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CCAUV.W-K2 FINAL REPORT
KEY COMPARISON CCAUV.W-K2: CALIBRATION OF HYDROPHONES IN THE FREQUENCY RANGE 250 HZ TO 500 KHZ

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CCAUV.W-K2 Final Report
Key Comparison CCAUV.W-K2: Calibration of Hydrophones in the Frequency Range from 250 Hz to 500 kHz

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Abstract

This report is the Final Report for Key Comparison CCAUV.W-K2. This Key Comparison covers primary free-field standards for sound in water at frequencies between 250 Hz and 500 kHz. This project is one of the Key Comparisons organised under the auspices of the Consultative Committee on Acoustics, Ultrasound and Vibration (CCAUV) of the CIPM.

This report has the status of a Final Report and has been submitted to the Key Comparison Database (KCDB). In the report, the results of participants are presented with the Key Comparison Reference Values and Degrees of Equivalence. The results are calculated according to the procedures agreed after consideration of the Draft A1 and A2 reports, and the Draft B report has been approved by the CCAUV. All participants have had the opportunity to give final agreement on the contents and amendments have been made to account for their comments.

In many respects, the comparison has been a success with good agreement achieved over an extended lower frequency range compared to the previous CCAUV.W-K1 comparison, the lower frequency limit for CCAUV.W-K2 being extended down by two octaves to 250 Hz. The generally more difficult frequency range from 100 kHz to 500 kHz has also shown very good agreement between the participants. However, in the range 60 kHz to 100 kHz the agreement was not as good, with three participants exhibiting some discrepant results.

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1 EXECUTIVE SUMMARY

This report is the Final Report for Key Comparison CCAUV.W-K2 covering primary free-field standards for sound in water at frequencies between 250 Hz and 500 kHz. For the comparison, two hydrophones were circulated to cover the above frequency range, the comparison being organised as a round-robin with the pilot laboratory being the National Physical Laboratory (NPL).

Of the two hydrophones circulated, a B&K8104 device covered the range from 250 Hz to 120 kHz, and a Reson TC4034 device covered the range from 100 kHz to 500 kHz. The requested parameter to be determined for each hydrophone was the magnitude of the end-of-cable open-circuit free-field receive sensitivity measured at a total of 102 discrete acoustic frequencies over the range of eleven octaves.

There were seven participants in the comparison: HAARI (CHN), INMETRO (BRA), NMISA (ZAF), NPL (GBR), TUBITAK-MAM (TUR), USRD (USA) and VNIIFTRI (RUS). In addition, NIOT (IND) participated as a guest participant (their results are not included in the calculations of Key Comparison Reference Values). Four of the main participants calibrated the hydrophones over the full frequency range, with the remaining participants omitting part of the frequency range (typically the lowest frequencies were the most challenging due to the size of test facility required), with INMETRO and NMISA calibrating only the B&K8104 device. The calibrations by the participants were completed by 2020, but there were delays in completing the analysis due to the COVID-19 pandemic and due to facility downtime at NPL where additional calibrations were undertaken to evaluate the variation of the hydrophone response with temperature.

The results of the comparison are now provided in this report which has the status of a Final Report, along with summary descriptions of the calibration methods provided. Previously, at the Draft A1 report stage, the participants were not identified with their respective results and participants were asked to check their own calibration results to ensure that their values were correct, and that the descriptions of the calibrations methods were accurate, and the proposed analysis methods were described by the pilot laboratory. When these checks were done and participants had commented on the proposed analysis methods, a Draft A2 report was prepared and circulated (with the identities of the participants now associated with their specific results). After final comments by participants, the Draft B report was prepared, which was approved by the CCAUV. Presented herein are the calculated Key Comparison Reference Values (KCRVs) and the Degrees of Equivalence (DOEs) for each participant.

The results showed that the agreement for the range 100 kHz to 500 kHz was generally very good, with only one participant exhibiting any discrepant results for the TC4034 hydrophone. This participant has now withdrawn their results for this hydrophone, leaving no discrepant results in this frequency range.

For the B&K8104 hydrophone, the results are generally in good agreement for the frequency range from 250 Hz to 60 kHz. However, the spread in the results for this hydrophone increases for the frequency range 60 kHz to 100 kHz, with two participants showing discrepant results for part of the frequency range (so that results do not form part of a consistent set).

One of the reasons for the differences observed for some participants is likely to be the differences in water temperature that pertain to the calibrations, which ranged from 17.7 °C to 31.5 °C. After the completion of the participant calibrations, NPL undertook calibrations at a selection of water temperatures to examine the hydrophone behaviour and to derive corrections. For the TC4034 hydrophone, the temperature corrections are only required for the guest participant, and they significantly improve the agreement in the frequency range from 300 kHz to 500 kHz (around and above the resonance frequency). For the B&K8104 hydrophone, the behaviour as a function of temperature was more difficult to determine precisely, and the corrections derived do not in general provide a significant improvement to the agreement between participants in the frequency range 60 kHz to 100 kHz.

There was also some evidence of a gradual temporal drift in the sensitivity of the hydrophones based on the check calibrations undertaken at NPL. This was particularly true at frequencies greater than 300 kHz for the TC4034 hydrophone. Although the TC4034 hydrophone results already showed reasonably good agreement, corrections were derived to account for the drift which, when applied, improve the agreement further. Drift corrections were also derived for the B&K8104 hydrophone, and though the observed drift was less significant for this device, these corrections have also been applied.

During the report preparation, participants were asked to read and comment on the Draft A1 and Draft A2 Reports, confirm their results were accurately represented in the reports, and confirm their agreement with the analysis methods outlined above. The CIPM MRA-G-11 procedure was followed in the consultation process.

Subsequent to the circulation of the Draft A1 report, all participants confirmed that they had checked and confirmed their results. No amendments were made to any of the declared results for hydrophone sensitivity. However, one participant (USRD) had offered provisional uncertainties with their initial results and have now amended their uncertainties to reflect the more recently declared uncertainties assessed by the US accreditation body, the National Voluntary Laboratory Accreditation Program (NVLAP). The uncertainties now reflect those declared in their scope of accreditation, and since these new uncertainties were publicly declared by the participant before the Draft A1 report was made available, they have been accepted for use in the Key Comparison. In addition, one participant (NMISA) withdrew their calibration of the TC4034 hydrophone at frequencies of 100 kHz to 230 kHz after discovery of a problem with the calibrations. These results exhibited a systematically low value of sensitivity and were discrepant after the analysis. These results are shown in an Annex for completeness but are no longer included in the calculations of Key Comparison Reference Values and Degrees of Equivalence.

In order to progress to the Draft B report and publication of the results in the Key Comparison Database, some decisions were required with regard to the way forward. The options were described in the Draft A1 report by the pilot laboratory (NPL). After the responses of the participants were received, the following actions were taken to produce the results circulated in the Draft A2 report:

- the results for the B&K8104 hydrophone are not used for calculation of the KCRV and DOEs in the frequency range of overlap (100 kHz to 120 kHz), with the results for the TC4034 hydrophone used instead (the TC4034 hydrophone results covering the whole range from 100 kHz to 500 kHz) except for the participants NMISA and INMETRO who did not calibrate the TC4034 hydrophone;
- the corrections for temporal drift are made to the calibration data for both hydrophones and all participants, based on the calibrations undertaken by NPL;
- the temperature corrections are applied to the measured data for INMETRO for the B&K8104 hydrophone, with the corrected data being used in the calculation of the KCRV;
- the temperature corrections are applied to the measured data for NIOT for both the B&K8104 hydrophone and the TC4034 hydrophone, but the corrected data is not used in the calculation of the KCRV (NIOT have the status of a guest participant).

After minor editorial corrections to Draft A2 suggested by the participants, the Draft B report was prepared and successfully submitted for approval by the CCAUV Key Comparison Working Group, followed by the CCAUV itself. This report now has the status of Final Report for CCAUV.W-K2.

In many respects, the comparison has been a success with good agreement achieved over an extended lower frequency range compared to the previous CCAUV.W-K1 comparison, the lower frequency limit for CCAUV.W-K2 being extended down by two octaves to 250 Hz. The generally more difficult frequency range from 100 kHz to 500 kHz has also shown very good agreement between the participants.

The main concern for the comparison is the relatively poor agreement in the frequency range 60 kHz to 100 kHz. This is likely to be in part due to the performance of the hydrophone chosen which appears to be more sensitive to influencing factors such as temperature and mounting in the frequency range around and above its resonance frequency. Certainly, the agreement in the overlap range of 100 kHz to 120 kHz is much better for the TC4034 hydrophone, and the results for the latter hydrophone have been chosen for the calculation of the DOEs in that range.

To address the problems of discrepancies in the frequency range 60 kHz to 100 kHz, participants have agreed that opportunities should be given to discrepant NMIs to calibrate using an alternative hydrophone over this problem frequency range. It is proposed that this is organised as an additional follow-on comparison exercise.

2 INTRODUCTION

2.1 SCOPE OF REPORT

This report is the Final Report for Key Comparison CCAUV.W-K2. This report is submitted to the CCAUV Key Comparison Working group (CCAUV KCWG) for comment and approval. This report has been produced by the pilot laboratory after all participants have had the opportunity to agree the content of the report.

This Key Comparison covers primary free-field standards for sound in water at frequencies between 250 Hz and 500 kHz. This project is one of the Key Comparisons organised under the auspices of the Consultative Committee on Acoustics, Ultrasound and Vibration (CCAUV) of the CIPM. This Key Comparison follows on from Key Comparison CCAUV.W-K1 which ended in 2005.

This Key Comparison is the successor to CCAUV.W-K1 which was completed in 2005. The current Key Comparison has offered the opportunity for participants to extend the range of their free-field calibrations down in frequency by two octaves to 250 Hz (CCAUV.W-K1 covered only frequencies from 1 kHz to 500 kHz). Frequencies greater than 500 kHz have been covered by Key Comparison CCAUV.U-K4.

The rules pertaining to the conduct of Key Comparisons, CIPM MRA-G-11, have been followed in the production of this report. This states that:

> *The report should include, or give reference to, most of the information specified in the Technical protocol. It should also include:*
>
> a. *measurement results identified for the individual participants;*
> b. *the key comparison reference value (reference value for supplementary comparisons) with a description how it was calculated (if applicable), or how the linking to the key comparison reference value was carried out;*
> c. *the degrees of equivalence and how these were evaluated (not mandatory for supplementary comparisons).*
>
> *The pilot institute is responsible for writing the report of the comparison with assistance from the coordinating group (where such a group has been established). The report passes through three stages before publication, referred to as Draft A, Draft B and Final Report. The stages are differentiated by:*
>
> − *Draft A being available only to the participants in the comparison;*
> − *Draft B being available to the relevant Consultative Committee;*
> − *Final Report being publicly available.*
>
> *In the case of any outliers, the results are not communicated until the participants concerned have been contacted to ensure that no arithmetic, typographical or transcription errors are present. Draft A includes the results transmitted by the participants, identified by name, including the degrees of equivalence and, in the case of CIPM key comparisons, the proposed key comparison reference value.*
>
> *The participants in the comparison may make comments on their own results and these may be modified if there were errors in the report of the result (typographical errors, different prefixes of units, transcription errors from the institute report to the Draft A report). In the case of results that are discrepant with the reference value or are not consistent with their published CMCs, the participants are not allowed to withdraw their results from the report unless a reason not attributable to the performance of the laboratory can be assigned (for example, if an excessive drift or a malfunction is detected in the transfer standard). Individual values and measurement uncertainties may be changed or removed or the complete comparison abandoned only with the agreement of all participants and on the basis of a clear failure of the transfer standard or some other phenomenon that renders the comparison or part of it invalid.*

There may be several successive versions of a report (A1, A2, etc), but the Draft A stage will not be complete until all participants have agreed on the report. Draft A shall be considered confidential and distributed among the participants only. As results can change, Draft A reports shall not be used to support CMC claims.

In calculating a key comparison reference value, the pilot institute will use the method considered most appropriate for the particular comparison (normally that proposed in the protocol), subject to confirmation by the participants and, in due course, the key comparison working group and the Consultative Committee. After deciding on the key comparison reference value and its uncertainty, the deviation from the reference value and the expanded uncertainty are deduced for each of the individual results.

Once the final version of Draft A is approved by the participants, the report becomes Draft B, which shall be submitted for approval by the corresponding Consultative Committee. The Draft B report of CIPM / RMO key comparisons can be used to support CMCs. At this stage, the measurement values are not considered confidential and may be used for presentations and publications. However, the key comparison reference value and the degrees of equivalence shall be considered confidential until they are approved by the Consultative Committee and published in the KCDB.

3 ORGANISATION OF THE COMPARISON

3.1 PARTICIPANTS

The participants in CCAUV.W-K2 are listed in Table 1.

Table 1. List of participating institutes. The alphanumeric code is the code that was used in the Draft A1 report. In the plots of results, the participants are now identified by their country code.

Participant	Acronym	Country	Country Code	Code
National Physical Laboratory	NPL	United Kingdom	GBR	A
TÜBİTAK – MAM	MAM	Turkey	TUR	B
All-Russian Scientific and Research Institute for Physical-Technical and Radiotechnical Measurements	VNIIFTRI	Russia	RUS	C
Underwater Sound Reference Division, NUWC	USRD	USA	USA	D
Hangzhou Applied Acoustic Research Institute	HAARI	China	CHN	E
National Metrology Institute for South Africa	NMISA	South Africa	ZAF	F
Instituto Nacional de Metrologia, Qualidade e Tecnologia	INMETRO	Brazil	BRA	G
National Institute for Ocean Technology	NIOT	India	IND	H

At the beginning of the comparison, KRISS (KOR) were scheduled to participate but withdrew from the exercise before attempting any measurements.

3.2 PROTOCOL

3.2.1 Basis of calibration methods

The comparison was organised as a round-robin (sometimes referred to as a “ring” comparison) with the pilot laboratory being the National Physical Laboratory (NPL). Two hydrophones were circulated to cover the desired frequency range from 250 Hz to 500 kHz.

The requested parameter to be determined for each hydrophone was the magnitude of the end-of-cable, open-circuit free-field receive sensitivity. This is defined as the quotient of the open-circuit voltage at the output terminals of the hydrophone to the sound pressure in the undisturbed free field of a plane wave which would exist at the position of the acoustic centre of the hydrophone if the hydrophone were removed from the field [IEC 60500].

The calibration methods are described in IEC 60565:2006, and participants were asked to conform to the requirements of this standard (with any exceptions recorded). Note that this standard has recently been updated [IEC 60565:2020]. Other standard procedures operated at a national level were also cited (for example, ANSI S1.20 2012).

The calibration was required only for the direction indicated by the alignment mark on the hydrophone body, with the hydrophone suspended vertically in the water.

3.2.2 Preparation of protocol

As pilot laboratory and coordinator, NPL sent a questionnaire to all potential participants to request information regarding the scope of their participation, and the scheduling of calibrations. From the replies, it became clear that the funding for most of the participants would not be available until at least 2016, and so the start of the comparison was delayed to 2016. NPL also circulated a draft technical protocol for comment and agreement by participants. The final version of this protocol is provided as Annex F in this report.

3.2.3 Hydrophones

Each participant received a set of two hydrophones for calibration containing:

- Hydrophone type 8104 manufactured by Brüel & Kjær.
- Hydrophone type TC 4034 manufactured by Teledyne Reson.

A nominal performance specification for each of the hydrophones is given below. Another set of nominally identical hydrophones was kept at NPL to act as spare hydrophones for the comparison.

Table 3.1 Nominal specification of the B&K8104 hydrophone

Brüel and Kjær 8104	
Frequency range for calibration	250 Hz – 120 kHz
Nominal voltage sensitivity (250 Hz)	-205 dB re 1 V/µPa
Nominal capacitance	7800 pF
Active element type	4 PZT rings (12 mm dia.)
Position of acoustic centre (from end of hydrophone boot)	16 mm
Length of integral cable	10 m
Horizontal directivity (at 100 kHz)	±2 dB (typical)
Vertical directivity (over 270º at 50 kHz)	±2 dB (typical)
Cable	twin conductor, shielded,
Connector	BNC
Length of cable	10 m
Weight with cable (in air)	1.6 kg

Table 3.2 Nominal specification of the TC4034 hydrophone

Reson TC4034	
Frequency range for calibration	100 kHz – 500 kHz
Nominal voltage sensitivity (250 Hz)	-218 dB re 1 V/μPa
Nominal capacitance	3000 pF
Active element type	6 mm diameter PZT sphere
Position of acoustic centre (from end of hydrophone boot)	5.5 mm
Length of integral cable	10 m
Horizontal directivity (at 100 kHz)	±2 dB (typical)
Vertical directivity (over 270º at 50 kHz)	±2 dB (typical)
Cable	twin conductor, shielded,
Connector	BNC
Length of cable	10 m
Weight with cable (in air)	1.6 kg

3.2.4 Mounting and alignment

Since the Key Comparison is intended to determine the Degrees of Equivalence of national primary standards (and not the ability to calibrate a specific hydrophone in a specific mount), it is desirable that the hydrophone mount is not a source of discrepancy. During CCAUV.W-K1, this was regarded as a source of some of the discrepancies observed, and it is known that hydrophone responses may be affected by the mounting method.

Therefore, for CCAUV.W-K2, a hydrophone mount designed to fit the two hydrophones used in the comparison was supplied by the pilot laboratory, NPL. This mount was used by each participant when suspending the hydrophones in the test tank for calibration, unless otherwise stated. The mount consists of a 16 mm diameter free-flooding carbon-fibre pole.

The B&K8104 and the TC4034 hydrophones are both mounted coaxially at the end of the carbon fibre pole provided. For alignment, a mark was chosen on the body of each hydrophone, and participants were requested to align this mark with the white alignment mark on the mounting pole. For the B&K8104 hydrophone, the chosen mark was the manufacturer's engraved alignment mark. For the TC4034 hydrophone, the mould line in the rubber boot closest to the word "RESON" was chosen.

Each of the above marks was aligned with the white alignment mark on the pole before calibration. When the pole is attached to the positioning carriage on the participants positioning system, the alignment mark on the pole must be aligned to a pre-defined reference orientation (for example, pointing toward the source transducer).

3.2.5 Acoustic frequencies

The hydrophone sensitivities were requested at a total of 102 discrete acoustic frequencies over the 11 octaves from 250 Hz to 500 kHz. The selected acoustic frequencies were as follows:

Table 3.3 Brüel and Kjær 8104 hydrophone: 61 frequencies in the range 250 Hz - 120 kHz

0.25	0.3	0.4	0.5	0.6	0.7	0.8	0.9		
1	2	3	4	5	6	7	8	9	
10	12	14	16	18	20	22	24	26	28
30	32	34	36	38	40	42	44	46	48
50	52	54	56	58	60	62	64	66	68
70	72	74	76	78	80	82	84	86	88
90	100	110	120						

Table 3.4 Reson TC4034 hydrophone: 41 frequencies in the range 100 kHz - 500 kHz

100	110	120	130	140	150	160	170	180	190
200	210	220	230	240	250	260	270	280	290
300	310	320	330	340	350	360	370	380	390
400	410	420	430	440	450	460	470	480	490
500									

For a participant unable to calibrate the hydrophones over the entire frequency range, a sub-set of the frequencies listed above were chosen depending on the capability of that participant.

Four of the participants calibrated the hydrophones over the full frequency range. The remaining participants omitted part of the frequency range (typically either the lowest or highest range of frequencies).

3.2.6 Environmental conditions

In CCAUV.W-K2, the water temperature for calibrations was required to be within the range 17 °C – 21 °C. The depth of immersion of the hydrophone in the water was required to be less than 10 m. The actual water temperature and depth of immersion during calibrations must be stated with the results.

During CCAUV.W-K1, the variation in water temperature during calibrations was regarded as a potential source of some of the discrepancies observed. Therefore, a restrictive range of water temperatures were required. If during the analysis of the results, it was considered that the temperature variation made a significant contribution to the differences between participant results, NPL agreed to undertake calibrations of the hydrophones used in the Key Comparison over the range of temperatures encountered to evaluate the effect Rather than exclude a participant that was not able to conform).

3.2.7 Uncertainties

Participants were requested to provide uncertainty values and a list of uncertainty contributions. Participants were advised to use the guidance provided in the JCGM Guide to the Expression of Uncertainty in Measurement (GUM) when describing the calculation of uncertainties.

For Type B contributions, the guidance provided in IEC 60565 was recommended as the basis of uncertainty assessments. Participants were asked to calculate the Type A contributions from the results of at least four repeated calibrations with the hydrophone removed from the test tank and remounted between repeats.

The pilot laboratory circulated a spreadsheet with an example uncertainty budget for use by the participants as guidance (included here as Annex G).

3.2.8 Schedule

The initial NPL calibrations were begun in 2014, well in advance of the start of participant calibrations. However, after discussion with participants, it became clear that the funding for many of the NMIs would not be available until 2016 or later. Therefore, the start of participant calibrations was delayed until the beginning of 2016, and the calibrations were completed in 2019.

The calibrations undertaken by the pilot laboratory (the first to be undertaken) were submitted to the Secretary of CCAUV before the results of the other participants were received.

4 CALIBRATIONS BY PARTICIPANTS

4.1 NPL (GBR)

The calibration method was the method of three-transducer spherical-wave reciprocity in conformance with IEC 60565:2006. No deviations from protocol were reported for the calibrations of either hydrophone. Calibrations were undertaken at all frequencies for both hydrophones.

Two water tanks were used: for the TC4034 hydrophone calibration at frequencies of 100 kHz to 500 kHz the measurements were conducted in a tank of dimensions 3 m by 1.5 m and 1.5 m deep with a two-carriage positioning system; for the B&K8104 hydrophone calibration at frequencies from 250 Hz to 120 kHz, a larger cylindrical test tank was used which is 5.5 m in diameter and 5 m deep with a three-carriage positioning system mounted on vibration-isolated beams.

No baffles or absorbers were used. The positioning systems of both tanks are controlled by the measurement software to achieve the required device separation, depth of immersion and alignment. Four repeated calibrations were made, each at a different device separation, and between each repeat the hydrophone was removed from the water and re-mounted.

Discrete-frequency tone-burst signals were used to cover the required frequency range, with time-gating used to eliminate reflected signals from the measurement. The measurements were made on the steady-state part of the signal. A calibrated current transformer was used to measure the drive current. A computer-controlled switch enables the drive current and hydrophone voltage to be measured using the same preamplifier and digitiser channel to minimise uncertainties from instrument calibration. To avoid any linearity issues in the measurement channel, a calibrated switchable attenuator is used to match the signal amplitude from the current probe to that from the hydrophone. No extra extension cable was added during calibration. The B&K8104 hydrophone and the TC4034 hydrophone were both mounted in the manner requested by the protocol (see Section 3.2.4). A dilute solution of household washing up liquid was used to clean the hydrophones which were then soaked overnight in the laboratory tank before any measurements were made.

The reciprocity method requires the use of auxiliary transducers (designated P and T in the experiment). All hydrophones employed as P and T in the calibrations were in-house reference devices that had established calibration histories to provide an additional calibration check (the method provides an absolute calibration of all three devices used). For the calibration of the TC4034, two additional TC4034 hydrophones were selected as P and T. For the calibration of the B&K8104 hydrophone, two sets of auxiliary transducers were used: for 20 kHz – 120 kHz, a Reson TC4033 and a Reson TC4040 were used; for 250 Hz – 20 kHz, ITC 1001 transducers were used.

Both water tanks are located in temperature-controlled laboratories. The environmental conditions are shown in Table 4.1.

Table 4.1 Conditions for calibrations by NPL

Hydrophone	Water temperature (°C)	Immersion depth (m)	Separation distances (m)
B&K8104	18.0	2.5	1.46 – 1.53
TC4034	19.2	0.8	0.925 – 1.00

The calibration uncertainties were evaluated according to the JCGM/ISO/IEC Guide to the Expression of Uncertainty in Measurement [JCGM 100:2008] and the guidance on components provided in IEC 60565:2006. The spreadsheet provided along with the protocol was used in the calculation of the combined uncertainty.

The combined uncertainties expressed as standard uncertainties varied with frequency, ranging from a minimum of 2 % at low to mid kilohertz frequencies, to a maximum of 6.3 % at the extremes of the frequency range (between 4 % and 12.6 % expressed as an expanded uncertainty for $k = 2$).

4.2 TÜBİTAK – MAM (TUR)

The calibration method was the method of three-transducer spherical-wave reciprocity in conformance with IEC 60565:2006. No deviations from protocol were reported for the calibrations of either hydrophone. Calibrations were undertaken at frequencies from 2 kHz to 500 kHz.

The dimensions of the water tank used are 15 m x 10 m x 7.5 m deep. It is constructed of reinforced concrete with side walls decoupled using vibration-isolation from the surrounding environment, and with the bottom of the test task isolated from the ground by polyurethane based decoupling material. No absorbers or baffles were used inside the tank. A positioning system enables the required device separation, depth of immersion and alignment. Two different support bridges are used for this purpose, with positioning accuracies of ± 150 µm. During the four repeated calibrations, the separation distances were identical (see Table 4.2). Before the elements are immersed in water the separation distance between them is measured by a laser distance meter. Four repeated calibrations were made, and between each repeat the hydrophone was removed from the water and re-mounted.

Discrete-frequency tone-burst signals were used to cover the required frequency range, with time-gating used to eliminate reflected signals and measurements were made on the steady-state part of the signal. For the calibration of the B&K hydrophone, a B&K model 9718 calibration system was used. For the calibration of the Reson hydrophone, the in-house High Frequency Hydrophone Calibration was used. For both systems, the drive current was measured from the received voltage across a reference resistor (1 Ω). The applied drive voltage was measured by means of voltage divider.

Both the received and the drive waveforms were measured by the system and the FFT for each signal was calculated, the frequency and the magnitude of the signal being obtained from the FFT. No pre-amplifier or extension cables were used during the calibration thus no corrections made for electrical loading of the hydrophone by the cable.

The B&K8104 and the TC4034 were both mounted in the manner requested by the protocol (see Section 3.2.4). A mechanical clamp was used to attach the hydrophone pole to the positioning system. A soaking time of one hour at the measurement depth for each hydrophone was adopted before doing measurements. Swarfega green gel was used as wetting agent before immersion.

The reciprocity method requires the use of auxiliary transducers (designated P and T in the experiment). All hydrophones employed as P and T in the calibrations were in-house reference devices that had established calibration histories to provide an additional calibration check. Two B&K type 8104 model hydrophones were used as P and T (these are calibrated in-house once a year by the free-field reciprocity calibration method, and one hydrophone has been calibrated externally by another NMI).

The environmental conditions are shown in Table 4.2.

Table 4.2 Conditions for calibrations by TÜBİTAK – MAM

Hydrophone	Water temperature (°C)	Immersion depth (m)	Separation distances (m)
B&K8104	18.2	3.5	2.0
TC4034	18.6	3.5	1.6

The calibration uncertainties were evaluated according to the JCGM/ISO/IEC Guide to the Expression of Uncertainty in Measurement [JCGM 100:2008] and the guidance on components provided in IEC 60565:2006.

The combined uncertainties expressed as standard uncertainties varied with frequency, ranging from a minimum of 2.95 % at high kilohertz frequencies, to a maximum of 4.2 % low kilohertz frequencies (between 6 % and 8.4 % expressed as an expanded uncertainty for $k = 2$).

4.3 VNIIFTRI (RUS)

The calibration method was the method of three-transducer spherical-wave reciprocity in conformance with IEC 60565:2006. No deviations from protocol were reported for the calibrations of either hydrophone. Calibrations were undertaken at all frequencies for both hydrophones.

Two water tanks were used: for the TC4034 calibration at frequencies of 100 kHz to 500 kHz the measurements were conducted in a small water tank of dimensions 1.5 m by 1.0 m, and depth of 1 m; for the B&K8104 hydrophone calibration at frequencies from 250 Hz to 120 kHz, a larger concrete water tank was used with dimensions of 10 m by 6 m, and 6 m in depth. No baffles or absorbers were used.

A laser alignment system was used to align the hydrophones and set the separation distance between them. The separation distance was estimated from the propagation delay of the received pulse. The dependence of sound velocity with temperature was accounted for (estimated by tabulated values). The accuracy of distance measurement was assessed as not exceeding 0.5 %. Repeated calibrations were made with the hydrophone removed from the water and re-mounted for each repeat.

Depending on the frequency measurement range, three signal types were used: quadrature-added pairs of gated tone-bursts, continuous linear frequency modulated (chirp) signals, and continuous noise signals. For calibration of hydrophone B&K 8104 in the frequency range 250 Hz – 40 kHz the in-phase (sinusoidal) and quadrature (co-sinusoidal) chirp signals with duration of 1.5 s were transmitted alternately. At frequencies from 20 to 80 kHz, continuous noise signals were transmitted with the same duration. At frequencies above 60 kHz, quadrature-added tone-burst signals were radiated. The overlapping frequency ranges were used to check the comparability of measurement results. During calibration of hydrophone TC 4034 all three types of signals (chirp, noise and tone-burst) were used to check the comparability of measurement results. To provide free-field conditions, the technique of complex moving weighted averaging (CMWA) was applied when radiating the continuous chirp and noise signals. With tone-burst signals a least-square method (LSM) or quadrature processing was used. To improve the signal-to-noise ratio, coherent averaging was used from 250 Hz to 500 kHz.

A digital oscilloscope and AD converter were used only for acquisition oscillogram of receiving signals, with further processing by computer. The values of the voltage ratio were measured, rather than absolute values of the voltages. The current was estimated from the ratio of the voltage across a resistor in the projector circuit to the value of the resistor's resistance. No extra extension cables were used.

The reciprocity method requires the use of auxiliary transducers (designated P and T in the experiment). Three pairs of non-directional piezoelectric hydrophones with a spherical active element were used at calibration as a projector and reversible transducers at different frequency ranges: from 250 Hz to 20 kHz, ITC 1001 transducers were used; from 10 to 60 kHz, in-house designed hydrophones with diameter of 20 mm were used; from 50 to 500 kHz, in-house designed hydrophones with diameter of 5 mm were used.

The hydrophones were mounted in the manner requested by the protocol (see Section 3.2.4). Before immersion, the rubber boots of the hydrophones were cleaned and wetted using a mild detergent (liquid soap). Total soaking time was initially 2 days, then 30 minutes between repeats. The environmental conditions are shown in Table 4.3.

Table 4.3 Conditions for calibrations by VNIIFTRI

Hydrophone	Water temperature (°C)	Immersion depth (m)	Separation distances (m)
B&K8104	17.5 ± 0.4	2.88	0.64 – 0.76
TC4034	18.0 ± 0.5	0.40	0.70 – 1.00

The calibration uncertainties were evaluated according to the JCGM/ISO/IEC Guide to the Expression of Uncertainty in Measurement [JCGM 100:2008] and the guidance on components provided in IEC 60565:2006.

The combined uncertainties expressed as standard uncertainties varied with frequency, ranging from a minimum of 2.4 % at low frequencies, to a maximum of 3.0 % at the high extremes of the frequency range (between 4.8 % and 6.0 % expressed as an expanded uncertainty for $k = 2$).

4.4 USRD (USA)

All acoustic measurements were performed in accordance with ANSI-ASA S1.20-2012 using the three-transducer, spherical-wave reciprocity method. Calibrations were undertaken at all frequencies for both hydrophones. Only one deviation from the protocol was reported: the water temperature for calibrations at frequencies below 1 kHz were slightly higher than required by the protocol.

The facility used for calibrations at frequencies from 1 kHz to 500 kHz is a climate-controlled concrete open-water tank, 9.1 meters long, 4.6 meters wide, and 4.6 meters deep. It features automated data acquisition systems and associated mechanical support equipment with an angular resolution of ±0.1°. For calibrations at frequencies below 1 kHz, an open-water facility was used located on a natural spring consisting of a deep circular pool about 120 m in diameter and 50 m deep, the bottom of which is covered with about 3 meters of soft sediment.

The hydrophone mounting pole was attached to free-flooding aluminium poles for attaching to the positioning system. Distances were measured using tape measures to record the distance between the acoustic centres of the source and receiver. Repeated calibrations were made, and between each repeat the hydrophone was removed from the water and re-mounted.

Discrete-frequency tone-burst signals were used to cover the required frequency range, with time-gating used to eliminate reflected signals from the measurement. The measurements were made on the steady-state part of the signal. A calibrated current transformer (coil) was used to measure the drive current. The calibration instrumentation includes a National Instruments PXI-5105 analogue-to-digital converter with 12-bit precision operating at a 5-MHz sample rate. Measurement control and data acquisition are provided by a special purpose software application that supports a variety of acoustic measurement tasks, including primary calibration of hydrophones. No extra extension cable was added during calibration.

The B&K8104 and the TC4034 were both mounted in the manner requested by the protocol (see Section 3.2.4). At both facilities the devices were left to soak in the water overnight before calibrations the following day. All transducers were washed with a surfactant prior to immersion.

The reciprocity method requires the use of auxiliary transducers (designated P and T in the experiment). For the calibration of the TC4034, two E27 transducers were selected as P and T. For the calibration of the B&K 8104, three sets of transducers were used: at frequencies below 1 kHz, two F56 transducers were used; for frequencies between 1 kHz and 20 kHz, two ITC1007 transducers were used; and for 22 kHz to 120 kHz, and F41 and an F83 transducer were used.

The environmental conditions are shown in Table 4.4.

Table 4.4 Conditions for calibrations by USRD

Hydrophone	Water temperature (°C)	Immersion depth (m)	Separation distances (m)
B&K8104 (0.25 – 1.0 kHz) B&K8104 (1 – 120 kHz)	22.5 19.9	7.8 2.28	2.00 1.50 – 2.00
TC4034	19.9	2.28	1.00

The combined uncertainties expressed as standard uncertainties varied with frequency, ranging from a minimum of 1.2 % at low kilohertz frequencies, to a maximum of 6.7 % at the lowest extreme of the frequency range (between 2.4 % and 13.4 % expressed as an expanded uncertainty for $k = 2$).

4.5 HAARI (CHN)

The calibration method was the method of three-transducer spherical-wave reciprocity in conformance with IEC 60565:2006. Calibrations were undertaken at all frequencies for both hydrophones.

Two water tanks were used: for the TC4034 calibration at frequencies of 100 kHz to 500 kHz the measurements were conducted in an anechoic water tank of dimensions 2 m by 1.2 m, and 1 m deep; for the B&K8104 hydrophone calibration at frequencies from 250 Hz to 120 kHz, a larger test tank was used of dimensions of 50 m by 15 m, and 10 m deep. Six independent repeated calibrations were made for each hydrophone.

For the frequency range 250 Hz to 1 kHz, the free-field three-transducer spherical-wave reciprocity method was augmented with the complex moving weighted average technique for calibration of the B&K8104 hydrophone. For the B&K8104 at 1 kHz to 120 kHz and the TC4034 at 100 kHz to 500 kHz, discrete-frequency tone-burst signals were used, with time-gating used to eliminate reflected signals from the measurement and discrete Fourier transform used to measure the steady-state part of the signal.

Two different digitisers were used depending on the frequency range (an NI 5922 and an Agilent 54624A). A calibrated current transformer was used to measure the drive current for 1 kHz to 500 kHz, with a VIT13 sensor was used at lower frequencies.

The B&K8104 was mounted in the manner requested by the protocol, but the TC4034 was mounted in a similar diameter pole but of shorter length for easier fitting to the smaller tank.

A non-corrosive detergent was used to clean the hydrophones before immersion, and a soaking time of 24 hours was used before measurements.

The reciprocity method requires the use of auxiliary transducers (designated P and T in the experiment). Three pairs of non-directional piezoelectric hydrophones with a spherical active element were used at calibration as a projector and reversible transducers at different frequency ranges: from 250 Hz to 1 kHz, G&W D11 transducers were used; from 1 kHz to 10 kHz in-house designed RHS-30 hydrophones were used, and from 12 kHz to 120 kHz two TC 4033 hydrophones were used; from 100 to 500 kHz, a TC3027 and a TC3029 transducer were used.

The environmental conditions are shown in Table 4.5.

Table 4.5 Conditions for calibrations by HAARI

Hydrophone	Water temperature (°C)	Immersion depth (m)	Separation distances (m)
B&K8104 (0.25 – 1.0 kHz)	17.4	5.0	1.00
B&K8104 (1 – 120 kHz)	18.5 – 19.2	5.0	0.50
TC4034	18.7 – 19.7	0.6	0.50

The calibration uncertainties were evaluated according to the JCGM/ISO/IEC Guide to the Expression of Uncertainty in Measurement [JCGM 100:2008] and the guidance on components provided in IEC 60565:2006.

The combined uncertainties expressed as standard uncertainties varied with frequency, ranging from a minimum of 2.9 % to a maximum of 4.26 % (between 5.8 % and 8.52 % expressed as an expanded uncertainty for $k = 2$).

4.6 NMISA (ZAF)

The calibration method was the method of three-transducer spherical-wave reciprocity in conformance with IEC 60565:2006. No deviations from protocol were reported. Calibrations were reported for frequencies from 4 kHz to 100 kHz. The results for the TC4034 at frequencies from 100 kHz to 230 kHz were withdrawn.

The water tank used for the calibrations had dimensions of 10 m by 5 m and was 5 m deep. No baffles or absorbers were used.

The hydrophones and transducers were attached to stainless-steel mounting poles fixed to a jig and mounted on to a gantry system over the tank in an equilateral triangle configuration. The bottom part of the mount was replaced with the free-flooding carbon-fibre pole provided and both hydrophones were mounted in the manner requested by the protocol (see Section 3.2.4). A tape measure was used to measure the separation distance and depth of immersion.

Discrete-frequency tone-burst signals were used to cover the required frequency range, with time-gating used to eliminate reflected signals from the measurement. The measurements were made on the steady-state part of the signal. No extra extension cable was added during calibration.

Before any measurements were made, the hydrophone was wetted by spraying with a mild diluted dishwashing detergent and then soaked in the water for 21 hours. For subsequent measurements, the hydrophones were removed, re-aligned, resprayed, re-attached and immersed for 30 minutes before measurements.

The reciprocity method requires the use of auxiliary transducers (designated P and T in the experiment). For the calibrations, two B&K 8104 hydrophones were used as P and T in the measurements.

The environmental conditions are shown in Table 4.6.

Table 4.6 Conditions for calibrations by NMISA

Hydrophone	Water temperature (°C)	Immersion depth (m)	Separation distances (m)
B&K8104	17.7	1.53	1.00
TC4034	17.7	1.53	1.00

The calibration uncertainties were evaluated according to the JCGM/ISO/IEC Guide to the Expression of Uncertainty in Measurement [JCGM 100:2008] and the guidance on components provided in IEC 60565:2006. The spreadsheet provided along with the protocol was used in the calculation of the combined uncertainty.

The combined uncertainties expressed as standard uncertainties varied with frequency, ranging from a minimum of 2 % high kilohertz frequencies, to a maximum of 3.27 % at the lowest extremes of the frequency range (between 4 % and 6.53 % expressed as an expanded uncertainty for $k = 2$).

4.7 INMETRO (BRA)

The calibration method was the method of three-transducer spherical-wave reciprocity in conformance with IEC 60565:2006. A deviation from protocol was reported because the water temperature in the test tank was 26 °C - 27 °C which is outside the range stipulated by the protocol (17 °C – 21 °C). Calibrations were undertaken only for the B&K8104 hydrophone at frequencies from 1 kHz to 100 kHz.

The water tank used for the calibrations was made of concrete and had dimensions of 10 m by 5 m by 6.0 m deep and was filled to 5 m deep. No baffles or absorbers were used.

The hydrophone under test was mounted in the manner requested by the protocol (see Section 3.2.4) with the mounting pole supplied then attached to a PVC mounting fixture. The alignment mark was visually adjusted toward the auxiliary hydrophones. The separation was calculated from the propagation delay and the speed of sound in the water (estimated from tabulated data).

Discrete-frequency tone-burst signals were used to cover the required frequency range, with time-gating used to eliminate reflected signals from the measurement. The measurements were made on the steady-state part of the signal. The drive current was measured with a resistor shunt of 1.8 Ω where the impedance was determined at the frequencies of measurement. No extra extension cable was added during calibration. An Agilent model DSO6032A oscilloscope was used for data acquisition, with control and processing obtained using LabViewTM software (National Instruments, USA).

The hydrophone was immersed in the water tank at working depth at least one day before the start of measurements. Before immersing in the water, the sensitive element was cleaned with neutral soap solution. Independent repeated calibrations were made for each hydrophone with the devices removed from the water and remounted.

The reciprocity method requires the use of auxiliary transducers (designated P and T in the experiment). An ITC 1001 and an ITC 1032 were used as the two additional transducers in the calibration.

The environmental conditions are shown in Table 4.7.

Table 4.7 Conditions for calibrations by INMETRO

Hydrophone	Water temperature (°C)	Immersion depth (m)	Separation distances (m)
B&K8104	26 – 27	2.4	1.00

The calibration uncertainties were evaluated according to the JCGM/ISO/IEC Guide to the Expression of Uncertainty in Measurement [JCGM 100:2008] and the guidance on components provided in IEC 60565:2006. The spreadsheet provided along with the protocol was used as a guide in the calculation of the combined uncertainty.

The combined uncertainties expressed as standard uncertainties varied with frequency, ranging from a minimum of 2.1 % at mid kilohertz frequencies, to a maximum of 9.4 % at the lowest extremes of the frequency range (between 4.2 % and 18.8 % expressed as an expanded uncertainty for $k = 2$).

4.8 SUMMARY OF CALIBRATION CONDITIONS

Table 4.8 Summary of conditions for calibrations for B&K8104

Participant	Method	Temperature of water (°C)	Depth (m)	Separation (m)
NPL (GBR)	Reciprocity	18.0	2.5	1.46 – 1.53
TÜBİTAK – MAM (TUR)	Reciprocity	18.2	3.5	2.0
VNIIFTRI (RUS)	Reciprocity	17.5	2.88	0.64 – 0.76
USRD (USA)	Reciprocity	22.5 19.9	7.8 2.28	2.0 1.5 – 2.0
HAARI (CHN)	Reciprocity	17.4 18.5 – 19.2	5.0 5.0	1.0 0.5
NMISA (ZAF)	Reciprocity	17.7	1.53	1.0
INMETRO (BRA)	Reciprocity	26 – 27	2.4	1.0

Table 4.9 Summary of conditions for calibrations for TC4034

Participant	Method	Temperature of water (°C)	Depth (m)	Separation (m)
NPL (GBR)	Reciprocity	19.2	0.8	0.925 – 1.00
TÜBİTAK – MAM (TUR)	Reciprocity	18.6	3.5	1.6
VNIIFTRI (RUS)	Reciprocity	18.0	0.40	0.70 – 1.00
USRD (USA)	Reciprocity	19.9	2.28	1.00
HAARI (CHN)	Reciprocity	18.7 – 19.7	0.6	0.50
NMISA (ZAF)	Reciprocity	17.7	1.53	1.0

5 RESULTS OF PARTICIPANTS

5.1 B&K8104 HYDROPHONE

The results declared by the participants for the B&K8104 hydrophone in the frequency range 250 Hz to 100 kHz are shown in the plots below and tabulated in the following pages.

Where the participant's results cover a subset of the frequency range, this is because that participant did not calibrate the hydrophone at all frequencies. This is particularly true for the lowest frequencies below 1 kHz where only four participants submitted results.

The declared uncertainties at each frequency, expressed in percent as a standard uncertainty are presented in Section 6.

The results for the guest participant (NIOT) are shown separately in Annex B.

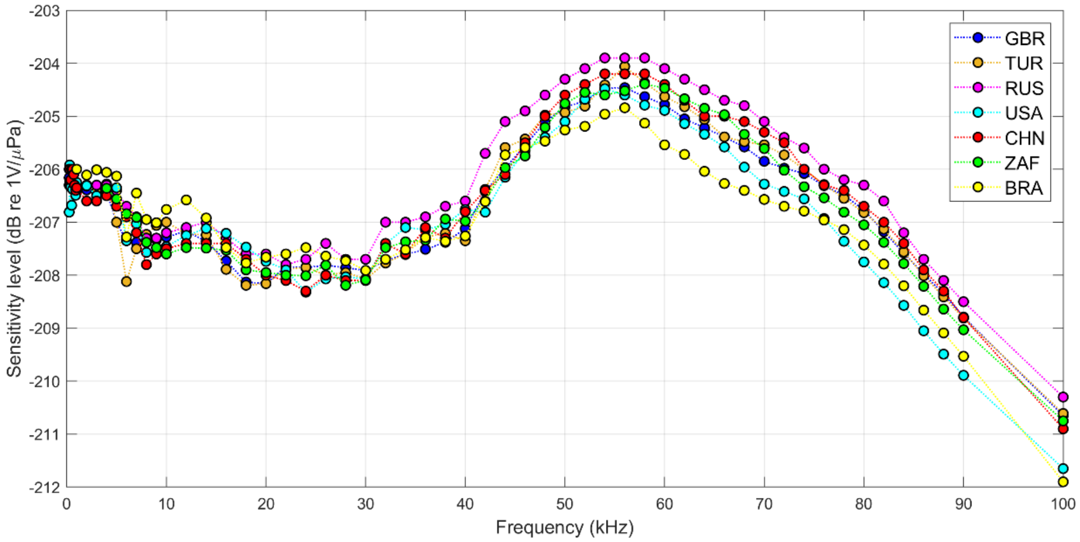


Figure 5.1 The reported sensitivity levels for the B&K8104 hydrophone from 250 Hz to 100 kHz.

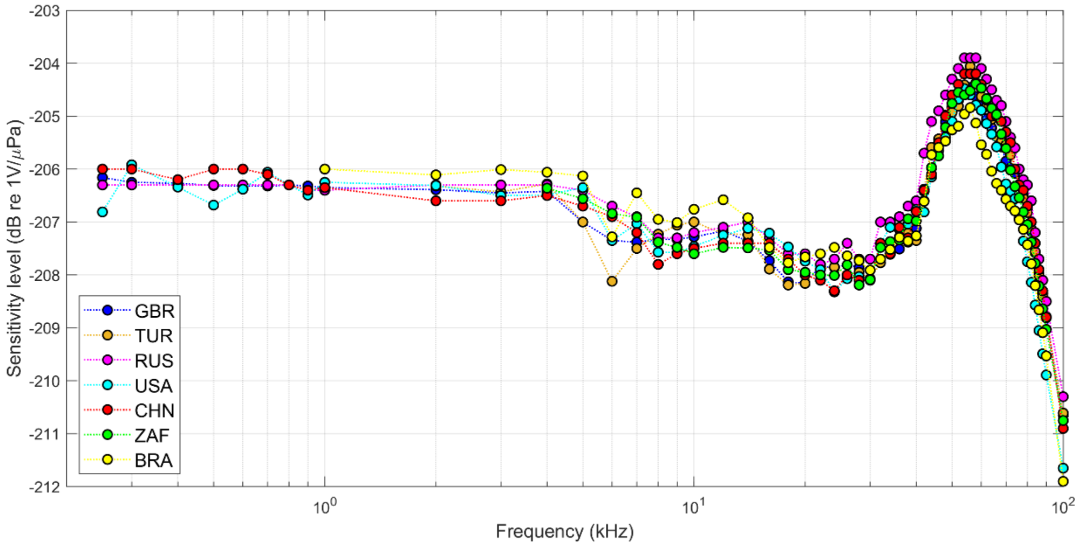


Figure 5.2 The reported sensitivity levels for the B&K8104 hydrophone from 250 Hz to 100 kHz (log frequency scale).

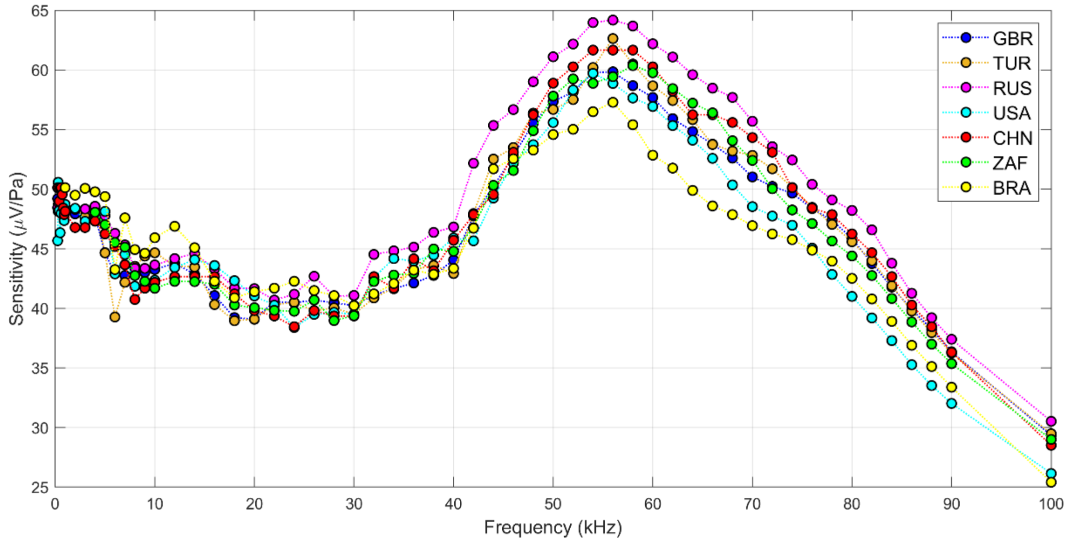


Figure 5.3 The reported linear sensitivities for the B&K8104 hydrophone from 250 Hz to 100 kHz.

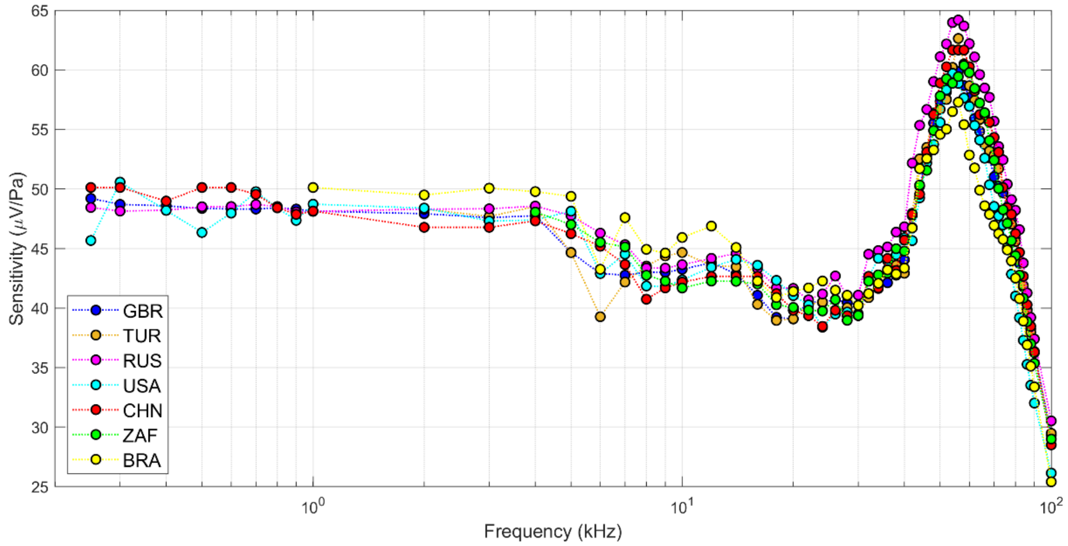


Figure 5.4 The reported linear sensitivities for the B&K8104 hydrophone from 250 Hz to 100 kHz (log frequency scale).

The results for each participant for the B&K8104 hydrophone are shown in Table 5.1.

The results are also presented in full along with equivalent sensitivity levels (in dB re 1 V/μPa) and uncertainties in Annex A.

Table 5.1 Tabulated results of participants for the B&K8104 hydrophone

Frequency (kHz)	Sensitivity (µV/Pa)						
	GBR NPL	TUR TÜBİTAK	RUS VNIIFTRI	USA USRD	CHN HAARI	ZAF NMISA	BRA INMETRO
0.25	49.20		48.44	45.67	50.12		
0.3	48.70		48.14	50.57	50.12		
0.4	48.58		48.21	48.20	48.98		
0.5	48.36		48.50	46.34	50.12		
0.6	48.31		48.52	47.97	50.12		
0.7	48.31		48.69	49.77	49.55		
0.8	48.42		48.52	48.41	48.42		
0.9	48.31		48.07	47.36	47.86		
1	48.14		48.11	48.72	48.14		50.12
2	47.92	48.31	48.30	48.39	46.77		49.49
3	47.59	47.69	48.33	47.30	46.77		50.06
4	47.75	48.52	48.56	47.39	47.32	48.06	49.77
5	44.67	44.65	47.76	48.13	46.24	47.01	49.37
6	42.90	39.27	46.29	42.89	45.19	45.52	43.25
7	42.76	42.18	45.32	44.52	43.65	45.13	47.59
8	43.00	43.52	43.36	41.85	40.74	42.75	44.93
9	43.00	44.38	43.35	41.79	41.69	42.26	44.62
10	43.25	44.66	43.64	42.36	42.17	41.68	45.92
12	43.80	43.57	44.17	43.42	42.66	42.26	46.88
14	42.85	43.46	44.58	44.08	42.66	42.24	45.08
16	41.07	40.31	43.31	43.59	42.66	42.02	42.27
18	39.22	38.96	41.69	42.32	41.21	40.27	40.88
20	39.08	39.09	41.65	41.04	39.81	40.05	41.40
22	40.55	40.31	40.69	40.26	39.36	39.83	41.69
24	40.46	40.50	41.18	38.39	38.46	39.75	42.27
26	40.69	39.79	42.69	39.49	39.81	40.70	41.50
28	40.46	40.04	41.01	39.66	39.36	38.97	41.07
30	40.23	39.51	41.08	39.50	39.36	39.38	40.23
32	41.11	40.87	44.52	42.60	42.66	42.25	41.21
34	41.64	41.74	44.82	44.17	41.69	42.79	42.07
36	42.12	43.24	45.13	43.97	44.16	42.93	43.20
38	42.76	43.60	46.37	44.46	43.15	44.98	42.85
40	44.06	42.92	46.82	45.90	45.71	44.78	43.35
42	47.75	47.95	52.17	45.66	47.86	46.76	46.72
44	50.23	52.52	55.34	49.25	49.55	50.32	51.70
46	52.78	53.49	56.67	52.18	53.09	51.56	52.54
48	55.53	56.37	59.01	53.73	56.23	54.90	53.27
50	57.35	56.68	61.10	55.58	58.88	57.80	54.58
52	58.14	57.51	62.17	58.32	60.26	59.24	55.02
54	59.77	60.20	63.97	59.71	61.66	58.87	56.49
56	59.84	62.63	64.18	58.86	61.66	59.43	57.28
58	58.68	60.49	63.68	57.64	61.66	60.36	55.40
60	57.68	58.66	62.19	56.93	60.26	59.76	52.84
62	55.91	57.43	61.08	55.33	58.21	58.43	51.76
64	54.83	55.83	59.60	54.10	56.23	57.21	49.89
66	53.77	53.74	58.47	52.58	56.23	56.40	48.58
68	52.60	53.19	57.69	50.35	55.59	54.06	47.86
70	51.02	52.83	55.69	48.53	54.33	52.41	46.94
72	50.23	51.70	53.56	47.74	53.09	50.03	46.24
74	49.66	50.13	52.44	46.97	50.12	48.25	45.76
76	48.36	48.47	50.40	45.05	48.42	47.11	44.87
78	47.37	47.04	49.10	42.84	47.86	45.65	43.95
80	45.87	45.58	48.21	41.00	46.24	44.39	42.51
82	43.75	43.99	46.58	39.19	44.67	42.75	40.78
84	41.78	41.89	43.78	37.29	42.66	40.82	38.90
86	39.90	39.77	41.26	35.27	40.27	38.86	36.90
88	38.24	37.96	39.21	33.52	38.46	36.99	35.12
90	36.35	36.25	37.40	32.02	36.31	35.36	33.38
100	29.34	29.48	30.52	26.14	28.51	29.00	25.41
110	22.70	22.88	24.26	20.68	22.65	22.94	
120	17.04	17.30	18.79	16.44	17.18	17.48	

5.2 TC4034 HYDROPHONE

The results declared by the participants for the TC4034 hydrophone in the frequency range 100 kHz to 500 kHz are shown in the plots below and in tables in the following pages.

The declared uncertainties at each frequency, expressed in percent as a standard uncertainty, are presented in Section 6.

The results for the guest participant (NIOT) are shown separately in Annex B.

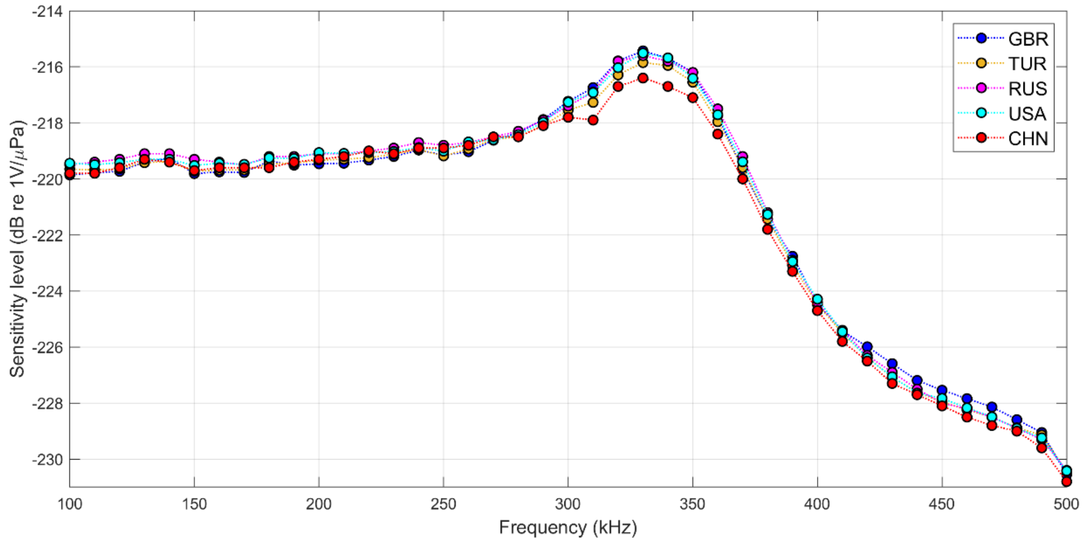


Figure 5.5 The sensitivity levels for the TC4034 hydrophone from 100 kHz to 500 kHz.

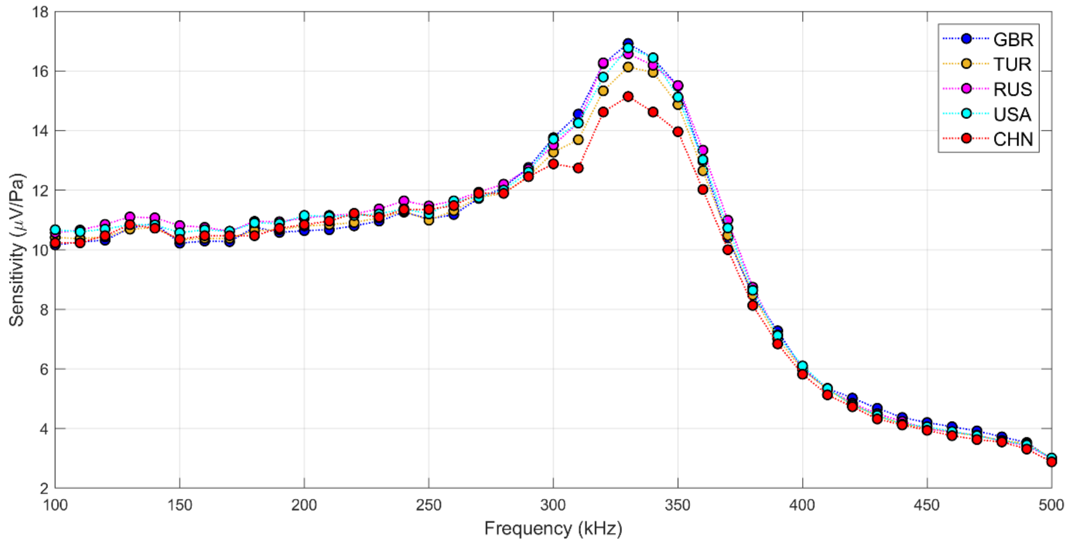


Figure 5.6 The linear sensitivities for the TC4034 hydrophone from 100 kHz to 500 kHz.

The results for each participant for the TC4034 hydrophone are shown in Table 5.2.

The results are also presented in full along with equivalent sensitivity levels (in dB re 1 V/μPa) and uncertainties in Annex A.

Table 5.2 Tabulated results of participants for the TC4034 hydrophone

Frequency (kHz)	Sensitivity (µV/Pa)				
	GBR NPL	TUR TÜBİTAK	RUS VNIIFTRI	USA USRD	CHN HAARI
100	10.16	10.41	10.57	10.67	10.23
110	10.26	10.37	10.66	10.60	10.23
120	10.32	10.43	10.85	10.69	10.47
130	10.72	10.69	11.10	10.84	10.84
140	10.89	10.74	11.07	10.83	10.72
150	10.22	10.33	10.81	10.57	10.35
160	10.29	10.38	10.75	10.67	10.47
170	10.27	10.38	10.62	10.62	10.47
180	10.76	10.64	10.95	10.90	10.47
190	10.58	10.67	10.94	10.88	10.72
200	10.64	10.80	11.06	11.15	10.84
210	10.67	10.84	11.15	11.11	10.96
220	10.80	10.91	11.20	11.15	11.22
230	10.96	11.07	11.37	11.20	11.09
240	11.26	11.29	11.64	11.37	11.35
250	11.03	10.99	11.47	11.20	11.35
260	11.18	11.31	11.64	11.64	11.48
270	11.72	11.76	11.93	11.75	11.89
280	12.09	11.89	12.20	12.00	11.89
290	12.76	12.46	12.70	12.61	12.45
300	13.76	13.27	13.51	13.71	12.88
310	14.55	13.69	14.26	14.25	12.74
320	16.24	15.33	16.27	15.79	14.62
330	16.92	16.13	16.57	16.77	15.14
340	16.42	15.95	16.19	16.44	14.62
350	15.49	14.87	15.51	15.12	13.96
360	12.97	12.65	13.34	13.02	12.02
370	10.40	10.48	10.99	10.73	10.00
380	8.48	8.48	8.74	8.64	8.13
390	7.28	7.01	7.14	7.12	6.84
400	6.00	5.97	6.05	6.10	5.82
410	5.35	5.31	5.35	5.34	5.13
420	5.02	4.80	4.85	4.79	4.73
430	4.68	4.43	4.50	4.44	4.32
440	4.37	4.16	4.24	4.15	4.12
450	4.20	4.00	3.99	4.06	3.94
460	4.06	3.87	3.88	3.90	3.76
470	3.92	3.76	3.78	3.76	3.63
480	3.72	3.60	3.58	3.59	3.55
490	3.53	3.49	3.42	3.45	3.31
500	2.97	3.01	3.01	3.01	2.88

6 UNCERTAINTIES

6.1 UNCERTAINTY CONTRIBUTIONS

For most participants, the list of uncertainty contributions provided in IEC 60565 was the basis of their uncertainty assessments. Most cited the JCGM Guide to the Expression of Uncertainty in Measurement (GUM) when describing the calculation of uncertainties, though some national guidance was also cited.

The pilot laboratory circulated a spreadsheet with an example uncertainty budget which was used by the majority of the participants as guidance. This is shown in Annex G.

The Type A contributions were derived from the standard deviation from at least four repeated calibrations with the hydrophone removed from the test tank and remounted between repeats.

Major Type B uncertainty contributions included:

- non-reciprocal behaviour by transducers;
- uncertainties in the measurement of the separation distance;
- lack of steady-state conditions, especially where bursts of sound waves are used (the resonance frequency and Q-factors of the transducers and the echo-free time influence this contribution);
- lack of free-field conditions (interference from acoustic reflections);
- lack of acoustic far-field conditions;
- misalignment, particularly at high frequencies;
- acoustic scattering from the hydrophone mount (or vibrations picked up and conducted by the mount);
- uncertainty in measurement of the receive voltage including uncertainty due to the measuring instrumentation (voltmeter, digitizers, etc.);
- uncertainty of the gains of any amplifiers, filters, and digitizers used;
- uncertainties in the measurement of the drive current or voltage;
- uncertainties due to the lack of linearity in the measurement system;
- uncertainty of any electrical signal attenuators used;
- electrical noise including RF pick-up;
- uncertainty of any electrical loading corrections made to account for loading by cables and amplifiers;
- bubbles or air clinging to transducers (minimized by adequate wetting and soaking of transducers).

6.2 UNCERTAINTIES DECLARED BY PARTICIPANTS

The standard uncertainties declared by the participants are shown in Tables 6.1 and 6.2 for the B&K8104 and TC4034 hydrophones respectively.

A few participants submitted uncertainties expressed in decibels. The values shown in percent are the average of the positive and negative uncertainties obtained after conversion from decibels. Where participants submitted uncertainties expressed as expanded uncertainties, these have been converted to standard uncertainties by dividing by the declared value of the coverage factor, k.

A template for the uncertainty budget for the free-field three-transducer reciprocity calibration method was provided to participants by the pilot laboratory. This is shown in Annex G. The full uncertainty budgets contain components which vary with frequency, requiring a large number to tables to present. They are not shown here but are available on request.

Table 6.1 The standard uncertainties for each participant for the B&K8104 hydrophone.

Frequency (kHz)	Uncertainties (%) [*k* =1]						
	GBR NPL	TUR TÜBİTAK	RUS VNIIFTRI	USA USRD	CHN HAARI	ZAF NMISA	BRA INMETRO
0.25	6.3		2.4	8.1	3.7		
0.3	5.0		2.4	8.1	3.7		
0.4	4.1		2.4	8.1	3.7		
0.5	3.1		2.4	6.1	3.7		
0.6	3.1		2.3	6.1	3.8		
0.7	2.9		2.3	6.1	3.7		
0.8	2.9		2.3	6.1	3.8		
0.9	2.6		2.3	6.1	3.8		
1	2.6		2.3	2.4	3.8		9.4
2	2.6	4.2	2.4	2.4	3.9		4.1
3	2.3	4.2	2.4	2.4	3.9		3.4
4	2.3	4.2	2.4	2.4	4.0	3.3	3.3
5	2.8	4.2	2.5	2.4	3.9	3.3	3.4
6	2.8	4.3	2.5	2.4	3.9	3.3	4.1
7	2.0	4.3	2.5	2.4	4.0	3.3	4.0
8	2.0	4.3	2.5	2.4	4.0	3.3	3.6
9	2.0	4.2	2.5	2.4	4.0	3.3	2.7
10	2.0	4.2	2.5	2.4	3.9	3.3	2.7
12	2.0	4.2	2.4	2.4	4.0	2.7	3.2
14	2.0	4.2	2.5	2.4	3.9	2.7	2.5
16	2.0	4.2	2.5	2.4	4.0	2.7	3.1
18	2.3	4.2	2.5	2.4	4.0	2.7	2.4
20	2.0	4.2	2.5	2.4	4.0	2.7	2.3
22	2.0	4.2	2.5	2.4	4.0	2.7	3.6
24	2.0	4.2	2.5	2.4	4.0	2.7	3.7
26	2.0	4.2	2.5	2.4	4.0	2.7	2.5
28	2.0	4.2	2.5	2.4	3.9	2.7	3.3
30	2.0	4.2	2.5	2.4	4.0	2.7	2.6
32	2.3	4.2	2.5	2.4	4.0	2.7	2.2
34	2.3	4.2	2.5	2.4	4.0	2.7	2.4
36	2.3	4.2	2.5	2.4	4.0	2.7	2.1
38	2.3	4.2	2.5	2.4	4.0	2.7	2.7
40	2.0	4.2	2.7	2.4	3.9	2.7	3.2
42	2.0	4.2	2.8	2.4	3.9	2.7	4.7
44	2.0	4.2	2.7	2.4	4.0	2.7	3.3
46	2.0	4.2	2.7	2.4	4.0	2.7	2.9
48	2.0	4.2	2.7	2.4	4.0	2.7	2.7
50	2.0	4.2	2.7	2.4	4.0	2.7	2.4
52	2.0	4.2	2.7	2.4	4.0	2.7	2.4
54	2.0	4.2	2.7	2.4	4.0	2.7	2.9
56	2.0	4.2	2.7	2.4	4.0	2.7	2.3
58	2.0	4.2	2.7	2.4	4.1	2.7	2.4
60	2.3	4.2	2.8	2.4	4.1	2.7	2.9
62	2.3	4.2	2.7	2.4	4.0	2.4	2.3
64	2.3	4.2	2.7	3.6	4.0	2.4	2.6
66	2.3	4.2	2.7	3.6	3.9	2.4	3.2
68	2.3	4.2	2.7	3.6	3.9	2.4	3.0
70	2.4	4.2	2.7	3.6	4.0	2.4	2.4
72	2.3	4.2	2.7	3.6	4.0	2.4	2.2
74	2.3	4.2	2.7	3.6	4.0	2.4	2.2
76	2.1	4.2	2.7	3.6	4.0	2.4	2.2
78	2.1	4.2	2.7	3.6	4.0	2.4	2.2
80	2.1	4.2	2.7	3.6	4.0	2.4	2.2
82	2.1	4.2	2.7	3.6	4.0	2.4	2.3
84	2.1	4.2	2.7	3.6	4.0	2.4	2.4
86	2.1	4.2	2.7	3.6	4.0	2.4	2.5
88	2.1	4.2	2.7	3.6	4.0	2.4	2.8
90	2.1	4.2	2.7	3.6	4.0	2.4	3.0
100	2.1	4.2	2.8	3.6	4.0	2.3	3.3
110	2.3	4.2	2.8	3.6	4.2	2.3	
120	2.3	4.2	2.8	3.6	4.3	2.3	

Table 6.2 The standard uncertainties for each participant for the TC4034 hydrophone.

Frequency (kHz)	Uncertainties (%) [*k* =1]				
	GBR NPL	TUR TÜBİTAK	RUS VNIIFTRI	USA USRD	CHN HAARI
100	2.1	2.9	2.9	3.6	5.1
110	2.1	2.9	2.9	3.6	5.1
120	2.1	2.9	3.0	3.6	5.1
130	2.1	2.9	2.9	3.6	5.1
140	2.1	3.0	2.9	3.6	5.1
150	2.1	3.0	2.9	3.6	5.1
160	2.1	3.0	2.9	3.6	5.1
170	2.1	3.0	2.9	3.6	5.1
180	2.1	2.9	2.9	3.6	5.1
190	2.1	2.9	2.9	3.6	5.1
200	2.1	3.0	2.9	3.6	5.1
210	2.1	3.0	2.9	3.6	5.1
220	2.1	3.0	2.9	3.6	5.1
230	2.1	3.0	2.9	3.6	5.1
240	2.1	3.0	2.9	3.6	5.1
250	2.1	3.0	2.9	3.6	5.1
260	2.1	3.0	2.9	3.6	5.1
270	2.1	3.0	2.9	3.6	5.1
280	2.1	3.0	2.9	3.6	5.1
290	2.1	3.0	2.9	3.6	5.1
300	2.9	3.0	2.9	3.6	5.1
310	3.0	3.0	3.0	3.6	5.1
320	3.0	3.0	2.9	3.6	5.1
330	3.0	3.0	3.0	3.6	5.1
340	3.0	3.0	3.0	3.6	5.1
350	3.0	3.0	2.9	3.6	5.1
360	3.0	3.0	2.9	3.6	5.1
370	3.0	3.0	2.9	3.6	5.1
380	3.0	3.0	2.9	3.6	5.1
390	3.0	3.0	2.9	3.6	5.1
400	3.0	3.0	2.9	3.6	5.1
410	3.5	3.0	2.9	3.6	5.1
420	3.5	3.0	2.9	3.6	5.1
430	3.5	3.0	2.9	3.6	5.1
440	3.5	3.0	3.0	3.6	5.1
450	3.5	3.0	2.9	3.6	5.1
460	3.5	3.0	3.0	3.6	5.1
470	3.5	3.0	3.0	3.6	5.1
480	3.5	3.0	2.9	3.6	5.1
490	3.5	3.0	3.0	3.6	5.1
500	3.5	3.0	3.0	3.6	5.1

7 HYDROPHONE STABILITY

7.1 CHECK CALIBRATIONS

To check the stability of the hydrophones, NPL undertook check calibrations at selected frequencies for each hydrophone in between the calibrations of the participants. The check calibrations were as follows:

B&K8104 hydrophone:

- free-field reciprocity method at 5 kHz and from 10 kHz to 120 kHz in 10 kHz steps (13 frequencies)
- pressure calibration by comparison in a closed coupler (using a reference microphone) at 250 Hz

TC4034 hydrophone:

- free-field reciprocity method from 100 kHz to 500 kHz in 50 kHz steps (9 frequencies)

The calibration at 250 Hz for the B&K8104 hydrophone was not a free-field calibration, but this was not considered important for the purposes of the check calibration (only the stability is being checked, but in any case, the free-field sensitivity should not be different to the pressure sensitivity at 250 Hz).

In addition, NPL undertook full free-field calibrations by the reciprocity method on three occasions: before the start of the comparison, after four further participants had performed calibrations, and finally after the last calibration by a participant. These three full calibrations are given the identifiers NPL1, NPL2 and NPL3.

Both of the above sets of data may be used to determine whether the hydrophone sensitivities are sufficiently stable. If the trends determined from the calibrations are close to zero (within uncertainties), the hydrophone may be considered to have no statistically significant drift. The full set of data for the check calibrations are presented in Annex D. A description is presented below of the method and the results of the analysis to determine the stability.

7.2 ESTIMATING TEMPORAL DRIFT

As stated, NPL undertook three calibrations of both hydrophones at all frequencies specified in the protocol for the comparison during the lifetime of the comparison. These measurements are denoted by “NPL1”, “NPL2” and “NPL3”, and NPL1 is the measurement submitted by NPL as its measurement result for the comparison. NPL also undertook check calibrations for both hydrophones at a subset of the frequencies specified in the protocol each time the hydrophone was returned to NPL.

7.2.1 Analysis of measurements NPL1, NPL2 and NPL3

The measurements NPL1, NPL2 and NPL3 were analysed in the following way. Let the measurement results be $(M_i, u(M_i)), i = 1,2,3,$ and suppose the squared standard uncertainty for each measured value decomposes as

$$u^2(M_i) = u_R^2(M_i) + u_S^2(M_i),$$

where $u_R(M_i)$ is the standard uncertainty associated with random effects, assumed to have a relative value of 1 %, and $u_S(M_i)$ is the standard uncertainty associated with systematic effects common to the three measurements. A straight-line fit to the measured values, of the form

$$M = \beta_0 + \beta_1(t - \tau_1),$$

where t is time in days and τ_i is the time of the ith measurement, is obtained by generalised least-squares [ISO28037]. Estimates of the parameters (β_0, β_1) in the straight-line model are obtained as the minimiser of

$$\boldsymbol{r}^{\mathrm{T}} V^{-1} \boldsymbol{r},$$

where

$$\boldsymbol{r} = \begin{bmatrix} M_1 \\ M_2 \\ M_3 \end{bmatrix} - \begin{bmatrix} 1 & 0 \\ 1 & (\tau_2 - \tau_1) \\ 1 & (\tau_3 - \tau_1) \end{bmatrix} \begin{bmatrix} \beta_0 \\ \beta_1 \end{bmatrix} \equiv \boldsymbol{M} - A\boldsymbol{\beta},$$

and V_M is the covariance matrix for the measured values given by

$$V_M = \begin{bmatrix} u_R^2(M_1) + u_S^2(M_1) & u_S(M_1)u_S(M_2) & u_S(M_1)u_S(M_3) \\ u_S(M_2)u_S(M_1) & u_R^2(M_2) + u_S^2(M_2) & u_S(M_2)u_S(M_3) \\ u_S(M_3)u_S(M_1) & u_S(M_3)u_S(M_2) & u_R^2(M_3) + u_S^2(M_3) \end{bmatrix}.$$

Formally, the solution can be expressed as

$$\hat{\boldsymbol{\beta}} = \left(A^{\mathrm{T}} V_M^{-1} A\right)^{-1} A^{\mathrm{T}} V_M^{-1} \boldsymbol{M},$$

with covariance matrix

$$V_\beta = \left(A^{\mathrm{T}} V_M^{-1} A\right)^{-1}.$$

7.2.2 Analysis of check calibrations

The check calibrations are analysed in the following way. A straight-line fit to the measured values is obtained by weighted least-squares with weights set equal to $1/s$ with $s = \sqrt{3} \times \sigma$. Here, s is the standard deviation of a t-distribution having three degrees of freedom and scale parameter σ given by the standard uncertainty of the mean of the measured values provided by four repeated measurements capturing information about random effects only. A chi-squared test is used to verify the consistency of the check calibration results with a straight-line model, and standard uncertainties associated with the estimates of the linear drift coefficients are evaluated in terms of the above standard deviations s.

7.3 CALCULATION OF CORRECTIONS FOR DRIFT

Figure 7.17.1 and Figure 7. show the results of the drift analysis applied to the full calibrations NPL1, NPL2 and NPL3, and applied also to the check calibrations. For the former, the estimates $\hat{\beta}_1$ of the linear drift coefficients β_1, corresponding to the slopes in the straight-line model fits, are shown as blue crosses in the figures, together with their uncertainty bars having semi-lengths $2u(\hat{\beta}_1)$. For the latter, the estimates of the linear drift coefficients are shown as red circles, together with uncertainty bars whose semi-lengths are equal to twice the standard uncertainties associated with those estimates.

The figures show that there is generally good agreement between the estimates of the linear drift coefficients provided by the two analyses (the blue and the red data points are in good agreement).

For both hydrophones there is evidence for temporal drift for some frequencies. For example, for the hydrophone TC4034 there is strong evidence for temporal drift in the neighbourhood of the resonance frequency of the hydrophone around 300 kHz. For the B&K8104 hydrophone, there is evidence of statistically significant drift around 10 kHz and around the resonance frequency.

Rather than select only the frequencies where the drift correction was statistically significant, the participants agreed that the drift corrections be applied at all frequencies, even where the correction is small and statistically insignificant. Consequently, drift corrections are applied to the measurement results for all participants and for both hydrophones. Note that although the drift corrections improve the agreement between participants, they do not in general affect the discrepant results (where results are discrepant, they remain so after correction).

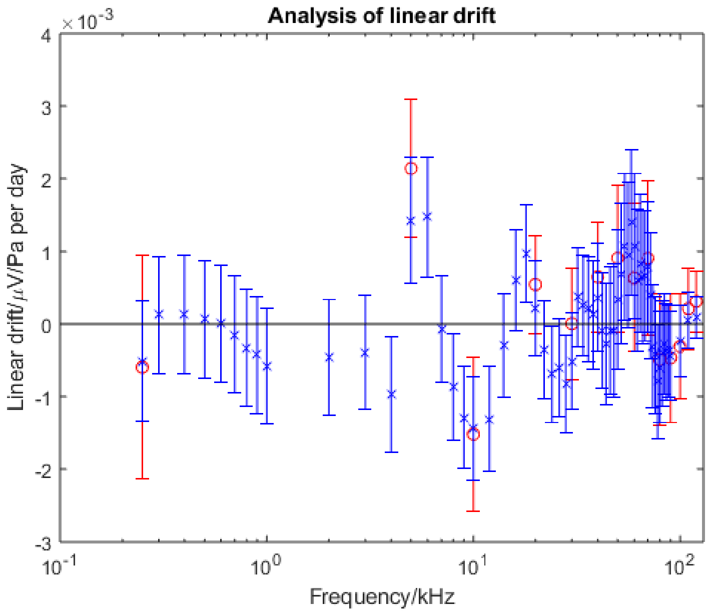


Figure 7.1 For the hydrophone B&K8104, estimates of linear drift (in µV/Pa per day) for different frequencies obtained from the measurements NPL1, NPL2 and NPL3 (in blue) and check calibrations (in red).

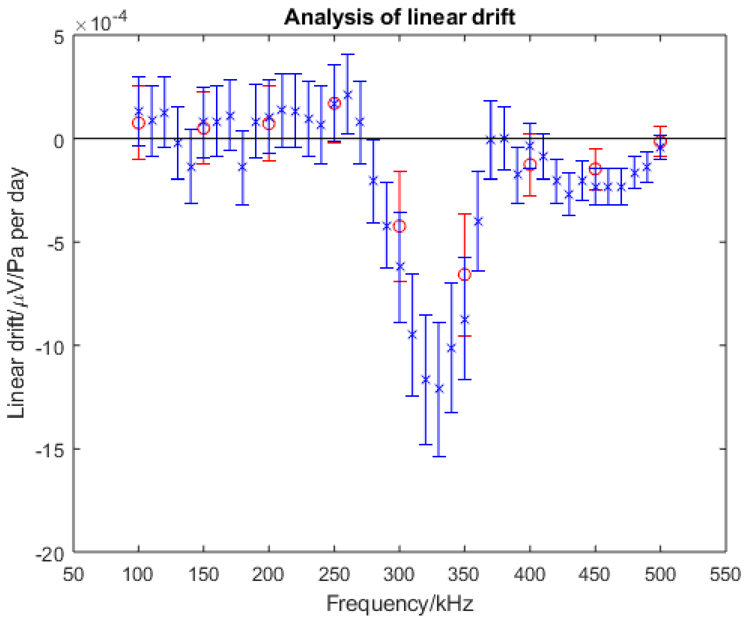


Figure 7.2 For the hydrophone TC4034, estimates of linear drift (in µV/Pa per day) for different frequencies obtained from the measurements NPL1, NPL2 and NPL3 (in blue) and check calibrations (in red).

7.3.1 Uncertainties on drift corrections

A complication in the analysis to apply corrections for linear drift to the measurement results provided by the participants is that this can only be done at each frequency based on the measurements NPL1, NPL2 and NPL3, and measurement NPL1 is the measurement submitted by NPL as its measurement result for the comparison. In consequence, the corrected measured values can be expected to be correlated through their dependence on the measurement NPL1.

For the ith participant, including NIOT, the formula for applying the correction for linear drift is

$$x_i' = x_i - \hat{\beta}_1(t_i - \tau_1), \quad i = 1, \dots, N+1,$$

where t_i is the time for the measurement made by the participant, with $t_1 = \tau_1$ for NPL1, and x_i and x_i' are the uncorrected and corrected measured values, respectively. In the case of INMETRO and NIOT, the value x_i is the temperature-corrected measured value and $u(x_i)$ is the corresponding standard uncertainty evaluated to account for the uncertainty associated with that correction (see Section 8.1.4). It follows that

$$x_i' = x_i - \boldsymbol{c}^{\mathrm{T}}\boldsymbol{M}(t_i - \tau_1),$$

where $\boldsymbol{c}^{\mathrm{T}}$ captures the dependence of $\hat{\beta}_1$ on the measured values M_1, M_2 and M_3 from the measurements NPL1, NPL2 and NPL3, and is given by the second row of the matrix $\left(A^{\mathrm{T}}V_M^{-1}A\right)^{-1}A^{\mathrm{T}}V_M^{-1}$ that is used to define formally the solution $\widehat{\boldsymbol{\beta}}$ to the generalised least-squares problem (see Section 7.2.1). Then,

$$x_i' = \begin{bmatrix} -\boldsymbol{c}^{\mathrm{T}}(t_i - \tau_1) & 1 \end{bmatrix} \begin{bmatrix} M_1 \\ M_2 \\ M_3 \\ x_i \end{bmatrix},$$

and extending to all $N + 1$ participants gives the measurement function

$$\begin{bmatrix} x_1' \\ x_2' \\ \vdots \\ x_{N+1}' \end{bmatrix} = \begin{bmatrix} (1,0,0) & 0 & \cdots & 0 \\ -\boldsymbol{c}^{\mathrm{T}}(t_2 - \tau_1) & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ -\boldsymbol{c}^{\mathrm{T}}(t_{N+1} - \tau_1) & 0 & \cdots & 1 \end{bmatrix} \begin{bmatrix} M_1 \\ M_2 \\ M_3 \\ x_2 \\ \vdots \\ x_{N+1} \end{bmatrix} \equiv C \begin{bmatrix} \boldsymbol{M} \\ x_2 \\ \vdots \\ x_{N+1} \end{bmatrix},$$

which uses the equivalence $x_1 \equiv M_1$. Finally, applying (the multivariate version of) the law of propagation of uncertainty [JCGM100, JCGM102] to this measurement function gives the covariance matrix V' for the corrected measured values as

$$V' = CVC^T,$$

where

$$V = \begin{bmatrix} V_M & \mathbf{0} & \cdots & \mathbf{0} \\ \mathbf{0} & u^2(x_2) & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{0} & 0 & \cdots & u^2(x_{N+1}) \end{bmatrix}.$$

The matrix V' contains on its diagonal the squares of the standard uncertainties $u^2(x_i')$ for the corrected measured values and in its off-diagonal elements the covariances $u(x_i', x_j')$ for those corrected values.

8 ANALYSIS OF KCRVS AND DOES

8.1 METHODOLOGY

8.1.1 General Approach

The basic approach for calculation of KCRVs and DOEs is described in the following sections. The results of the guest participant (NIOT) were not used in the calculation of the KCRVs, as required by the MRA guidance.

In the initial analysis for the B&K8104 hydrophone, where participants submitted results that were significantly outside the protocol requirements for water temperature, their results were excluded from the KCRV calculation. This applied only to INMETRO for the B&K8104 hydrophone. In order to incorporate the results of INMETRO into the calculation of the KCRVs, a correction was made to account for the temperature dependence of the sensitivity using measurements made by NPL at different temperatures. USRD also exceeded the water temperature requirements at very low frequencies to a minor extent (by 1.5 °C) but no correction was applied in this case because the deviation was small and no measurements were possible as a function of temperature at NPL at frequencies below 1 kHz.

For both the hydrophones, the KCRVs and DOEs were also calculated with and without a correction made for the temporal drift detected by the check calibrations and evaluated from analysis of the NPL1, NPL2 and NPL3 data, with the correction determined according to the procedure described in Section 7. Note that INMETRO did not calibrate the TC4034 hydrophone, and so there is no need to correct their TC4034 data for water temperature.

This means that for the B&K8104 hydrophone, three sets of KCRVs and DOEs were initially calculated and presented in the Draft A1 report: (i) with no corrections to the participants' data (and INMETRO excluded); (ii) with temperature-corrected data for INMETRO now included in the calculation; and (iii) with temperature-corrected data for INMETRO and temporal-drift corrections for all participants included in the calculation. After consultation with participants, option (iii) was adopted, and these were the results shown in the Draft B report approved by CCAUV, and now presented here in the Final Report for CCAUV.W-K2.

For the TC4034 hydrophone, two sets of KCRVs and DOEs were initially calculated: (i) with no corrections to the participants' data; and (ii) with temporal-drift corrections for all participants included in the calculation. After consultation with participants, option (ii) was adopted, and these are the results shown in this Final Report.

For the guest participant, NIOT, although the results cannot be included in the KCRV calculation, it is possible to calculate DOEs. Before the calculation, the NIOT data for both hydrophones were corrected to account for water temperature and temporal drift. The results of NIOT and the DOEs are given in Annex B.

8.1.2 Calculation of KCRVs and DOEs

In the following description, we consider the analysis of the measurement results provided by the participants in the Key Comparison (KC) for an individual hydrophone and a given frequency. The analysis is repeated for each hydrophone and for each frequency to obtain

- a Key Comparison Reference Value (KCRV) y with its associated uncertainty $u(y)$, and
- (unilateral) degrees of equivalence (DOEs) for all the participants. The DOE for each participant comprises a value component d equal to the difference between the measured value reported by the participant and the KCRV and an uncertainty component $U(d)$ equal to twice the standard uncertainty associated with that difference.

Let N denote the number of participants, excluding NIOT, and $(x_i, u(x_i))$ the measurement result reported by the ith participant comprising a measured value x_i and associated standard uncertainty $u(x_i)$, both given in units of μV/Pa. The measurement result $(x_{N+1}, u(x_{N+1}))$ provided by NIOT is not included in the analysis to determine the KCRV, but a DOE is to be evaluated for NIOT.

We start by undertaking an analysis of the provided measurement results based on using a weighted mean for the KCRV. That weighted mean is evaluated in terms of the measurement results associated with the largest subset of the N participants whose results are consistent, in a defined statistical sense, with the weighted mean.

We then discuss adapting that analysis

- to include a temperature correction for the measurement results provided by INMETRO (for the B&K8104 hydrophone) and NIOT (for both hydrophones) to account for the fact that INMETRO and NIOT made their measurements at temperatures different from those specified in the KC protocol, and
- to include a correction for all the measurement results to account for possible temporal drift in the responses of the hydrophones.

In both cases, measurements made by NPL at, respectively, different temperatures and different times are used to understand and quantify the extent of the dependencies of the responses of the hydrophones on temperature and time.

8.1.3 Analysis based on using a weighted mean for the KCRV

The paper [Cox2002] describes general procedures for the evaluation of KC data. Under the assumption that the participants are measuring the same quantity, the weighted mean of the measured values provided by the participants is used for the KCRV y, i.e.,

$$y = \sum_{i=1}^{N} w_i x_i, \quad w_i = \frac{\frac{1}{u^2(x_i)}}{\sum_{j=1}^{N} 1/u^2(x_j)},$$

with associated standard uncertainty $u(y)$ evaluated from

$$u^2(y) = \frac{1}{\sum_{j=1}^{N} 1/u^2(x_j)}.$$

A statistical test of the consistency of the measurement results, such as a chi-squared test, can be used to test the assumptions underpinning the use of the weighted mean. If the test passes, the assumptions are accepted on the basis of the available data. The idea behind the chi-squared test is to compare a measure of the observed dispersion of the measured values against a predicted dispersion. The comparison involves an aggregate measure of dispersion expressed as a sum of squares of individual weighted deviations, viz.,

$$\chi^2_{\text{obs}} = \sum_{i=1}^{N} \frac{(x_i - y)^2}{u^2(x_i)}.$$

Provided χ^2_{obs} is not bigger than expected, the measurement results are considered to be consistent, and the assumption is accepted. If the probability distributions for the measured quantities are known, it is possible in principle to determine the distribution for the random variable R^2 for which χ^2_{obs} is a realisation. Then, the probability can be calculated that χ^2_{obs} exceeds any particular quantile of the distribution, the latter used as an indication of predicted dispersion. For example, in the case that the quantities are independent, and their distributions are Gaussian, which are the usual assumptions made, the probability distribution for R^2 is the chi-squared distribution χ^2_ν with $\nu = N - 1$ degrees of freedom. Accordingly, the test of consistency fails if $\chi^2_{\text{obs}} > \chi^2_{\text{test}}$, where χ^2_{test} is chosen to satisfy $\text{Prob}[R^2 > \chi^2_{\text{test}}] = \alpha$ with, typically, $\alpha = 0.05$.

There are various approaches that can be used to address the situation when the test fails, for example, based on excluding measurement results considered discrepant or adjusting the uncertainties reported by the participants. The paper [Cox 2007] describes a method for determining the largest consistent subset (LCS) of measurement results from N participants, concentrating on presenting an efficient numerical solution approach that does not depend on full enumeration to consider all possible subsets. The method is based on determining the weighted mean and uses a chi-squared test for assessing consistency of that mean with the data as above. Specifically, in the published method, obtaining the LCS involves determining the best subsets (in the sense of having the smallest chi-squared value) comprising $2, \ldots, N$ measurement results from the original N. The determination of these $N-1$ best subsets is purely algebraic and numerical, requiring no statistical test. Each of these $N-1$ candidate solutions is assessed for consistency with its weighted mean using a chi-squared test to select the solution corresponding to the largest number of participants. The subsets of successive sizes $N, N-1, \ldots, 2$ participants are determined, the process being interrupted as soon as a chi-squared test with $\alpha = 0.05$ is satisfied.

Having determined the LCS comprising the participants with indices P (a subset of $\{1,2, \ldots, N\}$) and evaluated the KCRV y and its standard uncertainty $u(y)$ in terms of the LCS, the DOEs $\left(d_i, U(d_i)\right), i = 1,2, \ldots, N$, are evaluated from

$$d_i = x_i - y, \quad U(d_i) = 2\sqrt{u^2(x_i) - u^2(y)}, \quad i \in P,$$

and

$$d_i = x_i - y, \quad U(d_i) = 2\sqrt{u^2(x_i) + u^2(y)}, \quad i \notin P.$$

Finally, for NIOT, which is not used in the analysis to determine the KCRV, the DOE is evaluated from

$$d_{N+1} = x_{N+1} - y, \quad U(d_{N+1}) = 2\sqrt{u^2(x_{N+1}) + u^2(y)}.$$

8.1.4 Accounting for temperature dependence

The participants INMETRO (who calibrated only the device B&K8104) and NIOT (who calibrated both devices) provided measurement results at temperatures outside the interval specified in the protocol for the comparison. INMETRO was initially excluded from the analysis to evaluate KCRVs for this reason. Furthermore, the DOEs for both participants can be expected to be adversely affected. NPL undertook measurements at the reference temperature of 20 °C (within the range specified in the protocol) and at the temperatures of 27 °C and 30 °C at which, respectively, INMETRO and NIOT made their measurements. The measurements were undertaken using the NPL Acoustic pressure Vessel where the water temperature can be controlled within the desired range. The measurements are described in more detail in Annex C. The results of these calibrations are shown in Figure 8.1 and Figure 8.2. The differences obtained were used to derived corrections to apply to the measured data at higher water temperatures.

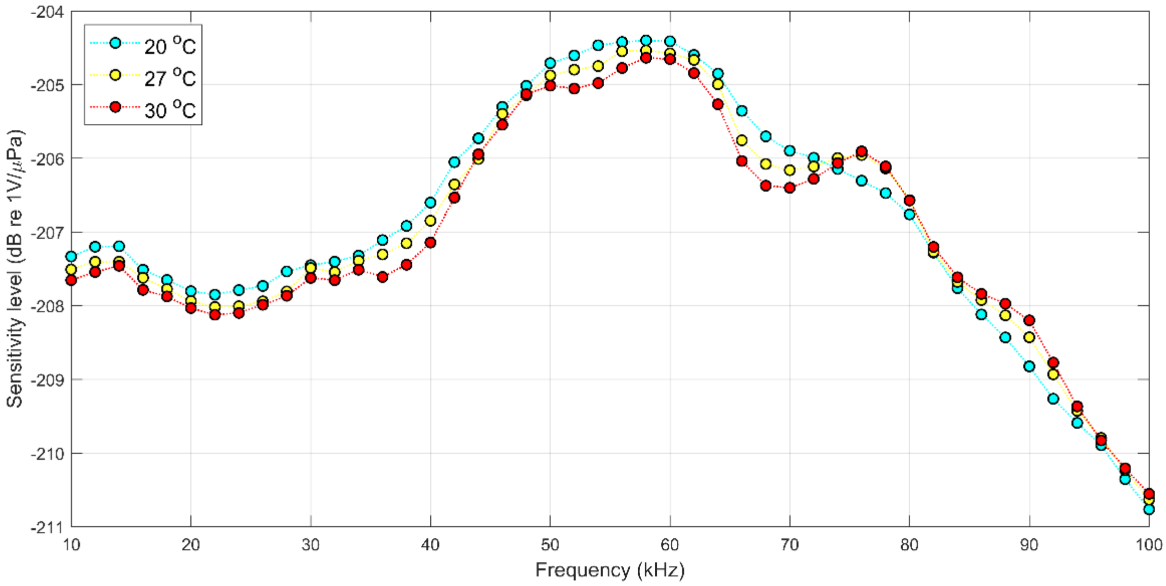


Figure 8.1 For the B&K8104 hydrophone, results of the NPL calibrations using the NPL Acoustic Pressure Vessel at water temperatures of 20 °C, 27 °C and 30 °C.

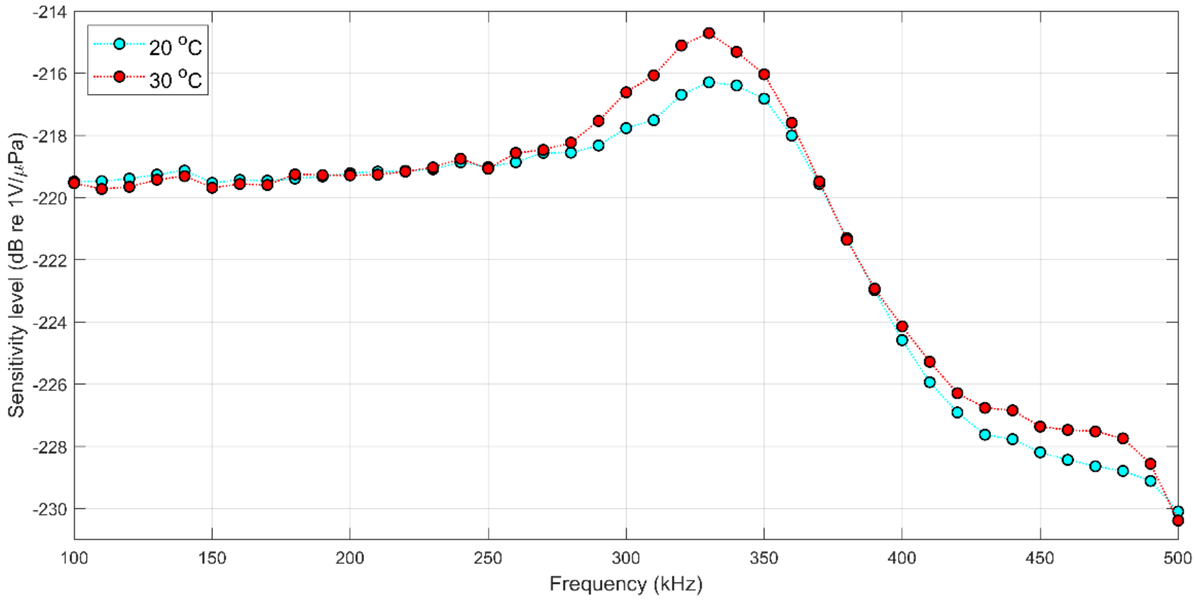


Figure 8.2 For the TC4034 hydrophone, results of the NPL calibrations using the NPL Acoustic Pressure Vessel at water temperatures of 20 °C and 30 °C.

For the B&K8104 hydrophone, there is a negative change in sensitivity with temperature observed at frequencies below resonance (the manufacturer declares a temperature variation of up to −0.04 dB/°C for the B&K8104 hydrophone). However, at frequencies above the resonance the behaviour is more complex with additional fluctuations observed at higher temperatures. The measured results for the TC4034 hydrophone show little change at frequencies below resonance, but a significant positive increase in sensitivity with temperature around resonance (280 – 360 kHz) and in the range 400 – 480 kHz. No data is available from the manufacturer for this hydrophone.

To include INMETRO in the analysis to determine KCRVs for the hydrophone B&K8104 hydrophone, and to evaluate DOEs for both INMETRO and NIOT, it is necessary to apply temperature corrections to their measurement results.

From the NPL measurements at 20 °C, 27 °C and 30 °C, corrections to the measurement results provided by INMETRO and NIOT were made in the following way.

Let x_T denote the (uncorrected) measured value obtained at temperature T, and M_T and M_{20} the measured values obtained by NPL at, respectively, the temperatures T and 20 °C. Then, the (corrected) value x_{20} corresponding to a temperature of 20 °C is given by

$$x_{20} = x_T \frac{M_{20}}{M_T}.$$

Furthermore, the standard uncertainty associated with the (corrected) value x_{20} is obtained from

$$u^2(x_{20}) = c_{x_T}^2 u^2(x_T) + c_{M_{20}}^2 u^2(M_{20}) + c_{M_T}^2 u^2(M_T),$$

where $u(M_{20})$ and $u(M_T)$ are the standard uncertainties associated with random effects in the measurements, respectively, of M_{20} and M_T, and the sensitivity coefficients are given by

$$c_{x_T} = \frac{M_{20}}{M_T},$$

$$c_{M_{20}} = x_T \frac{1}{M_T},$$

and

$$c_{M_T} = -x_T \frac{M_{20}}{M_T^2}.$$

The analysis described in Section 7 can be applied with the measurement results for INMETRO and NIOT replaced by their corrected versions.

8.1.5 Analysis accounting for both temperature and temporal corrections

In practice, the measured values $x_i', i = 1, \dots, N+1$, accounting for both temperature corrections (in the case of INMETRO and NIOT) and drift corrections (for all participants), are not strongly correlated. The maximum correlation coefficient across both hydrophones and all frequencies is found numerically to be 0.36. Consequently, the approach taken to evaluate KCRVs and DOEs follows that described in Sections 8.1.2 and 8.1.3 using the corrected measured values x_i' and the standard uncertainties $u(x_i')$ for those corrected values but *neglecting* their covariances $u(x_i', x_j')$. The results presented in this report are generated using that approach.

However, the robustness of the approach to the assumption that the covariances may be neglected has been tested. Specifically, for the LCS determined in the manner described in Section 8.1.3, the KCRV and its standard uncertainty have been evaluated also considering the full covariance matrix V' for the corrected measured values. Here, the determination of the KCRV and its standard uncertainty involves evaluating a generalised-weighted mean of the corrected measured values (as the solution to another generalised least-squares problem). Figure 8.3 and Figure 8.4 compare graphically the KCRVs and their uncertainties determined in the two ways and show that the influence of the covariances are minimal and can be safely ignored.

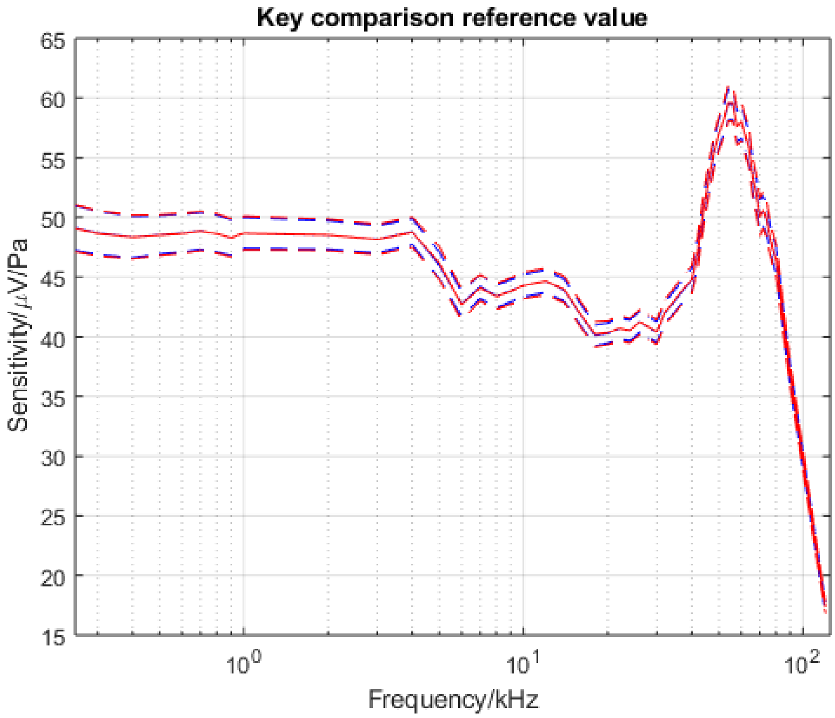


Figure 8.3 For the hydrophone B&K8104, KCRVs evaluated neglecting the correlations between corrected values (in blue) and considering those correlations (in red).

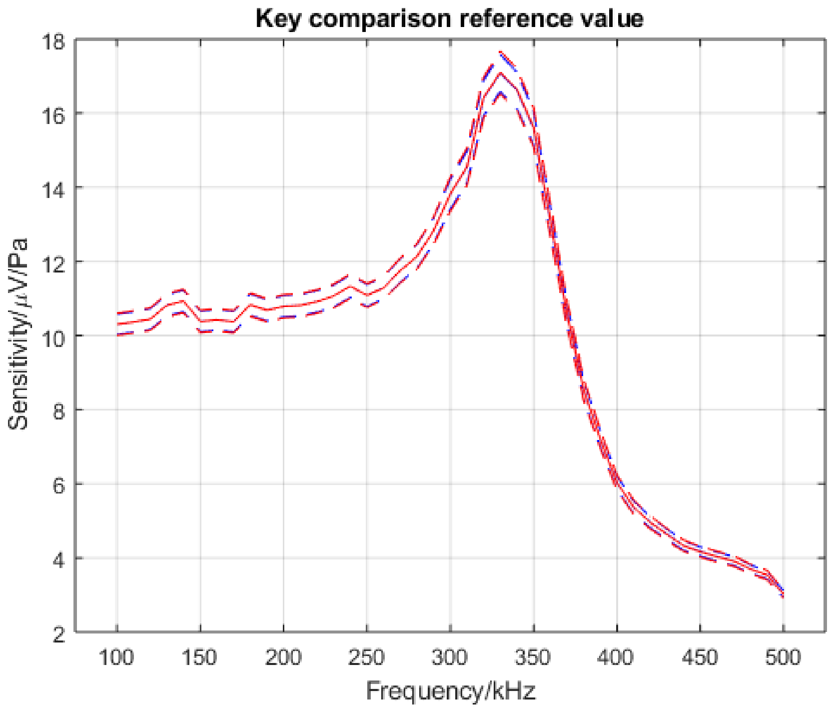


Figure 8.4 For the hydrophoneTC4034, KCRVs evaluated neglecting the correlations between corrected values (in blue) and considering those correlations (in red).

8.2 KEY COMPARISON REFERENCE VALUES

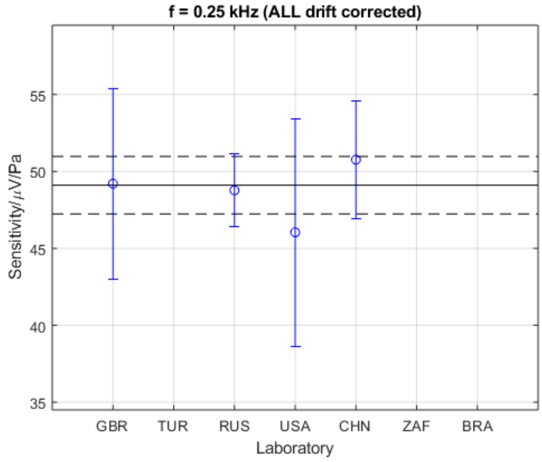
The figures in this section show the KCRVs at each frequency for the two hydrophones (expressed in µV/Pa), and the results for each participant showing the expanded uncertainty for that participant's results (error bars) and the expanded uncertainty for the KCRV (dotted line).

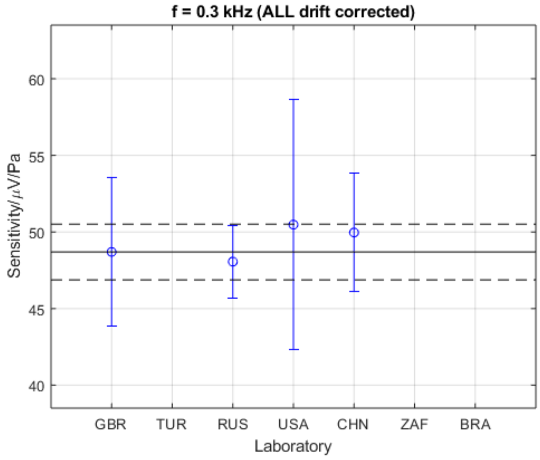
For the B&K8104 hydrophone at frequencies from 250 Hz to 120 kHz, the KCRVs are shown for each frequency choosing option (iii) outlined in Section 8.1.1, with temperature-corrected data for INMETRO and temporal-drift corrections for all participants included in the calculation. For the TC4034 hydrophone, the KCRVs and DOEs have been calculated using option (ii) described in Section 8.1.1, with temporal-drift corrections for all participants included in the calculation (no temperature corrections).

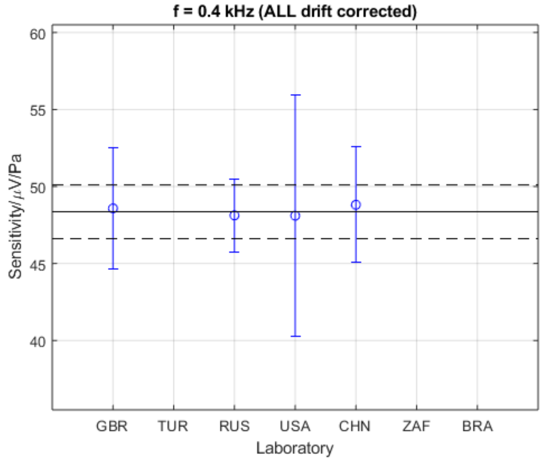
Note that the results of the guest participant (NIOT) are shown separately in Annex B.

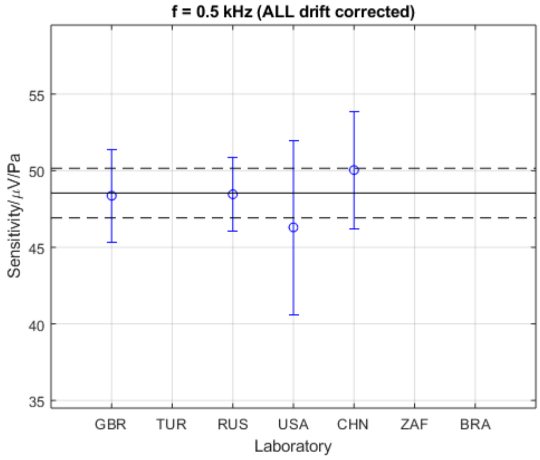
8.2.1 B&K8104 hydrophone: 250 Hz to 120 kHz

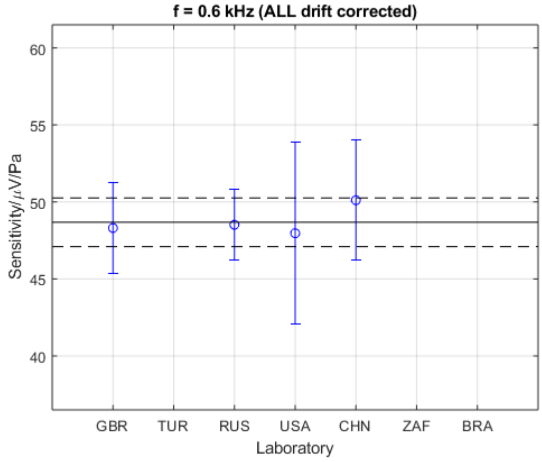
Figure 8.5 The KCRVs for each frequency for the B&K8104 hydrophone based on calculations including temperature-corrected INMETRO data and incorporating a temporal-drift correction to all the data.

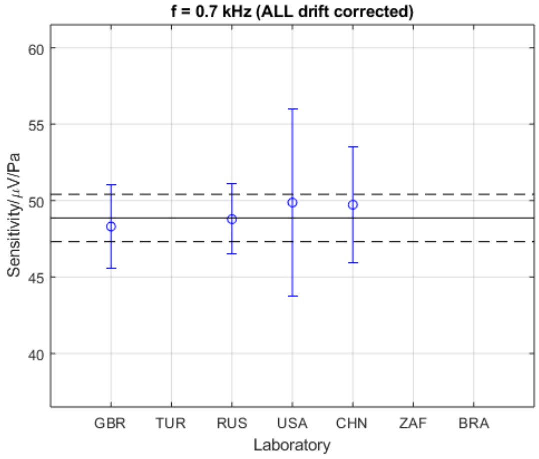

f = 0.25 kHz (ALL drift corrected)
Sensitivity/μV/Pa
35
40
45
50
55
GBR TUR RUS USA CHN ZAF BRA
Laboratory

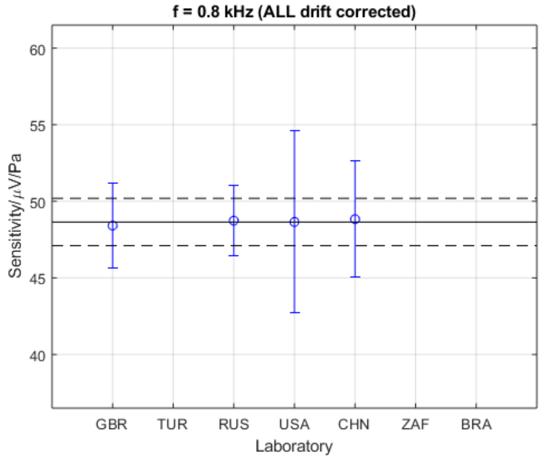

f = 0.3 kHz (ALL drift corrected)
Sensitivity/μV/Pa
40
45
50
55
60
GBR TUR RUS USA CHN ZAF BRA
Laboratory

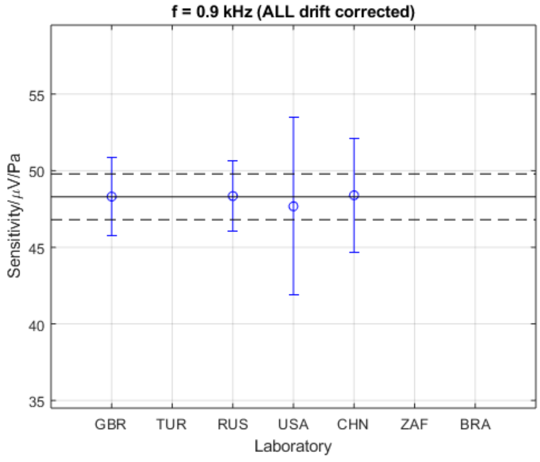

f = 0.4 kHz (ALL drift corrected)
Sensitivity/μV/Pa
40
45
50
55
60
GBR TUR RUS USA CHN ZAF BRA
Laboratory

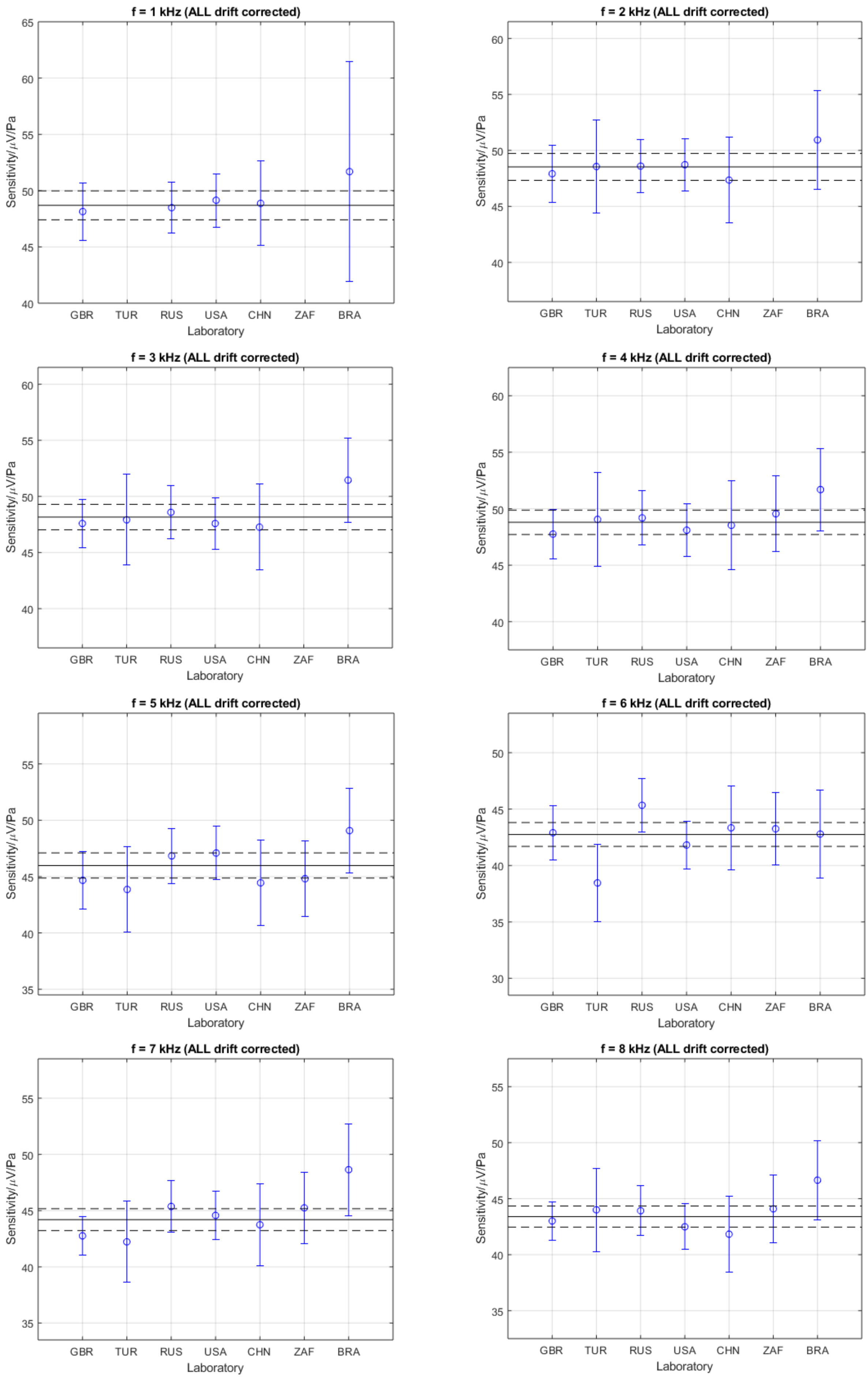

f = 0.5 kHz (ALL drift corrected)
Sensitivity/μV/Pa
35
40
45
50
55
GBR TUR RUS USA CHN ZAF BRA
Laboratory

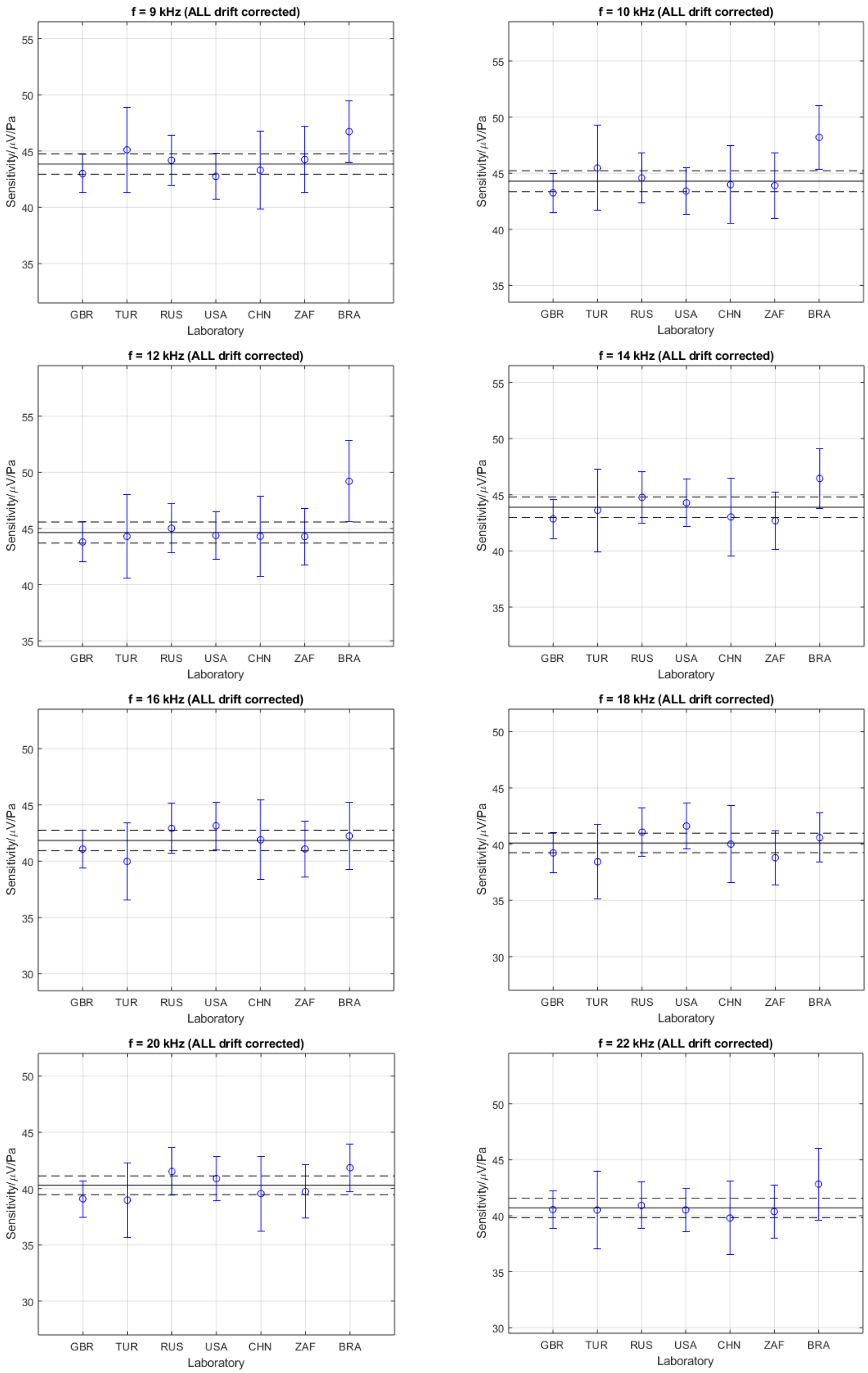

f = 0.6 kHz (ALL drift corrected)
Sensitivity/μV/Pa
40
45
50
55
60
GBR TUR RUS USA CHN ZAF BRA
Laboratory

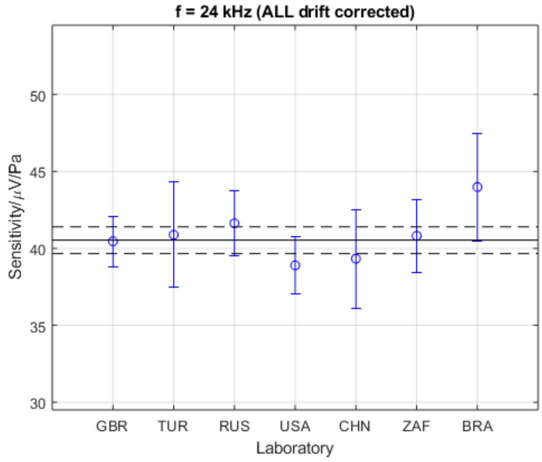

f = 0.7 kHz (ALL drift corrected)
Sensitivity/μV/Pa
40
45
50
55
60
GBR TUR RUS USA CHN ZAF BRA
Laboratory

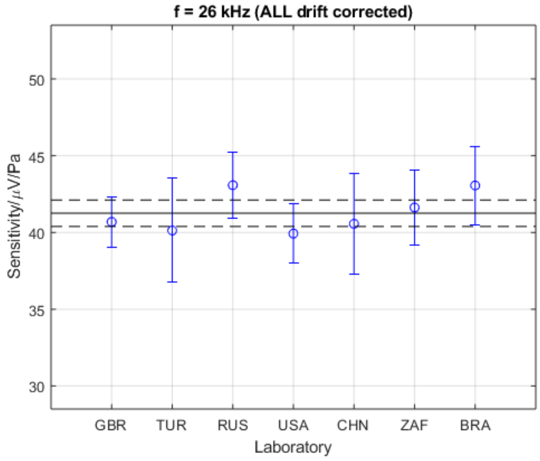

f = 0.8 kHz (ALL drift corrected)
Sensitivity/μV/Pa
40
45
50
55
60
GBR TUR RUS USA CHN ZAF BRA
Laboratory

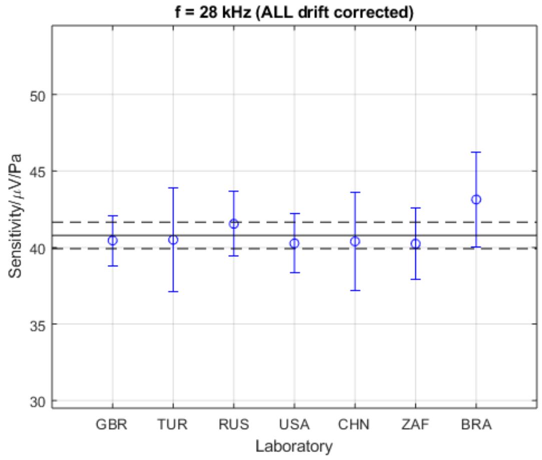

f = 0.9 kHz (ALL drift corrected)
Sensitivity/μV/Pa
35
40
45
50
55
GBR TUR RUS USA CHN ZAF BRA
Laboratory

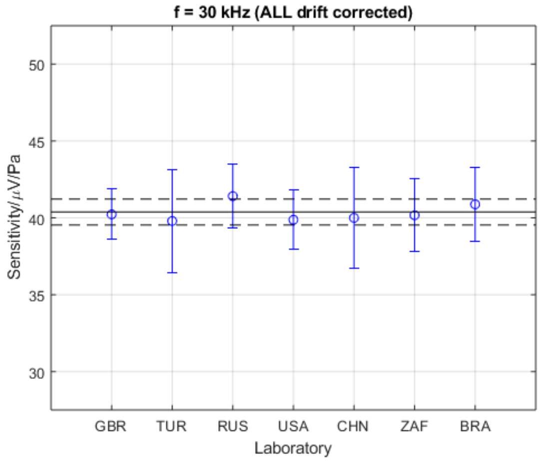

f = 1 kHz (ALL drift corrected)
Sensitivity/μV/Pa
65
60
55
50
45
40
GBR TUR RUS USA CHN ZAF BRA
Laboratory
f = 2 kHz (ALL drift corrected)
Sensitivity/μV/Pa
60
55
50
45
40
GBR TUR RUS USA CHN ZAF BRA
Laboratory
f = 3 kHz (ALL drift corrected)
Sensitivity/μV/Pa
60
55
50
45
40
GBR TUR RUS USA CHN ZAF BRA
Laboratory
f = 4 kHz (ALL drift corrected)
Sensitivity/μV/Pa
60
55
50
45
40
GBR TUR RUS USA CHN ZAF BRA
Laboratory
f = 5 kHz (ALL drift corrected)
Sensitivity/μV/Pa
55
50
45
40
35
GBR TUR RUS USA CHN ZAF BRA
Laboratory
f = 6 kHz (ALL drift corrected)
Sensitivity/μV/Pa
50
45
40
35
30
GBR TUR RUS USA CHN ZAF BRA
Laboratory
f = 7 kHz (ALL drift corrected)
Sensitivity/μV/Pa
55
50
45
40
35
GBR TUR RUS USA CHN ZAF BRA
Laboratory
f = 8 kHz (ALL drift corrected)
Sensitivity/μV/Pa
55
50
45
40
35
GBR TUR RUS USA CHN ZAF BRA
Laboratory

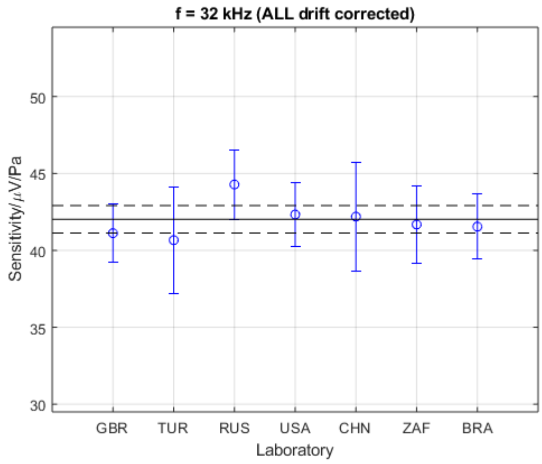

f = 9 kHz (ALL drift corrected)
f = 10 kHz (ALL drift corrected)
f = 12 kHz (ALL drift corrected)
f = 14 kHz (ALL drift corrected)
f = 16 kHz (ALL drift corrected)
f = 18 kHz (ALL drift corrected)
f = 20 kHz (ALL drift corrected)
f = 22 kHz (ALL drift corrected)
Sensitivity/μV/Pa
GBR TUR RUS USA CHN ZAF BRA
Laboratory

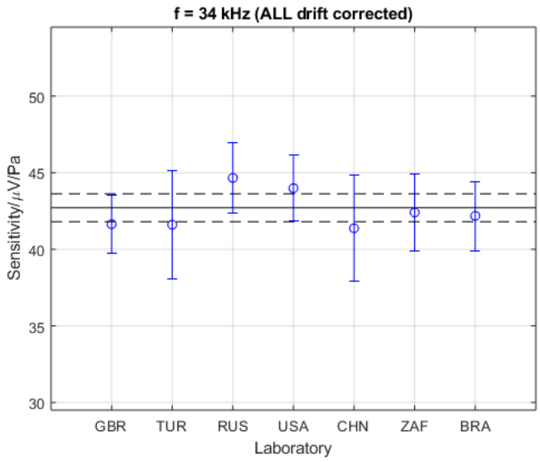

f = 24 kHz (ALL drift corrected)
Sensitivity/μV/Pa
30
35
40
45
50
GBR TUR RUS USA CHN ZAF BRA
Laboratory

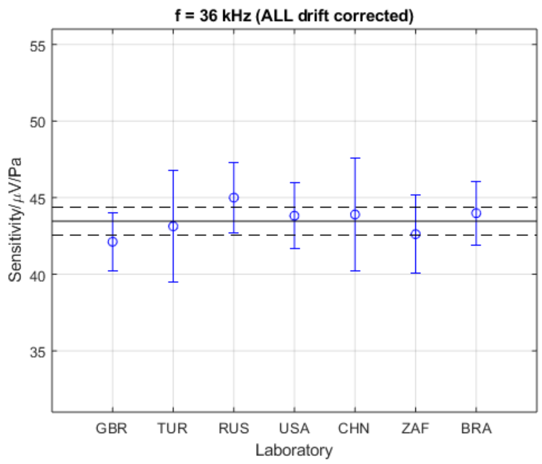

f = 26 kHz (ALL drift corrected)
Sensitivity/μV/Pa
30
35
40
45
50
GBR TUR RUS USA CHN ZAF BRA
Laboratory

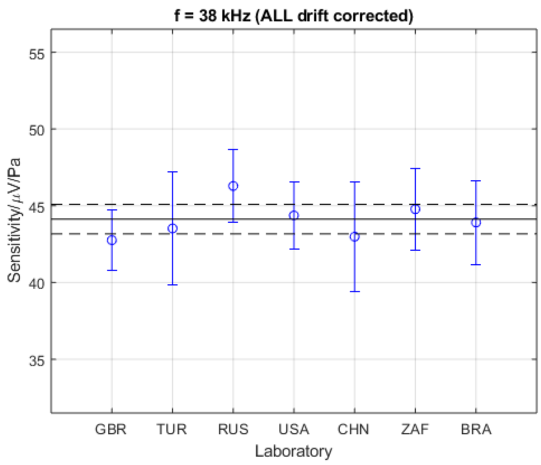

f = 28 kHz (ALL drift corrected)
Sensitivity/μV/Pa
30
35
40
45
50
GBR TUR RUS USA CHN ZAF BRA
Laboratory

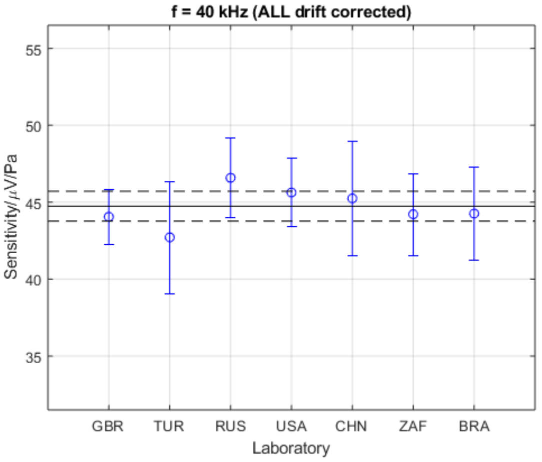

f = 30 kHz (ALL drift corrected)
Sensitivity/μV/Pa
30
35
40
45
50
GBR TUR RUS USA CHN ZAF BRA
Laboratory

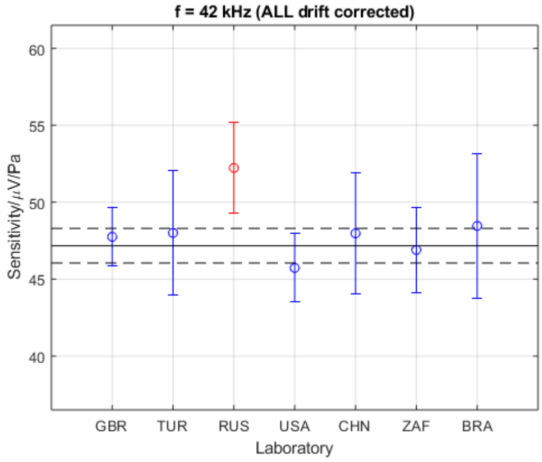

f = 32 kHz (ALL drift corrected)
Sensitivity/μV/Pa
30
35
40
45
50
GBR TUR RUS USA CHN ZAF BRA
Laboratory

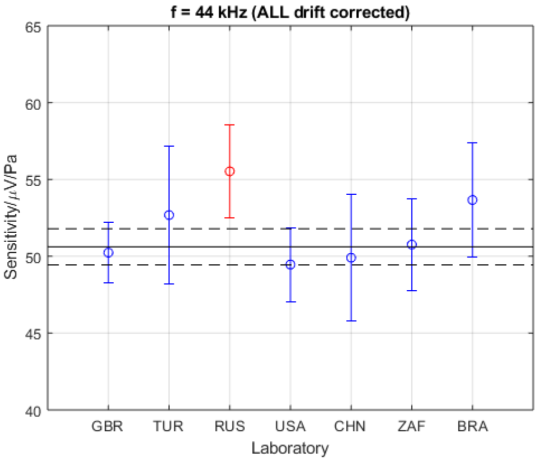

f = 34 kHz (ALL drift corrected)
Sensitivity/μV/Pa
30
35
40
45
50
GBR TUR RUS USA CHN ZAF BRA
Laboratory

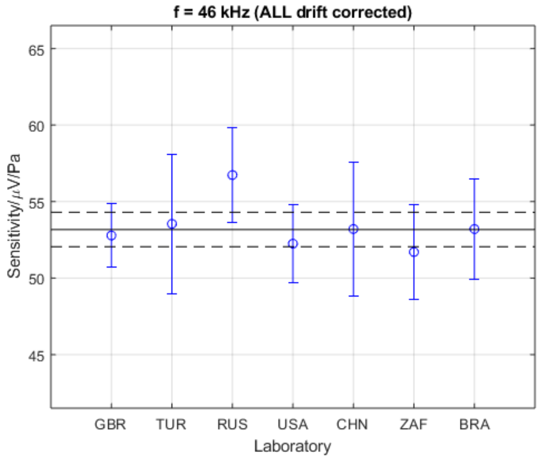

f = 36 kHz (ALL drift corrected)
Sensitivity/μV/Pa
35
40
45
50
55
GBR TUR RUS USA CHN ZAF BRA
Laboratory

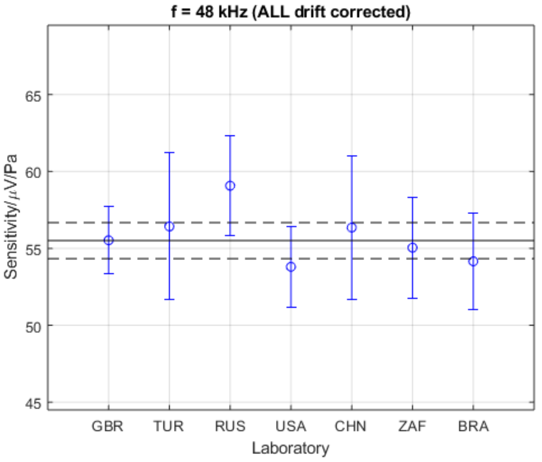

f = 38 kHz (ALL drift corrected)
Sensitivity/μV/Pa
35
40
45
50
55
GBR TUR RUS USA CHN ZAF BRA
Laboratory

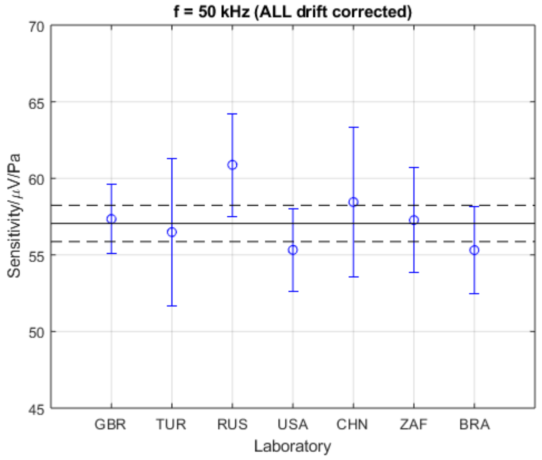

f = 40 kHz (ALL drift corrected)
Sensitivity/µV/Pa
55
50
45
40
35
GBR TUR RUS USA CHN ZAF BRA
Laboratory

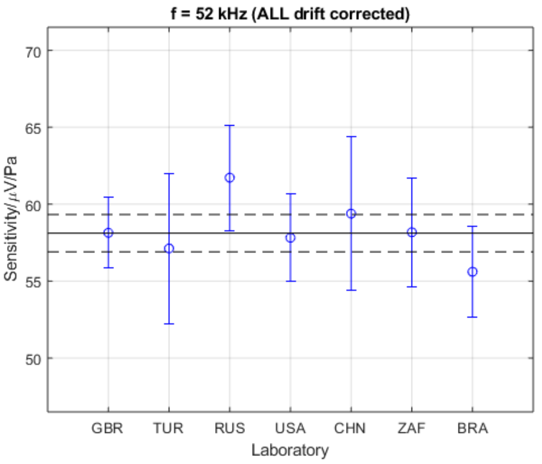

f = 42 kHz (ALL drift corrected)
Sensitivity/µV/Pa
60
55
50
45
40
GBR TUR RUS USA CHN ZAF BRA
Laboratory

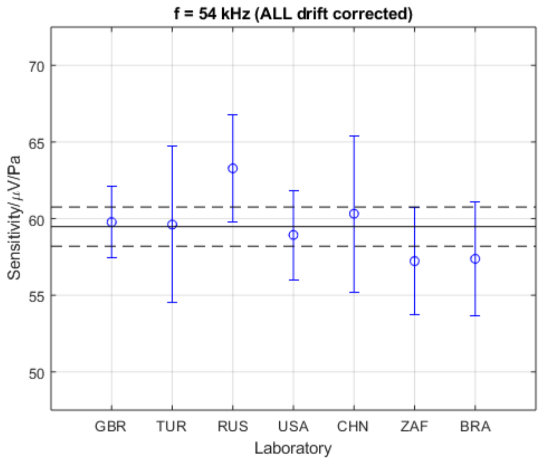

f = 44 kHz (ALL drift corrected)
Sensitivity/µV/Pa
65
60
55
50
45
40
GBR TUR RUS USA CHN ZAF BRA
Laboratory

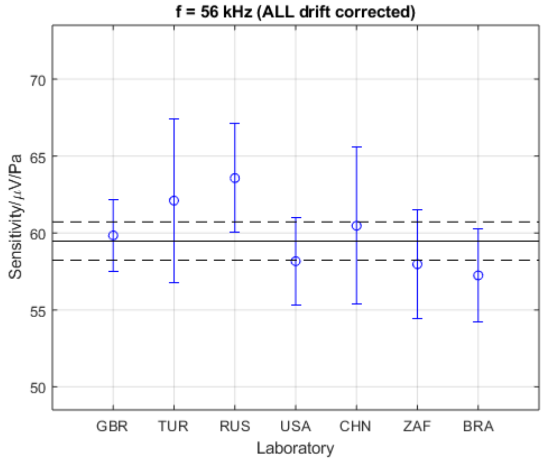

f = 46 kHz (ALL drift corrected)
Sensitivity/µV/Pa
65
60
55
50
45
GBR TUR RUS USA CHN ZAF BRA
Laboratory

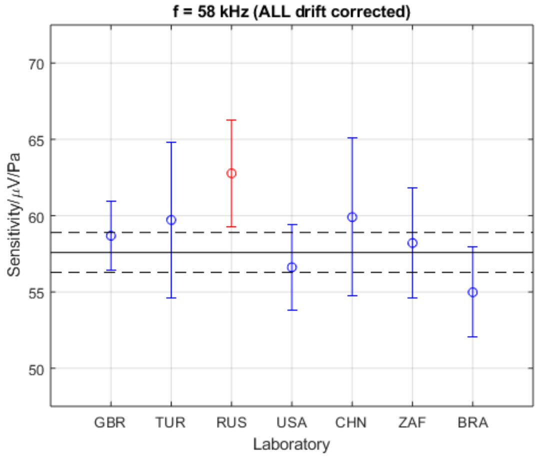

f = 48 kHz (ALL drift corrected)
Sensitivity/µV/Pa
65
60
55
50
45
GBR TUR RUS USA CHN ZAF BRA
Laboratory

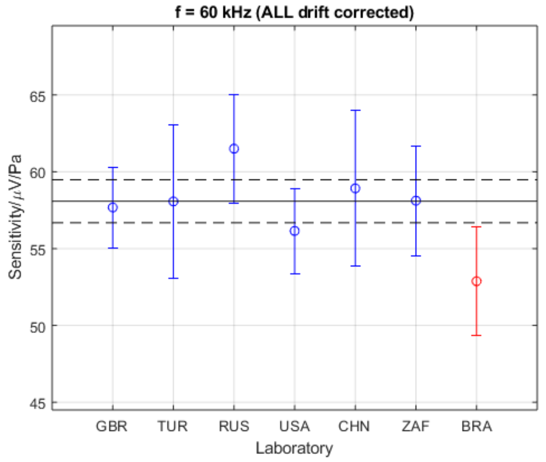

f = 50 kHz (ALL drift corrected)
Sensitivity/µV/Pa
70
65
60
55
50
45
GBR TUR RUS USA CHN ZAF BRA
Laboratory

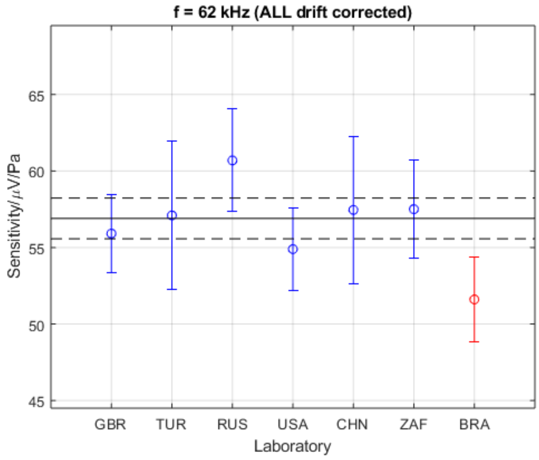

f = 52 kHz (ALL drift corrected)
Sensitivity/µV/Pa
70
65
60
55
50
GBR TUR RUS USA CHN ZAF BRA
Laboratory

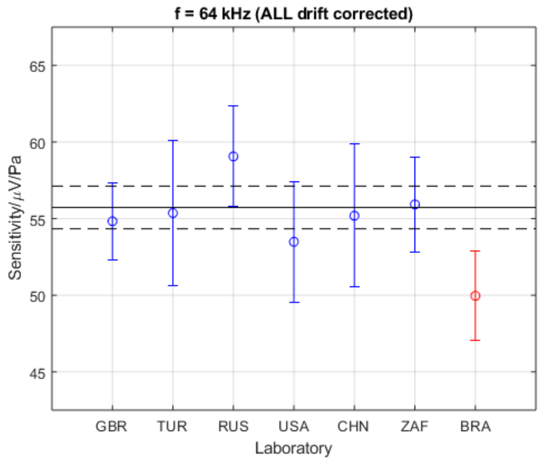

f = 54 kHz (ALL drift corrected)
Sensitivity/µV/Pa
70
65
60
55
50
GBR TUR RUS USA CHN ZAF BRA
Laboratory

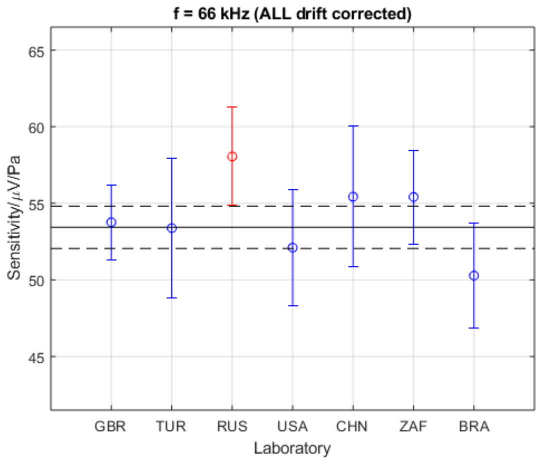

f = 56 kHz (ALL drift corrected)
Sensitivity/μV/Pa
50
55
60
65
70
GBR TUR RUS USA CHN ZAF BRA
Laboratory

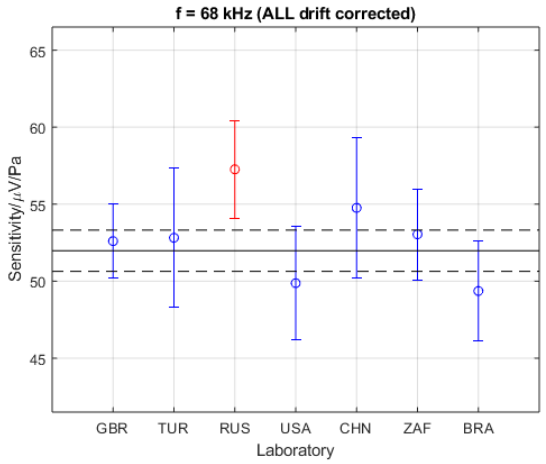

f = 58 kHz (ALL drift corrected)
Sensitivity/μV/Pa
50
55
60
65
70
GBR TUR RUS USA CHN ZAF BRA
Laboratory

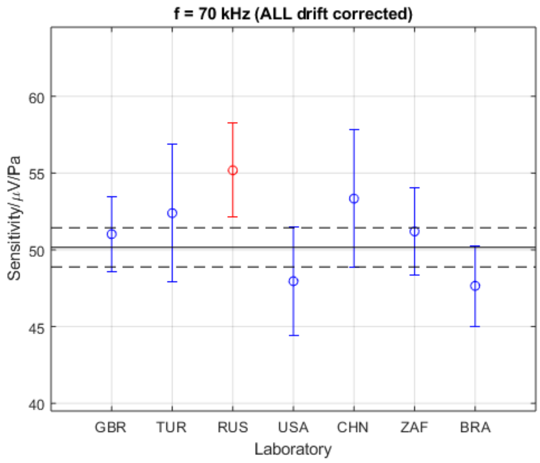

f = 60 kHz (ALL drift corrected)
Sensitivity/μV/Pa
45
50
55
60
65
GBR TUR RUS USA CHN ZAF BRA
Laboratory

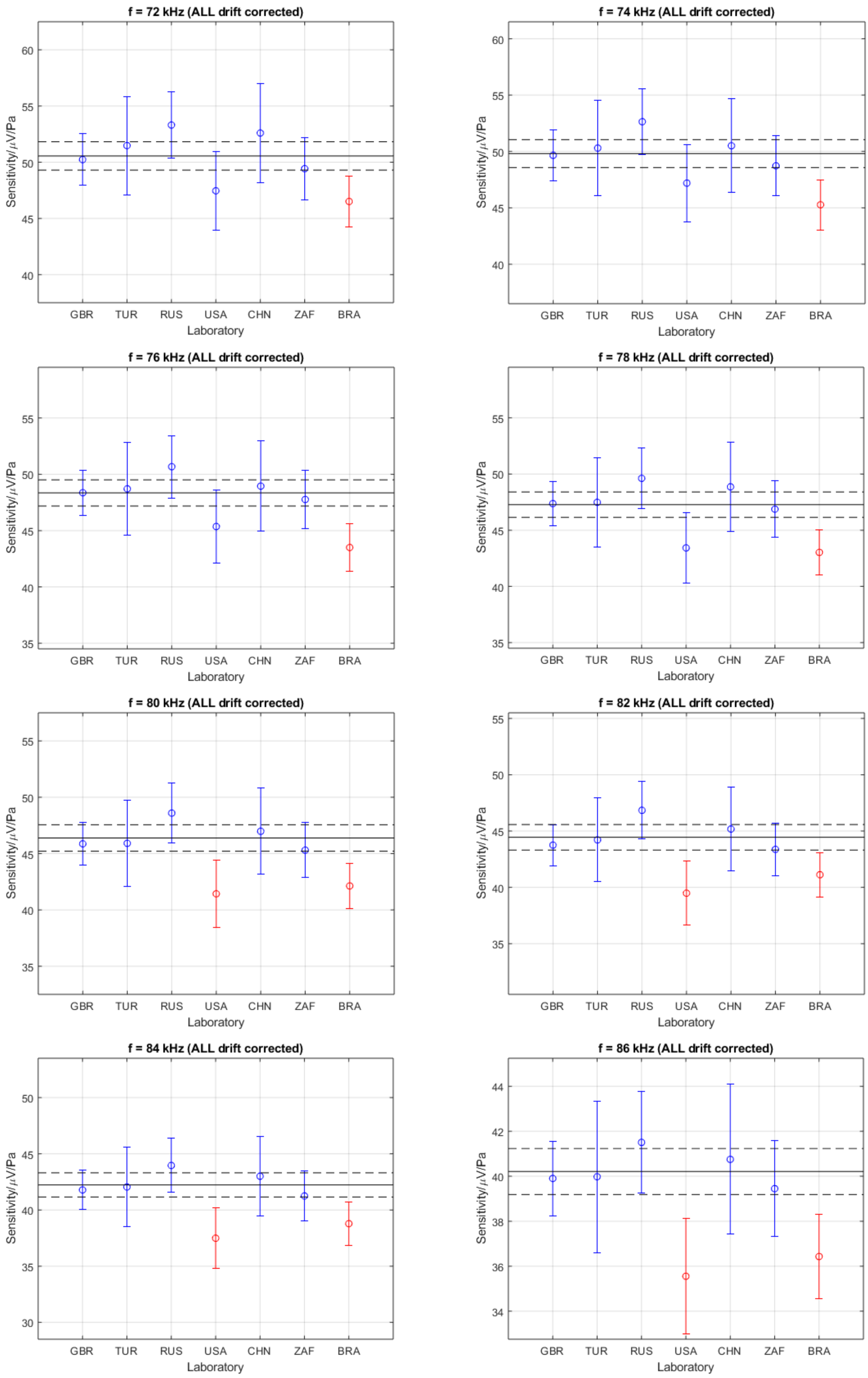

f = 62 kHz (ALL drift corrected)
Sensitivity/μV/Pa
45
50
55
60
65
GBR TUR RUS USA CHN ZAF BRA
Laboratory

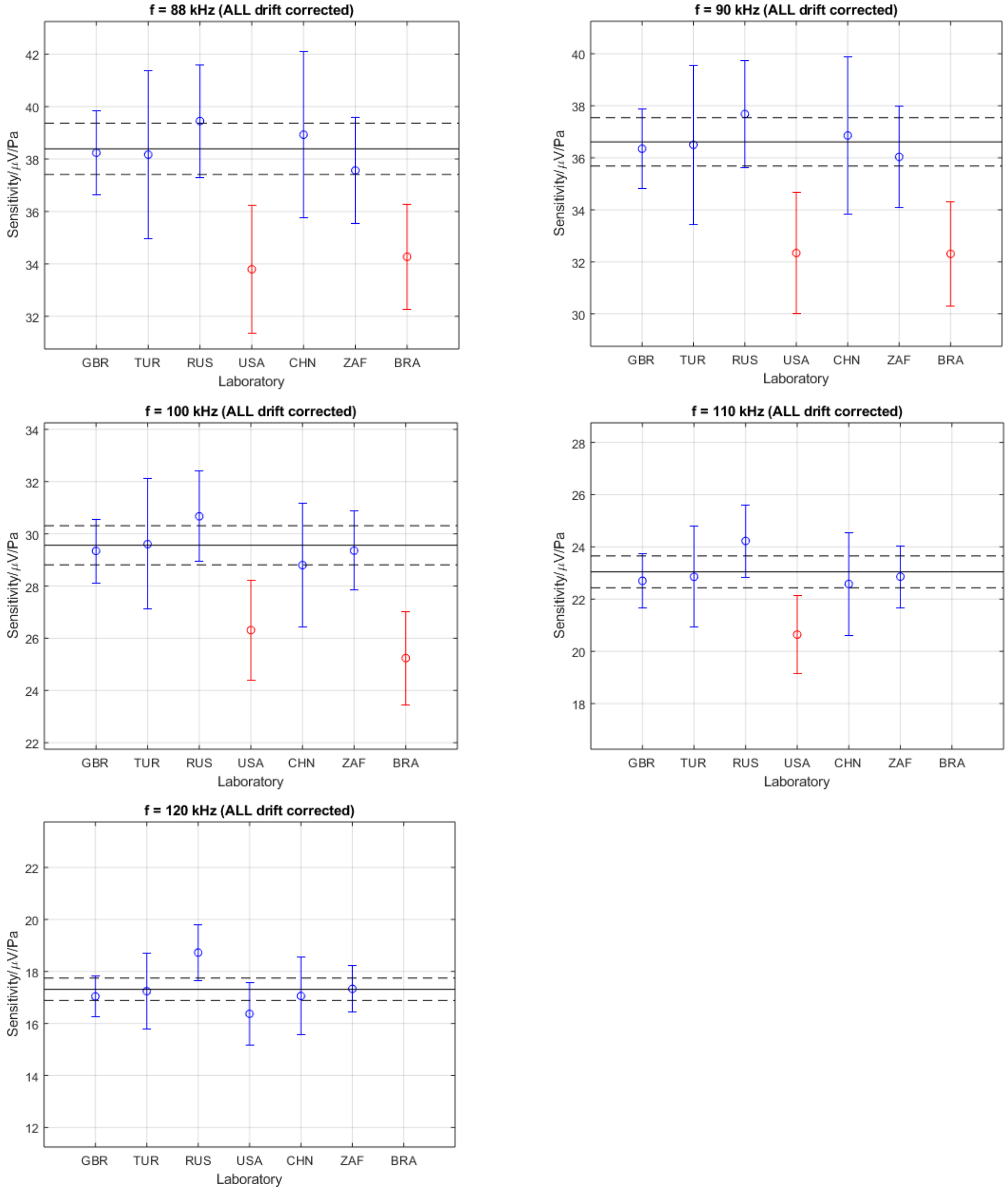

f = 64 kHz (ALL drift corrected)
Sensitivity/μV/Pa
45
50
55
60
65
GBR TUR RUS USA CHN ZAF BRA
Laboratory


f = 66 kHz (ALL drift corrected)
Sensitivity/μV/Pa
45
50
55
60
65
GBR TUR RUS USA CHN ZAF BRA
Laboratory


f = 68 kHz (ALL drift corrected)
Sensitivity/μV/Pa
45
50
55
60
65
GBR TUR RUS USA CHN ZAF BRA
Laboratory

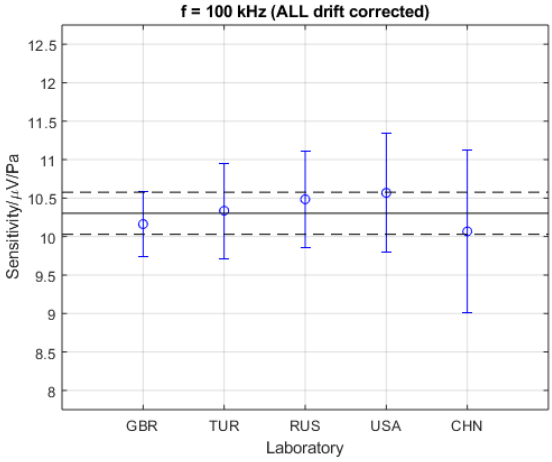

f = 70 kHz (ALL drift corrected)
Sensitivity/μV/Pa
40
45
50
55
60
GBR TUR RUS USA CHN ZAF BRA
Laboratory

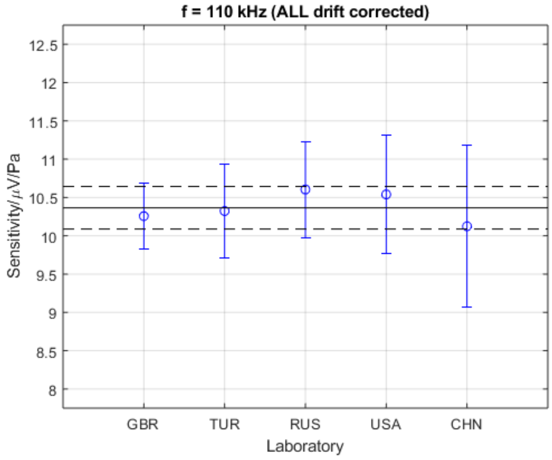

f = 72 kHz (ALL drift corrected)
f = 74 kHz (ALL drift corrected)
f = 76 kHz (ALL drift corrected)
f = 78 kHz (ALL drift corrected)
f = 80 kHz (ALL drift corrected)
f = 82 kHz (ALL drift corrected)
f = 84 kHz (ALL drift corrected)
f = 86 kHz (ALL drift corrected)
Sensitivity/μV/Pa
Laboratory
GBR
TUR
RUS
USA
CHN
ZAF
BRA

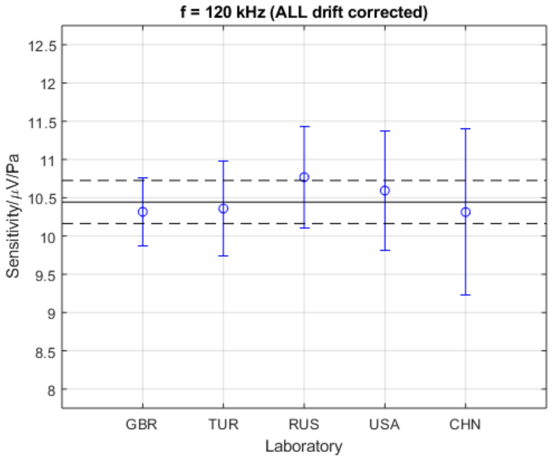


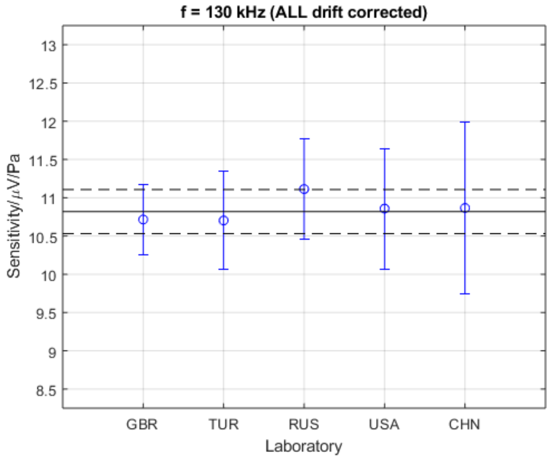
8.2.2 TC4034 hydrophone: 100 kHz to 500 kHz

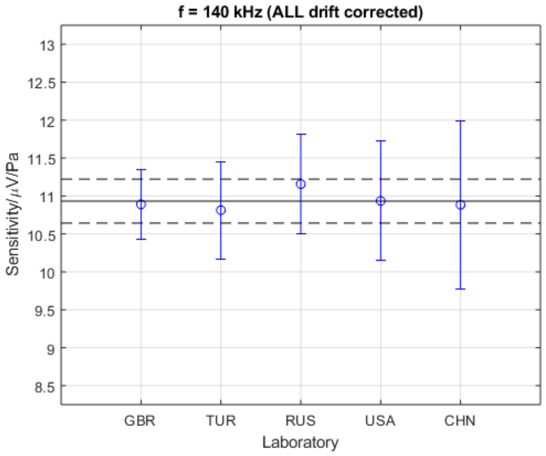
Figure 8.6 The KCRVs for each frequency for the TC4034 hydrophone based on calculations incorporating a temporal-drift correction to all the data (no temperature correction).

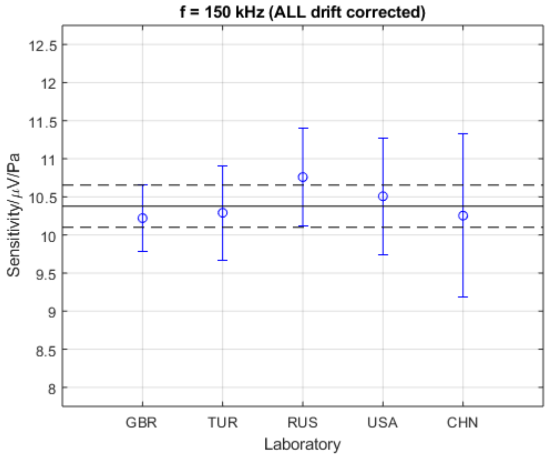

f = 100 kHz (ALL drift corrected)
Sensitivity/µV/Pa
GBR
TUR
RUS
USA
CHN
Laboratory

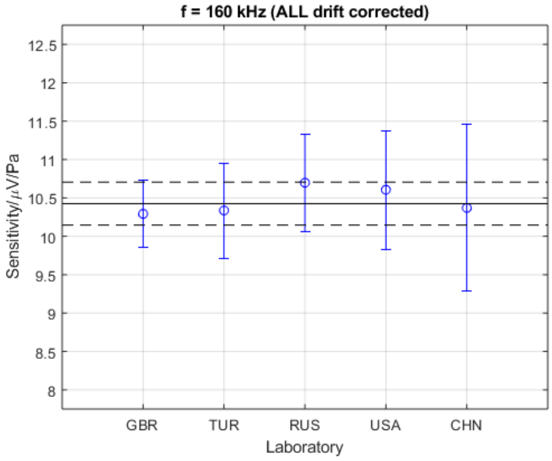

f = 110 kHz (ALL drift corrected)
Sensitivity/µV/Pa
GBR
TUR
RUS
USA
CHN
Laboratory

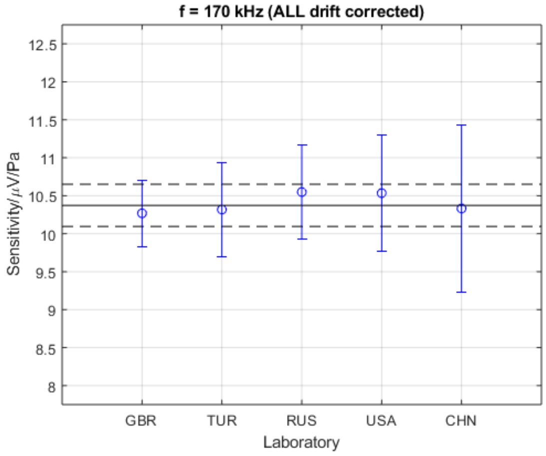

f = 120 kHz (ALL drift corrected)
Sensitivity/µV/Pa
GBR
TUR
RUS
USA
CHN
Laboratory

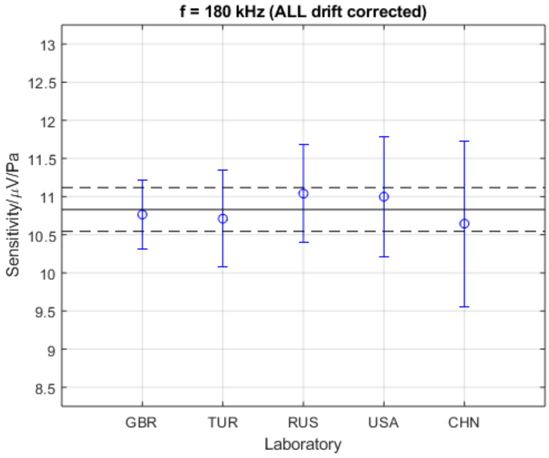

f = 130 kHz (ALL drift corrected)
Sensitivity/µV/Pa
GBR
TUR
RUS
USA
CHN
Laboratory

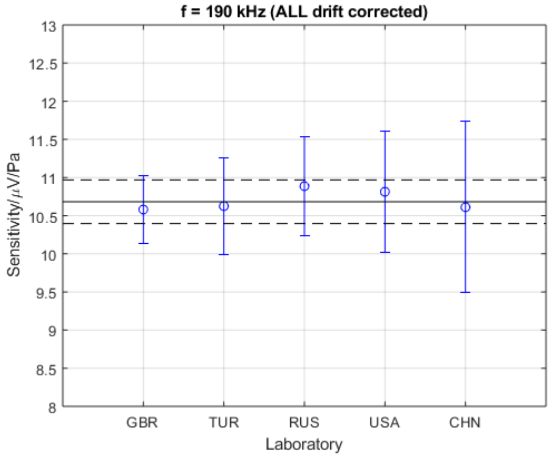

f = 140 kHz (ALL drift corrected)
Sensitivity/µV/Pa
GBR
TUR
RUS
USA
CHN
Laboratory

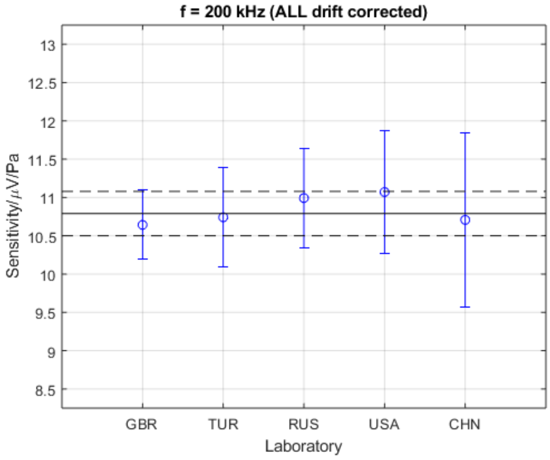

f = 150 kHz (ALL drift corrected)
Sensitivity/µV/Pa
GBR
TUR
RUS
USA
CHN
Laboratory

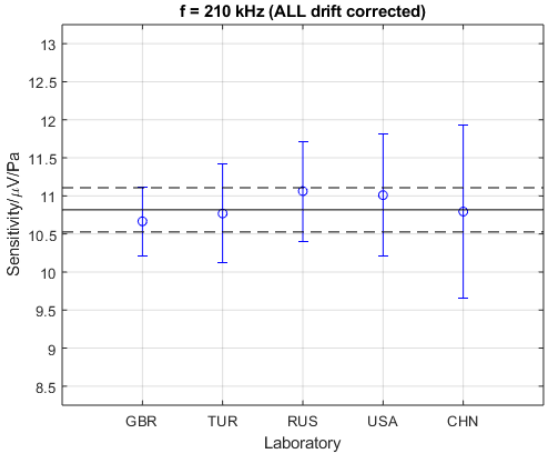

f = 160 kHz (ALL drift corrected)
Sensitivity/µV/Pa
GBR
TUR
RUS
USA
CHN
Laboratory

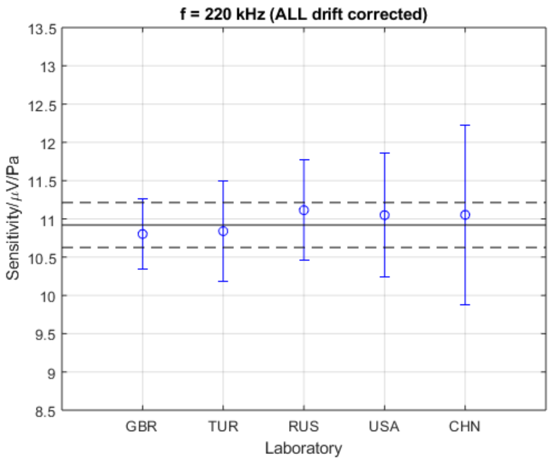

f = 170 kHz (ALL drift corrected)
Sensitivity/µV/Pa
GBR
TUR
RUS
USA
CHN
Laboratory

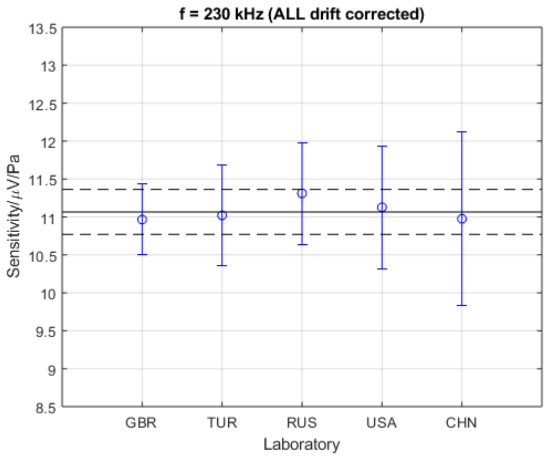

f = 180 kHz (ALL drift corrected)
13
12.5
12
11.5
11
10.5
10
9.5
9
8.5
Sensitivity/μV/Pa
GBR
TUR
RUS
USA
CHN
Laboratory

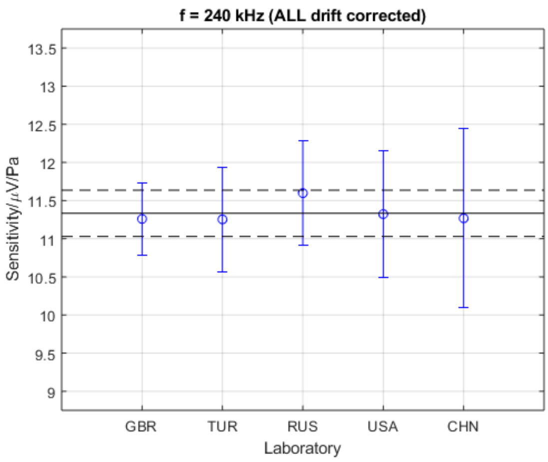

f = 190 kHz (ALL drift corrected)
13
12.5
12
11.5
11
10.5
10
9.5
9
8.5
8
Sensitivity/μV/Pa
GBR
TUR
RUS
USA
CHN
Laboratory

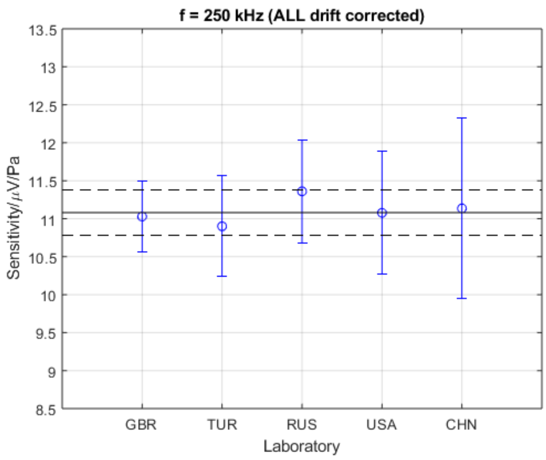

f = 200 kHz (ALL drift corrected)
13
12.5
12
11.5
11
10.5
10
9.5
9
8.5
Sensitivity/μV/Pa
GBR
TUR
RUS
USA
CHN
Laboratory

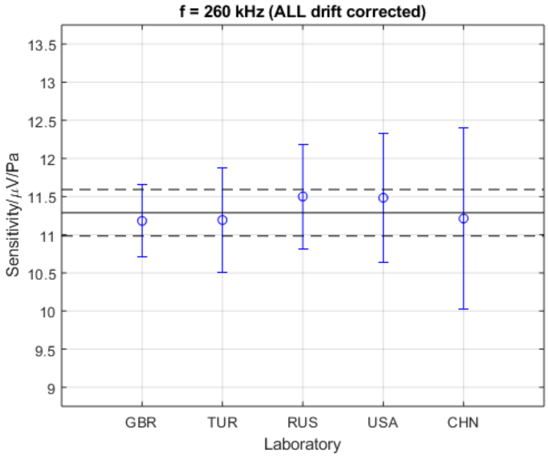

f = 210 kHz (ALL drift corrected)
13
12.5
12
11.5
11
10.5
10
9.5
9
8.5
Sensitivity/μV/Pa
GBR
TUR
RUS
USA
CHN
Laboratory

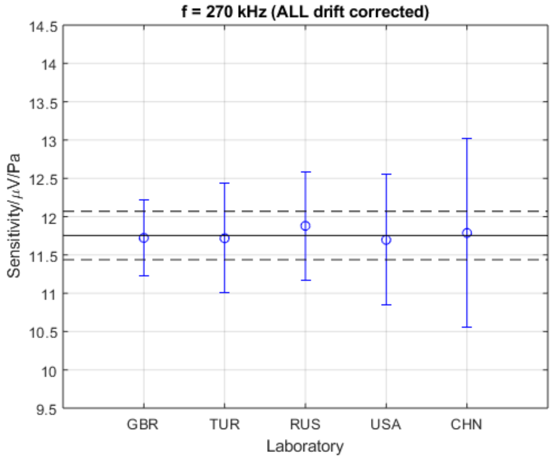

f = 220 kHz (ALL drift corrected)
13.5
13
12.5
12
11.5
11
10.5
10
9.5
9
8.5
Sensitivity/μV/Pa
GBR
TUR
RUS
USA
CHN
Laboratory

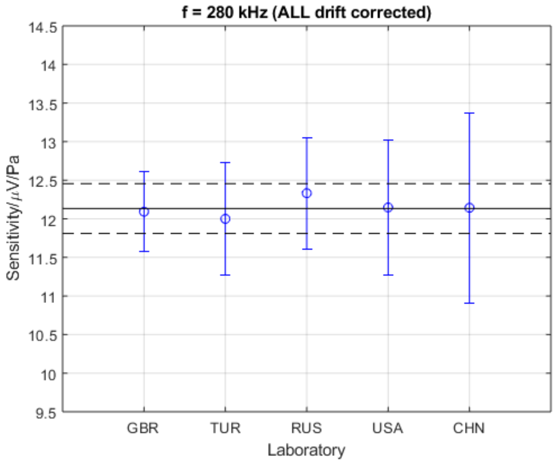

f = 230 kHz (ALL drift corrected)
13.5
13
12.5
12
11.5
11
10.5
10
9.5
9
8.5
Sensitivity/μV/Pa
GBR
TUR
RUS
USA
CHN
Laboratory

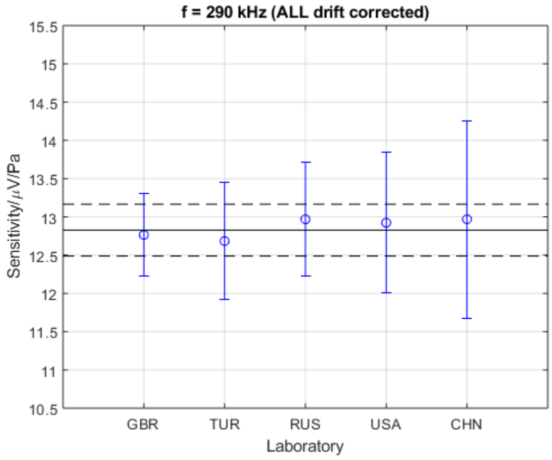

f = 240 kHz (ALL drift corrected)
13.5
13
12.5
12
11.5
11
10.5
10
9.5
9
Sensitivity/μV/Pa
GBR
TUR
RUS
USA
CHN
Laboratory

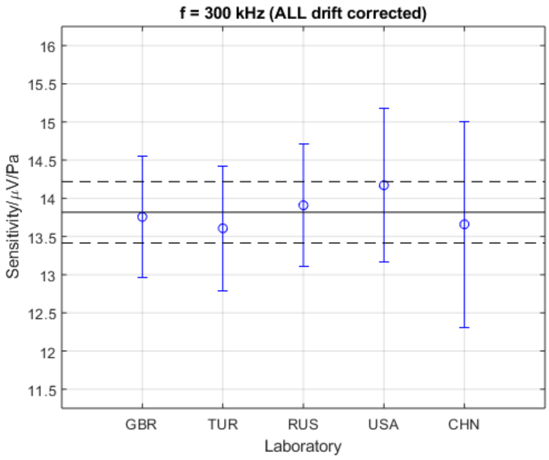

f = 250 kHz (ALL drift corrected)
13.5
13
12.5
12
11.5
11
10.5
10
9.5
9
8.5
Sensitivity/μV/Pa
GBR
TUR
RUS
USA
CHN
Laboratory

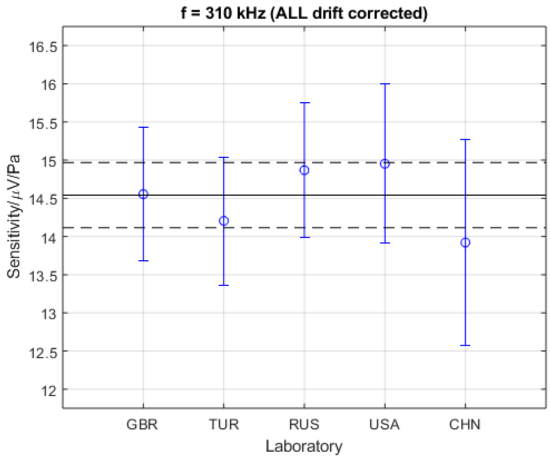

f = 260 kHz (ALL drift corrected)
Sensitivity/μV/Pa
13.5
13
12.5
12
11.5
11
10.5
10
9.5
9
GBR
TUR
RUS
USA
CHN
Laboratory

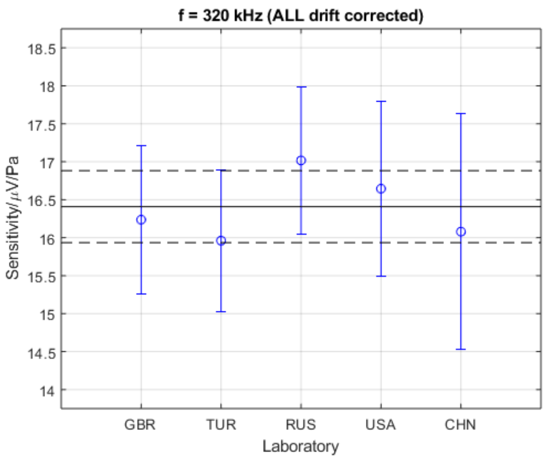

f = 270 kHz (ALL drift corrected)
Sensitivity/μV/Pa
14.5
14
13.5
13
12.5
12
11.5
11
10.5
10
9.5
GBR
TUR
RUS
USA
CHN
Laboratory

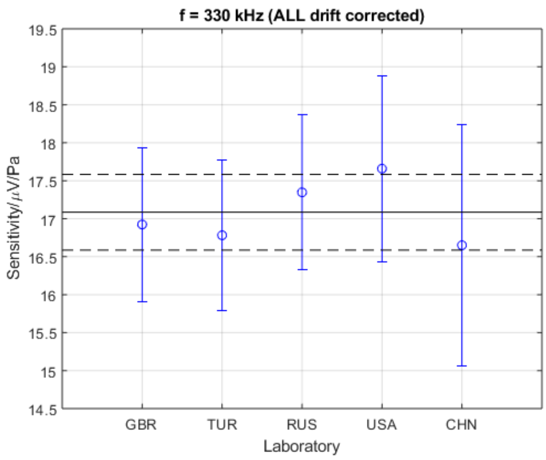

f = 280 kHz (ALL drift corrected)
Sensitivity/μV/Pa
14.5
14
13.5
13
12.5
12
11.5
11
10.5
10
9.5
GBR
TUR
RUS
USA
CHN
Laboratory

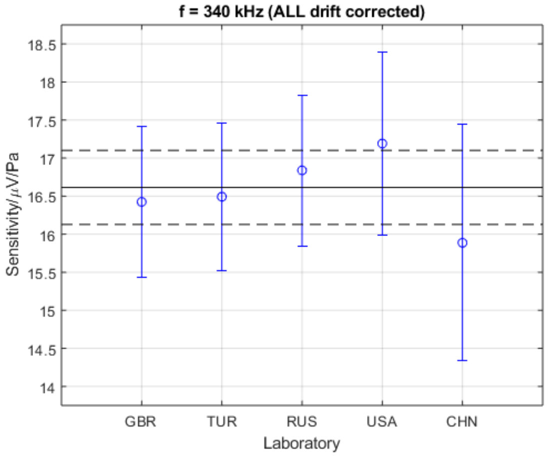

f = 290 kHz (ALL drift corrected)
Sensitivity/μV/Pa
15.5
15
14.5
14
13.5
13
12.5
12
11.5
11
10.5
GBR
TUR
RUS
USA
CHN
Laboratory

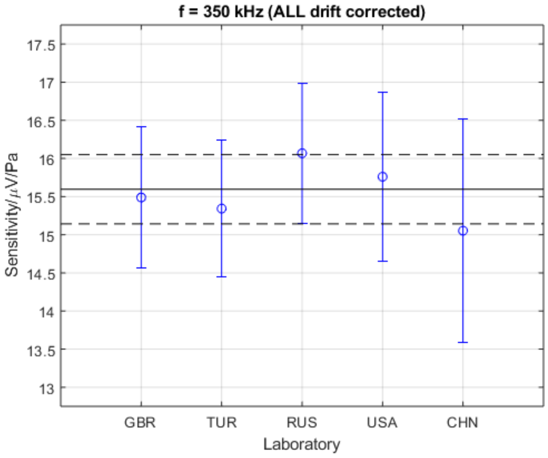

f = 300 kHz (ALL drift corrected)
Sensitivity/μV/Pa
16
15.5
15
14.5
14
13.5
13
12.5
12
11.5
GBR
TUR
RUS
USA
CHN
Laboratory

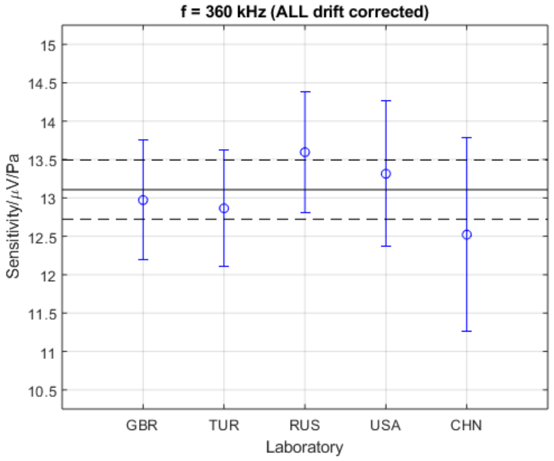

f = 310 kHz (ALL drift corrected)
Sensitivity/μV/Pa
16.5
16
15.5
15
14.5
14
13.5
13
12.5
12
GBR
TUR
RUS
USA
CHN
Laboratory

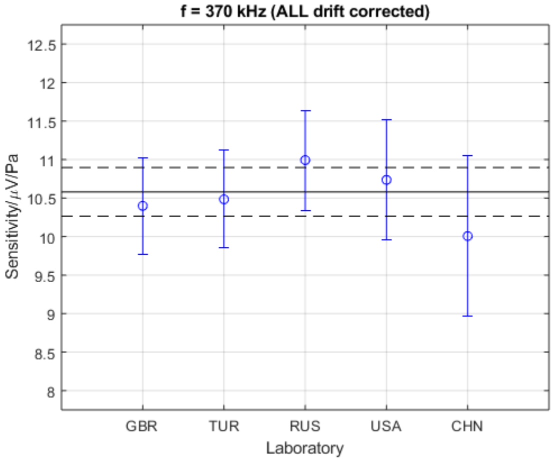

f = 320 kHz (ALL drift corrected)
Sensitivity/μV/Pa
18.5
18
17.5
17
16.5
16
15.5
15
14.5
14
GBR
TUR
RUS
USA
CHN
Laboratory

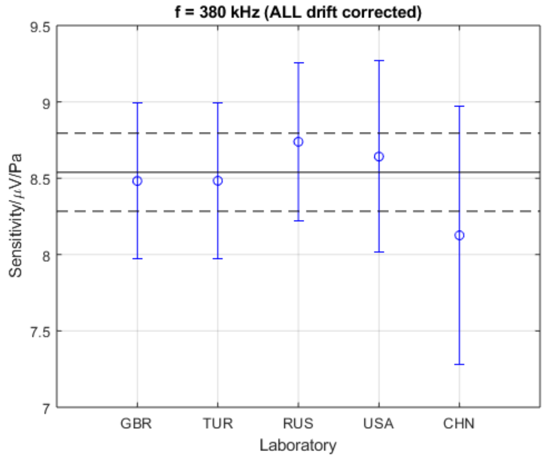

f = 330 kHz (ALL drift corrected)
Sensitivity/μV/Pa
19.5
19
18.5
18
17.5
17
16.5
16
15.5
15
14.5
GBR
TUR
RUS
USA
CHN
Laboratory

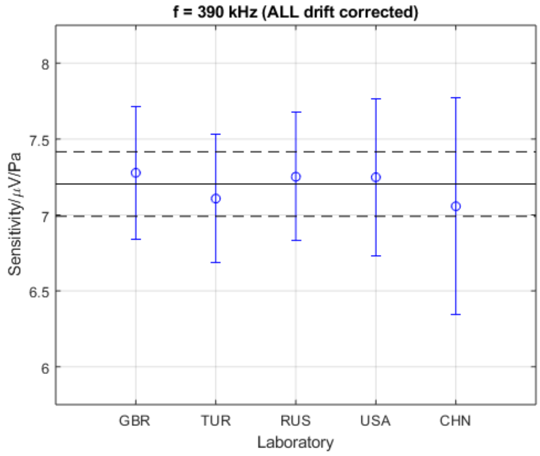

f = 340 kHz (ALL drift corrected)
Sensitivity/μV/Pa
GBR TUR RUS USA CHN
Laboratory

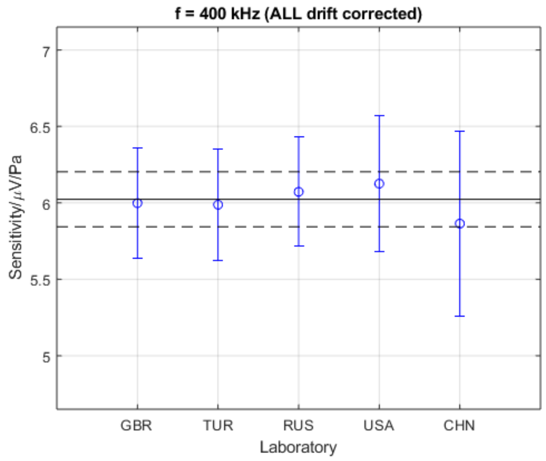

f = 350 kHz (ALL drift corrected)
Sensitivity/μV/Pa
GBR TUR RUS USA CHN
Laboratory

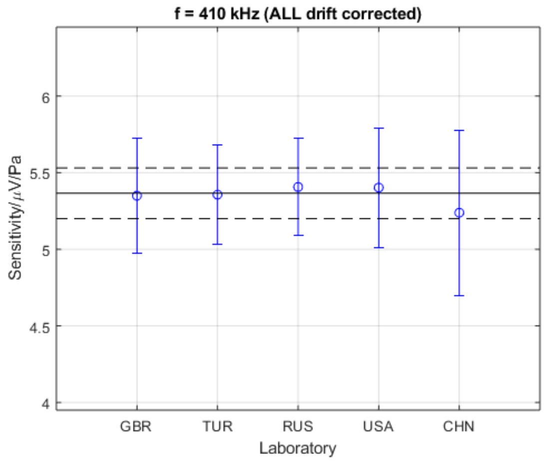

f = 360 kHz (ALL drift corrected)
Sensitivity/μV/Pa
GBR TUR RUS USA CHN
Laboratory

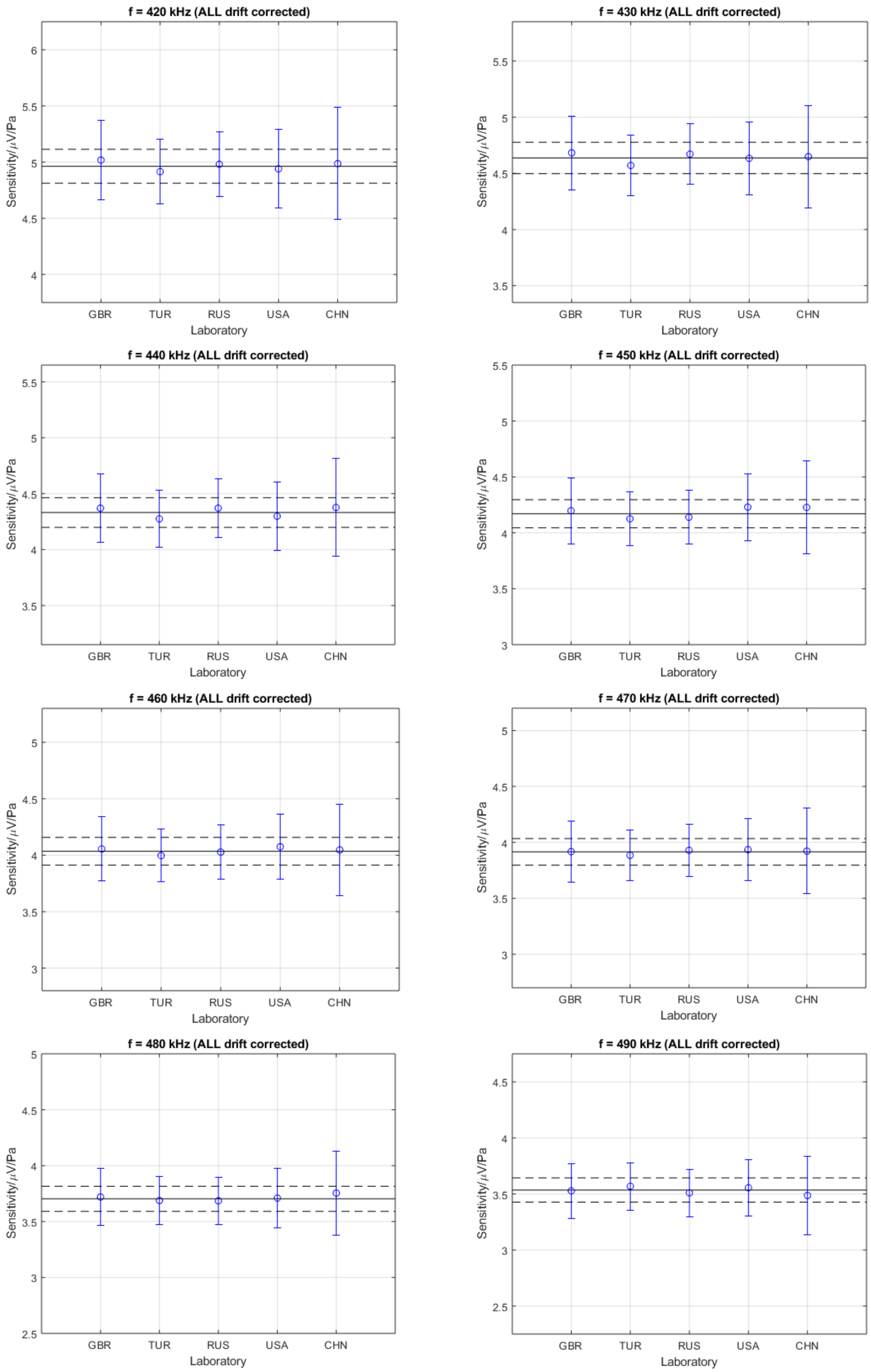

f = 370 kHz (ALL drift corrected)
Sensitivity/μV/Pa
GBR TUR RUS USA CHN
Laboratory

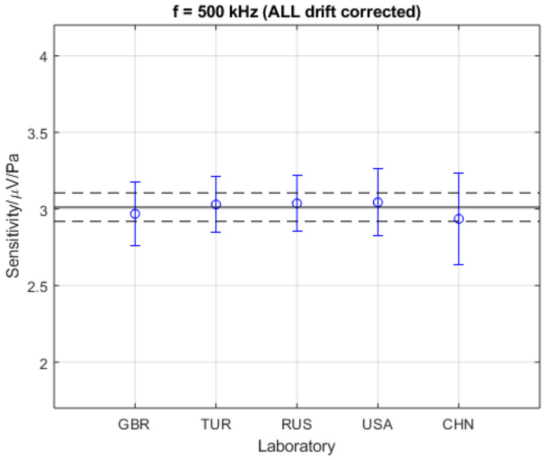

f = 380 kHz (ALL drift corrected)
Sensitivity/μV/Pa
GBR TUR RUS USA CHN
Laboratory


f = 390 kHz (ALL drift corrected)
Sensitivity/μV/Pa
GBR TUR RUS USA CHN
Laboratory


f = 400 kHz (ALL drift corrected)
Sensitivity/μV/Pa
GBR TUR RUS USA CHN
Laboratory


f = 410 kHz (ALL drift corrected)
Sensitivity/μV/Pa
GBR TUR RUS USA CHN
Laboratory


f = 420 kHz (ALL drift corrected)
f = 430 kHz (ALL drift corrected)
f = 440 kHz (ALL drift corrected)
f = 450 kHz (ALL drift corrected)
f = 460 kHz (ALL drift corrected)
f = 470 kHz (ALL drift corrected)
f = 480 kHz (ALL drift corrected)
f = 490 kHz (ALL drift corrected)
Sensitivity/μV/Pa
GBR
TUR
RUS
USA
CHN
Laboratory



8.3 DEGREES OF EQUIVALENCE

The tables in this section show the DOEs for each participant at all frequencies (expressed in percent) calculated from the differences of the participants' results from the KCRVs. Also shown are the uncertainties on the DOEs, calculated from the uncertainty of the participants' results and uncertainties on the KCRVs.

For the B&K8104 hydrophone at frequencies from 250 Hz to 120 kHz, the DOEs include a temporal-drift correction (as described in Section 7.2) and a temperature correction applied only to INMETRO data. For the TC4034 hydrophone at frequencies from 100 kHz to 500 kHz, the DOEs incorporate a temporal-drift correction to all the data (as described in Section 7.2).

8.3.1 DOEs: Tabulated values

Note that in the range 100 kHz to 120 kHz, where a participant provided data for the TC4034 hydrophone this was used for the DOE calculation. For NMISA and INMETRO where no TC4034 data was provided, the B&K8104 data was used.

Table 8.1 The DOEs for each participant across the range 250 Hz to 120 kHz based on calculations incorporating a temporal-drift correction to all the data.

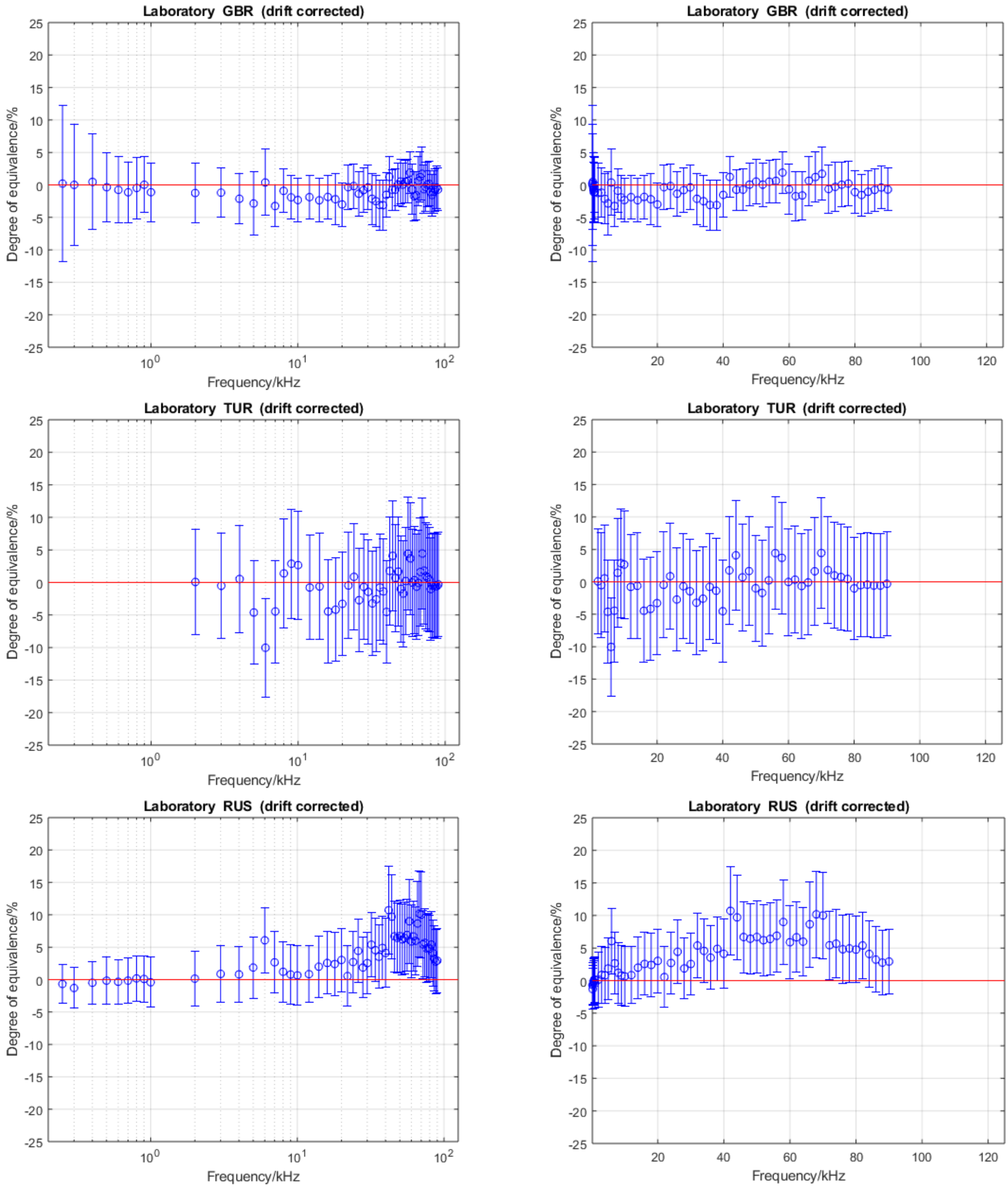
Frequency	GBR		TUR		RUS		USA		CHN		ZAF		BRA		IND	
(kHz)	DOE (%)	U_{DOE} (%)	DOE (%)	U_{DOE} (%)	DOE (%)	U_{DOE} (%)	DOE (%)	U_{DOE} (%)	DOE (%)	U_{DOE} (%)	DOE (%)	U_{DOE} (%)	DOE (%)	U_{DOE} (%)	DOE (%)	U_{DOE} (%)
0.25	0.2	12.0			-0.7	3.0	-6.2	14.6	3.4	6.9						
0.3	0.0	9.3			-1.3	3.1	3.7	16.4	2.6	7.0						
0.4	0.5	7.3			-0.5	3.3	-0.5	15.7	0.9	6.9						
0.5	-0.4	5.3			-0.2	3.6	-4.6	11.2	3.1	7.2						
0.6	-0.8	5.1			-0.3	3.4	-1.5	11.6	2.9	7.3						
0.7	-1.1	4.7			-0.2	3.5	2.1	12.1	1.8	7.1						
0.8	-0.5	4.7			0.2	3.5	0.0	11.8	0.4	7.1						
0.9	0.0	4.3			0.1	3.5	-1.3	11.6	0.2	7.1						
1	-1.1	4.5			-0.4	3.9	0.9	4.1	0.4	7.3			6.2	19.8		
2	-1.2	4.6	0.1	8.1	0.1	4.2	0.4	4.2	-2.4	7.5			5.0	8.7	3.7	12.0
3	-1.2	3.8	-0.5	8.1	0.9	4.3	-1.2	4.2	-1.9	7.6			6.8	7.5	7.9	12.4
4	-2.1	3.9	0.5	8.2	0.8	4.4	-1.4	4.2	-0.5	7.7	1.5	6.5	5.9	7.1	10.6	11.2
5	-2.9	4.9	-4.6	7.9	1.9	4.7	2.4	4.5	-3.3	7.9	-2.5	6.9	6.7	7.8	-8.1	10.3
6	0.4	5.1	-10.0	7.6	6.1	5.0	-2.2	4.3	1.4	8.3	1.2	7.2	0.1	8.7	-2.5	9.7
7	-3.3	3.2	-4.5	7.9	2.7	4.8	0.9	4.4	-1.0	7.9	2.4	6.8	10.1	9.0	1.6	9.5
8	-0.9	3.3	1.4	8.3	1.2	4.6	-2.1	4.2	-3.6	7.5	1.6	6.6	7.5	7.8	8.4	11.0
9	-1.9	3.3	2.9	8.4	0.8	4.6	-2.5	4.1	-1.2	7.6	0.9	6.4	6.6	5.9	12.3	10.0
10	-2.3	3.3	2.7	8.3	0.6	4.6	-2.0	4.2	-0.7	7.5	-0.9	6.3	8.8	6.1	18.0	10.4
12	-1.9	3.4	-0.8	8.0	0.8	4.4	-0.6	4.2	-0.8	7.6	-0.8	5.3	10.2	7.8	18.3	10.8
14	-2.4	3.4	-0.6	8.1	2.0	4.7	0.9	4.4	-2.0	7.7	-2.7	5.4	5.8	5.6	8.3	8.6
16	-1.8	3.4	-4.5	7.9	2.6	4.8	3.1	4.6	0.1	8.2	-1.8	5.6	0.9	6.8	5.6	8.7
18	-2.2	3.9	-4.2	8.0	2.4	4.9	3.8	4.6	-0.3	8.2	-3.3	5.6	1.2	5.0	3.3	8.4
20	-3.0	3.4	-3.3	8.0	3.0	4.9	1.5	4.5	-1.8	7.9	-1.4	5.5	3.9	4.8	5.5	8.3
22	-0.4	3.4	-0.5	8.1	0.5	4.6	-0.4	4.3	-2.2	7.7	-0.8	5.4	5.2	7.6	8.1	8.5
24	-0.2	3.4	0.9	8.2	2.7	4.7	-4.0	4.1	-3.0	7.6	0.7	5.4	8.5	8.4	9.0	7.4
26	-1.4	3.4	-2.7	7.9	4.4	4.9	-3.2	4.2	-1.7	7.7	0.9	5.5	4.4	5.9	6.1	8.4
28	-0.8	3.4	-0.7	8.1	1.9	4.7	-1.3	4.2	-1.0	7.6	-1.3	5.3	5.8	7.3	7.8	7.5
30	-0.4	3.5	-1.4	8.1	2.6	4.8	-1.3	4.3	-1.0	7.8	-0.5	5.4	1.2	5.5	8.3	8.6
32	-2.1	3.9	-3.2	8.0	5.4	5.0	0.7	4.4	0.4	8.1	-0.8	5.6	-1.1	4.6	6.9	8.5
34	-2.5	3.9	-2.6	8.0	4.6	4.9	3.0	4.5	-3.1	7.8	-0.7	5.5	-1.2	4.8	6.1	8.5
36	-3.1	3.9	-0.8	8.2	3.5	4.9	0.8	4.5	1.0	8.1	-2.0	5.5	1.2	4.3	9.5	8.6
38	-3.1	3.8	-1.4	8.1	4.9	4.9	0.5	4.4	-2.6	7.8	1.5	5.7	-0.5	5.8	13.5	10.6
40	-1.5	3.4	-4.5	7.8	4.1	5.3	2.0	4.5	1.1	8.0	-1.2	5.5	-1.1	6.4	11.4	8.8
42	1.2	3.2	1.8	8.3	10.7	6.7	-3.1	4.1	1.7	7.9	-0.6	5.4	2.7	9.7	10.0	8.7
44	-0.7	3.1	4.1	8.5	9.7	6.4	-2.3	4.1	-1.4	7.8	0.3	5.4	6.0	7.0	5.9	7.4
46	-0.7	3.3	0.7	8.3	6.7	5.5	-1.7	4.3	0.1	8.0	-2.8	5.4	0.1	5.8	2.9	8.2
48	0.0	3.3	1.7	8.3	6.4	5.5	-3.1	4.2	1.5	8.1	-0.8	5.5	-2.4	5.3	1.7	9.2
50	0.5	3.4	-1.0	8.2	6.7	5.5	-3.0	4.3	2.4	8.3	0.4	5.7	-3.1	4.5	3.6	8.2
52	0.0	3.3	-1.7	8.1	6.2	5.5	-0.5	4.4	2.2	8.3	0.1	5.7	-4.3	4.6	5.0	7.1
54	0.5	3.3	0.2	8.3	6.4	5.5	-0.9	4.4	1.4	8.3	-3.8	5.5	-3.5	5.8	4.9	8.6
56	0.6	3.4	4.4	8.7	6.9	5.5	-2.2	4.4	1.7	8.3	-2.5	5.6	-3.8	4.6	4.5	8.4
58	1.9	3.3	3.7	8.6	9.0	6.5	-1.7	4.3	4.0	8.7	1.1	5.8	-4.5	4.6	5.3	8.6
60	-0.7	3.8	0.0	8.2	5.9	5.6	-3.3	4.1	1.4	8.4	0.1	5.6	-9.0	6.5	1.7	8.4
62	-1.7	3.8	0.3	8.2	6.7	5.4	-3.5	4.1	1.0	8.2	1.1	5.1	-9.3	5.4	1.4	9.5
64	-1.6	3.7	-0.7	8.1	6.0	5.3	-4.0	6.6	-1.0	8.0	0.4	5.0	-10.4	5.8	1.3	9.4
66	0.6	3.8	-0.1	8.1	8.7	6.5	-2.5	6.7	3.7	8.2	3.7	5.1	-5.9	5.9	9.5	8.8
68	1.2	3.8	1.6	8.3	10.2	6.6	-4.0	6.6	5.4	8.3	2.1	5.0	-5.0	5.6	9.8	8.9
70	1.7	4.1	4.4	8.6	10.0	6.6	-4.4	6.6	6.3	8.6	2.1	5.1	-5.0	4.6	9.9	9.0
72	-0.6	3.8	1.8	8.3	5.4	5.3	-6.1	6.4	4.0	8.3	-2.2	4.8	-8.0	5.1	6.2	8.5
74	-0.3	3.8	1.0	8.2	5.7	5.2	-5.3	6.4	1.4	8.0	-2.2	4.7	-9.1	5.1	5.3	8.3
76	0.0	3.4	0.7	8.1	4.8	5.2	-6.2	6.3	1.2	7.9	-1.2	4.8	-10.0	4.9	4.9	8.2
78	0.2	3.4	0.4	8.1	5.0	5.2	-8.1	6.1	3.4	8.0	-0.9	4.7	-9.0	4.9	8.9	8.4
80	-1.1	3.2	-1.0	7.9	4.8	5.1	-10.7	6.9	1.3	7.9	-2.3	4.6	-9.2	5.0	11.2	9.8
82	-1.6	3.2	-0.5	8.0	5.4	5.2	-11.2	6.9	1.7	7.9	-2.4	4.6	-7.5	5.1	14.3	10.1
84	-1.1	3.2	-0.4	8.0	4.1	5.1	-11.2	6.9	1.8	8.0	-2.3	4.6	-8.2	5.3	13.6	10.1
86	-0.8	3.3	-0.6	8.0	3.2	5.0	-11.6	6.9	1.3	7.9	-1.9	4.6	-9.4	5.3	12.7	10.0
88	-0.4	3.3	-0.6	8.0	2.8	5.0	-12.0	6.9	1.4	7.9	-2.1	4.6	-10.7	5.8	10.5	9.8
90	-0.7	3.3	-0.3	8.0	2.9	5.0	-11.7	6.9	0.7	7.8	-1.6	4.6	-11.8	6.0	10.1	9.7
100											-0.7	4.4	-14.6	6.5		
110											-0.8	4.4				
120											0.1	4.6				

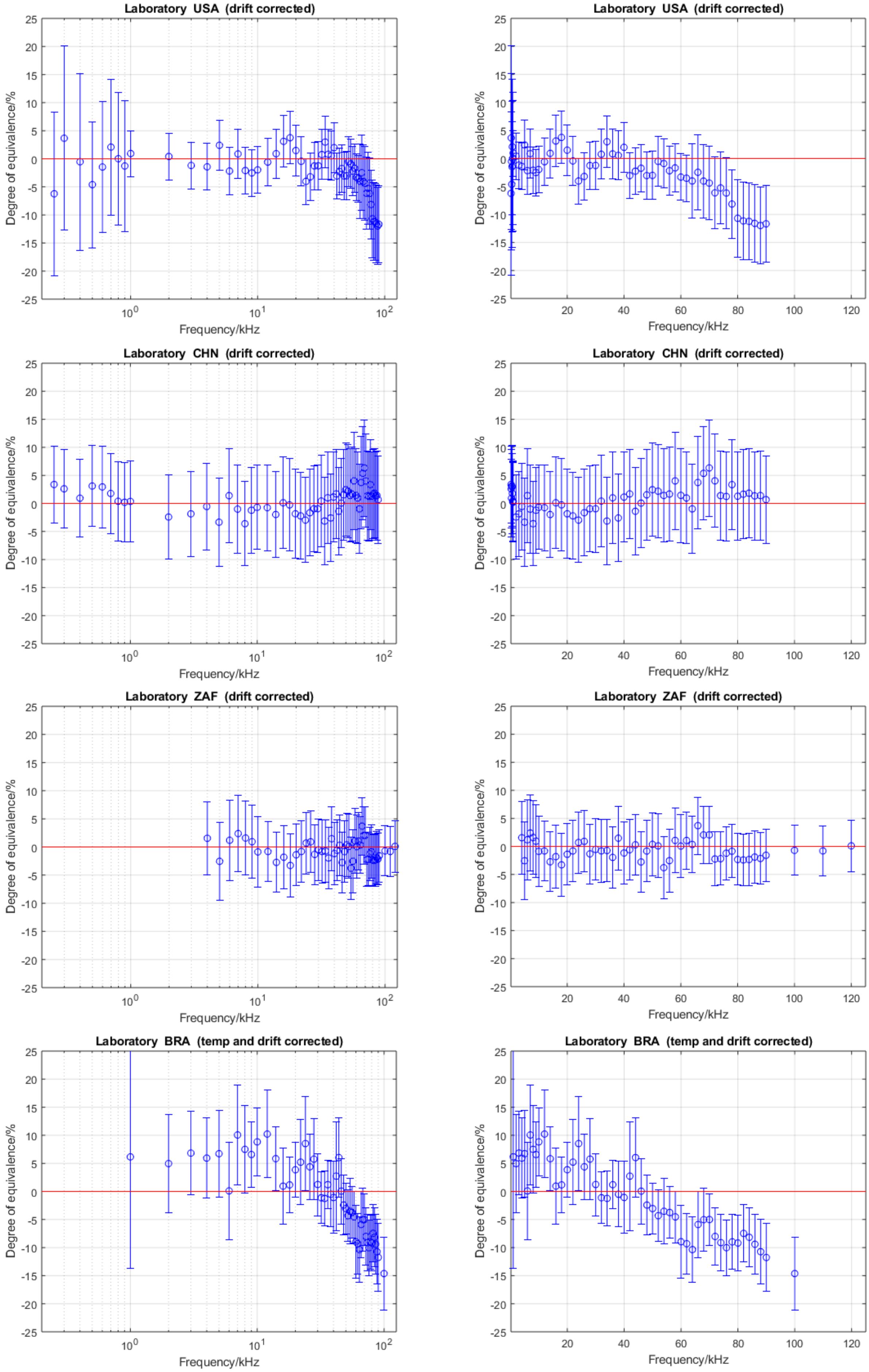
Table 8.2 The DOEs for each participant across the range 100 Hz to 500 kHz based on calculations incorporating a temporal-drift correction to all the data.

Frequency	GBR		TUR		RUS		USA		CHN	
(kHz)	DOE (%)	U_{DOE} (%)	DOE (%)	U_{DOE} (%)	DOE (%)	U_{DOE} (%)	DOE (%)	U_{DOE} (%)	DOE (%)	U_{DOE} (%)
100	-1.4	3.1	0.3	5.4	1.8	5.4	2.6	7.0	-2.3	9.9
110	-1.1	3.2	-0.4	5.3	2.3	5.4	1.7	6.9	-2.3	9.9
120	-1.2	3.2	-0.8	5.3	3.1	5.7	1.4	6.9	-1.3	10.0
130	-1.0	3.3	-1.1	5.3	2.7	5.4	0.4	6.8	0.4	10.0
140	-0.4	3.3	-1.1	5.2	2.1	5.3	0.0	6.7	-0.4	9.8
150	-1.5	3.2	-0.8	5.3	3.7	5.5	1.3	6.9	-1.2	10.0
160	-1.3	3.2	-0.9	5.3	2.6	5.5	1.7	6.9	-0.5	10.1
170	-1.0	3.2	-0.5	5.3	1.7	5.4	1.6	6.9	-0.4	10.2
180	-0.6	3.3	-1.1	5.2	1.9	5.3	1.6	6.8	-1.7	9.7
190	-1.0	3.2	-0.5	5.3	1.9	5.4	1.2	6.9	-0.7	10.2
200	-1.4	3.2	-0.5	5.3	1.9	5.4	2.6	7.0	-0.8	10.2
210	-1.4	3.2	-0.4	5.4	2.3	5.4	1.8	6.9	-0.2	10.1
220	-1.1	3.2	-0.7	5.4	1.8	5.4	1.2	6.9	1.2	10.4
230	-0.9	3.2	-0.4	5.4	2.2	5.4	0.6	6.8	-0.8	10.0
240	-0.7	3.3	-0.7	5.4	2.3	5.4	-0.1	6.8	-0.6	10.0
250	-0.5	3.3	-1.6	5.4	2.5	5.5	0.0	6.8	0.5	10.4
260	-0.9	3.2	-0.8	5.4	1.9	5.5	1.7	7.0	-0.7	10.2
270	-0.3	3.3	-0.3	5.5	1.1	5.4	-0.5	6.7	0.3	10.1
280	-0.3	3.3	-1.1	5.4	1.6	5.3	0.1	6.7	0.1	9.8
290	-0.5	3.3	-1.1	5.3	1.1	5.2	0.8	6.6	1.1	9.7
300	-0.4	5.0	-1.5	5.1	0.7	5.0	2.6	6.6	-1.1	9.3
310	0.1	5.2	-2.3	5.0	2.2	5.3	2.8	6.5	-4.3	8.8
320	-1.0	5.2	-2.7	4.9	3.7	5.1	1.4	6.4	-2.0	9.0
330	-0.9	5.2	-1.8	5.0	1.5	5.2	3.4	6.5	-2.5	8.8
340	-1.1	5.2	-0.7	5.0	1.3	5.2	3.5	6.6	-4.4	8.9
350	-0.7	5.2	-1.6	5.0	3.0	5.1	1.0	6.4	-3.5	8.9
360	-1.0	5.2	-1.9	5.0	3.7	5.3	1.6	6.6	-4.5	9.1
370	-1.7	5.1	-0.9	5.2	3.9	5.4	1.5	6.7	-5.4	9.4
380	-0.7	5.2	-0.7	5.2	2.3	5.3	1.2	6.7	-4.8	9.5
390	1.0	5.3	-1.3	5.1	0.7	5.1	0.6	6.6	-2.0	9.5
400	-0.4	5.2	-0.6	5.2	0.8	5.1	1.7	6.7	-2.6	9.6
410	-0.3	6.3	-0.2	5.2	0.8	5.1	0.7	6.6	-2.4	9.6
420	1.1	6.4	-1.0	5.0	0.4	5.0	-0.5	6.4	0.5	9.6
430	1.0	6.4	-1.4	5.0	0.7	5.0	-0.1	6.3	0.2	9.4
440	0.9	6.4	-1.3	5.0	0.9	5.2	-0.8	6.3	1.0	9.7
450	0.6	6.4	-1.1	5.0	-0.7	4.9	1.4	6.5	1.4	9.5
460	0.5	6.3	-0.9	4.9	-0.2	5.1	1.0	6.4	0.3	9.5
470	0.1	6.3	-0.8	4.9	0.4	5.1	0.5	6.4	0.2	9.3
480	0.4	6.2	-0.4	5.0	-0.5	4.9	0.2	6.4	1.4	9.6
490	-0.2	6.2	1.0	5.1	-0.7	5.1	0.6	6.5	-1.4	9.4
500	-1.5	6.1	0.6	5.2	0.8	5.3	1.1	6.6	-2.5	9.5

8.3.2 B&K8104 hydrophone

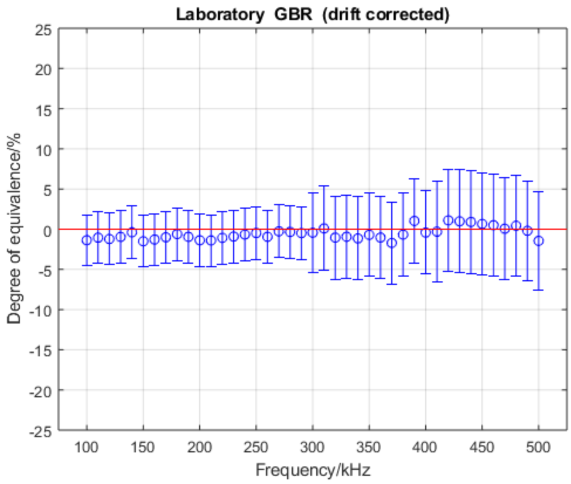
Figure 8.7 The DOEs for each participant across the range 250 Hz to 120 kHz calculated using the B&K8104 data and incorporating a temporal-drift correction to all the data and a temperature correction applied only to INMETRO data. For extra clarity at both low and high frequencies, the plots are shown with both a logarithmic and linear frequency scale for each participant.

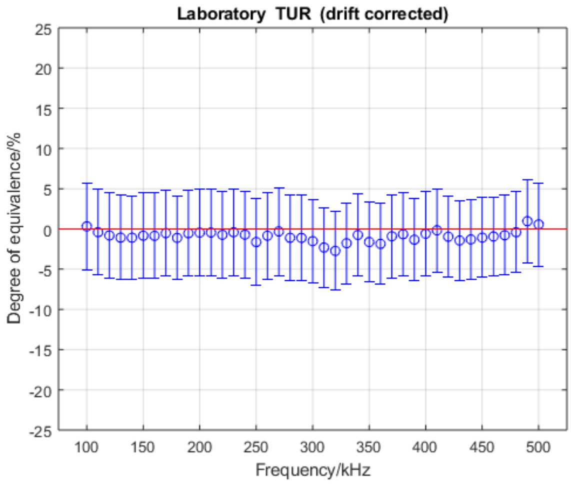


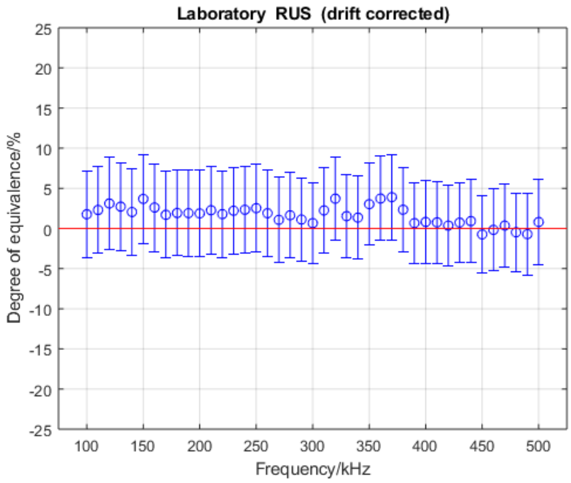

Laboratory USA (drift corrected)
Laboratory USA (drift corrected)
Laboratory CHN (drift corrected)
Laboratory CHN (drift corrected)
Laboratory ZAF (drift corrected)
Laboratory ZAF (drift corrected)
Laboratory BRA (temp and drift corrected)
Laboratory BRA (temp and drift corrected)
Degree of equivalence/%
Frequency/kHz

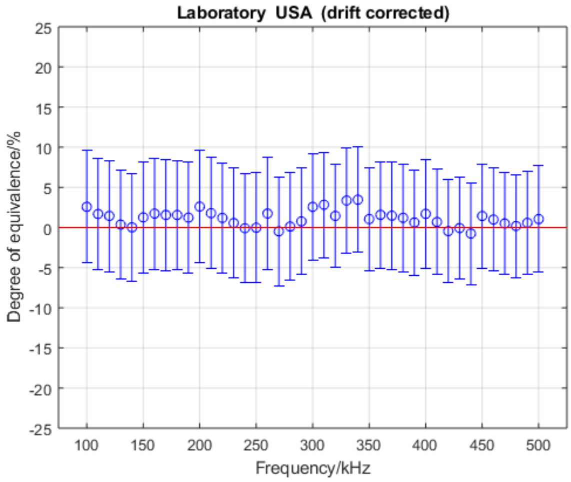
8.3.3 TC4034 hydrophone

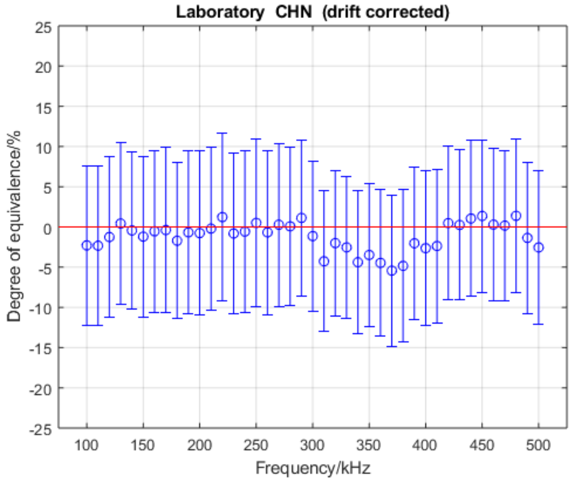
Figure 8.8 The DOEs for each participant across the range 100 kHz to 500 kHz calculated using the TC4034 data and incorporating a temporal-drift correction to all the data.








Laboratory USA (drift corrected)
Degree of equivalence/%
Frequency/kHz


Laboratory CHN (drift corrected)
Degree of equivalence/%
Frequency/kHz

9 CONCLUSIONS

9.1 SUMMARY AND DISCUSSION

This report is the Final Report for Key Comparison CCAUV.W-K2 covering primary free-field standards for sound in water at frequencies between 250 Hz and 500 kHz with the pilot laboratory being the National Physical Laboratory (NPL). Two hydrophones were circulated as a round-robin to cover the frequency range: a B&K8104 device covered the range from 250 Hz to 120 kHz, and a Reson TC4034 device covered the range from 100 kHz to 500 kHz. The magnitude of the end-of-cable open-circuit free-field receive sensitivity was requested at a total of 102 discrete acoustic frequencies over eleven octaves.

There were seven participants in the comparison: HAARI (CHN), INMETRO (BRA), NMISA (ZAF), NPL (GBR), TUBITAK-MAM (TUR), USRD (USA) and VNIIFTRI (RUS). In addition, an eighth laboratory, NIOT (IND), participated as a guest participant (and their results are not included in the calculations of the KCRVs). For the B&K8104 hydrophone, four of the main participants calibrated the hydrophone over the full frequency range, with the remaining participants omitting some of the lowest frequencies (INMETRO, NMISA, TUBITAK-MAM). For the TC4034 hydrophone, five participants reported calibrations over the full frequency range, with two participants deciding not to submit results for the TC4034 hydrophone (INMETRO, NMISA). Note that NMISA withdrew their results for the TC4034 hydrophone after discovery of a technical problem.

Each participant declared their uncertainties along with their results according to the requirements of the protocol. USRD had initially offered provisional uncertainties with their results, and later amended their uncertainties to reflect the more recently declared uncertainties assessed by the US accreditation body, the National Voluntary Laboratory Accreditation Program (NVLAP). These uncertainties were publicly declared before the Draft A1 report was made available and have been used for the analysis in the Key Comparison.

The check calibrations undertaken by the pilot laboratory (NPL) showed some evidence of statistically-significant temporal drift in the hydrophone sensitivities, most clearly seen for the TC4034 hydrophone around and above the resonance frequency, but also over a small part of the frequency range of the B&K8104 hydrophone. Therefore, corrections for temporal drift have been made to the calibration data for both hydrophones, based on the calibrations undertaken by NPL. This improves the agreement at high frequencies for the TC4034 hydrophone (although it should be noted that the TC4034 showed no discrepant results even without the drift corrections). The improvements in the agreement for the B&K8104 hydrophone are marginal except at a few frequencies, and do little to improve the discrepant results observed, but the corrections have been made all frequencies for consistency of approach.

In the overlapping frequency range of 100 kHz to 120 kHz, the results for the TC4034 hydrophone have been preferred to those for the B&K8104 hydrophone on account of the much better agreement for the TC4034 hydrophone. Therefore, where participants reported data for the TC4034 hydrophone, this data has been used for the calculation of the KCRV and DOEs in the frequency range of overlap (100 kHz to 120 kHz). For participants calibrating only the B&K8104 hydrophone (NMISA and INMETRO), the data for that hydrophone was used (in the absence of the TC4034 data).

The protocol prescribed the environmental conditions for the comparison, including the water temperature which had to be between 17 °C and 21 °C for conformance. Inevitably, it is difficult to control the water temperature in large test tanks in hot climates, and this led to significant deviation for two participants. INMETRO undertook calibrations at water temperatures significantly higher than the range prescribed in the protocol (at between 26 °C and 27 °C). In addition, the guest participant (NIOT) also undertook calibrations of both hydrophones at elevated temperatures (between 28.5 °C and 31.5 °C). In order for the results of INMETRO to be included in the KCRVs and to allow calculation of their DOEs (and for the DOEs of NIOT to be calculated as a guest participant), NPL undertook calibrations of the two hydrophones at the water temperatures used by INMETRO and NIOT using the NPL Acoustic Pressure Vessel facility which enables calibrations to be made at a range of temperatures. Corrections derived from these calibrations were used to correct the results of INMETRO for the B&K8104 hydrophone so that the results could be used in the KCRV calculation and so their DOEs could be calculated, and to correct the results of NIOT for both hydrophones so that DOEs could be calculated for NIOT as a guest participant (but still without the results of NIOT included in the KCRV).

The calculated Key Comparison Reference Values (KCRVs) and the Degrees of Equivalence (DOEs) for each participant have been calculated and presented in this report.

The results show that the agreement for the range 100 kHz to 500 kHz is very good indeed, with no participant exhibiting any discrepant results for the TC4034 hydrophone.

For the B&K8104 hydrophone, the results are generally in agreement for the frequency range from 250 Hz to 60 kHz. There are occasional discrepant results at a few frequencies, but with a total of 61 frequencies of calibration, this may be expected and does not negate the conclusion that the agreement is generally acceptable. In particular, the extension of the CCAUV.W-K1 key comparison to lower frequencies (from 1 kHz down to 250 Hz) may be judged as a success with good agreement obtained between participants at what might be considered a challenging frequency range for free-field calibrations.

However, the spread in the results for this hydrophone increases for the frequency range above about 60 kHz. For the range from 58 kHz to 70 kHz, VNIIFTRI and INMETRO have occasional discrepant results, with VNIIFTRI showing occasional high results, and INMETRO exhibiting occasional low results. For frequencies greater than 70 kHz, INMETRO show discrepant results which are consistently low, and for frequencies greater than 80 kHz, USRD also show discrepant results which again are consistently low. (Note that for frequencies above 70 kHz, the results of VNIIFTRI are no longer discrepant).

The main concern for the comparison is the relatively poor agreement in the frequency range 60 kHz to 100 kHz. This is likely to be in part due to the performance of the hydrophone chosen, which appears to be more sensitive to influencing factors such as temperature and mounting in the frequency range around and above its resonance frequency. Certainly, the agreement in the overlap range of 100 kHz to 120 kHz is much better for the TC4034. This suggests that the increase in spread of results is dependent on the hydrophone calibrated, which motivates the preference for the results for the latter hydrophone for calculation of the DOEs in that range.

Note that the temporal drift observed in the NPL check calibrations is not a cause of the discrepant results. Although correcting for this drift improves the general agreement for certain parts of the frequency range (for example, for the TC4034 at frequencies above 300 kHz), it has little effect at the frequencies where discrepant results were observed for the B&K8104.

One of the reasons for the differences observed for the B&K8104 hydrophone at frequencies around and above the resonance frequency for some participants is likely to be the differences in water temperature that pertain to the calibrations. Although NPL undertook calibrations as a function of temperature, the behaviour of the B&K8104 hydrophone was more difficult to determine precisely (the changes observed are not a smooth monotonic increase in sensitivity), and the corrections derived do not in general provide a significant improvement to the agreement between participants in the frequency range 60 kHz to 100 kHz. For this hydrophone, during the check calibrations a fault was discovered with the BNC connector at the end of the cable. This caused the signal to cut out intermittently and was repaired with no recorded change in sensitivity. However, although the fault did not show a change in measured electrical impedance (the fault was manifest as a complete loss of signal), it is not impossible that before the failure a change in capacitance was caused.

9.2 NEXT STEPS

This report is the Final Report for Key Comparison CCAUV.W-K2, which is now completed.

To address the problems of discrepancies in the frequency range 60 kHz to 100 kHz, participants have agreed that opportunities should be given to discrepant NMIs to calibrate using an alternative hydrophone over this problem frequency range. This will need approval of CCAUV and will be organised as an additional follow-on comparison exercise. NPL is willing to lead this exercise and supply a suitable hydrophone for use. A Reson TC4033 hydrophone (resonance frequency approximately 100 kHz) is available which shows more temperature stability than the B&K8014 hydrophone originally selected. In addition, should any further participants be unable to conform to the requirements of the protocol for temperature, NPL has already calibrated this hydrophone over the range of temperatures used by participants in the current comparison (this was done during the investigation of the response of the B&K8104 hydrophone).

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12 ANNEX A: FULL RESULTS OF PARTICIPANTS WITH UNCERTAINTIES

Frequency (kHz)	Sensitivity level (dB re 1V/µPa)	Sensitivity (µV/Pa)	Uncertainty k=1 (%)
0.25	-206.16	49.20	6.3
0.3	-206.25	48.70	5.0
0.4	-206.27	48.58	4.1
0.5	-206.31	48.36	3.1
0.6	-206.32	48.31	3.1
0.7	-206.32	48.31	2.9
0.8	-206.30	48.42	2.9
0.9	-206.32	48.31	2.6
1	-206.35	48.14	2.6
2	-206.39	47.92	2.6
3	-206.45	47.59	2.3
4	-206.42	47.75	2.3
5	-207.00	44.67	2.8
6	-207.35	42.90	2.8
7	-207.38	42.76	2.0
8	-207.33	43.00	2.0
9	-207.33	43.00	2.0
10	-207.28	43.25	2.0
12	-207.17	43.80	2.0
14	-207.36	42.85	2.0
16	-207.73	41.07	2.0
18	-208.13	39.22	2.3
20	-208.16	39.08	2.0
22	-207.84	40.55	2.0
24	-207.86	40.46	2.0
26	-207.81	40.69	2.0
28	-207.86	40.46	2.0
30	-207.91	40.23	2.0
32	-207.72	41.11	2.3
34	-207.61	41.64	2.3
36	-207.51	42.12	2.3
38	-207.38	42.76	2.3
40	-207.12	44.06	2.0
42	-206.42	47.75	2.0
44	-205.98	50.23	2.0
46	-205.55	52.78	2.0
48	-205.11	55.53	2.0
50	-204.83	57.35	2.0
52	-204.71	58.14	2.0
54	-204.47	59.77	2.0
56	-204.46	59.84	2.0
58	-204.63	58.68	2.0
60	-204.78	57.68	2.3
62	-205.05	55.91	2.3
64	-205.22	54.83	2.3
66	-205.39	53.77	2.3
68	-205.58	52.60	2.3
70	-205.85	51.02	2.4
72	-205.98	50.23	2.3
74	-206.08	49.66	2.3
76	-206.31	48.36	2.1
78	-206.49	47.37	2.1
80	-206.77	45.87	2.1
82	-207.18	43.75	2.1
84	-207.58	41.78	2.1
86	-207.98	39.90	2.1
88	-208.35	38.24	2.1
90	-208.79	36.35	2.1
100	-210.65	29.34	2.1
110	-212.88	22.70	2.3
120	-215.37	17.04	2.3

Table 12.1
Results for NPL (GBR) for B&K8104 hydrophone from 250 Hz to 120 kHz

Frequency (kHz)	Sensitivity level (dB re 1V/μPa)	Sensitivity (μV/Pa)	Uncertainty k=1 (%)
2	-206.32	48.31	4.2
3	-206.43	47.69	4.2
4	-206.28	48.52	4.2
5	-207.00	44.65	4.2
6	-208.12	39.27	4.3
7	-207.50	42.18	4.3
8	-207.23	43.52	4.3
9	-207.06	44.38	4.2
10	-207.00	44.66	4.2
12	-207.22	43.57	4.2
14	-207.24	43.46	4.2
16	-207.89	40.31	4.2
18	-208.19	38.96	4.2
20	-208.16	39.09	4.2
22	-207.89	40.31	4.2
24	-207.85	40.50	4.2
26	-208.00	39.79	4.2
28	-207.95	40.04	4.2
30	-208.07	39.51	4.2
32	-207.77	40.87	4.2
34	-207.59	41.74	4.2
36	-207.28	43.24	4.2
38	-207.21	43.60	4.2
40	-207.35	42.92	4.2
42	-206.38	47.95	4.2
44	-205.59	52.52	4.2
46	-205.43	53.49	4.2
48	-204.98	56.37	4.2
50	-204.93	56.68	4.2
52	-204.81	57.51	4.2
54	-204.41	60.20	4.2
56	-204.06	62.63	4.2
58	-204.37	60.49	4.2
60	-204.63	58.66	4.2
62	-204.82	57.43	4.2
64	-205.06	55.83	4.2
66	-205.39	53.74	4.2
68	-205.48	53.19	4.2
70	-205.54	52.83	4.2
72	-205.73	51.70	4.2
74	-206.00	50.13	4.2
76	-206.29	48.47	4.2
78	-206.55	47.04	4.2
80	-206.82	45.58	4.2
82	-207.13	43.99	4.2
84	-207.56	41.89	4.2
86	-208.01	39.77	4.2
88	-208.41	37.96	4.2
90	-208.81	36.25	4.2
100	-210.61	29.48	4.2
110	-212.81	22.88	4.2
120	-215.24	17.30	4.2

Table 12.2
Results for TUBITAK-MAM (TUR) for B&K8104 hydrophone from 2 kHz to 120 kHz

Frequency (kHz)	Sensitivity level (dB re 1V/µPa)	Sensitivity (µV/Pa)	Uncertainty k=1 (%)
0.25	-206.30	48.44	2.4
0.3	-206.30	48.14	2.4
0.4	-206.30	48.21	2.4
0.5	-206.30	48.50	2.4
0.6	-206.30	48.52	2.3
0.7	-206.30	48.69	2.3
0.8	-206.30	48.52	2.3
0.9	-206.40	48.07	2.3
1	-206.40	48.11	2.3
2	-206.30	48.30	2.4
3	-206.30	48.33	2.4
4	-206.30	48.56	2.4
5	-206.40	47.76	2.5
6	-206.70	46.29	2.5
7	-206.90	45.32	2.5
8	-207.30	43.36	2.5
9	-207.30	43.35	2.5
10	-207.20	43.64	2.5
12	-207.10	44.17	2.4
14	-207.00	44.58	2.5
16	-207.30	43.31	2.5
18	-207.60	41.69	2.5
20	-207.60	41.65	2.5
22	-207.80	40.69	2.5
24	-207.70	41.18	2.5
26	-207.40	42.69	2.5
28	-207.70	41.01	2.5
30	-207.70	41.08	2.5
32	-207.00	44.52	2.5
34	-207.00	44.82	2.5
36	-206.90	45.13	2.5
38	-206.70	46.37	2.5
40	-206.60	46.82	2.7
42	-205.70	52.17	2.8
44	-205.10	55.34	2.7
46	-204.90	56.67	2.7
48	-204.60	59.01	2.7
50	-204.30	61.10	2.7
52	-204.10	62.17	2.7
54	-203.90	63.97	2.7
56	-203.90	64.18	2.7
58	-203.90	63.68	2.7
60	-204.10	62.19	2.8
62	-204.30	61.08	2.7
64	-204.50	59.60	2.7
66	-204.70	58.47	2.7
68	-204.80	57.69	2.7
70	-205.10	55.69	2.7
72	-205.40	53.56	2.7
74	-205.60	52.44	2.7
76	-206.00	50.40	2.7
78	-206.20	49.10	2.7
80	-206.30	48.21	2.7
82	-206.60	46.58	2.7
84	-207.20	43.78	2.7
86	-207.70	41.26	2.7
88	-208.10	39.21	2.7
90	-208.50	37.40	2.7
100	-210.30	30.52	2.8
110	-212.30	24.26	2.8
120	-214.50	18.79	2.8

Table 12.3
Results for VNIIFTRI (RUS) for B&K8104 hydrophone from 250 Hz to 120 kHz

Frequency (kHz)	Sensitivity level (dB re 1V/μPa)	Sensitivity (μV/Pa)	Uncertainty k=1 (%)
0.25	-206.81	45.67	8.1
0.3	-205.92	50.57	8.1
0.4	-206.34	48.20	8.1
0.5	-206.68	46.34	6.1
0.6	-206.38	47.97	6.1
0.7	-206.06	49.77	6.1
0.8	-206.30	48.41	6.1
0.9	-206.49	47.36	6.1
1	-206.25	48.72	2.4
2	-206.31	48.39	2.4
3	-206.50	47.30	2.4
4	-206.49	47.39	2.4
5	-206.35	48.13	2.4
6	-207.35	42.89	2.4
7	-207.03	44.52	2.4
8	-207.57	41.85	2.4
9	-207.58	41.79	2.4
10	-207.46	42.36	2.4
12	-207.25	43.42	2.4
14	-207.12	44.08	2.4
16	-207.21	43.59	2.4
18	-207.47	42.32	2.4
20	-207.74	41.04	2.4
22	-207.90	40.26	2.4
24	-208.32	38.39	2.4
26	-208.07	39.49	2.4
28	-208.03	39.66	2.4
30	-208.07	39.50	2.4
32	-207.41	42.60	2.4
34	-207.10	44.17	2.4
36	-207.14	43.97	2.4
38	-207.04	44.46	2.4
40	-206.76	45.90	2.4
42	-206.81	45.66	2.4
44	-206.15	49.25	2.4
46	-205.65	52.18	2.4
48	-205.40	53.73	2.4
50	-205.10	55.58	2.4
52	-204.68	58.32	2.4
54	-204.48	59.71	2.4
56	-204.60	58.86	2.4
58	-204.79	57.64	2.4
60	-204.89	56.93	2.4
62	-205.14	55.33	2.4
64	-205.34	54.10	3.6
66	-205.58	52.58	3.6
68	-205.96	50.35	3.6
70	-206.28	48.53	3.6
72	-206.42	47.74	3.6
74	-206.56	46.97	3.6
76	-206.93	45.05	3.6
78	-207.36	42.84	3.6
80	-207.75	41.00	3.6
82	-208.14	39.19	3.6
84	-208.57	37.29	3.6
86	-209.05	35.27	3.6
88	-209.49	33.52	3.6
90	-209.89	32.02	3.6
100	-211.65	26.14	3.6
110	-213.69	20.68	3.6
120	-215.68	16.44	3.6

Table 12.4
Results for USRD (USA) for B&K8104 hydrophone from 250 Hz to 120 kHz

Frequency (kHz)	Sensitivity level (dB re 1V/μPa)	Sensitivity (μV/Pa)	Uncertainty % k=1
0.25	-206.00	50.12	3.7
0.3	-206.00	50.12	3.7
0.4	-206.20	48.98	3.7
0.5	-206.00	50.12	3.7
0.6	-206.00	50.12	3.8
0.7	-206.10	49.55	3.7
0.8	-206.30	48.42	3.8
0.9	-206.40	47.86	3.8
1	-206.35	48.14	3.8
2	-206.60	46.77	3.9
3	-206.60	46.77	3.9
4	-206.50	47.32	4.0
5	-206.70	46.24	3.9
6	-206.90	45.19	3.9
7	-207.20	43.65	4.0
8	-207.80	40.74	4.0
9	-207.60	41.69	4.0
10	-207.50	42.17	3.9
12	-207.40	42.66	4.0
14	-207.40	42.66	3.9
16	-207.40	42.66	4.0
18	-207.70	41.21	4.0
20	-208.00	39.81	4.0
22	-208.10	39.36	4.0
24	-208.30	38.46	4.0
26	-208.00	39.81	4.0
28	-208.10	39.36	3.9
30	-208.10	39.36	4.0
32	-207.40	42.66	4.0
34	-207.60	41.69	4.0
36	-207.10	44.16	4.0
38	-207.30	43.15	4.0
40	-206.80	45.71	3.9
42	-206.40	47.86	3.9
44	-206.10	49.55	4.0
46	-205.50	53.09	4.0
48	-205.00	56.23	4.0
50	-204.60	58.88	4.0
52	-204.40	60.26	4.0
54	-204.20	61.66	4.0
56	-204.20	61.66	4.0
58	-204.20	61.66	4.1
60	-204.40	60.26	4.1
62	-204.70	58.21	4.0
64	-205.00	56.23	4.0
66	-205.00	56.23	3.9
68	-205.10	55.59	3.9
70	-205.30	54.33	4.0
72	-205.50	53.09	4.0
74	-206.00	50.12	4.0
76	-206.30	48.42	4.0
78	-206.40	47.86	4.0
80	-206.70	46.24	4.0
82	-207.00	44.67	4.0
84	-207.40	42.66	4.0
86	-207.90	40.27	4.0
88	-208.30	38.46	4.0
90	-208.80	36.31	4.0
100	-210.90	28.51	4.0
110	-212.90	22.65	4.2
120	-215.30	17.18	4.3

Table 12.5
Results for HAARI (CHN) for B&K8104 hydrophone from 250 Hz to 120 kHz

Frequency (kHz)	Sensitivity level (dB re 1V/µPa)	Sensitivity (µV/Pa)	Uncertainty k=1 (%)
4	-206.36	48.06	3.3
5	-206.56	47.01	3.3
6	-206.84	45.52	3.3
7	-206.91	45.13	3.3
8	-207.38	42.75	3.3
9	-207.48	42.26	3.3
10	-207.60	41.68	3.3
12	-207.48	42.26	2.7
14	-207.49	42.24	2.7
16	-207.53	42.02	2.7
18	-207.90	40.27	2.7
20	-207.95	40.05	2.7
22	-208.00	39.83	2.7
24	-208.01	39.75	2.7
26	-207.81	40.70	2.7
28	-208.19	38.97	2.7
30	-208.09	39.38	2.7
32	-207.48	42.25	2.7
34	-207.37	42.79	2.7
36	-207.34	42.93	2.7
38	-206.94	44.98	2.7
40	-206.98	44.78	2.7
42	-206.60	46.76	2.7
44	-205.97	50.32	2.7
46	-205.75	51.56	2.7
48	-205.21	54.90	2.7
50	-204.76	57.80	2.7
52	-204.55	59.24	2.7
54	-204.60	58.87	2.7
56	-204.52	59.43	2.7
58	-204.39	60.36	2.7
60	-204.47	59.76	2.7
62	-204.67	58.43	2.4
64	-204.85	57.21	2.4
66	-204.97	56.40	2.4
68	-205.34	54.06	2.4
70	-205.61	52.41	2.4
72	-206.02	50.03	2.4
74	-206.33	48.25	2.4
76	-206.54	47.11	2.4
78	-206.81	45.65	2.4
80	-207.05	44.39	2.4
82	-207.38	42.75	2.4
84	-207.78	40.82	2.4
86	-208.21	38.86	2.4
88	-208.64	36.99	2.4
90	-209.03	35.36	2.4
100	-210.75	29.00	2.3
110	-212.79	22.94	2.3
120	-215.15	17.48	2.3

Table 12.6
Results for NMISA (ZAF) for B&K8104 hydrophone from 4 kHz to 120 kHz

Frequency (kHz)	Sensitivity level (dB re 1V/µPa)	Sensitivity (µV/Pa)	Uncertainty k=1 (%)
1	-206.00	50.12	9.4
2	-206.11	49.49	4.1
3	-206.01	50.06	3.4
4	-206.06	49.77	3.3
5	-206.13	49.37	3.4
6	-207.28	43.25	4.1
7	-206.45	47.59	4.0
8	-206.95	44.93	3.6
9	-207.01	44.62	2.7
10	-206.76	45.92	2.7
12	-206.58	46.88	3.2
14	-206.92	45.08	2.5
16	-207.48	42.27	3.1
18	-207.77	40.88	2.4
20	-207.66	41.40	2.3
22	-207.60	41.69	3.6
24	-207.48	42.27	3.7
26	-207.64	41.50	2.5
28	-207.73	41.07	3.3
30	-207.91	40.23	2.6
32	-207.70	41.21	2.2
34	-207.52	42.07	2.4
36	-207.29	43.20	2.1
38	-207.36	42.85	2.7
40	-207.26	43.35	3.2
42	-206.61	46.72	4.7
44	-205.73	51.70	3.3
46	-205.59	52.54	2.9
48	-205.47	53.27	2.7
50	-205.26	54.58	2.4
52	-205.19	55.02	2.4
54	-204.96	56.49	2.9
56	-204.84	57.28	2.3
58	-205.13	55.40	2.4
60	-205.54	52.84	2.9
62	-205.72	51.76	2.3
64	-206.04	49.89	2.6
66	-206.27	48.58	3.2
68	-206.40	47.86	3.0
70	-206.57	46.94	2.4
72	-206.70	46.24	2.2
74	-206.79	45.76	2.2
76	-206.96	44.87	2.2
78	-207.14	43.95	2.2
80	-207.43	42.51	2.2
82	-207.79	40.78	2.3
84	-208.20	38.90	2.4
86	-208.66	36.90	2.5
88	-209.09	35.12	2.8
90	-209.53	33.38	3.0
100	-211.90	25.41	3.3

Table 12.7
Results for INMETRO (BRA) for B&K8104 hydrophone from 1 kHz to 100 kHz

Frequency (kHz)	Sensitivity level (dB re 1V/μPa)	Sensitivity (μV/Pa)	Uncertainty k=1 (%)
100	-219.86	10.16	2.1
110	-219.78	10.26	2.1
120	-219.73	10.32	2.1
130	-219.40	10.72	2.1
140	-219.26	10.89	2.1
150	-219.81	10.22	2.1
160	-219.75	10.29	2.1
170	-219.77	10.27	2.1
180	-219.36	10.76	2.1
190	-219.51	10.58	2.1
200	-219.46	10.64	2.1
210	-219.44	10.67	2.1
220	-219.33	10.80	2.1
230	-219.20	10.96	2.1
240	-218.97	11.26	2.1
250	-219.15	11.03	2.1
260	-219.03	11.18	2.1
270	-218.62	11.72	2.1
280	-218.35	12.09	2.1
290	-217.88	12.76	2.1
300	-217.23	13.76	2.9
310	-216.74	14.55	3.0
320	-215.79	16.24	3.0
330	-215.43	16.92	3.0
340	-215.69	16.42	3.0
350	-216.20	15.49	3.0
360	-217.74	12.97	3.0
370	-219.66	10.40	3.0
380	-221.43	8.48	3.0
390	-222.76	7.28	3.0
400	-224.44	6.00	3.0
410	-225.43	5.35	3.5
420	-225.99	5.02	3.5
430	-226.59	4.68	3.5
440	-227.19	4.37	3.5
450	-227.54	4.20	3.5
460	-227.84	4.06	3.5
470	-228.14	3.92	3.5
480	-228.59	3.72	3.5
490	-229.05	3.53	3.5
500	-230.55	2.97	3.5

Table 12.8
Results for NPL (GBR) for TC4034 hydrophone from 100 kHz to 500 kHz

Frequency (kHz)	Sensitivity level (dB re 1V/µPa)	Sensitivity (µV/Pa)	Uncertainty k=1 (%)
100	-219.65	10.41	2.9
110	-219.68	10.37	2.9
120	-219.64	10.43	2.9
130	-219.42	10.69	2.9
140	-219.38	10.74	3.0
150	-219.72	10.33	3.0
160	-219.68	10.38	3.0
170	-219.68	10.38	3.0
180	-219.47	10.64	2.9
190	-219.44	10.67	2.9
200	-219.33	10.80	3.0
210	-219.30	10.84	3.0
220	-219.24	10.91	3.0
230	-219.12	11.07	3.0
240	-218.95	11.29	3.0
250	-219.18	10.99	3.0
260	-218.93	11.31	3.0
270	-218.59	11.76	3.0
280	-218.50	11.89	3.0
290	-218.09	12.46	3.0
300	-217.54	13.27	3.0
310	-217.27	13.69	3.0
320	-216.29	15.33	3.0
330	-215.85	16.13	3.0
340	-215.95	15.95	3.0
350	-216.55	14.87	3.0
360	-217.96	12.65	3.0
370	-219.59	10.48	3.0
380	-221.43	8.48	3.0
390	-223.08	7.01	3.0
400	-224.48	5.97	3.0
410	-225.50	5.31	3.0
420	-226.37	4.80	3.0
430	-227.08	4.43	3.0
440	-227.61	4.16	3.0
450	-227.96	4.00	3.0
460	-228.24	3.87	3.0
470	-228.50	3.76	3.0
480	-228.88	3.60	3.0
490	-229.14	3.49	3.0
500	-230.44	3.01	3.0

Table 12.9
Results for TUBITAK-MAM (TUR) for TC4034 hydrophone from 100 kHz to 500 kHz

Frequency (kHz)	Sensitivity level (dB re 1V/μPa)	Sensitivity (μV/Pa)	Uncertainty k=1 (%)
100	-219.50	10.57	2.9
110	-219.40	10.66	2.9
120	-219.30	10.85	3.0
130	-219.10	11.10	2.9
140	-219.10	11.07	2.9
150	-219.30	10.81	2.9
160	-219.40	10.75	2.9
170	-219.50	10.62	2.9
180	-219.20	10.95	2.9
190	-219.20	10.94	2.9
200	-219.10	11.06	2.9
210	-219.10	11.15	2.9
220	-219.00	11.20	2.9
230	-218.90	11.37	2.9
240	-218.70	11.64	2.9
250	-218.80	11.47	2.9
260	-218.70	11.64	2.9
270	-218.50	11.93	2.9
280	-218.30	12.20	2.9
290	-217.90	12.70	2.9
300	-217.40	13.51	2.9
310	-216.90	14.26	3.0
320	-215.80	16.27	2.9
330	-215.60	16.57	3.0
340	-215.80	16.19	3.0
350	-216.20	15.51	2.9
360	-217.50	13.34	2.9
370	-219.20	10.99	2.9
380	-221.20	8.74	2.9
390	-222.90	7.14	2.9
400	-224.40	6.05	2.9
410	-225.40	5.35	2.9
420	-226.30	4.85	2.9
430	-226.90	4.50	2.9
440	-227.50	4.24	3.0
450	-228.00	3.99	2.9
460	-228.20	3.88	3.0
470	-228.50	3.78	3.0
480	-228.90	3.58	2.9
490	-229.30	3.42	3.0
500	-230.40	3.01	3.0

Table 12.10
Results for VNIIFTRI (RUS) for TC4034 hydrophone from 100 kHz to 500 kHz

Frequency (kHz)	Sensitivity level (dB re 1V/μPa)	Sensitivity (μV/Pa)	Uncertainty k=1 (%)
100	-219.44	10.67	3.6
110	-219.49	10.60	3.6
120	-219.42	10.69	3.6
130	-219.30	10.84	3.6
140	-219.30	10.83	3.6
150	-219.52	10.57	3.6
160	-219.44	10.67	3.6
170	-219.48	10.62	3.6
180	-219.25	10.90	3.6
190	-219.27	10.88	3.6
200	-219.06	11.15	3.6
210	-219.09	11.11	3.6
220	-219.06	11.15	3.6
230	-219.02	11.20	3.6
240	-218.88	11.37	3.6
250	-219.01	11.20	3.6
260	-218.68	11.64	3.6
270	-218.60	11.75	3.6
280	-218.42	12.00	3.6
290	-217.98	12.61	3.6
300	-217.26	13.71	3.6
310	-216.92	14.25	3.6
320	-216.03	15.79	3.6
330	-215.51	16.77	3.6
340	-215.68	16.44	3.6
350	-216.41	15.12	3.6
360	-217.71	13.02	3.6
370	-219.39	10.73	3.6
380	-221.27	8.64	3.6
390	-222.95	7.12	3.6
400	-224.29	6.10	3.6
410	-225.45	5.34	3.6
420	-226.39	4.79	3.6
430	-227.06	4.44	3.6
440	-227.64	4.15	3.6
450	-227.83	4.06	3.6
460	-228.17	3.90	3.6
470	-228.49	3.76	3.6
480	-228.90	3.59	3.6
490	-229.24	3.45	3.6
500	-230.42	3.01	3.6

Table 12.12
Results for USRD (USA) for TC4034 hydrophone from 100 kHz to 500 kHz

Frequency (kHz)	Sensitivity level (dB re 1V/μPa)	Sensitivity (μV/Pa)	Uncertainty % k=1
100	-219.80	10.23	5.1
110	-219.80	10.23	5.1
120	-219.60	10.47	5.1
130	-219.30	10.84	5.1
140	-219.40	10.72	5.1
150	-219.70	10.35	5.1
160	-219.60	10.47	5.1
170	-219.60	10.47	5.1
180	-219.60	10.47	5.1
190	-219.40	10.72	5.1
200	-219.30	10.84	5.1
210	-219.20	10.96	5.1
220	-219.00	11.22	5.1
230	-219.10	11.09	5.1
240	-218.90	11.35	5.1
250	-218.90	11.35	5.1
260	-218.80	11.48	5.1
270	-218.50	11.89	5.1
280	-218.50	11.89	5.1
290	-218.10	12.45	5.1
300	-217.80	12.88	5.1
310	-217.90	12.74	5.1
320	-216.70	14.62	5.1
330	-216.40	15.14	5.1
340	-216.70	14.62	5.1
350	-217.10	13.96	5.1
360	-218.40	12.02	5.1
370	-220.00	10.00	5.1
380	-221.80	8.13	5.1
390	-223.30	6.84	5.1
400	-224.70	5.82	5.1
410	-225.80	5.13	5.1
420	-226.50	4.73	5.1
430	-227.30	4.32	5.1
440	-227.70	4.12	5.1
450	-228.10	3.94	5.1
460	-228.50	3.76	5.1
470	-228.80	3.63	5.1
480	-229.00	3.55	5.1
490	-229.60	3.31	5.1
500	-230.80	2.88	5.1

Table 12.13
Results for HAARI (CHN) for TC4034 hydrophone from 100 kHz to 500 kHz

13 ANNEX B: CALIBRATIONS BY NIOT (GUEST PARTICIPANT)

13.1 GUEST PARTICIPANT STATUS

The National Institute for Ocean Technology in India participated in CCAUV.W-K2 as a guest participant. According to the rules of the MRA (CIPM MRA-G-11), this means that the results if NIOT cannot be incorporated into the calculation of the KCRVs. However, DOEs for NIOT can be calculated based on their results, and the institute may then use the resulting DOEs to support future applications for DI status or CMC submission.

13.2 CALIBRATION METHOD

The calibration method was the method of three-transducer spherical wave reciprocity in conformance with IEC 60565: 2006.

A deviation from protocol was reported because the water temperature in the test tank was 28.5 °C – 31.5 °C which is outside the range stipulated by the protocol (17 °C – 21 °C).

The test facility consists of an acoustic tank made of concrete and has a dimension of 16 m x 9 m on top, and 14.2 m by 7.2 m at the bottom (water depth of 7 m). No baffles or absorbers were used. The transducer positioning system consists of two special purpose platforms moving over the tank which have longitudinal and transverse movements across the tank, and are driven by electric motor coupled with gearbox. Vertical movement of the device under test is achieved by means of a hydraulic system and this can also be rotated around its axis (1˚ angular resolution). Longitudinal, transverse and depth movements are controlled by a PLC based system. Required positional values can be set through a touch panel in the control cabin or via remote computer.

Both hydrophones were mounted in the manner requested by the protocol (see Section 3.2.4). Hydrophones are mounted by using a single platform for calibration. The hydrophone along with the carbon fibre pole are rigidly fixed at the tail end of the vertical hydraulic system. The transducers are separated by 1 m with an accuracy of approximately ± 2 mm by using a special positioning structure.

Discrete-frequency tone-burst signals were used to cover the required frequency range, with time-gating used to eliminate reflected signals from the measurement. The measurements were made on the steady-state part of the signal. The signal level was determined from the magnitude of the auto power spectrum. The tone burst signal with the length of between 0.5 ms to 2 ms was used for signal transmission. B&K PULSE Labshop software is used for calibration in the frequency range 2 kHz to 100 kHz. A LabVIEW program developed by NIOT is used for calibration of hydrophones in the frequency range 100 kHz to 500 kHz. No extra extension cable was added during calibration.

The hydrophones are immersed in water one day before the commencement of calibration and it remained in water till calibration is completed. The sensitive element of the hydrophones is gently cleaned before immersion. Independent repeated calibrations were made for each hydrophone with the devices removed from the water and remounted.

The environmental conditions are shown in Table 13.1.

Table 13.1 Conditions for calibrations by NIOT

Hydrophone	Water temperature (°C)	Immersion depth (m)	Separation distances (m)
B&K8104	28.5 – 31.5	2.0	1.00
TC4034	28.5 – 31.5	2.0	1.00

The calibration uncertainties were evaluated according to the JCGM/ISO/IEC Guide to the Expression of Uncertainty in Measurement [JCGM 100:2008] and the guidance on components provided in IEC 60565:2006. The spreadsheet provided along with the protocol was used as a guide in the calculation of the combined uncertainty.

The combined uncertainties expressed as standard uncertainties varied with frequency, ranging from a minimum of 2.4% at mid kilohertz frequencies, to a maximum of 5.5% at the lowest extremes of the frequency range (between 4.8% and 11.0% expressed as an expanded uncertainty for *k*=2).

For frequencies between 250 Hz and 1 kHz, a calibration of the B&K8104 was undertaken by the vibrating column method. The system uses calibration by comparison and is a modification of an absolute method described in IEC 60565. A reference hydrophone and the hydrophone under calibration are placed in a hydrodynamic pressure field (in water), with the acoustical centres at the mid of the water column with the accuracy of ±2 mm. The sensitivity of the hydrophone under test is determined from the sensitivity of a known reference standard. The excitation signal is a discrete sine wave or a random signal of required bandwidth up to 1 kHz. The auto-spectra for the FRF (frequency response function) is measured by means of 1/24 octave CPB filters in this method. The main elements of the calibration system include a cylindrical Aluminium test vessel with the dimension of 0.3 m inner diameter and 2 cm wall thickness, vibration shaker of make LDS V450, B&K PULSE IO module for signal generation and data acquisition and power amplifier of model B&K 2721.

Note that this method is not a free-field method and so falls outside the scope of this key comparison. In addition, it has been implemented as a relative and not an absolute calibration method in this instance. The results are presented here for completeness.

13.3 RESULTS

The results declared by NIOT for the B&K8104 hydrophone in the frequency range 2 kHz to 120 kHz and the TC4034 in the range 100 kHz to 500 kHz are shown in the tables in the following pages.

Results are also shown for the low frequency pressure calibrations undertaken using the vibrating column method.

Also shown in the tables are the declared uncertainties at each frequency, expressed in percent as a standard uncertainty (for a coverage factor *k*=1). The declared uncertainties were expressed in decibels. The values in percent are the average of the positive and negative uncertainties obtained after conversion from decibels. If the submitted uncertainties were expressed as expanded uncertainties, these have been converted to standard uncertainties using the declared value of the coverage factor, *k*.

13.3.1 Tabulated results

Frequency (kHz)	Sensitivity level (dB re 1V/μPa)	Sensitivity (μV/Pa)	Uncertainty k=1 (%)
2	-206.40	47.86	5.5
3	-206.10	49.55	5.5
4	-205.90	50.70	4.8
5	-207.40	42.66	4.8
6	-207.50	42.17	4.2
7	-207.30	43.15	4.2
8	-207.10	44.16	4.8
9	-206.80	45.71	4.2
10	-206.30	48.42	4.2
12	-206.20	48.98	4.2
14	-206.80	45.71	3.6
16	-207.20	43.65	3.6
18	-207.60	41.69	3.6
20	-207.60	41.69	3.6
22	-207.50	42.17	3.6
24	-207.60	41.69	3.0
26	-207.60	41.69	3.6
28	-207.70	41.21	3.0
30	-207.50	42.17	3.6
32	-207.10	44.16	3.6
34	-207.00	44.67	3.6
36	-206.90	45.19	3.6
38	-206.50	47.32	4.2
40	-206.50	47.32	3.6
42	-206.20	48.98	3.6
44	-205.70	51.88	3.0
46	-205.50	53.09	3.6
48	-205.10	55.59	4.2
50	-204.80	57.54	3.6
52	-204.60	58.88	3.0
54	-204.40	60.26	3.6
56	-204.30	60.95	3.6
58	-204.30	60.95	3.6
60	-204.60	58.88	3.6
62	-204.90	56.89	4.2
64	-205.20	54.95	4.2
66	-205.20	54.95	3.6
68	-205.40	53.70	3.6
70	-205.50	53.09	3.6
72	-205.60	52.48	3.6
74	-205.60	52.48	3.6
76	-205.60	52.48	3.6
78	-205.60	52.48	3.6
80	-205.70	51.88	4.2
82	-205.90	50.70	4.2
84	-206.30	48.42	4.2
86	-206.70	46.24	4.2
88	-207.10	44.16	4.2
90	-207.40	42.66	4.2
100	-209.60	33.11	4.2
110	-212.40	23.99	4.2
120	-215.20	17.38	4.8

Table 13.1
Results for NIOT for B&K8104 hydrophone from 2 kHz to 120 kHz

Frequency kHz	Sensitivity level (dB re 1V/μPa)	Sensitivity (μV/Pa)	Uncertainty % k=1
100	-219.2	10.96	2.4
110	-219.3	10.84	2.4
120	-219.6	10.47	2.4
130	-219.3	10.84	2.4
140	-219.3	10.84	2.4
150	-219.3	10.84	2.4
160	-219.2	10.96	2.4
170	-219.4	10.72	2.4
180	-219.1	11.09	2.4
190	-219.2	10.96	2.4
200	-219.2	10.96	2.4
210	-219.2	10.96	2.4
220	-219.1	11.09	3.0
230	-218.9	11.35	3.0
240	-218.8	11.48	3.6
250	-218.9	11.35	4.2
260	-218.4	12.02	4.2
270	-218.3	12.16	3.6
280	-217.8	12.88	3.6
290	-217.1	13.96	3.6
300	-216.1	15.67	3.6
310	-215.9	16.03	3.0
320	-214.5	18.84	3.6
330	-214.4	19.05	3.6
340	-215.0	17.78	4.8
350	-215.8	16.22	4.2
360	-217.4	13.49	4.2
370	-219.3	10.84	4.2
380	-221.1	8.81	4.2
390	-222.4	7.59	4.2
400	-223.4	6.76	4.2
410	-224.8	5.75	3.6
420	-225.8	5.13	3.6
430	-226.0	5.01	3.6
440	-226.3	4.84	3.6
450	-226.5	4.73	4.2
460	-227.1	4.42	4.2
470	-227.2	4.37	4.2
480	-227.3	4.32	3.0
490	-228.4	3.80	3.0
500	-230.1	3.13	3.0

Table 13.2
Results for NIOT
for TC4034 hydrophone
from 2 kHz to 120 kHz

13.3.2 Plots of results

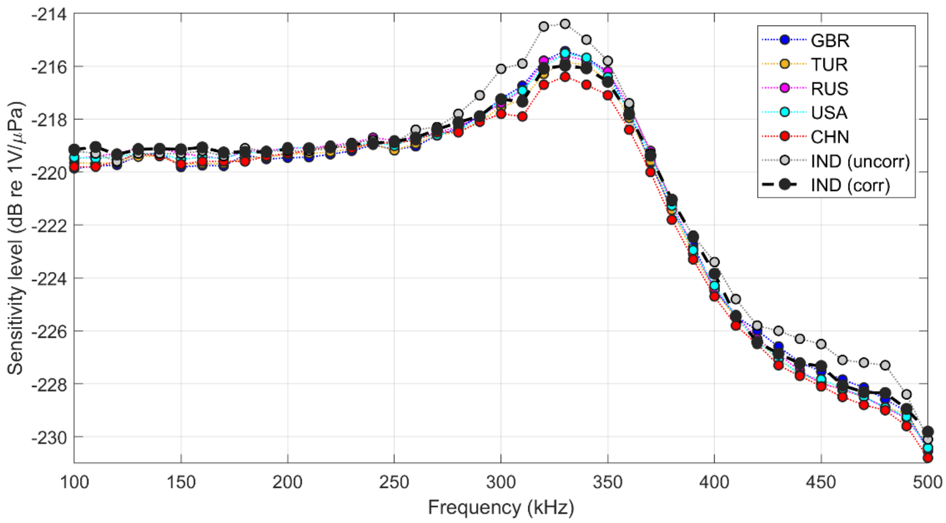


Figure 13.1 The sensitivity levels for the TC4034 hydrophone from 100 kHz to 500 kHz showing the NIOT results

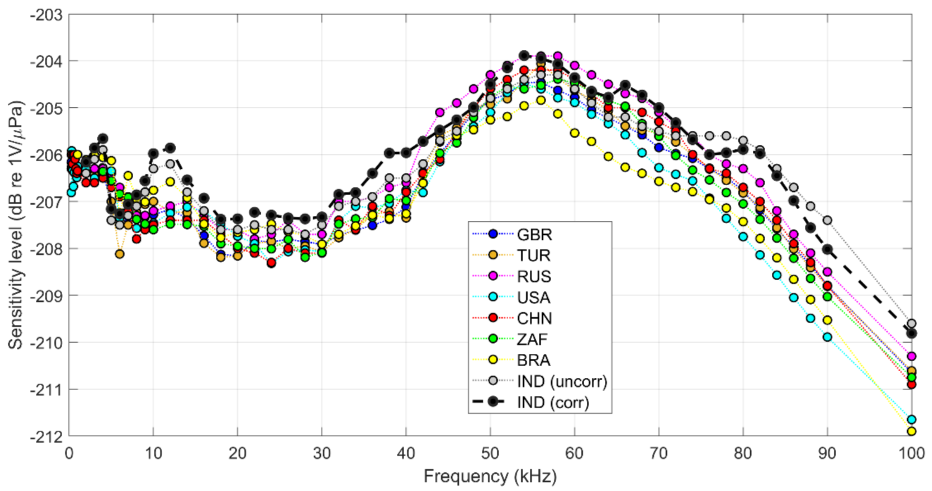


Figure 13.2 The sensitivity levels for the B&K8104 hydrophone from 250 Hz to 100 kHz showing the NIOT results

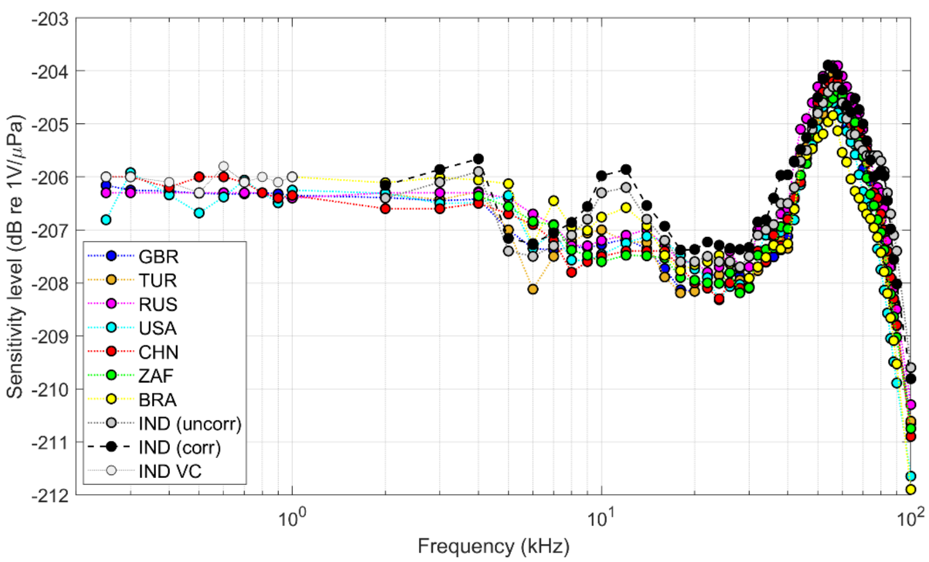


Figure 13.3 The sensitivity levels for the B&K8104 hydrophone from 250 Hz to 100 kHz showing the NIOT results and the NIOT low frequency results ((VC)) on a log frequency scale

13.3.3 Corrected results

The results below show the results for NIOT before and after correction for temperature using the method described in Section 8.1.

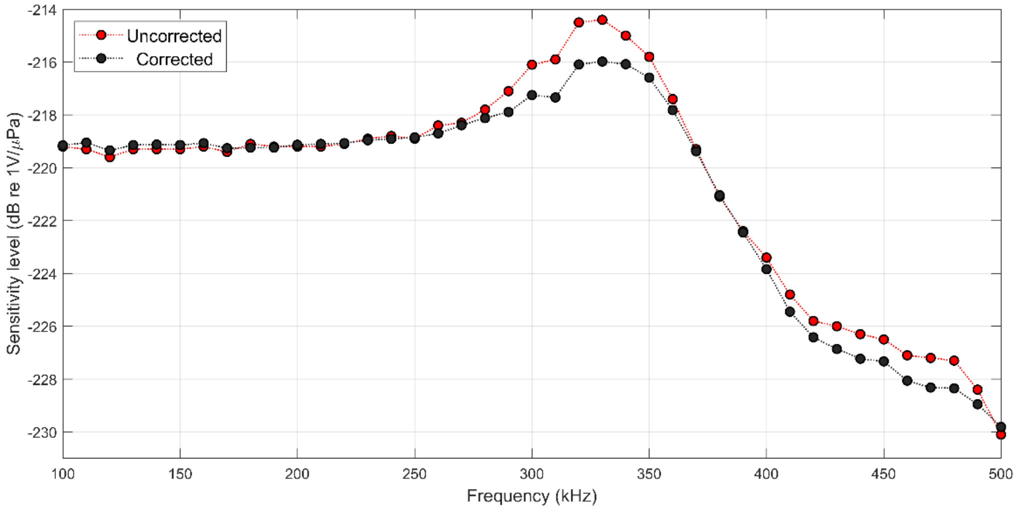


Figure 13.4 The sensitivity levels for the TC4034 hydrophone from 100 kHz to 500 kHz for NIOT before and after correction for temperature.

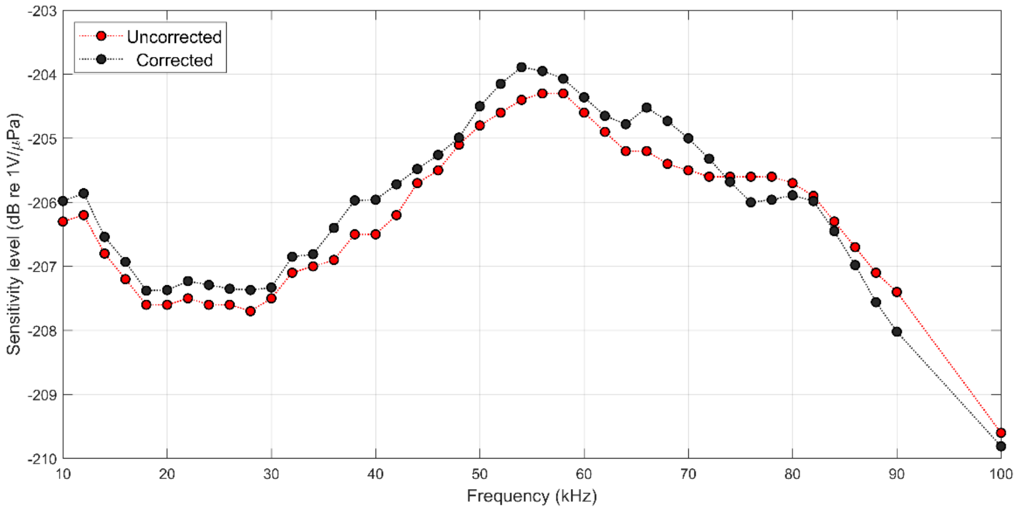


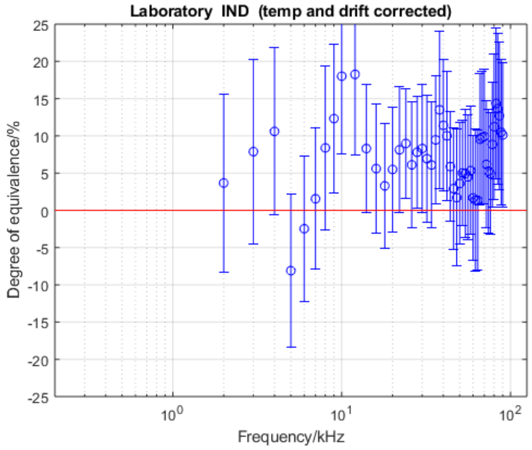
Figure 13.5 The sensitivity levels for the B&K8104 hydrophone from 10 kHz to 100 kHz for NIOT before and after correction for temperature.

13.4 DEGREES OF EQUIVALENCE

The tables in this section show the DOEs for NIOT at all frequencies (expressed in percent) calculated from the differences of NIOT's results from the KCRVs. Also shown are the uncertainties on the DOEs, calculated from the uncertainty of NIOT's results and uncertainties on the KCRVs accounting for correlation (see Section 8.1.1).

For both hydrophones, the three candidate approaches are shown: the first shows the DOEs for the NIOT results with no corrections, the second shows the DOEs for temperature-corrected NIOT results, and the third includes the temperature-correction *and* a temporal-drift correction (as described in Section 7.2).

Figure 13.6 The DOEs for NIOT across the range 2 kHz to 100 kHz for the B&K8104 hydrophone showing DOEs for NIOT results with application of the temperature-correction and a temporal-drift correction.



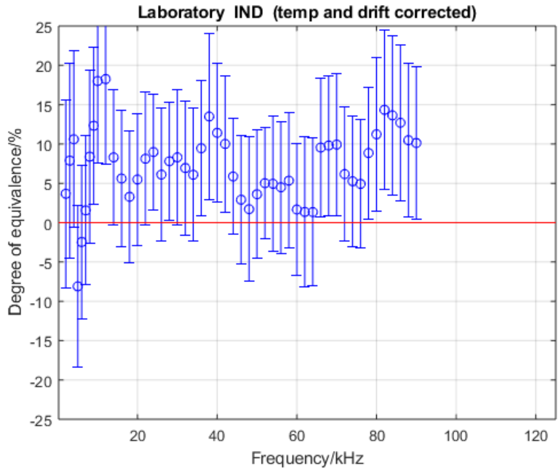


Figure 13.7 The DOEs for NIOT across the range 100 kHz to 500 kHz for the TC4034 hydrophone showing DOEs for NIOT results with application of the temperature-correction and a temporal-drift correction.

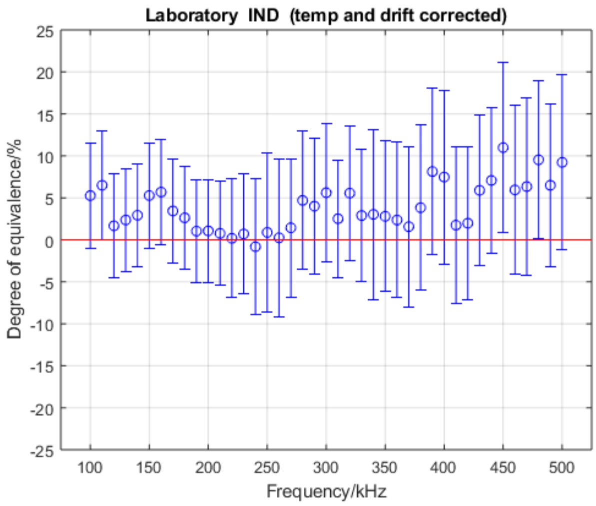


Table 13.3 The DOEs for NIOT across the range 2 kHz to 500 kHz for with application of the temperature-correction and a temporal-drift correction.

Frequency	IND	
(kHz)	DOE (%)	U_{DOE} (%)
0.25		
0.3		
0.4		
0.5		
0.6		
0.7		
0.8		
0.9		
1		
2	3.7	12.0
3	7.9	12.4
4	10.6	11.2
5	-8.1	10.3
6	-2.5	9.7
7	1.6	9.5
8	8.4	11.0
9	12.3	10.0
10	18.0	10.4
12	18.3	10.8
14	8.3	8.6
16	5.6	8.7
18	3.3	8.4
20	5.5	8.3
22	8.1	8.5
24	9.0	7.4
26	6.1	8.4
28	7.8	7.5
30	8.3	8.6
32	6.9	8.5
34	6.1	8.5
36	9.5	8.6
38	13.5	10.6
40	11.4	8.8
42	10.0	8.7
44	5.9	7.4
46	2.9	8.2
48	1.7	9.2
50	3.6	8.2
52	5.0	7.1
54	4.9	8.6
56	4.5	8.4
58	5.3	8.6
60	1.7	8.4
62	1.4	9.5
64	1.3	9.4
66	9.5	8.8
68	9.8	8.9
70	9.9	9.0
72	6.2	8.5
74	5.3	8.3
76	4.9	8.2
78	8.9	8.4
80	11.2	9.8
82	14.3	10.1
84	13.6	10.1
86	12.7	10.0
88	10.5	9.8
90	10.1	9.7

Frequency	IND	
(kHz)	DOE (%)	U_{DOE} (%)
100	5.3	6.3
110	6.5	6.4
120	1.7	6.2
130	2.4	6.1
140	2.9	6.1
150	5.3	6.3
160	5.7	6.3
170	3.4	6.2
180	2.6	6.2
190	1.0	6.2
200	1.1	6.1
210	0.8	6.2
220	0.2	7.1
230	0.7	7.1
240	-0.8	8.1
250	0.9	9.4
260	0.2	9.4
270	1.4	8.2
280	4.7	8.2
290	4.0	8.0
300	5.6	8.3
310	2.5	7.0
320	5.6	8.0
330	2.9	7.9
340	3.0	10.1
350	2.8	9.0
360	2.4	9.3
370	1.6	9.6
380	3.8	9.8
390	8.1	9.9
400	7.5	10.3
410	1.7	9.4
420	2.0	9.1
430	5.9	9.0
440	7.1	8.7
450	11.0	10.2
460	5.9	10.0
470	6.3	10.6
480	9.5	9.4
490	6.5	9.7
500	9.2	10.5

14 ANNEX C: TEMPERATURE DEPENDENCE OF HYDROPHONE SENSITIVITY

14.1 CALIBRATION METHOD

The temperature dependence of the sensitivity for each hydrophone was determined using the NPL Acoustic Pressure vessel facility [Ablitt et al 2006, Beamiss et al 2002, Ford et al 2021]. For the measurements, the method of free-field reciprocity was used in conformance to IEC 60565:2021 Part 1.

For the measurements, the hydrophones were configured in a colinear arrangement. Four repeated calibrations were undertaken at each temperature. Auxiliary transducers were used as part of the calibration: two TC4033 hydrophones were for the B&K8104 calibrations, and two TC4034 hydrophones were used for the calibration of the Reson TC4034. Calibrations were undertaken in the frequency range 10 kHz to 120 kHz for the B&K8104 and 100 kHz to 500 kHz for the TC4034.

The Acoustic Pressure Vessel has the capability to operate over a range of water temperatures ranging from 2 ºC to 35 ºC. A diagram of the APV is shown in Figure 14.1.

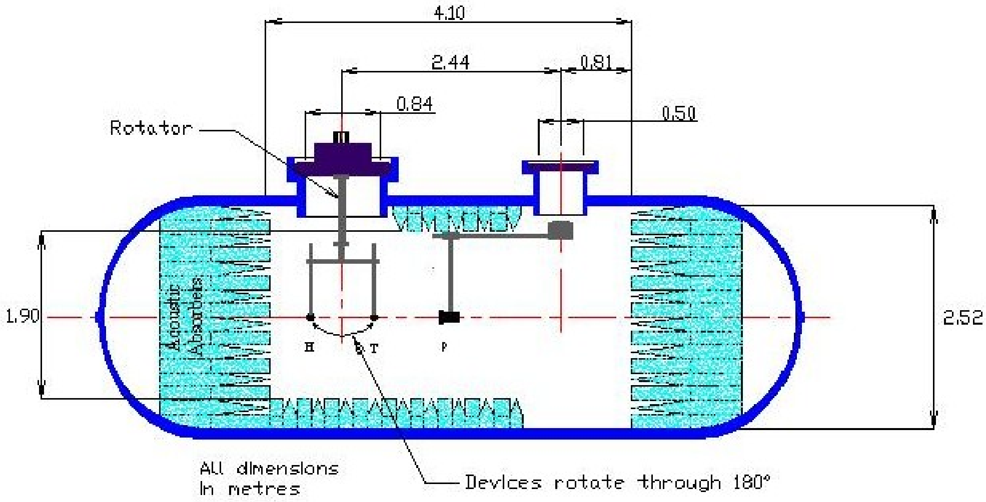


Figure 14.1 Schematic diagram of NPL Acoustic Pressure Vessel.

14.2 RESULTS

NPL undertook measurements at the reference temperature of 20 °C (within the range specified in the protocol) and at the temperatures of 27 °C and 30 °C at which, respectively, INMETRO and NIOT made their measurements. The results of these calibrations are shown in Figure 14.2 and Figure 14.3. The differences obtained were used to derived corrections to apply to the measured data at higher water temperatures.

For the B&K8104, there is a negative change in sensitivity with temperature observed at frequencies below resonance. However, at frequencies above the resonance the behaviour is more complex with additional fluctuations observed at higher temperatures. The manufacturer declares a temperature variation of up to −0.04 dB/°C for the B&K8104.

The measured results for the TC4034 show little change at frequencies below resonance, but a significant positive increase in sensitivity with temperature around resonance (280 kHz – 360 kHz) and in the range 400 kHz to 480 kHz. No data is available from the manufacturer for this hydrophone.

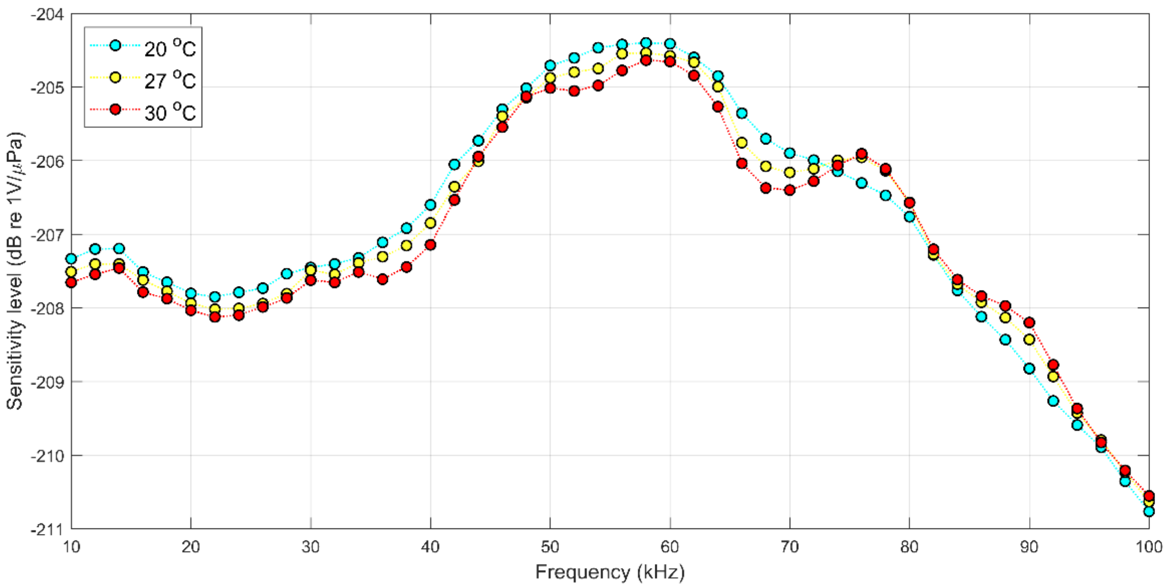


Figure 14.2 For the B&K8104, results of the NPL calibrations using the NPL Acoustic Pressure Vessel at water temperatures of 20 °C, 27 °C and 30 °C.

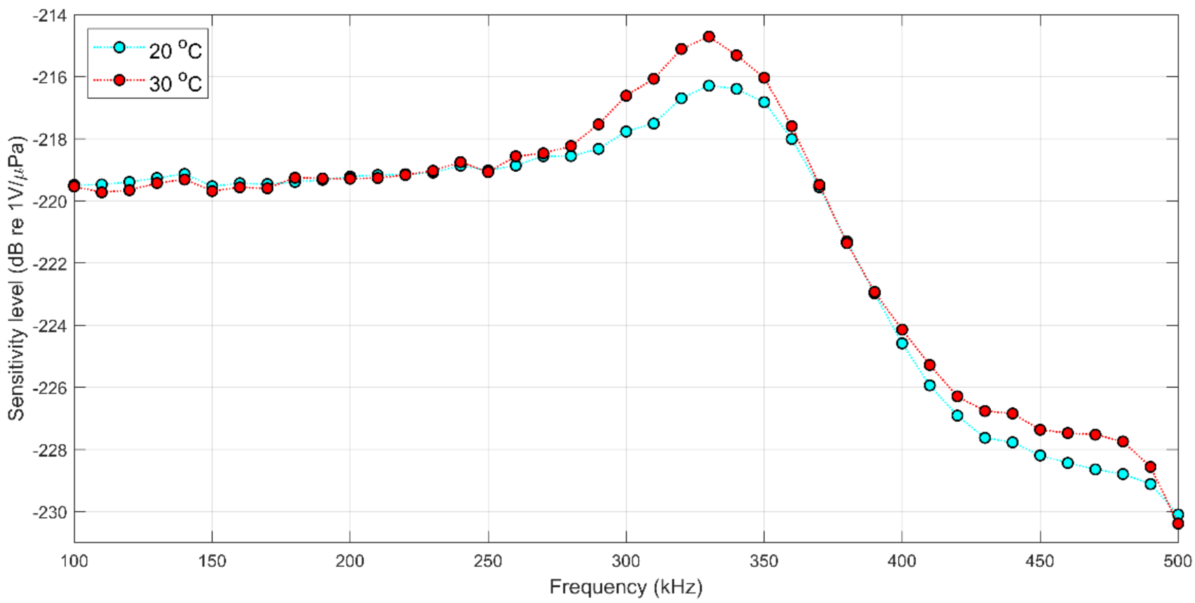


Figure 14.3 For the TC4034, results of the NPL calibrations using the NPL Acoustic Pressure Vessel at water temperatures of 20 °C and 30 °C.

14.3 CORRECTED RESULTS (INMETRO AND NIOT)

Table 14.1 shows the results for INMETRO for the B&K8104 hydrophone before and after correction for water temperature using the data derived from the measurements described above.

Tables 14.2 and 14.3 show the results for NIOT before and after correction for water temperature using the data derived from the measurements described above for the B&K 8104 hydrophone and the TC4034 hydrophone respectively.

Table 14.1 Results for INMETRO with and without temperature correction (B&K8104)

INMETRO (B&K8104)		
	Uncorrected	Corrected
Frequency kHz	Sensitivity µV/Pa	Sensitivity µV/Pa
1	50.12	50.93
2	49.49	50.29
3	50.06	50.87
4	49.77	50.58
5	49.37	50.18
6	43.25	43.95
7	47.59	48.36
8	44.93	45.66
9	44.62	45.34
10	45.92	46.87
12	46.88	48.00
14	45.08	46.18
16	42.27	42.80
18	40.88	41.46
20	41.40	42.04
22	41.69	42.50
24	42.27	43.35
26	41.50	42.51
28	41.07	42.37
30	40.23	40.41
32	41.21	41.88
34	42.07	42.41
36	43.20	44.18
38	42.85	44.03
40	43.35	44.60
42	46.72	48.38
44	51.70	53.40
46	52.54	53.12
48	53.27	54.07
50	54.58	55.63
52	55.02	56.24
54	56.49	58.36
56	57.28	58.12
58	55.40	56.27
60	52.84	53.86
62	51.76	52.16
64	49.89	50.73
66	48.58	50.88
68	47.86	49.97
70	46.94	48.38
72	46.24	46.87
74	45.76	44.99
76	44.87	43.11
78	43.95	42.29
80	42.51	41.58
82	40.78	40.75
84	38.90	38.53
86	36.90	36.08
88	35.12	33.92
90	33.38	31.90
100	25.41	25.03

Table 14.2 Results for NIOT with and without temperature correction (B&K8104)

NIOT (B&K8104)		
	Uncorrected	Corrected
Frequency kHz	Sensitivity µV/Pa	Sensitivity µV/Pa
2	47.86	49.20
3	49.55	50.93
4	50.70	52.12
5	42.66	43.85
6	42.17	43.35
7	43.15	44.36
8	44.16	45.39
9	45.71	46.99
10	48.42	50.24
12	48.98	50.95
14	45.71	47.12
16	43.65	45.05
18	41.69	42.77
20	41.69	42.80
22	42.17	43.51
24	41.69	43.20
26	41.69	42.93
28	41.21	42.81
30	42.17	43.02
32	44.16	45.45
34	44.67	45.67
36	45.19	47.86
38	47.32	50.27
40	47.32	50.36
42	48.98	51.77
44	51.88	53.18
46	53.09	54.59
48	55.59	56.32
50	57.54	59.60
52	58.88	62.01
54	60.26	63.91
56	60.95	63.48
58	60.95	62.62
60	58.88	60.55
62	56.89	58.52
64	54.95	57.65
66	54.95	59.44
68	53.70	58.00
70	53.09	56.25
72	52.48	54.23
74	52.48	52.00
76	52.48	50.13
78	52.48	50.35
80	51.88	50.76
82	50.70	50.25
84	48.42	47.60
86	46.24	44.78
88	44.16	41.89
90	42.66	39.70
100	33.11	32.32
110	23.99	24.40
120	17.38	18.00

Table 14.2 Results for NIOT with and without temperature correction (TC4034)

NIOT (TC4034)		
	Uncorrected	Corrected
Frequency kHz	Sensitivity µV/Pa	Sensitivity µV/Pa
100	10.96	11.03
110	10.84	11.16
120	10.47	10.80
130	10.84	11.04
140	10.84	11.06
150	10.84	11.03
160	10.96	11.13
170	10.72	10.88
180	11.09	10.92
190	10.96	10.91
200	10.96	11.05
210	10.96	11.09
220	11.09	11.13
230	11.35	11.27
240	11.48	11.33
250	11.35	11.42
260	12.02	11.62
270	12.16	12.03
280	12.88	12.41
290	13.96	12.75
300	15.67	13.72
310	16.03	13.58
320	18.84	15.69
330	19.05	15.88
340	17.78	15.70
350	16.22	14.81
360	13.49	12.86
370	10.84	10.74
380	8.81	8.87
390	7.59	7.55
400	6.76	6.42
410	5.75	5.34
420	5.13	4.78
430	5.01	4.54
440	4.84	4.35
450	4.73	4.30
460	4.42	3.95
470	4.37	3.84
480	4.32	3.83
490	3.80	3.57
500	3.13	3.23

15 ANNEX D: DETAILED RESULTS OF CHECK CALIBRATIONS

Presented below are the results of the measurements made to check the stability of the hydrophones. NPL undertook check calibrations at selected frequencies for each hydrophone in between the calibrations of the participants. For the B&K8104 hydrophone, these included: (i) free-field reciprocity method from 10 kHz to 120 kHz in 10 kHz steps (11 frequencies); (ii) pressure calibration by comparison in a closed coupler (using a reference microphone) at 250 Hz. For the TC4034 hydrophone, they included: free-field reciprocity method from 100 kHz to 500 kHz in 50 kHz steps (9 frequencies). In addition, NPL undertook full free-field calibrations by the reciprocity method on three occasions: before the start of the comparison, after four further participants had performed calibrations, and finally after the last calibration by a participant. These three full calibrations are given the identifiers NPL1, NPL2 and NPL3.

15.1 B&K8104 HYDROPHONE CHECK CALIBRATIONS

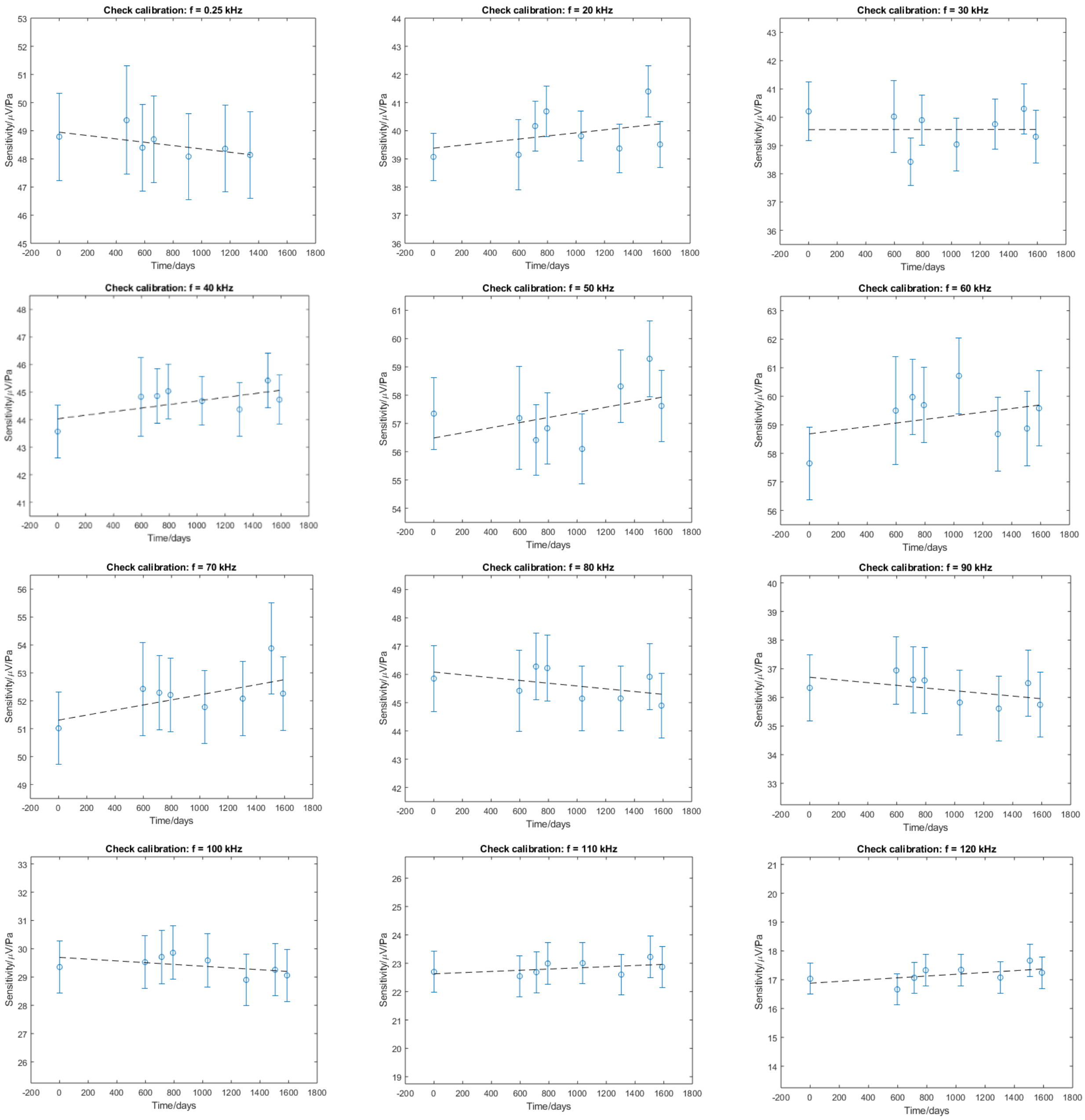


Figure 15.1 Check calibrations for the B&K8104 hydrophone with uncertainties and straight-line fits

15.2 TC4034 HYDROPHONE CHECK CALIBRATIONS

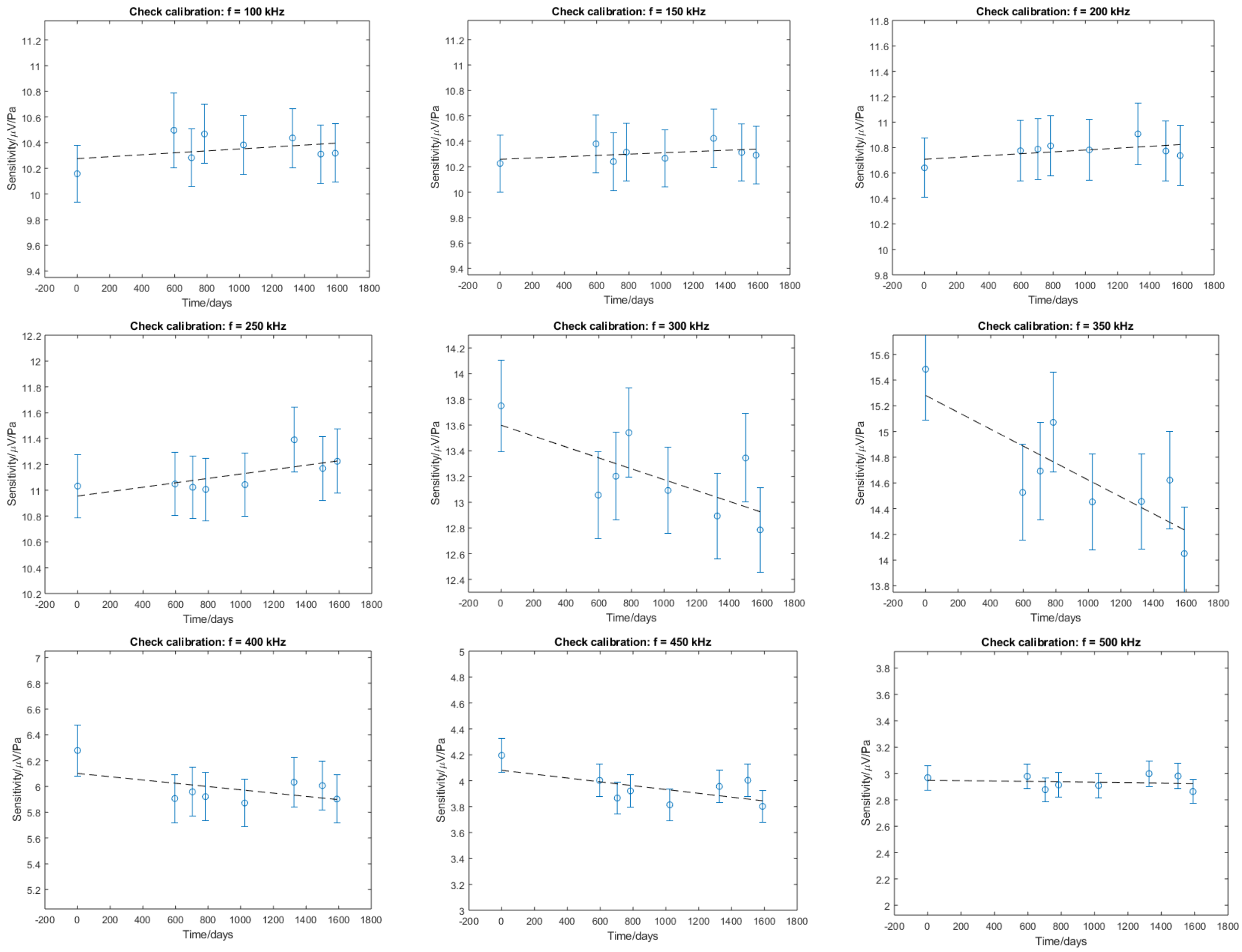


Figure 15.2 Check calibrations for the TC4034 hydrophone with uncertainties and straight-line fits

15.3 RESULTS FROM THE THREE FULL NPL CALIBRATIONS

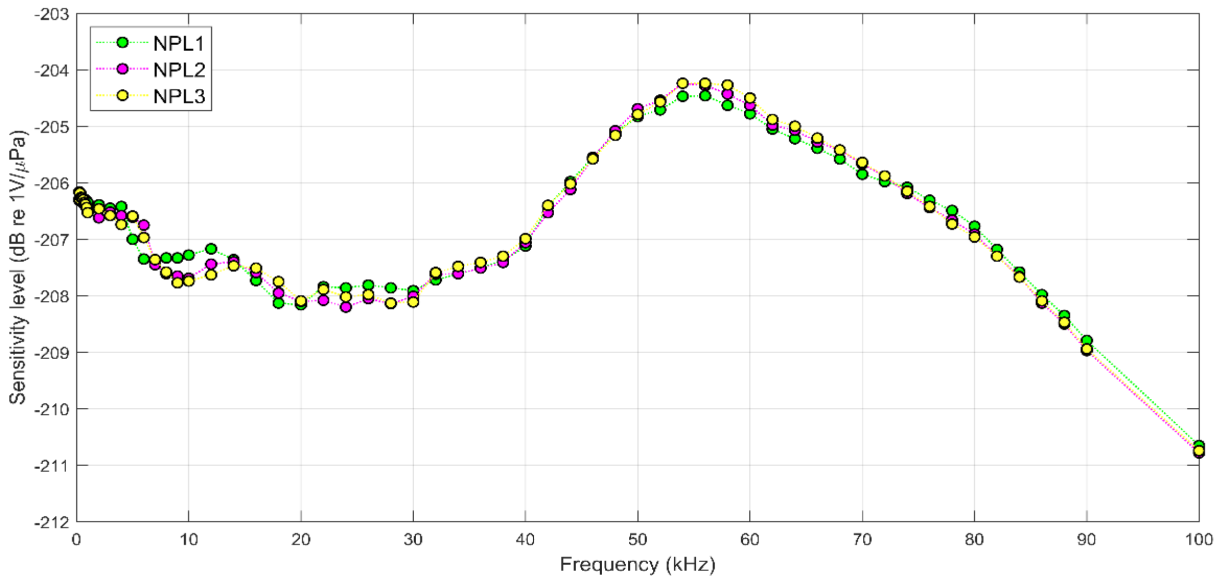


Figure 15.3 The three full calibrations for the B&K8104 hydrophone (linear frequency axis).

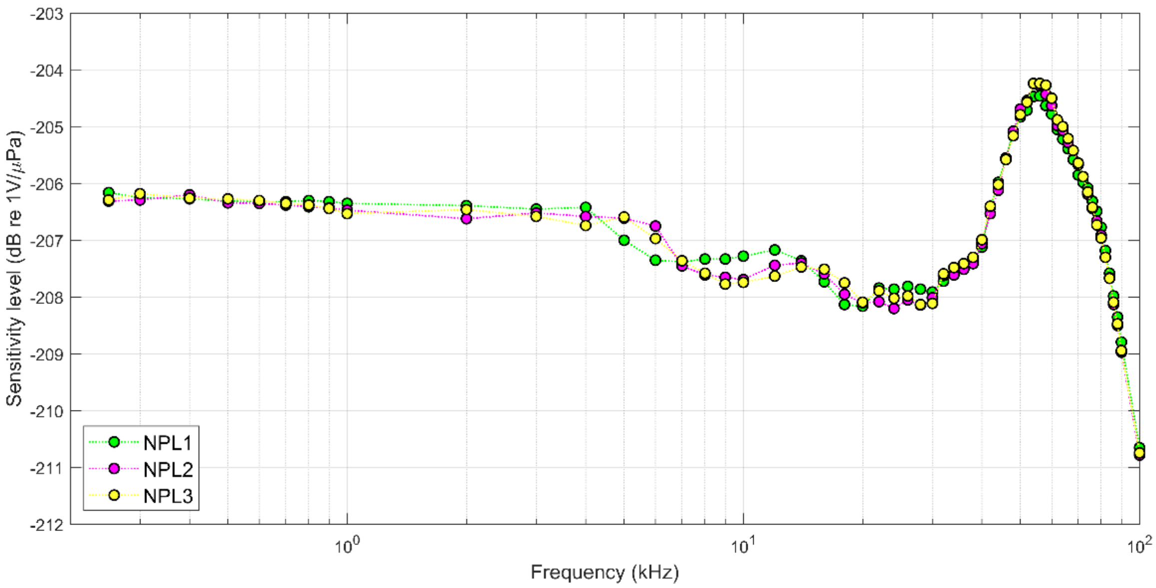


Figure 15.4 The three full calibrations for the B&K8104 hydrophone (log frequency axis).

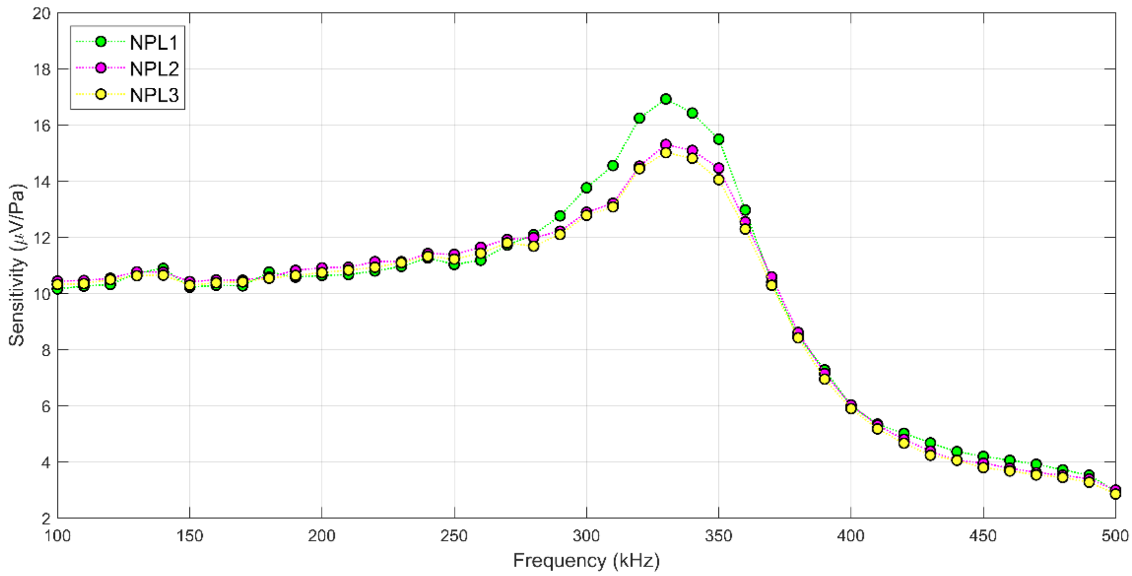
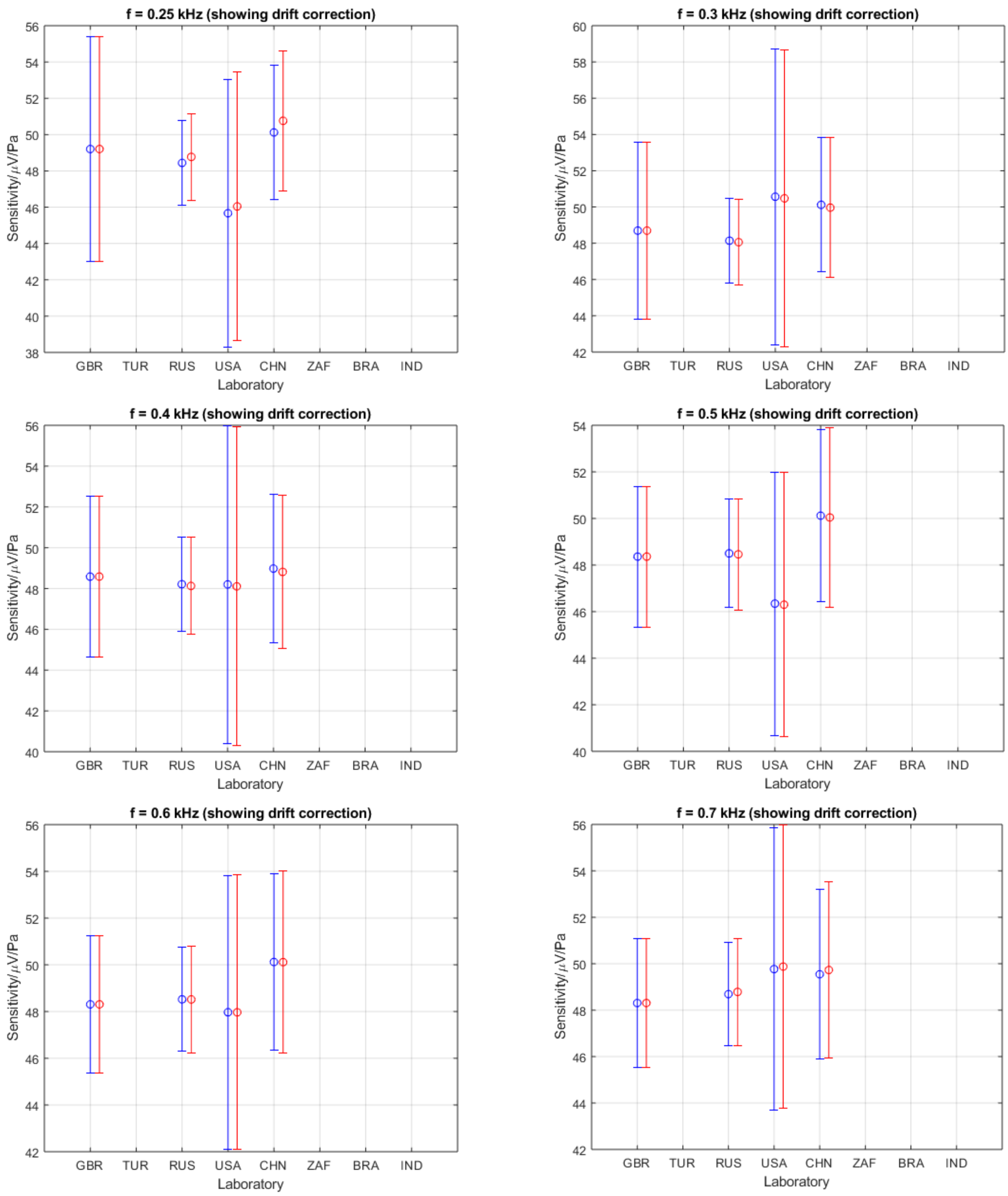


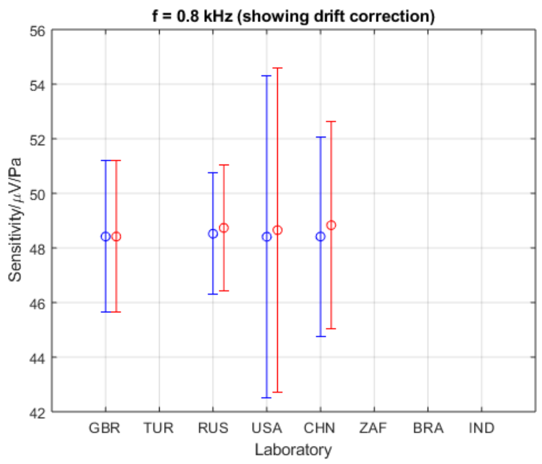
Figure 15.5 The three full calibrations for the TC4034 hydrophone

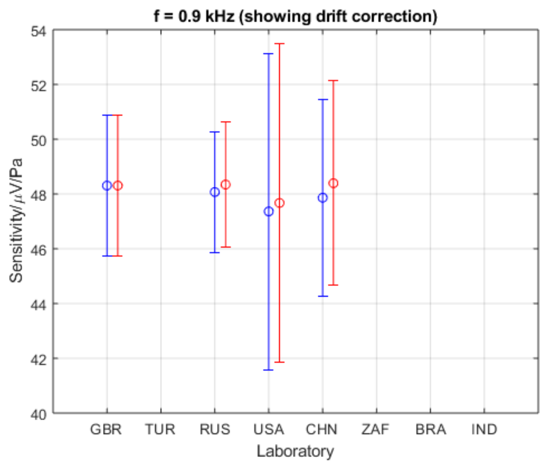
15.4 RESULTS WITH AND WITHOUT TEMPORAL DRIFT CORRECTION

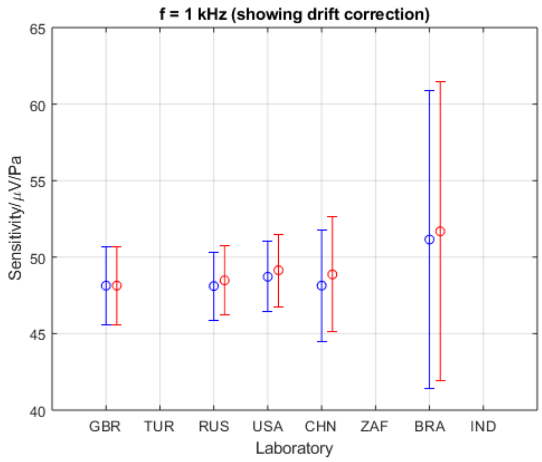
Figures 15.6 and 15.7 show the KCRVs for each frequency with and without the temporal-drift correction to the data.

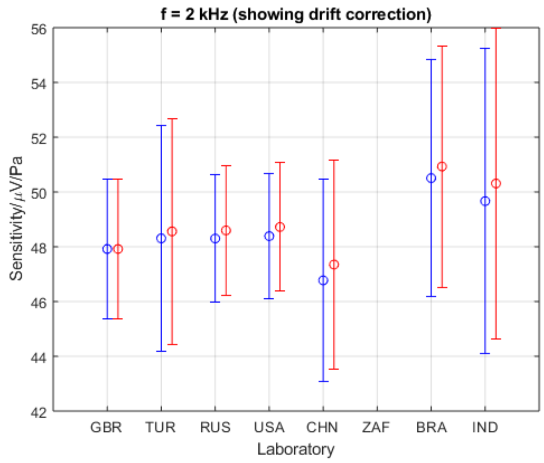
Figure 15.6 The measurement results for each frequency for the B&K8104 hydrophone showing the temporal-drift correction to the data (in red) and without the temporal-drift correction to the data (in blue).

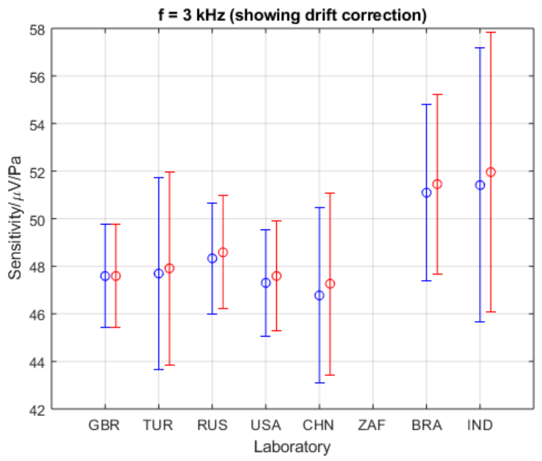


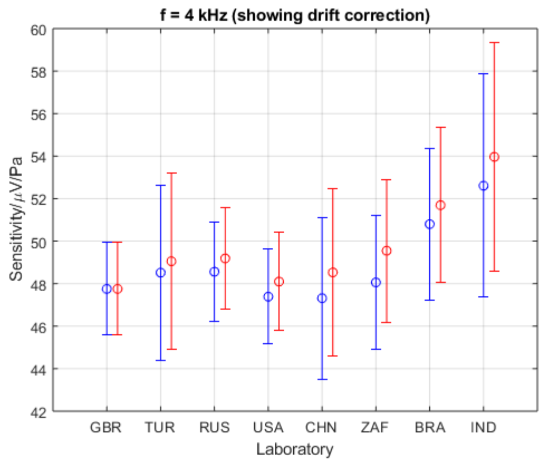

f = 0.8 kHz (showing drift correction)
Sensitivity/μV/Pa
Laboratory
GBR TUR RUS USA CHN ZAF BRA IND

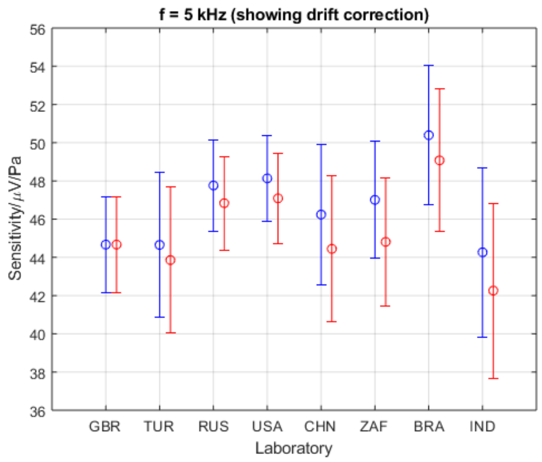

f = 0.9 kHz (showing drift correction)
Sensitivity/μV/Pa
Laboratory
GBR TUR RUS USA CHN ZAF BRA IND

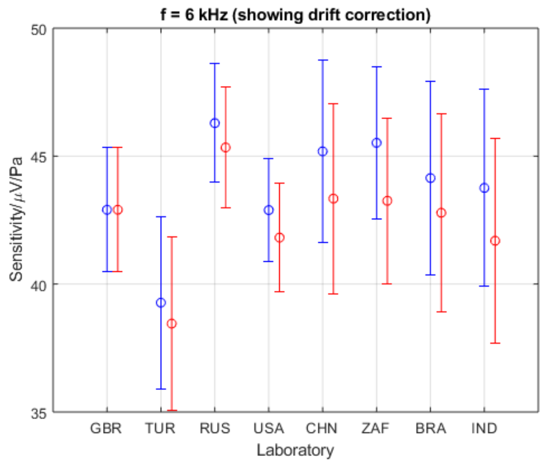

f = 1 kHz (showing drift correction)
Sensitivity/μV/Pa
Laboratory
GBR TUR RUS USA CHN ZAF BRA IND

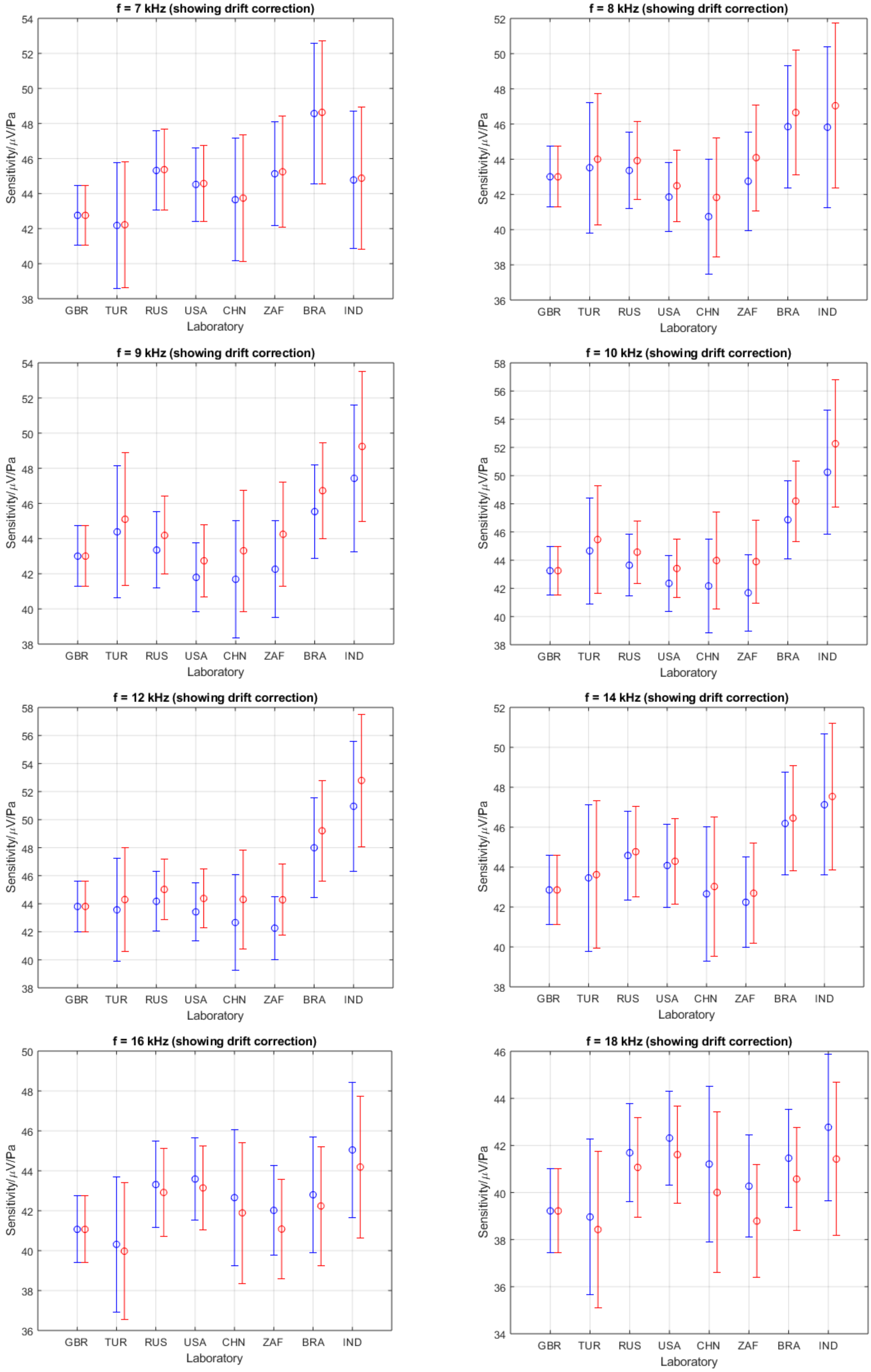

f = 2 kHz (showing drift correction)
Sensitivity/μV/Pa
Laboratory
GBR TUR RUS USA CHN ZAF BRA IND

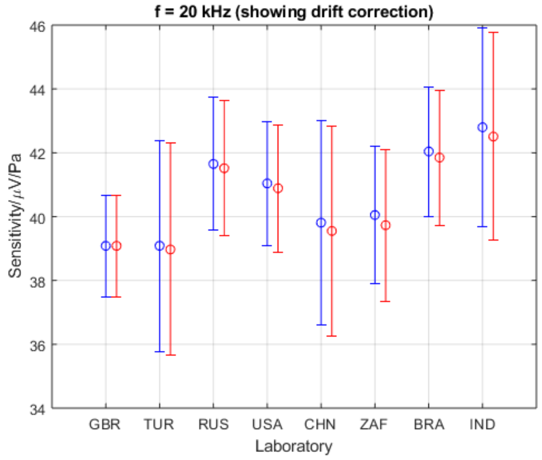

f = 3 kHz (showing drift correction)
Sensitivity/μV/Pa
Laboratory
GBR TUR RUS USA CHN ZAF BRA IND

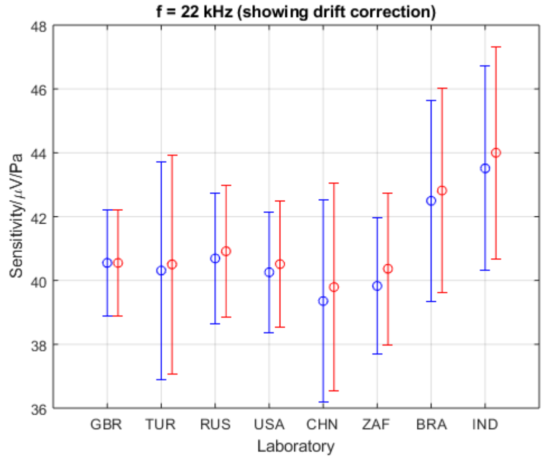

f = 4 kHz (showing drift correction)
Sensitivity/μV/Pa
Laboratory
GBR TUR RUS USA CHN ZAF BRA IND

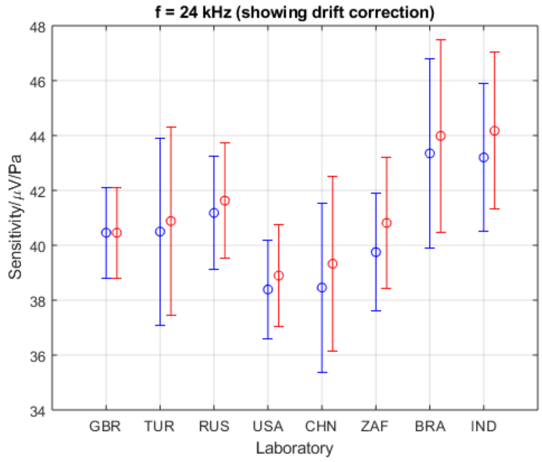

f = 5 kHz (showing drift correction)
Sensitivity/μV/Pa
Laboratory
GBR TUR RUS USA CHN ZAF BRA IND

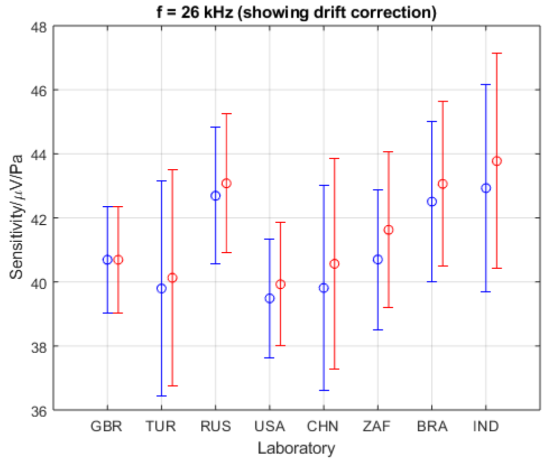

f = 6 kHz (showing drift correction)
Sensitivity/μV/Pa
Laboratory
GBR TUR RUS USA CHN ZAF BRA IND

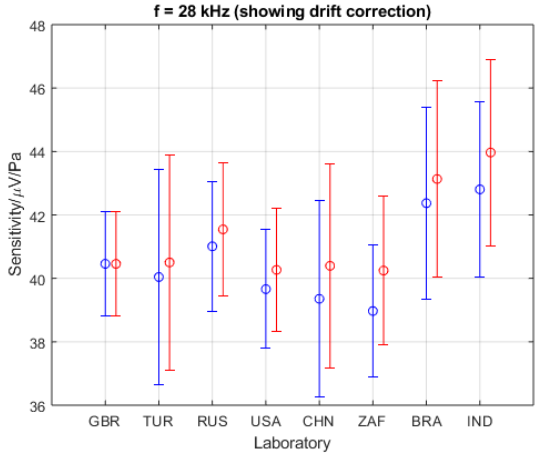

f = 7 kHz (showing drift correction)
f = 8 kHz (showing drift correction)
f = 9 kHz (showing drift correction)
f = 10 kHz (showing drift correction)
f = 12 kHz (showing drift correction)
f = 14 kHz (showing drift correction)
f = 16 kHz (showing drift correction)
f = 18 kHz (showing drift correction)
Sensitivity/µV/Pa
Laboratory
GBR TUR RUS USA CHN ZAF BRA IND

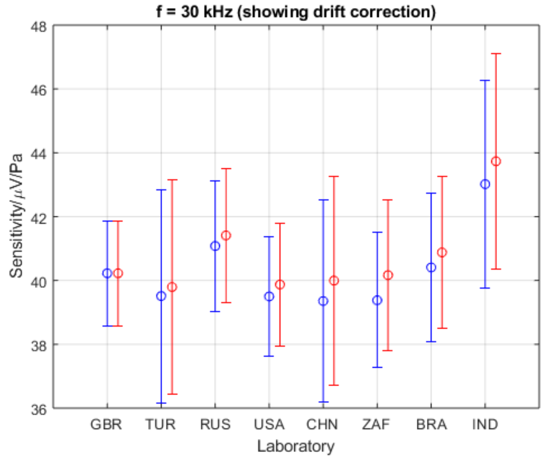

f = 20 kHz (showing drift correction)
Sensitivity/μV/Pa
Laboratory
GBR TUR RUS USA CHN ZAF BRA IND
34 36 38 40 42 44 46

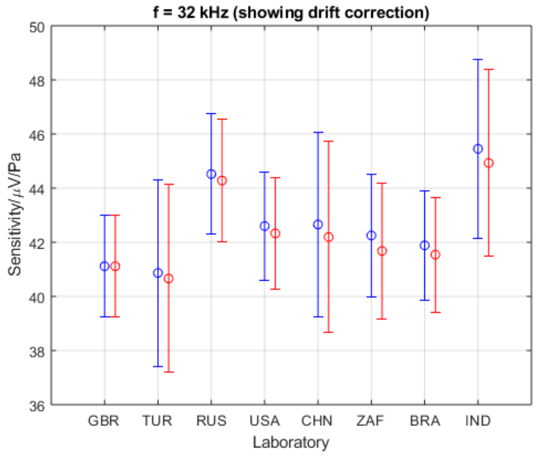

f = 22 kHz (showing drift correction)
Sensitivity/μV/Pa
Laboratory
GBR TUR RUS USA CHN ZAF BRA IND
36 38 40 42 44 46 48

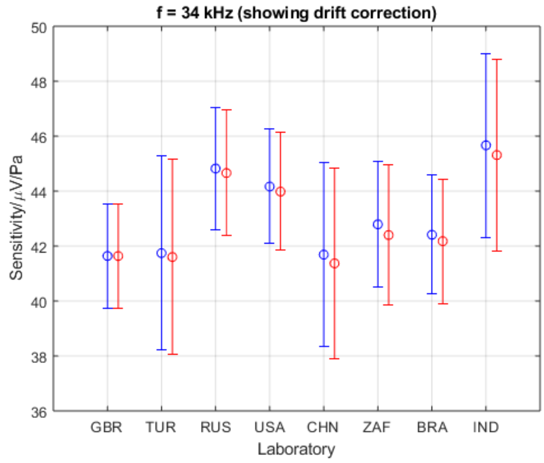

f = 24 kHz (showing drift correction)
Sensitivity/μV/Pa
Laboratory
GBR TUR RUS USA CHN ZAF BRA IND
34 36 38 40 42 44 46 48

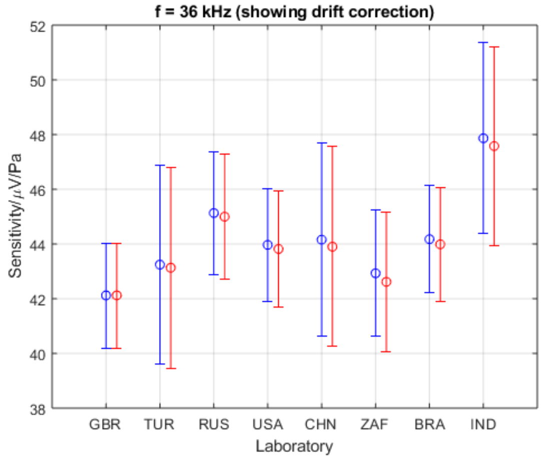

f = 26 kHz (showing drift correction)
Sensitivity/μV/Pa
Laboratory
GBR TUR RUS USA CHN ZAF BRA IND
36 38 40 42 44 46 48

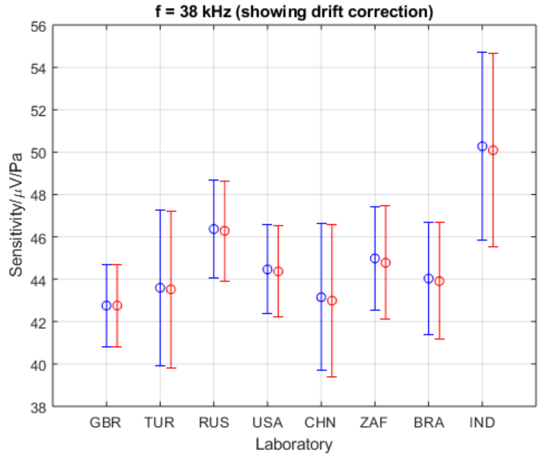

f = 28 kHz (showing drift correction)
Sensitivity/μV/Pa
Laboratory
GBR TUR RUS USA CHN ZAF BRA IND
36 38 40 42 44 46 48

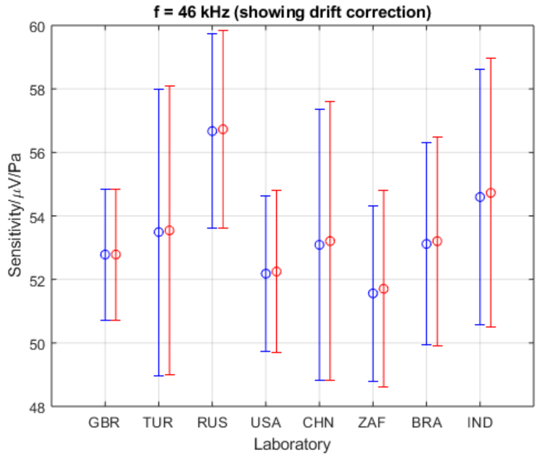

f = 30 kHz (showing drift correction)
Sensitivity/μV/Pa
Laboratory
GBR TUR RUS USA CHN ZAF BRA IND
36 38 40 42 44 46 48

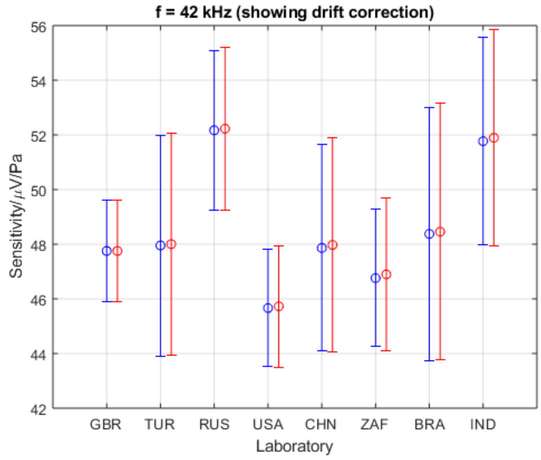

f = 32 kHz (showing drift correction)
Sensitivity/μV/Pa
Laboratory
GBR TUR RUS USA CHN ZAF BRA IND
36 38 40 42 44 46 48 50

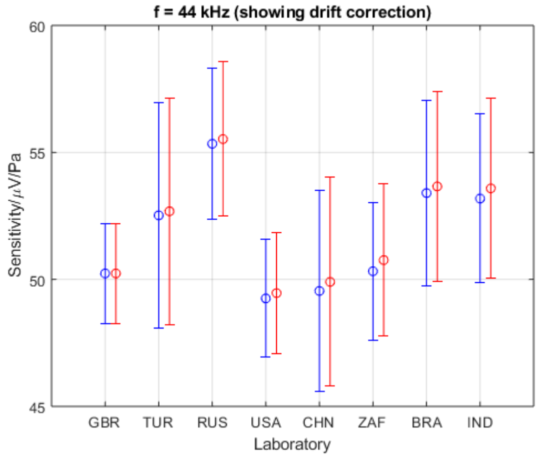

f = 34 kHz (showing drift correction)
Sensitivity/μV/Pa
Laboratory
GBR TUR RUS USA CHN ZAF BRA IND
36 38 40 42 44 46 48 50

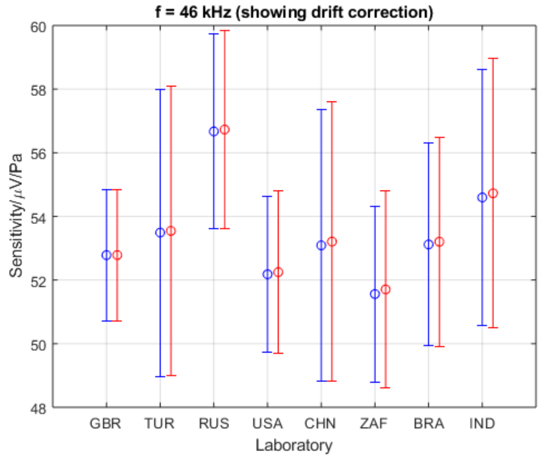

f = 36 kHz (showing drift correction)
Sensitivity/µV/Pa
52
50
48
46
44
42
40
38
GBR TUR RUS USA CHN ZAF BRA IND
Laboratory

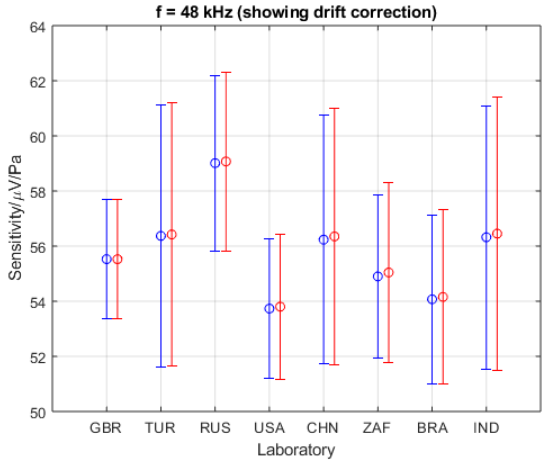

f = 38 kHz (showing drift correction)
Sensitivity/µV/Pa
56
54
52
50
48
46
44
42
40
38
GBR TUR RUS USA CHN ZAF BRA IND
Laboratory

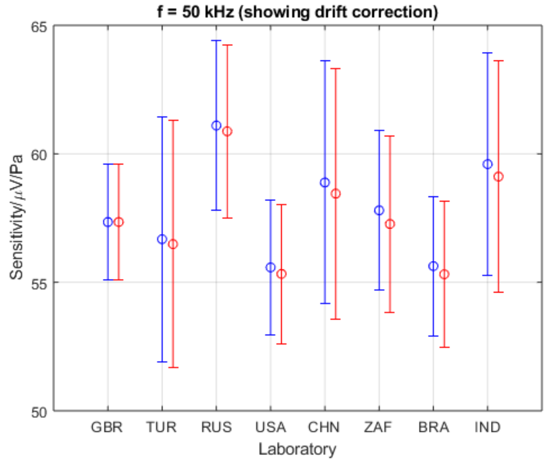

f = 46 kHz (showing drift correction)
Sensitivity/µV/Pa
60
58
56
54
52
50
48
GBR TUR RUS USA CHN ZAF BRA IND
Laboratory

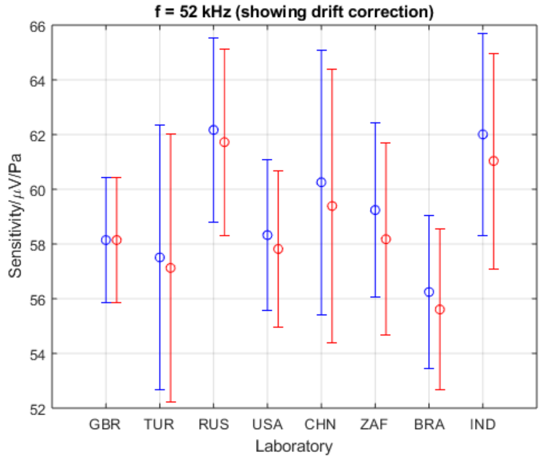

f = 42 kHz (showing drift correction)
Sensitivity/µV/Pa
56
54
52
50
48
46
44
42
GBR TUR RUS USA CHN ZAF BRA IND
Laboratory

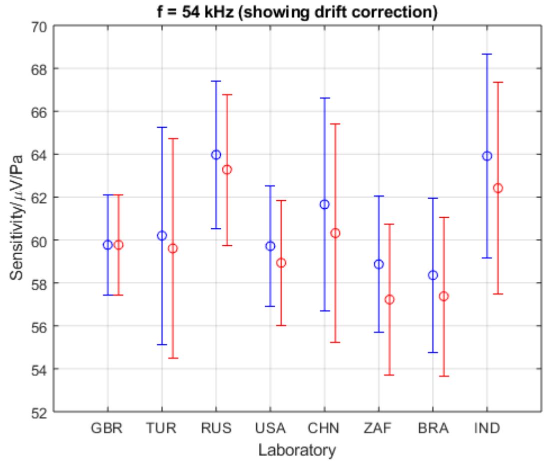

f = 44 kHz (showing drift correction)
Sensitivity/µV/Pa
60
55
50
45
GBR TUR RUS USA CHN ZAF BRA IND
Laboratory

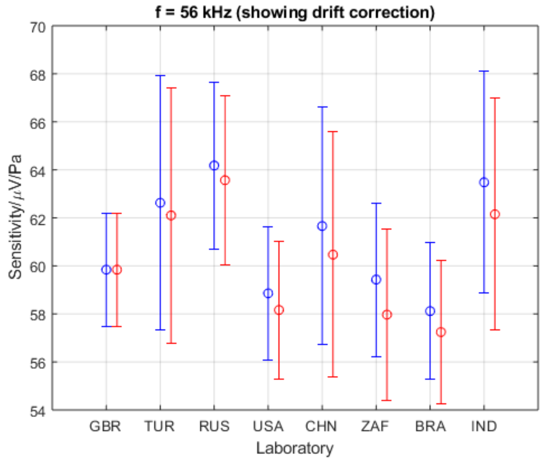

f = 46 kHz (showing drift correction)
Sensitivity/µV/Pa
60
58
56
54
52
50
48
GBR TUR RUS USA CHN ZAF BRA IND
Laboratory

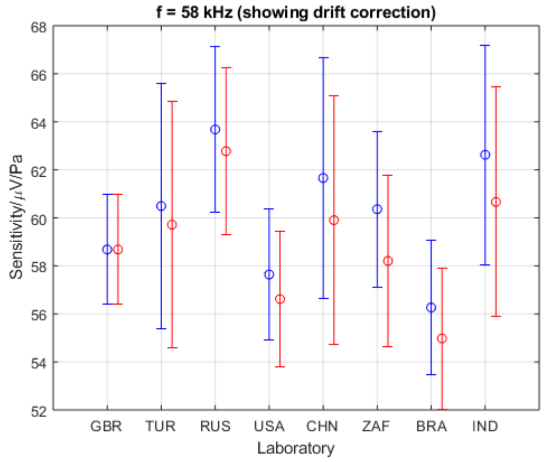

f = 48 kHz (showing drift correction)
Sensitivity/µV/Pa
64
62
60
58
56
54
52
50
GBR TUR RUS USA CHN ZAF BRA IND
Laboratory

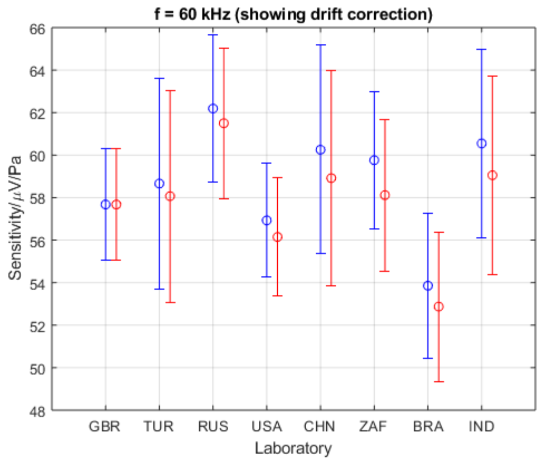

f = 50 kHz (showing drift correction)
Sensitivity/µV/Pa
65
60
55
50
GBR TUR RUS USA CHN ZAF BRA IND
Laboratory

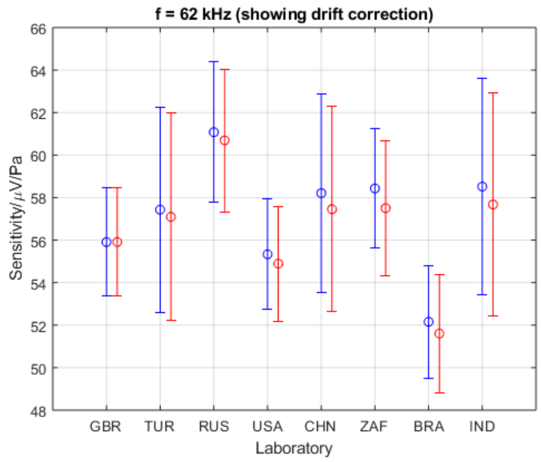

f = 52 kHz (showing drift correction)
Sensitivity/μV/Pa
GBR TUR RUS USA CHN ZAF BRA IND
Laboratory

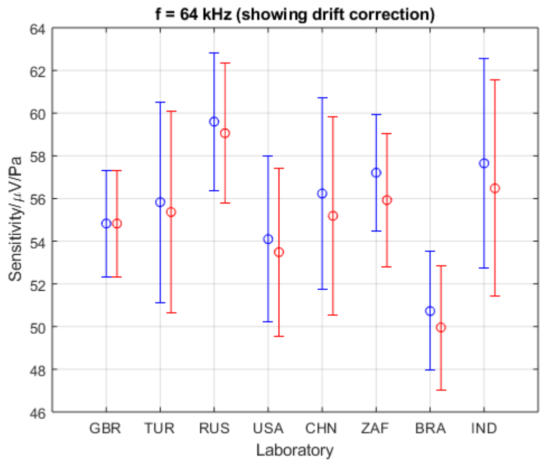

f = 54 kHz (showing drift correction)
Sensitivity/μV/Pa
GBR TUR RUS USA CHN ZAF BRA IND
Laboratory

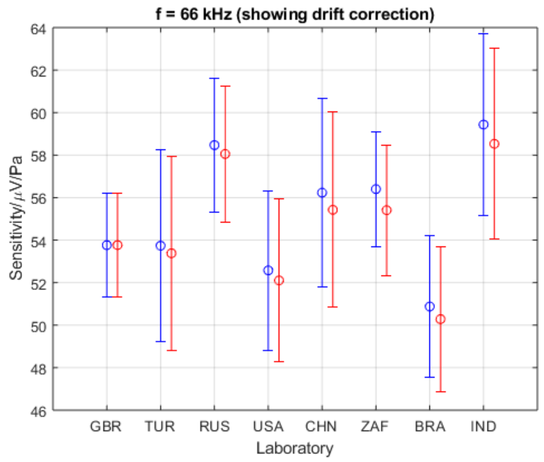

f = 56 kHz (showing drift correction)
Sensitivity/μV/Pa
GBR TUR RUS USA CHN ZAF BRA IND
Laboratory

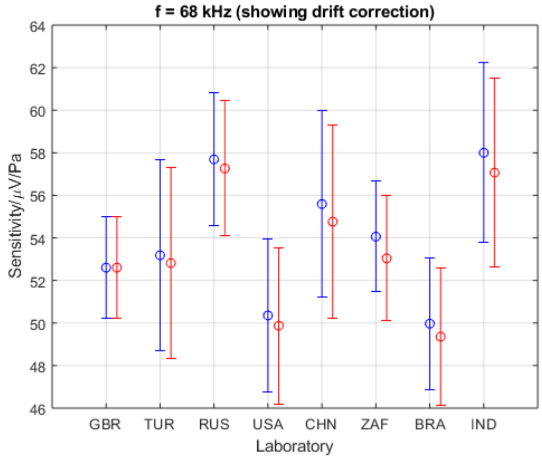

f = 58 kHz (showing drift correction)
Sensitivity/μV/Pa
GBR TUR RUS USA CHN ZAF BRA IND
Laboratory

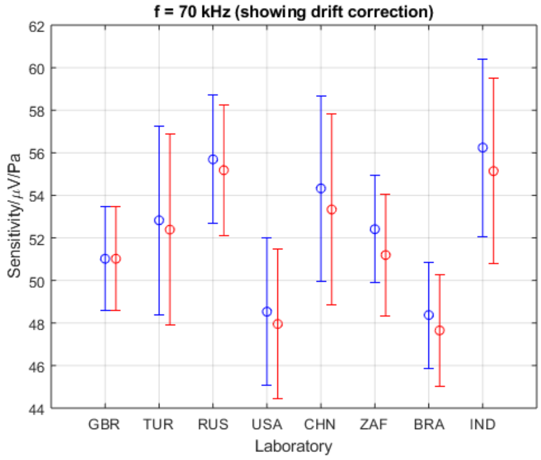

f = 60 kHz (showing drift correction)
Sensitivity/μV/Pa
GBR TUR RUS USA CHN ZAF BRA IND
Laboratory

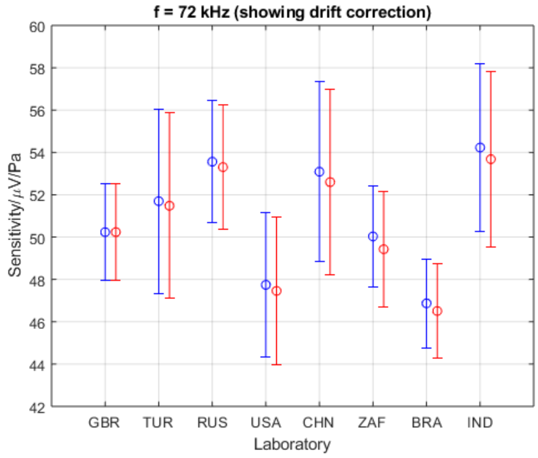

f = 62 kHz (showing drift correction)
Sensitivity/μV/Pa
GBR TUR RUS USA CHN ZAF BRA IND
Laboratory

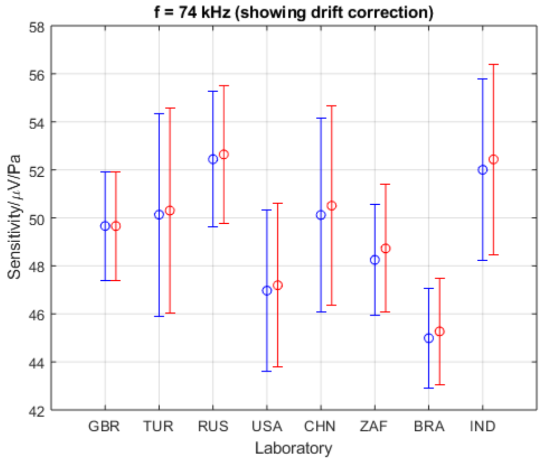

f = 64 kHz (showing drift correction)
Sensitivity/μV/Pa
GBR TUR RUS USA CHN ZAF BRA IND
Laboratory

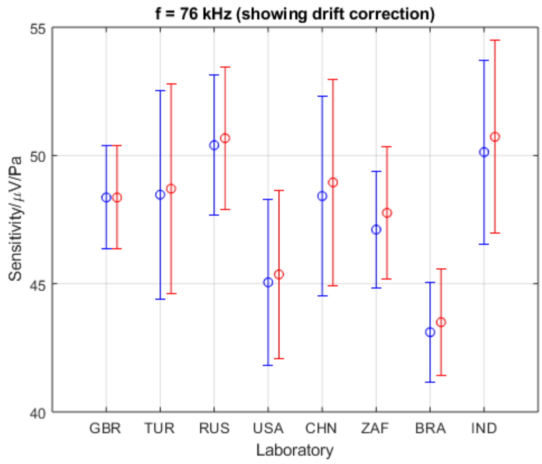

f = 66 kHz (showing drift correction)
Sensitivity/μV/Pa
GBR TUR RUS USA CHN ZAF BRA IND
Laboratory

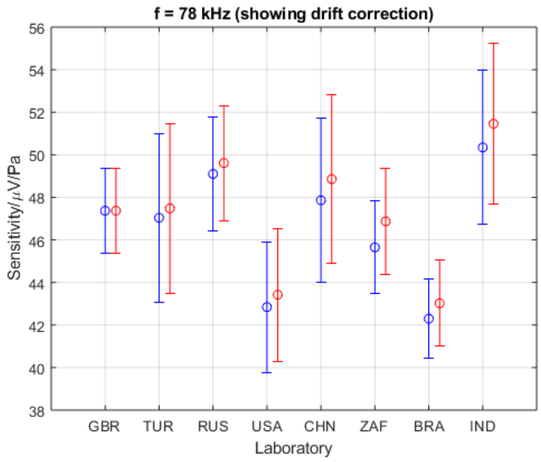

f = 68 kHz (showing drift correction)
Sensitivity/μV/Pa
GBR TUR RUS USA CHN ZAF BRA IND
Laboratory

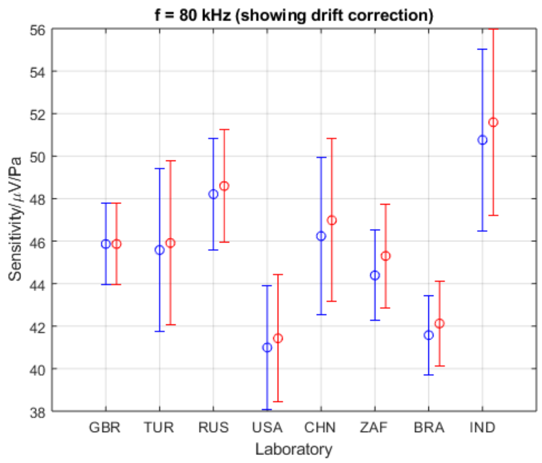

f = 70 kHz (showing drift correction)
Sensitivity/μV/Pa
GBR TUR RUS USA CHN ZAF BRA IND
Laboratory

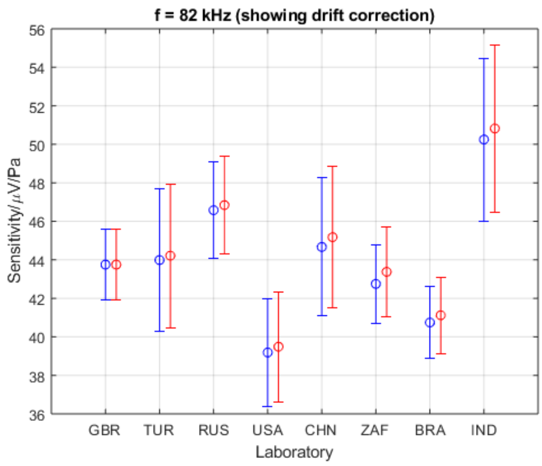

f = 72 kHz (showing drift correction)
Sensitivity/μV/Pa
GBR TUR RUS USA CHN ZAF BRA IND
Laboratory

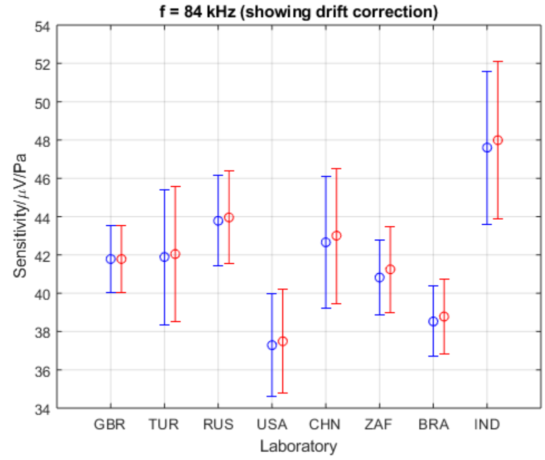

f = 74 kHz (showing drift correction)
Sensitivity/μV/Pa
GBR TUR RUS USA CHN ZAF BRA IND
Laboratory

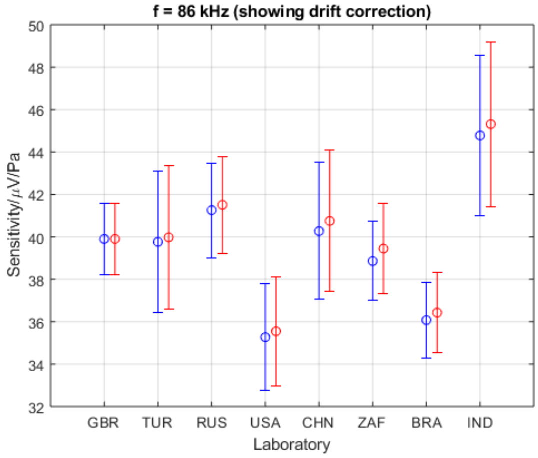

f = 76 kHz (showing drift correction)
Sensitivity/μV/Pa
GBR TUR RUS USA CHN ZAF BRA IND
Laboratory

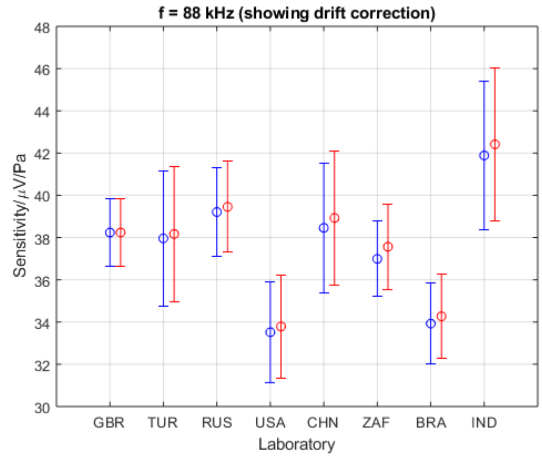

f = 78 kHz (showing drift correction)
Sensitivity/μV/Pa
GBR TUR RUS USA CHN ZAF BRA IND
Laboratory

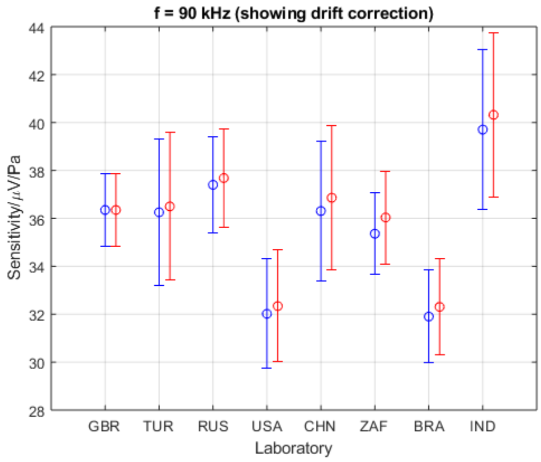

f = 80 kHz (showing drift correction)
Sensitivity/μV/Pa
GBR TUR RUS USA CHN ZAF BRA IND
Laboratory

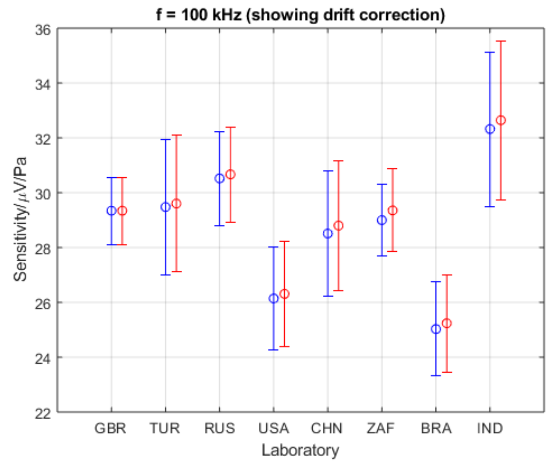

f = 82 kHz (showing drift correction)
Sensitivity/μV/Pa
GBR TUR RUS USA CHN ZAF BRA IND
Laboratory

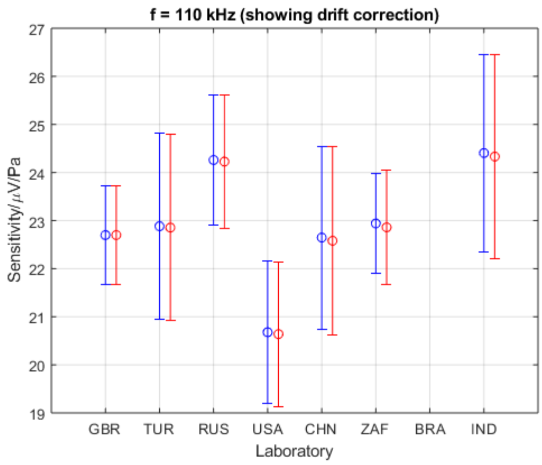

f = 84 kHz (showing drift correction)
Sensitivity/μV/Pa
54
52
50
48
46
44
42
40
38
36
34
GBR
TUR
RUS
USA
CHN
ZAF
BRA
IND
Laboratory


f = 86 kHz (showing drift correction)
Sensitivity/μV/Pa
50
48
46
44
42
40
38
36
34
32
GBR
TUR
RUS
USA
CHN
ZAF
BRA
IND
Laboratory


f = 88 kHz (showing drift correction)
Sensitivity/μV/Pa
48
46
44
42
40
38
36
34
32
30
GBR
TUR
RUS
USA
CHN
ZAF
BRA
IND
Laboratory


f = 90 kHz (showing drift correction)
Sensitivity/μV/Pa
44
42
40
38
36
34
32
30
28
GBR
TUR
RUS
USA
CHN
ZAF
BRA
IND
Laboratory


f = 100 kHz (showing drift correction)
Sensitivity/μV/Pa
36
34
32
30
28
26
24
22
GBR
TUR
RUS
USA
CHN
ZAF
BRA
IND
Laboratory


f = 110 kHz (showing drift correction)
Sensitivity/μV/Pa
27
26
25
24
23
22
21
20
19
GBR
TUR
RUS
USA
CHN
ZAF
BRA
IND
Laboratory

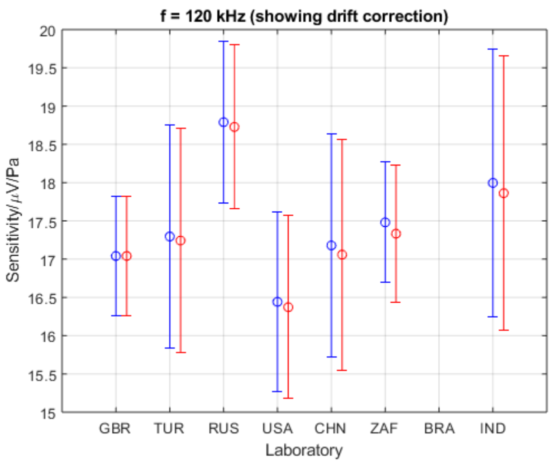
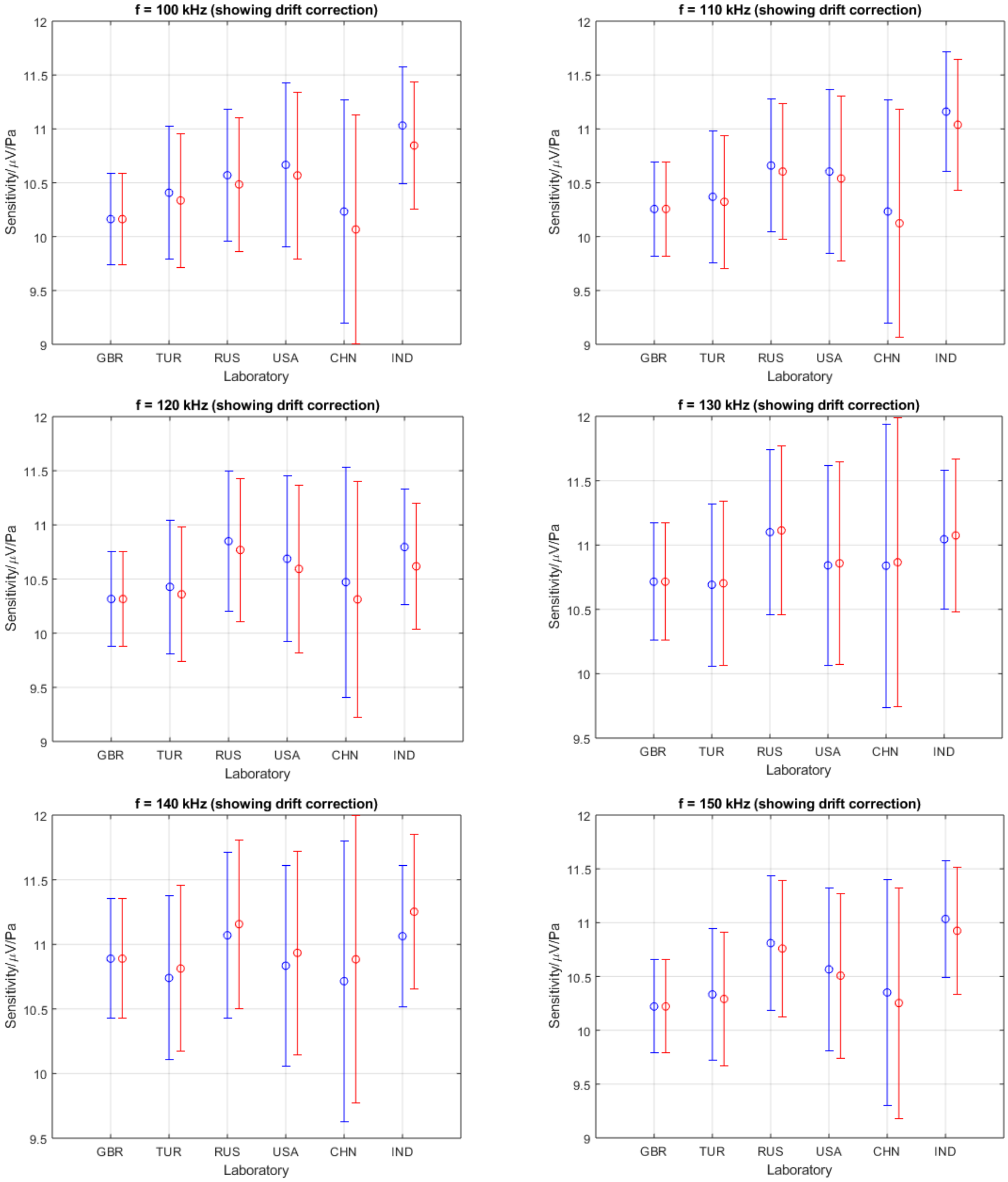
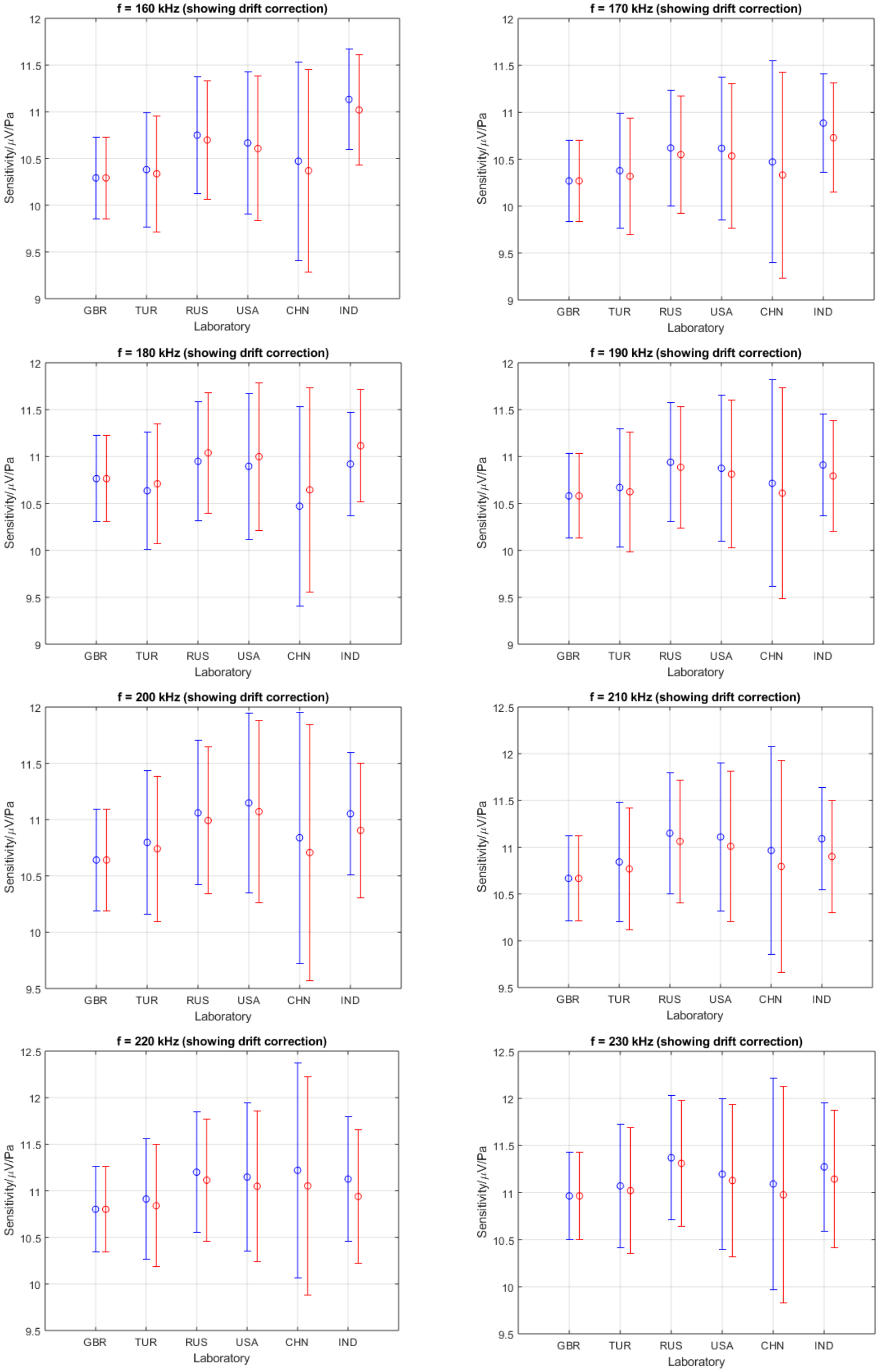
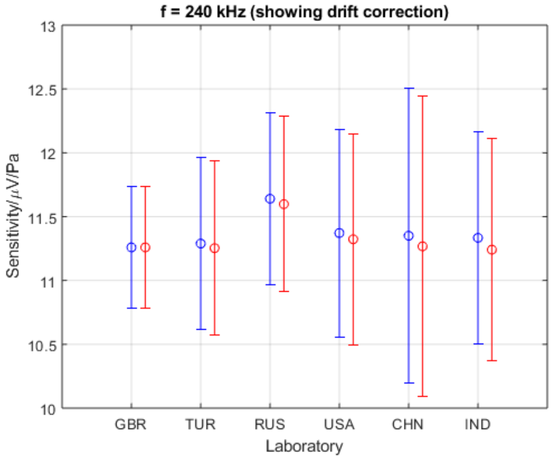
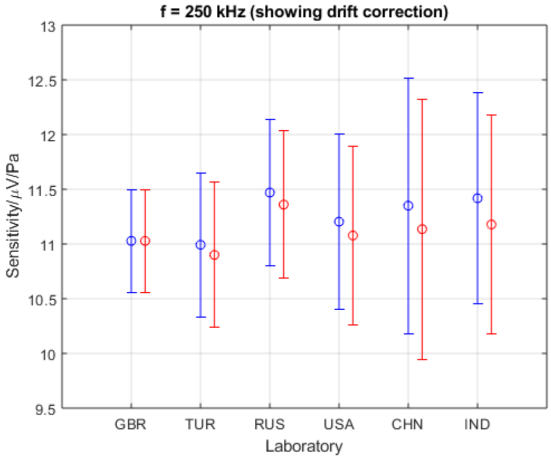

f = 120 kHz (showing drift correction)
Sensitivity/μV/Pa
20
19.5
19
18.5
18
17.5
17
16.5
16
15.5
15
GBR
TUR
RUS
USA
CHN
ZAF
BRA
IND
Laboratory

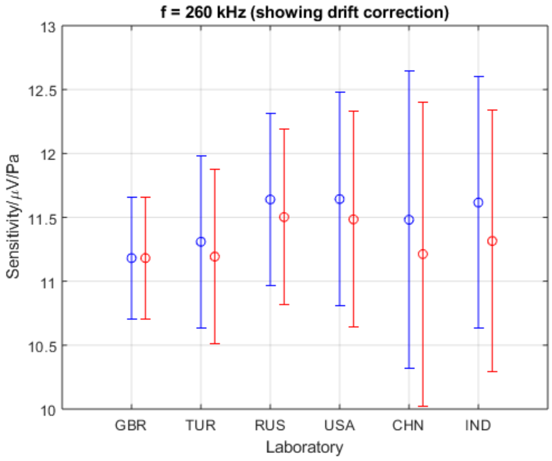
Figure 15.7 The measurement results for each frequency for the TC4034 hydrophone showing the temporal-drift correction to the data (in red) and without the temporal-drift correction to the data (in blue).

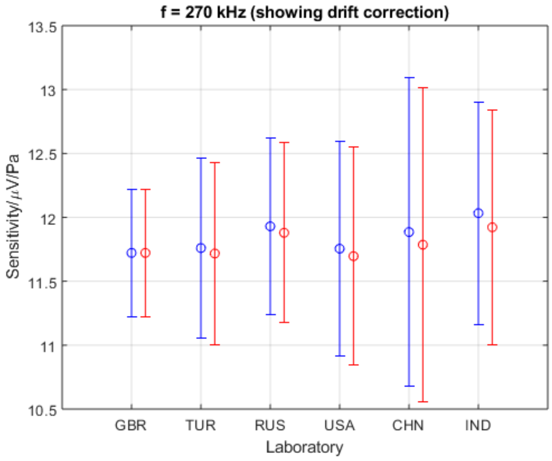


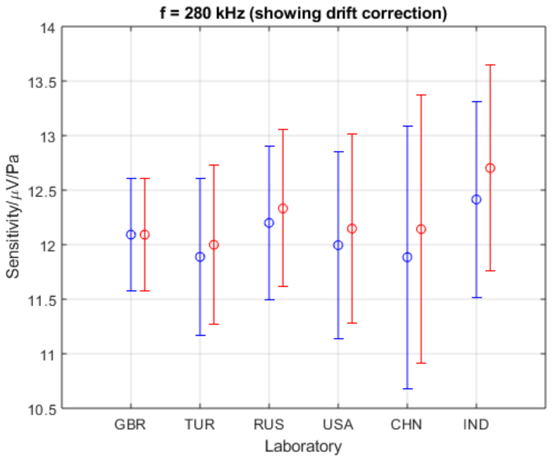

f = 160 kHz (showing drift correction)
f = 170 kHz (showing drift correction)
f = 180 kHz (showing drift correction)
f = 190 kHz (showing drift correction)
f = 200 kHz (showing drift correction)
f = 210 kHz (showing drift correction)
f = 220 kHz (showing drift correction)
f = 230 kHz (showing drift correction)
Sensitivity/μV/Pa
Laboratory
GBR
TUR
RUS
USA
CHN
IND

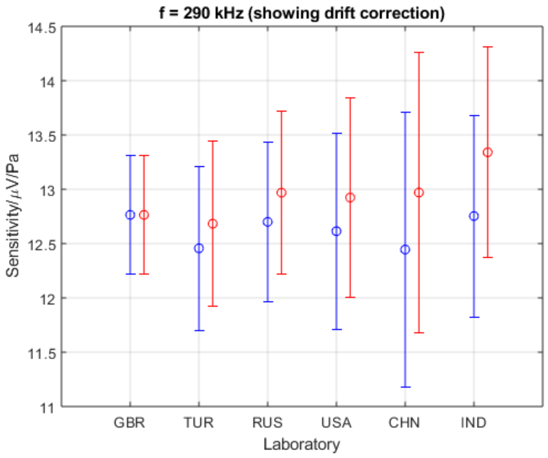

f = 240 kHz (showing drift correction)
Sensitivity/μV/Pa
Laboratory
GBR TUR RUS USA CHN IND

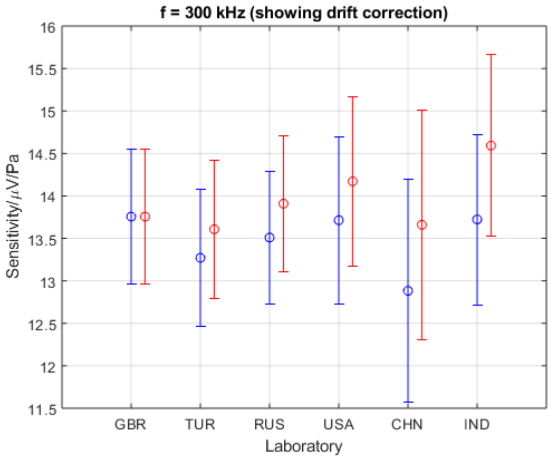

f = 250 kHz (showing drift correction)
Sensitivity/μV/Pa
Laboratory
GBR TUR RUS USA CHN IND

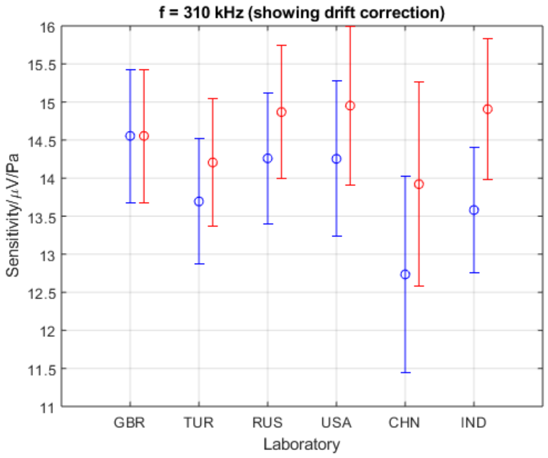

f = 260 kHz (showing drift correction)
Sensitivity/μV/Pa
Laboratory
GBR TUR RUS USA CHN IND

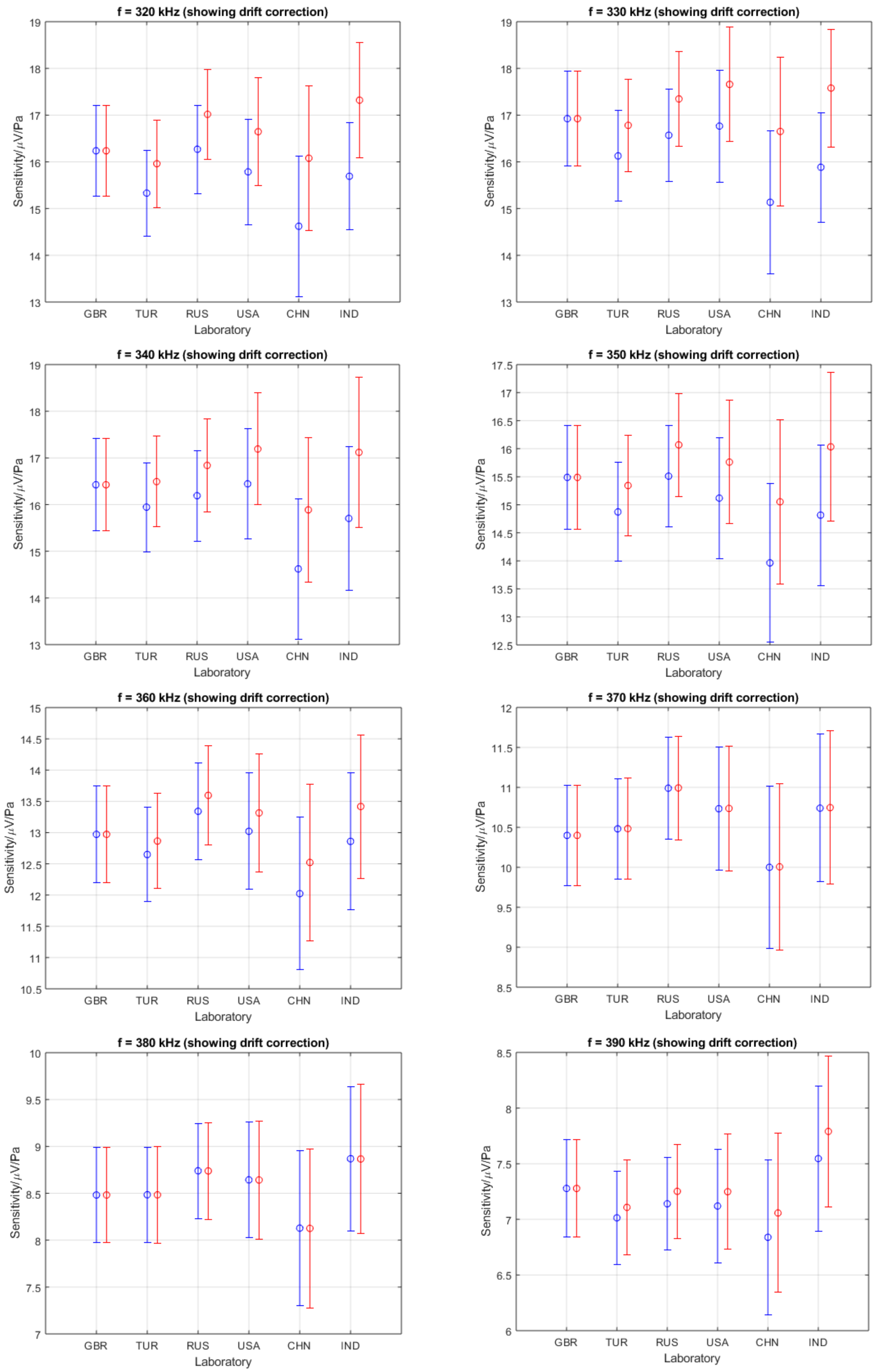

f = 270 kHz (showing drift correction)
Sensitivity/μV/Pa
Laboratory
GBR TUR RUS USA CHN IND

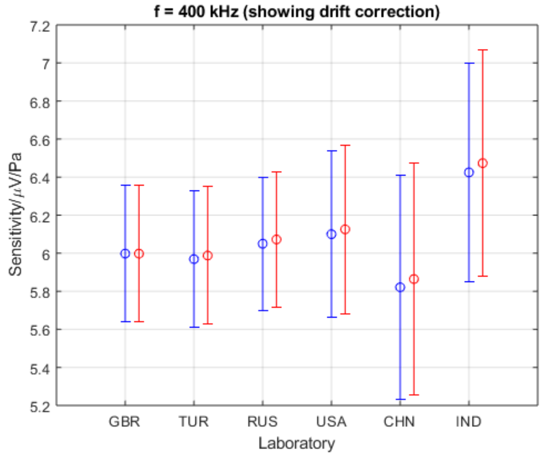

f = 280 kHz (showing drift correction)
Sensitivity/μV/Pa
Laboratory
GBR TUR RUS USA CHN IND

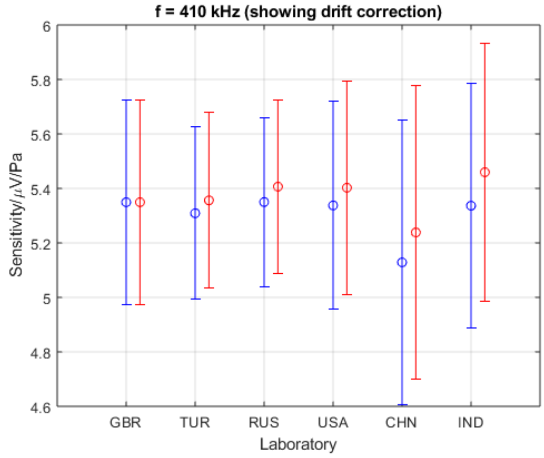

f = 290 kHz (showing drift correction)
Sensitivity/μV/Pa
Laboratory
GBR TUR RUS USA CHN IND

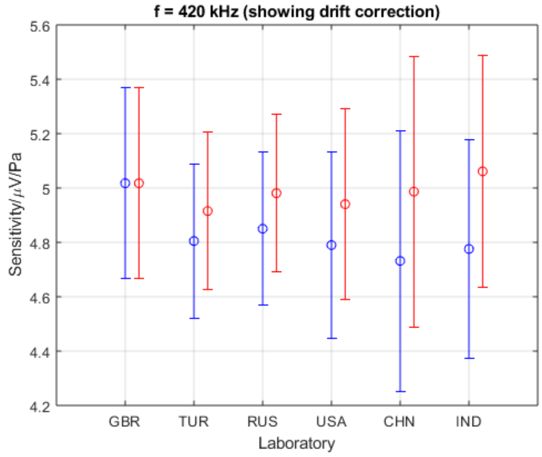

f = 300 kHz (showing drift correction)
Sensitivity/μV/Pa
Laboratory
GBR TUR RUS USA CHN IND

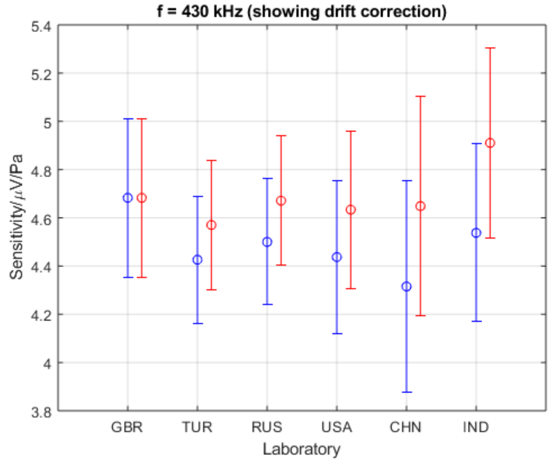

f = 310 kHz (showing drift correction)
Sensitivity/μV/Pa
Laboratory
GBR TUR RUS USA CHN IND

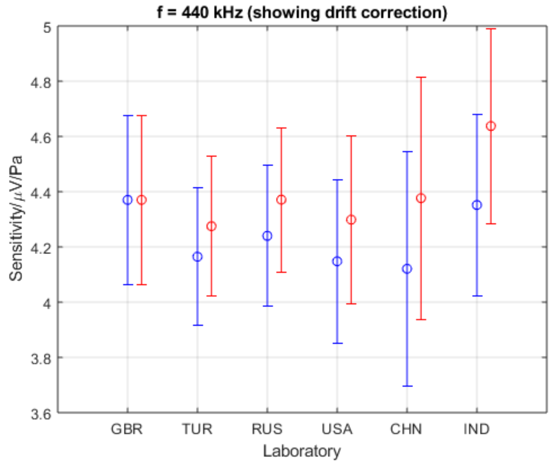

f = 320 kHz (showing drift correction)
f = 330 kHz (showing drift correction)
f = 340 kHz (showing drift correction)
f = 350 kHz (showing drift correction)
f = 360 kHz (showing drift correction)
f = 370 kHz (showing drift correction)
f = 380 kHz (showing drift correction)
f = 390 kHz (showing drift correction)
Sensitivity/μV/Pa
Laboratory
GBR
TUR
RUS
USA
CHN
IND

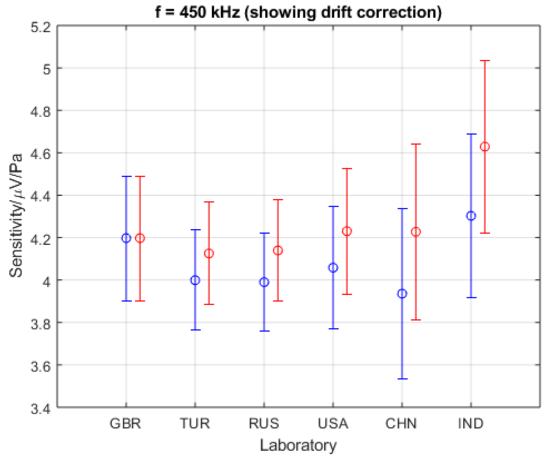

f = 400 kHz (showing drift correction)
Sensitivity/μV/Pa
7.2 7 6.8 6.6 6.4 6.2 6 5.8 5.6 5.4 5.2
GBR TUR RUS USA CHN IND
Laboratory

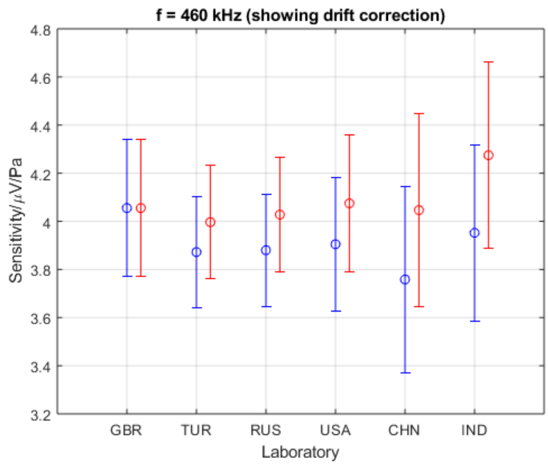

f = 410 kHz (showing drift correction)
Sensitivity/μV/Pa
6 5.8 5.6 5.4 5.2 5 4.8 4.6
GBR TUR RUS USA CHN IND
Laboratory

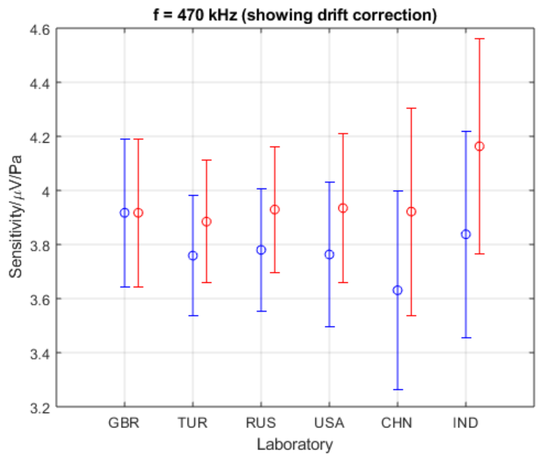

f = 420 kHz (showing drift correction)
Sensitivity/μV/Pa
5.6 5.4 5.2 5 4.8 4.6 4.4 4.2
GBR TUR RUS USA CHN IND
Laboratory

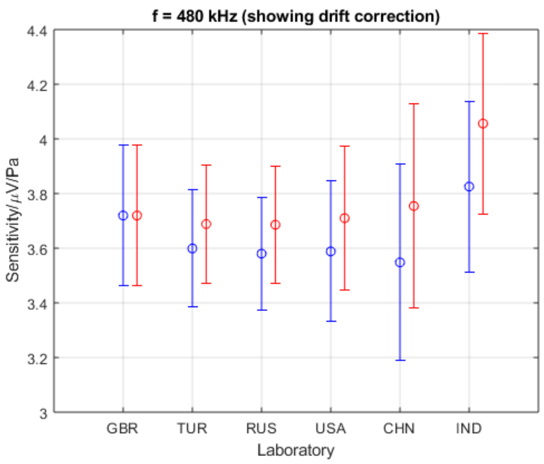

f = 430 kHz (showing drift correction)
Sensitivity/μV/Pa
5.4 5.2 5 4.8 4.6 4.4 4.2 4 3.8
GBR TUR RUS USA CHN IND
Laboratory

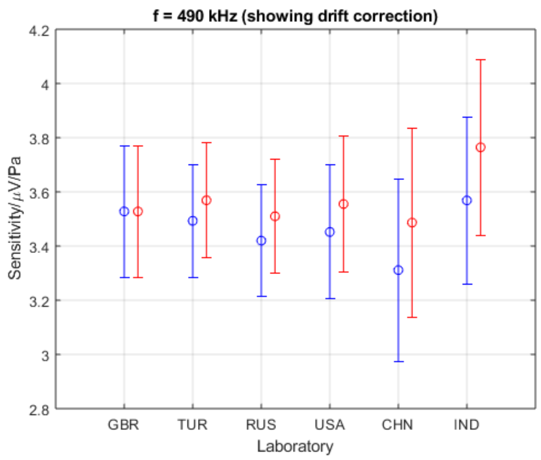

f = 440 kHz (showing drift correction)
Sensitivity/μV/Pa
5 4.8 4.6 4.4 4.2 4 3.8 3.6
GBR TUR RUS USA CHN IND
Laboratory

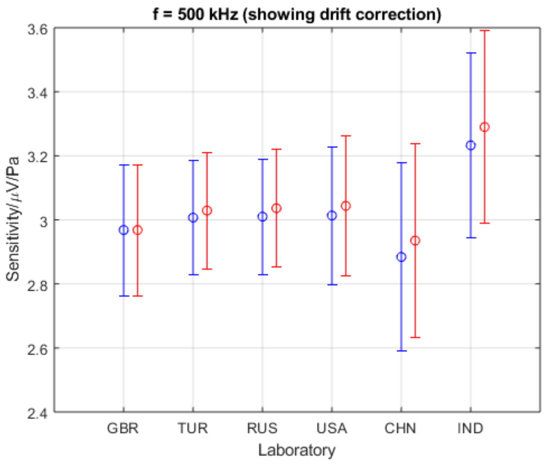

f = 450 kHz (showing drift correction)
Sensitivity/μV/Pa
5.2 5 4.8 4.6 4.4 4.2 4 3.8 3.6 3.4
GBR TUR RUS USA CHN IND
Laboratory


f = 460 kHz (showing drift correction)
Sensitivity/μV/Pa
4.8 4.6 4.4 4.2 4 3.8 3.6 3.4 3.2
GBR TUR RUS USA CHN IND
Laboratory


f = 470 kHz (showing drift correction)
Sensitivity/μV/Pa
4.6 4.4 4.2 4 3.8 3.6 3.4 3.2
GBR TUR RUS USA CHN IND
Laboratory


f = 480 kHz (showing drift correction)
Sensitivity/μV/Pa
Laboratory
GBR
TUR
RUS
USA
CHN
IND


f = 490 kHz (showing drift correction)
Sensitivity/μV/Pa
Laboratory
GBR
TUR
RUS
USA
CHN
IND


f = 500 kHz (showing drift correction)
Sensitivity/μV/Pa
Laboratory
GBR
TUR
RUS
USA
CHN
IND

16 ANNEX E: TC4034 RESULTS PROVIDED BY NMISA (WITHDRAWN)

Below are the results originally provided by NMISA for the TC4034 hydrophone in the frequency range 100 kHz to 230 kHz.

These results were systematically low in value and most of them were classed as discrepant. After some consideration, NMISA decided to withdraw these results from the comparison, and they have not been included in the calculation of the KCRV, with no DOEs being calculated.

Frequency (kHz)	Sensitivity level (dB re 1V/µPa)	Sensitivity (µV/Pa)	Uncertainty k=1 (%)
100	-220.3	9.69	2.0
110	-220.2	9.77	2.0
120	-220.0	9.98	2.0
130	-220.0	10.05	2.0
140	-219.9	10.08	2.0
150	-220.3	9.71	2.0
160	-220.2	9.83	2.0
170	-220.1	9.86	2.0
180	-220.1	9.93	2.0
190	-219.9	10.07	2.0
200	-219.8	10.29	2.0
210	-220.3	9.69	2.0
220	-220.2	9.77	2.0
230	-220.0	9.98	2.0

Table 16.1
Results for NMISA (ZAF) for TC4034 hydrophone from 100 kHz to 230 kHz

17 ANNEX F PROTOCOL

THE NATIONAL PHYSICAL LABORATORY

TECHNICAL PROTOCOL FOR KEY COMPARISON CCAUV.W-K2

ISSUE 1

SEPTEMBER 2015

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TECHNICAL PROTOCOL FOR KEY COMPARISON CCAUV.W-K2

BACKGROUND

This document describes the technical protocol to be used for the Key Comparison CCAUV-W.K2: free-field calibration of hydrophones in the frequency range 250 Hz to 500 kHz. This is one of the Key Comparisons organised under the auspices of the Consultative Committee on Acoustics, Ultrasound and Vibration (CCAUV) of the Committee International des Poids et Mesures (CIPM).

The aim of the Key Comparison is to provide technical data to underpin the mutual recognition of national measurement standards as outlined in the Mutual Recognition Agreement (MRA) [1]. Data derived from the comparison will be used to provide the Key Comparison Reference Values (KCRV's) required by the MRA to evaluate the degree of equivalence of national measurement standards.

The purpose of this document is to specify the procedures required for the comparison, but not the procedures for the realisation of the primary standards within each laboratory. This technical protocol may be read in conjunction with the document CIPM MRA – D-05: "Measurement comparisons in the CIPM MRA".

This Key Comparison follows on from Key Comparison CCAUV.W-K1 which ended in 2004. A number of the recommendations which originated from that comparison have been implemented in this technical protocol (such as greater environmental control of water temperature, and standardisation of the method of mounting hydrophones, and reporting of uncertainties).

The comparison will be organised as a round-robin (sometimes referred to as a "ring" comparison) with the pilot laboratory being the National Physical Laboratory (NPL).

At the 9th CCAUV meeting, this Key Comparison was agreed in principle, and a total of seven NMIs and DIs came forward to take part from UK, USA, Russia, China, Turkey, Brazil and Korea. It was agreed that the National Physical Laboratory (NPL) in the UK would act as pilot laboratory.

As coordinator, NPL sent a questionnaire to all potential participants to request information regarding the scope of their participation, and the scheduling of calibrations. The responses are summarised in Annex H. From the replies, it became clear that the funding for most of the participants would be available in 2016, and so the start of the comparison has been delayed until late 2015. NPL also circulated a discussion document containing the contents of the technical protocol for comment by participants.

PARTICIPANTS

In the Table 1, the first column identifies the participating laboratory by their acronyms. A list of the full names of the laboratories and the contact person is given in Annex A.

In the second column, the country represented by the participant is shown, followed (in the third column) by the NMI listed as representing that country in the List of participants in the CIPM MRA given on the BIPM web-site at: http://www.bipm.org/en/cipm-mra/participation/signatories.html

Finally, the Regional Metrology Organisation (RMO) represented by that participant is shown in the fourth column. In this Key Comparison, there are two laboratories each from APMP, EURAMET and SIM, and one from COOMET.

A number of other laboratories have expressed interest in participation. However, as of the date of this technical protocol, these laboratories have not attained the status of Designated Institute or obtained permission to represent their country in a Key Comparison. Should an additional eligible laboratory wish to join the Key Comparison after the project has commenced, this will be given due consideration by the coordinator (subject to the agreement of the CCAUV, and subject to the participant's ability to satisfy the requirements of this Technical Protocol).

ORGANISATION

The comparison will be organised as a round-robin comparison (sometimes referred to as a "ring" comparison) with the pilot laboratory being the National Physical Laboratory (NPL). NPL will coordinate the exercise and perform check calibrations of the hydrophones between the measurements made by the participating laboratories. NPL will also be responsible for the analysis of the results and the preparation of the Draft A and Draft B reports.

NPL will undertake its calibrations at the start of the Key Comparison, and the results will be submitted to the CCAUV secretariat.

Any questions relating to this project should be communicated to the coordinator at the address below:

Contact:	Stephen P Robinson
Telephone:	+44 20 8943 7152
Fax:	+44 20 8614 0583
Email:	stephen.robinson@npl.co.uk
Address:	National Physical Laboratory Hampton Road Teddington TW11 0LW UNITED KINGDOM

Scheduling of calibrations by participants

From the replies to the questionnaire circulated by NPL (see Annex H for a summary), it is clear most of the participants would be able to calibrate the hydrophones during the period from late 2015 to the end of 2016. Participants indicated that a duration of 4 weeks would typically be required for the calibrations.

A proposed schedule for the comparison has been prepared and is shown in Annex B. This will change only if there are unavoidable delays with any of the measurements.

If necessary, NPL staff will visit the participant at the conclusion of measurements to discuss any difficulties with the calibrations.

Participants are responsible for their own costs of participation, including labour costs and any consumable items.

Transport and delivery

NPL will undertake to arrange for transport of the hydrophones to the participant on the date agreed with the participant. The hydrophones (and the mounting pole with adaptor) will arrive in a protective transit case which must be used to return the hydrophones. The participant must inform NPL (by email) of the safe arrival of the hydrophones.

After calibrations have been completed, the hydrophones and mounting pole must be packed away in the transit case and stored along with any associated paperwork. The participant must then arrange for the devices to be returned to NPL by the agreed date. The participant must inform NPL (by email) when the hydrophones are despatched along with the relevant tracking number for any courier used.

NPL will pay for transport and insurance of the hydrophones when they are being transported from NPL to the participants, including cost of insurance, and any customs fees and duties.

Each participant is responsible for the cost of the return of the hydrophones to NPL after calibrations are completed, including cost of insurance, and any customs fees and duties.

For insurance purposes, the hydrophones should be valued at €6,000.

MEASUREMENTS

Devices for calibration

Each participant will receive a set of two hydrophones for calibration. Each set contains one each of the following:

- Hydrophone type 8104 manufactured by Brüel & Kjær.
- Hydrophone type TC 4034 manufactured by RESON.

A performance specification for each of the hydrophones is given in Annex C. The specification includes information on the nominal performance of the hydrophones, and also information such as the nominal position of the acoustic centre of the hydrophone element.

Another set of nominally identical hydrophones will be kept at NPL to check the stability of the measurements made at NPL and to act as spare hydrophones for the comparison.

Parameter to be determined

The parameter to be determined for each hydrophone is the following:

- the magnitude of the end-of-cable, open-circuit free-field receive sensitivity.

This is defined as the quotient of the open-circuit voltage at the output terminals of the hydrophone to the sound pressure in the undisturbed free field of a plane wave which would exist at the position of the acoustic centre of the hydrophone if the hydrophone were removed from the field [2].

The calibration is required only for the direction indicated by the alignment mark on the hydrophone body (see Alignment section).

The sensitivity must be expressed using S.I. units, as either µV/Pa or as a sensitivity level in dB re 1 V/µPa.

Acoustic frequencies for calibration

The sensitivity should be measured for each of the two hydrophones over the following frequency ranges:

B&K 8104	250 Hz - 120 kHz
TC 4034	100 kHz - 500 kHz

The specific acoustic frequencies within the above ranges at which measurements are to be made are listed in Annex D. Participants should not calibrate the hydrophones at frequencies other than those listed in Annex D.

For a participant unable to calibrate the hydrophones over the entire frequency range, a sub-set of the frequencies listed in Annex D should be chosen which are spanned by the range of frequencies which define the capability of that participant.

Calibration method

The calibration method used is at the discretion of the participant but must be a primary calibration method that is able to determine the magnitude of the free-field receive sensitivity of the hydrophones, and be regarded as the primary standard method for that participant.

The calibration procedure must be described in the participant's report of results. If desired, to make the description shorter, reference may be made to appropriate specification standards such as IEC 60565:2006 [2, 3]. In this case, any deviation from the method described in the standards must be stated.

Hydrophone mount

Since the Key Comparison is intended to determine the degrees of equivalence of national primary standards (and not the ability to calibrate a specific hydrophone is a specific mount), it is desirable that the hydrophone mount is not a source of discrepancy. During CCAUV.W-K1, this was regarded as a source of some of the discrepancies observed, and it is known that hydrophones may be affected by the mounting method used.

Therefore, for CCAUV.W-K2, a hydrophone mount which is designed to fit the two hydrophones used in the comparison will be supplied by the coordinator. This mount must be used by each participant when suspending the hydrophones in the test tank for calibration.

The mount attaches to a 16 mm diameter free-flooding carbon-fibre pole. It is recognised that, depending on the tank facility, the mounting pole will need to be attached to a mounting fixture within the test tank or open-water facility employed.

A diagram and details of the mount and pole are given in Annex E. Precise details for alignment and fitting the hydrophones to the mounting pole will be provided when the hydrophones are dispatched.

Environmental conditions

During CCAUV.W-K1, the variation in water temperature during calibrations was regarded as a potential source of some of the discrepancies observed.

Therefore, in CCAUV.W-K2, the water temperature for calibrations must be within the range 17 °C – 21 °C.

The depth of immersion of the hydrophone in the water must be less than 10 m.

The actual water temperature and depth of immersion during calibrations must be stated with the results.

If, during the analysis of the results, it is considered that the water residual temperature variation has made a significant contribution to the differences between participant results, NPL will undertake calibrations of the hydrophones used in the Key Comparison over the range of temperatures encountered using the NPL Acoustic Pressure Vessel to evaluate the effect.

Alignment

Each hydrophone has an alignment mark on its body to indicate the reference direction for calibration. During calibrations, the hydrophone should be oriented such that its alignment mark is pointing at the projecting transducer in a direction parallel to the direction of propagation of the incoming acoustic wave. To achieve this, it may be necessary to rotate the hydrophone to face toward the projecting transducer during the calibration depending on the geometry of the mounting arrangement used.

If a participant has any doubt whatsoever as to the correct reference direction, the coordinator must be contacted before measurements are begun.

Stability checks by coordinator

NPL, as coordinator, will undertake stability check calibrations in between calibrations by the participants. The results of these calibrations will be used to determine if there are any sudden changes in sensitivity, or any gradual drift with time. These check calibrations will be undertaken under controlled environmental conditions and will consist of calibrations at a subset of acoustic frequencies for each hydrophone. The acoustic frequencies for checking the hydrophones' stability will include the lowest and highest frequency in their useable frequency ranges.

REPORTING OF RESULTS

The participants must report their results to the coordinator not later than four weeks after the measurements are concluded.

The results must be provided electronically to NPL by email in the form of a Microsoft Excel spreadsheet, the columns of which contain the acoustic frequency, the hydrophone sensitivity and the combined uncertainty for each hydrophone calibrated. NPL will provide a spreadsheet for this purpose which may be completed by the participants.

The written results may be provided in a standard certificate or test report (of the form typically provided by the participant to customers), or in a bespoke short report produced for this Key Comparison. Annex F provides guidance on reporting the results.

In whatever form the written results are provided, the report must contain a full description of the calibration method used, and provide (at minimum) report all the information requested by Annex F. Where the procedures of an international standard are followed, all deviations from that standard must be specified.

The results and calibration report should be sent to NPL as soon as possible, but no more than four weeks after the hydrophones are returned to NPL.

Note: the hydrophones themselves must be returned immediately after calibrations are completed to allow the next participant to receive them in good time.

NPL will undertake its calibrations at the start of the Key Comparison, and the NPL results will be submitted to the CCAUV secretariat at the beginning of the project.

Expression of uncertainties

An assessment of the calibration uncertainties must be provided by each participant. This must take the form of an uncertainty budget which should conform to the ISO Guide to the expression of Uncertainty in Measurement [4]. It should consist of a list of the components of uncertainty, along with their estimated values. Where appropriate, the uncertainty evaluation may refer to previously published documents describing the calibration method used. Further guidance is provided in Annex G with regard to some of the sources of uncertainty that may need to be considered (depending upon the procedure used).

The Type A uncertainty shall be estimated from a minimum of four independent measurements.

If requested, NPL will provide a template for the uncertainty budget which participants may use to express their uncertainties. Note that this will only be a guide - not all the components listed in the template may be appropriate and each participant must make their own assessment of their uncertainties.

It should be noted that since the overall calibration uncertainties will be required for the analysis and interpretation of the results, it is important that the uncertainty contributions are realistically estimated and combined in a common manner. Should there be any aspect of the uncertainty assessment of an individual participant which requires clarification (perhaps because of unusually large or small values, or inadequate description of the derivation) the coordinator will seek more extensive information from that participant and confirmation of the uncertainty assessment.

ANALYSIS OF RESULTS

After all calibrations by participants have been completed, NPL will calculate the Key Comparison Reference Values (KCRVs) for the data at each acoustic frequency. In order to calculate the KCRVs, two steps are required. Firstly, a set of consistent measurements must be obtained. This may require some investigation and discussion with participants in order to decide on the elimination of possible outliers. Ideally, the results of participants will be consistent as determined by statistical testing (i.e. they appear to be samples from the same population with overall uncertainties consistent with the deviation from the KCRV).

Having achieved a statistically consistent set of results, the KCRVs may then be calculated. When calculating the KCRV, a weighted mean shall be the preferred method in order to derive an unbiased estimator. The weighted mean will be calculated as an arithmetic mean of the hydrophone sensitivities expressed in linear units (eg µV/Pa), with participants' sensitivity values weighted according to the inverse of the overall uncertainty. However, should unusually wide variation be observed in either the data or the quoted overall uncertainties, the coordinator may also analyse the results using other estimators for comparison.

The deviation of each participant's results from the KCRV will then be calculated to determine the Degree of Equivalence (DOE). This will be calculated as a unilateral DOE (equivalence with respect to the KCRV) for each frequency. The DOE comprises two values: the deviation and its associated uncertainty.

The results of the analysis will be presented for consideration by the participants in a Draft A final report. After agreement, the Draft B final report will be distributed to the KCWG for review and the final report is later submitted for approval by the CCAUV. All individual results will be presented so that further analysis may be performed at a later date if required.

If the results of the stability checks on the hydrophones undertaken by the coordinator demonstrate a drift or sudden change in sensitivity, consideration will be given of how to correct for the effect by use of the data obtained from the stability checks.

If it is suspected that the variation in environmental conditions pertaining to the calibrations by a participant has significantly influenced the calibration results, where possible the coordinator will endeavour to establish the extent of the influence by making parallel measurements under the same conditions. Examples of such influences include the water temperature, the method of mounting the hydrophone, the wetting and soaking procedure.

PRACTICAL NOTES FOR HYDROPHONE USE

Care of Hydrophones

Please take special care when using the hydrophones. In particular, avoid subjecting the hydrophones to mechanical and thermal stress or shock and do not expose them to harmful solvents. Always replace the hydrophones in their cases when they are not being used.

Wetting and soaking

Before use, the rubber boots of the hydrophones should be gently cleaned and wetted using a mild detergent. This is to prevent air bubbles from adhering to the surface of the hydrophones after immersion in the water. Before measurements are begun, the hydrophones should be soaked in the water tank until the hydrophones are fully wetted and they have reached thermal equilibrium with the water medium.

Alignment marks

Each hydrophone has an alignment mark on its body to indicate the reference direction for calibration. For the B&K8104, the alignment mark is that put on by the manufacturer, and is engraved mark on the "shoulder" of the metal part of the hydrophone body. For the TC4034 hydrophone, a painted mark has been placed on the hydrophone body. This mark is coincident with one of the two "seams" in the rubber mould of the body (the seam which is closest to the word "RESON").

If a participant has any doubt whatsoever as to the correct reference direction, the coordinator must be contacted before measurements are begun.

During calibrations, the hydrophone should be oriented using its alignment mark so that it is pointing at the projecting transducer. To achieve this, it may be necessary to rotate the hydrophone to face toward the projecting transducer during the calibration depending on the geometry of the mounting arrangement used.

Maximum acoustic pressure levels

An estimate of the maximum acoustic pressure level at the hydrophones during calibration should be made. This should be stated with the results.

Electrical loading corrections

The quantity to be measured is the end-of-cable open-circuit sensitivity. Therefore, the effect of electrical loading due to extension cables or amplifier input impedance must be accounted for in the measurements. The value of any electrical corrections applied (and their derivation) must be stated with the results, along with the results of any necessary hydrophone impedance measurements.

Use of KC hydrophones as projectors

It should not be necessary to drive the hydrophones and use them as sound transmitting devices. Although the hydrophones circulated are reciprocal devices, driving the hydrophones electrically runs the risk of damaging them. The hydrophones used in the Key Comparison become highly valuable when calibrated, and the cost of time for repeat calibrations (and complexity of analysis) if hydrophones need to be replaced will be prohibitive. Therefore, use of the Key Comparison hydrophones as sound sources is strongly discouraged.

If the three-transducer free-field reciprocity calibration method is used, two other transducers should be chosen for use as the projector and reciprocal transducer in the calibration procedure

References

1. Mutual recognition of national measurement standards and of calibration and measurement certificates issued by national metrology institutes. CIPM, Paris, October 1999.

2. IEC 60565:2006. *Underwater acoustics – Hydrophones - Calibration in the frequency range 0.01 Hz to 1 MHz* International Electrotechnical Commission, Geneva.

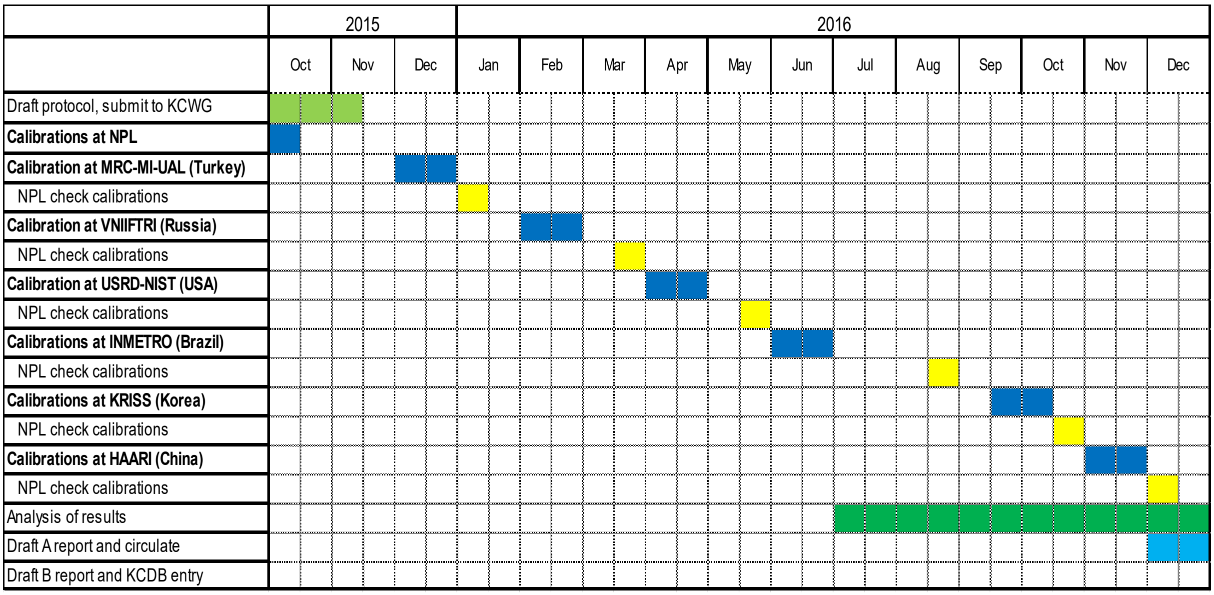
3. ANSI/ASA S1.20:2012 *Procedures for Calibration of Underwater Electroacoustic Transducers*. American National Standards Institute, New York, USA.

4. JCGM 100:2008, Evaluation of measurement data – *Guide to the Expression of Uncertainty in Measurement* (GUM), joint publication by BIPM, IEC, IFCC, ILAC, ISO, IUPAC, IUPAP and OIML, 2008. Available from www.bipm.org

Protocol Annex A: List of participants and contact details

HAARI: Chen Yi Hangzhou Applied Acoustics Research Institute, Guihuaxi Road 82, Hangzhou Fuyang, Zhejiang, 311400 China Tel: +86 (571) 6333 2051 Email: y.chen@163.com	**INMETRO:** Rodrigo Costa-Felix INMETRO – Instituto Nacional de Metrologia, Qualidade e Tecnologia, Laboratório de Ultrasound Av. N. Sra. das Gracas, 50 (Bld 1), Xerem, Duque de Caxias, RJ, Brazil, ZIP 25.250-020 Tel: +55 (21) 2679 9720 Email: rpfelix@inmetro.gov.br
KRISS: Kyungmin Baik Korea Research Institute of Standards and Science Acoustics and Vibration Group Division of Physical Metrology 1 Doryong-Dong, Yuseong 305-340 Daejeon Republic of Korea, Tel: +82 42 868 5300 Email: kbaik@kriss.re.kr	**MRC-MI-UAL (TÜBITAK):** Alper Biber TÜBITAK Underwater Acoustics Laboratory Marmara Research Center Materials Institute Gebze Kocaeli TURKEY Tel: +90 (262) 677 30 85 Email: alper.biber@tubitak.gov.tr
NPL: Stephen Robinson National Physical Laboratory Acoustics Group, Room F10-A5 Teddington, Middlesex TW11 0LW United Kingdom Tel: +44 20 8943 7152 Fax: +44 20 8614 0583 Email: stephen.robinson@npl.co.uk	**USRD (NIST):** Steven Crocker Undersea Reference Division Naval Undersea Warfare Center Newport, Rhode Island USA Tel: +1 401-832-8961 Email: steven.crocker@navy.mil
VNFIITRI: Alexander Isaev Institute for Physical-Technical and Radiotechnical Measurements, Laboratory for Acoustics 141570 Mendeleevo, Moscow Region Russian Federation Tel: +7 (495) 660 21 66 Email: isaev@vniiftri.ru	

Protocol Annex B: Proposed schedule for calibrations



Protocol Annex C – Hydrophone specification and mount

Mounting and alignment

Since the Key Comparison is intended to determine the degrees of equivalence of national primary standards (and not the ability to calibrate a specific hydrophone in a specific mount), it is desirable that the hydrophone mount is not a source of discrepancy. During CCAUV.W-K1, this was regarded as a source of some of the discrepancies observed, and it is known that hydrophone responses may be affected by the mounting method.

Therefore, for CCAUV.W-K2, a hydrophone mount designed to fit the two hydrophones used in the comparison was supplied by the pilot laboratory, NPL. This mount was used by each participant when suspending the hydrophones in the test tank for calibration, unless otherwise stated. The mount consists of a 16 mm diameter free-flooding carbon-fibre pole.

The B&K 8104 and the Reson TC4034 are both mounted coaxially at the end of the carbon fibre pole provided. For alignment of the B&K8104, the manufacturer's engraved alignment mark is aligned with the white alignment mark on the pole. For the Reson TC4034, the mould line in the rubber boot closest to the word "RESON" is aligned with the white alignment mark on the pole. When the pole was then attached to the positioning carriage on the participants positioning system, the alignment mark on the pole must be aligned to a pre-defined reference orientation.

Hydrophone specifications

A nominal performance specification for each of the hydrophones is given below. Another set of nominally identical hydrophones was kept at NPL to act as spare hydrophones for the comparison.

Table 3.1 Nominal specification of the B&K8104 hydrophone

Brüel and Kjær 8104	
Frequency range for calibration	250 Hz – 120 kHz
Nominal voltage sensitivity (250 Hz)	-205 dB re 1 V/µPa
Nominal capacitance	7800 pF
Active element type	4 PZT rings (12 mm dia.)
Position of acoustic centre (from end of hydrophone boot)	16 mm
Length of integral cable	10 m
Horizontal directivity (at 100 kHz)	±2 dB (typical)
Vertical directivity (over 270º at 50 kHz)	±2 dB (typical)
Cable	twin conductor, shielded,
Connector	BNC
Length of cable	10 m
Weight with cable (in air)	1.6 kg

Table 3.2 Nominal specification of the TC4034 hydrophone

Reson TC4034	
Frequency range for calibration	100 kHz – 500 kHz
Nominal voltage sensitivity (250 Hz)	-218 dB re 1 V/µPa
Nominal capacitance	3000 pF
Active element type	6 mm diameter PZT sphere
Position of acoustic centre (from end of hydrophone boot)	5.5 mm
Length of integral cable	10 m
Horizontal directivity (at 100 kHz)	±2 dB (typical)
Vertical directivity (over 270º at 50 kHz)	±2 dB (typical)
Cable	twin conductor, shielded,
Connector	BNC
Length of cable	10 m
Weight with cable (in air)	1.6 kg

Protocol Annex D – Acoustic frequencies of measurement

The following acoustic frequencies are required for the key comparison (frequencies are in kHz).

Each participant received a set of two hydrophones for calibration containing:

- Hydrophone type 8104 manufactured by Brüel & Kjær.
- Hydrophone type TC 4034 manufactured by Teledyne Reson.

The hydrophone sensitivities were requested at a total of 102 discrete acoustic frequencies over the 11 octaves from 250 Hz to 500 kHz. The selected acoustic frequencies were as follows:

Table 3.3 Brüel and Kjær 8104: 61 frequencies in the range 250 Hz - 120 kHz

0.25	0.3	0.4	0.5	0.6	0.7	0.8	0.9		
1	2	3	4	5	6	7	8	9	
10	12	14	16	18	20	22	24	26	28
30	32	34	36	38	40	42	44	46	48
50	52	54	56	58	60	62	64	66	68
70	72	74	76	78	80	82	84	86	88
90	100	110	120						

Table 3.4 Reson TC4034: 41 frequencies in the range 100 kHz - 500 kHz

100	110	120	130	140	150	160	170	180	190
200	210	220	230	240	250	260	270	280	290
300	310	320	330	340	350	360	370	380	390
400	410	420	430	440	450	460	470	480	490
500									

Protocol Annex E – Hydrophone mount

A hydrophone mount will be supplied by the coordinator with the hydrophones under test. This is a carbon-fibre free-flooding pole which has a 16 mm outer diameter at the opposite end to the hydrophone. The pole has locating lugs for use in alignment, but an adaptor is available for use which converts the end of the pole to a simple 16 mm diameter tube. Figure 1 shows a diagram of the pole, and the adaptor.

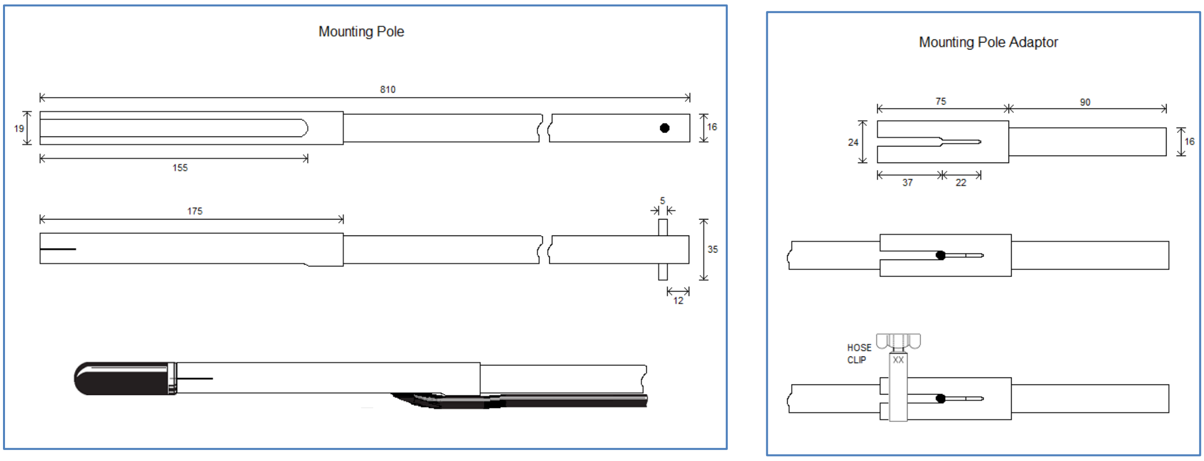


Figure 1. Mounting pole (left) and adaptor (right) to be supplied with hydrophones. Dimensions in millimetres.

The mounting pole is designed to fit the two hydrophones used in the comparison. The hydrophones fit snugly into the free-flooding pole and the cable is routed through a slot in the side of the pole. The precise details for alignment and fitting the hydrophone to the mounting pole will be provided when the hydrophone is dispatched.

Protocol Annex F – Reporting of results

The information requested below must be reported when stating the results of the calibrations undertaken in the Key Comparison CCAUV.W-K2. The information is based on that required by IEC 60565:2006.

The language used must be English.

Calibration Results

The calibration results must be reported in three columns containing:

Acoustic frequency, Free-field sensitivity, Expanded uncertainty

Along with the calibration results, the following data must also be provided:

- date of the calibrations;
- water temperature;
- depth of immersion;
- type of rigging used to attach the hydrophone mount to the positioning system;
- length of soaking time and any wetting procedure adopted;
- any alignment procedure used to align the hydrophone under test;
- assumptions made about the device under test (e.g., the position of the reference centre).

Description of calibration method

The description of the hydrophone calibration method should include the following information:

1. A full description of the method used to calibrate the hydrophones. If reference was made to any written standards (e.g. IEC), give details of how they were applied to this calibration.
2. A description of the type of acoustic signal used for the calibration (e.g. continuous-wave, gated tone-burst, pulsed, etc.).
3. Details of any reference transducers used in the calibration. How were these reference transducers calibrated?
4. A description of the facility in which measurements were made. What are the dimensions of the water tank or open-water site? What is the tank constructed of? Were any baffles or absorbers used?
5. The method of measuring the water temperature (including where is was measured and whether any temperature gradient may have been present).
6. The method of determining the hydrophone depth in the water during measurements.
7. The length of any extension cable used for the hydrophones. If added cable was used, were any corrections made for electrical loading of the hydrophone by the added cable? If so, describe how the corrections were calculated.
8. The electrical input impedance of the electrical equipment to which the hydrophone was connected (typically, this would be a hydrophone pre-amplifier). Were any corrections made for electrical loading of the hydrophone by the amplifier? If so, describe how the corrections were calculated.
9. How the electrical voltages and currents measured during calibrations.
10. How the acoustic frequency was measured. Were any other quantities required for the calibration (e.g. density of water)? If so, how were they determined?
11. How the transducer-hydrophone separation distance was measured and to what accuracy? Were different separation distances used for repeated measurements?
12. The length of time the hydrophones immersed in water before the first measurements were taken. Specify the total length of time that the hydrophones were immersed in water. Give details of any wetting agent used on the hydrophones.

If it was not possible to comply with the procedures specified in this protocol document, or if there were any in-house procedures used which are considered superior, then the differences should be specified in the report. Please specify the reasons for the differences if they are not obvious.

Protocol Annex G: Reporting of uncertainties

The uncertainty assessment by each participant shall be undertaken in accordance with the Guide to the Expression of Uncertainty in Measurement (GUM) – JCGM 100:2008. This is a joint publication by BIPM, IEC, IFCC, ILAC, ISO, IUPAC, IUPAP and OIML.

Type A uncertainty

State how the Type A uncertainty (repeatability) was calculated from the calibration results, including how many repeated measurements were made during the calibrations, and whether the hydrophones removed from the tank and remounted between each calibration set.

Type B uncertainty

State a list of the components which were considered to contribute to the Type B uncertainty for the calibration. The list should include the value of the uncertainty for each contribution. Please state the derivation of the components where this is not obvious.

Uncertainty budget

Please list the uncertainty budget and state the overall uncertainty expressed for a coverage factor of k=1. Specify how the overall total was calculated from the individual contributions (e.g. by the method described in the GUM). Indicate the number of effective degrees of freedom so that a proper estimate of the level of confidence may be made. The uncertainty budget must be specific to the individual participant and requires an individual assessment to be made for the calibration method and procedure adopted by that participant. However, some sources of uncertainty are common within hydrophone calibration, and as a guide, these are listed in the following section. Not all of these uncertainties may apply to a specific implementation of a calibration method.

Common sources of Type B uncertainty

Sources of Type B uncertainty specific to free-field reciprocity calibrations include:

- uncertainty of any assumptions about the acoustic field, e.g. that the field is a spherical-wave field (this may be checked by varying the separation distance between transducers and checking that the product of electrical transfer impedance and distance is invariant; see IEC 60565:2006);
- non-reciprocal behaviour by transducers (can be evaluated by checking the equivalence of the Z_{PT} and Z_{TP} electrical transfer impedances; see IEC 60565:2006);
- uncertainties in the measurement of the separation distance;
- uncertainties in the values for acoustic frequency and water density (required to calculate the reciprocity parameter).

Other sources of uncertainty might include:

- lack of steady-state conditions, especially where bursts of single-frequency sound waves are used (the resonance frequency and Q-factors of the transducers and the echo-free time of the test tank will influence this contribution);
- interference from acoustic reflections, leading to a lack of free-field conditions;
- lack of acoustic far-field conditions;

- the spatial averaging effects of the hydrophones under calibration due to their finite size and the lack of perfect plane-wave conditions (typically, only an issue at very high frequencies);
- misalignment, particularly at high frequencies where the hydrophone response may be far from omnidirectional;
- acoustic scattering from the hydrophone mount (or vibrations picked up and conducted by the mount); this should be minimised by the use of a common hydrophone mount, but the rigging used to attach the hydrophone pole to the positioning framework may have an influence;
- uncertainty in measurement of the receive voltage (including uncertainty due to the measuring instrumentation (voltmeter, digitizers, etc.);
- uncertainty of the gains of any amplifiers, filters, and digitizers used (the use of a common measurement channel and the measurement of voltage ratios may reduce this component);
- uncertainties in the measurement of the drive current or voltage;
- uncertainties due to the lack of linearity in the measurement system (the use of a calibrated attenuator to equalize the measured signals may significantly reduce this contribution);
- uncertainty of any electrical signal attenuators used;
- electrical noise include RF pick-up;
- uncertainty of any electrical loading corrections made to account for loading by extension cables and preamplifiers.

Protocol Annex H: Summary of replies to participant questionnaire

Table 2. Summary of questionnaire replies (CCAUV.W-K2)

Participant	Frequency range	Resolution	Hydrophone choice	Mount requested	Uncertainty budget available	Environment (temperature in range 17-21 °C)	Timing and duration of calibrations
NPL	250 Hz – 500 kHz	Full	OK	Yes	OK	OK	Completed
USRD-NIST	250 Hz – 500 kHz	Full	OK	Yes	OK Template requested	OK	Unspecified (3 weeks)
VNIIFTRI	250 Hz – 500 kHz	Full	OK	Yes	OK Template requested	OK	Feb 2016 (4 weeks)
HAARI	250 Hz – 500 kHz	Full	OK	Yes	OK	OK	Sep-Oct 2016 (4 weeks)
TUBITAK-MAM	**2 kHz** – 500 kHz	Full	OK	Yes	OK Template requested	OK	Sep – Oct 2015, or Sep-Oct 2016 (4 weeks)
KRISS	**100 kHz** – 500 kHz	Full (or 20 kHz steps)	TC4034 only	Yes	OK	OK	Oct 2016
INMETRO	250 Hz – **150 kHz**	Full	OK	Yes	OK Template requested	OK	Mar – Jun 2016 (4 weeks)

18 ANNEX G: TEMPLATE FOR UNCERTAINTY BUDGET

Source of uncertainty	Uncertainty value (± %)	Probability distribution	Divisor	c_i	u_i (± %)	v_i or v_{eff}
Acoustic frequency	0.0	rectangular	1.73	0.5	0.00	infinity
Water density	0.0	rectangular	1.73	0.5	0.00	infinity
Non-reciprocal behaviour	0.0	rectangular	1.73	0.5	0.00	infinity
Transfer impedance Zpt:						
Separation distance	0.0	rectangular	1.73	0.5	0.00	infinity
Current measurement repeatability (Type A)	0.0	normal	1.00	0.5	0.00	n-1
Current measurement systematic (Type B)	0.0	normal	1.00	0.5	0.00	infinity
Voltage measurement repeatability (Type A)	0.0	normal	1.00	0.5	0.00	n-1
Voltage measurement systematic (Type B)	0.0	normal	1.00	0.5	0.00	infinity
Electrical loading on hydrophone	0.0	rectangular	1.73	0.5	0.00	infinity
Non-spherical field	0.0	rectangular	1.73	0.5	0.00	infinity
Non steady-state	0.0	rectangular	1.73	0.5	0.00	infinity
Orientation & alignment	0.0	rectangular	1.73	0.5	0.00	infinity
Wetting	0.0	rectangular	1.73	0.5	0.00	infinity
Additional uncertainty component	0.0	rectangular	1.73	0.5	0.00	infinity
Additional uncertainty component	0.0	rectangular	1.73	0.5	0.00	infinity
Transfer impedance Zph:						
Separation distance	0.0	rectangular	1.73	0.5	0.00	infinity
Current measurement repeatability (Type A)	0.0	normal	1.00	0.5	0.00	n-1
Current measurement systematic (Type B)	0.0	normal	1.00	0.5	0.00	infinity
Voltage measurement repeatability (Type A)	0.0	normal	1.00	0.5	0.00	n-1
Voltage measurement systematic (Type B)	0.0	normal	1.00	0.5	0.00	infinity
Electrical loading on hydrophone	0.0	rectangular	1.73	0.5	0.00	infinity
Non-spherical field	0.0	rectangular	1.73	0.5	0.00	infinity
Non steady-state	0.0	rectangular	1.73	0.5	0.00	infinity
Orientation & alignment	0.0	rectangular	1.73	0.5	0.00	infinity
Wetting	0.0	rectangular	1.73	0.5	0.00	infinity
Additional uncertainty component	0.0	rectangular	1.73	0.5	0.00	infinity
Additional uncertainty component	0.0	rectangular	1.73	0.5	0.00	infinity
Transfer impedance Zth:						
Separation distance	0.0	rectangular	1.73	0.5	0.00	infinity
Current measurement repeatability (Type A)	0.0	normal	1.00	0.5	0.00	n-1
Current measurement systematic (Type B)	0.0	normal	1.00	0.5	0.00	infinity
Voltage measurement repeatability (Type A)	0.0	normal	1.00	0.5	0.00	n-1
Voltage measurement systematic (Type B)	0.0	normal	1.00	0.5	0.00	infinity
Electrical loading on hydrophone	0.0	rectangular	1.73	0.5	0.00	infinity
Non-spherical field	0.0	rectangular	1.73	0.5	0.00	infinity
Non steady-state	0.0	rectangular	1.73	0.5	0.00	infinity
Orientation & alignment	0.0	rectangular	1.73	0.5	0.00	infinity
Wetting	0.0	rectangular	1.73	0.5	0.00	infinity
Additional uncertainty component	0.0	rectangular	1.73	0.5	0.00	infinity
Additional uncertainty component	0.0	rectangular	1.73	0.5	0.00	infinity
Type A (repeatability of calibration)	0.0	normal	1.00	1.0	0.00	*n-1*
Combined uncertainty		normal			0.00	
Expanded uncertainty (k=2)		normal (k=2)			0.00	