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Final Report for Key Comparison CCAUV.W-K1: Calibration of hydrophones in the frequency range from 1 kHz to 500 kHz.

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ABSTRACT

This document is the final report for the Key Comparison CCAUV.W-K1. This project is one of the Key Comparisons organised under the auspices of the Consultative Committee on Acoustics, Ultrasound and Vibration of the CIPM.

The results are presented for the comparison of the primary free-field standards for sound in water at frequencies between 1 kHz and 500 kHz. The standards were compared by use of three hydrophones as transfer standards, with each hydrophone calibrated by all participants. The results of the participants are used to provide the Key Comparison Reference Values (KCRV) at each acoustic frequency, as required by the Mutual Recognition Arrangement. The degree of equivalence of national measurement standards is then calculated from the differences of the participants' results from the KCRV. The bilateral degree of equivalence between national measurement standards in each pair of countries is then calculated.

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CONTENTS

1. INTRODUCTION

This report presents results for the first Key Comparison for the primary free-field standards for sound in water at frequencies between 1 kHz and 500 kHz. This project is one of the Key Comparisons organised under the auspices of the Consultative Committee on Acoustics, Ultrasound and Vibration of the CIPM (comparison identifier: CCAUV.W-K1). The results of the participants are used to provide the Key Comparison Reference Values (KCRV) at each acoustic frequency, as required by the MRA [1]. The degree of equivalence of national measurement standards is then calculated from the differences of the participants' results from the KCRV.

This document is the final report for the Key Comparison CCAUV.W-K1. It has been ratified by CCAUV and is a publicly available document.

2. ORGANISATION OF THE COMPARISON

2.1 THE COMPARISON

The project was organised as a round-robin exercise with each participant asked to determine the free-field open-circuit voltage sensitivity of the same three hydrophones at selected frequencies in the range 1 kHz to 500 kHz. The pilot laboratory for the project was the National Physical Laboratory (NPL), UK.

NPL has also undertaken initial assessment and calibration of the hydrophones and performed checks on the hydrophone sensitivities between the calibrations by participants to ensure that the hydrophone sensitivities were stable.

2.2 PROTOCOL DOCUMENT

As pilot laboratory, at the beginning of the exercise, NPL prepared and circulated a protocol document describing the measurements required. This was circulated first as a draft, the contents then being agreed by the participants. The protocol contained a questionnaire, which provided a means for the participants to report the results of measurements and describe the calibration method.

2.3 THE PARTICIPANTS

The comparison had a total of seven participating organisations representing seven countries. These are listed in Table 1 along with their country and relevant Regional Metrology Organisation. In cases where the participant undertaking the measurements is not a National Metrology Institute (NMI), the relevant NMI has decreed that the organisation is able to officially represent the country.

Table 1. Participants in Key Comparison CCAUV.W-K1 in chronological order of participation

INSTITUTE NAME	***COUNTRY***	***RMO***
NPL	U.K.	EUROMET
WTD (PTB)	GERMANY	EUROMET
USRD/NUWC	U.S.A.	SIM
VNIIFTRI	RUSSIA	COOMET
NIM	CHINA	APMP
DRDC	CANADA	SIM
CSIR	SOUTH AFRICA	SADCMET

2.4 THE HYDROPHONES

Each participant has calibrated the same three hydrophones at approximately 40 discrete acoustic frequencies in the range 1 kHz to 500 kHz. The devices used for the calibration are detailed in Table 2.

Table 2. Details of the three hydrophones used Key Comparison CCAUV.W-K1.

Hydrophone type	*Serial number*	*Manufacturer*	*Frequency range (kHz)*	*Nominal sensitivity at 1 kHz (dB re 1 V/µPa)*	*Integral preamplifier*
H52	50	USRD	1 - 100	-177.5	Yes
8104	1757065	Brüel & Kjær	10 - 150	-205.5	No
4034	426001	Reson	100 – 500	-218.0	No

2.5 COMPARISON SCHEDULE

The hydrophones were circulated to the participants in a round robin fashion, with the devices being returned to NPL after each set of calibrations by the participants. Table 3 shows the dates for the calibrations by each participant. The exercise began in the summer of 2000 with NPL calibrating the hydrophones between the calibrations of the participants. Each participant was given 8 weeks to complete the calibrations of the three hydrophones. There were occasional delays, with the most significant source being the need to conform to customs and excise procedures. These delays also affected the scheduling of the subsequent calibrations.

The USA initially undertook calibrations of all three hydrophones in December 2000 and January 2001. However, the discovery of a malfunction with one of the instruments used for the USA calibration necessitated a recalibration of two of the hydrophones, this recalibration being performed at the end of the comparison.

Table 3. Schedule of calibrations for the comparison

	Participants							
	UK	Germany	USA	Russia	China	Canada	South Africa	USA
H52	Aug-00	Sep-00	Dec-01	May-01	Sep-01	Mar-02	May-02	
B&K8104	Apr-00	Sep-00		May-01	Sep-01	Mar-02	May-02	Dec-02
TC4034	Jun-00	Sep-00		May-01	Sep-01	Mar-02	May-02	Dec-02

3. THE CALIBRATIONS

3.1 CALIBRATION METHODS

Participants were asked to perform an absolute measurement of the end-of-cable free-field open-circuit sensitivity of each hydrophone using their own in-house methods and procedures for the calibrations. For this project, the “left-hand” XYZ coordinate system suggested by IEC 60565 [2] was adopted, with each participant asked to align the hydrophones such that an alignment mark on the hydrophone body pointed in a direction parallel to the direction of propagation of the incoming acoustic wave.

The method of calibration used by participants was the method of three-transducer spherical-wave reciprocity. By use of this method, which is described in an international standard [2], a hydrophone may be calibrated absolutely by making purely electrical measurements.

Most commonly, participants used laboratory tank facilities of varying sizes, the largest being 15 x 7.5 x 7 metres and the smallest dimension of any of the test tanks used being 4.5 metres. All of the tanks had a framework or traversing system used for mounting and positioning the transducers. One participant used an open-water facility on a lake, which had a water depth of 11 metres, a laboratory platform being created using a pier or pontoon based structure from which transducers may be lowered into the water. For all participants, discrete-frequency tone-burst signals were employed, with reflections isolated from the direct-path signal by use of gating and time-windowing techniques. Table 4 presents the calibration details for each participant.

Table 4. Summary of information provided in the calibration reports of the participants.

UK (NPL)

Facility	Laboratory water tank made of wood and of diameter 5.5 m and depth 5.0 m filled with fresh water. Smaller 2 x 1.5 x 1.5 m tank available for high frequencies. Precision positioning systems on each tank to facilitate accurate positioning of transducers.
Water temperature	B&K 8104: 18.3 °C - 18.5 °C; Reson TC4034: 20.2 °C - 20.5 °C; H52: 20.5 °C -21.1 °C
Depth of immersion	Depth 2.5 m in large tank, 0.7 m in small tank
Mounting/rigging	Hydrophones mounted coaxially at the end of a free-flooding carbon fibre pole. The transducer mounting poles are supported by individual positioning carriages, which in turn are mounted on a vibration-isolated steel frame. The carbon-fibre poles are custom-made to suit particular transducers.
Type of signal	Gated tone burst
Cable extensions	None used.
Corrections made	For B&K8104 and TC4034 only, small electrical loading corrections calculated using the complex impedance of hydrophone and amplifier input impedance. Sensitivities corrected to give end-of-cable open-circuit values. Small corrections made for absorption of sound in water (negligible except for very highest frequencies).

Specification standards	Method conforms to IEC 565:1977 – The calibration of hydrophones.
Soaking/wetting	All transducers soaked in the water tank overnight prior to commencing the calibration. Transducers remained submerged in the water tank for the duration of the calibration and were only removed from the tank for short periods to allow for remounting. Prior to placing the devices into the tank a surfactant was applied to the transducer by brush to aid the wetting process.
Constants used in calculations	Water temperature is measured via a calibrated digital scanning thermometer. The measured temperature is then used in the equations of Del Grosso to calculate the water density (and sound speed – used for time-delay calculations in windowing) .

Germany (WTD71)

Facility	The test facility is on a fresh water lake of water depth 11 m.
Water temperature	The water temperature is measured continuously by a weather station. The temperature varied between 14 and 18 ºC over the 30-day test period.
Depth of immersion	4 m below the water surface.
Mounting/rigging	The transducers were mounted in pairs, onto rods set 1 m apart. To reduce the influence of structure borne noise from the support, both were decoupled by rubber material at the brass fixing clamps.
Type of signal	Gated sinusoid with a pulse length of 1 ms -10 ms.
Cable extensions	None used.
Corrections made	No corrections made.
Specification standards	None quoted.
Soaking/wetting	After arriving, the hydrophones were immersed in water until the last measurement had finished. Only for changing the measurement set-up were the corresponding hydrophones/transducers taken out of the water. After mounting, the rubber boots of the hydrophones/transducers were gently cleaned using liquid soap before each immersion.
Constants used in calculations	For the calculation of the reciprocity parameter, a water density value of 1 kg/dm^3 was used

U.S.A (USRD/NUWC)

Facility	Laboratory tank of dimensions 9.14 m long by 4.57 m wide and 4.57 m deep.
Water temperature	All measurements were taken at a water temperature of 18.4 ºC.
Depth of immersion	Depth was 2.28 m for all measurements.
Mounting/rigging	The B&K and Reson had tape wrapped around the top of the hydrophone so that they fit the standard fixtures constructed of brass and bronze. Other offset fixtures and the rigging shafts are made of stainless steel.
Type of signal	Gated sinusoid signals.
Cable extensions	None used.
Corrections made	No corrections made.
Specification standards	American National Standard “Procedures for Calibration of Underwater Electroacoustic Transducers” (ANSI S1.20-1988)
Soaking/wetting	The transducers were rigged and submerged in the tank for 10 minutes before the measurements were made. It is estimated that the hydrophones stayed immersed (on average) for a 3 hour time period. The temperature of the test tank water was comparable to that of the ambient air temperature. Extreme

	differences between these two temperatures would have required additional time for the device under test to reach thermal equilibrium before testing could have begun. Each standard hydrophone projector, transducer, and unknown hydrophone was washed down prior to immersion with "AEROSOL RT" (manufactured commercially by Fisher Scientific).
Constants used in calculations	A value for water density of 1000 kg/m^3 was used

Russia (VNIIFTRI)

Facility	Laboratory tank of dimension 10 m long, 6 m wide and 6 m deep for calibrations of all hydrophones at frequencies less than 340 kHz. For calibrations of the TC4034 hydrophone at frequencies between 340 kHz and 500 kHz, a smaller tank of dimensions 1.6 m long by 1.1 m wide by 1.0 m deep was used. Both tanks are filled with specially prepared, degassed water. Before calibrations, the quality of the water was checked by measurement of time-stability of the transfer impedance of a pair of hydrophones.
Water temperature	The temperature of the water in the large tank ranged between 14 °C and 15 °C. For the smaller tank, the water temperature was 19.5 °C. A thermometer measured the temperature with an accuracy of ± 0.5 °C.
Depth of immersion	The depth of submersion of the hydrophones was 3 m for the larger tank and 0.5 m for the smaller tank used for the 340 kHz to 500 kHz range.
Mounting/rigging	The transducers were fixed with the help of thin titanium strings under water. The transducers were fixed on the strings by means of grips of minimal size. The grips are made of plastic. A similar positioning system was used for both large and small tanks.
Type of signal	A "tone-burst" signal with fixed initial phase was used for the calibration. The time interval between repetitions was not less than 1 sec (more than the time of reverberation in the tank). The burst duration depended on the calibration frequencies and was not less than 20 periods of the tone burst at high frequencies. The spatial length of the pulse was not more than 6m at low frequencies.
Cable extensions	None used.
Corrections made	No corrections applied.
Specification standards	The standard IEC 565 was followed as part of the calibration.
Soaking/wetting	The hydrophones were immersed in the water tank at working depth for the duration of the measurements. The hydrophones were placed in water at least one day before the beginning of measurements. After re-clamping and re-wiring, the hydrophones were maintained at working depth for at least 1 hour before measurements. Before immersing in the water, the surface and sensitive element of the hydrophone were cleaned with alcohol solution.
Constants used in calculations	The water density is defined from tabular values with an accuracy of ± 0.1%.

China – NIM

Facility	Laboratory tank of dimension 15 m long, 7.5 m wide and 5 m deep.
Water temperature	The water temperature was 17 ºC during the calibration, measured by an underwater electronic thermometer.

Depth of immersion	The hydrophones were at a depth of 2.5 m during calibration.
Mounting/rigging	The hydrophones were mounted on an adjustable stainless steel scale with a total length of 1200 mm. Two transducers at a time could be mounted on this scale at a separation of 1000 mm.
Type of signal	Gated tone burst
Cable extensions	None used
Corrections made	No corrections made.
Specification standards	The written standards followed were the National Standard of China “GB/T 3223-1994 Acoustics—Free field calibration method of underwater sound transducers” (equivalent to the IEC 565 – 1977 Calibration of hydrophones).
Soaking/wetting	Before doing calibration, hydrophones were immersed in water 24 hrs. After fixing the transducer on the specially designed supporter and immersing it in water at the measurement depth (2.5 m) for about 30 min, the first measurement was taken. The total length the hydrophones were immersed in water throughout all the measurements was 72 hrs. Before the transducers were immersed in water, they were washed with a cleaning agent.
Constants used in calculations	A value for density of water of 1000 kg/m^3 was used.

Canada (DRDC)

Facility	Cylindrical laboratory tank of dimension 7.5 m in diameter and 4.5 m deep.
Water temperature	Water temperature ranged from 17.4 °C at the start of the calibrations to 17.7 °C at the end.
Depth of immersion	Hydrophones were calibrated at 1.83 m (± 0.003 m) depth. Depth was measured with a steel tape measure before immersion by subtracting the distance from a reference point on the motor station to the water surface, from the distance from the station to the hydrophones centre.
Mounting/rigging	The hydrophones under test, projector, and reciprocal transducers were mounted on tee-bars suspended from 2 remote controlled rotary stations. The stations are motor driven with optical shaft encoders with 0.1 degree readouts. Hydrophones were supported on hollow slender fibreglass (FRP) mounting rods. Rods are stepped construction, having a top section of larger diameter to mount to the station apparatus, and a smaller diameter bottom section to affix the hydrophone.
Type of signal	Gated tone-burst.
Cable extensions	None used
Corrections made	Corrections were made for electrical loading of the B&K8104 and the TC4034 based on the nominal 100 pF input impedance of Krohn-Hite Model 3988, using the end of cable capacitances measured with HP LCR meter model 4261A at 100 Hz.
Specification standards	None specified.
Soaking/wetting	Immersion times: B&K 8104: 121.75 hours; USRD H52: 119.25 hours; Reson TC4034: 149.75 hours. Wetting agent was 10% Sunlight$^{\mathrm{TM}}$ liquid soap and water.
Constants used in calculations	A specific gravity measurement of a sample of the tank water using a hydrometer traceable to NIST yielded an estimate for density of 998.5 ± 2 kg/m^3 at a temperature of 18.5 °C. This agreed well with a value of

998.51 kg/m^3 interpolated from published values of the density of pure water as a function of temperature.

South Africa (CSIR)

Facility	Laboratory tank of dimension 10 m long, 5 m wide and 5 m deep filled with tap water.
Water temperature	The water temperature varied from 20 °C during the first week of measurement to between 18.4 and 18.6 °C for the rest of the period.
Depth of immersion	Hydrophones were submerged at a depth of 2 m below the water surface. The transducer cables are marked at 2 m from the approximate acoustic centre. When submerged this mark is lined up with the water surface. This depth is accurate to within 10 mm or 0.5%.
Mounting/rigging	Sensors were suspended 2 m below the water surface by clipping the cable in special jigs on the positional structure. The hydrophones were not mounted to any fixed structure below the water surface. Graphite rods were attached to the cables of hydrophones of lighter mass (including the TC 4034). The hydrophones were attached to the rods using cable ties.
Type of signal	Gated tone burst was used. Pulse length was measured in number of cycles and number of cycles was increased with frequency.
Cable extensions	None used.
Corrections made	No corrections applied.
Specification standards	In house procedures comply with IEC 565:1977.
Soaking/wetting	The hydrophones were soaked for 30 minutes prior to commencing with measurements. None of the audit samples were soaked for more than five days, and they were never left in the tank over night. A mild diluted dishwashing detergent was used to limit the formation of bubbles on the transducer face.
Constants used in calculations	The water density was defined from tabulated values.

3.2 INFLUENCES ON THE CALIBRATIONS

From the results of previous comparison exercises [3], it is clear that a number of factors may influence the results of calibrations and contribute to the variations in results between participants, either because of unavoidable differences in environmental conditions, or because of differences in the procedures used by the participants. Potential influences identified in the protocol document include:

i. poor alignment (hydrophone directional response);
ii. lack of acoustic far-field conditions;
iii. length of wetting and soaking time;
iv. lack of steady-state conditions;
v. interference from acoustic reflections;
vi. influence of noise;
vii. electrical loading by cables/amplifiers;
viii. influence of mounting/rigging;

ix. water temperature;
x. depth of immersion.

The first seven of the influences listed above are related to the particular implementation of the calibration method. Each participant produces an uncertainty budget for the calibrations and this should include estimates for the uncertainty contributions due to these influences.

It is known that the mounting configuration used can also affect the measured sensitivity for some hydrophones, and this may contribute to the variation in results. Ideally, the mount should not cause any reflections or reverberations in the acoustic signal, but should be rigid enough to allow precise positioning of the hydrophones. Fortunately, there has been a general similarity between the mounting arrangements used by participants, with many using some form of free-flooded tube, often made of metal or plastic.

The last two influences listed depend on environmental conditions which may not be completely controlled. Table 5 provides a summary of the conditions under which calibrations have been undertaken.

Table 5. Summary of environmental conditions

Participant	Depth (m)	Temperature (ºC)
Canada	1.83	17.4 - 17.7
Germany	4.00	14.0 - 18.0
China	2.50	17.0
Russia	3.00	14.0 - 15.0; 19.5
South Africa	2.00	18.6 – 20.0
UK	2.50	20.5 - 21.1; 18.4; 20.4
USA	2.28	18.4

For this comparison, the depths of immersion during calibrations by different participants has ranged between 1.8 m to 4.0 m and the water temperatures ranged from 14.0 ºC to 21.1 ºC. To determine whether these variations in environmental conditions were likely to influence the agreement between the results of different participants, NPL has characterised the variation in hydrophone response with temperature for the three hydrophone models using the NPL Acoustic Pressure Vessel [4-6]. The results are summarised in Appendix 1.

For the range of depths employed by the participants in this comparison, it is highly unlikely that the depth variation has significantly influenced the results. However, the water temperature ranged over approximately 7 °C, and this could have an influence on the apparent agreement between results from different participants. The data shown in Appendix 1 indicates the maximum variation in the responses of the hydrophones caused by variation in water temperature is of the order of only 0.2 dB for the H52 hydrophone, 0.25 dB for the TC4034 hydrophone, but is of the order of 0.5 dB for the B&K8104 hydrophone. The NPL values for the H52 are in good agreement with those already published by USRD for this hydrophone [7].

The results showing the temperature dependence of the three hydrophones may be used to inform any judgements made about the agreement between participants. However, it should be noted that although the data shown in Appendix 1 were derived from measurements of the same types of hydrophone, the devices tested were not the actual hydrophones used in the comparison. Since there is some uncertainty regarding the appropriate values to use for corrections, no corrections have been made to the data submitted by participants to account for temperature variation. All values stated in this report are therefore uncorrected.

4. STABILITY OF THE HYDROPHONES

As coordinating laboratory, NPL undertook check calibrations on each hydrophone in between the calibrations of the other participants in order to monitor the stability of the hydrophones. The results of those checks are presented in this section. The NPL calibration system was not modified during the comparison exercise, and so any systematic bias that may be present in the NPL calibrations should be present to the same degree for all the calibrations. Assuming no undetected drift in the NPL system, the results should provide the required check on hydrophone stability. To save time between calibrations by participants, the check calibrations were performed at only 5 of the acoustic frequencies used for the comparison.

For each hydrophone, the results of the check calibrations are presented in tabular form. Unfortunately, due to technical problems with the laboratory environmental control, it was not possible to maintain the NPL test tanks at a constant temperature during the period of the comparison, and so the water temperature is given along with the date of calibration. No corrections have been made for the effect of temperature on the results. An additional table provides a summary of these results showing the mean of all the check calibrations at each frequency, the maximum and minimum deviation from the mean, the overall variation (maximum to minimum) and the mean Type A uncertainty for the NPL check calibrations. The means are simply shown to assist in making a judgment of the overall spread of results and have no other significance. Although expressed in decibels, to calculate the means the sensitivities were first converted to linear units. No weighting was used in calculating the means. The typical Type A standard uncertainty for the check calibrations was of the order of between 0.5% and 1%, calculated from at least four repeated calibrations. To express this for a confidence level of 95%, the standard uncertainty was multiplied by a coverage factor derived form the Student's t-factor for the appropriate degrees of freedom. The mean value for the Type A uncertainty of all the check measurements was calculated and is shown in the table, expressed in decibels. This allows some judgment to be made regarding the significance of the variations observed in the check calibrations.

Table 6 presents the results of the checks on the H52 hydrophone at 5, 10, 20, 50 and 100 kHz. A total of seven calibrations were performed from August 2000 to July 2002, with the water temperature ranging from 16.9 ºC to 21.6 ºC.

Table 6. Results of check calibrations for the H52 hydrophone.

Frequency	Sensitivities in dB re 1 V/µPa						
(kHz)	Aug-00	Oct-00	Mar-01	Jul-01	Jan-02	Apr-02	Jul-02
5	-177.61	-177.49	-177.53	-177.44	-177.30	-177.29	-177.36
10	-178.15	-177.97	-177.99	-177.91	-177.89	-177.85	-177.86
20	-178.52	-178.33	-178.34	-178.16	-178.20	-178.20	-178.20
50	-177.90	-177.75	-177.65	-177.74	-177.47	-177.57	-177.57
100	-179.58	-179.79	-179.82	-179.53	-179.69	-179.40	-179.67
Temp (°C)	21.0	20.1	18.5	21.6	16.9	20.3	20.9

Table 7. Variation in check calibration results for the H52 hydrophone (in dB).

Frequency (kHz)	Overall Mean	Maximum Deviation	Minimum Deviation	Total Variation	Mean Type A Uncertainty (95% confidence)
5	-177.43	0.14	-0.18	0.32	0.21
10	-177.94	0.10	-0.20	0.30	0.19
20	-178.28	0.12	-0.24	0.36	0.19
50	-177.66	0.19	-0.23	0.43	0.21
100	-179.64	0.24	-0.18	0.42	0.22

The summary provided in Table 7 shows that the maximum variation from the mean value at each frequency is generally within the Type A uncertainty, but the minimum deviation exceeds the Type A uncertainty by 0.01 dB at 10 kHz, 0.05 dB at 20 kHz and 0.02 dB at 50 kHz. Closer inspection of the data in Table 6 shows that there may be a slight increase in sensitivity for this hydrophone with time of typically 0.20 dB to 0.25 dB over the 23 months of the exercise (equivalent to an increase of approximately 0.01 dB per month). A full calibration was performed by NPL at the end of the comparison and this also shows a similar value systematic increase compared to the NPL calibration submitted as part of the comparison (undertaken at the start of the exercise). The results of the before and after calibrations by NPL are presented in Appendix 2. Such a systematic increase is not observed for the other hydrophones. Nevertheless, the increase for the H52 is of small value and no attempt has been made to correct for it in presenting the participants' results.

Table 8. Results of check calibrations for the B&K8104 hydrophone.

Frequency	Sensitivities in dB re 1 V/μPa							
(kHz)	Apr-00	Oct-00	Feb-01	Jul-01	Jan-02	Apr-02	Jul-02	Feb-03
10	-206.22	-206.26	-206.25	-206.38	-206.46	-206.22	-206.27	-206.45
20	-206.89	-206.81	-206.86	-206.50	-206.55	-206.59	-206.65	-206.61
50	-203.59	-203.77	-203.87	-203.74	-203.45	-203.46	-203.72	-203.59
100	-211.28	-211.39	-211.46	-211.21	-211.26	-211.40	-211.32	-211.13
150	-218.72	-218.95	-218.72	-218.71	-218.47	-218.83	-218.75	-218.52
Temp (^{o}C)	18.4	20.0	18.8	20.5	16.7	20.1	20.6	16.0

Table 9. Variation in check calibration results for the B&K8104 hydrophone (in dB).

Frequency (kHz)	Overall Mean	Maximum Deviation	Minimum Deviation	Total Variation	Mean Type A Uncertainty (95% confidence)
10	-206.31	0.10	-0.14	0.24	0.25
20	-206.68	0.18	-0.21	0.39	0.25
50	-203.65	0.20	-0.22	0.42	0.27
100	-211.31	0.18	-0.16	0.34	0.21
150	-218.71	0.23	-0.24	0.47	0.22

Table 8 presents the results of the checks on the B&K8104 hydrophone at 10, 20, 50, 100 and 150 kHz. A total of eight calibrations were performed from April 2000 to February 2003, with the water temperature ranging from 16.0 ºC to 20.6 ºC.

The summary provided in Table 9 shows that the maximum and minimum variation from the mean value at each frequency is generally within the Type A uncertainty. However, at 150 kHz, the minimum deviation exceeds the Type A uncertainty by 0.02 dB. This frequency is the highest used for this hydrophone in the comparison and is well above the resonance frequency for this hydrophone, and could be regarded as being above its normal operating range.

Table 10 presents the results of the checks on the TC4034 hydrophone at 100, 200, 300, 400 and 500 kHz. A total of eight calibrations were performed from June 2000 to February 2003, with the water temperature ranging from 18.3 ºC to 20.4 ºC.

Table 10 . Results of check calibrations for the TC4034 hydrophone.

Frequency	Sensitivities in dB re 1 V/µPa							
(kHz)	Jun-00	Oct-00	Feb-01	Aug-01	Jan-02	Apr-02	Jul-02	Feb-03
100	-218.80	-218.80	-218.63	-218.61	-218.58	-218.59	-218.72	-218.92
200	-218.22	-218.24	-218.39	-218.18	-218.54	-218.39	-218.31	-218.66
300	-216.12	-216.23	-215.87	-215.91	-215.84	-216.02	-216.05	-216.26
400	-219.54	-219.21	-219.07	-219.32	-219.33	-219.16	-219.50	-218.99
500	-229.98	-229.95	-230.25	-229.77	-229.68	-229.69	-230.37	-230.35
Temp (^{o}C)	20.4	19.9	18.8	18.7	16.2	19.4	18.3	16.4

Table 11. Variation in check calibration results for the TC4034 hydrophone (in dB).

Frequency (kHz)	Overall Mean	Maximum Deviation	Minimum Deviation	Total Variation	Mean Type A Uncertainty (95% confidence)
100	-218.71	0.12	-0.22	0.34	0.21
200	-218.36	0.19	-0.30	0.49	0.21
300	-216.04	0.20	-0.22	0.42	0.21
400	-219.26	0.27	-0.27	0.54	0.25
500	-230.00	0.32	-0.37	0.69	0.31

Table 11 shows that the maximum and minimum deviation from the mean value at each frequency exceeds the typical Type A uncertainty by a maximum of 0.01 dB at 100 kHz, 0.09 dB at 200 kHz, 0.01 dB at 300 kHz, 0.02 dB at 400 kHz, and 0.06 dB at 500 kHz.

It is likely that some of the variation observed in the check calibrations is due to the variation in water temperature in the test tank between calibrations. This may well be more acute for the B&K8104 hydrophone, the H52 and TC4034 design having been demonstrated as more stable with temperature [4, 7]. However, if corrections are to be applied, it would be better to determine the variation in response with temperature for the actual hydrophones used in the comparison (rather than for other hydrophones of the same type). This would involve further work and was not considered worthwhile when the variation in the check calibrations is considered against the variation in participants' results (presented in the next Section).

In summary, the reference hydrophones used as traveling standards for the comparison exercise may be considered stable to within the tolerances given in Tables 6-11. Slightly greater variation was observed in the check calibrations than was expected when considering the Type A uncertainties in the NPL calibrations, and this is most likely to be in part due to the variation in water temperature of the test tank between calibrations. There is some evidence that there may have been a gradual increase in the sensitivity of the H52 of 0.01 dB per month during the comparison. No corrections have been made to the results of participants to attempt to account for any perceived variation in hydrophone sensitivity due to temperature or drift with time.

The variations observed in the check calibrations can be used to inform any judgments made regarding the disagreement between the results of participants. Any disagreement between the results of participants which is significantly higher than the variation shown in the check calibrations is likely to be due to genuine differences in the calibrations rather than instability in the hydrophones.

5. RESULTS

Table 12 shows the results for the H52 hydrophone for each participant along with the overall standard uncertainty expressed for a coverage factor of k=1.

Table 12. Results obtained by the participants for the H52 hydrophone in dB re. 1V/µPa.

Country	UK		Germany		USA		Russia		China		Canada		South Africa	
Temp (^{o}C)	20.8		14.0 - 18.0		18.4		14.5 (&19.5)		17.0		17.5		20.0	
Depth (m)	2.5		4.0		2.3		3.0 (&0.5)		2.5		1.83		2	
F (kHz)	Mh	Ut	Mh	Ut	Mh	Ut	Mh	Ut	Mh	Ut	Mh	Ut	Mh	Ut
1.0	-177.37	0.33	-178.30	0.43	-177.58	0.20	-177.52	0.19	-177.70	0.23				
1.5	-177.63	0.29	-178.30	0.43	-177.46	0.20	-177.44	0.19	-177.40	0.23				
2.0	-177.63	0.25	-178.10	0.43	-178.02	0.20	-177.45	0.19	-177.60	0.23	-177.54	0.32		
2.5	-177.62	0.23	-178.10	0.43	-177.56	0.20	-177.51	0.19	-177.40	0.23	-177.46	0.32		
3.0	-177.60	0.22	-178.20	0.43	-177.58	0.18	-177.57	0.19	-177.20	0.23	-177.66	0.32	-177.40	0.70
3.5	-177.52	0.22	-178.30	0.43	-177.40	0.18	-177.51	0.19	-177.40	0.23	-177.73	0.32	-177.50	0.70
4.0	-177.75	0.23	-178.30	0.43	-177.53	0.18	-177.52	0.19	-177.60	0.23	-177.71	0.32	-177.50	0.70
4.5	-177.57	0.21	-178.40	0.43	-177.52	0.18	-177.48	0.19	-177.50	0.23	-177.69	0.32	-177.60	0.70
5.0	-177.61	0.21	-178.30	0.43	-177.34	0.18	-177.51	0.19	-177.40	0.23	-177.64	0.32	-177.60	0.70
6.0	-177.82	0.21	-178.30	0.43	-177.64	0.18	-177.60	0.19	-177.30	0.23	-177.57	0.32	-177.90	0.70
7.0	-177.70	0.21	-178.30	0.43	-177.28	0.18	-177.43	0.19	-177.90	0.23	-177.62	0.32	-177.80	0.70
8.0	-177.87	0.21	-178.30	0.43	-177.72	0.18	-177.64	0.19	-177.50	0.23	-177.90	0.32	-178.00	0.70
9.0	-178.05	0.21	-178.10	0.43	-177.44	0.18	-177.68	0.19	-177.50	0.23	-177.87	0.32	-178.10	0.70
10.0	-178.15	0.21	-178.30	0.43	-177.67	0.18	-177.80	0.19	-177.70	0.23	-177.84	0.32	-178.20	0.70
12.0	-178.37	0.21	-178.50	0.43	-177.87	0.18	-178.00	0.19	-178.20	0.23	-178.31	0.32	-178.40	0.70
14.0	-178.68	0.21	-178.60	0.43	-178.16	0.18	-178.29	0.19	-178.60	0.23	-178.52	0.32	-178.70	0.70
16.0	-178.74	0.21	-178.80	0.43	-178.54	0.18	-178.24	0.19	-179.00	0.23	-178.55	0.32	-178.90	0.70
18.0	-178.44	0.21	-178.80	0.43	-178.19	0.18	-178.20	0.19	-178.40	0.23	-178.42	0.32	-178.70	0.70
20.0	-178.52	0.21	-178.50	0.43	-178.23	0.18	-177.90	0.19	-178.05	0.23	-178.32	0.32	-178.50	0.70
22.0	-178.11	0.21	-178.40	0.43	-177.77	0.18	-177.68	0.19	-177.60	0.23	-177.95	0.32	-178.20	0.70
24.0	-178.09	0.21	-178.10	0.43	-177.47	0.18	-177.60	0.19	-177.60	0.23	-177.78	0.32	-178.00	0.70
26.0	-178.21	0.21	-178.30	0.43	-177.92	0.18	-177.85	0.19	-178.00	0.23	-178.09	0.32	-178.00	0.70
28.0	-178.28	0.21	-178.70	0.43	-177.97	0.18	-177.85	0.19	-178.30	0.23	-178.17	0.32	-178.10	0.70
30.0	-178.12	0.21	-178.50	0.43	-177.60	0.18	-177.69	0.19	-178.30	0.23	-178.02	0.32	-178.00	0.70
35.0	-177.67	0.21	-178.00	0.43	-177.36	0.18	-177.33	0.19	-177.80	0.23	-177.67	0.32	-178.00	0.70
40.0	-177.59	0.21	-177.90	0.43	-177.21	0.18	-177.20	0.19	-177.70	0.23	-177.54	0.32	-177.80	0.70
45.0	-177.73	0.21	-177.90	0.43	-177.72	0.18	-177.23	0.19	-177.80	0.23	-177.71	0.32	-178.10	0.70
50.0	-177.90	0.21	-177.90	0.43	-177.42	0.18	-177.26	0.19	-177.70	0.23	-177.76	0.32	-178.00	0.70
55.0	-178.05	0.21	-178.10	0.43	-177.67	0.18	-177.47	0.19	-178.30	0.23	-177.89	0.32	-178.20	0.70
60.0	-178.40	0.21	-178.50	0.43	-178.17	0.18	-177.95	0.19	-178.80	0.23	-178.12	0.32	-178.30	0.70
65.0	-178.96	0.21	-178.90	0.43	-178.43	0.18	-178.58	0.19	-179.20	0.23	-178.48	0.32	-178.80	0.70
70.0	-179.20	0.21	-179.40	0.43	-178.67	0.18	-178.94	0.19	-179.50	0.23	-178.98	0.32	-179.00	0.70
75.0	-179.59	0.21	-179.60	0.43	-179.13	0.18	-179.32	0.19	-180.00	0.23	-179.10	0.32	-179.40	0.70
80.0	-179.49	0.21	-179.80	0.43	-178.67	0.18	-179.50	0.19	-180.00	0.23	-178.95	0.32	-179.60	0.90
85.0	-180.00	0.21	-180.40	0.43	-178.88	0.18	-180.15	0.19	-180.80	0.23	-179.37	0.32	-180.00	0.90
90.0	-180.38	0.21	-180.70	0.43	-179.41	0.18	-180.41	0.19	-180.80	0.23	-179.82	0.32	-180.30	0.90
95.0	-179.83	0.21	-180.20	0.43	-178.88	0.18	-180.10	0.19	-180.00	0.23	-179.53	0.32	-180.10	0.90
100.0	-179.58	0.21	-180.00	0.43	-178.72	0.18	-179.81	0.19	-180.30	0.23	-179.32	0.32	-180.00	0.90

Table 13 shows the results for the B&K8104 hydrophone for each participant along with the overall standard uncertainty expressed for a coverage factor of k=1.

Table 13. Results obtained by the participants for the B&8104 hydrophone in dB re. 1V/µPa.

Country	UK		Germany		USA		Russia		China		Canada		South Africa	
Temp (^{o}C)	18.4		14.0 - 18.0		18.4		14.5		17.0		17.5		20.0	
Depth (m)	2.5		4.0		2.3		3.0		2.5		1.83		2	
F (kHz)	Mh	Ut	Mh	Ut	Mh	Ut	Mh	Ut	Mh	Ut	Mh	Ut	Mh	Ut
10.0	-206.22	0.21	-205.80	0.43	-206.44	0.23	-206.39	0.19	-206.70	0.23	-205.79	0.31	-206.30	0.50
12.5	-206.19	0.21	-206.30	0.43	-206.72	0.23	-206.62	0.19	-206.20	0.23	-206.05	0.31	-206.50	0.50
15.0	-206.67	0.21	-206.60	0.43	-207.29	0.23	-206.80	0.19	-206.00	0.23	-206.47	0.31	-206.90	0.50
17.5	-206.80	0.21	-206.60	0.43	-207.40	0.23	-206.90	0.19	-206.40	0.23	-206.79	0.31	-206.70	0.50
20.0	-206.89	0.21	-206.50	0.43	-206.96	0.23	-207.06	0.19	-206.70	0.23	-207.03	0.31	-206.90	0.50
22.5	-207.08	0.21	-206.70	0.43	-206.73	0.23	-207.11	0.19	-206.60	0.23	-207.13	0.31	-207.10	0.50
25.0	-207.06	0.23	-206.80	0.43	-206.69	0.21	-206.87	0.19	-206.80	0.23	-206.84	0.31	-207.00	0.50
27.5	-206.52	0.21	-207.00	0.43	-206.48	0.21	-206.70	0.19	-206.50	0.23	-206.46	0.31	-206.80	0.50
30.0	-206.35	0.28	-206.90	0.43	-206.52	0.21	-206.71	0.19	-206.10	0.23	-206.39	0.31	-206.60	0.50
32.5	-206.15	0.31	-207.00	0.43	-206.58	0.21	-206.45	0.19	-206.60	0.23	-206.17	0.31	-206.40	0.50
35.0	-205.53	0.25	-206.70	0.43	-206.19	0.21	-205.90	0.19	-205.90	0.23	-205.68	0.31	-206.00	0.50
37.5	-205.40	0.21	-206.40	0.43	-206.02	0.21	-205.58	0.19	-205.70	0.23	-205.46	0.31	-205.80	0.50
40.0	-205.07	0.21	-206.10	0.43	-205.02	0.21	-205.30	0.19	-205.30	0.23	-205.26	0.31	-205.40	0.50
42.5	-205.12	0.29	-205.30	0.43	-204.51	0.21	-204.75	0.19	-205.00	0.23	-204.89	0.31	-204.90	0.50
45.0	-204.60	0.23	-204.60	0.43	-204.56	0.21	-204.40	0.19	-204.50	0.23	-204.45	0.31	-204.30	0.50
47.5	-204.05	0.21	-204.20	0.43	-204.45	0.21	-204.07	0.19	-204.00	0.23	-204.05	0.31	-204.20	0.90
50.0	-203.59	0.21	-204.00	0.43	-204.36	0.21	-203.73	0.19	-203.80	0.23	-203.66	0.31	-204.00	0.90
52.5	-203.29	0.21	-203.80	0.43	-203.71	0.21	-203.47	0.19	-203.40	0.23	-203.25	0.31	-203.70	0.90
55.0	-203.29	0.26	-203.80	0.43	-203.00	0.21	-203.41	0.19	-203.40	0.23	-203.19	0.31	-203.50	0.90
57.5	-203.22	0.22	-203.60	0.43	-202.94	0.21	-203.45	0.19	-203.40	0.23	-203.27	0.31	-203.40	0.90
60.0	-203.39	0.21	-203.70	0.43	-203.71	0.21	-203.41	0.19	-203.60	0.23	-203.44	0.31	-203.60	0.90
62.5	-203.64	0.21	-204.20	0.43	-204.44	0.21	-203.45	0.19	-203.90	0.23	-203.87	0.31	-203.80	0.90
65.0	-203.96	0.21	-204.60	0.43	-204.29	0.21	-203.66	0.19	-204.10	0.23	-204.07	0.31	-204.00	0.90
67.5	-204.38	0.21	-205.00	0.43	-204.35	0.21	-204.00	0.19	-204.60	0.23	-204.31	0.31	-204.60	0.90
70.0	-204.92	0.21	-205.50	0.43	-204.99	0.21	-204.72	0.19	-205.10	0.23	-204.85	0.31	-205.20	0.90
72.5	-205.54	0.21	-206.10	0.43	-205.76	0.21	-205.40	0.19	-205.60	0.23	-205.43	0.31	-205.60	0.90
75.0	-205.94	0.21	-206.50	0.43	-206.46	0.21	-205.86	0.19	-206.10	0.23	-205.91	0.31	-206.00	0.90
77.5	-206.37	0.21	-207.00	0.43	-206.89	0.21	-206.38	0.19	-206.50	0.23	-206.44	0.31	-206.70	0.90
80.0	-206.98	0.21	-207.60	0.43	-207.31	0.21	-206.99	0.19	-207.20	0.23	-207.00	0.31	-207.30	0.90
85.0	-208.13	0.21	-208.90	0.43	-208.41	0.21	-208.29	0.19	-208.20	0.23	-208.22	0.31	-208.50	0.90
90.0	-209.43	0.21	-210.10	0.43	-209.79	0.21	-209.40	0.19	-209.50	0.23	-209.49	0.31	-209.80	0.90
95.0	-210.41	0.21	-211.10	0.43	-210.77	0.21	-210.50	0.19	-210.70	0.23	-210.52	0.31	-210.70	0.90
100.0	-211.28	0.21	-211.90	0.43	-211.60	0.21	-211.31	0.19	-211.40	0.23	-211.38	0.31	-211.50	0.90
110.0	-212.53	0.21	-213.30	0.43	-213.00	0.21	-212.58	0.19	-212.70	0.23	-212.63	0.31	-212.70	0.90
120.0	-214.24	0.22	-214.70	0.43	-214.58	0.21	-214.01	0.19	-214.50	0.23	-214.35	0.31	-214.40	0.90
130.0	-215.69	0.21	-215.70	0.43	-215.85	0.21	-215.33	0.19	-215.90	0.23	-215.60	0.31	-215.70	0.90
140.0	-217.26	0.21	-217.10	0.43	-217.49	0.21	-216.90	0.19	-217.50	0.23	-217.20	0.31	-217.50	0.90
150.0	-218.72	0.21	-218.70	0.43	-218.64	0.21	-218.42	0.19	-219.20	0.23	-218.49	0.31	-219.10	0.90

Table 14 shows the results for the TC4034 hydrophone for each participant along with the overall standard uncertainty expressed for a coverage factor of k=1.

Table 14. Results obtained by the participants for the TC4034 hydrophone in dB re. 1V/µPa.

Country	UK		Germany		USA		Russia		China		Canada		South Africa	
Temp (^{o}C)	20.4		14.0 - 18.0		18.4		14.5		17.0		17.5		20.0	
Depth (m)	2.5		4.0		2.3		3.0		2.5		1.83		2	
F (kHz)	Mh	Ut	Mh	Ut	Mh	Ut	Mh	Ut	Mh	Ut	Mh	Ut	Mh	Ut
100	-218.80	0.21	-218.50	0.43	-218.31	0.27	-218.50	0.19	-218.80	0.35	-218.43	0.53	-219.00	1.30
110	-219.44	0.21	-218.80	0.43	-219.14	0.27	-219.29	0.19	-219.70	0.35	-219.22	0.53	-219.50	1.30
120	-220.03	0.21	-220.20	0.43	-219.99	0.27	-219.99	0.19	-220.20	0.35	-219.60	0.53	-219.60	1.30
130	-220.28	0.21	-220.60	0.43	-219.94	0.27	-220.20	0.19	-220.70	0.35	-219.83	0.53	-219.90	1.30
140	-220.16	0.21	-220.80	0.43	-219.94	0.27	-220.10	0.19	-220.40	0.35	-219.81	0.53	-219.40	1.30
150	-220.18	0.21	-220.50	0.43	-219.64	0.27	-219.86	0.19	-220.00	0.35	-219.45	0.53	-219.30	1.30
160	-219.41	0.21	-219.90	0.43	-219.35	0.27	-219.66	0.30	-219.60	0.35	-219.33	0.53	-219.40	1.30
170	-219.07	0.21	-220.00	0.43	-218.89	0.27	-218.80	0.30	-218.80	0.35	-218.76	0.53	-219.10	1.30
180	-218.46	0.21	-219.80	0.43	-218.41	0.27	-218.30	0.30	-218.40	0.35	-218.38	0.53	-219.20	1.30
190	-218.59	0.21	-219.50	0.43	-218.40	0.27	-218.30	0.30	-218.50	0.35	-218.50	0.53	-219.10	1.30
200	-218.22	0.21	-219.10	0.43	-218.24	0.27	-218.40	0.30	-218.40	0.35	-218.23	0.53	-218.80	1.30
210	-218.41	0.22	-218.90	0.43	-218.09	0.34	-218.20	0.30	-218.20	0.35	-218.09	0.53	-218.90	1.30
220	-218.26	0.21	-218.30	0.43	-218.37	0.34	-218.32	0.30	-218.80	0.35	-217.92	0.53	-218.70	1.30
230	-218.56	0.22	-218.50	0.43	-218.23	0.34	-218.10	0.30	-219.10	0.35	-217.80	0.53	-218.70	1.30
240	-218.57	0.22	-218.50	0.43	-218.05	0.34	-217.80	0.30	-218.80	0.35	-218.59	0.53	-218.40	1.30
250	-218.25	0.22	-218.00	0.43	-217.97	0.34	-217.90	0.30	-217.90	0.35	-217.45	0.53	-218.30	1.30
260	-217.86	0.22	-217.70	0.43	-217.82	0.34	-217.60	0.30	-217.90	0.35	-217.82	0.53	-218.10	1.30
270	-217.66	0.25	-217.40	0.43	-217.47	0.34	-216.80	0.30	-217.20	0.35	-217.25	0.53	-218.00	1.30
280	-217.30	0.22	-217.00	0.43	-217.12	0.34	-216.90	0.30	-217.10	0.35	-217.50	0.53	-217.90	1.30
290	-216.77	0.22	-216.40	0.43	-216.51	0.34	-216.30	0.30	-216.80	0.35	-217.47	0.53	-217.30	1.30
300	-216.12	0.25	-215.90	0.43	-215.95	0.38	-215.60	0.30	-216.10	0.35	-217.24	0.53	-217.00	1.30
310	-216.09	0.25	-215.20	0.43	-215.84	0.38	-215.10	0.30	-215.70	0.35	-216.31	0.53	-216.40	1.30
320	-215.65	0.25	-215.00	0.43	-215.12	0.39	-214.70	0.30	-215.30	0.35	-215.22	0.53	-215.80	1.30
330	-215.61	0.25	-214.60	0.43	-215.69	0.39	-214.90	0.30	-215.30	0.35	-215.20	0.53	-215.70	1.30
340	-215.36	0.25	-214.60	0.43	-215.18	0.38	-215.50	0.30	-215.30	0.35	-215.41	0.53	-215.50	1.30
350	-215.20	0.25	-214.80	0.43	-215.30	0.38	-215.30	0.30	-215.60	0.35	-215.26	0.53	-216.20	1.30
360	-215.55	0.25	-215.40	0.43	-215.58	0.38	-215.80	0.30	-216.10	0.35	-215.88	0.53	-217.10	1.30
370	-215.94	0.25	-216.00	0.43	-215.85	0.38	-216.20	0.30	-216.40	0.35	-216.04	0.53	-217.40	2.20
380	-216.45	0.25	-216.80	0.43	-216.77	0.38	-217.10	0.30	-216.80	0.35	-216.41	0.53	-218.00	2.20
390	-218.21	0.25	-218.20	0.43	-217.90	0.38	-218.10	0.30	-218.10	0.35	-217.31	0.53	-219.10	2.20
400	-219.54	0.25	-219.30	0.43	-219.39	0.38	-219.20	0.30	-219.60	0.35	-217.89	0.53	-220.30	2.20
410	-220.53	0.25	-220.40	0.43	-220.35	0.38	-220.80	0.30	-220.70	0.35	-219.36	0.53	-221.80	2.20
420	-221.41	0.25	-221.90	0.43	-221.08	0.38	-221.60	0.30	-221.90	0.35	-220.81	0.53	-222.70	2.20
430	-222.82	0.25	-223.50	0.43	-221.81	0.38	-222.30	0.30	-222.30	0.35	-221.82	0.53	-223.60	2.20
440	-223.30	0.25	-225.00	0.43	-223.35	0.38	-223.60	0.30	-223.60	0.35	-223.75	0.53	-224.80	2.20
450	-224.72	0.25	-226.20	0.43	-224.68	0.38	-225.10	0.30	-225.00	0.35	-225.73	0.53	-226.30	2.20
460	-225.98	0.25	-227.30	0.43	-225.73	0.38	-226.38	0.30	-225.90	0.35	-227.50	0.53	-227.00	2.20
470	-227.20	0.25	-228.20	0.43	-227.15	0.38	-227.95	0.30	-228.00	0.35	-229.05	0.53	-228.10	2.20
480	-228.38	0.25	-228.80	0.43	-228.29	0.38	-228.38	0.30	-229.00	0.35	-229.33	0.53	-228.80	2.20
490	-229.15	0.25	-229.40	0.43	-229.30	0.38	-229.62	0.30	-229.40	0.35	-229.31	0.53	-229.50	2.20
500	-229.98	0.25	-230.00	0.43	-230.19	0.38	-231.08	0.30	-230.00	0.35	-230.88	0.53	-230.50	2.20

6. UNCERTAINTIES

Each participant were requested to provide a value for the overall uncertainty for the calibrations assessed according to the ISO Guide [8] and these are summarized in Table 15. In general, the values quoted varied with frequency and with device under test, and the full range of values is shown in the table.

Table 15. Summary of the range of overall uncertainties quoted by participants expressed in percent and in decibels for a coverage factor of k=1.

	UK	Germany	U.S.A	Russia	China	Canada	South Africa
Combined uncertainty (k=1) in %	2.5 - 3.9	5.0	2.0 - 4.6	2.2 - 3.5	2.7 - 4.1	3.6 - 6.3	5.9 - 28.8
Combined uncertainty (k=1) in dB	0.21 - 0.33	0.43	0.18 - 0.39	0.19 - 0.30	0.23 - 0.35	0.31-0.53	0.5 - 2.2

In addition, each participant was requested to provide a breakdown of the uncertainties. Since each participant has used a slightly different implementation of the reciprocity method, the sources of uncertainty and the values of the individual components may vary. Indeed, some sources of uncertainty will be unique to specific implementations of the calibration method. However, there are some common sources of uncertainty for which all participants quoted values. Table 16 provides a comparison of the sources of uncertainty quoted by participants and shows the range of values attributed to each source. Again, the values varied with frequency (and to a lesser degree depended on the device under test) and so the table shows the range of values attributed to each component.

From the table, it is clear that for some type B components, participants have attributed very similar values to the uncertainty, whereas for other components the variation is significant. In addition, there are some sources of uncertainty which, though significant for some participants, are neglected completely by others. It should be noted that the assessment process used by participants varied and some participants attributed a value of uncertainty to a single component which effectively combines several components quoted by some other participants. For example, this is the case for the USA (in the table an asterisk indicates the components covered by the combined values given at the bottom of the table). In addition, some participants deemed that some sources were already included in the assessment for other sources, and so need not be listed separately. For example, any error due to misalignment may be considered to contribute to the Type A uncertainty if the hydrophone is removed from the mount and then re-mounted and re-aligned between each repeated calibration.

Table 16. Comparison of the sources of uncertainty quoted by participants and their values (in %)

	Source of uncertainty (%)	UK	Germany	U.S.A	Russia	China	Canada	South Africa
	Type "A"	0.5 - 2.0	3.5	0.6 - 1.2	1.0 - 1.5	1.7 - 2.3	1 - 3.5	4.7
	Type "B" components							
1	Misalignment	0.5 - 2.5		*		2.1		
2	Lack of spherical wave field (far field conditions)	2.0				0.7		7.2
3	Non-reciprocal behaviour by transducers	1.5		*		2.3 - 3.4		1.2
4	Measurement of receive voltage		0.6			0.8	2.3	
5	Accuracy of amplifiers, filters, digitisers		3.4			2.1		1.0
6	Measurement of drive current	1.2 - 3.0	0.6			0.6	1.0 - 5.0	3.0
7	Accuracy of resistor (to measure drive current)		1.0		0.1			
8	Measurement of separation distance	1.0	0.1	*		0.5 - 0.9	0.3	0.5
9	Lack of linearity in the measurement system				2.5 - 3.5	0.5 - 1.4		1.2
10	Accuracy of any electrical signal attenuators used	0.2						
11	Interference (reflections and scattering from mount)	0.5 - 1.0		*		1.2- 1 .7		0.2
12	Lack of steady-state conditions	1.0 - 3.0		*		0.6		1.7
13	Electrical noise, including RF pick-up.	0.5 - 2.0			1.1	1.0 - 1.2		2.0
14	Accuracy of electrical loading corrections	1.0				0.6		0.1
15	Bubbles or air clinging to transducer							2.3
16	Errors in value for acoustic frequency	0.2	0.0		0.01	0.1	0.0002	0.26
17	Errors in values for water density	0.2	0.1		0.1	0.2	0.009	1.0
18	Residual Cross talk				1.0			
19	Combined for items 1 and 8			1.2 - 2.9				
20	Combined uncertainty for electrical measurements			1.2 - 2.3				
21	Combined for items 3, 11, 12			1.2 - 2.3				

7. ANALYSIS

7.1 REQUIREMENTS OF THE MRA

The main aim of the Key Comparison is to determine the degree of equivalence of the primary standards maintained by the participating countries. The following definitions of equivalence are given in the MRA:

(i) The degree of equivalence of each national measurement standard is expressed quantitatively by two terms:
   (a) Its deviation from the Key Comparison Reference Value.
   (b) The uncertainty of this deviation at the 95% level of confidence.

(ii) The degree of equivalence between pairs of national measurement standards is expressed quantitatively by two terms:
   (a) The difference of their deviations from the Key Comparison Reference Value.
   (b) The uncertainty of this difference at the 95% level of confidence.

Some basic analysis is necessary when making even the most cursory examination of the results. A simple plot of all the results can in itself be useful since it can provide a clear visual indication of the agreement between participants. However, since the sensitivity of the hydrophones is not constant with frequency, it is preferable to normalize the results by use of some reference value estimator such as the mean. A plot showing the differences from the reference value will then provide a clear indication of the spread of results without suffering from difficulties with the compressed scales necessary to fit widely differing sensitivities on to the same plot. Since the choice of this reference value estimator is an important consideration for the calculation of the KCRV, it is perhaps worth some initial discussion.

7.2 CANDIDATE METHODS FOR REFERENCE VALUE ESTIMATORS

In considering the choice of method, use has been made of guidance given in a number of papers presented in the literature, for example, two recent publications in Metrologia [9, 10]. Although the guidance contained in the papers is not mandatory, it provides a useful starting point for the analysis. Two methods are suggested in these papers for the reference value: the weighted mean and the median.

The weighted mean is calculated by weighting the contribution to the mean of each result according to the inverse of the square of the calibration uncertainty. This method has the advantage that it is readily implemented using a least squares approach, is based on classical statistics and takes account of the uncertainties in the calibrations. It is straightforward to calculate the uncertainty on the weighted mean and also the uncertainty on the degree of equivalence between participants. An assumption is made of a Gaussian distribution, but it is possible to perform a consistency test to check whether this assumption holds true for the data set used (a chi-squared test). Disadvantages in this method are that it places faith in the uncertainties estimated by participants (therefore these must be accurately assessed), and that the mean can be biased by any outliers, particularly those which have small uncertainties (and therefore high weights).

The median is less sensitive to outliers and hence may be regarded as a more robust estimator than the mean. However, the implementation is not as straightforward when the median is used, and to calculate the uncertainties a technique for propagating distributions is sometimes used (for example, techniques based on Monte Carlo simulation). With the median, the uncertainties may be disregarded when calculating the reference value but may still be used in evaluating the uncertainties associated with the reference value and degrees of equivalence.

Finally, the unweighted mean may be used. This involves calculating the reference value using the usual formula for the mean with no weighting applied. This method is not sensitive to any unrealistic or underestimated uncertainties (since the calibration uncertainties of the participants are disregarded in the calculation), but it is very sensitive to outliers which can severely bias the calculated mean even if the uncertainty on the outlying measurement is large. However, this method has been used to calculate the reference value in other comparisons [3].

7.3 COMPARISON BETWEEN DIFFERENT ESTIMATORS

To determine the sensitivity to the type of estimator used, all three of the analysis methods have been applied to the data for this comparison. The weighted mean and median were calculated in the manner described in reference [10]. It should be noted that for the analysis, the sensitivities and uncertainties were first expressed in linear units of microvolts per pascal.

Figure 1, Figure 2 and Figure 3 show the absolute results of the calculation of the weighted mean, median and unweighted mean for the H52, B&K8104 and TC4034 hydrophones respectively. Note that the sensitivities are displayed in linear units. Also shown are the uncertainties on the weighted mean calculated according to reference [10] and expressed for a confidence level of 95%. As can be seen, the three methods produce very similar results with the different values hardly distinguishable in the plots, and with the values for the median and unweighted mean falling within the uncertainties of the weighted mean.

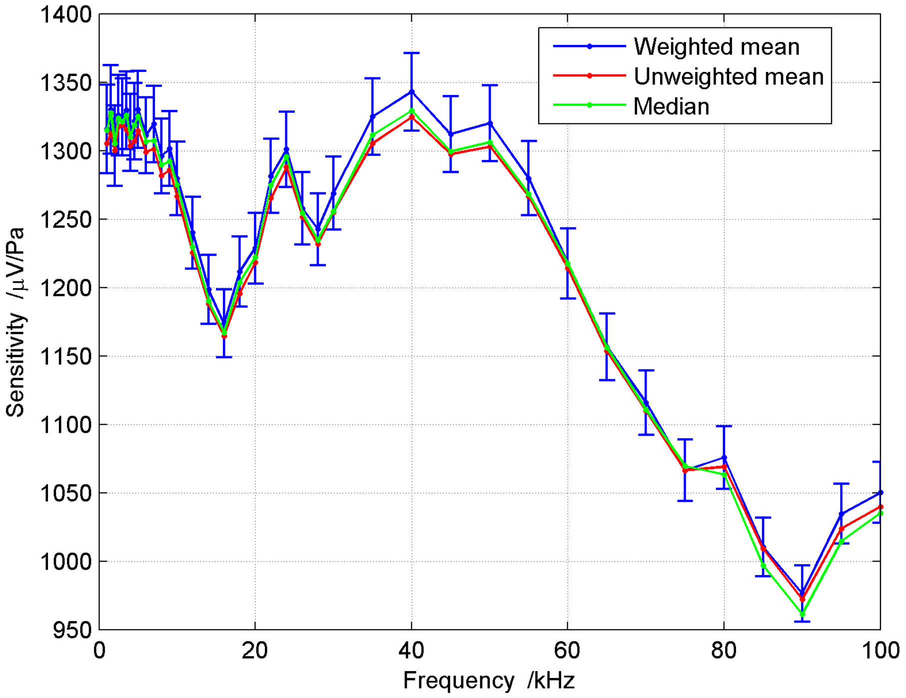

Figure 1. Reference values calculated by the three methods for the H52 hydrophone.

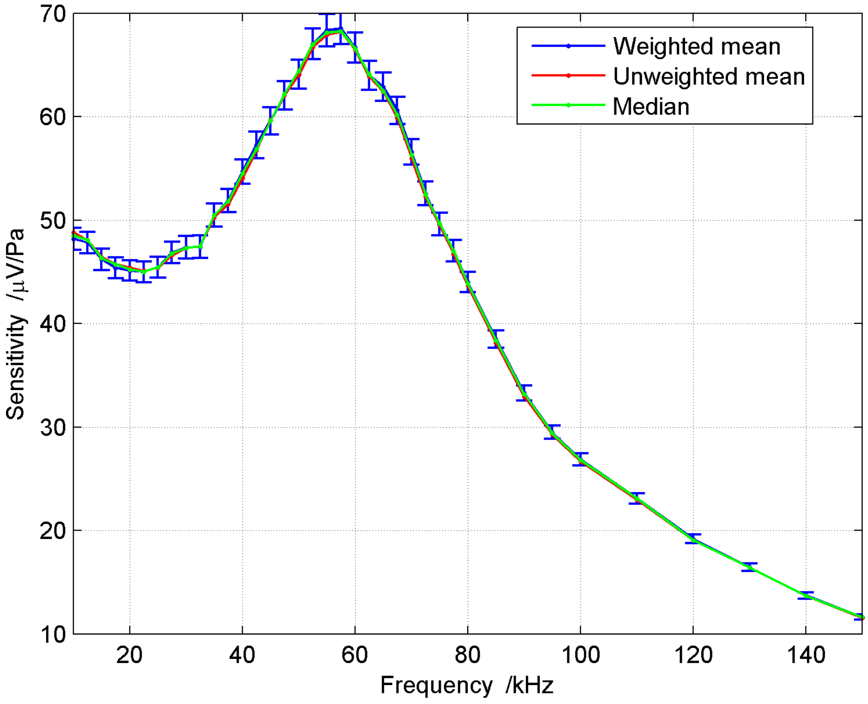

Figure 2. Reference values calculated by the three methods for the B&K8104 hydrophone.

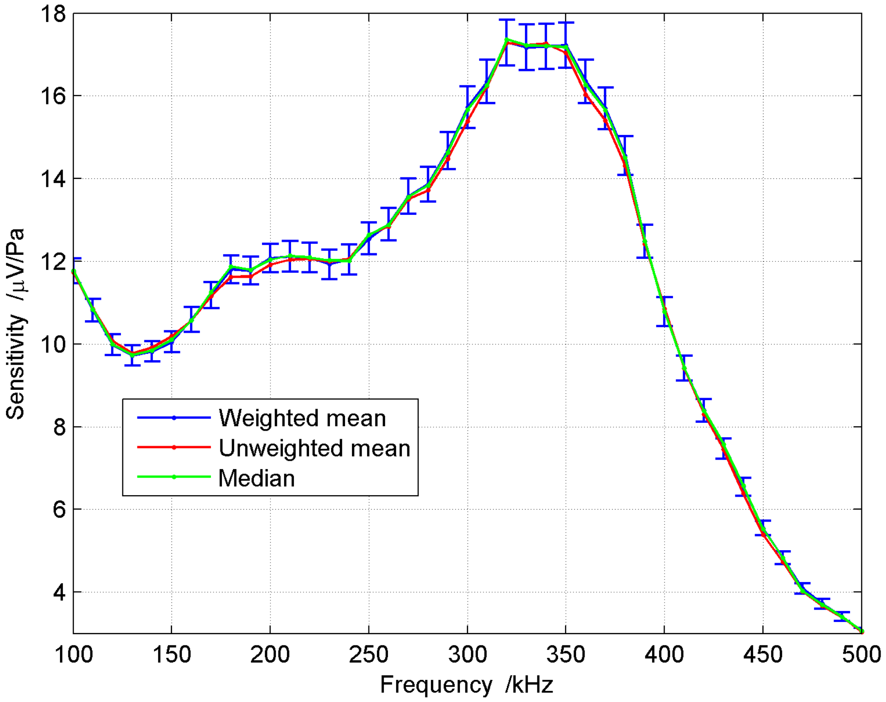

Figure 3. Reference values calculated by the three methods for the TC4034 hydrophone.

A clearer indication of the differences between the three methods is given in Figures 4, 5 and 6 which show the differences between the weighted mean and the two other estimators for the H52, B&K8104 and TC4034 hydrophones respectively along with the uncertainties for the weighted mean expressed for a confidence level of 95%.

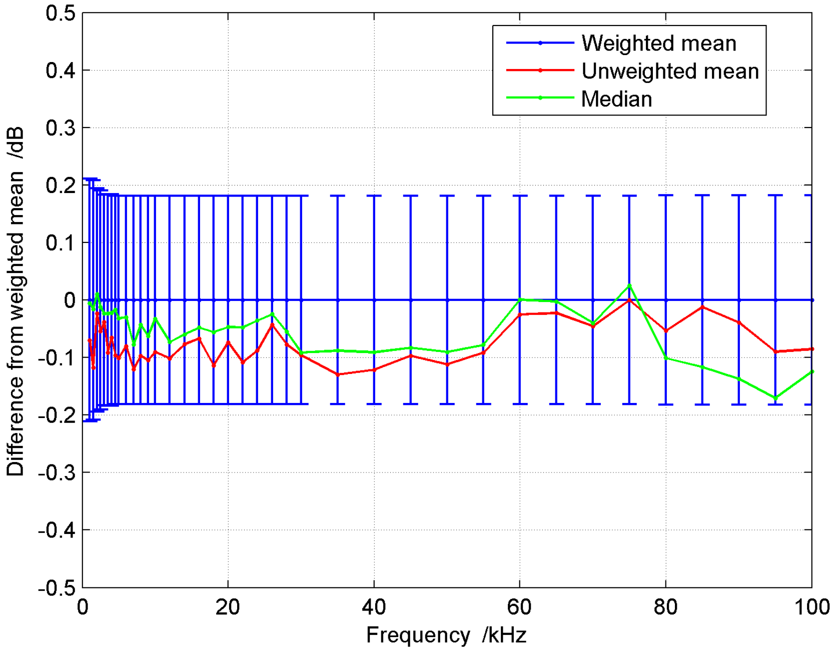

Figure 4. Difference between the three methods for the H52 hydrophone.

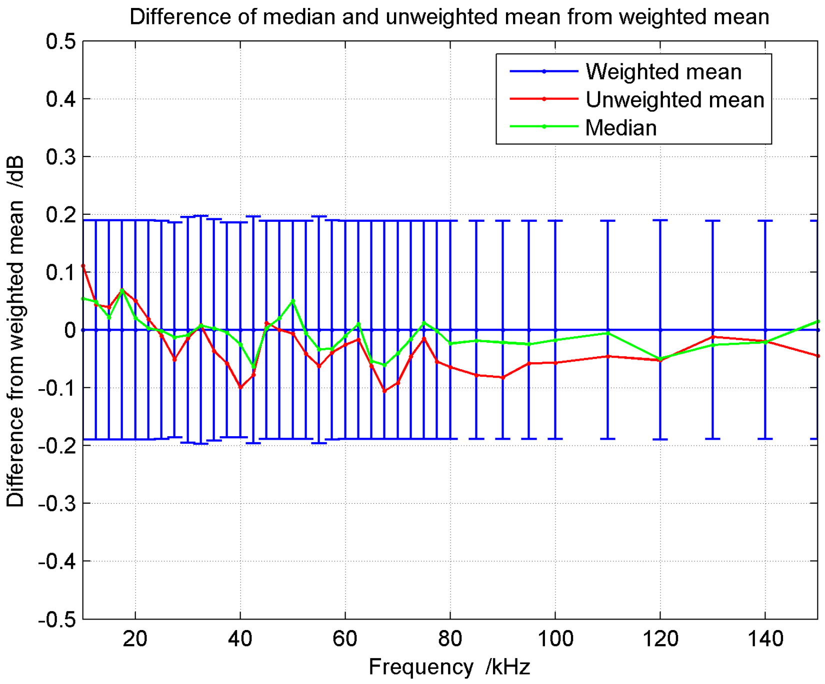

Figure 5. Difference between the three methods for the B&K8104 hydrophone.

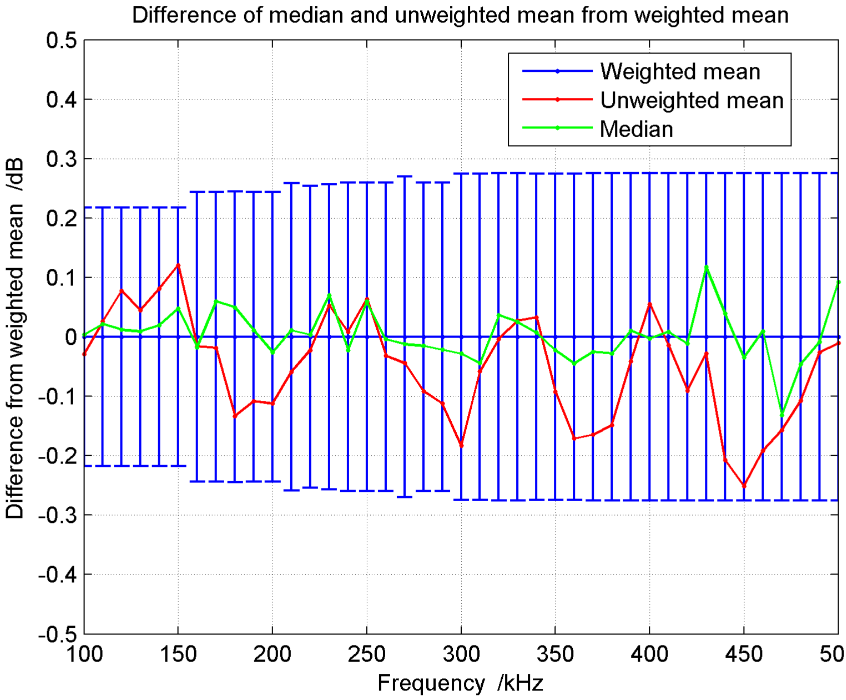

Figure 6. Difference between the three methods for the TC4034 hydrophone.

As can be seen, in general the values are in fairly close agreement, with the median and unweighted mean agreeing within the uncertainties of the weighted mean at all frequencies for all hydrophones. For the H52 hydrophone, the unweighted mean and median are less than the weighted mean by an average of 0.078 dB and 0.059 dB respectively. For the B&K 8104 hydrophone, the unweighted mean is less than the weighted mean by an average of 0.028 dB, and the median is in even better agreement being in general less than the weighted mean by an average of only 0.006 dB. And finally, for the TC4034 hydrophone, the unweighted mean is less than the weighted mean by an average of 0.052 dB, and the median shows excellent agreement being on average greater than it by only 0.004 dB.

In general, for the B&K8104 and TC4034 hydrophone, the weighted mean and the median are closer together with the unweighted mean generally showing the lowest value. The agreement between the weighted mean and median is generally encouraging. The unweighted mean generally exhibits poorer agreement and shows greater fluctuation in value due to its greater sensitivity to outliers. However, for the H52 hydrophone, the weighted mean is consistently the highest value over a significant part of the frequency range covered.

A test was performed to determine whether the observed value of the chi-squared statistic was significant at the 95% level of confidence. This was done for the data at each frequency to check the consistency of the measured data and associated uncertainties with the weighted mean model. In general, the test confirmed that the vast majority of the data is consistent, showing that no participant has produced a set of results that may be classified as discrepant. For the B&K8104 hydrophone, the test failed at only two out of 38 frequencies: 15 kHz and 62.5 kHz. For the TC4034 hydrophone, the test failed at only four out of 41 frequencies: 430 kHz, 440 kHz, 460 kHz and 470 kHz. Of course, *on the basis of statistical variability alone*, 5% of the data would be expected to be classified as discrepant and cause the chi-squared test to fail. For the H52 hydrophone, out of a total of 38 frequencies the test is failed at the five frequencies in the range 80 kHz to 100 kHz inclusive, but is passed at all frequencies less than 80 kHz. This is symptomatic of a general increase in the spread of results for this hydrophone, as is clearly evident in the plots shown in the next Section.

7.4 SPREAD OF PARTICIPANTS RESULTS

The overall spread of the results is shown in Figures 7, 8 and 9 for the H52, B&K8104 and TC4034 hydrophones respectively. For these plots, the weighted mean has been chosen as the reference value and the results are shown relative to the reference value in decibels. In the plots of Figures 7-9, the following is the key to the legend used throughout:

United Kingdom	UK	red
Germany	DE	black
U.S.A.	US	cyan
Russia	RU	green
China	CN	yellow
Canada	CA	blue
South Africa	ZA	magenta

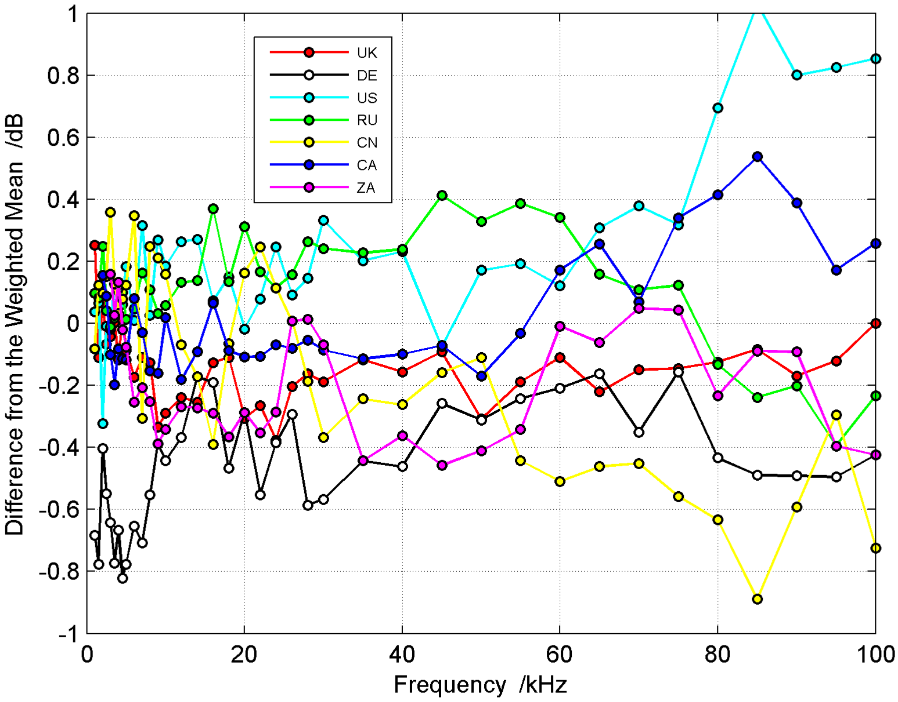

Figure 7. Results of participants plotted as difference from the weighted mean for the H52.

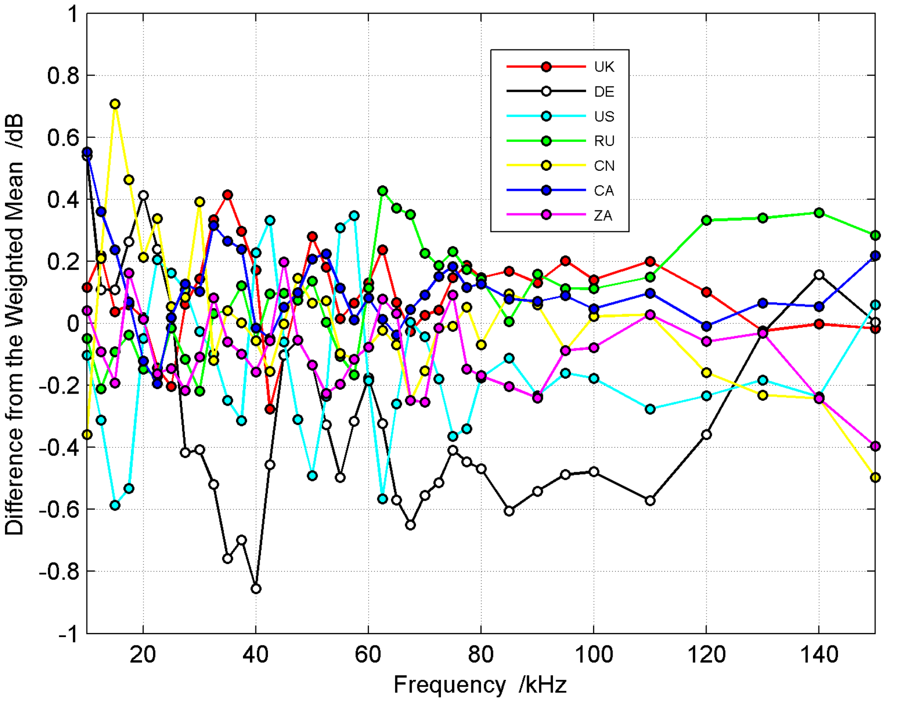

Figure 8. Results of participants plotted as difference from the weighted mean for the B&K8104.

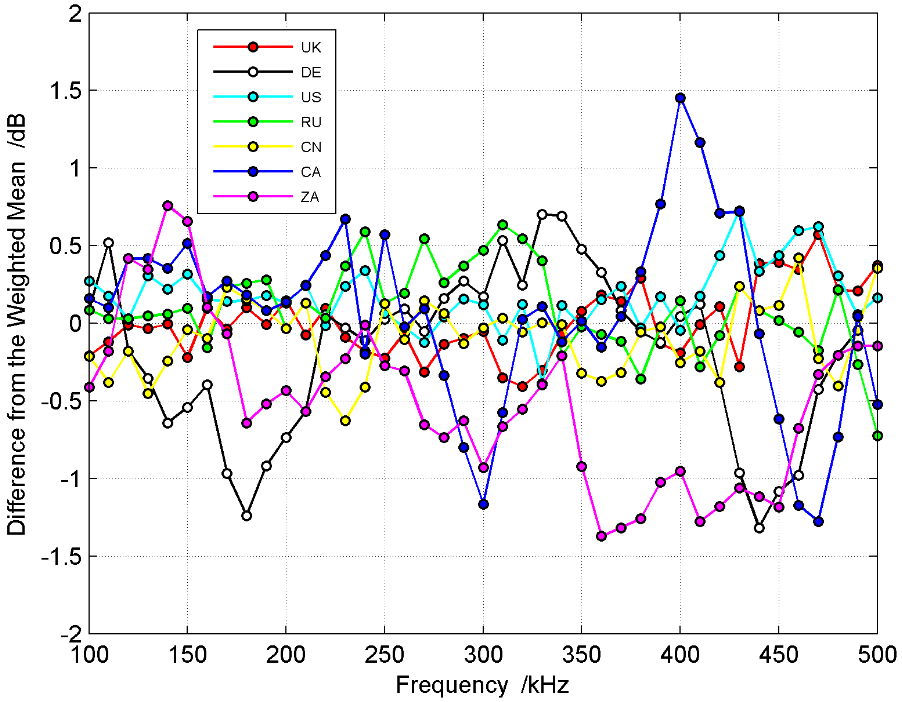

Figure 9. Results of participants plotted as difference from the weighted mean for the TC4034.

From a visual inspection of the results and consideration of the uncertainties quoted by participants (see Tables 12-14), it can be seen that no participant would appear to be a clear outlier leading to results being classified as discrepant, as might happen for example if a participant showed a clear systematic bias in the results for a particular hydrophone. This is confirmed by the chi-squared test described in the last Section. However, at specific frequencies, a greater spread of results is observed, for example at the frequencies where the chi-squared test fails (listed in Section 7.2).

For the H52 hydrophone, the results mostly lie within a band of approximately -0.5 dB to +0.4 dB of the mean in the frequency range 1 kHz to 75 kHz. At frequencies between 80 kHz and 100 kHz, the spread of results increases rapidly and approaches ±1 dB. The reason for this increase in spread of results is not known, but it casts some doubt on the results for this hydrophone in this high frequency range. The variation in sensitivity with temperature for the H52 shown in Appendix A does increase somewhat with frequency, with some unexplained fluctuations in the response at approximately 90 kHz, but the largest variation is reserved for frequencies greater than 100 kHz. Since these frequencies are at the top end of the operating frequency range of the device, and since the range is covered adequately by another hydrophone (B&K8104), it would be possible to omit the 80 kHz to 100 kHz data for the H52 from analysis to derive the Degrees of Equivalence.

For the B&K8104 hydrophone, apart from a few frequencies the results mostly lie within a band of approximately -0.6 dB to +0.4 dB of the mean. A feature of the results is the rapid fluctuation in sensitivity observed for a number of participants in the frequency range 10 kHz to 60 kHz. This may possibly be due to the influence on the hydrophone response of the different mounts or rigging used by participants.

For the TC4034 hydrophone, the spread is somewhat greater than for the other hydrophones. Although in the frequency range 100 kHz to 250 kHz, most of the results lie within a band of approximately ±0.5 dB, the spread increases at higher frequencies. This is perhaps not too unexpected since some of the uncertainty contributions increase with frequency (and this is reflected in most of the uncertainty budgets provided by the participants).

Both the B&K8104 and TC4034 hydrophone models were used in the EUROMET comparison undertaken in the late 1990's. As perhaps might be expected, the spread in results for the CIPM Key Comparison is considerably less than for the EUROMET comparison.

7.5 COMMENTS AND AMENDMENTS AFTER CIRCULATION OF DRAFT A REPORT

When the Draft A report was circulated to participants, a number of issues regarding the treatment of the data were put to the participants for consideration. In particular, these covered the following points.

(i) Confirmation of results and uncertainties
The calibration data reported in the Draft A report was confirmed by participants as being correct with only one error identified. A mistake in transcription (by the pilot laboratory) had caused an error in the calibration values provided by Russia for the H52 hydrophone at frequencies between 1 kHz and 3 kHz. The error has now been corrected. The error was small and does not have a significant effect on the results of the analysis.

(ii) Corrections to data
There was some discussion regarding whether to correct for the effect of water temperature variation using the data provided by NPL for the typical variation of hydrophone sensitivity with temperature. The range of temperatures encountered covered a range of about 7 ºC and although the influence is unlikely to be great, it is likely that the variation in temperature has contributed to the variation in results obtained for the B&K8104 and TC4034 hydrophones. However, making an accurate correction relies on the ready availability of accurate temperature coefficient data for each hydrophone. To undertake this properly may require further work to determine these coefficients for the specific hydrophones used. Therefore, it was decided not to apply any corrections for variations in water temperature.

There is also some evidence that the H52 hydrophone may have changed sensitivity very gradually over the course of the comparison. However, the change is very slight and is only just discernible from the data for the NPL checks (and the two NPL calibrations undertaken at the start and end of the comparison), and so it was decided not to make any corrections for this effect.

(iii) Method for calculation of KCRV

In general, those participants expressing an opinion were in favour of using the weighted mean approach to determining the KCRV, though one participant offered tentative support for the median. Several participants were keen to utilize all available data, including the uncertainties. No participant supported the use of the unweighted mean.

(iv) Method for dealing with overlapping frequency ranges

In order to derive one single value for DOEs at each frequency, the data for individual hydrophones must be combined in some manner. No method for attempting this was suggested in the Draft A report and no participant proposed a candidate method. However, several participants suggested that when considering the significance of any difference between DOEs calculated for separate hydrophones at a single frequency, the uncertainties associated with the DOEs should be taken into account. This is clearly a sensible approach since although the DOEs may vary depending on the hydrophone, the variation may not be significant if the uncertainties are large enough to cover the difference.

(v) How to present the KCRV and Degree of Equivalence

The comparison has generated a large amount of data and this makes it difficult to present the results in a digestible manner. In general, participants supported the reduction of the data to present it in a form that is more accessible. This requires point (iv) to be addressed. In addition, there was some support for presenting the data broken down into frequency bands, with the data in each band represented by some "average" value.

(vi) Disclosure of absolute sensitivities

It was generally agreed that the absolute sensitivities of the hydrophones should be revealed in the Draft B report.

(vii) Uncertainty analysis

An uncertainty analysis was undertaken independently by each participant and this is good since it reduces the likelihood of sources of uncertainty being missed because all participants are adopting the same approach. However, the components of the uncertainty budgets varied significantly between laboratories. It was generally agreed that further work was justified in investigating some of the sources of uncertainty in more depth to develop a consensus view on the common sources prevalent in hydrophone calibration. However, this is beyond the scope of the current project.

(viii) Journal paper

Those participants expressing an opinion agreed that an abridged version of the final report be prepared for submission to a scientific journal as a paper co-authored by all the participants. NPL is willing to prepare such a paper and circulate it for comment after the publication of the final Draft B report.

7.6 KEY COMPARISON REFERENCE VALUES

It is perhaps worth noting that any analysis adopted will not be perfect, and no individual reference value estimator is an ideal solution to the problem of calculating a KCRV, each candidate method having both advantages and disadvantages. Similarly, the data provided for sensitivity values and uncertainty budgets may not always be comprehensive, since all efforts are limited by time and resources. However, one method must be chosen if progress is to be made with generating the Degrees of Equivalence required by the MRA. The plots of Section 7.3 demonstrate that there is in fact little significant difference between the values of weighted mean, unweighted mean and median, and that therefore the values of the Degrees of Equivalence are not in fact highly sensitive to the choice of estimator. In any case, all the data for the comparison exercise is made available in this report and so should future consensus among metrologists dictate that some new estimator be the method of choice, the data can always be reprocessed using the new method at some future date.

After circulation and comment on the Draft A report, it was decided that the weighted mean would be chosen to calculate the Key Comparison Reference Values. The unweighted mean is perhaps the least attractive choice since the value is more sensitive to outlying results which cause the value of the mean to fluctuate somewhat. The weighted mean has the advantage that it makes use of all of the data provided by the participants, that is the quoted uncertainties as well as the sensitivity values. The chi-squared test for overall consistency of the data with the weighted mean model is passed for all except a few frequencies.

For the results, x_i, from a given device and associated uncertainties, u_i, where i is the index for a particular laboratory and $i = 1 \ldots N$, the weighted mean, y, is evaluated from:

$$y = \frac{\sum_{i=1}^{N} w_i x_i}{\sum_{i=1}^{N} w_i}, \qquad w_i = \frac{1}{u_i^2}, \tag{7.1}$$

with its associated uncertainty $u(y)$ determined from

$$\frac{1}{u^2(y)} = \sum_{i=1}^{N} \frac{1}{u_i^2}. \tag{7.2}$$

This has been applied to the results at each frequency for each hydrophone to derive the KCRVs for each device. These are given in Appendix D along with their associated uncertainties. For this comparison, the actual values of the KCRVs have little inherent value in themselves, being merely the sensitivities of some arbitrarily chosen hydrophones. Their value is in their role in evaluating the Degrees of Equivalence.

7.7 DEGREE OF EQUIVALENCES FOR EACH HYDROPHONE

The degree of equivalence of laboratory i is evaluated from

$$d_i = x_i - y \tag{7.3}$$

with associated standard uncertainty $u(d_i)$ determined from

$$u^2(d_i) = u^2(x_i) - u^2(y\ ). \qquad (7.4)$$

The results for the Degrees of Equivalence for each hydrophone are given in Appendix E along with the associated uncertainties. These are given in both tabular and graphical form. The tabular presentation gives the DOEs for each hydrophone separately. Note that Canada was not able to undertake calibrations at frequencies less than 2 kHz, and South Africa was not able to undertake calibrations at frequencies less than 3 kHz, so it is not possible to calculate DOEs for these participants at these frequencies. The plots in Appendix E show the DOEs for each participant separately, with the DOE data for all three hydrophones shown on the same plots. For clarity, the data has been divided into two frequency ranges, so that data is plotted separately for 1 kHz to 100 kHz and 100 kHz to 500 kHz respectively.

7.8 COMBINING THE DEGREES OF EQUIVALENCE

In order to derive, at each frequency, a single value for the Degree of Equivalence with the KCRV and for the bilateral Degree of Equivalence between participants requires that the data for the three hydrophones be combined in some manner. At some frequencies, where more than one hydrophone has been calibrated, two (or, in one case, three) separate DOEs are available along with their associated uncertainties. The situation is presented most clearly in the plots contained in Appendix E where the overlapping frequency ranges for each hydrophone can be easily seen. Moreover, it is clear from these plots that in the majority of cases, the difference between the DOEs for separate hydrophones is well within the combined expanded uncertainties. This is reassuring, since it would be hoped that the data for different hydrophones but for the same participant would show some consistency. In general, some statistical variability may be introduced, the calibrations undertaken by an individual laboratory should be subject to the same Type B uncertainty. (It is possible that some of the Type B components may depend on the model of hydrophone under test, but it is assumed that this effect is very small). It is therefore desirable that this common Type B component should be used to inform the calculation of the combined DOE by taking into account the correlation that it represents.

The procedure used to calculate the combined DOE can be considered to have the following requirements:

(i) the valid operational frequency range for each hydrophone (and therefore the overlap frequencies) must be decided first and any frequency ranges where the data is considered invalid should be rejected before the data are combined;
(ii) the method used should provide one value of DOE at each frequency;
(iii) the method used should “collapse down” to the DOE value for a single hydrophone for frequencies where only one hydrophone has been calibrated;
(iv) the method should perform some kind of “averaging” function and be informed by the uncertainties of the DOEs;
(v) the method should make use of any knowledge we have of correlations present in the DOEs.

To address point (i), the data for the H52 hydrophone between 80 kHz and 100 kHz was not used in calculating the combined DOEs. This is because the quality of the calibration data for that hydrophone at the highest frequencies in its operating range are in some doubt, as has been indicated in section 7.4. Evidence for this is indicated by the spread of data for that hydrophone which is nominally -0.5 dB to +0.4 dB of the mean in the frequency range 1 kHz to 75 kHz, but increases rapidly to ±1 dB at frequencies between 80 kHz and 100 kHz. This is also indicated by the failure of the chi-squared test at all frequencies between 80 kHz and 100 kHz for that hydrophone.

Of the 94 distinct frequencies of measurement covered by the three devices, a calibration of more than one device has been undertaken at only 18 of these frequencies. Consequently, the requirement to combine multiple Degrees of Equivalence to a single value occurs at less than 20% of the frequencies. These frequencies are 10, 20, 30, 35, 40, 45, 50, 55, 60, 65, 70 and 75 kHz where the H52 and B&K8104 hydrophones share common frequency points; and 100, 110, 120, 130, 140 and 150 kHz where the B&K8104 and the TC4034 share common frequency points.

The method used is to perform a weighted mean of the DOEs for each hydrophone with allowance made for mutual dependencies between the measurements made of the different devices by the same laboratory. This method is described in detail in Appendix F. In the method, the solution is found to a least-squares problem with design matrix A and vector of observations $\mathbf{x}$ with associated uncertainty matrix V. The diagonal elements of the associated uncertainty matrix V contain the variances associated with the individual DOEs, and the off-diagonal elements contain their covariances. In this way, the correlations between the different calibrations undertaken by a given laboratory are taken into account. This method satisfies the requirements of points (ii) to (v) above.

In order to derive the data for the covariances, use was made of the uncertainty budgets provided by participants. The overall uncertainty for each participant was split into the Type A and Type B components according to the information provided in the uncertainty budget, with the Type B components used to provide information for the covariances. There is some approximation involved in this, since for some participants, Type A components were not stated for every frequency – instead the value was said to range between two values for a given hydrophone and frequency range. In this case, the typical value given was used as the Type A component for all the frequencies in the range. The values of the common frequencies of calibration, the overall uncertainties and the Type A uncertainties are listed in Appendix J.

Results of using this method are presented in Appendix G in tabular form at the 94 individual frequencies of measurement. In addition, the data is presented in graphical form, with two plots shown for each participant covering the frequency range 1 kHz to 100 kHz and 100 kHz to 500 kHz respectively.

7.9 BILATERAL DEGREES OF EQUIVALENCE

The degree of equivalence between laboratory i and j is evaluated from

$$d_{i,j} = x_i - x_j \tag{7.5}$$

with associated standard uncertainty $u(d_{i,j})$ evaluated from

$$u^2(d_{i,j}) = u^2(x_i) + u^2(x_j). \qquad (7.6)$$

Where more than one device has been calibrated at a given frequency, the Bilateral Degrees of Equivalence for the devices have been combined in a similar manner to that outlined in Section 7.8.

The results of the calculation of the Bilateral Degrees of Equivalence between laboratories is presented in Appendix H. To reduce the amount of data to a manageable amount, the results are shown in tabular form for 15 selected frequencies out of a total of 94 frequencies in the range 1 kHz to 500 kHz.

7.10 DEGREES OF EQUIVALENCE AT SELECTED FREQUENCIES

In Appendix I, the Degrees of Equivalence for all participating laboratories are given at the same 15 selected frequencies used in Appendix I.

8. CONCLUSION

8.1 SUMMARY

In conclusion, the results for the Key Comparison CCAUV.W-K1 show agreement that is in general commensurate with the uncertainties quoted by participants. It is interesting to note that two of the hydrophones (the B&K8104 and the Reson TC4034) are the same devices used in the EUROMET comparison (EUROMET Project 480). However, the results obtained in this exercise show far less spread in the results for those hydrophones than was observed for the European comparison.

The results also demonstrate that no country can be designated as an outlier or as consistently discrepant, and the results of all countries have been used in deriving the Degrees of Equivalence.

The weighted mean was chosen to form Key Comparison Reference Values for each hydrophone used in the comparison. The chi-squared consistency check applied to the data demonstrated that the weighted mean was an acceptable model to use for this data set. The KCRVs were also determined using an unweighted mean and a median approach to determine the sensitivity of the KCRV to the estimator used to form it. The three approaches agreed within the uncertainty of the weighted mean showing that the data was not highly sensitive to the choice of KCRV estimator. The DOEs for each participant and for each hydrophone were then calculated.

In the regions of frequency overlaps where more than one hydrophone was calibrated at a particular frequency (a total of 18 of the 94 frequencies), the DOE data were combined to provide a single DOE value by use of a weighted mean approach with due consideration given to the correlation in the calibrations undertaken on the different hydrophones by the same participant. The bilateral DOEs between participants were also calculated in a similar manner.

Although the H52 hydrophone was calibrated over the frequency range 1 kHz to 100 kHz, the data for the frequency range 80 kHz to 100 kHz were not used to form the combined DOE value since the spread in the results for that hydrophone in that frequency range indicated that the results may have been of doubtful quality, this being close to the upper limit of the operating frequency range of the device.

It was decided to publish all the absolute values for all hydrophones in the final report. No corrections were made for variations in temperature between the calibrations of participants, and no attempt was made to correct for any slight drift in sensitivity which may be just discernible for one of the devices.

8.2 DISCUSSION

The comparison has generated a large amount of data which is not easy to assimilate or present in a convenient form. It may be desirable to generate representative values for DOEs and bilateral DOEs averaged over frequency bands (eg over octaves). This data reduction would make the results easier to digest for those reading the results on the BIPM web-site.

In general, the participants feel that the comparison has been extremely valuable, with much confidence gained in the performance of primary standards, and generally encouraging agreement observed between results from different countries. However, when considering future comparisons and future research in underwater acoustical metrology, there are one or two lessons which may be learned from the exercise that are perhaps worth stating here:

(i) It is highly likely that the variation in water temperature between the laboratories of the participants contributed to the discrepancies observed between results. In any future exercise, it would be better to stipulate a greater control on water temperature such that all the calibrations were undertaken in a range of perhaps 3 °C. For certain facilities (for example, open-water facilities), this would require the calibrations to be scheduled carefully to take advantage of seasonal variation in temperatures.

(ii) The variations in the mounting or rigging for the hydrophones used almost certainly contributed to the discrepancies observed between the results of participants. In future it would be better to prescribe the type of mount to be used, or perhaps circulate the mounts with the hydrophones under test.

(iii) The choice of hydrophones for future comparisons is also worth reconsideration. In this exercise, devices were chosen partly because they were familiar through common use. It would be preferable to use hydrophones which were highly stable with temperature. For the hydrophones used in this comparison, the H52 device proved to be an excellent choice for frequencies from 1 kHz to 80 kHz. It also had the advantage that it was fairly stable with temperature, as had already been determined by USRD [7]. The TC4034 proved a good choice for frequencies from 100 kHz to 300 kHz but the spread of results became larger at higher frequencies, and it is possible that a different type of hydrophone may have been a better choice for 300 kHz to 500 kHz. The B&K8104 was more sensitive to variations in temperature than the other hydrophones, a fact not known at the start of the exercise. It also may be sensitive to the exact mounting configuration used, leading to small fluctuations in the measured response.

(iv) The components of Type B uncertainty within the uncertainty budgets of participants varied significantly. It was generally agreed that further work was justified in investigating some of the sources of uncertainty in more depth to develop a consensus view on the common sources prevalent in hydrophone calibration.

(v) The comparison covered only free-field measurements at frequencies between 1 kHz and 500 kHz. There is some gap between the coverage of this comparison and that of CCAUV.U-K2 which covers 1 MHz to 15 MHz. However, there is more importantly a lack of coverage at frequencies less than 1 kHz. Applications of marine acoustics cover a frequency range down to a few hertz (in extremes, sometimes covering sub-hertz frequencies), and a comparison covering this important frequency range would be worth considering for the future.

9. ACKNOWLEDGMENTS

Of course, the comparison would not have been possible without the effort put in by participants and the author would like to express gratitude to all those who took part. The author would also like to thank the Underwater Sound Reference Division of NUWC, USA, for the loan of the H52 hydrophone for the comparison. In addition, the support and guidance of the CCAUV (in particular Dr Allisy-Roberts, Secretary, CCAUV) and the BIPM is gratefully acknowledged. The author would also like to express gratitude to Dr Peter M. Harris and Professor Maurice G. Cox of NPL for assistance with the analysis of the data and the calculation of KCRVs and DOEs.

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APPENDIX A: VARIATION IN HYDROPHONE RESPONSE TO TEMPERATURE

NPL has calibrated each of the types of hydrophone used in the Key Comparison in the APV to determine the variation in response with depth and temperature for that hydrophone type. For the USRD H52 and the Reson TC4034 hydrophones, the results reported here were obtained from independent absolute calibrations of the hydrophones using the three-transducer spherical-wave reciprocity method using the NPL Acoustic Pressure Vessel. To decide whether observed variations are significant, consideration must be given to the calibration uncertainties. The overall uncertainties for this method depend on frequency but are typically in the range 0.5 dB to 0.7 dB. Since all measurements were made with the same system at the same laboratory (so that Type B uncertainties should be the same for each calibration), when considering differences, we need consider only the Type A (random) uncertainties which are typically 0.1 dB to 0.2 dB. All the above uncertainties are expanded uncertainties quoted for a coverage factor of k=2. Figures A1 and A2 show how the sensitivity of the H52 hydrophone varies with temperature.

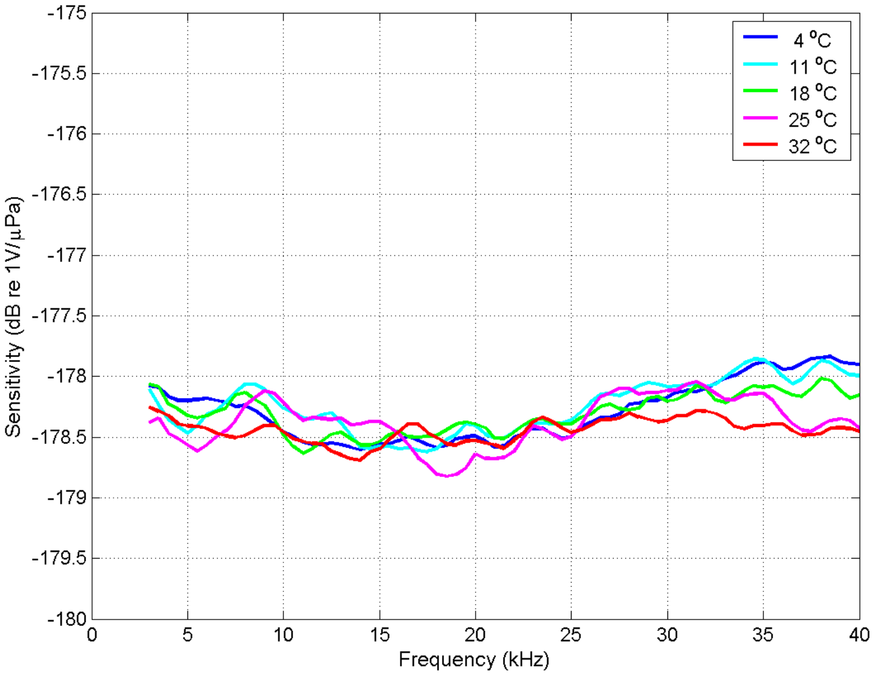

Figure A1. Variation in response of the H52 hydrophone with temperature in the frequency range 3 kHz to 40 kHz.

The results for the H52 show that there is a small but measurable change in response with temperature. It can be seen that the variation is quite complex, with increasing temperature causing a reduction in response in the frequency range 20 kHz to 60 kHz, but in general causing an increase in response at higher frequencies. At frequencies greater than 120 kHz, the largest variation is observed with a possible change in resonance frequency being seen with changing temperature. In the frequency range of interest for the hydrophone used in the comparison (1 kHz to 100 kHz), the maximum magnitude of the variation observed is a 0.7 dB change in response for a 24 °C change in temperature (a rate of approximately

0.03 dB/ºC). Since the maximum temperature variation for the calibrations by the comparison participants is about 7 ºC, this leads to a maximum discrepancy of 0.21 dB caused by temperature differences. NPL have also determined the variation in response of the H52 with temperature in the lower frequency range of 3 kHz to 20 kHz in a separate series of calibrations. Here the variation is in general less than that observed at higher frequencies. The results presented here for the H52 are in general agreement with those published in by USRD over the frequency range 20 kHz to 100 kHz [7].

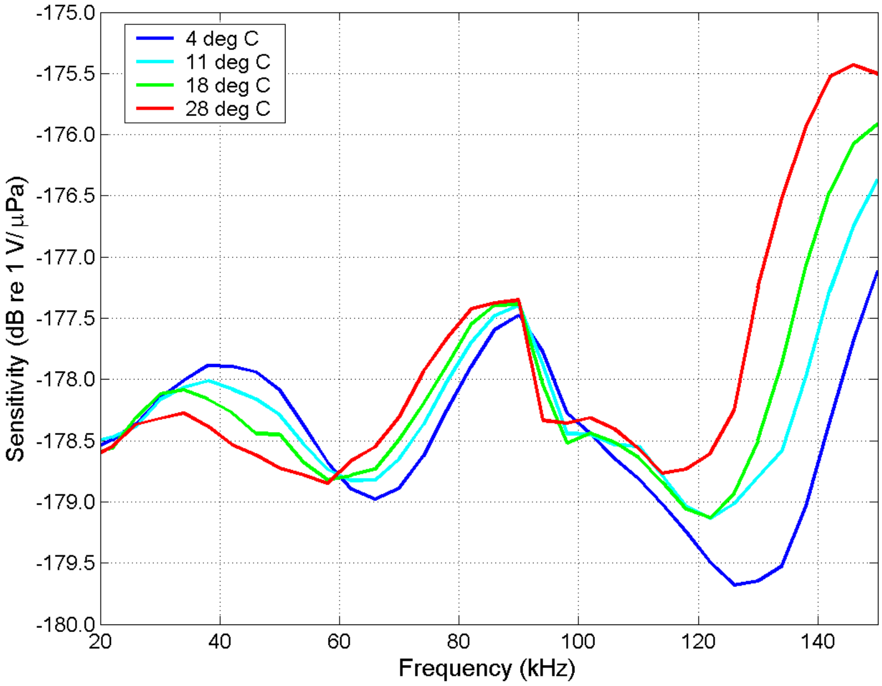

Figure A2. Variation in response of the H52 hydrophone with temperature in the frequency range 20 kHz to 150 kHz.

The results of calibrations undertaken at elevated hydrostatic pressure indicate that there is relatively little change in response with depth for the H52 hydrophone, with only between 0.1 dB and 0.3 dB change in response from atmospheric pressure to 6 MPa. This stability is also observed at lower frequencies as demonstrated by independent calibrations in the frequency range 3 kHz to 20 kHz. Since in the Key Comparison the depth of immersion varied from 1.8 m to 4.0 m, the influence of the differences in depth is therefore of the order of 0.001 dB and is negligible for all practical purposes.

The B&K8104 has also been calibrated by NPL over a range of temperatures and pressures, in this case the calibrations being undertaken using a comparison technique. Here, a significant but gradual variation in response with applied pressure is observed (equivalent to about 0.005 dB/m in the worst case). Again this is not significant for the Key Comparison calibrations due to the limited range of depths used. However, more significant variations were observed with temperature (see Figures A3 and A4) in the range 20 kHz to 70 kHz with a change between the measured response at 5 ºC and 32 ºC of up to 2 dB (equivalent to

0.07 dB/ºC). This could lead to differences of up to about 0.5 dB in the frequency range used for the Key Comparison.

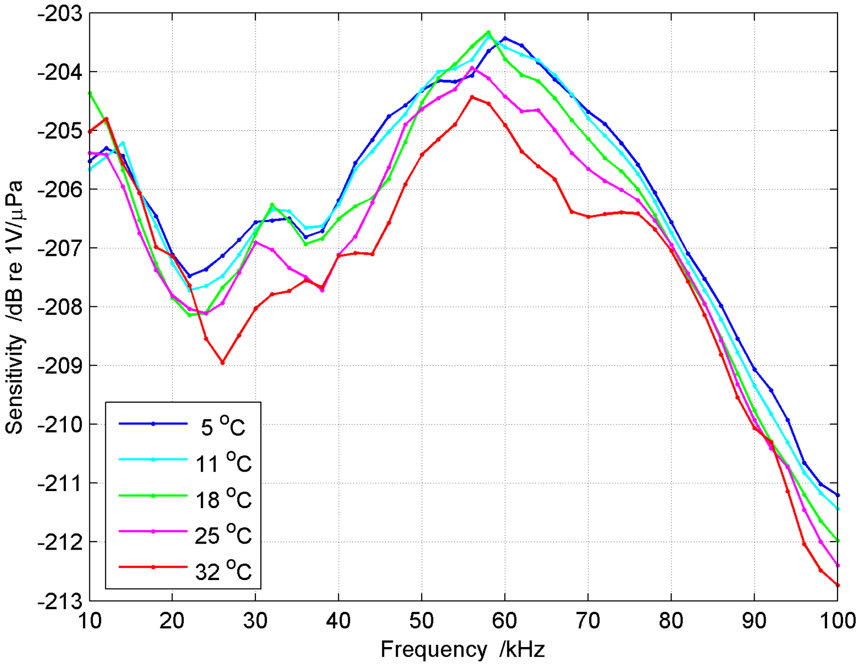

Figure A3. Variation in response of the B&K8104 hydrophone with temperature in the frequency range 10 kHz to 100 kHz.

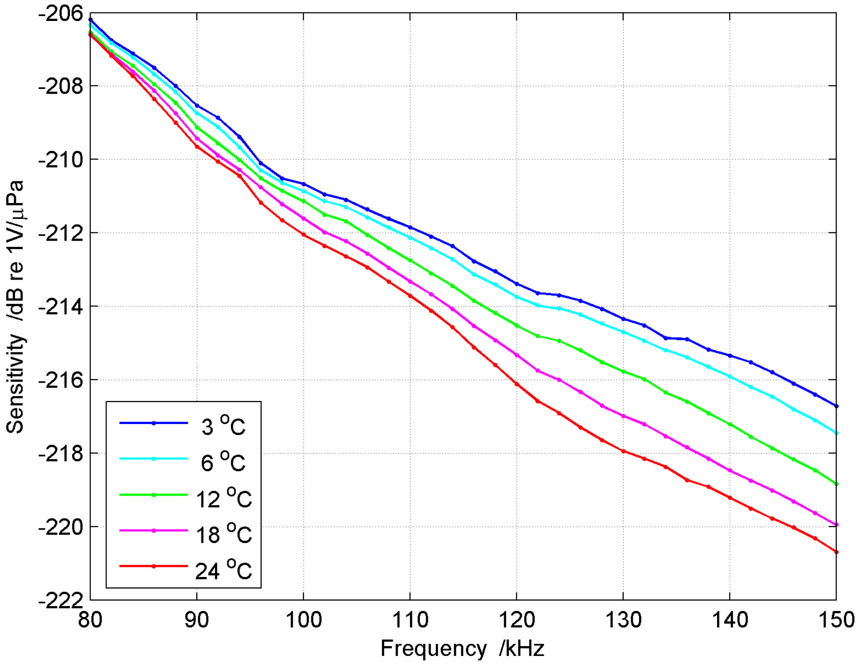

Figure A4. Variation in response of the B&K8104 hydrophone with temperature in the frequency range 80 kHz to 150 kHz.

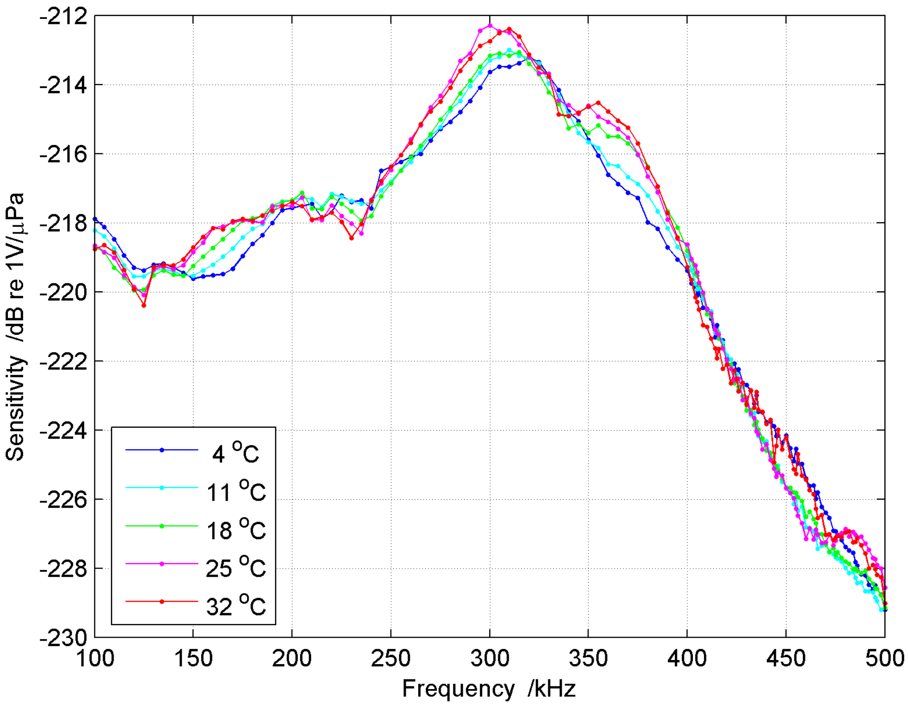

Figure A5. Variation in response of the TC4034 hydrophone with temperature in the frequency range 100 kHz to 500 kHz.

The results for the TC4034 at intervals of 5 kHz and at 5 different temperatures are shown in Figure A5. Once again, the behaviour is complex with particular sensitivity to changes in temperature evident at certain frequencies such as 125 Hz. A peculiar resonance effect is observed around 450 kHz which may be an artefact of the measurements unique to the device under test. For a temperature change from 4 ºC to 32 ºC, the maximum variation observed is over 3 dB (at 450 kHz), but this is untypical and the mean variation is 1.0 dB corresponding to 0.035 dB/ºC. This could lead to differences of up to about 0.25 dB in the frequency range used for the Key Comparison.

For the variation of the TC4034 response with depth, the results obtained indicate that there is a measurable change in response with a maximum variation of 1.5 dB at 100 kHz and a mean change of 0.57 dB when the pressure is raised from atmospheric pressure to 6.8 MPa. For the Key Comparison calibrations, the influence of the differences in depth is therefore likely to be less than 0.005 dB and is again negligible for all practical purposes.

APPENDIX B: NPL CALIBRATIONS AT START AND END OF COMPARISON

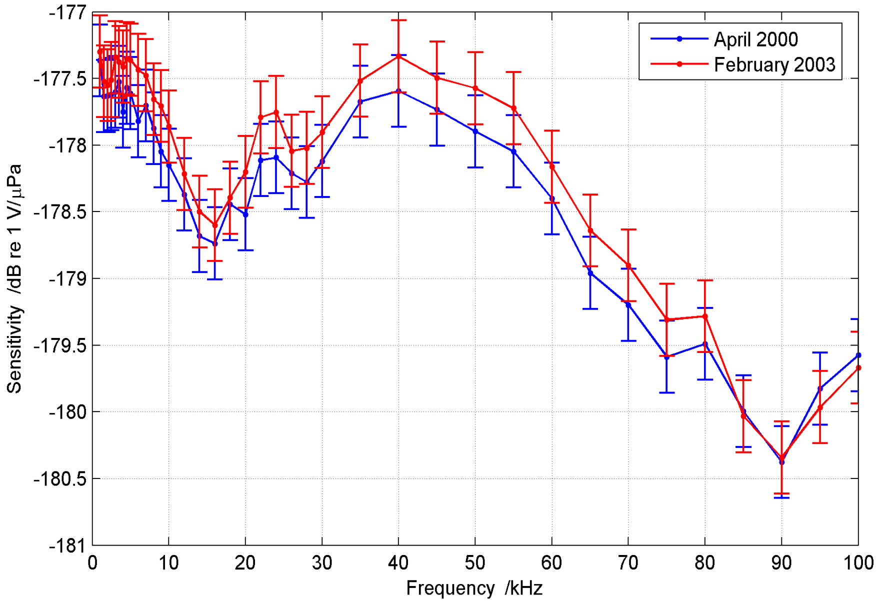

Figure B1. NPL calibrations of the H52 hydrophone at the start and end of the comparison (error bars indicate Type A uncertainties expressed at 95% confidence level).

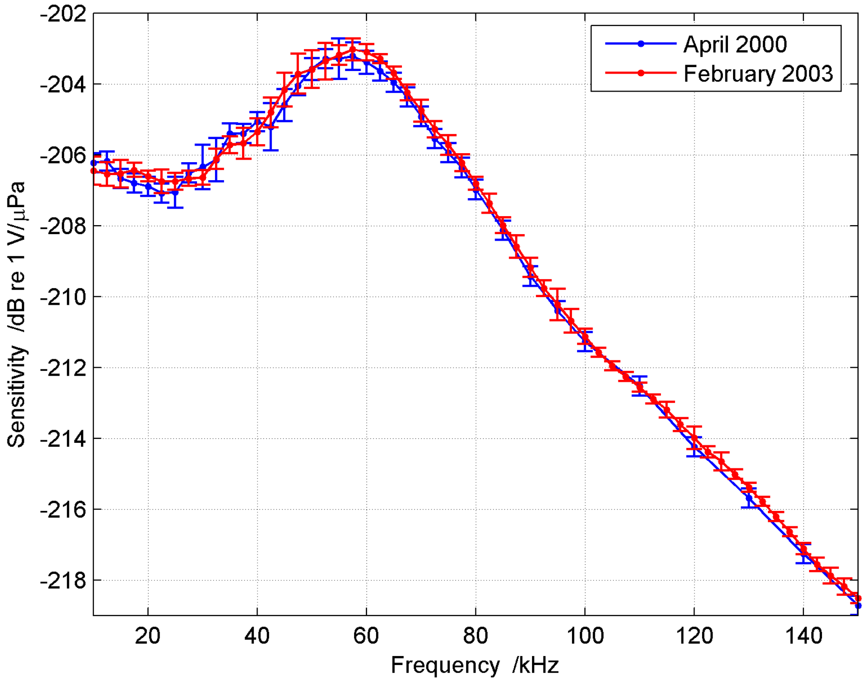

Figure B2. NPL calibrations of the B&K8104 hydrophone at the start and end of the comparison (error bars indicate Type A uncertainties expressed at 95% confidence level).

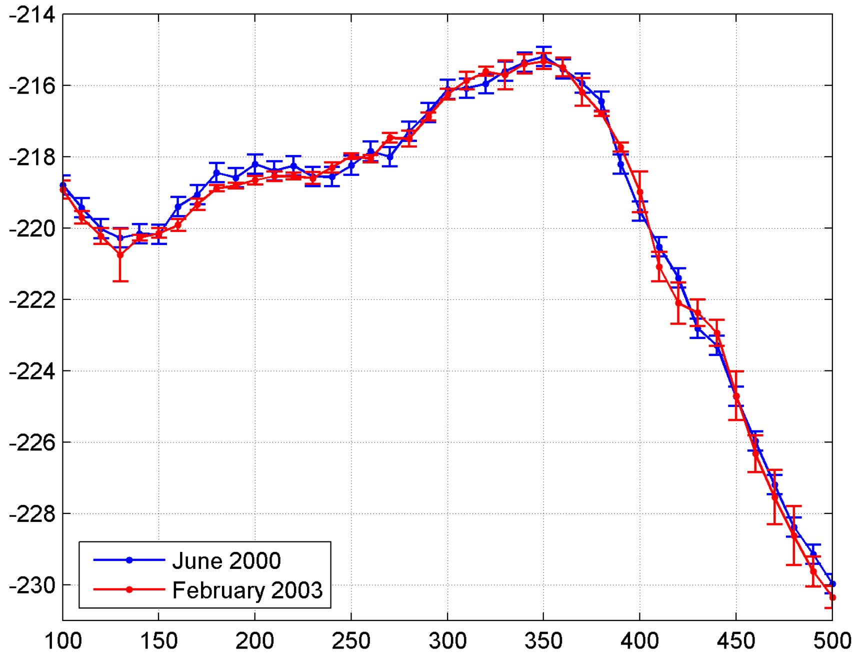

Figure B3. NPL calibrations of the TC4034 hydrophone at the start and end of the comparison (error bars indicate Type A uncertainties expressed at 95% confidence level).

APPENDIX C: VALUES OF WEIGHTED MEAN, UNWEIGHTED MEAN AND MEDIAN

Table C1. The values for the H52 hydrophone in dB re 1V/µPa calculated using the weighted mean, unweighted mean and median.

H52			
Frequency (kHz)	Weighted mean	Unweighted mean	Median
1.0	-177.62	-177.69	-177.62
1.5	-177.52	-177.64	-177.54
2.0	-177.70	-177.72	-177.69
2.5	-177.55	-177.61	-177.56
3.0	-177.56	-177.60	-177.58
3.5	-177.53	-177.62	-177.55
4.0	-177.63	-177.70	-177.65
4.5	-177.58	-177.67	-177.60
5.0	-177.52	-177.62	-177.55
6.0	-177.65	-177.73	-177.68
7.0	-177.59	-177.71	-177.67
8.0	-177.75	-177.85	-177.79
9.0	-177.71	-177.82	-177.77
10.0	-177.86	-177.95	-177.89
12.0	-178.13	-178.23	-178.20
14.0	-178.43	-178.50	-178.49
16.0	-178.61	-178.68	-178.66
18.0	-178.33	-178.45	-178.39
20.0	-178.21	-178.29	-178.26
22.0	-177.85	-177.95	-177.89
24.0	-177.71	-177.80	-177.75
26.0	-178.01	-178.05	-178.03
28.0	-178.11	-178.19	-178.17
30.0	-177.93	-178.03	-178.02
35.0	-177.56	-177.69	-177.65
40.0	-177.44	-177.56	-177.53
45.0	-177.64	-177.74	-177.72
50.0	-177.59	-177.70	-177.68
55.0	-177.86	-177.95	-177.94
60.0	-178.29	-178.32	-178.29
65.0	-178.74	-178.76	-178.74
70.0	-179.05	-179.09	-179.09
75.0	-179.44	-179.44	-179.42
80.0	-179.37	-179.42	-179.47
85.0	-179.91	-179.92	-180.03
90.0	-180.21	-180.25	-180.35
95.0	-179.70	-179.79	-179.88
100.0	-179.58	-179.66	-179.70

Table C2. The reference values for the B&K8104 hydrophone in dB re 1V/µPa calculated using the weighted mean, unweighted mean and median.

B&K8104			
Frequency (kHz)	Weighted mean	Unweighted mean	Median
10.0	-206.34	-206.23	-206.29
12.5	-206.41	-206.37	-206.36
15.0	-206.71	-206.67	-206.69
17.5	-206.86	-206.79	-206.79
20.0	-206.91	-206.86	-206.89
22.5	-206.94	-206.92	-206.94
25.0	-206.85	-206.86	-206.86
27.5	-206.58	-206.63	-206.60
30.0	-206.49	-206.51	-206.50
32.5	-206.48	-206.47	-206.47
35.0	-205.94	-205.98	-205.94
37.5	-205.70	-205.76	-205.71
40.0	-205.24	-205.34	-205.27
42.5	-204.84	-204.92	-204.91
45.0	-204.50	-204.49	-204.49
47.5	-204.15	-204.15	-204.12
50.0	-203.87	-203.87	-203.82
52.5	-203.47	-203.51	-203.48
55.0	-203.30	-203.37	-203.34
57.5	-203.28	-203.32	-203.32
60.0	-203.52	-203.55	-203.53
62.5	-203.88	-203.89	-203.87
65.0	-204.03	-204.09	-204.09
67.5	-204.35	-204.46	-204.41
70.0	-204.95	-205.04	-204.99
72.5	-205.59	-205.63	-205.60
75.0	-206.09	-206.11	-206.08
77.5	-206.55	-206.61	-206.55
80.0	-207.13	-207.20	-207.15
85.0	-208.30	-208.37	-208.31
90.0	-209.56	-209.64	-209.58
95.0	-210.61	-210.67	-210.64
100.0	-211.42	-211.48	-211.44
110.0	-212.73	-212.77	-212.73
120.0	-214.34	-214.39	-214.39
130.0	-215.67	-215.68	-215.70
140.0	-217.26	-217.28	-217.28
150.0	-218.70	-218.75	-218.69

Table C3. The reference values for the TC4034 hydrophone in dB re 1V/µPa calculated using the weighted mean, unweighted mean and median.

TC4034			
Frequency (kHz)	Weighted mean	Unweighted mean	Median
100	-218.59	-218.62	-218.58
110	-219.32	-219.29	-219.30
120	-220.02	-219.94	-220.01
130	-220.25	-220.20	-220.24
140	-220.16	-220.08	-220.14
150	-219.96	-219.84	-219.91
160	-219.50	-219.52	-219.52
170	-219.03	-219.05	-218.97
180	-218.56	-218.69	-218.51
190	-218.58	-218.69	-218.57
200	-218.37	-218.48	-218.39
210	-218.33	-218.39	-218.32
220	-218.35	-218.38	-218.35
230	-218.47	-218.42	-218.40
240	-218.39	-218.38	-218.41
250	-218.03	-217.96	-217.97
260	-217.80	-217.83	-217.80
270	-217.35	-217.39	-217.36
280	-217.16	-217.25	-217.18
290	-216.67	-216.78	-216.69
300	-216.07	-216.25	-216.10
310	-215.73	-215.79	-215.78
320	-215.25	-215.25	-215.21
330	-215.30	-215.28	-215.28
340	-215.29	-215.26	-215.28
350	-215.28	-215.37	-215.30
360	-215.73	-215.90	-215.77
370	-216.08	-216.25	-216.11
380	-216.74	-216.89	-216.77
390	-218.08	-218.12	-218.07
400	-219.35	-219.29	-219.35
410	-220.52	-220.54	-220.51
420	-221.52	-221.61	-221.53
430	-222.54	-222.57	-222.42
440	-223.68	-223.89	-223.64
450	-225.12	-225.37	-225.15
460	-226.32	-226.51	-226.31
470	-227.77	-227.93	-227.90
480	-228.60	-228.70	-228.64
490	-229.36	-229.38	-229.36
500	-230.36	-230.37	-230.26

APPENDIX D: KCRVs FOR EACH HYDROPHONE

Table D1. KCRVs for each hydrophone expressed in dB re 1 V/μPa calculated using the weighted mean, along with standard uncertainties (in dB) expressed for a coverage factor of *k*=1.

KCRVs and associated uncertainties for each of the hydrophones								
H52			B&K8104			TC4034		
F	M	u	F	M	u	F	M	u
1	-177.62	0.11	10	-206.34	0.10	100	-218.59	0.11
1.5	-177.52	0.11	12.5	-206.41	0.10	110	-219.32	0.11
2	-177.70	0.10	15	-206.71	0.10	120	-220.02	0.11
2.5	-177.55	0.10	17.5	-206.86	0.10	130	-220.25	0.11
3	-177.56	0.09	20	-206.91	0.10	140	-220.16	0.11
3.5	-177.53	0.09	22.5	-206.94	0.10	150	-219.96	0.11
4	-177.63	0.09	25	-206.85	0.10	160	-219.50	0.13
4.5	-177.58	0.09	27.5	-206.58	0.10	170	-219.03	0.13
5	-177.52	0.09	30	-206.49	0.10	180	-218.56	0.13
6	-177.65	0.09	32.5	-206.48	0.10	190	-218.58	0.13
7	-177.59	0.09	35	-205.94	0.10	200	-218.37	0.13
8	-177.75	0.09	37.5	-205.70	0.10	210	-218.33	0.13
9	-177.71	0.09	40	-205.24	0.10	220	-218.35	0.13
10	-177.86	0.09	42.5	-204.84	0.10	230	-218.47	0.13
12	-178.13	0.09	45	-204.50	0.10	240	-218.39	0.13
14	-178.43	0.09	47.5	-204.15	0.10	250	-218.03	0.13
16	-178.61	0.09	50	-203.87	0.10	260	-217.80	0.13
18	-178.33	0.09	52.5	-203.47	0.10	270	-217.35	0.14
20	-178.21	0.09	55	-203.30	0.10	280	-217.16	0.13
22	-177.85	0.09	57.5	-203.28	0.10	290	-216.67	0.13
24	-177.71	0.09	60	-203.52	0.10	300	-216.07	0.14
26	-178.01	0.09	62.5	-203.88	0.10	310	-215.73	0.14
28	-178.11	0.09	65	-204.03	0.10	320	-215.25	0.14
30	-177.93	0.09	67.5	-204.35	0.10	330	-215.30	0.14
35	-177.56	0.09	70	-204.95	0.10	340	-215.29	0.14
40	-177.44	0.09	72.5	-205.59	0.10	350	-215.28	0.14
45	-177.64	0.09	75	-206.09	0.10	360	-215.73	0.14
50	-177.59	0.09	77.5	-206.55	0.10	370	-216.08	0.14
55	-177.86	0.09	80	-207.13	0.10	380	-216.74	0.14
60	-178.29	0.09	85	-208.30	0.10	390	-218.08	0.14
65	-178.74	0.09	90	-209.56	0.10	400	-219.35	0.14
70	-179.05	0.09	95	-210.61	0.10	410	-220.52	0.14
75	-179.44	0.09	100	-211.42	0.10	420	-221.52	0.14
80	-179.37	0.09	110	-212.73	0.10	430	-222.54	0.14
85	-179.91	0.09	120	-214.34	0.10	440	-223.68	0.14
90	-180.21	0.09	130	-215.67	0.10	450	-225.12	0.14
95	-179.70	0.09	140	-217.26	0.10	460	-226.32	0.14
100	-179.58	0.09	150	-218.70	0.10	470	-227.77	0.14
						480	-228.60	0.14
						490	-229.36	0.14
						500	-230.36	0.14

APPENDIX E: DOEs FOR EACH HYDROPHONE

Table E1. Degree of Equivalence calculated for each participant relative to the KCRV for the H52 hydrophone and the expanded uncertainty on the Degree of Equivalence expressed for a coverage factor of *k*=2.

	UK		DE		US		RU		CN		CA		ZA	
Frequency	M_i	$2u_i$	M_i	$2u_i$	M_i	$2u_i$	M_i	$2u_i$	M_i	$2u_i$	M_i	$2u_i$	M_i	$2u_i$
kHz	dB		dB		dB		dB		dB		dB		dB	
1.0	0.25	0.64	-0.68	0.74	0.04	0.34	0.10	0.32	-0.08	0.40				
1.5	-0.11	0.52	-0.78	0.74	0.06	0.34	0.08	0.32	0.12	0.41				
2.0	0.07	0.47	-0.40	0.77	-0.32	0.33	0.25	0.33	0.10	0.42	0.16	0.61		
2.5	-0.07	0.41	-0.55	0.76	-0.01	0.35	0.04	0.33	0.15	0.42	0.09	0.61		
3.0	-0.04	0.40	-0.64	0.75	-0.02	0.30	-0.01	0.33	0.36	0.44	-0.10	0.60	0.16	1.36
3.5	0.00	0.40	-0.77	0.74	0.13	0.31	0.02	0.33	0.13	0.42	-0.20	0.59	0.03	1.34
4.0	-0.12	0.40	-0.67	0.75	0.11	0.31	0.11	0.33	0.03	0.42	-0.08	0.60	0.13	1.36
4.5	0.01	0.37	-0.82	0.74	0.06	0.31	0.10	0.33	0.08	0.42	-0.11	0.59	-0.02	1.33
5.0	-0.09	0.37	-0.78	0.74	0.18	0.32	0.01	0.33	0.12	0.42	-0.12	0.59	-0.08	1.33
6.0	-0.17	0.36	-0.65	0.75	0.01	0.31	0.05	0.33	0.35	0.44	0.08	0.61	-0.25	1.30
7.0	-0.11	0.37	-0.71	0.75	0.32	0.32	0.16	0.34	-0.31	0.40	-0.03	0.60	-0.21	1.31
8.0	-0.13	0.37	-0.55	0.76	0.03	0.31	0.11	0.33	0.25	0.43	-0.15	0.59	-0.25	1.30
9.0	-0.33	0.36	-0.39	0.78	0.27	0.32	0.03	0.33	0.21	0.43	-0.16	0.59	-0.39	1.28
10.0	-0.29	0.36	-0.44	0.77	0.18	0.32	0.06	0.33	0.16	0.43	0.02	0.60	-0.34	1.29
12.0	-0.24	0.36	-0.37	0.78	0.26	0.32	0.13	0.34	-0.07	0.41	-0.18	0.59	-0.27	1.30
14.0	-0.25	0.36	-0.17	0.80	0.27	0.32	0.14	0.34	-0.17	0.41	-0.09	0.60	-0.27	1.30
16.0	-0.13	0.37	-0.19	0.80	0.07	0.31	0.37	0.35	-0.39	0.40	0.06	0.61	-0.29	1.30
18.0	-0.11	0.37	-0.47	0.77	0.15	0.31	0.13	0.34	-0.07	0.41	-0.09	0.60	-0.37	1.29
20.0	-0.31	0.36	-0.29	0.79	-0.02	0.31	0.31	0.34	0.16	0.43	-0.11	0.60	-0.29	1.30
22.0	-0.27	0.36	-0.55	0.76	0.08	0.31	0.17	0.34	0.25	0.43	-0.11	0.60	-0.35	1.29
24.0	-0.38	0.35	-0.39	0.78	0.25	0.32	0.11	0.33	0.11	0.42	-0.07	0.60	-0.29	1.30
26.0	-0.20	0.36	-0.29	0.79	0.09	0.31	0.16	0.34	0.01	0.42	-0.08	0.60	0.01	1.34
28.0	-0.16	0.37	-0.59	0.76	0.15	0.31	0.26	0.34	-0.19	0.41	-0.05	0.60	0.01	1.34
30.0	-0.19	0.36	-0.57	0.76	0.33	0.32	0.24	0.34	-0.37	0.40	-0.09	0.60	-0.07	1.33
35.0	-0.12	0.37	-0.44	0.77	0.20	0.32	0.23	0.34	-0.24	0.40	-0.11	0.59	-0.44	1.27
40.0	-0.16	0.37	-0.46	0.77	0.23	0.32	0.24	0.34	-0.26	0.40	-0.10	0.60	-0.36	1.29
45.0	-0.09	0.37	-0.26	0.79	-0.08	0.30	0.41	0.35	-0.16	0.41	-0.07	0.60	-0.46	1.27
50.0	-0.31	0.36	-0.31	0.78	0.17	0.31	0.33	0.35	-0.11	0.41	-0.17	0.59	-0.41	1.28
55.0	-0.19	0.36	-0.24	0.79	0.19	0.32	0.39	0.35	-0.44	0.39	-0.03	0.60	-0.34	1.29
60.0	-0.11	0.37	-0.21	0.79	0.12	0.31	0.34	0.35	-0.51	0.39	0.17	0.62	-0.01	1.34
65.0	-0.22	0.36	-0.16	0.80	0.31	0.32	0.16	0.34	-0.46	0.39	0.25	0.62	-0.06	1.33
70.0	-0.15	0.37	-0.35	0.78	0.38	0.32	0.11	0.33	-0.45	0.39	0.07	0.61	0.05	1.34
75.0	-0.14	0.37	-0.16	0.80	0.32	0.32	0.12	0.34	-0.56	0.39	0.34	0.63	0.04	1.34
80.0	-0.12	0.37	-0.43	0.77	0.69	0.34	-0.13	0.32	-0.63	0.38	0.41	0.63	-0.23	1.67
85.0	-0.08	0.37	-0.49	0.77	1.03	0.36	-0.24	0.32	-0.89	0.37	0.54	0.64	-0.09	1.69
90.0	-0.17	0.36	-0.49	0.77	0.80	0.34	-0.20	0.32	-0.59	0.38	0.39	0.63	-0.09	1.69
95.0	-0.12	0.37	-0.50	0.77	0.82	0.35	-0.40	0.31	-0.30	0.40	0.17	0.62	-0.40	1.64
100.0	0.00	0.37	-0.42	0.77	0.85	0.35	-0.23	0.32	-0.72	0.38	0.26	0.62	-0.42	1.63

Table E2. Degree of Equivalence calculated for each participant relative to the KCRV for the B&K8104 hydrophone and the expanded uncertainty on the Degree of Equivalence expressed for a coverage factor of *k*=2.

	UK		DE		US		RU		CN		CA		ZA	
Frequency	M_i	$2u_i$	M_i	$2u_i$	M_i	$2u_i$	M_i	$2u_i$	M_i	$2u_i$	M_i	$2u_i$	M_i	$2u_i$
kHz	dB		dB		dB		dB		dB		dB		dB	
10.0	0.12	0.38	0.54	0.86	-0.10	0.41	-0.05	0.32	-0.36	0.39	0.55	0.62	0.04	0.96
12.5	0.22	0.38	0.11	0.82	-0.31	0.40	-0.21	0.31	0.21	0.43	0.36	0.61	-0.09	0.95
15.0	0.04	0.37	0.11	0.82	-0.59	0.38	-0.09	0.32	0.71	0.45	0.24	0.60	-0.19	0.94
17.5	0.06	0.37	0.26	0.84	-0.53	0.38	-0.04	0.32	0.46	0.44	0.07	0.59	0.16	0.97
20.0	0.02	0.37	0.41	0.85	-0.05	0.41	-0.15	0.32	0.21	0.43	-0.12	0.57	0.01	0.96
22.5	-0.14	0.36	0.24	0.83	0.21	0.43	-0.17	0.32	0.34	0.43	-0.19	0.57	-0.16	0.94
25.0	-0.20	0.40	0.05	0.82	0.16	0.38	-0.02	0.32	0.05	0.42	0.02	0.58	-0.15	0.94
27.5	0.06	0.37	-0.42	0.77	0.11	0.38	-0.12	0.32	0.08	0.42	0.13	0.59	-0.22	0.93
30.0	0.14	0.54	-0.41	0.77	-0.03	0.37	-0.22	0.31	0.39	0.43	0.10	0.59	-0.11	0.94
32.5	0.33	0.59	-0.52	0.76	-0.10	0.36	0.03	0.32	-0.12	0.40	0.32	0.60	0.08	0.96
35.0	0.41	0.48	-0.76	0.74	-0.25	0.36	0.04	0.33	0.04	0.41	0.27	0.60	-0.06	0.95
37.5	0.30	0.39	-0.70	0.75	-0.31	0.36	0.12	0.33	0.00	0.41	0.24	0.60	-0.10	0.95
40.0	0.17	0.38	-0.86	0.74	0.23	0.38	-0.06	0.32	-0.06	0.41	-0.01	0.58	-0.16	0.94
42.5	-0.28	0.53	-0.46	0.77	0.33	0.38	0.09	0.33	-0.16	0.40	-0.05	0.57	-0.06	0.95
45.0	-0.10	0.41	-0.10	0.80	-0.06	0.37	0.10	0.33	0.00	0.41	0.05	0.58	0.20	0.98
47.5	0.09	0.38	-0.05	0.81	-0.31	0.35	0.08	0.33	0.15	0.42	0.10	0.59	-0.05	1.70
50.0	0.28	0.39	-0.13	0.80	-0.49	0.34	0.14	0.33	0.07	0.42	0.21	0.60	-0.13	1.68
52.5	0.18	0.38	-0.33	0.78	-0.23	0.36	0.00	0.33	0.07	0.42	0.22	0.60	-0.23	1.67
55.0	0.01	0.48	-0.50	0.76	0.31	0.38	-0.11	0.32	-0.10	0.40	0.11	0.59	-0.20	1.67
57.5	0.06	0.39	-0.32	0.78	0.35	0.39	-0.17	0.32	-0.12	0.41	0.01	0.58	-0.12	1.69
60.0	0.13	0.38	-0.18	0.80	-0.18	0.36	0.11	0.33	-0.08	0.41	0.08	0.59	-0.08	1.69
62.5	0.24	0.38	-0.32	0.78	-0.57	0.34	0.43	0.35	-0.02	0.41	0.01	0.58	0.08	1.72
65.0	0.07	0.37	-0.57	0.76	-0.26	0.36	0.37	0.34	-0.07	0.41	-0.04	0.58	0.03	1.71
67.5	-0.03	0.37	-0.65	0.75	0.00	0.37	0.35	0.34	-0.25	0.40	0.04	0.58	-0.25	1.66
70.0	0.03	0.37	-0.55	0.76	-0.04	0.37	0.23	0.34	-0.15	0.41	0.09	0.59	-0.25	1.66
72.5	0.04	0.37	-0.51	0.77	-0.18	0.36	0.19	0.33	-0.01	0.41	0.15	0.59	-0.01	1.70
75.0	0.15	0.38	-0.41	0.77	-0.37	0.35	0.23	0.34	-0.01	0.41	0.18	0.59	0.09	1.72
77.5	0.19	0.38	-0.45	0.77	-0.34	0.35	0.17	0.33	0.05	0.42	0.11	0.59	-0.15	1.68
80.0	0.15	0.38	-0.47	0.77	-0.18	0.36	0.14	0.33	-0.07	0.41	0.13	0.59	-0.17	1.68
85.0	0.17	0.38	-0.60	0.76	-0.11	0.36	0.01	0.33	0.10	0.42	0.08	0.59	-0.20	1.67
90.0	0.13	0.38	-0.54	0.76	-0.23	0.36	0.16	0.33	0.06	0.42	0.07	0.59	-0.24	1.66
95.0	0.20	0.38	-0.49	0.77	-0.16	0.36	0.11	0.33	-0.09	0.41	0.09	0.59	-0.09	1.69
100.0	0.14	0.38	-0.48	0.77	-0.18	0.36	0.11	0.33	0.02	0.41	0.05	0.58	-0.08	1.69
110.0	0.20	0.38	-0.57	0.76	-0.28	0.36	0.15	0.33	0.03	0.42	0.10	0.59	0.03	1.71
120.0	0.10	0.39	-0.36	0.78	-0.23	0.36	0.33	0.34	-0.16	0.40	-0.01	0.58	-0.06	1.70
130.0	-0.02	0.38	-0.03	0.81	-0.18	0.36	0.34	0.34	-0.23	0.40	0.07	0.59	-0.03	1.70
140.0	0.00	0.37	0.16	0.83	-0.24	0.36	0.36	0.34	-0.24	0.40	0.05	0.58	-0.24	1.66
150.0	-0.02	0.37	0.00	0.81	0.06	0.37	0.28	0.34	-0.50	0.39	0.22	0.60	-0.40	1.64

Table E3. Degree of Equivalence calculated for each participant relative to the KCRV for the TC4034 hydrophone and the expanded uncertainty on the Degree of Equivalence expressed for a coverage factor of *k*=2.

	UK		DE		US		RU		CN		CA		ZA	
Frequency	M_i	$2u_i$	M_i	$2u_i$	M_i	$2u_i$	M_i	$2u_i$	M_i	$2u_i$	M_i	$2u_i$	M_i	$2u_i$
kHz	dB		dB		dB		dB		dB		dB		dB	
100	-0.21	0.34	0.09	0.81	0.27	0.50	0.09	0.31	-0.21	0.64	0.16	1.03	-0.41	2.32
110	-0.12	0.35	0.52	0.86	0.18	0.50	0.03	0.31	-0.38	0.62	0.10	1.02	-0.18	2.38
120	-0.01	0.35	-0.18	0.79	0.03	0.49	0.03	0.31	-0.18	0.64	0.42	1.06	0.42	2.53
130	-0.04	0.35	-0.35	0.77	0.31	0.51	0.05	0.31	-0.45	0.62	0.42	1.06	0.35	2.51
140	-0.01	0.35	-0.64	0.75	0.22	0.50	0.06	0.31	-0.24	0.63	0.35	1.05	0.76	2.62
150	-0.22	0.34	-0.54	0.76	0.32	0.51	0.10	0.31	-0.04	0.65	0.51	1.07	0.66	2.59
160	0.10	0.34	-0.40	0.76	0.15	0.48	-0.16	0.53	-0.10	0.64	0.17	1.02	0.10	2.45
170	-0.04	0.34	-0.97	0.71	0.14	0.48	0.23	0.56	0.23	0.66	0.27	1.04	-0.07	2.41
180	0.10	0.34	-1.24	0.69	0.14	0.48	0.26	0.56	0.16	0.66	0.18	1.02	-0.64	2.27
190	-0.01	0.34	-0.92	0.71	0.18	0.49	0.28	0.56	0.08	0.65	0.08	1.01	-0.52	2.30
200	0.15	0.35	-0.73	0.73	0.13	0.48	-0.03	0.54	-0.03	0.64	0.14	1.02	-0.43	2.32
210	-0.08	0.35	-0.57	0.74	0.25	0.64	0.13	0.54	0.13	0.65	0.24	1.03	-0.57	2.28
220	0.10	0.34	0.05	0.80	-0.02	0.62	0.03	0.54	-0.45	0.60	0.44	1.05	-0.35	2.34
230	-0.09	0.34	-0.03	0.79	0.24	0.64	0.37	0.56	-0.63	0.59	0.67	1.08	-0.23	2.37
240	-0.18	0.35	-0.11	0.78	0.34	0.64	0.59	0.58	-0.41	0.60	-0.20	0.98	-0.01	2.42
250	-0.22	0.34	0.03	0.80	0.06	0.62	0.13	0.54	0.13	0.65	0.57	1.07	-0.27	2.35
260	-0.06	0.35	0.10	0.80	-0.02	0.61	0.20	0.55	-0.10	0.63	-0.02	1.00	-0.30	2.35
270	-0.31	0.40	-0.05	0.79	-0.12	0.60	0.55	0.57	0.15	0.65	0.09	1.01	-0.65	2.26
280	-0.14	0.35	0.16	0.81	0.04	0.62	0.26	0.55	0.06	0.64	-0.33	0.96	-0.74	2.25
290	-0.10	0.35	0.27	0.82	0.16	0.63	0.37	0.56	-0.13	0.63	-0.80	0.91	-0.63	2.27
300	-0.05	0.41	0.17	0.81	0.12	0.71	0.47	0.56	-0.03	0.63	-1.16	0.87	-0.93	2.20
310	-0.35	0.39	0.53	0.84	-0.11	0.68	0.63	0.57	0.03	0.63	-0.58	0.93	-0.67	2.26
320	-0.41	0.39	0.25	0.81	0.12	0.73	0.55	0.57	-0.05	0.63	0.03	1.00	-0.55	2.29
330	-0.30	0.39	0.70	0.86	-0.39	0.68	0.40	0.55	0.00	0.63	0.11	1.01	-0.40	2.32
340	-0.07	0.41	0.69	0.86	0.12	0.70	-0.21	0.51	-0.01	0.63	-0.12	0.98	-0.21	2.37
350	0.08	0.42	0.48	0.84	-0.02	0.69	-0.02	0.52	-0.32	0.61	0.02	1.00	-0.92	2.20
360	0.18	0.43	0.33	0.82	0.15	0.71	-0.07	0.52	-0.37	0.60	-0.15	0.98	-1.37	2.10
370	0.14	0.42	0.08	0.80	0.24	0.72	-0.12	0.51	-0.32	0.61	0.04	1.00	-1.32	3.49
380	0.29	0.44	-0.06	0.78	-0.03	0.69	-0.36	0.50	-0.06	0.63	0.33	1.04	-1.26	3.51
390	-0.13	0.41	-0.12	0.78	0.17	0.71	-0.02	0.52	-0.02	0.63	0.77	1.09	-1.02	3.59
400	-0.19	0.40	0.05	0.79	-0.05	0.69	0.15	0.53	-0.25	0.61	1.45	1.18	-0.95	3.61
410	-0.01	0.41	0.12	0.80	0.17	0.71	-0.28	0.50	-0.18	0.62	1.16	1.14	-1.28	3.50
420	0.11	0.42	-0.38	0.75	0.44	0.73	-0.08	0.52	-0.38	0.60	0.71	1.08	-1.18	3.53
430	-0.28	0.40	-0.96	0.70	0.73	0.76	0.24	0.54	0.24	0.65	0.72	1.08	-1.06	3.57
440	0.38	0.44	-1.32	0.67	0.34	0.72	0.08	0.53	0.08	0.64	-0.07	0.99	-1.12	3.56
450	0.39	0.44	-1.08	0.69	0.44	0.73	0.02	0.52	0.12	0.64	-0.62	0.93	-1.18	3.53
460	0.35	0.44	-0.98	0.70	0.60	0.75	-0.06	0.52	0.42	0.67	-1.17	0.87	-0.68	3.71
470	0.57	0.45	-0.43	0.75	0.62	0.75	-0.18	0.51	-0.23	0.61	-1.28	0.86	-0.33	3.83
480	0.21	0.43	-0.20	0.77	0.31	0.72	0.22	0.54	-0.40	0.60	-0.73	0.91	-0.20	3.87
490	0.21	0.43	-0.04	0.78	0.06	0.70	-0.26	0.50	-0.04	0.63	0.05	1.00	-0.14	3.90
500	0.37	0.44	0.36	0.82	0.16	0.71	-0.72	0.47	0.36	0.66	-0.52	0.94	-0.14	3.90

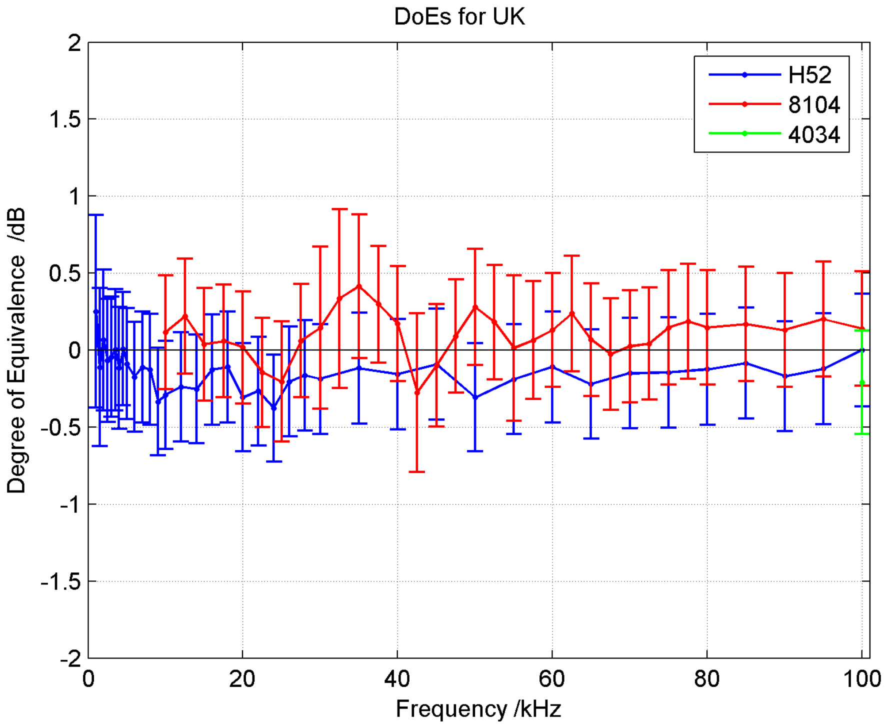

Figure E1. Degrees of equivalence for the UK in the frequency range 1 kHz to 100 kHz. Error bars indicate expanded uncertainties for a coverage factor of *k*=2.

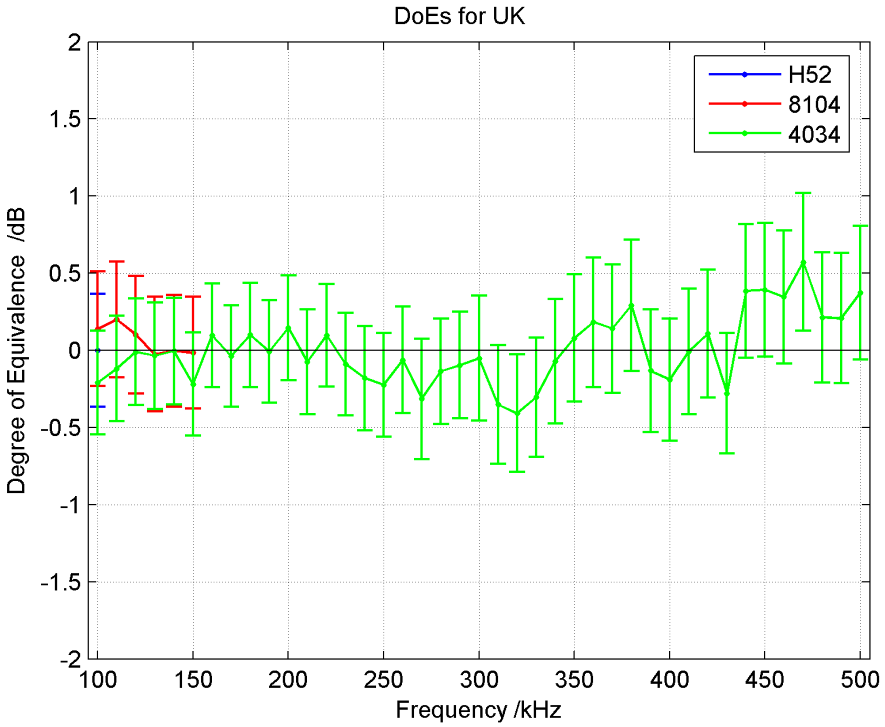

Figure E2. Degrees of equivalence for the UK in the frequency range 100 kHz to 500 kHz. Error bars indicate expanded uncertainties for a coverage factor of *k*=2.

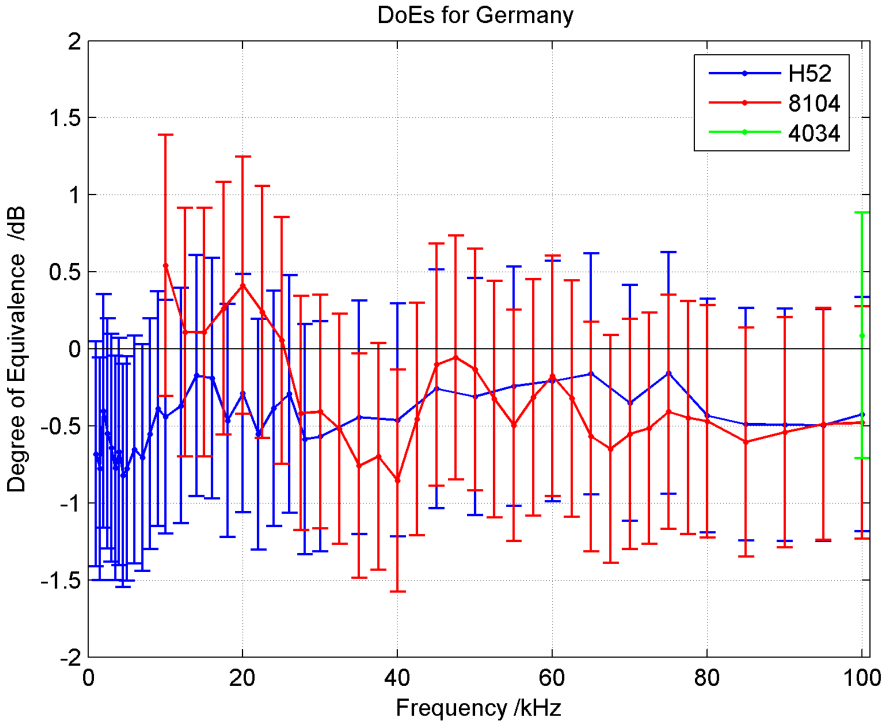

Figure E3. Degrees of equivalence for Germany in the frequency range 1 kHz to 100 kHz. Error bars indicate expanded uncertainties for a coverage factor of *k*=2.

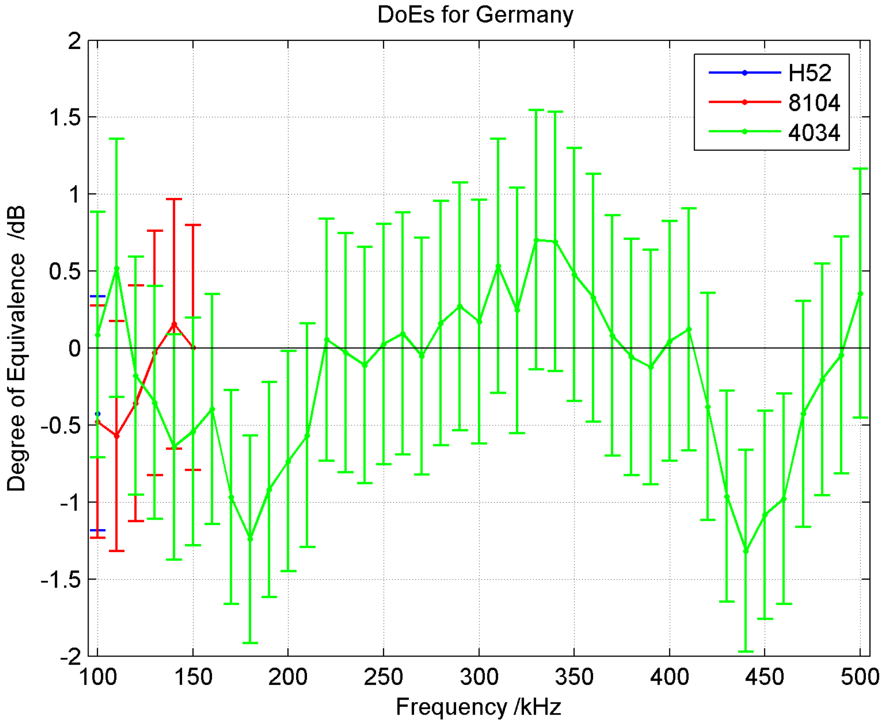

Figure E4. Degrees of equivalence for Germany in the frequency range 100 kHz to 500 kHz. Error bars indicate expanded uncertainties for a coverage factor of *k*=2.

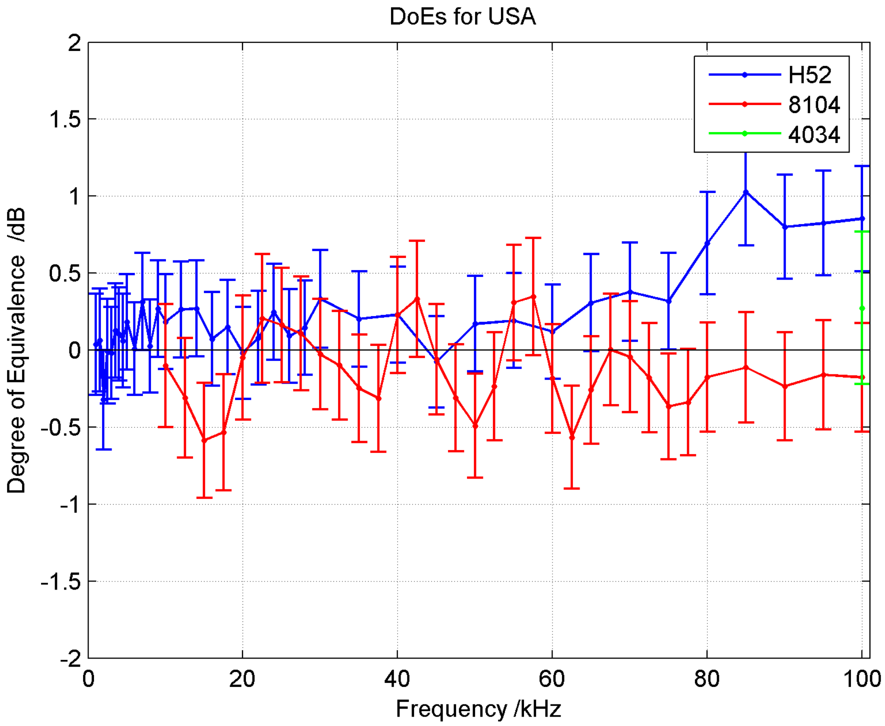

Figure E5. Degrees of equivalence for the USA in the frequency range 1 kHz to 100 kHz. Error bars indicate expanded uncertainties for a coverage factor of *k*=2.

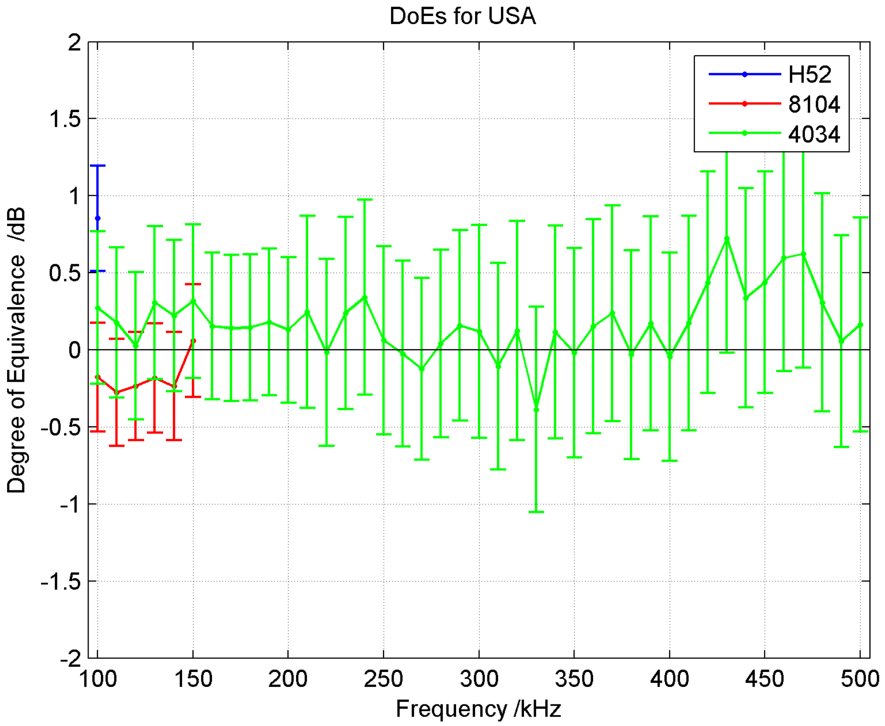

Figure E6. Degrees of equivalence for the USA in the frequency range 100 kHz to 500 kHz. Error bars indicate expanded uncertainties for a coverage factor of *k*=2.

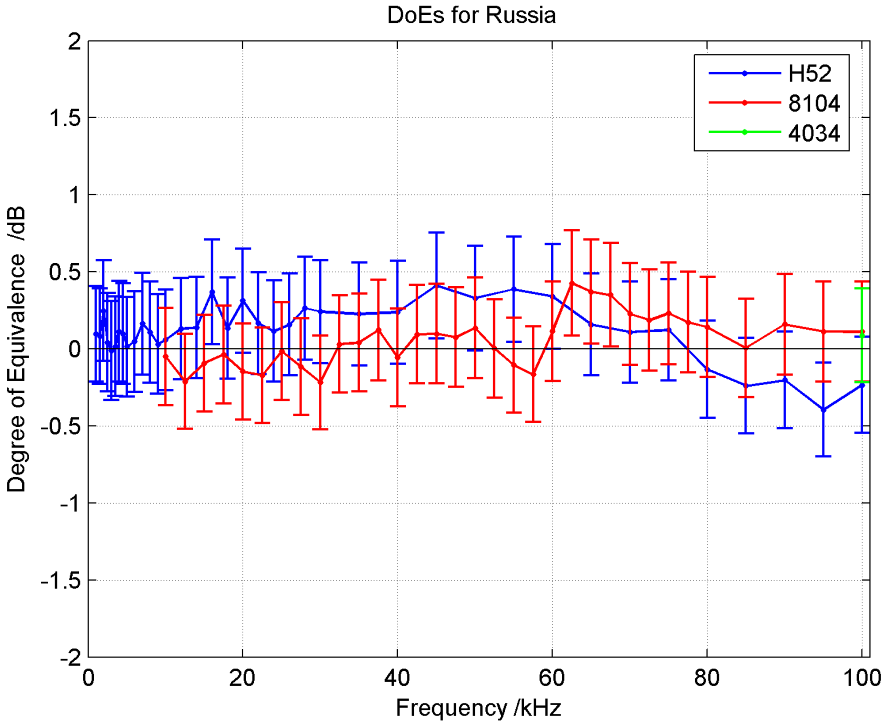

Figure E7. Degrees of equivalence for Russia in the frequency range 1 kHz to 100 kHz. Error bars indicate expanded uncertainties for a coverage factor of *k*=2.

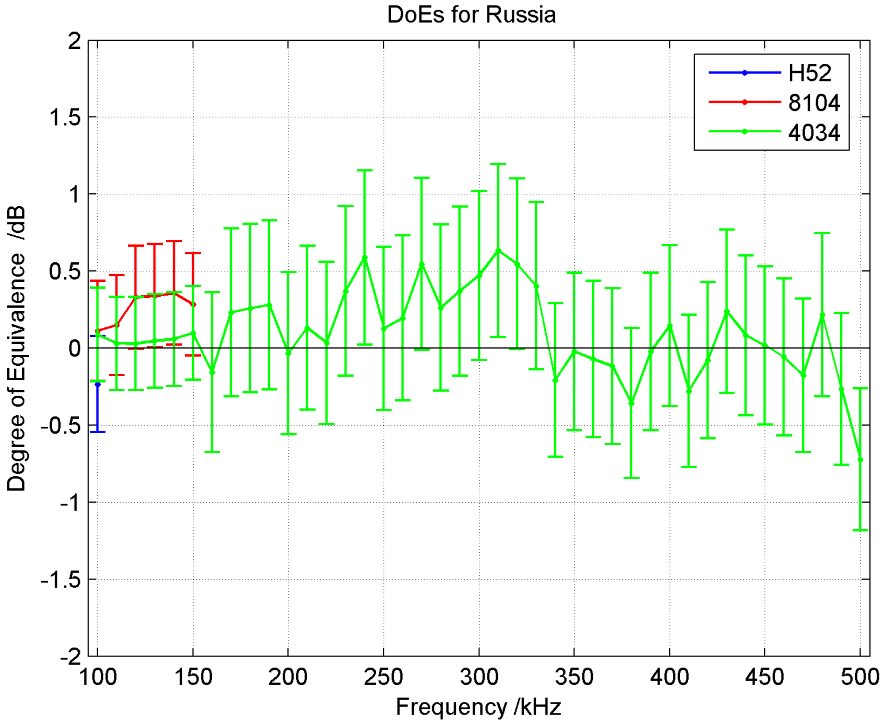

Figure E8. Degrees of equivalence for Russia in the frequency range 100 kHz to 500 kHz. Error bars indicate expanded uncertainties for a coverage factor of *k*=2.

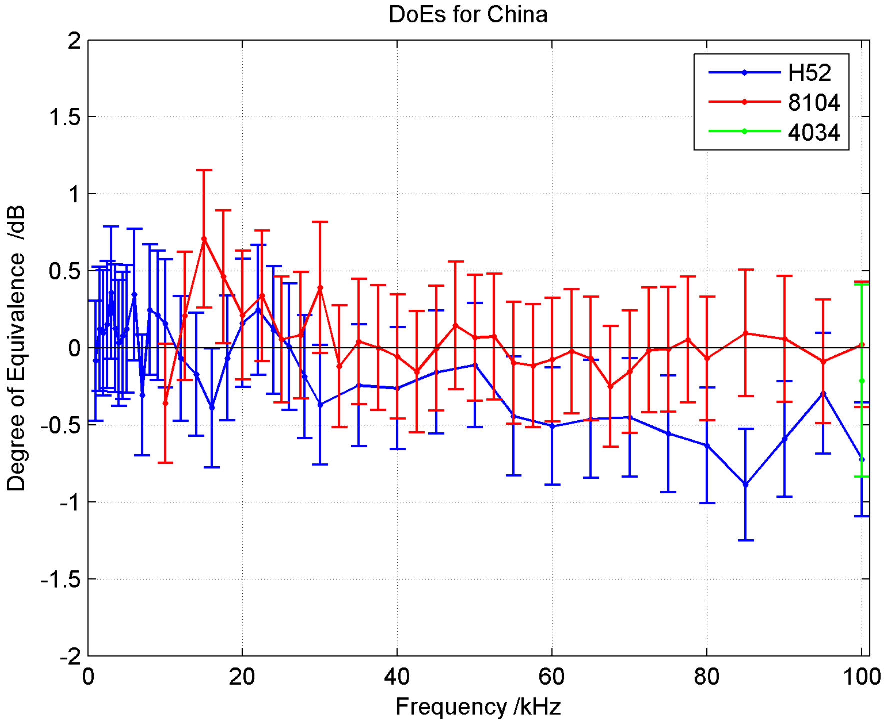

Figure E9. Degrees of equivalence for China in the frequency range 1 kHz to 100 kHz. Error bars indicate expanded uncertainties for a coverage factor of *k*=2.

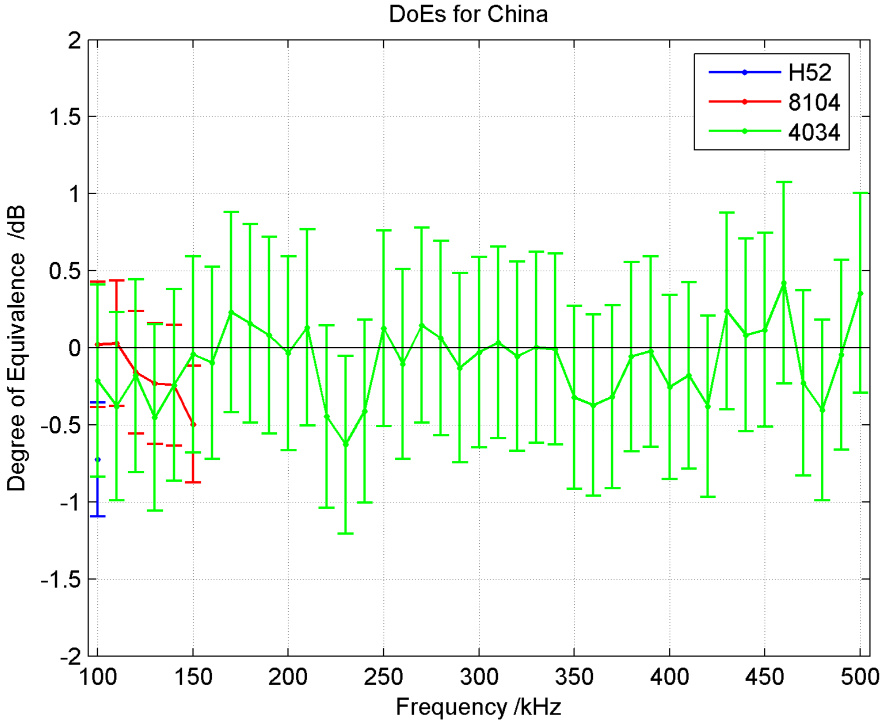

Figure E10. Degrees of equivalence for China in the frequency range 100 kHz to 500 kHz. Error bars indicate expanded uncertainties for a coverage factor of *k*=2.

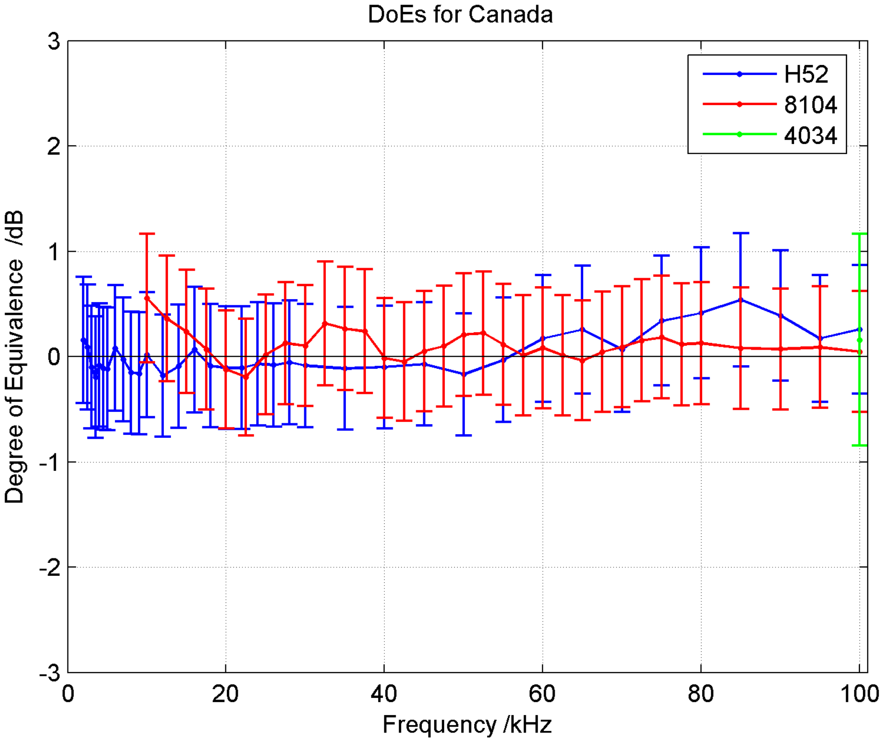

Figure E11. Degrees of equivalence for Canada in the frequency range 1 kHz to 100 kHz. Error bars indicate expanded uncertainties for a coverage factor of *k*=2.

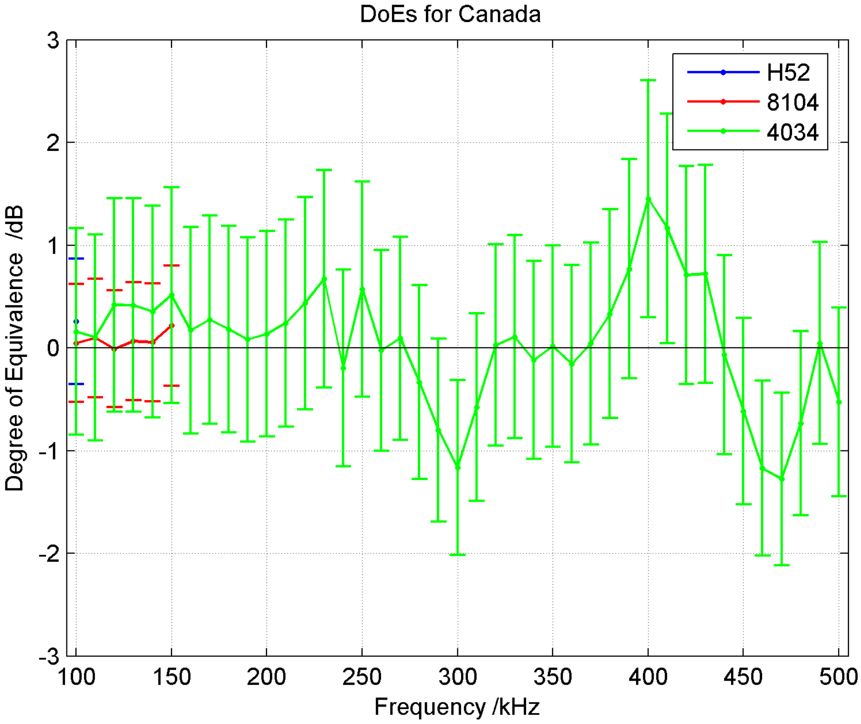

Figure E12. Degrees of equivalence for Canada in the frequency range 100 kHz to 500 kHz. Error bars indicate expanded uncertainties for a coverage factor of *k*=2.

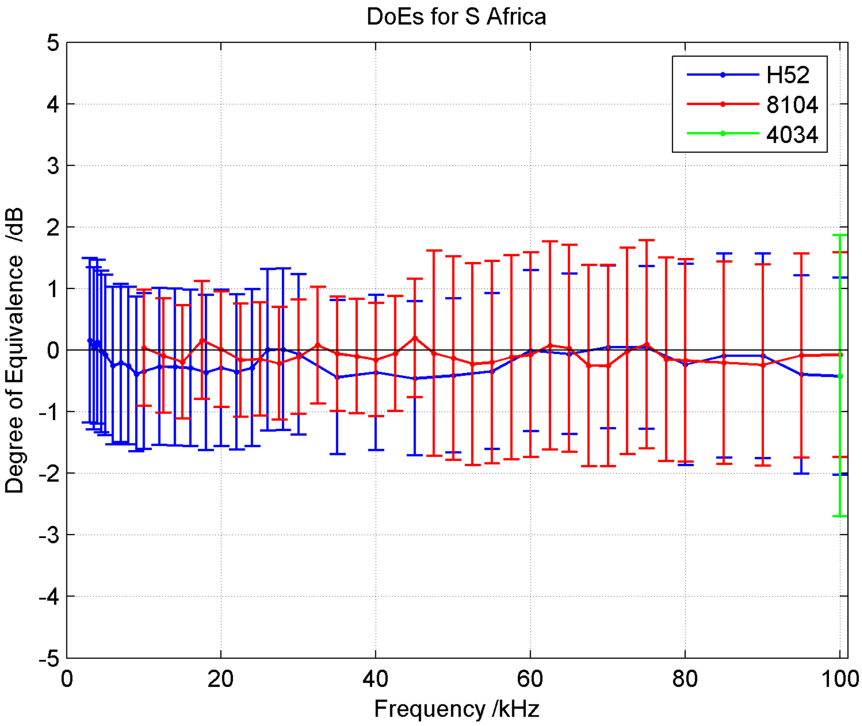

Figure E13. Degrees of equivalence for South Africa in the frequency range 1 kHz to 100 kHz. Error bars indicate expanded uncertainties for a coverage factor of *k*=2.

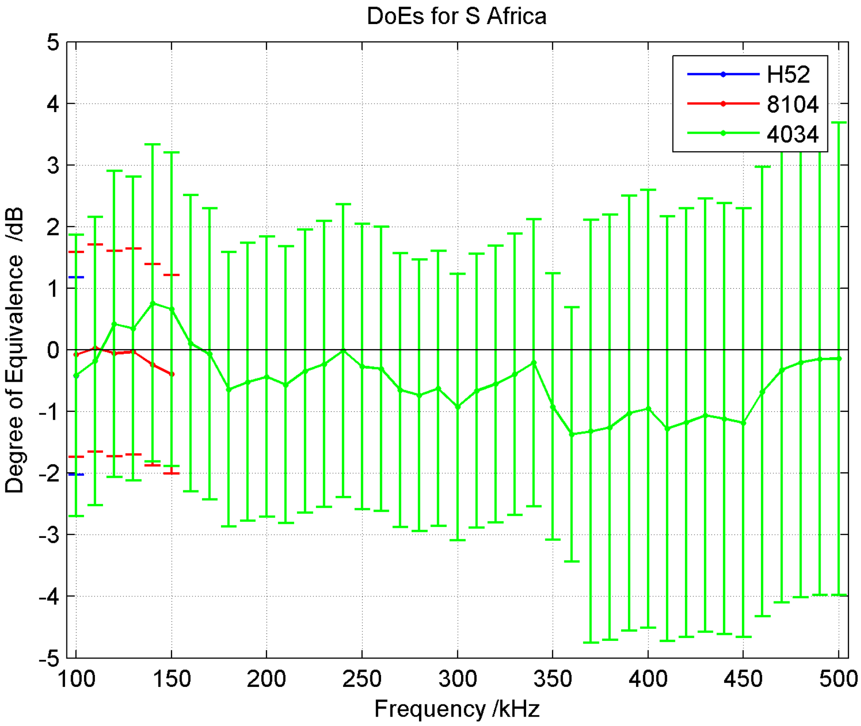

Figure E14. Degrees of equivalence for South Africa in the frequency range 100 kHz to 500 kHz. Error bars indicate expanded uncertainties for a coverage factor of *k*=2.

APPENDIX F: CALCULATING COMBINED DEGREES OF EQUIVALENCE

In order to obtain an appropriate methodology to enable the degrees of equivalence for separate hydrophones to be combined, it useful to consider first the situation where the calibrations are mutually independent. In this case, the calibrations have no common sources of uncertainty and the data is uncorrelated. This is not the situation that pertains with the data for this comparison, but this is a simpler situation to deal with, and this is described in Section F1.

In section F2, a method is proposed to combine the data for different devices which takes account of the correlation in the data due to the calibrations from a given laboratory sharing common type B uncertainties.

F1. Evaluating key comparison reference values and degrees of equivalence for mutually independent measurements

Suppose, for $i = 1, \ldots, N$, and $k = 1, \ldots, n$, that $x_{i,k}$ denotes the measurement made by laboratory i of device k at a given frequency, and $u_{i,k} = u(x_{i,k})$ is the standard uncertainty associated with $x_{i,k}$. Since there are seven participants in this key comparison, N is generally seven (although for a small number of very low frequencies only five or six laboratories provided measurement results) and, depending to the frequency, the number of devices calibrated, n, may be equal to 1, 2 or 3. Throughout, it is assumed that $x_{i,k}$, $i = 1, \ldots, N$, $k = 1, \ldots, n$, are the *available* measurements (so that the association of index i with “laboratory” and index k with “device” is understood).

In the analysis presented in this section, all the measurements are regarded as mutually independent, i.e.,

(i) there is no correlation between the measurements made by one laboratory with another, and
(ii) for each laboratory, there is no correlation between the measurements made by the laboratory of one device with those made by the same laboratory of a different device.

An analysis of the measurements to evaluate key comparison reference values and degrees of equivalence for which condition 2 above does not hold is presented in the Section F2.

A consequence of condition 2 above is that the measurements relating to the different devices may be treated independently. A consequence of condition 1 above is that the weighted mean y_k of the laboratories’ measurements corresponding to device k provides a candidate method for determining the key comparison reference value.

For $k = 1, \ldots, n$, y_k is evaluated from

$$y_k = \frac{\sum_{i=1}^{N} w_i x_{i,k}}{\sum_{i=1}^{N} w_i}, \qquad w_i = \frac{1}{u_{i,k}^2},$$

with associated uncertainty $u(y_k)$ determined from

$$\frac{1}{u^2(y_k)} = \sum_{i=1}^{N} \frac{1}{u_{i,k}^2}.$$

If a chi-squared test of the overall consistency of the data with the weighted mean model is passed, y_k may be accepted as the key comparison reference value and $u(y_k)$ as the standard uncertainty associated with the key comparison reference value.

Then, the degree of equivalence of laboratory i for device k is evaluated from

$$d_{i,k} = x_{i,k} - y_k,$$

with associated standard uncertainty $u(d_{i,k})$ determined from

$$u^2(d_{i,k}) = u^2(x_{i,k}) - u^2(y_k).$$

Also, the degree of equivalence between laboratory i and j for device k is evaluated from

$$d_{i,j,k} = x_{i,k} - x_{j,k},$$

with associated standard uncertainty $u(d_{i,j,k})$ evaluated from

$$u^2(d_{i,j,k}) = u^2(x_{i,k}) + u^2(x_{j,k}).$$

In this analysis a key comparison reference value, with an associated uncertainty, is evaluated using the weighted mean model for each device measured by the laboratories at a given frequency. Furthermore, a degree of equivalence for each laboratory, and for each pair of laboratories, with associated uncertainties, is evaluated separately for each device. Consideration is now given to how the evaluation of a *single* degree of equivalence for each laboratory, and for each pair of laboratories, with associated uncertainties, may be evaluated.

The approach is to determine an “average” value of the degrees of equivalence for each laboratory (and each pair of laboratories) expressed as a *proportion* of the respective key comparison values. Relative values are considered because the devices used in the comparison are (intended to be) different and, consequently, the sensitivities evaluated for the devices (key comparison reference values, degrees of equivalence, etc.) are not comparable in absolute terms. Furthermore, it is common in the field of acoustics to express differences between calibration values, and the uncertainties associated with the calibration values, in relative terms expressed either as percentages or in decibels (relative to a reference level.

Define, for $i = 1,\ldots, N$, and $j = 1, \ldots, n$, the relative degree of equivalence

$$r_{i,k} = \frac{d_{i,k}}{y_k},$$

with associated relative standard uncertainty

$$u(r_{i,k}) = \frac{u(d_{i,k})}{y_k}.$$

Then, the relative degree of equivalence r_i for laboratory i is evaluated as the weighted mean of the values $r_{i,k}$, i.e.,

$$r_i = \frac{\sum_{k=1}^{n} w_k r_{i,k}}{\sum_{k=1}^{n} w_k}, \qquad w_k = \frac{1}{u^2(r_{i,k})},$$

with associated uncertainty $u(r_i)$ determined from

$$\frac{1}{u^2(r_i)} = \sum_{k=1}^{n} \frac{1}{u^2(r_{i,k})}.$$

In the case of a single device ($n = 1$), there is only one relative degree of equivalence and the analysis gives $r_i = r_{i,1}$, the relative degree of equivalence for laboratory i for the (single) measured device.

Similar considerations apply for the evaluation of a relative degree of equivalence for a pair of laboratories.

F2. Evaluating key comparison reference values and degrees of equivalence for mutually dependent measurements

A generalisation of the analysis presented in the previous section is now considered to allow for mutual dependencies between the measurements made of the different devices by each laboratory. The aim is to undertake an analysis of the data to evaluate:

a) A key comparison reference value for each device with an associated standard uncertainty

b) A relative degree of equivalence for each laboratory with an associated standard uncertainty

c) A relative degree of equivalence for each pair of laboratories with an associated standard uncertainty.

We suppose a model for the *Nn* measurements in the form

$$x_{i,k} = y_k + \alpha_{i,k}, \quad i = 1,\ldots,N, \quad k = 1,\ldots,n,$$

where y_k is (an estimate of) the key comparison reference value for device *k*, and the $\alpha_{i,k}$ are samples from a multivariate Gaussian distribution with zero mean and covariance matrix *V* of order *Nn*. The matrix *V* has the variances (squares of the standard uncertainties) $u^2_{i,k} = u^2(x_{i,k})$ as its diagonal elements, and the covariances $u(x_{i,k}, x_{j,k})$ for $i \neq j$, and $u(x_{i,k}, x_{i,l})$ for $k \neq l$, as its off-diagonal elements.

We still assume the measurements made by laboratories *i* and *j* ($i \neq j$) are mutually independent (condition 1 of the previous section), and so $u(x_{i,k}, x_{j,k}) = 0$, $k = 1, \ldots, n$. To evaluate $u(x_{i,k}, x_{i.l})$, $k \neq l$, we write

$$\alpha_{i,k} = \lambda_i + \delta_{i,k},$$
$$\alpha_{i,l} = \lambda_i + \delta_{i,l},$$

where λ_i is a common (systematic) effect associated with the measurements $x_{i,k}$ and $x_{i,l}$, and $\delta_{i,k}$ and $\delta_{i,l}$ are (random) effects independent of each other and λ_i. The random and systematic effects are assumed to correspond to, respectively, the components of uncertainty provided by each laboratory for each measurement from a Type A and a Type B evaluation. For the analysis described below both components are assumed to be available. Then,

$$u(x_{i,k}, x_{i,l}) = u(\alpha_{i,k}, \alpha_{i,l}) = u^2(\lambda_i), \quad i = 1,\ldots,N.$$

For ease of presentation, suppose $n = 2$ devices have been measured. The generalisation to $n = 3$ devices is straightforward. Let

$$\mathbf{d}_i = \begin{pmatrix} x_{i,1} - y_1 \\ x_{i,2} - y_2 \end{pmatrix}, \qquad V_i = \begin{pmatrix} u^2(x_{i,1}) & u(x_{i,1}, x_{i,2}) \\ u(x_{i,1}, x_{i,2}) & u^2(x_{i,2}) \end{pmatrix}, \qquad i = 1, \ldots, N.$$

Then, estimates y_1 and y_2 are obtained by solving the least-squares problem

$$\min_{y_1, y_2} \quad \sum_{i=1}^{N} \mathbf{d}_i^{\mathrm{T}} V_i^{-1} \mathbf{d}_i.$$

Let

$$\mathbf{x} = \begin{pmatrix} x_{1,1} \\ x_{1,2} \\ \vdots \\ x_{N,1} \\ x_{N,2} \end{pmatrix}, \qquad A = \begin{pmatrix} 1 & 0 \\ 0 & 1 \\ \vdots & \vdots \\ 1 & 0 \\ 0 & 1 \end{pmatrix}, \qquad \mathbf{y} = \begin{pmatrix} y_1 \\ y_2 \end{pmatrix}, \qquad \mathbf{d} = \begin{pmatrix} \mathbf{d}_1 \\ \vdots \\ \mathbf{d}_N \end{pmatrix}, \qquad V = \begin{pmatrix} V_1 & & \\ & \ddots & \\ & & V_N \end{pmatrix}.$$

Then,

$$\sum_{i=1}^{N} \mathbf{d}_i^{\mathrm{T}} V_i^{-1} \mathbf{d}_i = \mathbf{d}^{\mathrm{T}} V^{-1} \mathbf{d} = (\mathbf{x} - A\mathbf{y})^{\mathrm{T}} V^{-1} (\mathbf{x} - A\mathbf{y}),$$

and, formally, the solution is given by

$$\mathbf{y} = \left(A^{\mathrm{T}} V^{-1} A\right)^{-1} A^{\mathrm{T}} V^{-1} \mathbf{x}, \tag{F1}$$

with associated uncertainty matrix

$$V_{\mathbf{y}} = \left(A^{\mathrm{T}} V^{-1} A\right)^{-1}.$$

The vector **y** contains the key comparison reference values y_1 and y_2 for the two devices. The diagonal elements of the associated uncertainty matrix $V_{\mathbf{y}}$ contain the variances associated with these values, and the off-diagonal element their covariance. The values correspond to those obtained in the previous section, but their evaluation accounts for the mutual dependencies between the measurements made by the same laboratory on the two devices. In the case that $x_{i,1}$ and $x_{i,2}$ are mutually independent, V_i will be a diagonal matrix, and the least-squares problem for y_1 and y_2 reduces to

$$\min_{y_1, y_2} \quad \sum_{i=1}^{N} \frac{(x_{i,1} - y_1)^2}{u_{i,1}^2} + \sum_{i=1}^{N} \frac{(x_{i,2} - y_2)^2}{u_{i,2}^2},$$

with y_1 and y_2 given by the (usual) “weighted means” of the data. It should be noted that equation (F1) is a *generic* statement of the solution to a least-squares problem with design matrix A and vector of observations **x** with associated uncertainty matrix V.

The uncertainty matrix $V_{\mathbf{d}}$ associated with **d** evaluated at the solution is, after a few lines of algebra,

$$V_{\mathbf{d}} = V - A\left(A^{\mathrm{T}} V^{-1} A\right)^{-1} A^{\mathrm{T}}.$$

Now, $\mathbf{d}_i$ contains the degrees of equivalence $d_{i,1}$ and $d_{i,2}$ for laboratory i for the two devices. The estimates correspond to those obtained in the previous section, but their evaluation also accounts for the mutual dependencies between the measurements made by each laboratory of the different devices. The sub-matrix $V_{\mathbf{d},i}$ of $V_{\mathbf{d}}$ relating to $\mathbf{d}_i$ contains the variances and covariance associated with the degrees of equivalence $d_{i,1}$ and $d_{i,2}$ evaluated in this way.

To determine a *single* degree of equivalence for laboratory i we proceed as in the previous section but accounting for the mutual dependence between $d_{i,1}$ and $d_{i,2}$. Define

$$r_{i,1} = \frac{d_{i,1}}{y_1}, \quad r_{i,2} = \frac{d_{i,2}}{y_2},$$

with associated uncertainty matrix

$$V_{\mathbf{r},i} = \begin{pmatrix} u^2(d_{i,1})/y_1^2 & u(d_{i,1}, d_{i,2})/y_1 y_2 \\ u(d_{i,1}, d_{i,2})/y_1 y_2 & u^2(d_{i,2})/y_2^2 \end{pmatrix}.$$

Then, the relative degree of equivalence r_i for laboratory i is obtained by solving the least-squares problem

$$\min_{r_i} \quad (\mathbf{r}_i - A r_i)^{\mathrm{T}} V_{\mathbf{r},i}^{-1} (\mathbf{r}_i - A r_i), \quad A = \begin{pmatrix} 1 \\ 1 \end{pmatrix}.$$

Similar considerations apply for the evaluation of a relative degree of equivalence for a pair of laboratories.

APPENDIX G: COMBINED DEGREES OF EQUIVALENCE

Table G1. Combined Degree of Equivalence calculated for each participant and the expanded uncertainty on the Degree of Equivalence expressed for a coverage factor of *k*=2.

	UK		DE		US		RU		CN		CA		ZA	
F	M	2u	M	2u	M	2u	M	2u	M	2u	M	2u	M	2u
kHz	dB		dB		dB		dB		dB		dB		dB	
1.0	0.25	0.64	-0.68	0.74	0.04	0.34	0.10	0.32	-0.08	0.40				
1.5	-0.11	0.52	-0.78	0.74	0.06	0.34	0.08	0.32	0.12	0.41				
2.0	0.07	0.47	-0.40	0.77	-0.32	0.33	0.25	0.33	0.10	0.42	0.16	0.61		
2.5	-0.07	0.41	-0.55	0.76	-0.01	0.35	0.04	0.33	0.15	0.42	0.09	0.61		
3.0	-0.04	0.40	-0.64	0.75	-0.02	0.30	-0.01	0.33	0.36	0.44	-0.10	0.60	0.16	1.36
3.5	0.00	0.40	-0.77	0.74	0.13	0.31	0.02	0.33	0.13	0.42	-0.20	0.59	0.03	1.34
4.0	-0.12	0.40	-0.67	0.75	0.11	0.31	0.11	0.33	0.03	0.42	-0.08	0.60	0.13	1.36
4.5	0.01	0.37	-0.82	0.74	0.06	0.31	0.10	0.33	0.08	0.42	-0.11	0.59	-0.02	1.33
5.0	-0.09	0.37	-0.78	0.74	0.18	0.32	0.01	0.33	0.12	0.42	-0.12	0.59	-0.08	1.33
6.0	-0.17	0.36	-0.65	0.75	0.01	0.31	0.05	0.33	0.35	0.44	0.08	0.61	-0.25	1.30
7.0	-0.11	0.37	-0.71	0.75	0.32	0.32	0.16	0.34	-0.31	0.40	-0.03	0.60	-0.21	1.31
8.0	-0.13	0.37	-0.55	0.76	0.03	0.31	0.11	0.33	0.25	0.43	-0.15	0.59	-0.25	1.30
9.0	-0.33	0.36	-0.39	0.78	0.27	0.32	0.03	0.33	0.21	0.43	-0.16	0.59	-0.39	1.28
10.0	-0.13	0.36	-0.03	0.71	0.20	0.32	-0.01	0.28	-0.17	0.36	0.26	0.60	-0.07	0.94
12.0	-0.24	0.36	-0.37	0.78	0.26	0.32	0.13	0.34	-0.07	0.41	-0.18	0.59	-0.27	1.30
12.5	0.22	0.38	0.11	0.82	-0.31	0.40	-0.21	0.31	0.21	0.43	0.36	0.61	-0.09	0.95
14.0	-0.25	0.36	-0.17	0.80	0.27	0.32	0.14	0.34	-0.17	0.41	-0.09	0.60	-0.27	1.30
15.0	0.04	0.37	0.11	0.82	-0.59	0.38	-0.09	0.32	0.71	0.45	0.24	0.60	-0.19	0.94
16.0	-0.13	0.37	-0.19	0.80	0.07	0.31	0.37	0.35	-0.39	0.40	0.06	0.61	-0.29	1.30
17.5	0.06	0.37	0.26	0.84	-0.53	0.38	-0.04	0.32	0.46	0.44	0.07	0.59	0.16	0.97
18.0	-0.11	0.37	-0.47	0.77	0.15	0.31	0.13	0.34	-0.07	0.41	-0.09	0.60	-0.37	1.29
20.0	-0.17	0.35	0.02	0.71	0.01	0.31	0.04	0.29	0.18	0.38	-0.14	0.57	-0.06	0.94
22.0	-0.27	0.36	-0.55	0.76	0.08	0.31	0.17	0.34	0.25	0.43	-0.11	0.60	-0.35	1.29
22.5	-0.14	0.36	0.24	0.83	0.21	0.43	-0.17	0.32	0.34	0.43	-0.19	0.57	-0.16	0.94
24.0	-0.38	0.35	-0.39	0.78	0.25	0.32	0.11	0.33	0.11	0.42	-0.07	0.60	-0.29	1.30
25.0	-0.20	0.40	0.05	0.82	0.16	0.38	-0.02	0.32	0.05	0.42	0.02	0.58	-0.15	0.94
26.0	-0.20	0.36	-0.29	0.79	0.09	0.31	0.16	0.34	0.01	0.42	-0.08	0.60	0.01	1.34
27.5	0.06	0.37	-0.42	0.77	0.11	0.38	-0.12	0.32	0.08	0.42	0.13	0.59	-0.22	0.93
28.0	-0.16	0.37	-0.59	0.76	0.15	0.31	0.26	0.34	-0.19	0.41	-0.05	0.60	0.01	1.34
30.0	-0.16	0.36	-0.47	0.67	0.29	0.32	-0.01	0.28	-0.04	0.37	0.04	0.58	-0.07	0.94
32.5	0.33	0.59	-0.52	0.76	-0.10	0.36	0.03	0.32	-0.12	0.40	0.32	0.60	0.08	0.96
35.0	-0.06	0.37	-0.61	0.66	0.13	0.32	0.13	0.29	-0.10	0.36	0.08	0.58	-0.12	0.93
37.5	0.30	0.39	-0.70	0.75	-0.31	0.36	0.12	0.33	0.00	0.41	0.24	0.60	-0.10	0.95
40.0	-0.01	0.36	-0.68	0.66	0.27	0.32	0.08	0.29	-0.15	0.36	-0.05	0.57	-0.21	0.92
42.5	-0.28	0.53	-0.46	0.77	0.33	0.38	0.09	0.33	-0.16	0.40	-0.05	0.57	-0.06	0.95
45.0	-0.10	0.35	-0.19	0.69	-0.07	0.31	0.23	0.30	-0.09	0.36	0.00	0.57	0.06	0.95
47.5	0.09	0.38	-0.05	0.81	-0.31	0.35	0.08	0.33	0.15	0.42	0.10	0.59	-0.05	1.70
50.0	-0.12	0.35	-0.24	0.69	-0.01	0.31	0.21	0.29	-0.04	0.37	0.00	0.58	-0.37	1.27
52.5	0.18	0.38	-0.33	0.78	-0.23	0.36	0.00	0.33	0.07	0.42	0.22	0.60	-0.23	1.67

	UK		DE		US		RU		CN		CA		ZA	
F	M	2u	M	2u	M	2u	M	2u	M	2u	M	2u	M	2u
kHz	dB		dB		dB		dB		dB		dB		dB	
55.0	-0.13	0.37	-0.36	0.68	0.24	0.32	0.11	0.29	-0.26	0.35	0.08	0.58	-0.28	1.28
57.5	0.06	0.39	-0.32	0.78	0.35	0.39	-0.17	0.32	-0.12	0.41	0.01	0.58	-0.12	1.69
60.0	-0.01	0.35	-0.20	0.69	0.07	0.31	0.21	0.29	-0.32	0.35	0.11	0.58	-0.04	1.31
62.5	0.24	0.38	-0.32	0.78	-0.57	0.34	0.43	0.35	-0.02	0.41	0.01	0.58	0.08	1.72
65.0	-0.13	0.36	-0.38	0.68	0.17	0.32	0.25	0.30	-0.29	0.35	0.04	0.58	-0.07	1.31
67.5	-0.03	0.37	-0.65	0.75	0.00	0.37	0.35	0.34	-0.25	0.40	0.04	0.58	-0.25	1.66
70.0	-0.09	0.36	-0.47	0.67	0.29	0.32	0.16	0.29	-0.32	0.35	0.08	0.58	-0.03	1.31
72.5	0.04	0.37	-0.51	0.77	-0.18	0.36	0.19	0.33	-0.01	0.41	0.15	0.59	-0.01	1.70
75.0	-0.05	0.36	-0.29	0.69	0.13	0.32	0.17	0.29	-0.33	0.35	0.24	0.59	0.03	1.32
77.5	0.19	0.38	-0.45	0.77	-0.34	0.35	0.17	0.33	0.05	0.42	0.11	0.59	-0.15	1.68
80.0	0.15	0.38	-0.47	0.77	-0.18	0.36	0.14	0.33	-0.07	0.41	0.13	0.59	-0.17	1.68
85.0	0.17	0.38	-0.60	0.76	-0.11	0.36	0.01	0.33	0.10	0.42	0.08	0.59	-0.20	1.67
90.0	0.13	0.38	-0.54	0.76	-0.23	0.36	0.16	0.33	0.06	0.42	0.07	0.59	-0.24	1.66
95.0	0.20	0.38	-0.49	0.77	-0.16	0.36	0.11	0.33	-0.09	0.41	0.09	0.59	-0.09	1.69
100	-0.08	0.35	-0.19	0.69	-0.20	0.36	0.15	0.28	0.00	0.40	0.06	0.59	-0.10	1.67
110	0.00	0.36	-0.11	0.70	-0.30	0.36	0.13	0.28	-0.02	0.40	0.12	0.59	0.03	1.70
120	0.05	0.36	-0.24	0.69	-0.22	0.36	0.19	0.29	-0.13	0.39	0.03	0.58	0.01	1.69
130	0.00	0.36	-0.17	0.69	-0.16	0.36	0.20	0.29	-0.23	0.39	0.13	0.59	0.06	1.70
140	0.03	0.36	-0.28	0.69	-0.21	0.36	0.22	0.29	-0.19	0.39	0.12	0.59	-0.14	1.67
150	-0.10	0.35	-0.25	0.69	0.07	0.38	0.23	0.29	-0.40	0.38	0.24	0.60	-0.33	1.64
160	0.10	0.34	-0.40	0.76	0.15	0.48	-0.16	0.53	-0.10	0.64	0.17	1.02	0.10	2.45
170	-0.04	0.34	-0.97	0.71	0.14	0.48	0.23	0.56	0.23	0.66	0.27	1.04	-0.07	2.41
180	0.10	0.34	-1.24	0.69	0.14	0.48	0.26	0.56	0.16	0.66	0.18	1.02	-0.64	2.27
190	-0.01	0.34	-0.92	0.71	0.18	0.49	0.28	0.56	0.08	0.65	0.08	1.01	-0.52	2.30
200	0.15	0.35	-0.73	0.73	0.13	0.48	-0.03	0.54	-0.03	0.64	0.14	1.02	-0.43	2.32
210	-0.08	0.35	-0.57	0.74	0.25	0.64	0.13	0.54	0.13	0.65	0.24	1.03	-0.57	2.28
220	0.10	0.34	0.05	0.80	-0.02	0.62	0.03	0.54	-0.45	0.60	0.44	1.05	-0.35	2.34
230	-0.09	0.34	-0.03	0.79	0.24	0.64	0.37	0.56	-0.63	0.59	0.67	1.08	-0.23	2.37
240	-0.18	0.35	-0.11	0.78	0.34	0.64	0.59	0.58	-0.41	0.60	-0.20	0.98	-0.01	2.42
250	-0.22	0.34	0.03	0.80	0.06	0.62	0.13	0.54	0.13	0.65	0.57	1.07	-0.27	2.35
260	-0.06	0.35	0.10	0.80	-0.02	0.61	0.20	0.55	-0.10	0.63	-0.02	1.00	-0.30	2.35
270	-0.31	0.40	-0.05	0.79	-0.12	0.60	0.55	0.57	0.15	0.65	0.09	1.01	-0.65	2.26
280	-0.14	0.35	0.16	0.81	0.04	0.62	0.26	0.55	0.06	0.64	-0.33	0.96	-0.74	2.25
290	-0.10	0.35	0.27	0.82	0.16	0.63	0.37	0.56	-0.13	0.63	-0.80	0.91	-0.63	2.27
300	-0.05	0.41	0.17	0.81	0.12	0.71	0.47	0.56	-0.03	0.63	-1.16	0.87	-0.93	2.20
310	-0.35	0.39	0.53	0.84	-0.11	0.68	0.63	0.57	0.03	0.63	-0.58	0.93	-0.67	2.26
320	-0.41	0.39	0.25	0.81	0.12	0.73	0.55	0.57	-0.05	0.63	0.03	1.00	-0.55	2.29
330	-0.30	0.39	0.70	0.86	-0.39	0.68	0.40	0.55	0.00	0.63	0.11	1.01	-0.40	2.32
340	-0.07	0.41	0.69	0.86	0.12	0.70	-0.21	0.51	-0.01	0.63	-0.12	0.98	-0.21	2.37
350	0.08	0.42	0.48	0.84	-0.02	0.69	-0.02	0.52	-0.32	0.61	0.02	1.00	-0.92	2.20
360	0.18	0.43	0.33	0.82	0.15	0.71	-0.07	0.52	-0.37	0.60	-0.15	0.98	-1.37	2.10
370	0.14	0.42	0.08	0.80	0.24	0.72	-0.12	0.51	-0.32	0.61	0.04	1.00	-1.32	3.49
380	0.29	0.44	-0.06	0.78	-0.03	0.69	-0.36	0.50	-0.06	0.63	0.33	1.04	-1.26	3.51
390	-0.13	0.41	-0.12	0.78	0.17	0.71	-0.02	0.52	-0.02	0.63	0.77	1.09	-1.02	3.59

	UK		DE		US		RU		CN		CA		ZA	
F	M	2u	M	2u	M	2u	M	2u	M	2u	M	2u	M	2u
kHz	dB		dB		dB		dB		dB		dB		dB	
400	-0.19	0.40	0.05	0.79	-0.05	0.69	0.15	0.53	-0.25	0.61	1.45	1.18	-0.95	3.61
410	-0.01	0.41	0.12	0.80	0.17	0.71	-0.28	0.50	-0.18	0.62	1.16	1.14	-1.28	3.50
420	0.11	0.42	-0.38	0.75	0.44	0.73	-0.08	0.52	-0.38	0.60	0.71	1.08	-1.18	3.53
430	-0.28	0.40	-0.96	0.70	0.73	0.76	0.24	0.54	0.24	0.65	0.72	1.08	-1.06	3.57
440	0.38	0.44	-1.32	0.67	0.34	0.72	0.08	0.53	0.08	0.64	-0.07	0.99	-1.12	3.56
450	0.39	0.44	-1.08	0.69	0.44	0.73	0.02	0.52	0.12	0.64	-0.62	0.93	-1.18	3.53
460	0.35	0.44	-0.98	0.70	0.60	0.75	-0.06	0.52	0.42	0.67	-1.17	0.87	-0.68	3.71
470	0.57	0.45	-0.43	0.75	0.62	0.75	-0.18	0.51	-0.23	0.61	-1.28	0.86	-0.33	3.83
480	0.21	0.43	-0.20	0.77	0.31	0.72	0.22	0.54	-0.40	0.60	-0.73	0.91	-0.20	3.87
490	0.21	0.43	-0.04	0.78	0.06	0.70	-0.26	0.50	-0.04	0.63	0.05	1.00	-0.14	3.90
500	0.37	0.44	0.36	0.82	0.16	0.71	-0.72	0.47	0.36	0.66	-0.52	0.94	-0.14	3.90

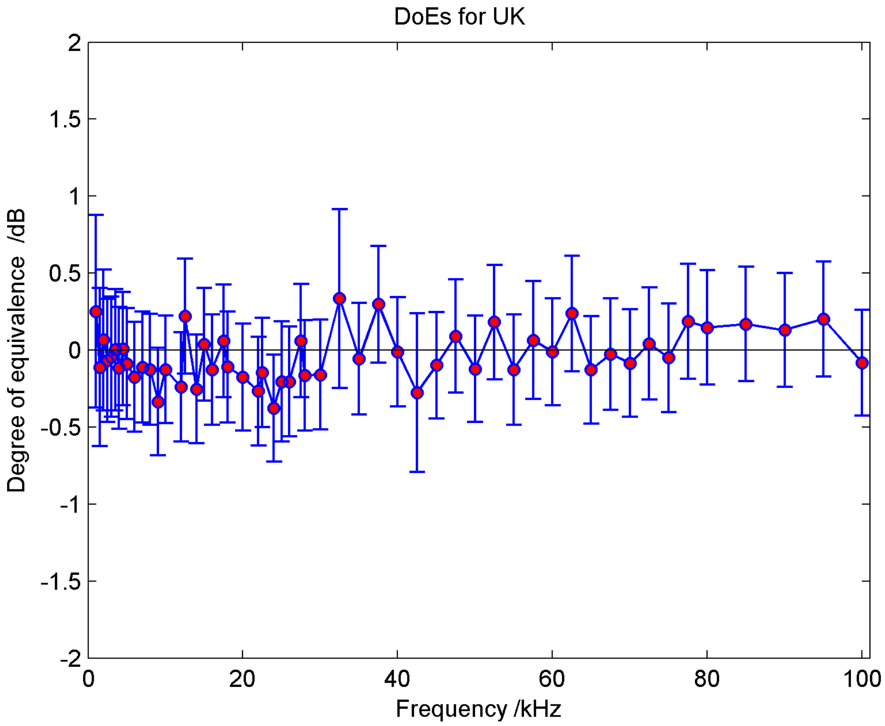

Figure G1. Combined Degrees of Equivalence for the UK in the frequency range 1 kHz to 100 kHz. Error bars indicate expanded uncertainties for a coverage factor of *k*=2.

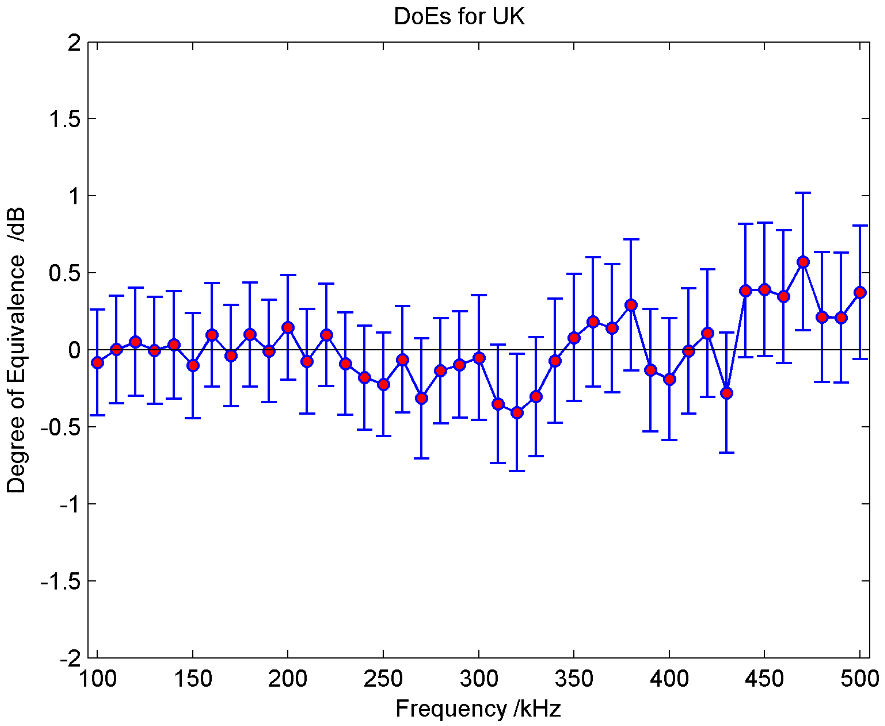

Figure G2. Combined Degrees of Equivalence for the UK in the frequency range 100 kHz to 500 kHz. Error bars indicate expanded uncertainties for a coverage factor of *k*=2.

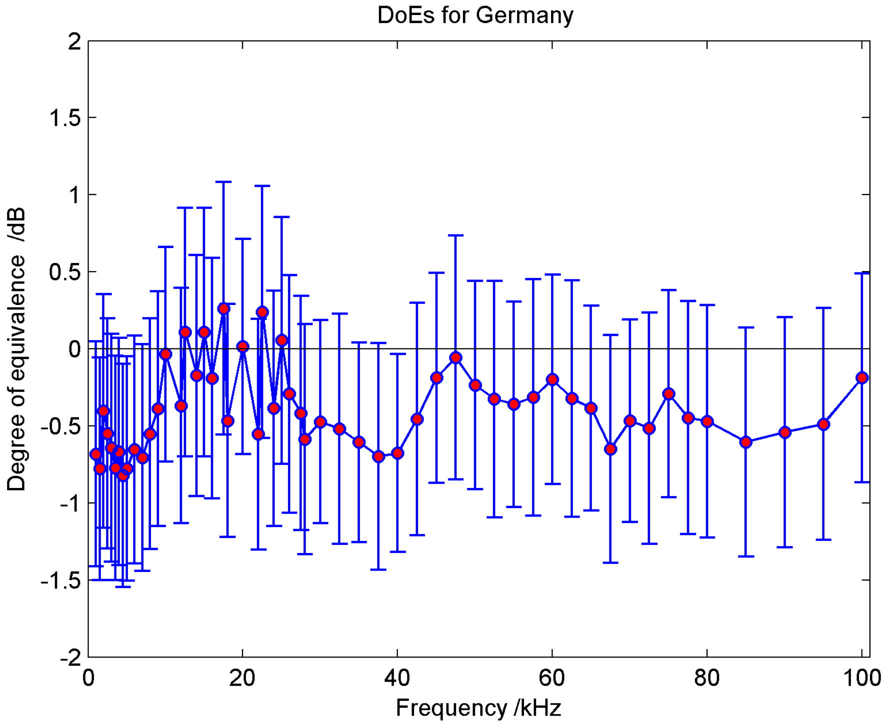

Figure G3. Combined Degrees of Equivalence for Germany in the frequency range 1 kHz to 100 kHz. Error bars indicate expanded uncertainties for a coverage factor of *k*=2.

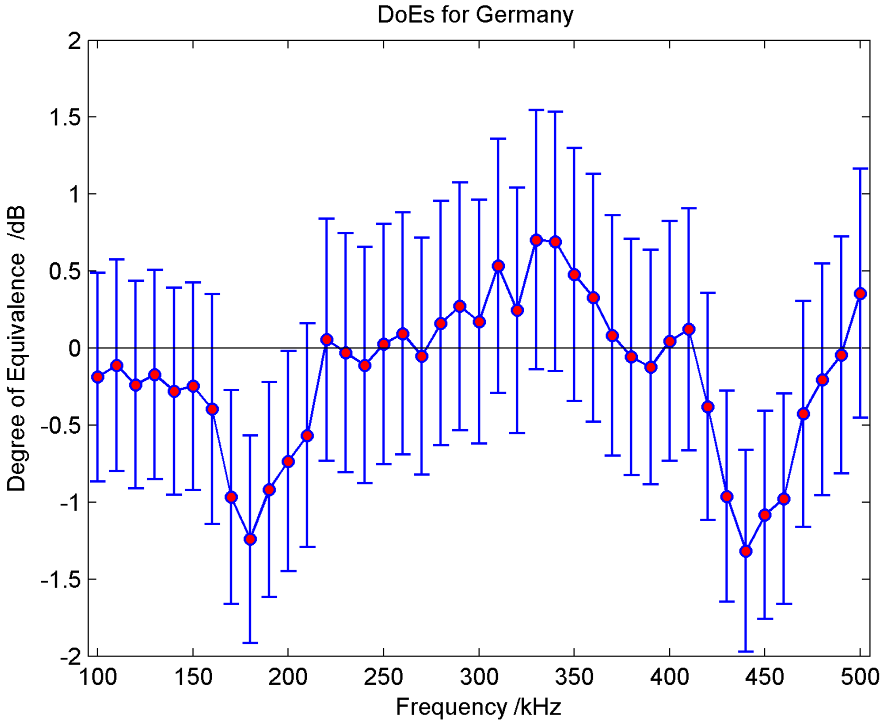

Figure G4. Combined Degrees of Equivalence for Germany in the frequency range 100 kHz to 500 kHz. Error bars indicate expanded uncertainties for a coverage factor of *k*=2.

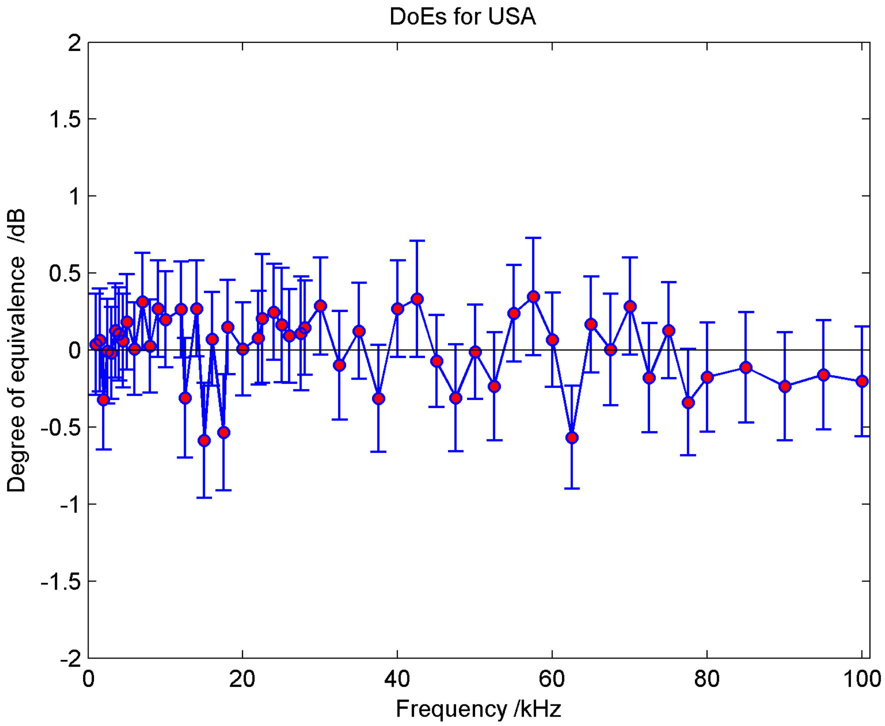

Figure G5. Combined Degrees of Equivalence for the USA in the frequency range 1 kHz to 100 kHz. Error bars indicate expanded uncertainties for a coverage factor of *k*=2.

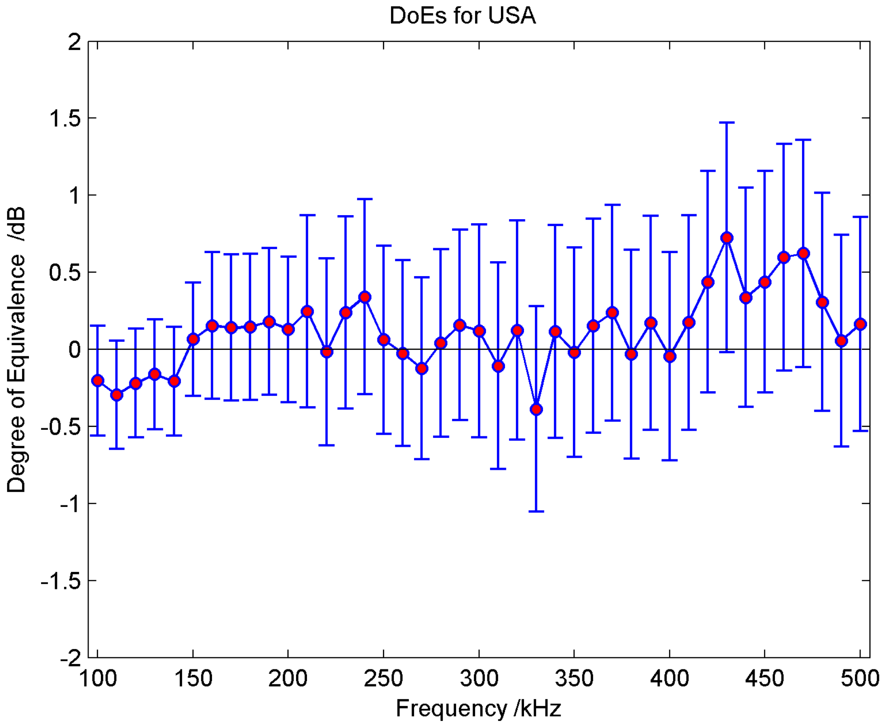

Figure G6. Combined Degrees of Equivalence for the USA in the frequency range 100 kHz to 500 kHz. Error bars indicate expanded uncertainties for a coverage factor of *k*=2.

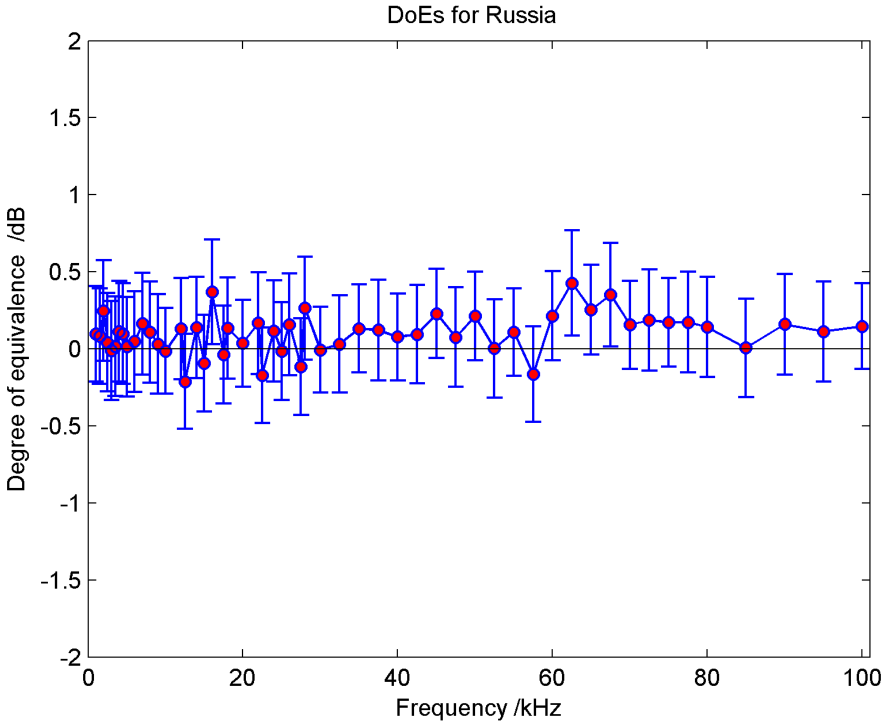

Figure G7. Combined Degrees of Equivalence for Russia in the frequency range 1 kHz to 100 kHz. Error bars indicate expanded uncertainties for a coverage factor of *k*=2.

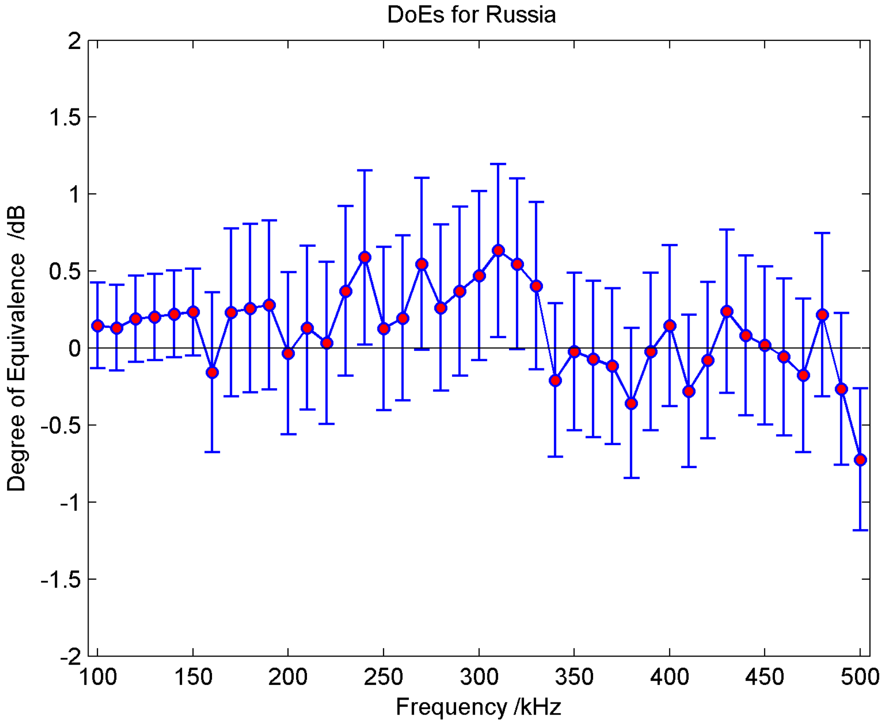

Figure G8. Combined Degrees of Equivalence for Russia in the frequency range 100 kHz to 500 kHz. Error bars indicate expanded uncertainties for a coverage factor of *k*=2.

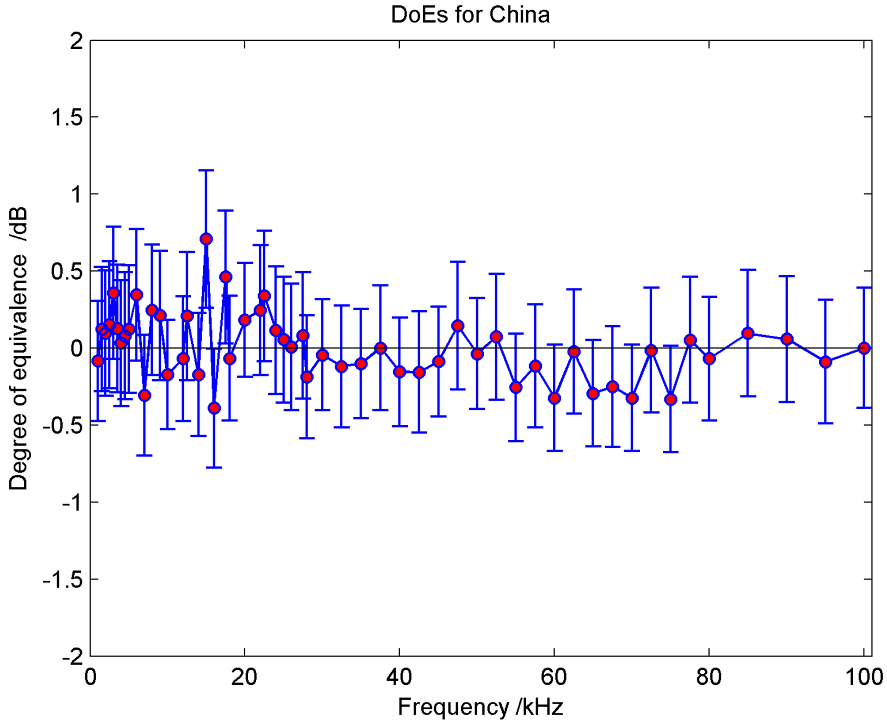

Figure G9. Combined Degrees of Equivalence for China in the frequency range 1 kHz to 100 kHz. Error bars indicate expanded uncertainties for a coverage factor of *k*=2.

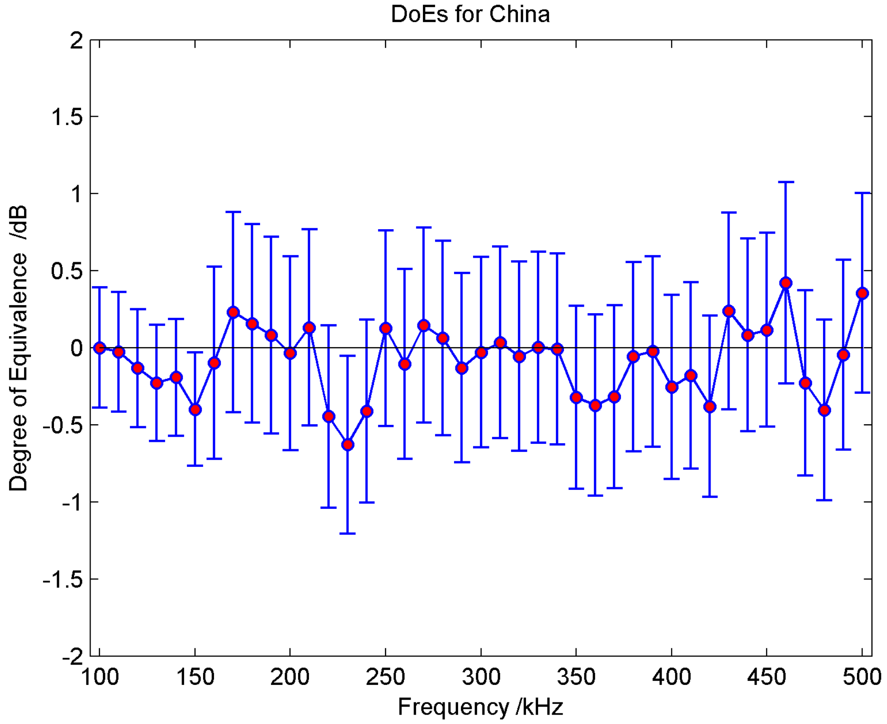

Figure G10. Combined Degrees of Equivalence for China in the frequency range 100 kHz to 500 kHz. Error bars indicate expanded uncertainties for a coverage factor of *k*=2.

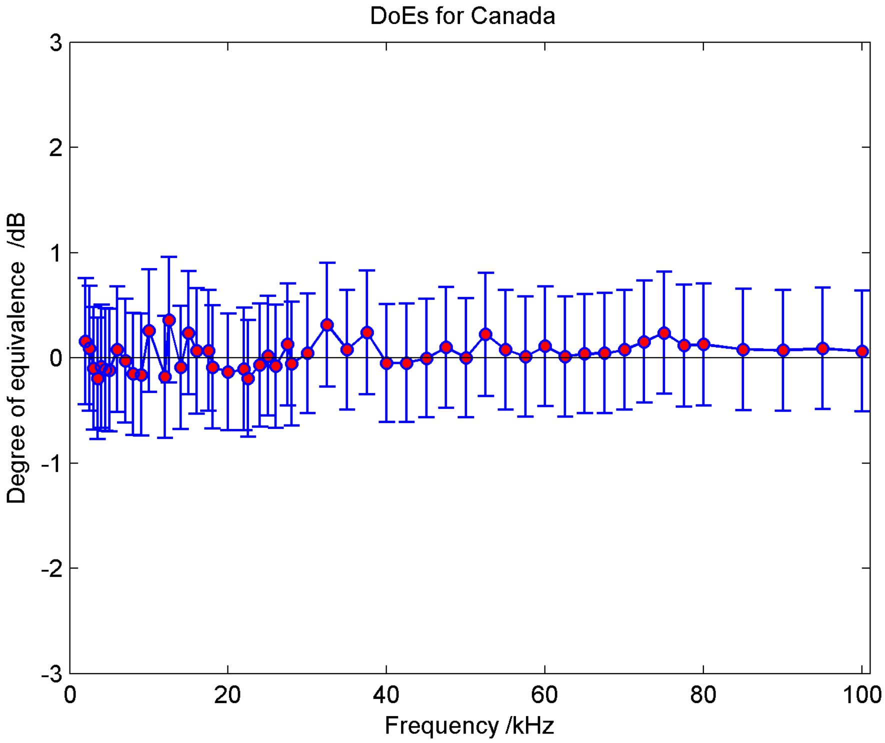

Figure G11. Combined Degrees of Equivalence for Canada in the frequency range 1 kHz to 100 kHz. Error bars indicate expanded uncertainties for a coverage factor of *k*=2.

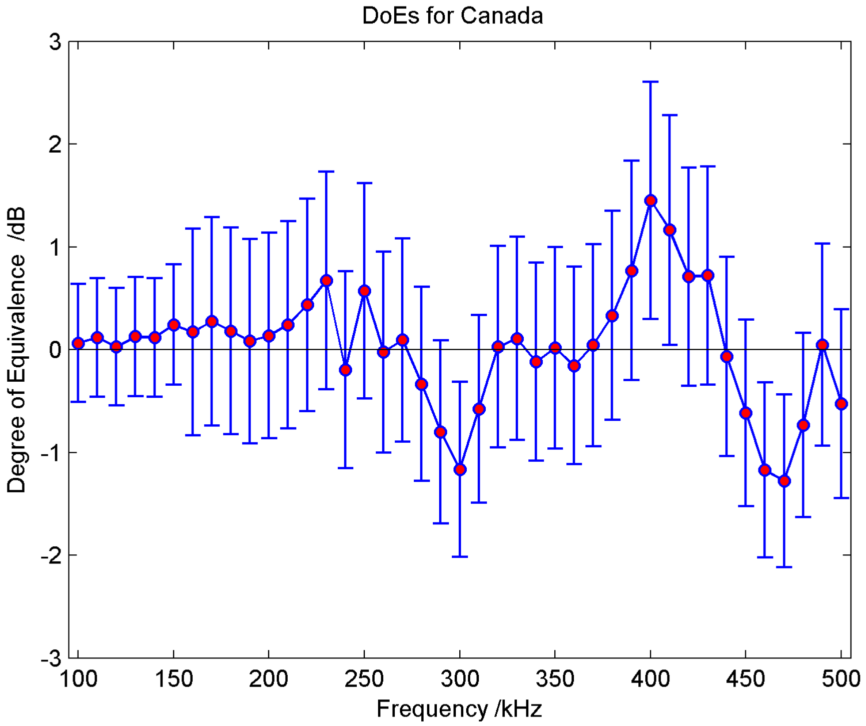

Figure G12. Combined Degrees of Equivalence for Canada in the frequency range 100 kHz to 500 kHz. Error bars indicate expanded uncertainties for a coverage factor of *k*=2.

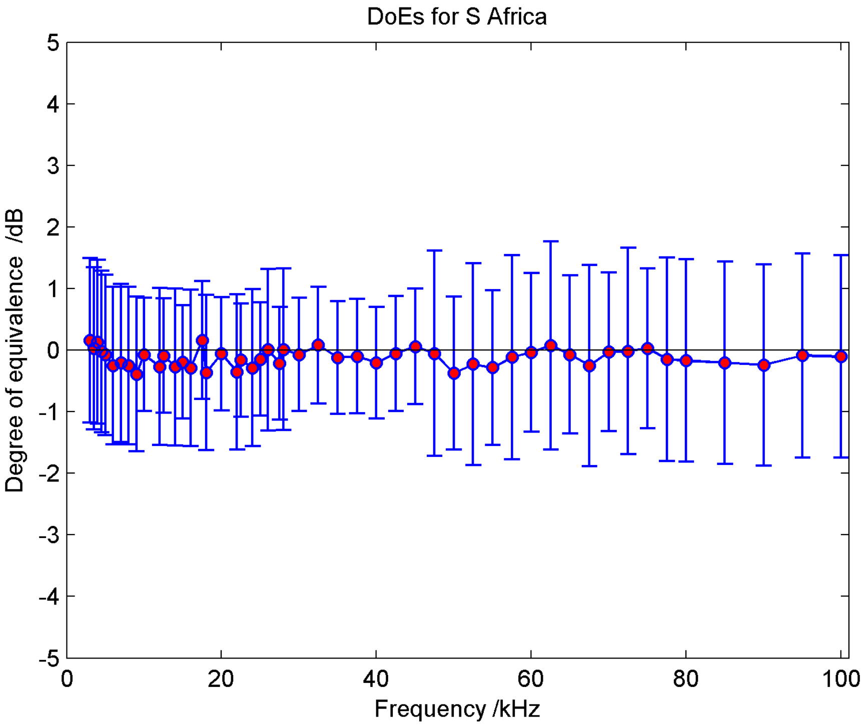

Figure G13. Combined Degrees of Equivalence for South Africa in the frequency range 1 kHz to 100 kHz. Error bars indicate expanded uncertainties for a coverage factor of *k*=2.

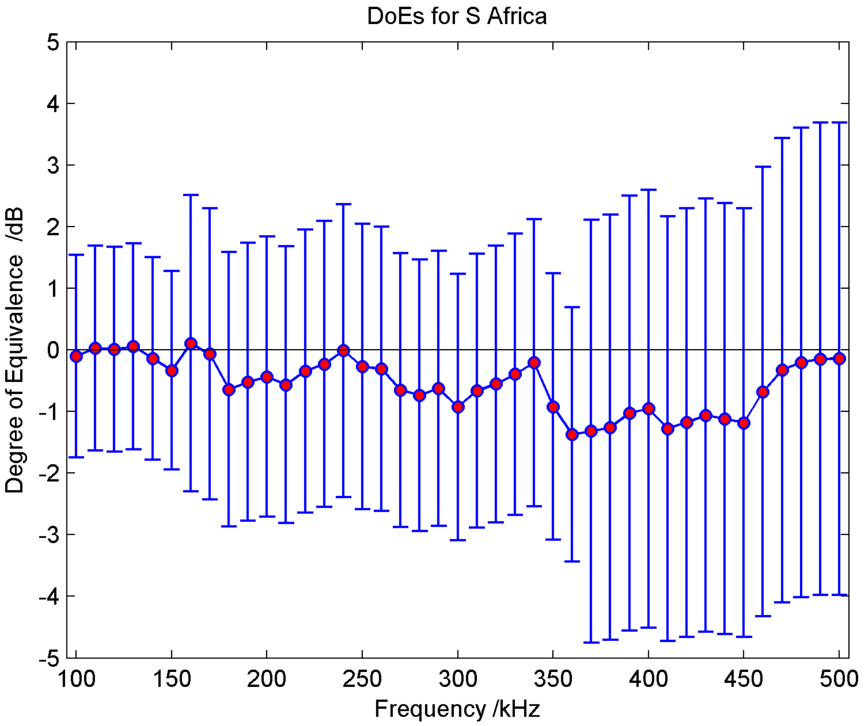

Figure G14. Combined Degrees of Equivalence for South Africa in the frequency range 100 kHz to 500 kHz. Error bars indicate expanded uncertainties for a coverage factor of *k*=2.

APPENDIX H: BILATERAL DEGREES OF EQUIVALENCE

Table H1. Bilateral Degrees of Equivalence for a frequency of 1 kHz, with values stated in percent and expanded uncertainties expressed for a coverage factor of *k*=2.

(%)	UK		DE		US		RU		CN		CA		ZA	
	Di	2ui	Di	2ui	Di	2ui	Di	2ui	Di	2ui	Di	2ui	Di	2ui
UK			-10.50	12.28	-2.51	9.30	-1.81	9.19	-3.89	9.63				
DE	10.50	12.28			7.99	10.40	8.69	10.31	6.61	10.71				
US	2.51	9.30	-7.99	10.40			0.70	6.47	-1.38	7.08				
RU	1.81	9.19	-8.69	10.31	-0.70	6.47			-2.07	6.95				
CN	3.89	9.63	-6.61	10.71	1.38	7.08	2.07	6.95						
CA														
ZA														

Table H2. Bilateral Degrees of Equivalence for a frequency of 2 kHz, with values stated in percent and expanded uncertainties expressed for a coverage factor of *k*=2.

(%)	UK		DE		US		RU		CN		CA		ZA	
	Di	2ui	Di	2ui	Di	2ui	Di	2ui	Di	2ui	Di	2ui	Di	2ui
UK			-5.29	11.31	-4.41	7.48	2.13	7.51	0.37	8.07	1.04	9.70		
DE	5.29	11.31			0.88	10.60	7.42	10.62	5.66	11.03	6.33	12.27		
US	4.41	7.48	-0.88	10.60			6.54	6.39	4.77	7.04	5.45	8.86		
RU	-2.13	7.51	-7.42	10.62	-6.54	6.39			-1.76	7.08	-1.08	8.89		
CN	-0.37	8.07	-5.66	11.03	-4.77	7.04	1.76	7.08			0.68	9.37		
CA	-1.04	9.70	-6.33	12.27	-5.45	8.86	1.08	8.89	-0.68	9.37				
ZA														

Table H3. Bilateral Degrees of Equivalence for a frequency of 3 kHz, with values stated in percent and expanded uncertainties expressed for a coverage factor of *k*=2.

(%)	UK		DE		US		RU		CN		CA		ZA	
	Di	2ui	Di	2ui	Di	2ui	Di	2ui	Di	2ui	Di	2ui	Di	2ui
UK			-6.62	10.67	0.28	6.64	0.36	6.79	4.71	7.61	-0.67	9.03	2.34	17.86
DE	6.62	10.67			6.90	10.23	6.99	10.33	11.33	10.88	5.96	11.93	8.96	19.48
US	-0.28	6.64	-6.90	10.23			0.09	6.08	4.43	6.98	-0.94	8.51	2.06	17.60
RU	-0.36	6.79	-6.99	10.33	-0.09	6.08			4.35	7.13	-1.03	8.63	1.97	17.66
CN	-4.71	7.61	-11.33	10.88	-4.43	6.98	-4.35	7.13			-5.38	9.29	-2.37	17.99
CA	0.67	9.03	-5.96	11.93	0.94	8.51	1.03	8.63	5.38	9.29			3.00	18.63
ZA	-2.34	17.86	-8.96	19.48	-2.06	17.60	-1.97	17.66	2.37	17.99	-3.00	18.63		

Table H4. Bilateral Degrees of Equivalence for a frequency of 5 kHz, with values stated in percent and expanded uncertainties expressed for a coverage factor of *k*=2.

(%)	UK		DE		US		RU		CN		CA		ZA	
	Di	2ui	Di	2ui	Di	2ui	Di	2ui	Di	2ui	Di	2ui	Di	2ui
UK			-7.55	10.39	3.13	6.46	1.16	6.56	2.44	7.29	-0.34	8.85	0.13	17.33
DE	7.55	10.39			10.67	10.14	8.71	10.21	9.98	10.68	7.21	11.80	7.67	19.01
US	-3.13	6.46	-10.67	10.14			-1.97	6.16	-0.69	6.92	-3.47	8.55	-3.00	17.18
RU	-1.16	6.56	-8.71	10.21	1.97	6.16			1.28	7.02	-1.50	8.63	-1.03	17.22
CN	-2.44	7.29	-9.98	10.68	0.69	6.92	-1.28	7.02			-2.78	9.19	-2.31	17.51
CA	0.34	8.85	-7.21	11.80	3.47	8.55	1.50	8.63	2.78	9.19			0.47	18.21
ZA	-0.13	17.33	-7.67	19.01	3.00	17.18	1.03	17.22	2.31	17.51	-0.47	18.21		

Table H5. Bilateral Degrees of Equivalence for a frequency of 10 kHz, with values stated in percent and expanded uncertainties expressed for a coverage factor of *k*=2.

(%)	UK		DE		US		RU		CN		CA		ZA	
	Di	2ui	Di	2ui	Di	2ui	Di	2ui	Di	2ui	Di	2ui	Di	2ui
UK			1.00	9.89	3.49	6.32	1.09	6.05	-0.55	6.61	4.24	8.71	-0.82	12.55
DE	-1.00	9.89			1.69	9.76	0.38	9.57	-0.67	9.95	3.16	11.43	-3.68	14.95
US	-3.49	6.32	-1.69	9.76			-0.71	5.85	-1.41	6.46	1.05	8.55	0.02	12.59
RU	-1.09	6.05	-0.38	9.57	0.71	5.85			-1.43	6.09	3.24	8.33	-0.03	12.30
CN	0.55	6.61	0.67	9.95	1.41	6.46	1.43	6.09			4.84	8.75	2.53	12.57
CA	-4.24	8.71	-3.16	11.43	-1.05	8.55	-3.24	8.33	-4.84	8.75			-5.68	13.82
ZA	0.82	12.55	3.68	14.95	-0.02	12.59	0.03	12.30	-2.53	12.57	5.68	13.82		

Table H6. Bilateral Degrees of Equivalence for a frequency of 20 kHz, with values stated in percent and expanded uncertainties expressed for a coverage factor of *k*=2.

(%)	UK		DE		US		RU		CN		CA		ZA	
	Di	2ui	Di	2ui	Di	2ui	Di	2ui	Di	2ui	Di	2ui	Di	2ui
UK			2.09	9.91	2.41	6.25	2.46	6.05	3.88	6.71	0.06	8.42	-0.01	12.55
DE	-2.09	9.91			-0.21	9.78	0.92	9.62	1.84	10.04	-1.71	11.27	-3.26	14.93
US	-2.41	6.25	0.21	9.78			2.02	5.86	2.43	6.52	-0.96	8.29	-0.10	12.61
RU	-2.46	6.05	-0.92	9.62	-2.02	5.86			1.35	6.25	-1.76	8.04	0.20	12.31
CN	-3.88	6.71	-1.84	10.04	-2.43	6.52	-1.35	6.25			-3.53	8.56	-2.89	12.69
CA	-0.06	8.42	1.71	11.27	0.96	8.29	1.76	8.04	3.53	8.56			0.91	13.59
ZA	0.01	12.55	3.26	14.93	0.10	12.61	-0.20	12.31	2.89	12.69	-0.91	13.59		

Table H7. Bilateral Degrees of Equivalence for a frequency of 30 kHz, with values stated in percent and expanded uncertainties expressed for a coverage factor of *k*=2.

(%)	UK		DE		US		RU		CN		CA		ZA	
	Di	2ui	Di	2ui	Di	2ui	Di	2ui	Di	2ui	Di	2ui	Di	2ui
UK			-5.00	9.71	5.00	6.42	2.46	6.34	-0.85	6.82	0.76	8.70	-1.91	13.11
DE	5.00	9.71			7.54	9.35	5.70	9.15	5.42	9.56	5.57	10.95	3.93	14.56
US	-5.00	6.42	-7.54	9.35			-1.57	5.85	-3.53	6.43	-2.27	8.38	-1.55	12.51
RU	-2.46	6.34	-5.70	9.15	1.57	5.85			-0.47	6.17	0.26	8.15	0.46	12.29
CN	0.85	6.82	-5.42	9.56	3.53	6.43	0.47	6.17			0.24	8.61	-4.12	12.73
CA	-0.76	8.70	-5.57	10.95	2.27	8.38	-0.26	8.15	-0.24	8.61			-2.02	13.68
ZA	1.91	13.11	-3.93	14.56	1.55	12.51	-0.46	12.29	4.12	12.73	2.02	13.68		

Table H8. Bilateral Degrees of Equivalence for a frequency of 50 kHz, with values stated in percent and expanded uncertainties expressed for a coverage factor of *k*=2.

(%)	UK		DE		US		RU		CN		CA		ZA	
	Di	2ui	Di	2ui	Di	2ui	Di	2ui	Di	2ui	Di	2ui	Di	2ui
UK			-2.26	9.68	0.73	6.21	3.15	6.10	0.14	6.62	0.55	8.50	-1.70	16.48
DE	2.26	9.68			1.08	9.48	5.28	9.39	2.27	9.74	2.71	11.11	-0.85	18.18
US	-0.73	6.21	-1.08	9.48			4.27	5.79	0.90	6.33	0.94	8.28	-5.02	16.36
RU	-3.15	6.10	-5.28	9.39	-4.27	5.79			-2.97	6.20	-2.47	8.18	-7.57	16.39
CN	-0.14	6.62	-2.27	9.74	-0.90	6.33	2.97	6.20			0.43	8.58	-3.17	16.59
CA	-0.55	8.50	-2.71	11.11	-0.94	8.28	2.47	8.18	-0.43	8.58			-2.89	17.39
ZA	1.70	16.48	0.85	18.18	5.02	16.36	7.57	16.39	3.17	16.59	2.89	17.39		

Table H9. Bilateral Degrees of Equivalence for a frequency of 80 kHz, with values stated in percent and expanded uncertainties expressed for a coverage factor of *k*=2.

(%)	UK		DE		US		RU		CN		CA		ZA	
	Di	2ui	Di	2ui	Di	2ui	Di	2ui	Di	2ui	Di	2ui	Di	2ui
UK			-6.96	10.75	-3.70	6.91	-0.07	6.71	-2.49	7.29	-0.23	8.90	-3.63	21.99
DE	6.96	10.75			3.26	10.66	6.89	10.53	4.47	10.91	6.73	12.05	3.33	23.44
US	3.70	6.91	-3.26	10.66			3.63	6.57	1.21	7.17	3.47	8.80	0.07	21.94
RU	0.07	6.71	-6.89	10.53	-3.63	6.57			-2.43	6.97	-0.16	8.64	-3.56	21.88
CN	2.49	7.29	-4.47	10.91	-1.21	7.17	2.43	6.97			2.26	9.10	-1.14	22.07
CA	0.23	8.90	-6.73	12.05	-3.47	8.80	0.16	8.64	-2.26	9.10			-3.40	22.65
ZA	3.63	21.99	-3.33	23.44	-0.07	21.94	3.56	21.88	1.14	22.07	3.40	22.65		

Table H10. Bilateral Degrees of Equivalence for a frequency of 100 kHz, with values stated in percent and expanded uncertainties expressed for a coverage factor of *k*=2.

(%)	UK		DE		US		RU		CN		CA		ZA	
	Di	2ui	Di	2ui	Di	2ui	Di	2ui	Di	2ui	Di	2ui	Di	2ui
UK			-2.42	9.78	-2.10	6.86	1.65	6.14	-1.04	7.04	-0.71	8.82	-2.49	21.89
DE	2.42	9.78			2.95	9.98	3.75	9.44	2.54	10.09	4.86	11.62	2.67	23.14
US	2.10	6.86	-2.95	9.98			2.01	6.41	1.05	7.08	2.43	8.74	-0.13	21.88
RU	-1.65	6.14	-3.75	9.44	-2.01	6.41			-1.70	6.58	-0.60	8.51	-2.73	21.75
CN	1.04	7.04	-2.54	10.09	-1.05	7.08	1.70	6.58			0.66	9.00	-1.31	21.96
CA	0.71	8.82	-4.86	11.62	-2.43	8.74	0.60	8.51	-0.66	9.00			-2.09	22.58
ZA	2.49	21.89	-2.67	23.14	0.13	21.88	2.73	21.75	1.31	21.96	2.09	22.58		

Table H11. Bilateral Degrees of Equivalence for a frequency of 150 kHz, with values stated in percent and expanded uncertainties expressed for a coverage factor of *k*=2.

(%)	UK		DE		US		RU		CN		CA		ZA	
	Di	2ui	Di	2ui	Di	2ui	Di	2ui	Di	2ui	Di	2ui	Di	2ui
UK			-1.89	9.70	1.79	6.90	3.59	6.13	-3.88	6.85	3.06	8.91	-3.66	21.44
DE	1.89	9.70			4.90	10.08	5.47	9.40	-1.13	10.13	4.90	11.98	-2.86	23.05
US	-1.79	6.90	-4.90	10.08			1.26	6.53	-6.00	6.99	1.86	8.95	-4.81	21.45
RU	-3.59	6.13	-5.47	9.40	-1.26	6.53			-7.13	6.48	-0.28	8.69	-7.10	21.36
CN	3.88	6.85	1.13	10.13	6.00	6.99	7.13	6.48			8.01	8.98	1.43	21.47
CA	-3.06	8.91	-4.90	11.98	-1.86	8.95	0.28	8.69	-8.01	8.98			-6.69	22.17
ZA	3.66	21.44	2.86	23.05	4.81	21.45	7.10	21.36	-1.43	21.47	6.69	22.17		

Table H12. Bilateral Degrees of Equivalence for a frequency of 200 kHz, with values stated in percent and expanded uncertainties expressed for a coverage factor of *k*=2.

(%)	UK		DE		US		RU		CN		CA		ZA	
	Di	2ui	Di	2ui	Di	2ui	Di	2ui	Di	2ui	Di	2ui	Di	2ui
UK			-9.81	10.51	-0.19	8.13	-2.09	8.60	-2.09	9.60	-0.11	13.73	-6.58	31.12
DE	9.81	10.51			9.61	11.24	7.71	11.59	7.71	12.35	9.69	15.77	3.23	32.07
US	0.19	8.13	-9.61	11.24			-1.90	9.49	-1.90	10.40	0.08	14.30	-6.38	31.38
RU	2.09	8.60	-7.71	11.59	1.90	9.49			0.00	10.78	1.98	14.57	-4.48	31.50
CN	2.09	9.60	-7.71	12.35	1.90	10.40	0.00	10.78			1.98	15.18	-4.48	31.79
CA	0.11	13.73	-9.69	15.77	-0.08	14.30	-1.98	14.57	-1.98	15.18			-6.46	33.27
ZA	6.58	31.12	-3.23	32.07	6.38	31.38	4.48	31.50	4.48	31.79	6.46	33.27		

Table H13. Bilateral Degrees of Equivalence for a frequency of 300 kHz, with values stated in percent and expanded uncertainties expressed for a coverage factor of *k*=2.

(%)	UK		DE		US		RU		CN		CA		ZA	
	Di	2ui	Di	2ui	Di	2ui	Di	2ui	Di	2ui	Di	2ui	Di	2ui
UK			2.58	11.81	1.98	10.80	6.16	9.46	0.25	10.08	-11.97	12.47	-9.56	29.60
DE	-2.58	11.81			-0.60	13.69	3.58	12.66	-2.32	13.13	-14.54	15.04	-12.13	30.78
US	-1.98	10.80	0.60	13.69			4.18	11.72	-1.72	12.22	-13.94	14.26	-11.53	30.40
RU	-6.16	9.46	-3.58	12.66	-4.18	11.72			-5.91	11.06	-18.13	13.27	-15.72	29.95
CN	-0.25	10.08	2.32	13.13	1.72	12.22	5.91	11.06			-12.22	13.72	-9.81	30.15
CA	11.97	12.47	14.54	15.04	13.94	14.26	18.13	13.27	12.22	13.72			2.41	31.03
ZA	9.56	29.60	12.13	30.78	11.53	30.40	15.72	29.95	9.81	30.15	-2.41	31.03		

Table H14. Bilateral Degrees of Equivalence for a frequency of 400 kHz, with values stated in percent and expanded uncertainties expressed for a coverage factor of *k*=2.

(%)	UK		DE		US		RU		CN		CA		ZA	
	Di	2ui	Di	2ui	Di	2ui	Di	2ui	Di	2ui	Di	2ui	Di	2ui
UK			2.70	11.64	1.65	10.60	3.86	9.19	-0.72	9.85	20.38	15.95	-8.24	51.98
DE	-2.70	11.64			-1.05	13.47	1.16	12.38	-3.41	12.88	17.68	17.98	-10.93	52.63
US	-1.65	10.60	1.05	13.47			2.22	11.41	-2.36	11.96	18.73	17.33	-9.88	52.41
RU	-3.86	9.19	-1.16	12.38	-2.22	11.41			-4.58	10.72	16.51	16.50	-12.10	52.15
CN	0.72	9.85	3.41	12.88	2.36	11.96	4.58	10.72			21.09	16.88	-7.52	52.27
CA	-20.38	15.95	-17.68	17.98	-18.73	17.33	-16.51	16.50	-21.09	16.88			-28.61	53.75
ZA	8.24	51.98	10.93	52.63	9.88	52.41	12.10	52.15	7.52	52.27	28.61	53.75		

Table H15. Bilateral Degrees of Equivalence for a frequency of 500 kHz, with values stated in percent and expanded uncertainties expressed for a coverage factor of *k*=2.

(%)	UK		DE		US		RU		CN		CA		ZA	
	Di	2ui	Di	2ui	Di	2ui	Di	2ui	Di	2ui	Di	2ui	Di	2ui
UK			-0.21	12.15	-2.48	11.00	-12.39	8.93	-0.21	10.55	-10.25	13.35	-6.04	57.03
DE	0.21	12.15			-2.27	13.88	-12.18	12.31	0.00	13.53	-10.04	15.81	-5.83	57.66
US	2.48	11.00	2.27	13.88			-9.91	11.18	2.27	12.51	-7.77	14.95	-3.56	57.43
RU	12.39	8.93	12.18	12.31	9.91	11.18			12.18	10.73	2.14	13.50	6.35	57.07
CN	0.21	10.55	0.00	13.53	-2.27	12.51	-12.18	10.73			-10.04	14.62	-5.83	57.34
CA	10.25	13.35	10.04	15.81	7.77	14.95	-2.14	13.50	10.04	14.62			4.21	57.92
ZA	6.04	57.03	5.83	57.66	3.56	57.43	-6.35	57.07	5.83	57.34	-4.21	57.92		

APPENDIX I: DEGREES OF EQUIVALENCE AT SELECTED FREQUENCIES

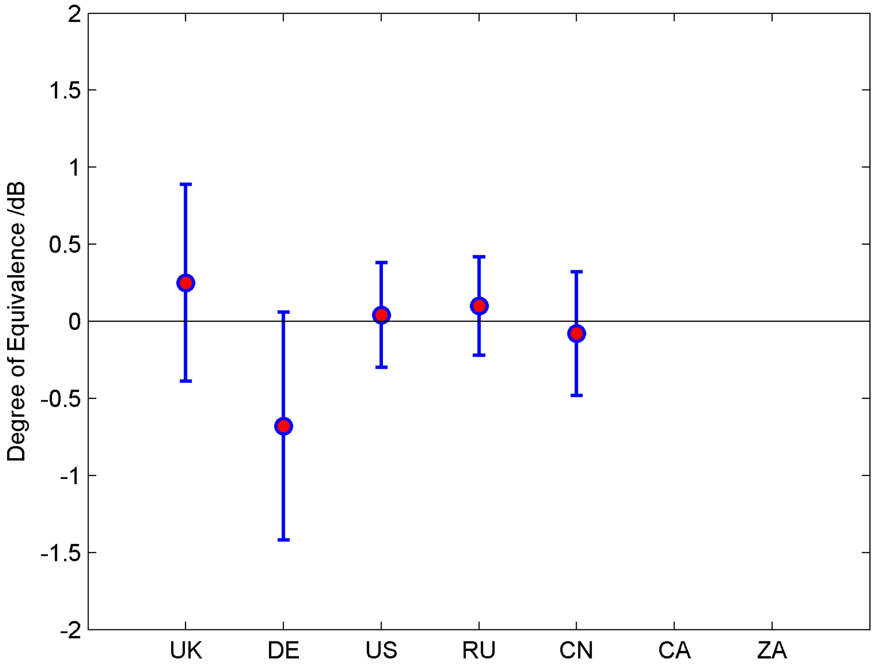

Figure I1. Degrees of Equivalence for a frequency of 1 kHz, with values stated in dB and expanded uncertainties expressed for a coverage factor of *k*=2.

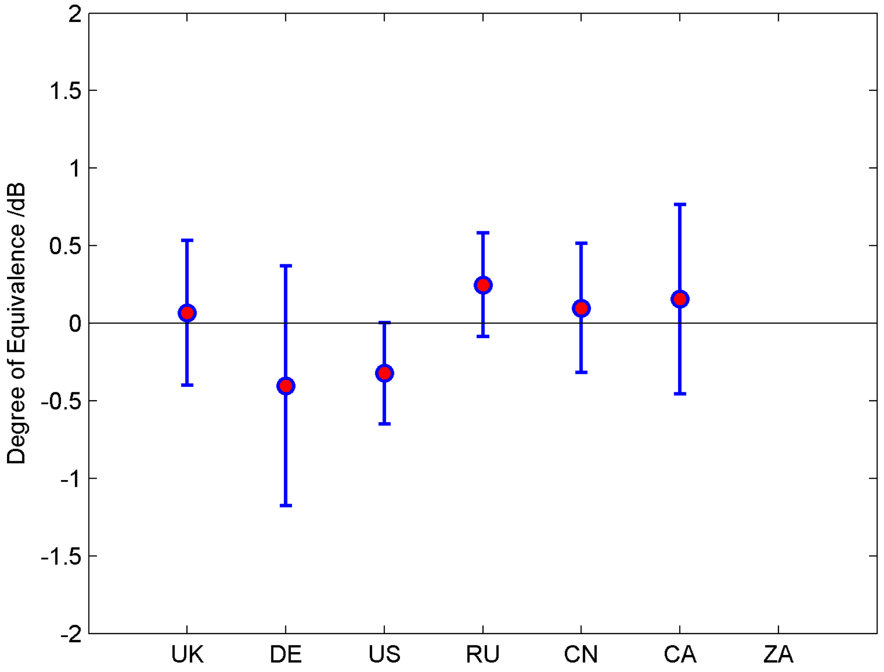

Figure I2. Degrees of Equivalence for a frequency of 2 kHz, with values stated in dB and expanded uncertainties expressed for a coverage factor of *k*=2.

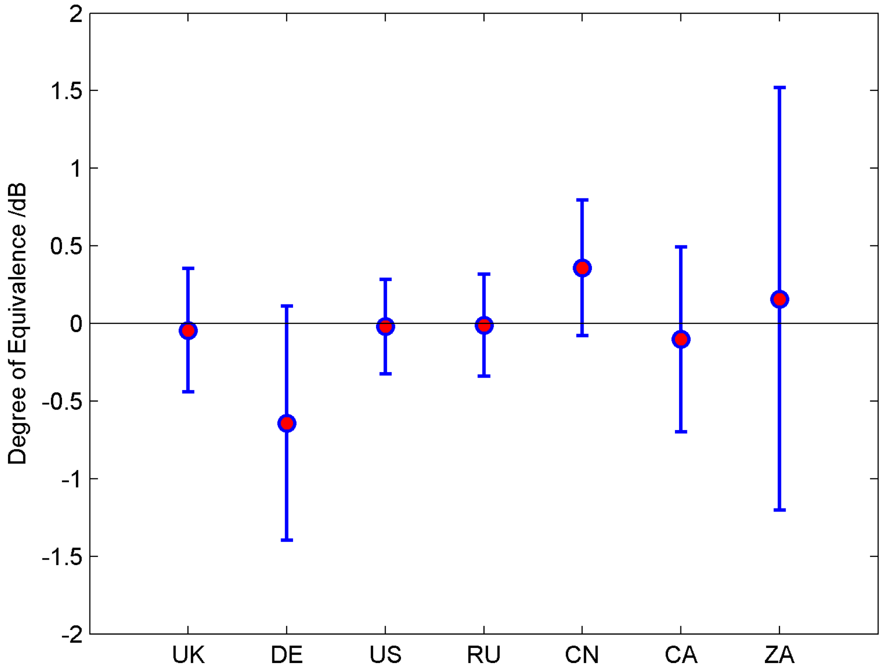

Figure I3. Degrees of Equivalence for a frequency of 3 kHz, with values stated in dB and expanded uncertainties expressed for a coverage factor of *k*=2.

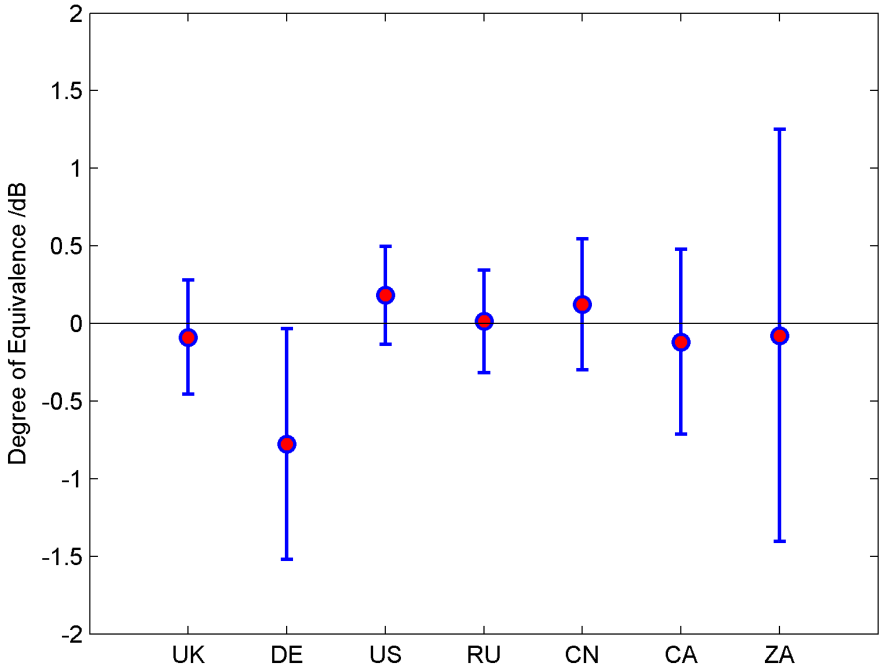

Figure I4. Degrees of Equivalence for a frequency of 5 kHz, with values stated in dB and expanded uncertainties expressed for a coverage factor of *k*=2.

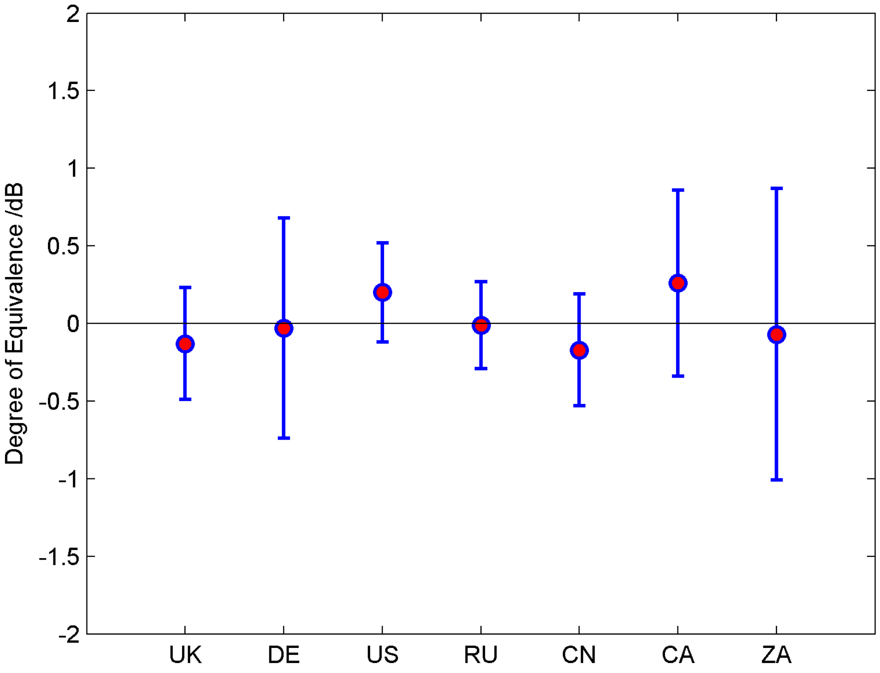

Figure I5. Degrees of Equivalence for a frequency of 10 kHz, with values stated in dB and expanded uncertainties expressed for a coverage factor of *k*=2.

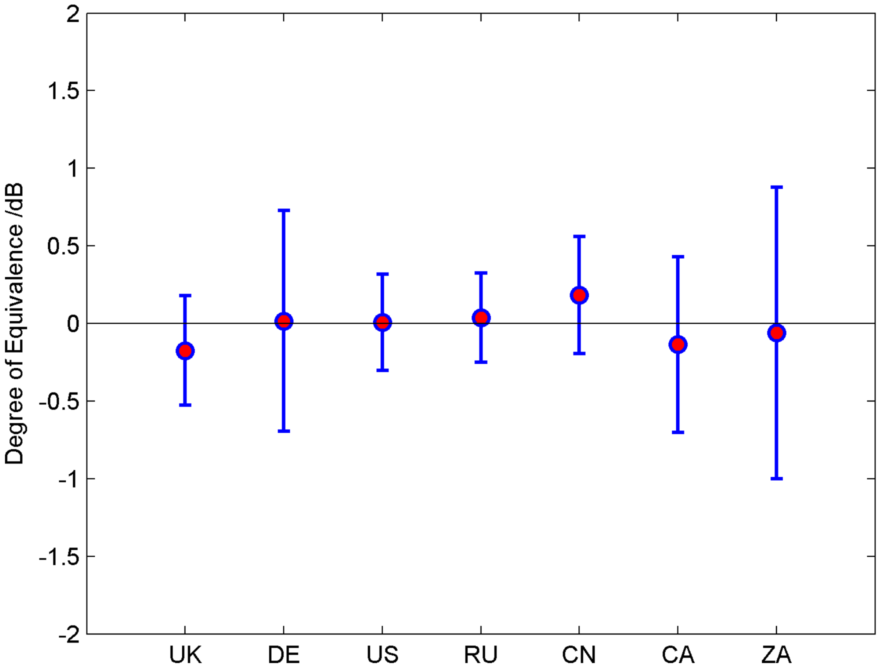

Figure I6. Degrees of Equivalence for a frequency of 20 kHz, with values stated in dB and expanded uncertainties expressed for a coverage factor of *k*=2.

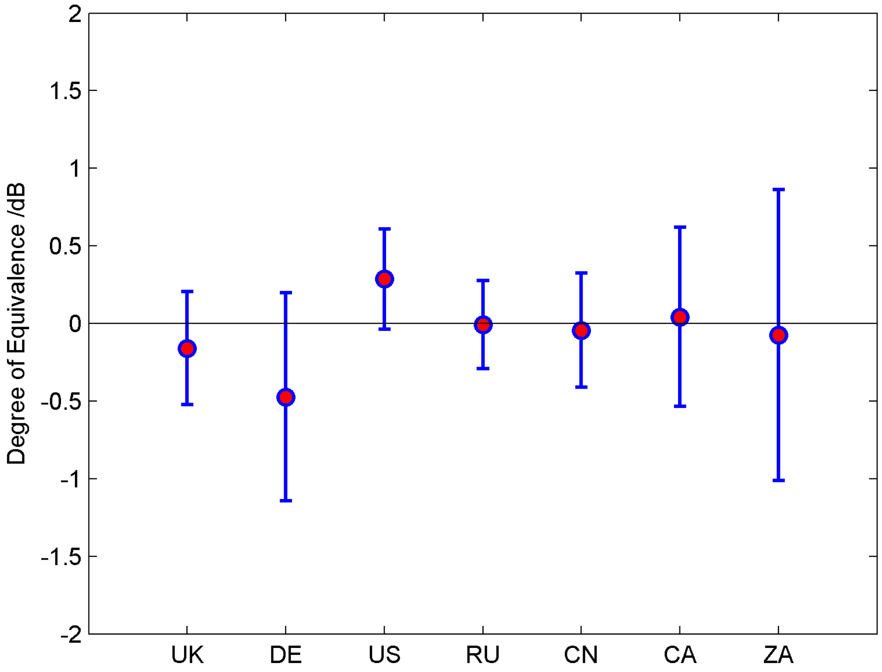

Figure I7. Degrees of Equivalence for a frequency of 30 kHz, with values stated in dB and expanded uncertainties expressed for a coverage factor of *k*=2.

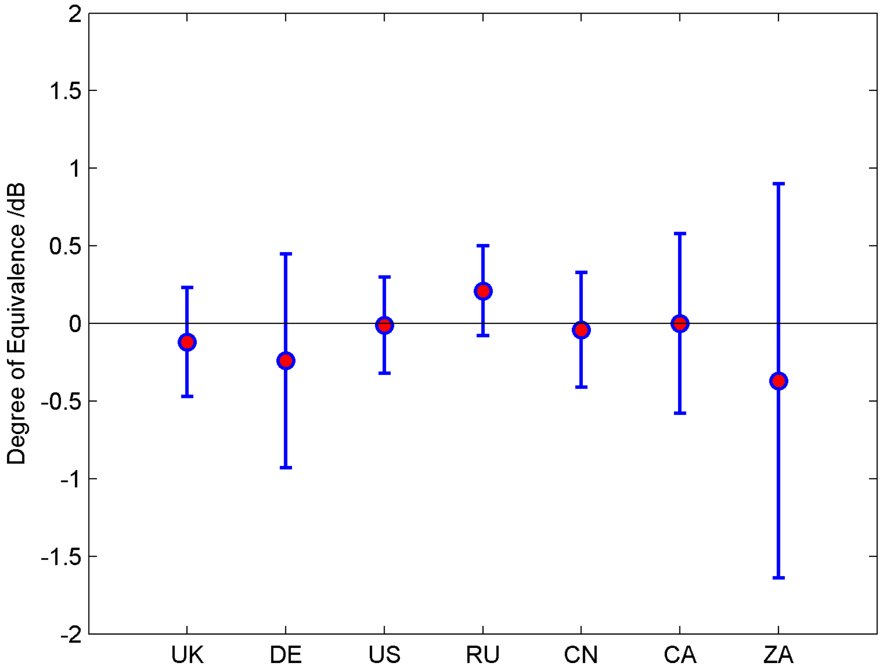

Figure I8. Degrees of Equivalence for a frequency of 50 kHz, with values stated in dB and expanded uncertainties expressed for a coverage factor of *k*=2.

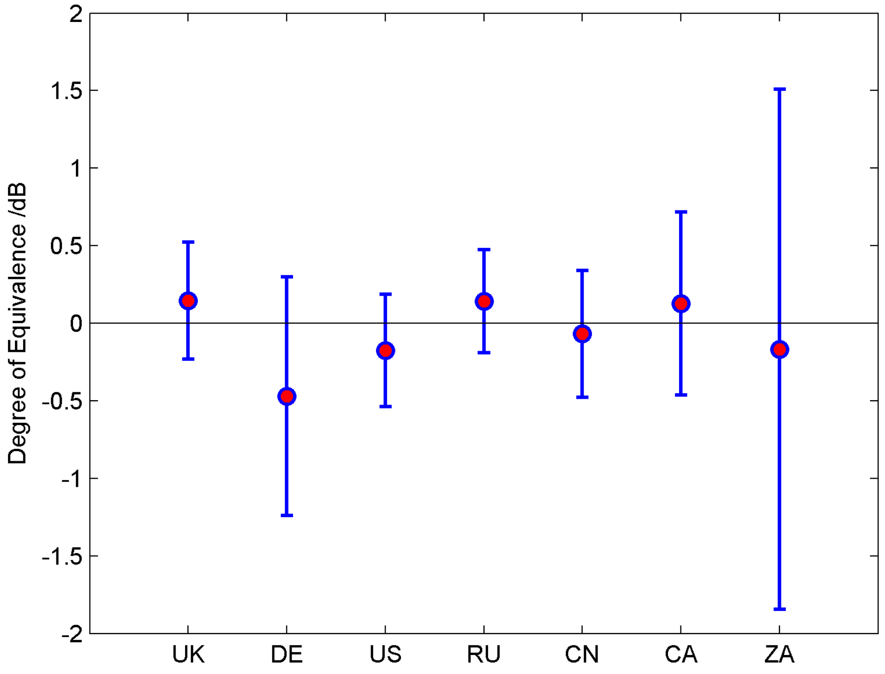

Figure I9. Degrees of Equivalence for a frequency of 80 kHz, with values stated in dB and expanded uncertainties expressed for a coverage factor of *k*=2.

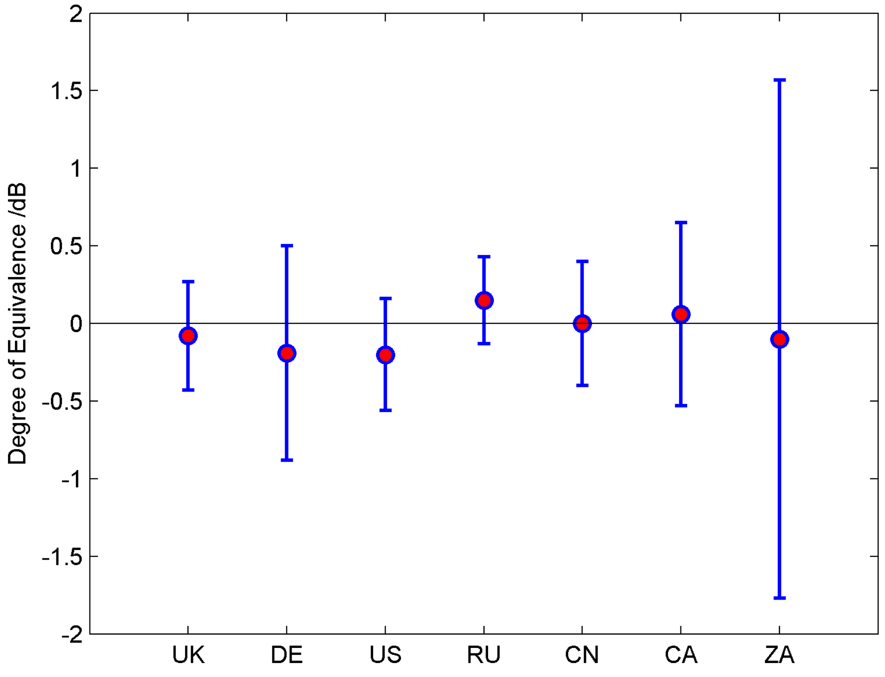

Figure I10. Degrees of Equivalence for a frequency of 100 kHz, with values stated in dB and expanded uncertainties expressed for a coverage factor of *k*=2.

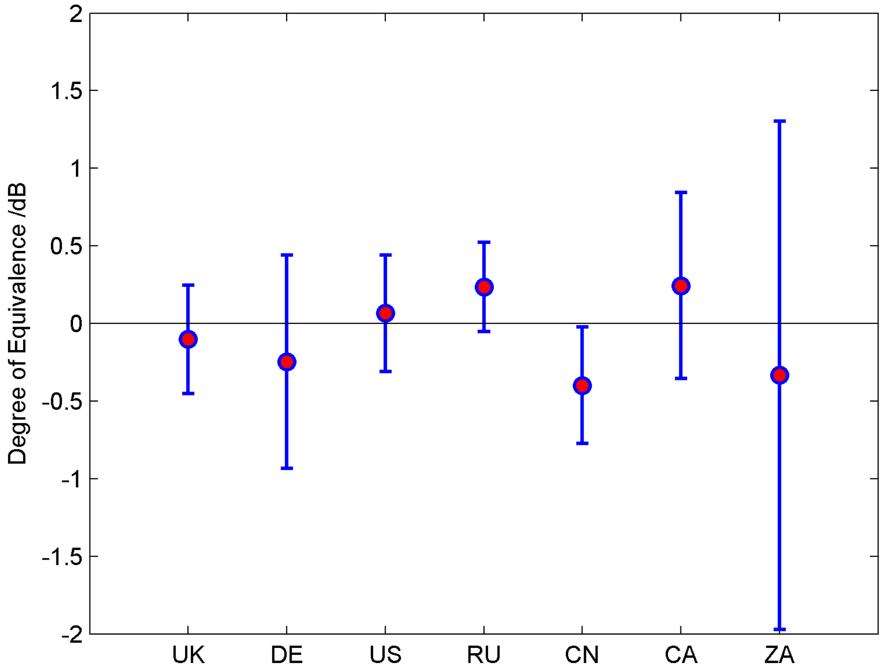

Figure I11. Degrees of Equivalence for a frequency of 150 kHz, with values stated in dB and expanded uncertainties expressed for a coverage factor of *k*=2.

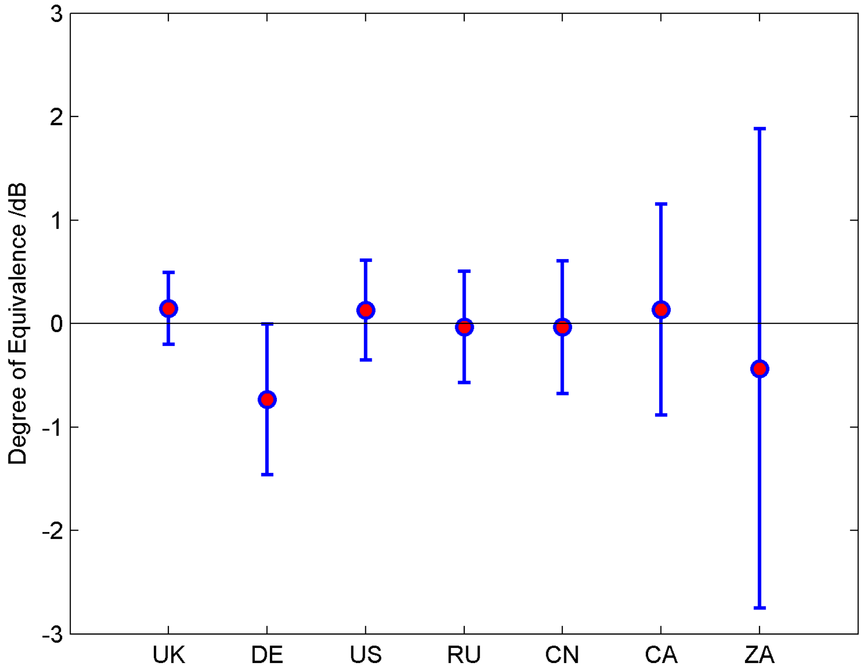

Figure I12. Degrees of Equivalence for a frequency of 200 kHz, with values stated in dB and expanded uncertainties expressed for a coverage factor of *k*=2.

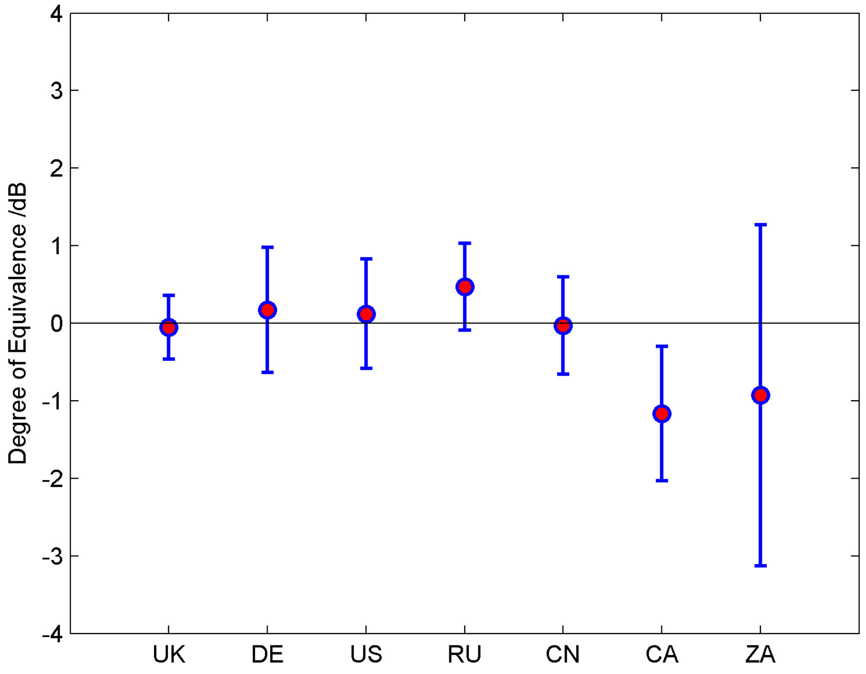

Figure I13. Degrees of Equivalence for a frequency of 300 kHz, with values stated in dB and expanded uncertainties expressed for a coverage factor of *k*=2.

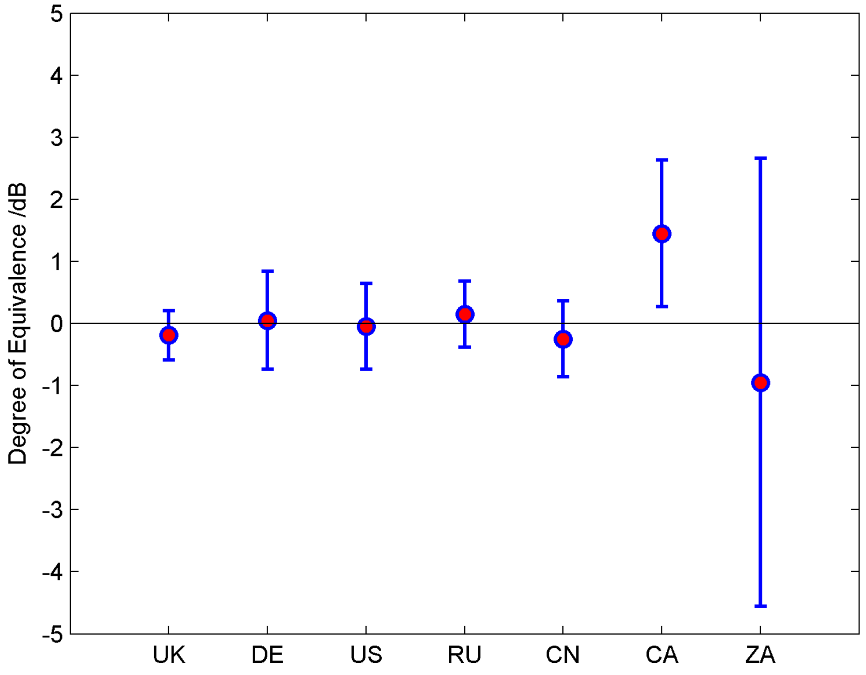

Figure I14. Degrees of Equivalence for a frequency of 400 kHz, with values stated in dB and expanded uncertainties expressed for a coverage factor of *k*=2.

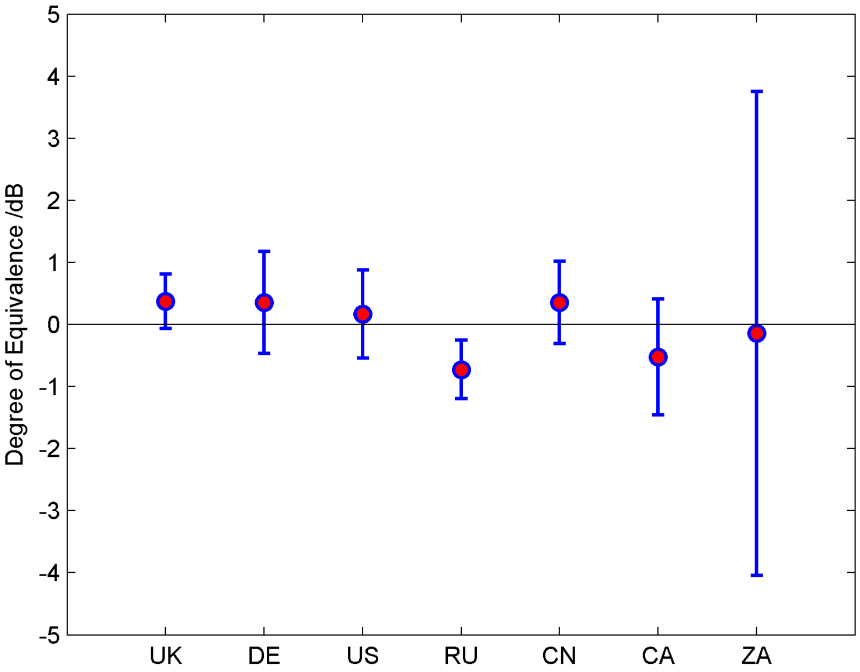

Figure I15. Degrees of Equivalence for a frequency of 500 kHz, with values stated in dB and expanded uncertainties expressed for a coverage factor of *k*=2.

APPENDIX J: COMMON FREQUENCIES OF CALIBRATION

Below are listed the common frequencies of calibration for the hydrophones along with the Type A uncertainties (Ur) and overall uncertainties (Ut) stated by the participants at those frequencies for each hydrophone (uncertainties stated as standard uncertainties for a coverage factor *k*=1). These values were used in the calculation of the Combined Degree of Equivalence. There is some approximation involved in this, since for some participants, Type A components were not stated for every frequency – instead the value was said to range between two values for a given hydrophone and frequency range. In this case, the typical value given was used as the Type A component for all the frequencies in the range.

Country	UK		DE		US		RU		CN		CA		ZA	
F (kHz)	Ur	Ut	Ur	Ut	Ur	Ut	Ur	Ut	Ur	Ut	Ur	Ut	Ur	Ut
10	0.09	0.21	0.30	0.43	0.05	0.18	0.13	0.19	0.15	0.23	0.10	0.32	0.31	0.70
20	0.09	0.21	0.30	0.43	0.05	0.18	0.13	0.19	0.15	0.23	0.10	0.32	0.31	0.70
30	0.09	0.21	0.30	0.43	0.05	0.18	0.13	0.19	0.15	0.23	0.10	0.32	0.31	0.70
35	0.09	0.21	0.30	0.43	0.05	0.18	0.13	0.19	0.15	0.23	0.10	0.32	0.31	0.70
40	0.09	0.21	0.30	0.43	0.05	0.18	0.13	0.19	0.15	0.23	0.10	0.32	0.31	0.70
45	0.09	0.21	0.30	0.43	0.05	0.18	0.13	0.19	0.15	0.23	0.10	0.32	0.31	0.70
50	0.09	0.21	0.30	0.43	0.05	0.18	0.13	0.19	0.15	0.23	0.10	0.32	0.31	0.70
55	0.09	0.21	0.30	0.43	0.05	0.18	0.13	0.19	0.15	0.23	0.10	0.32	0.31	0.70
60	0.09	0.21	0.30	0.43	0.05	0.18	0.13	0.19	0.15	0.23	0.10	0.32	0.31	0.70
65	0.09	0.21	0.30	0.43	0.05	0.18	0.13	0.19	0.15	0.23	0.10	0.32	0.31	0.70
70	0.09	0.21	0.30	0.43	0.05	0.18	0.13	0.19	0.15	0.23	0.10	0.32	0.31	0.70
75	0.09	0.21	0.30	0.43	0.05	0.18	0.13	0.19	0.15	0.23	0.10	0.32	0.31	0.70

Table J1. Values for overall uncertainty (Ut) and Type A uncertainty (Ur) expressed for a coverage factor k=1 for the H52 at the frequencies of calibration shared with the B&K8104.

Country	UK		DE		US		RU		CN		CA		ZA	
F (kHz)	Ur	Ut	Ur	Ut	Ur	Ut	Ur	Ut	Ur	Ut	Ur	Ut	Ur	Ut
10	0.09	0.21	0.30	0.43	0.10	0.23	0.13	0.19	0.15	0.23	0.10	0.31	0.22	0.50
20	0.09	0.21	0.30	0.43	0.10	0.23	0.13	0.19	0.15	0.23	0.10	0.31	0.22	0.50
30	0.20	0.28	0.30	0.43	0.05	0.21	0.13	0.19	0.15	0.23	0.10	0.31	0.22	0.50
35	0.09	0.25	0.30	0.43	0.05	0.21	0.13	0.19	0.15	0.23	0.10	0.31	0.22	0.50
40	0.09	0.21	0.30	0.43	0.05	0.21	0.13	0.19	0.15	0.23	0.10	0.31	0.22	0.50
45	0.14	0.23	0.30	0.43	0.05	0.21	0.13	0.19	0.15	0.23	0.10	0.31	0.22	0.50
50	0.10	0.21	0.30	0.43	0.05	0.21	0.13	0.19	0.15	0.23	0.10	0.31	0.40	0.90
55	0.18	0.26	0.30	0.43	0.05	0.21	0.13	0.19	0.15	0.23	0.10	0.31	0.40	0.90
60	0.10	0.21	0.30	0.43	0.05	0.21	0.13	0.19	0.15	0.23	0.10	0.31	0.40	0.90
65	0.09	0.21	0.30	0.43	0.05	0.21	0.13	0.19	0.15	0.23	0.10	0.31	0.40	0.90
70	0.09	0.21	0.30	0.43	0.05	0.21	0.13	0.19	0.15	0.23	0.10	0.31	0.40	0.90
75	0.09	0.21	0.30	0.43	0.05	0.21	0.13	0.19	0.15	0.23	0.10	0.31	0.40	0.90

Table J2. Values for overall uncertainty (Ut) and Type A uncertainty (Ur) expressed for a coverage factor k=1 for the B&K8104 at the frequencies of calibration shared with the H52.

Country	UK		DE		US		RU		CN		CA		ZA	
F (kHz)	**Ur**	**Ut**	**Ur**	**Ut**	**Ur**	**Ut**	**Ur**	**Ut**	**Ur**	**Ut**	**Ur**	**Ut**	**Ur**	**Ut**
100	0.09	0.21	0.30	0.43	0.05	0.21	0.13	0.19	0.15	0.23	0.10	0.31	0.40	0.90
110	0.09	0.21	0.30	0.43	0.05	0.21	0.13	0.19	0.15	0.23	0.10	0.31	0.40	0.90
120	0.09	0.22	0.30	0.43	0.05	0.21	0.13	0.19	0.15	0.23	0.10	0.31	0.40	0.90
130	0.09	0.21	0.30	0.43	0.05	0.21	0.13	0.19	0.15	0.23	0.10	0.31	0.40	0.90
140	0.09	0.21	0.30	0.43	0.05	0.21	0.13	0.19	0.15	0.23	0.10	0.31	0.40	0.90
150	0.09	0.21	0.30	0.43	0.05	0.21	0.13	0.19	0.15	0.23	0.10	0.31	0.40	0.90

Table J3. Values for overall uncertainty (Ut) and Type A uncertainty (Ur) expressed for a coverage factor k=1 for the B&K8104 at the frequencies of calibration shared with the TC4034.

Country	UK		DE		US		RU		CN		CA		ZA	
F (kHz)	**Ur**	**Ut**	**Ur**	**Ut**	**Ur**	**Ut**	**Ur**	**Ut**	**Ur**	**Ut**	**Ur**	**Ut**	**Ur**	**Ut**
100	0.09	0.21	0.30	0.43	0.05	0.27	0.13	0.19	0.20	0.35	0.30	0.53	0.58	1.30
110	0.09	0.21	0.30	0.43	0.05	0.27	0.13	0.19	0.20	0.35	0.30	0.53	0.58	1.30
120	0.09	0.21	0.30	0.43	0.05	0.27	0.13	0.19	0.20	0.35	0.30	0.53	0.58	1.30
130	0.09	0.21	0.30	0.43	0.05	0.27	0.13	0.19	0.20	0.35	0.30	0.53	0.58	1.30
140	0.09	0.21	0.30	0.43	0.05	0.27	0.13	0.19	0.20	0.35	0.30	0.53	0.58	1.30
150	0.09	0.21	0.30	0.43	0.05	0.27	0.13	0.19	0.20	0.35	0.30	0.53	0.58	1.30

Table J4. Values for overall uncertainty (Ut) and Type A uncertainty (Ur) expressed for a coverage factor k=1 for the TC4034 at the frequencies of calibration shared with the B&K8104.