, environmental vibration still causes movements of the pellicle which although lower in frequency are much greater in amplitude than the ultrasonic displacement. This introduces changes of optical phase into the signal 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 Pockels cell. The feedback circuitry is designed to respond only to low frequency signals so that the ultrasonic displacement may still be detected at the interferometer output. The feedback circuit is adjusted to ensure that the interferometer is balanced in its most sensitive mode, where the output is linear for small displacements.

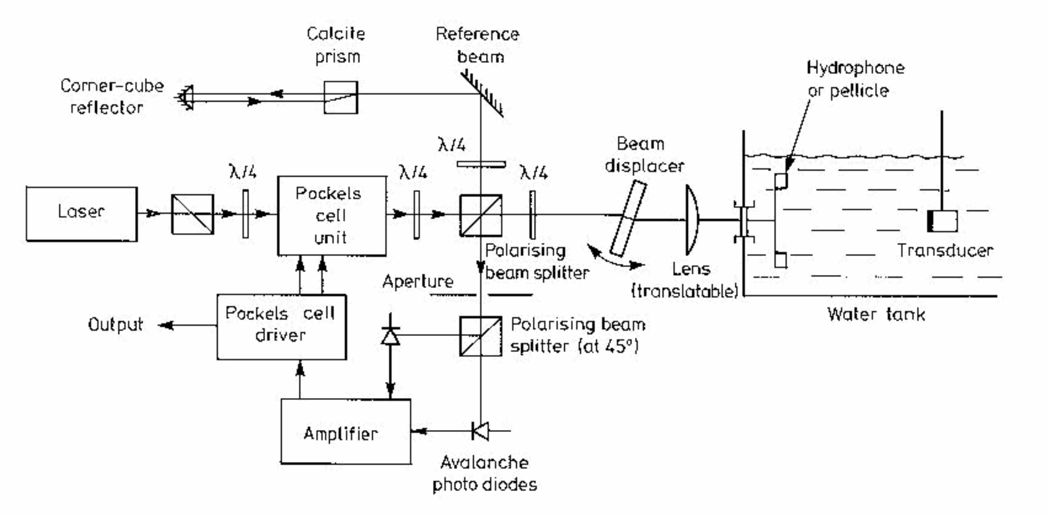

Figure 1: Schematic diagram of the NPL laser interferometer.

The reference voltage, V_0, provides a calibration of the interferometer which is necessary since the output depends on the intensity of light in the signal beam, which can vary if the pellicle moves due to environmental vibration in a direction perpendicular to the laser beam. It is desirable to measure both V_0 and V_I at the same instant, but in practice V_0 is measured just before and after the ultrasound is detected. To do this, the feedback circuit is disabled and the interferometer output is measured while simultaneously the Pockels cell is used to drive the interferometer over a complete interference fringe at a frequency of 2 kHz.

A thorough investigation of the uncertainties in the method has been undertaken [4] which identified a number of corrections that must be made to the measurements. The interferometer actually responds to changes in optical phase that are caused not just by the displacement of the pellicle but also by changes in refractive index of the water caused by the propagating acoustic wave. For a plane acoustic wave travelling in a direction parallel to the optical beam, this acousto-optic interaction may be accounted for simply by use of an effective refractive index in equations 1 and 2 (a value of approximately unity is used instead of the usual 1.332 for water) [5]. The frequency response of the diode/amplifier combination is also important since the reference voltage is measured at a frequency of 2 kHz, whereas the displacement is measured at high ultrasonic frequencies. The variation in interferometer response with frequency has been measured [6] and this information is used to correct the calibrations, the uncertainty on the correction being the largest single source of uncertainty in the method. Other corrections are made to account for the fact that the pellicle is not acoustically transparent but reflects some of the ultrasound, and the acoustic field is not an ideal plane-wave, requiring a correction for the spatial-averaging effect of the hydrophone. As part of the validation of the calibration method, NPL took part in a European comparison of calibrations of miniature ultrasonic hydrophones organised under the auspices of the Commission of the European Communities, and achieved a mean difference from the overall grand means of only 0.2 dB [7].

Advantages of this method are its direct traceability to primary standards of length and its insensitivity to the properties of the ultrasonic field generated by the transducer. Using the interferometer, a reference hydrophone can be calibrated in the frequency range 200 kHz to 20 MHz with typical overall uncertainties (expressed for a confidence level of 95%) of between ±3% and ±5% depending on frequency and hydrophone properties.

2.2 MEASUREMENTS

In accordance with the Protocol Document [8], the water in which the measurements are carried out was prepared so it had a low electrical conductivity and low gas content. The water was first distilled and then circulated and stored in a vacuum chamber (set to a pressure of between 10 and 20 mBar) until needed. Before the calibration tank was filled, the water is passed through a deioniser to ensure the electrical conductivity is kept as low as possible. The electrical conductivity is measured with a Hanna Instruments HI9635 hand-held meter and the dissolved oxygen content is measured with a Hanna Instruments HI9145 hand-held meter. The temperature of the water is not controlled but the air temperature within the laboratory is controlled to within ±2°C. The calibration tank was filled with fresh water before each hydrophone was calibrated.

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

During the measurements, the hydrophone earth pin was connected to the metal hydrophone mount within the tank. The hydrophone mount is bolted to the wall of the metal calibration tank, which is connected by earth shielding to the optical table.

Amplifier serial number 553901 was used for all measurements on the hydrophones and the interferometer, the open-circuit correction factors were calculated from impedance measurements of the hydrophone and amplifier and used to calculate the open-circuit sensitivity of each hydrophone.

Table 1: Propagation parameters for calibration by optical interferometry.

Source transducer details				Typical acoustic pressure (kPa)	Propagation Distance (mm)
Manufacturer	Type	Nominal frequency (MHz)	Active element diameter (mm)		
Panametrics	V391	1	25.40	12.0 - 13.4	450 - 525
Panametrics	V306	2.25	12.70	26.6 - 26.9	300 - 380
Panametrics	V309	5	12.70	74.7 - 86.6	330 - 410
Panametrics	V312	10	6.35	25.2 - 33.2	295 - 370
Panametrics	V313	15	6.35	4.7 - 6.8	265 - 325

Table 1 presents typical figures for the propagation parameters used during the calibration process. The acoustic pressures generated are low to ensure no non-linear distortion is present during the calibration procedure.

3 RESULTS

For hydrophone IP027, the data obtained from the four independent runs is presented in Tables 2 to 6 and for hydrophone IP039 the equivalent data is presented in Tables 8 to 12. Tables 7 and 13 present a summary of the data obtained for hydrophones IP027 and IP039.

3.1 IP027

Table 2: Calibration report table for hydrophone IP027 at 15 MHz

Institution: NPL			**Calibration method:** Optical Interferometry	
Date(s) of calibrations: 8 June 1999			**Hydrophone serial number:** IP027	
Nominal frequency (MHz): 15				
Measurement Number	**1**	**2**	**3**	**4**
Actual frequency (MHz)	15.017	15.012	15.012	15.011
Temperature, T (°C)	20.0	20.2	20.2	20.2
Open-circuit correction	1.0382	1.0382	1.0382	1.0382
Water conductivity (μS)	<1 μS	<1 μS	<1 μS	<1 μS
Oxygen content (mg l^{-1}), or alternative (ppm or % saturation)	<2 ppm	<2 ppm	< 2 ppm	<3 ppm
Amplifier gain (dB)	-	-	-	-
Measured sensitivity (nV Pa^{-1})	238.50	235.46	233.37	235.21
Open-circuit sensitivity at T °C (nV Pa^{-1})	247.61	244.45	242.28	244.20
Notes (e.g. of any unusual difficulties)				

Table 3: Calibration report table for hydrophone IP027 at 10 MHz

Institution: NPL			**Calibration method:** Optical Interferometry	
Date(s) of calibrations: 8 June 1999			**Hydrophone serial number:** IP027	
Nominal frequency (MHz): 10				
Measurement Number	**1**	**2**	**3**	**4**
Actual frequency (MHz)	10.150	10.154	10.154	10.147
Temperature, T (°C)	20.2	20.2	20.2	20.2
Open-circuit correction	1.0398	1.0398	1.0398	1.0398
Water conductivity (µS)	<1 µS	<1 µS	<1 µS	<1 µS
Oxygen content (mg l^{-1}), or alternative (ppm or % saturation)	<3 ppm	<4 ppm	<4 ppm	<4 ppm
Amplifier gain (dB)	-	-	-	-
Measured sensitivity (nV Pa^{-1})	187.81	187.50	185.36	187.42
Open-circuit sensitivity at T °C (nV Pa^{-1})	195.28	194.96	192.74	194.88
Notes (e.g. of any unusual difficulties)				

Table 4: Calibration report table for hydrophone IP027 at 5 MHz

Institution: NPL		**Calibration method:** Optical Interferometry		
Date(s) of calibrations: 8 June 1999		**Hydrophone serial number:** IP027		
Nominal frequency (MHz): 5				
Measurement Number	**1**	**2**	**3**	**4**
Actual frequency (MHz)	5.000	5.000	5.001	5.001
Temperature, T (°C)	20.2	20.2	20.2	20.2
Open-circuit correction	1.0397	1.0397	1.0397	1.0397
Water conductivity (μS)	<1 μS	<1 μS	<1 μS	<1 μS
Oxygen content (mg l^{-1}), or alternative (ppm or % saturation)	<4 ppm	<4 ppm	<4 ppm	<5 ppm
Amplifier gain (dB)	-	-	-	-
Measured sensitivity (nV Pa^{-1})	163.35	166.95	163.42	163.79
Open-circuit sensitivity at T °C (nV Pa^{-1})	169.83	173.58	169.91	170.29
Notes (e.g. of any unusual difficulties)				

Table 5: Calibration report table for hydrophone IP027 at 2 MHz

Institution: NPL		**Calibration method:** Optical Interferometry		
Date(s) of calibrations: 8 and 10 June 1999		**Hydrophone serial number:** IP027		
Nominal frequency (MHz): 2				
Measurement Number	**1**	**2**	**3**	**4**
Actual frequency (MHz)	2.000	2.000	1.996	2.001
Temperature, T (°C)	20.2	20.2	20.0	20.0
Open-circuit correction	1.0392	1.0392	1.0392	1.0392
Water conductivity (μS)	<1 μS	<1 μS	<1 μS	<1 μS
Oxygen content (mg l^{-1}), or alternative (ppm or % saturation)	<5 ppm	<5 ppm	<9 ppm	<9 ppm
Amplifier gain (dB)	-	-	-	-
Measured sensitivity (nV Pa^{-1})	152.31	152.36	151.22	152.39
Open-circuit sensitivity at T °C (nV Pa^{-1})	158.28	158.33	157.14	158.36
Notes (e.g. of any unusual difficulties)				

Table 6: Calibration report table for hydrophone IP027 at 1 MHz

Institution: NPL		**Calibration method:** Optical Interferometry		
Date(s) of calibrations: 10 June 1999		**Hydrophone serial number:** IP027		
Nominal frequency (MHz): 1				
Measurement Number	**1**	**2**	**3**	**4**
Actual frequency (MHz)	1.002	1.002	1.002	1.002
Temperature, T (°C)	20.0	20.0	20.0	20.0
Open-circuit correction	1.038	1.038	1.038	1.038
Water conductivity (μS)	<1 μS	<1 μS	<1 μS	<1 μS
Oxygen content (mg l^{-1}), or alternative (ppm or % saturation)	<10 ppm	<10 ppm	<10 ppm	<10 ppm
Amplifier gain (dB)	-	-	-	-
Measured sensitivity (nV Pa^{-1})	149.32	150.64	155.61	151.37
Open-circuit sensitivity at T °C (nV Pa^{-1})	154.99	156.36	161.52	157.12
Notes (e.g. of any unusual difficulties)				

Table 7: Calibration report table for hydrophone IP027

Institution: NPL			**Calibration method: Optical Interferometry**		
Dates: 8 and 10 June 1999	**Hydrophone Serial Number: IP027**				
Nominal frequency (MHz)	**1**	**2**	**5**	**10**	**15**
Actual frequency (MHz)	1.002	1.999	5.001	10.151	15.013
Mean open-circuit sensitivity at T °C (nV Pa^{-1})	157.50	158.03	170.90	194.46	244.64
Type A standard uncertainty (%)	0.90	0.19	0.53	0.30	0.45
Type B standard uncertainty (%)	1.24	1.35	1.28	1.38	1.57
Expanded uncertainty (%)	3.21 (k=2.09)	2.72 (k=2.00)	2.76 (k=2.00)	2.82 (k=2.00)	3.42 (k=2.00)

3.2 IP039

Table 8: Calibration report table for hydrophone IP039 at 15 MHz

Institution: NPL		**Calibration method:** Optical Interferometry		
Date(s) of calibrations: 3 June 1999		**Hydrophone serial number:** IP039		
Nominal frequency (MHz): 15				
Measurement Number	**1**	**2**	**3**	**4**
Actual frequency (MHz)	15.003	15.005	15.004	15.004
Temperature, T (°C)	20.0	20.0	20.0	20.0
Open-circuit correction	1.0414	1.0414	1.0414	1.0414
Water conductivity (µS)	<1 µS	<1 µS	<1 µS	<1 µS
Oxygen content (mg l^{-1}), or alternative (ppm or % saturation)	<2 ppm	<2 ppm	<2 ppm	<3 ppm
Amplifier gain (dB)	-	-	-	-
Measured sensitivity (nV Pa^{-1})	246.19	244.66	256.86	245.83
Open-circuit sensitivity at T °C (nV Pa^{-1})	256.38	254.79	267.49	256.01
Notes (e.g. of any unusual difficulties)				

Table 9: Calibration report table for hydrophone IP039 at 10 MHz

Institution: NPL			**Calibration method:** Optical Interferometry	
Date(s) of calibrations: 4 June 1999			**Hydrophone serial number:** IP039	
Nominal frequency (MHz): 10				
Measurement Number	**1**	**2**	**3**	**4**
Actual frequency (MHz)	10.142	10.147	10.149	10.150
Temperature, T (°C)	20.0	20.0	20.0	20.0
Open-circuit correction	1.0431	1.0431	1.0431	1.0431
Water conductivity (μS)	<1 μS	<1 μS	<1 μS	<1 μS
Oxygen content (mg l^{-1}), or alternative (ppm or % saturation)	<8 ppm	<8 ppm	<8 ppm	<8 ppm
Amplifier gain (dB)	-	-	-	-
Measured sensitivity (nV Pa^{-1})	192.26	193.40	192.68	191.85
Open-circuit sensitivity at T °C (nV Pa^{-1})	200.55	201.74	200.98	200.12
Notes (e.g. of any unusual difficulties)				

Table 10: Calibration report table for hydrophone IP039 at 5 MHz

Institution: NPL		**Calibration method:** Optical Interferometry		
Date(s) of calibrations: 7 June 1999		**Hydrophone serial number:** IP039		
Nominal frequency (MHz): 5				
Measurement Number	**1**	**2**	**3**	**4**
Actual frequency (MHz)	5.000	4.995	4.997	4.996
Temperature, T (°C)	20.0	20.0	20.0	20.0
Open-circuit correction	1.0433	1.0433	1.0433	1.0433
Water conductivity (μS)	<1 μS	<1 μS	<1 μS	<1 μS
Oxygen content (mg l^{-1}), or alternative (ppm or % saturation)	<10 ppm	<10 ppm	<10 ppm	<10 ppm
Amplifier gain (dB)	-	-	-	-
Measured sensitivity (nV Pa^{-1})	171.35	170.32	168.19	168.86
Open-circuit sensitivity at T °C (nV Pa^{-1})	178.77	177.69	175.47	176.17
Notes (e.g. of any unusual difficulties)				

Table 11: Calibration report table for hydrophone IP039 at 2 MHz

Institution: NPL		**Calibration method:** Optical Interferometry		
Date(s) of calibrations: 7 June 1999		**Hydrophone serial number:** IP039		
Nominal frequency (MHz): 2				
Measurement Number	**1**	**2**	**3**	**4**
Actual frequency (MHz)	1.998	1.998	1.998	1.999
Temperature, T (°C)	20.0	20.0	20.0	20.0
Open-circuit correction	1.0596	1.0596	1.0596	1.0596
Water conductivity (µS)	<1 µS	<1 µS	<1 µS	<1 µS
Oxygen content (mg l^{-1}), or alternative (ppm or % saturation)	<10 ppm	<10 ppm	<10 ppm	<11 ppm
Amplifier gain (dB)	-	-	-	-
Measured sensitivity (nV Pa^{-1})	161.56	160.01	161.60	161.16
Open-circuit sensitivity at T °C (nV Pa^{-1})	171.19	169.55	171.23	170.77
Notes (e.g. of any unusual difficulties)				

Table 12: Calibration report table for hydrophone IP039 at 1 MHz

Institution: NPL		**Calibration method:** Optical Interferometry		
Date(s) of calibrations: 7 June 1999		**Hydrophone serial number:** IP039		
Nominal frequency (MHz): 1				
Measurement Number	**1**	**2**	**3**	**4**
Actual frequency (MHz)	1.001	1.002	1.002	1.002
Temperature, T (°C)	20.0	20.0	20.0	20.0
Open-circuit correction	1.0572	1.0572	1.0572	1.0572
Water conductivity (µS)	<1 µS	<1 µS	<1 µS	<1 µS
Oxygen content (mg l^{-1}), or alternative (ppm or % saturation)	<11 ppm	<11 ppm	<11 ppm	<11 ppm
Amplifier gain (dB)	-	-	-	-
Measured sensitivity (nV Pa^{-1})	161.11	162.00	159.26	158.74
Open-circuit sensitivity at T °C (nV Pa^{-1})	170.33	171.27	168.37	167.82
Notes (e.g. of any unusual difficulties)				

Table 13: Calibration report table for hydrophone IP039

Institution: NPL			**Calibration method: Optical Interferometry**		
Dates: 4 to 7 June 1999	**Hydrophone Serial Number: IP039**				
Nominal frequency (MHz)	**1**	**2**	**5**	**10**	**15**
Actual frequency (MHz)	1.002	1.998	4.997	10.147	15.004
Mean open-circuit sensitivity at T °C (nV Pa^{-1})	169.45	170.69	177.03	200.84	258.67
Type A standard uncertainty (%)	0.48	0.23	0.43	0.18	1.15
Type B standard uncertainty (%)	1.24	1.35	1.28	1.38	1.57
Expanded uncertainty (%)	2.66 (k=2.00)	2.74 (k=2.00)	2.69 (k=2.00)	2.78 (k=2.00)	4.07 (k=2.09)

4 UNCERTAINTIES

4.1 TYPE B SYSTEMATIC UNCERTAINTIES

This section presents the Type B Systematic uncertainty contributions to the overall uncertainty budget with respect to frequency.

Table 14: Type B individual components within the uncertainty budget.

Symbol	Source of uncertainty	Probability distribution	Divisor	c_i	v_i or v_{eff}
f	Frequency response	normal	2.00	1.0	infinity
Sv	Sampling voltmeter accuracy	rectangular	1.73	1.0	infinity
Ld	Linearity of digitiser	rectangular	1.73	1.0	infinity
Si	Signal-to-noise ratio	rectangular	1.73	1.0	infinity
Ri	Effective refractive index	rectangular	1.73	1.0	infinity
Ao	Acousto-optic interaction	rectangular	1.73	1.0	infinity
Sp	Spatial averaging	rectangular	1.73	1.0	infinity
Ss	Pellicle transmission coefficient	rectangular	1.73	1.0	infinity
Lw	Lamb waves	rectangular	1.73	1.0	infinity
Pp	Pellicle position	rectangular	1.73	1.0	infinity
Al	Amplifier loading	rectangular	1.73	1.0	infinity
U_T	Total systematic uncertainty	normal	1.00	1.0	infinity

Table 15: Type B individual component values within the uncertainty budget.

Symbol	1.0 MHz		2.0 MHz		5.0 MHz		10.0 MHz		15.0 MHz	
	value ± %	ui ± %	value ± %	ui ± %	value ± %	ui ± %	value ± %	ui ± %	value ± %	ui ± %
f	1.75	0.88	2.02	1.01	1.66	0.83	1.83	0.92	2.15	1.08
Sv	0.35	0.20	0.35	0.20	0.35	0.20	0.35	0.20	0.35	0.20
Ld	0.40	0.23	0.40	0.23	0.40	0.23	0.40	0.23	0.40	0.23
Si	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.06	0.18	0.10
Ri	1.00	0.58	1.00	0.58	1.00	0.58	1.00	0.58	1.00	0.58
Ao	0.01	0.01	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Sp	0.08	0.05	0.14	0.08	0.22	0.13	0.28	0.16	0.80	0.46
Ss	0.20	0.12	0.30	0.17	0.70	0.40	0.90	0.52	1.00	0.58
Lw	0.04	0.02	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Pp	0.03	0.02	0.04	0.02	0.04	0.02	0.06	0.03	0.10	0.06
Al	1.00	0.58	1.00	0.58	1.00	0.58	1.00	0.58	1.00	0.58
U_T		1.24		1.35		1.28		1.38		1.57

4.2 TYPE A RANDOM UNCERTAINTIES

The type ‘A’ random uncertainties for each hydrophone are presented in Tables 7 and 13 and have been calculated from the standard deviations between the four independent measurement runs in accordance with UKAS document M3003 [9].

4.3 COMBINED AND EXPANDED UNCERTAINTIES

At some frequencies, the combined standard uncertainty is sometimes dominated by the value of the type ‘A’ random uncertainty. When this happens, following the procedures stated in the UKAS document M3003 [9] the effective degrees of freedom are calculated and the results obtained are used to calculate a revised coverage factor, k. The combined uncertainty is obtained by:

$$U_c = \sqrt{(U^2_A + U^2_B)}$$

After calculation of the effective degrees of freedom and the associated coverage factor, k, the expanded uncertainty is obtained by:

$$U = k \bullet U_c$$

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