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Methods of free-field calibration of working standard microphones by comparison techniques: Euromet project 400

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METHODS OF FREE-FIELD CALIBRATION OF WORKING STANDARD MICROPHONES BY COMPARISON TECHNIQUES: EUROMET PROJECT 400

Peter Hanes
Centre for Mechanical and Acoustical Metrology
National Physical Laboratory
Teddington
Middlesex
United Kingdom
TW11 0LW

ABSTRACT

The majority of acoustical measurements are made in free-field conditions using working standard microphones. Working standard microphones are not necessarily able to be calibrated by reciprocity techniques, and their calibration must therefore be achieved by another technique. The technique of free-field calibration by comparison with a calibrated reference microphone will be standardised as part of the IEC 61094 series. In order to assist in the preparation of the new Standard, a Euromet project was undertaken to gather information on comparison methods of free-field calibration. After a period of development, the four participating laboratories carried out an intercomparison exercise involving calibration of working standard microphones.

The exercise found agreement between the results of all four participants better than 0.12 dB at frequencies up to and including 2 kHz, and better than 0.5 dB at higher frequencies. The expanded uncertainties of measurement quoted by the laboratories were sufficient to explain all the between-laboratory differences. The influences of experimental arrangements, environmental conditions, free-field corrections for laboratory standard microphones and performance of the anechoic chambers on the results are discussed. Several issues are identified by the participants as requiring further examination in the course of preparing the new Standard.

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National Physical Laboratory,
Teddington, Middlesex, UK TW11 0LW.

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by Dr Graham Torr, Head, Centre for Mechanical and Acoustical Metrology

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1. INTRODUCTION

1.1 WORKING STANDARD MICROPHONES

Two basic types of measurement microphone exist. Laboratory standard microphones are designed to have a simple geometry, with the diaphragm exposed, and to be highly stable both in time and in their dependence on environmental conditions, as specified in IEC 61094-1[1]. In order to preserve their stability, laboratory standard microphones are usually only used in calibration laboratories. Measurement microphones in everyday use are known as working standard microphones. These are used to transfer the standard of sound pressure from one acoustical measuring instrument to another, and are specified by IEC 61094-4[2]. Working standard microphones are fitted with a perforated grid in order to prevent damage to the diaphragm.

The most important property of any measurement microphone is its sensitivity. Measurement microphones are designed to have a sensitivity that is almost constant, within their frequency range of use, in one of three sound fields: pressure, free field or diffuse field. A pressure-response microphone is usually used to measure the actual sound pressure level at the diaphragm. Free-field response microphones are used where the sound waves are traveling in one direction; the microphones are designed to compensate for the effects of diffraction and interference at the microphone diaphragm, such that the measured sound pressure level is that that would exist if the microphone were not present. Conditions approximating those of a free field are encountered in everyday life, particularly when outdoors.

1.2 CALIBRATION METHODS AND PERFORMANCE OF FREE-FIELD ROOM

The IEC 61094 series of standards currently provides methods for calibration of the pressure response[3] and free-field response[4] of a laboratory standard microphone. These methods rely on the requirement that laboratory standard microphones are reciprocal transducers to enable very accurate calibration. Working standard microphones are not necessarily reciprocal transducers, and their mechanical configuration is not usually suited to reciprocity calibration, so their calibration must therefore be achieved by another technique. This requires comparison of the sensitivity of the microphone under test with that of a reference standard, by exposing the microphones to the same sound pressure level either simultaneously or sequentially. Work is in progress within IEC/TC29/WG5 to develop a standard (IEC 61094-5) that will specify a method for calibration of the pressure response of working standard microphones.

Values of the differences $\Delta_{f,p}$ between pressure and free-field sensitivity levels of "one-inch" microphones, derived from pressure and free-field reciprocity calibrations, were published in 1979[5]. These allow the calculation of the free-field sensitivity level of a microphone by adding the published $\Delta_{f,p}$ for the type of microphone to the individual microphone's calibrated pressure sensitivity level. Work is also in progress within IEC/TC29/WG5 to produce more accurate estimates of $\Delta_{f,p}$ for laboratory standard microphones.

Given the prevalence of measurements made in approximately free-field conditions, a standardised method for calibration of the free-field response of working standard microphones is required. One important difference from the calibration of pressure response is that, at some point in the calibration process, the microphone under test must be exposed to a free field. Therefore all measurements in the 'traditional' method of free-field calibration are performed in a room lined with wedge-shaped absorbent material to minimise the reflections from the room surfaces[6]. Any reflection of sound back into the room will cause a deviation from ideal free-field conditions and, therefore, may influence the results of the calibration. The reflections tend to increase at low frequencies.

There is no internationally-standardised method for determining, or quantity for describing, the performance of a free-field room with the accuracy required for calibration of measurement microphones. One proposed quantity is that of root mean square deviation (rmsd) from an ideal free field[7]. The rmsd can be determined by measuring the sound pressure at a range of distances from a sound source: if the source were a monopole radiating into hemispherical free space, the acoustic pressure at any point would be inversely proportional to the distance from the source. Therefore, the deviation from this inverse proportionality is an indication of the deviation from an ideal free field. Although originally envisaged as an indicator of the effect of different treatments within a single room, the rmsd is a single value, expressed in dB, that can be used to describe the deviation from free-field conditions along a specified path in a room. The rmsd does not provide a quantitative estimate of the influence of the room performance on the results of a comparison calibration.

The expense of building and maintaining free-field rooms has led some laboratories to experiment with other techniques which have the potential to reduce the influence of imperfections in the free field, or even to obviate the need for a free-field room. Such techniques usually involve gating of the microphone signals to eliminate any portion of the signal that has undergone reflection from the room boundaries. The gating can be achieved with a conventional digital frequency analyser[8], or by using an alternative method such as the maximum-length sequence (MLS) technique[9].

1.3 EUROMET PROJECT 400

A EUROMET project to carry out some evaluation of potential methods for free-field calibration of working standard microphones was proposed, with the intention of providing information sufficient to enable the production of a new standard in the IEC 61094 series. Ideas for the project were first discussed at a meeting held in conjunction with the meeting of EUROMET acoustics contacts in Helsinki in 1997. DPLA (Denmark), IA (Spain), IEN (Italy), NPL (UK) and PTB (Germany) volunteered to participate, with NPL agreeing to act as the pilot laboratory in a ‘radial’ arrangement. IA were eventually unable to take part. Details of the participants are given in Appendix 1.

After initial development work at the participating laboratories and further discussion, a measurement protocol for an intercomparison exercise was drawn up and circulated. The measurement protocol is reproduced in Appendix 2. The first part of the work required the participants to determine the free-field sensitivity level (L_{Mf}) of a working standard “one-inch” free-field response (IEC type WS1F) microphone under the following conditions:

- the WS1F microphone was a Brüel & Kjær type 4145, fitted with its protection grid, forwarded to the participants after calibration at NPL
- the comparison calibration should be performed with reference microphones of IEC types LS1P and LS2P owned by the participant whose pressure response had been calibrated by the reciprocity method.
- L_{Mf} of the reference microphones should be determined by adding corrections $\Delta_{f,p}$, specified in the measurement protocol, to the calibrated pressure sensitivity levels (L_{Mp})
- L_{Mf} should be reported, with the associated expanded uncertainties of measurement, at least at octave-band centre frequencies from 125 Hz to 8 kHz, and at 12.5 kHz

The WS1F type and the two laboratory standard microphone types were selected to enable investigation of the effect of using test and reference microphones of different directivity patterns. It was expected that the difference in directivity pattern of the WS1F and the LS2P would make the comparison calibration involving these two types more susceptible to imperfections in the free-field.

Five examples of Brüel & Kjær type 4145 were collected for use in the project. The microphones were calibrated at NPL and then distributed in a radial pattern to the other participants, for calibration by any techniques they wished to employ. Finally the microphones were returned to NPL for re-calibration.

The second element in the project was the evaluation of performance of the free-field rooms used by the laboratories. A method was specified in the measurement protocol that required:

- traverse of a WS2F microphone along a straight line path from the sound source in the room
- coverage of at least the positions at which microphone calibrations are performed
- calculation of a line of best fit for the inverse of measured pressure versus distance, allowing for the effect of air attenuation
- calculation of the rms deviation between the best fit line and the measured values

2. WORK PERFORMED BY EACH PARTICIPANT

This section summarises the work performed by each participant. Full information on each laboratory's facilities and measurement methods is given in Appendix 3.

2.1 DPLA

The pressure sensitivity levels (L_{Mp}) of the LS1P reference microphones and WS1F microphone under test (4145 1102232) were first determined by reciprocity calibration. DPLA then determined ($L_{Mf\ 4145}$ - $\Delta_{f,p\ LS1P}$) by calculating the difference between the frequency response of the measurement system measured with the reference microphone and the frequency response of the system with the microphone under test substituted for the reference microphone. Measurements were made with the 4145 in three different geometric configurations:

1) mounted with a ring (Brüel & Kjær DB0111) to simulate the geometry of an LS1P microphone
2) mounted with the normal protection grid
3) with open diaphragm (without ring or grid)

It is likely that DPLA used a preamplifier in grounded ground-shield configuration during the measurements. If so, this is thought to introduce an error of about + 0.02 dB in the reported values of L_{Mf} of the microphone under test.

The free-field measurements were performed in a small anechoic room (free space 1.8 m^3) designed for free-field reciprocity calibrations and located in a temperature-controlled room[10]. The microphone under test was fixed at 48 cm from the sound source. Three different 30 mm diameter sound sources (two dynamic tweeter units and a home-built PVDF-source) were used.

A pure tone, swept five times from 500 Hz to 40 kHz in one-twelfth-octave steps, was used as the test signal, giving a sound pressure level of between 50 dB and 90 dB at the microphone for a driving voltage of 1 V. The complex rms value of the microphone output was measured using a Brüel & Kjær type 2012 Audio Analyzer. Three measurements of the system with the microphone under test were interleaved with four using the reference microphone. The ambient conditions during the measurements were in the ranges 23.5 °C to 23.8 °C, 100.7 kPa to 101.2 kPa, 50.0 % to 54.5 % RH. No climatic corrections were applied to the results. The values of L_{Mf} for the microphone under test with its normal protection grid fitted are shown in Figure 1.

The room performance, in terms of rmsd and peak deviation from ideal free-field conditions, was determined.

2.2 IEN

L_{Mf} for the microphone under test (4145 2071918) was determined at one-third-octave frequency intervals from 125 Hz to 12.5 kHz using a method of sequential comparison with a reference microphone. The measurements were repeated with both an LS1P and an LS2P reference microphone. Two loudspeakers were used in turn to provide the sinusoidal excitation signal, with the cross-over frequency between 1.6 kHz and 2 kHz. The distance between the loudspeaker and the microphone position was 1.695 m. The outputs of the reference or test microphone and a monitor microphone were fed to a Brüel & Kjær type 2133 one-third-octave band analyser. The reference/test microphone was connected via an insert voltage preamplifier Brüel & Kjær type 2645 to an IEN switching box that enabled the insert voltage technique to be used.

Eight replications of the measurement were carried out for each reference microphone. Environmental conditions during the measurements were in the ranges 24 °C to 27 °C, 99.0 kPa to 100.0 kPa, 55 % to 70 % RH. No climatic corrections were applied to the results.

The room performance, in terms of rmsd, was established.

Some experiments using the MLS technique were carried out, but the results were insufficient for a reliable uncertainty evaluation and were not submitted for the present project.

2.3 NPL

The WS1F microphones were calibrated using NPL's calibration system at octave-band centre frequencies from 125 Hz to 8 kHz, and at 10 kHz and 12.5 kHz, using an LS1P microphone as the reference, before circulation to the other participants. On the return of the WS1F microphones from the participants, NPL re-calibrated the microphones at the same frequencies and additionally at 16 kHz and 20 kHz, using an LS2P reference microphone. The WS1F microphones were also pressure-reciprocity calibrated at this time.

The method used for the free-field calibrations was sequential comparison of the microphone under test with a reference laboratory standard microphone. The true free-field sound pressure level is set up using the reference microphone (using the insert voltage method). The free-field sound pressure level is then duplicated when the reference microphone is replaced by the microphone under test. This is achieved by referring to the output voltage of a monitor microphone placed near the sound source (for frequencies below 4 kHz), or by applying the same driving voltage to the sound source as was applied when the reference microphone was in position (for 4 kHz and above). The free-field sensitivity level is calculated by measuring the output voltage of the microphone under test. Six replications of each measurement were performed, with the microphone at distances between 1.0 m and 1.25 m from the source. Environmental conditions during the measurements were in the ranges 17.7 °C to 20.4 °C and 100.5 kPa to 102.4 kPa. No climatic corrections were applied to the results.

NPL is also beginning to investigate the use of the MLS technique for free-field comparison calibrations[9], but the work was not sufficiently advanced to be ready to test the microphones used in this project.

The room performance, in terms of rmsd, was established.

2.4 PTB

The microphone under test (4145 2071917) was calibrated at one-third-octave frequency intervals using a method of sequential comparison. The frequency ranges were 125 Hz to 12.5 kHz when using an LS1P reference microphone and 125 Hz to 20 kHz when using an LS2P reference microphone.

The method used was a sequential comparison of the microphone under test with a reference laboratory standard microphone. The noise source comprised two coaxially-arranged loudspeakers (crossover at 2500 Hz) mounted in the wall of the anechoic room. Pure tones with a sound pressure level of 84 dB and frequencies in one-third-octave intervals from 100 Hz to 20 kHz were used as test signals. The microphones were located on the axis of the loudspeaker at 1.0 m from the loudspeaker housing. Five replications of the measurements were performed. Environmental conditions during the measurements were in the ranges 22.5 °C to 22.9 °C, 100.8 kPa to 101.2 kPa, 33 % to 39 % RH. No climatic corrections were applied.

Alternative values of the free-field corrections $\Delta_{f,p}$ for the reference microphones were calculated.

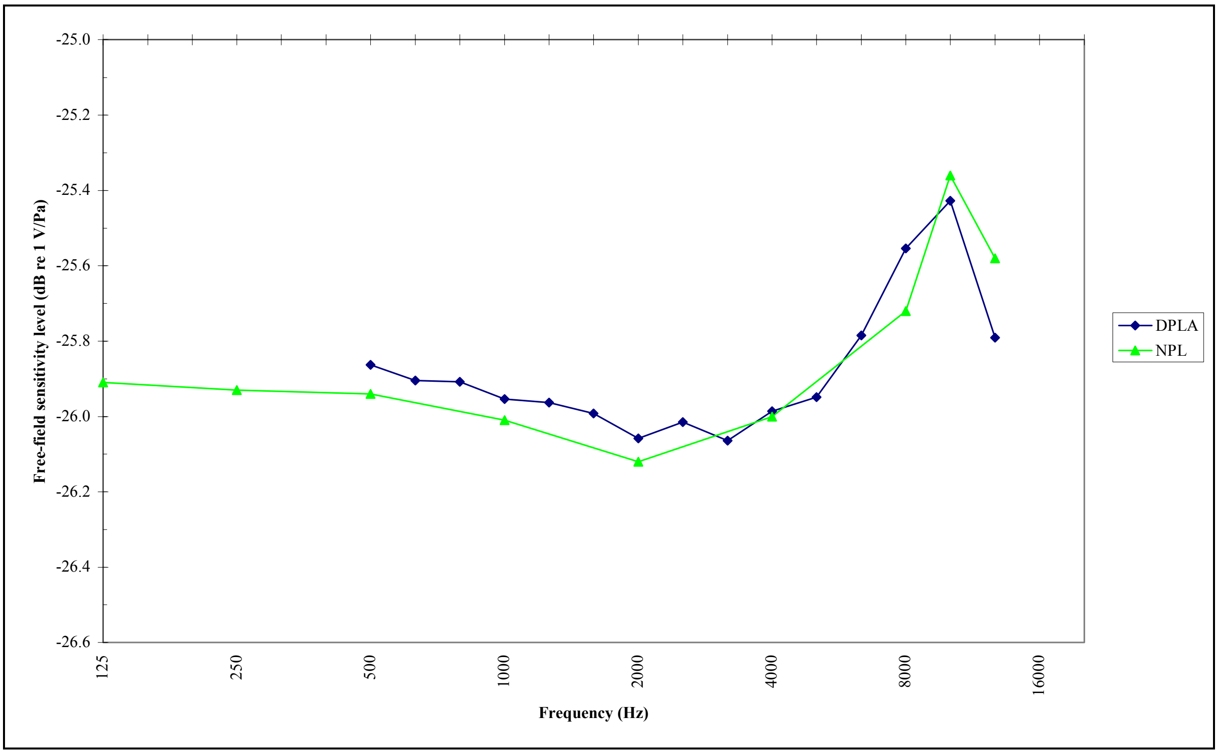
The room arrangements and performance of the room were also investigated.

3. MEASUREMENT RESULTS

The values of L_{Mf} for each microphone under test reported by the participants (without any correction for ambient temperature and static pressure) are shown in Figure 1 to Figure 5. For each microphone, the differences between the uncorrected values of L_{Mf} determined by NPL and by the other participant were determined, and the grand mean of these differences was calculated. The deviation of each laboratory's results from this grand mean are shown in Figure 6 (LS1P reference microphone) and in Figure 7 (LS2P reference microphone).

3.1 4145 1102232

Figure 1. Uncorrected L_{Mf} of 4145 1102232 measured using an LS1P reference microphone



3.2 4145 2071918

Figure 2. Uncorrected L_{Mf} of 4145 2071918 measured using an LS1P reference microphone

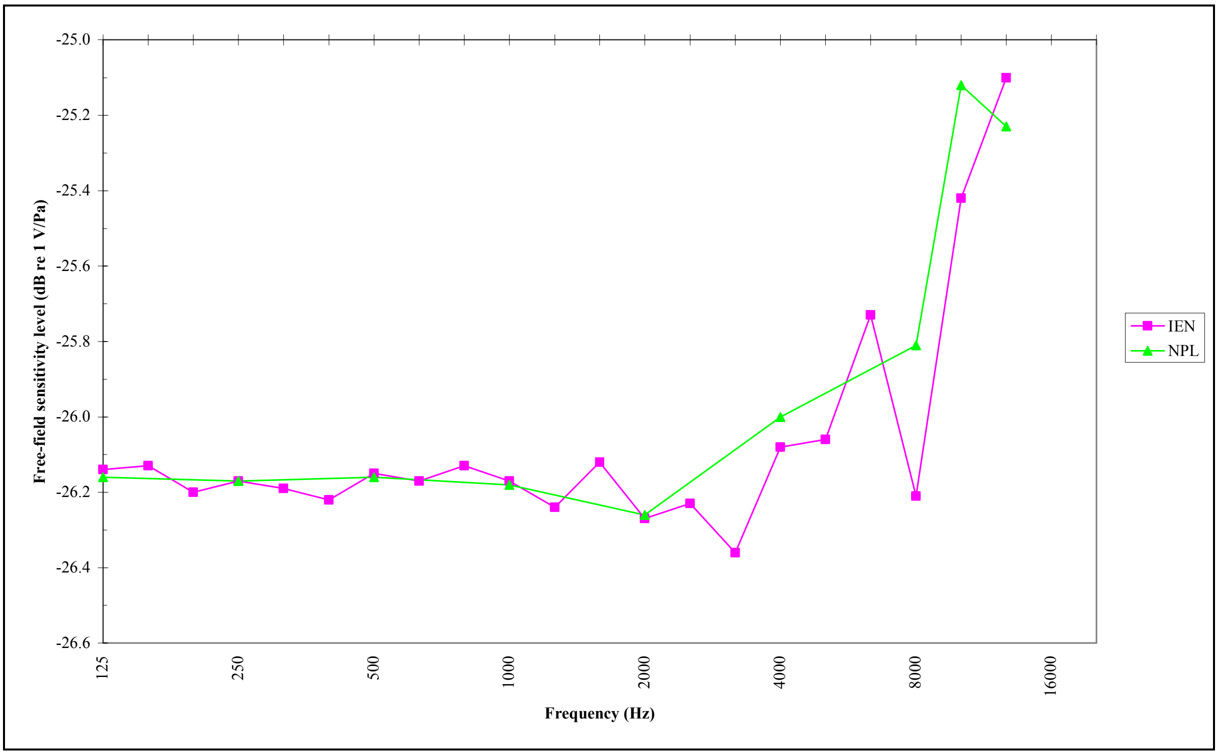
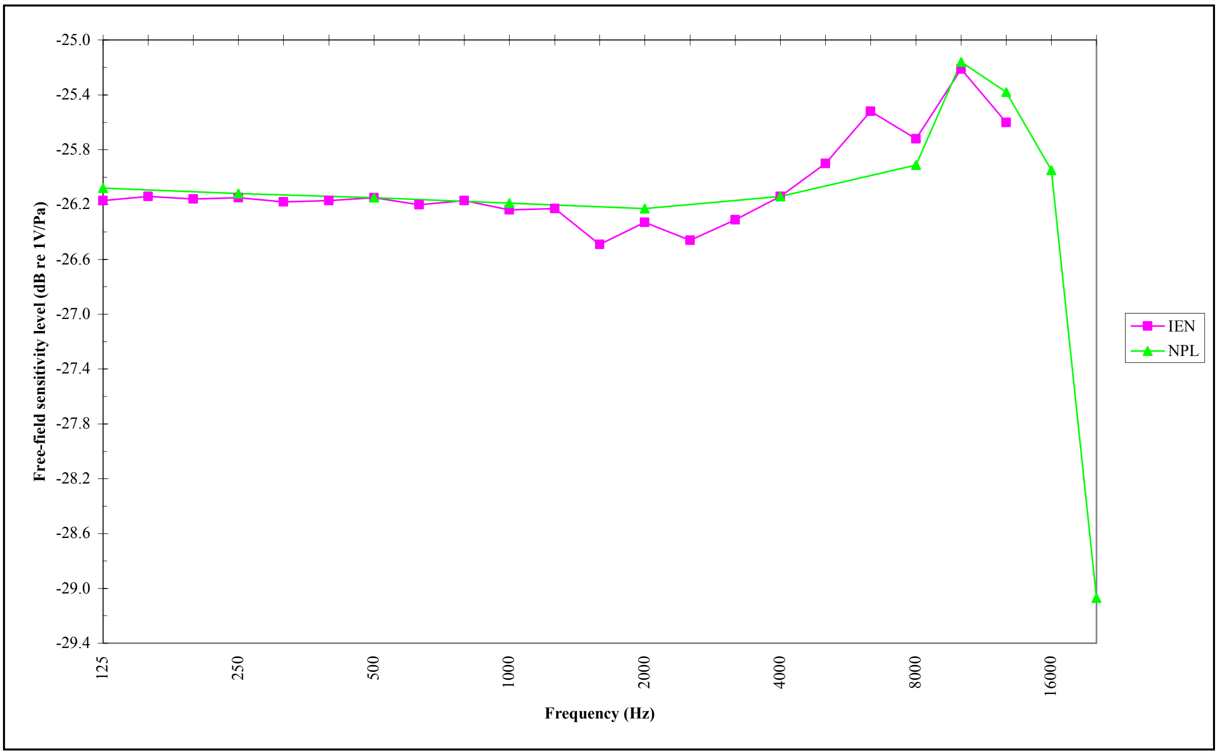


Figure 3. Uncorrected L_{Mf} of 4145 2071918 measured using an LS2P reference microphone



3.3 4145 2071917

Figure 4. Uncorrected L_{Mf} of 4145 2071917 measured using an LS1P reference microphone

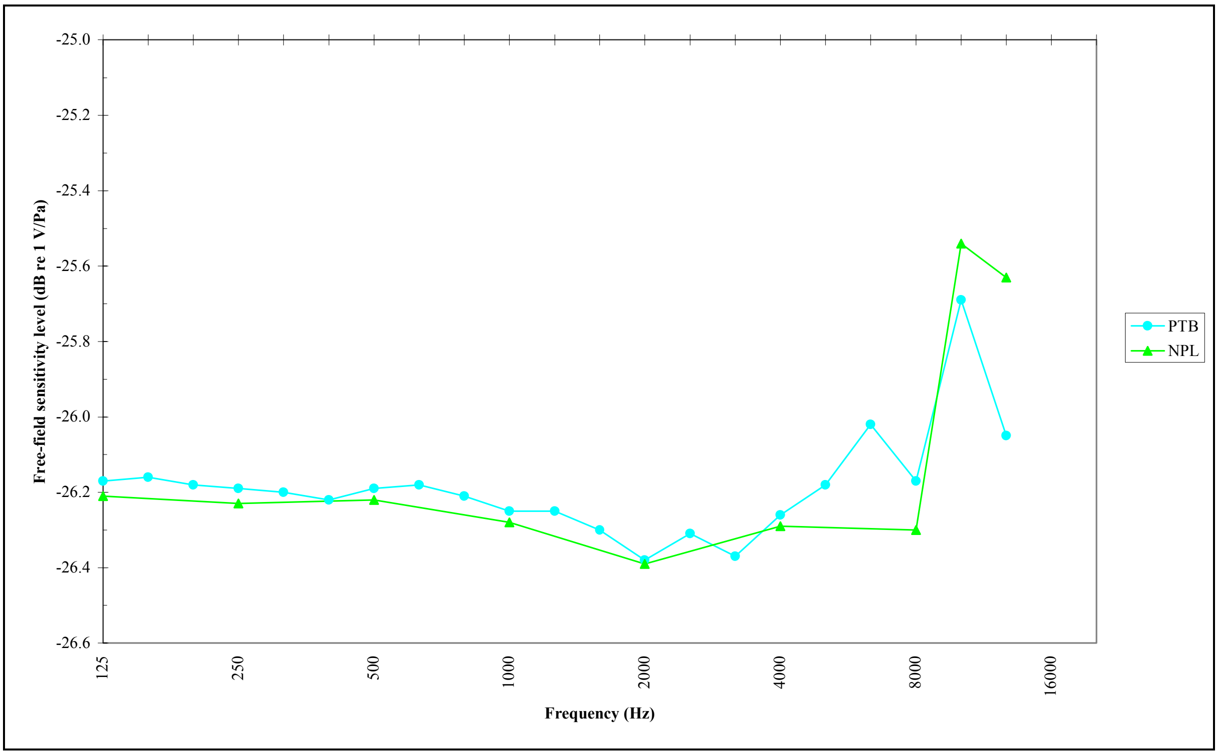
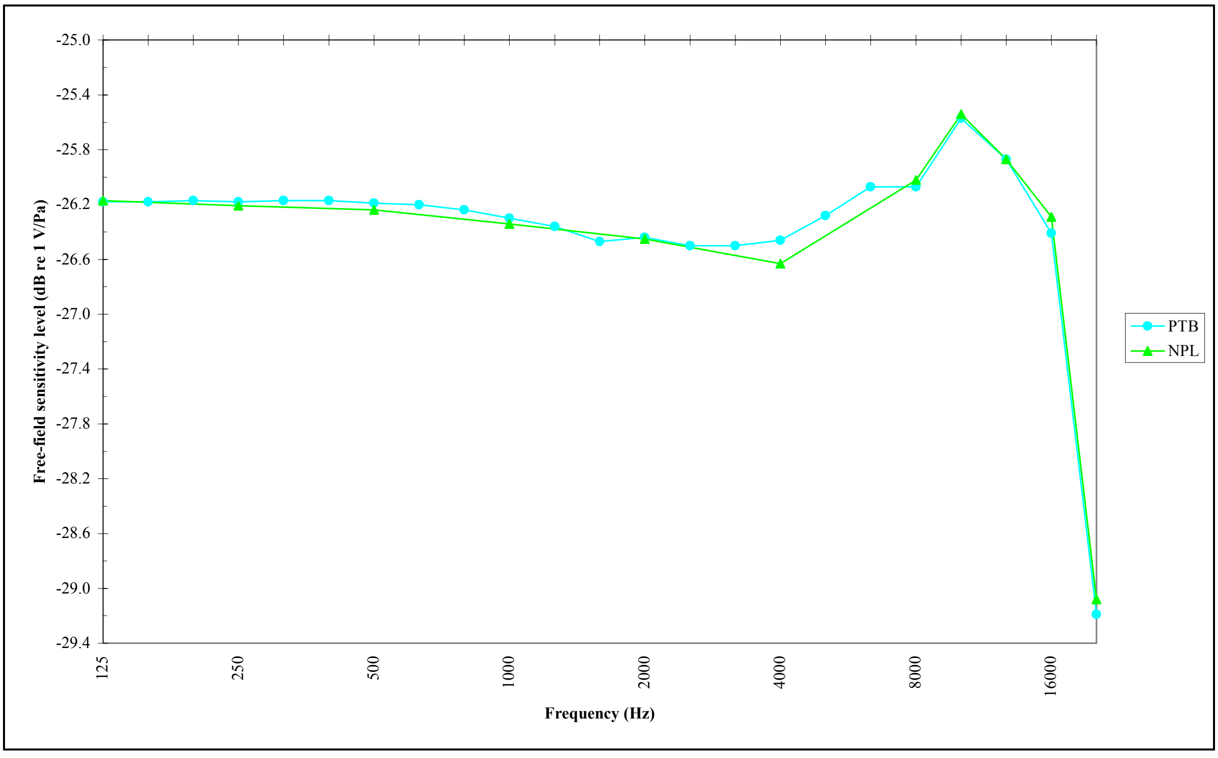


Figure 5. Uncorrected L_{Mf} of 4145 2071917 measured using an LS2P reference microphone



3.4 DEVIATION FROM GRAND MEAN

Figure 6. Deviation of uncorrected L_{Mf} from grand mean (LS1P reference microphone)

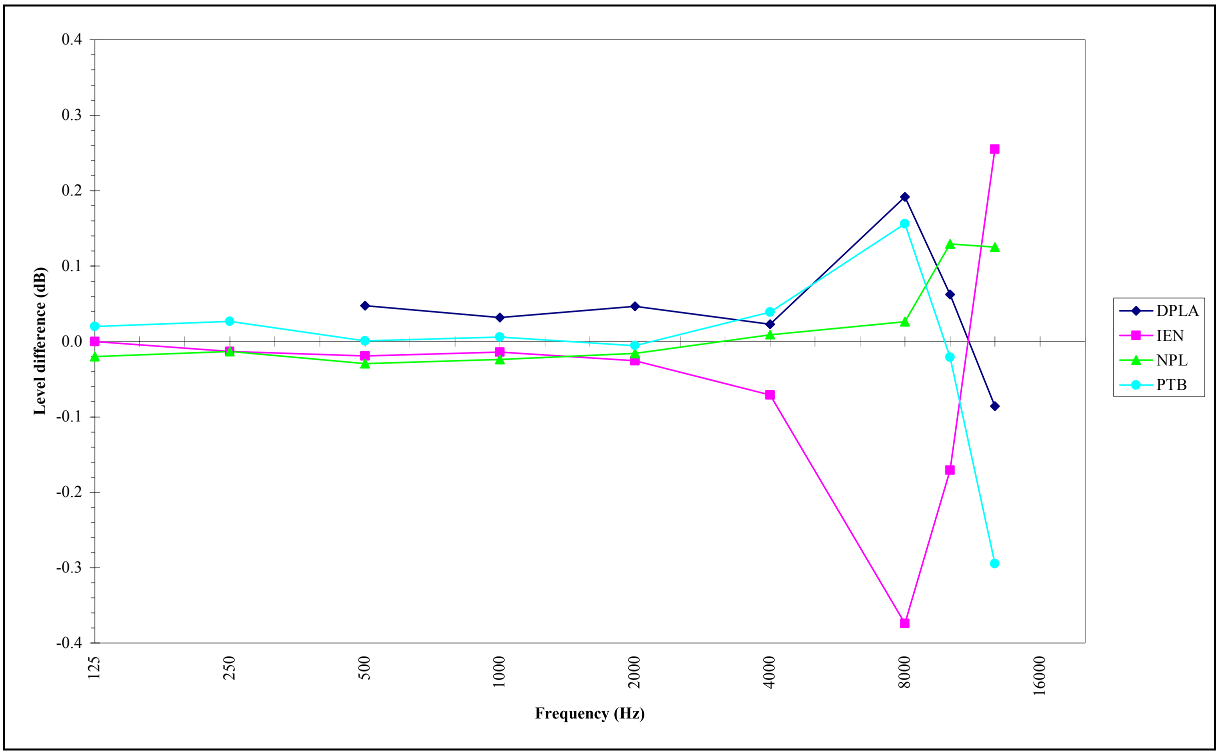
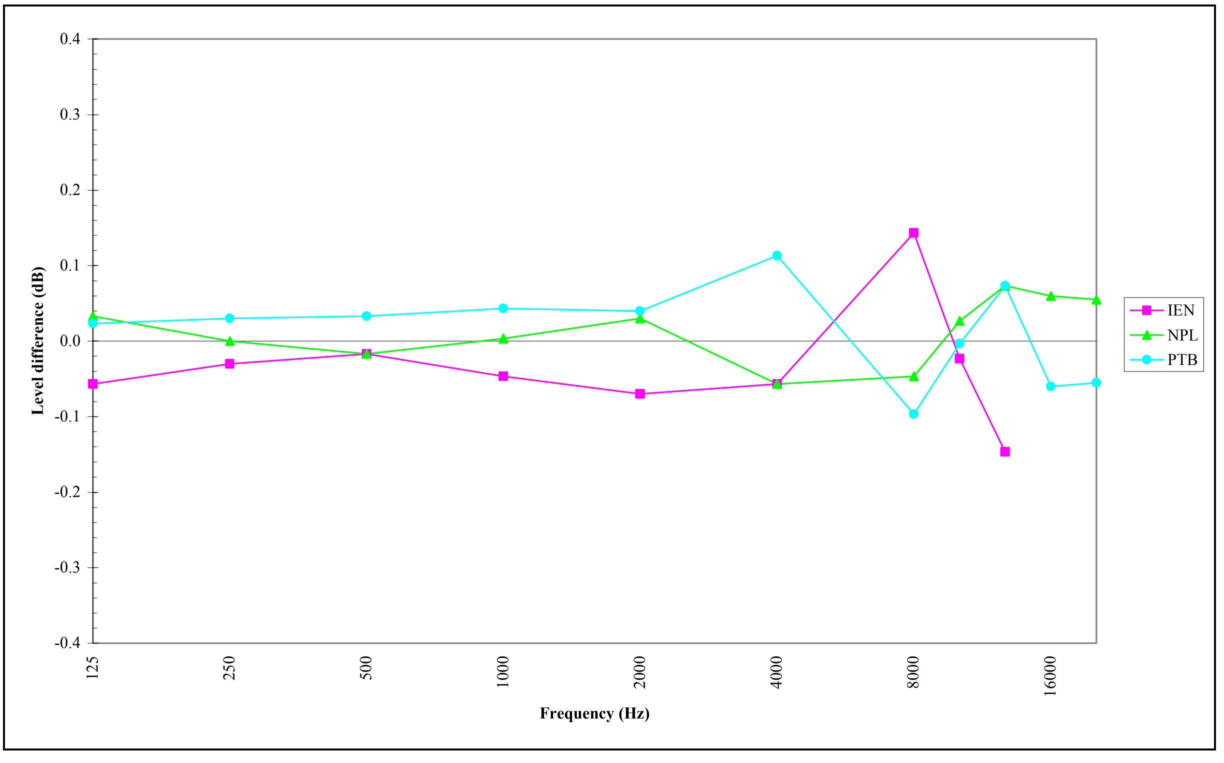


Figure 7. Deviation of uncorrected L_{Mf} from grand mean (LS2P reference microphone)



4. DISCUSSION

4.1 MEASUREMENT UNCERTAINTIES

Budgets for measurement uncertainties or estimates of individual uncertainty contributions for all four laboratories are given in Appendix 4. The expanded uncertainties reported by the laboratories are dependent on frequency and on the configuration of the reference microphone, although IEN derived an overall uncertainty based on results using both reference microphones; the values are listed in Table 1. Although the contributions have been assessed slightly differently by each laboratory, the expanded uncertainties are consistently less than ± 0.20 dB at frequencies of 4 kHz and below. At higher frequencies, the expanded uncertainties increase, to maxima of ± 0.31 dB for DPLA, ± 0.24 dB for PTB, ± 0.34 dB for NPL and ± 0.72 dB for IEN.

Table 1. Summary of expanded uncertainties of calibration

Lab	Expanded uncertainty (± dB) at frequency (kHz) using an LS1P reference microphone									
	0.125	0.25	0.5	1.0	2.0	4.0	8.0	10.0	12.5	16.0	20.0
DPLA	-	-	0.11	0.11	0.11	0.11	0.22	0.24	0.31	-	-
IEN	0.07	0.07	0.12	0.18	0.16	0.19	0.62	0.72	0.59	-	-
NPL	0.12	0.12	0.16	0.16	0.16	0.17	0.26	0.27	0.34	-	-
PTB	0.07	0.07	0.12	0.12	0.12	0.14	0.24	0.24	0.24	-	-
Lab	Expanded uncertainty (± dB) at frequency (kHz) using an LS2P reference microphone										
	0.125	0.25	0.5	1.0	2.0	4.0	8.0	10.0	12.5	16.0	20.0
IEN	0.07	0.07	0.12	0.18	0.16	0.19	0.62	0.72	0.59	-	-
NPL	0.13	0.13	0.16	0.16	0.16	0.17	0.26	0.27	0.27	0.28	0.31
PTB	0.09	0.09	0.14	0.14	0.14	0.15	0.24	0.24	0.24	-	-

The effects of the most significant sources of uncertainty on the expanded uncertainties are considered below.

4.1.1 Repeatability

The repeatabilities of measurement, in terms of the sample standard deviation divided by the square root of number of replications, at DPLA, NPL and PTB are 0.06 dB or less. The repeatabilities for IEN are typically 0.04 dB at the lower frequencies but increase to up to 0.22 dB above 4 kHz: this may be because the arrangement for suspension of the microphone in the room was less steady during each replication than was achieved in the other laboratories, because of greater variation in air temperature during each replication, or because of the fittings or quality of absorbent material in the free-field room.

The repeatability is a Type A component of uncertainty, and the repeatability for IEN at frequencies above 4 kHz is sufficiently great to require use of a coverage factor greater than 2.00 in calculating the expanded uncertainty. The greater repeatability is one cause of the expanded uncertainties reported by IEN being greater than those for the other laboratories.

4.1.2 Calibration of reference standard microphone

The expanded uncertainties in the pressure calibrations of the reference microphones range from ± 0.03 dB (DPLA, NPL, PTB) and ± 0.05 dB (IEN) for the LS1P at low frequencies to ± 0.06 dB (PTB), ± 0.12 dB (IEN) and ± 0.22 dB (NPL) for the LS1P at 12.5 kHz.

The NPL expanded uncertainty of 0.22 dB includes a component to due radial non-uniformity of the sound pressure in the coupler. It is likely that this non-uniformity will also occur in the pressure reciprocity calibrations performed by the other laboratories, and the uncertainties quoted are likely to be underestimate the true measurement pressure reciprocity uncertainties at 12.5 kHz. Therefore the uncertainties in the free-field comparison calibration at IEN and PTB at this frequency are likely to be higher than those reported.

4.1.3 Influence of air temperature and static pressure

None of the laboratories made corrections to the results for the influence of static pressure and air temperature on the microphones. The NPL uncertainty budget includes contributions for the effect on the sensitivity level of the reference microphone of changes in static pressure and air temperature from the reference conditions at which the microphone was calibrated. During the measurements at PTB, the environmental conditions were very close to the reference conditions, so uncertainty contributions of zero were used in the uncertainty budget.

4.1.4 Performance of free-field room

The estimates of the uncertainty introduced by non-ideal performance of the free-field room varied between the laboratories. DPLA claim an influence of much less than 0.1 dB at the chosen source-microphone distance, calculated by considering the effects of differences in the positions of the acoustic centres of the reference and test microphones, uncertainties in the positioning of the microphones, and differences in the directivity patterns of the microphones.

IEN provided estimates that generally increased with frequency from 0.0 dB to 0.5 dB. The estimates were calculated from the differences in the measured L_{Mf} of the microphone under test when using the two types of reference microphone.

NPL includes no uncertainty contribution for the performance of the room. The free-field sensitivity levels are averaged from the results from the six replications performed at different source-microphone distances in order to negate any imperfection in room performance.

PTB estimates an influence of between 0.04 dB and 0.10 dB that increases with frequency. The uncertainty contribution due to difference in acoustic centre of microphones was calculated separately (see 4.1.5).

DPLA, IEN and NPL determined rmsd within their free-field rooms. Over the ranges of source-to-microphone distances used in the calibrations, the rmsd did not exceed 0.09 dB for NPL and PTB at frequencies up to and including 20 kHz, and did not exceed 0.23 dB for IEN at frequencies up to and including 12.5 kHz. PTB's investigations of free-field room performance showed some deviation between measured and ideal free-field levels in the range of distances used in the calibrations, with the differences assumed to mostly be due to the loudspeaker arrangement and housing.

The rmsd does not provide an uncertainty contribution for the comparison calibration, especially where measurements are made at one fixed source-microphone distance. The influence of the room performance will be strongly dependent on the differences in directivity pattern of the reference and test microphone and on the accuracy of positioning the microphones in the room.

IEC 61094-3 recommends that "deviations from the inverse pressure/distance law, excluding the air attenuation, should not be greater than 0.05 dB in the region between the source and the receiver microphone during a calibration" by the free-field reciprocity technique[4]. Any standardised method of calibration by comparison must allow much greater deviation from ideal free-field conditions to cover the rooms in which the comparison measurements are likely to be made.

4.1.5 Difference in acoustic centres
DPLA estimate that a difference of 1 mm in the position of the acoustic centres of the reference and test microphone will result in an error of 0.02 dB. It is assumed that the position of the acoustic centre for type 4145 fitted with a LS1 adaptor will be the same as for a Brüel & Kjær type 4160 microphone, while some difference (yet to be quantified) can be expected at higher frequencies when the microphone is fitted with its normal protection grid or without grid at all.

PTB calculated the acoustic centres of the laboratory standard reference microphones. The difference between the two acoustic centres was found to be 4.4 mm at 1 kHz; the difference reduced with increasing frequency. PTB determined an estimate of the influence of this difference in acoustic centre, that could be applied as a correction to the sensitivity levels that were determined using the LS2P reference microphone. The necessary correction was estimated as -0.03 dB at frequencies up to 1 kHz, reducing in magnitude with increasing frequency (Appendix 6). However, applying these corrections was seen to actually increase the difference between the values of L_{Mf} determined with the different reference microphones. However, the actual values of acoustic centre, change of sound field and location of the measurement point were not exactly known, and so it is recommended that the difference in acoustic centres be treated as an uncertainty rather than a correction.

4.2 COMPARISON OF UNCORRECTED FREE-FIELD SENSITIVITY LEVELS
Figure 6 and Figure 7 show that the spread of differences between all laboratories is less than 0.12 dB at frequencies up to and including 2 kHz. The true spread of differences when using the LS1P reference microphone may be up to 0.02 dB less than that indicated in Figure 6, because of the error introduced by DPLA's probable use of a preamplifier with a grounded ground-shield configuration. The differences increase to give a spread of about 0.6 dB at 8 kHz and 12.5 kHz when using an LS1P reference microphone, and of about 0.24 dB at the same frequencies when using an LS2P reference microphone.

The larger spread with the LS1P reference microphone is due to the IEN results. The DPLA, NPL and PTB results agree within 0.2 dB in all instances except when using LS1P reference microphone at 12.5 kHz. This exception is likely to be caused by the difficulty in determining the pressure sensitivity of the LS1P microphone at this frequency. The IEN results do not agree so closely, and differ from the results from the other laboratories by about 0.4 dB at 8 kHz when using the LS1P reference microphone. The IEN uncertainty budget shows that non-uniformity of the free-field is the dominant factor at these two frequencies, and the standard deviation of the measured sensitivity levels is also large at these frequencies. The difference in sensitivity patterns between the WS1F and LS2P microphones is greater than the difference in sensitivity patterns between the WS1F and LS1P microphones; however, using the LS2P as reference microphone does not appear to provide the expected worse agreement between laboratories.

The between-laboratory differences, given the calculated expanded uncertainties of measurement, show satisfactory agreement between all laboratories at all frequencies.

4.3 CORRECTIONS FOR EFFECTS OF ENVIRONMENTAL CONDITIONS

The effects of changes in air temperature and static pressure on the free-field responses of laboratory standard microphones are estimated in IEC 61094-3[4], although the estimates of temperature coefficient are known to be unreliable. The effects of changes in these conditions on the free-field responses of working standard microphones are even less well-known.

In spite of the paucity of information, corrections to the free-field sensitivity levels reported by each participant for the effect of air temperature, t (°C), and static pressure, P (kPa) were calculated. The corrections were calculated as:

$$C = \left(\delta_{t,LS} - \delta_{t,4145}\right)(t - 23) + \left(\delta_{P,LS} - \delta_{P,4145}\right)(P - 101.3)$$

where δ_t is the temperature coefficient (dB/K) of L_{Mf} and δ_P is the static pressure coefficient (dB/kPa) of L_{Mf}.

δ_t and δ_P of L_{Mf} for the 4145 microphones are not known. However, δ_t and δ_P of the pressure responses of 4145 2071917 and 4145 2071918 were determined by DPLA before distribution of the microphones. δ_t and δ_P for 4145 1102232 were estimated from values for other 4145 microphones. In the absence of coefficients for the free-field response, these pressure-response values have had to be used in performing the corrections for the effects of environmental conditions.

δ_t and δ_P for the LS1P microphones were calculated from IEC 61094-3[4], offset by low frequency values[11]. Without more specific information, it was assumed that the resonance frequencies f_0 were 8.5 kHz for all the LS1P microphones and 21.6 kHz for all the LS2P microphones.

The values of t and P used were the means of the ranges reported by each laboratory. Since the measurements were performed over a number of days, and the environmental conditions fluctuate during individual days, the mean temperature and static pressure only approximate the actual values. The correct values of the environmental coefficients are also unknown, as discussed above. Therefore, the corrections calculated are unlikely to truly correct for the influence of temperature and static pressure on the calibration results, especially at the higher frequencies (around and above f_0) for the results using LS1P reference microphone, where the coefficients have zero crossings and turning points, and f_0 itself may differ from the assumed value[11].

The deviations of the corrected sensitivity levels from the recalculated grand means are shown in Figure 8 and Figure 9. The only significant change is to the deviation of the IEN results from the grand mean for the LS2P reference microphone, because the measurements at IEN were carried out at higher temperatures than pertained at the other laboratories. For the results with the LS1P reference microphone, the spread of the levels is unchanged at frequencies below 8 kHz, slightly reduced at 8 kHz and 10 kHz and increased at 12.5 kHz by an increase in the difference from the mean of the IEN result. For the LS2P reference microphone the spread of levels is reduced to no more than 0.05 dB below 4 kHz, but increased at 4 kHz and higher frequencies.

The corrected sensitivity levels show satisfactory agreement in all cases, given the measurement uncertainties. However, it can be seen that IEN underestimate by about 0.3 dB the level reported by the other laboratories at 8 kHz and overestimates by about 0.3 dB the level reported at 12.5 kHz, for both the LS1P and LS2P reference microphones.

Figure 8. Deviation of corrected L_{Mf} from grand mean (LS1P reference microphone)

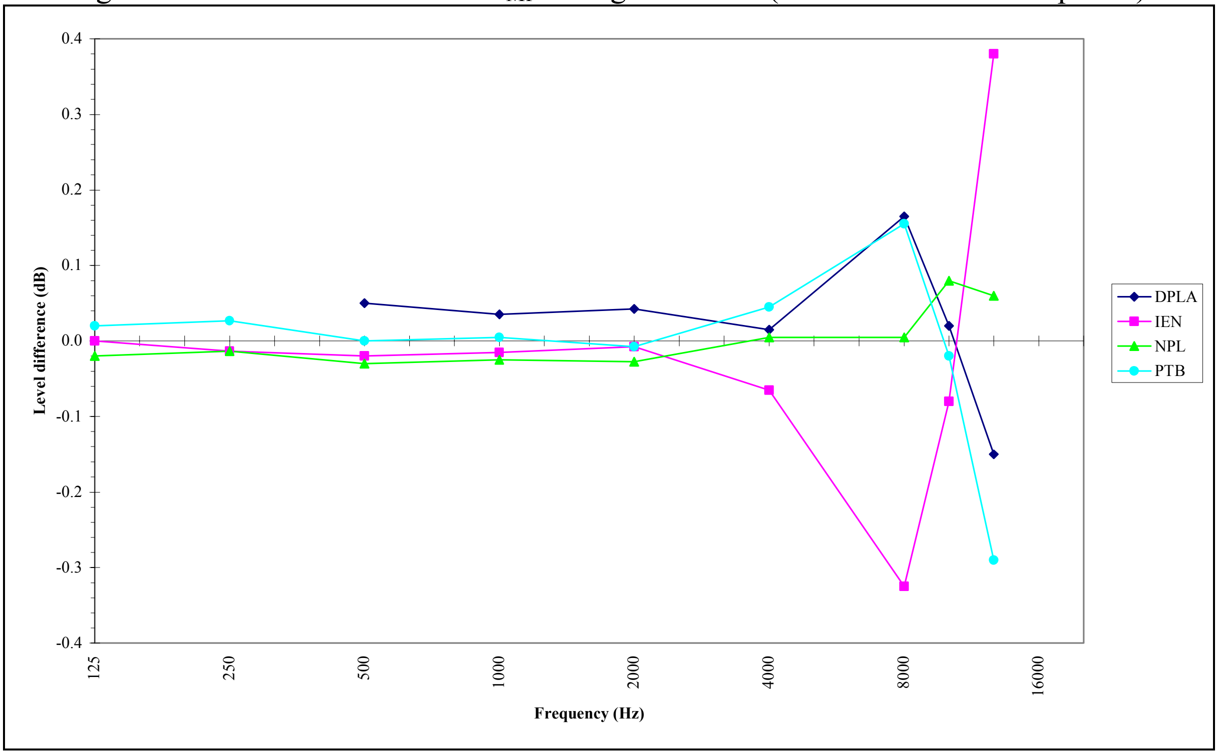
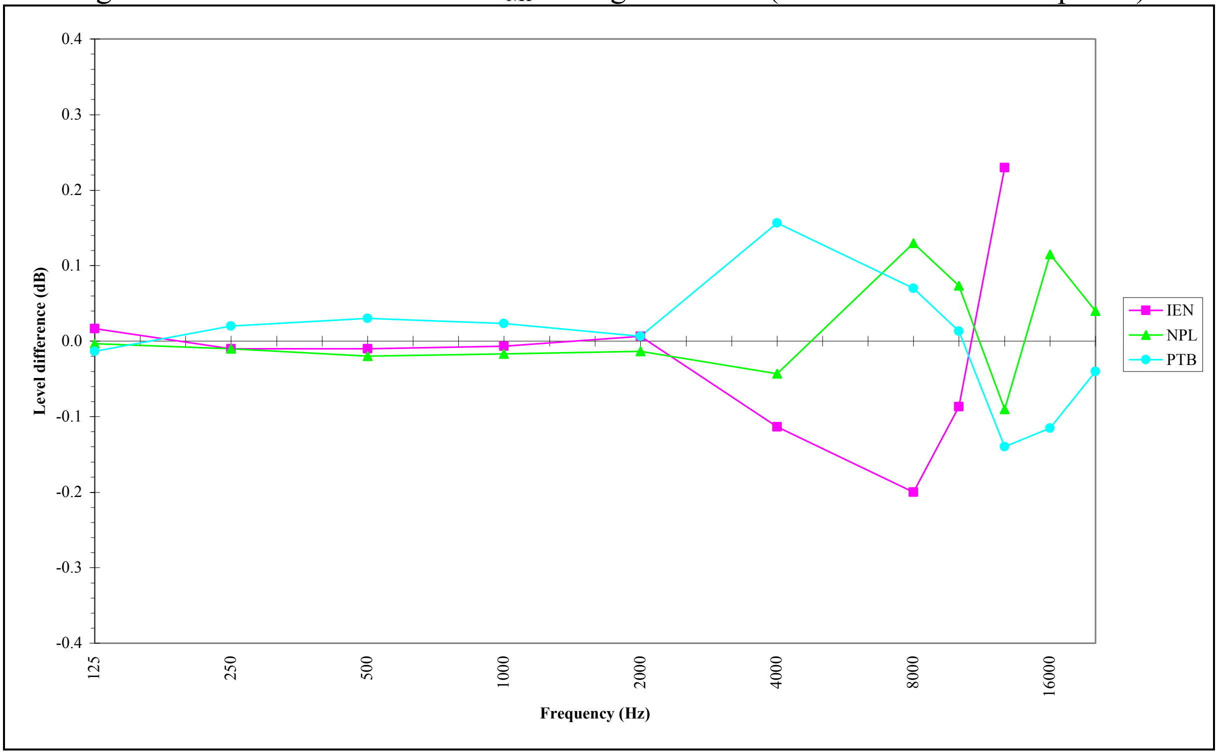


Figure 9. Deviation of corrected L_{Mf} from grand mean (LS2P reference microphone)



4.4 USE OF ALTERNATIVE FREE-FIELD CORRECTIONS

Alternative values of the free-field corrections $\Delta_{f,p}$ for the LS1P and LS2P microphones were calculated by PTB and are listed in Appendix 7. The differences in the WS1F sensitivity levels when calibrated using LS1P and LS2P reference microphones were recalculated using the new values of $\Delta_{f,p}$. The original and recalculated differences are shown in Appendix 7. Apart from 12.5 kHz, where no recalculation was possible, the magnitude of the greatest difference in the PTB results was reduced from 0.20 dB to 0.06 dB. Applying the recalculated values of $\Delta_{f,p}$ to the temperature- and pressure-corrected results of the other participants also generally improved the agreement of their results to a lesser extent, but in some cases between 1.25 kHz and 8 kHz the difference was increased slightly. This reflects the imprecision in the corrections applied as discussed above, the differences between the reference microphones employed by each laboratory, and that $\Delta_{f,p}$ itself will have static pressure and temperature coefficients that vary with the construction of individual microphones.

On the basis of their results, PTB suggest that the comparison method may be suitable for checking $\Delta_{f,p}$ of different laboratory standard microphones at frequencies up to 10 kHz, and may provide an easier method than free-field reciprocity measurements for determining $\Delta_{f,p}$ for working standard microphones. It is certainly likely that, in the future, a combination of calculation of $\Delta_{f,p}$ using the known properties of laboratory standard microphones and further measurements made under carefully controlled conditions will provide better estimates of $\Delta_{f,p}$ than those provided in the measurement protocol, with uncertainties of about half of the values assumed for this project.

4.5 FUTURE DEVELOPMENTS

IEN consider that the results demonstrate the need to improve uncertainty of comparison calibrations at IEN by the following:

- use of the room in semi-anechoic configuration with the source flush with the floor, in order to reduce diffraction around the source and improve the volume of the room
- use of MLS measurements, followed by echo removal and transfer function evaluation

PTB identified further work required in:

- testing the sound source positioned in the centre of the room
- finding a more convenient loudspeaker type and arrangement
- measuring Type A uncertainty contributions
- recalculating the expanded uncertainty of measurement

In general, there is a need to examine the following issues:

- use of 'non-traditional' (eg MLS) techniques
- determining the influence of the performance of the free-field room
- standardisation of $\Delta_{f,p}$, with reduced uncertainty
- investigation of the effect of difference of acoustic centres of microphones
- arrangements of apparatus

5. CONCLUSIONS

The free-field sensitivity levels of the WS1F microphones calibrated by sequential comparison with a laboratory standard reference microphone at DPLA, IEN, NPL and PTB agreed satisfactorily at all frequencies. Using an LS1P reference microphone at frequencies up to 10 kHz and an LS2P reference microphone at frequencies up to 20 kHz resulted in a spread of inter-laboratory differences between corrected levels of less than 0.12 dB at frequencies up to and including 2 kHz, and of less than 0.5 dB at higher frequencies.

The expanded uncertainties of measurement quoted by the laboratories were sufficient to explain all the between-laboratory differences. However, the uncertainty budgets provided were not completely consistent, with some contributions either not included or considered to be negligible by some of the participants. All participants may wish to review their uncertainty budgets in the light of the contributions identified by the other laboratories.

The most consistent agreement was found between those laboratories who were able to use dedicated or other well-established facilities and measurement systems. In these cases, the spread of measured sensitivity levels was less than 0.25 dB at all frequencies. Where uncertainty contributions from field non-uniformity or repeatability of results (due to the performance of the room, positioning of the microphone or changes in environmental conditions between replications) dominate the uncertainty budget, expanded uncertainties of up to about 0.8 dB were recorded and differences in measured sensitivity levels of about 0.4 dB can occur. DPLA, IEN and NPL measured the root mean square deviation from ideal free-field conditions as a measure of the performance of their free-field rooms, but rmsd does not provide a quantitative estimate of the influence of the room performance on the results of a comparison calibration.

PTB calculated new values of $\Delta_{f,p}$ for LS1P and LS2P microphones that generally gave better agreement between calibrations with the two types of reference microphone than the provisional values of $\Delta_{f,p}$ provided in the measurement protocol.

The participants identified a number of areas in which they wish to examine or develop their existing measurement systems. Some of these issues, especially that of determining the influence of the free-field room, must be resolved before the method of free-field calibration by comparison can be standardised.

6. ACKNOWLEDGEMENTS

The work at DPLA was carried out by Knud Rasmussen. The work at IEN was carried out by Claudio Guglielmone and A Agostino. The work at PTB was performed by Utz Richter and Jürgen Beckmann. DPLA supplied three Brüel & Kjær type 4145 microphones for use in the project.

Duncan Jarvis initiated the work at NPL, as the UK EUROMET contact person for acoustics. Stephen Watkins and Karen Smart performed some of the calibrations of the microphones at NPL. Stephen Watkins evaluated the performance of the NPL free-field room. The author acknowledges the financial support of the National Measurement System Policy Unit of the UK Department of Trade and Industry for the work carried out at NPL.

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APPENDIX 1. LIST OF PARTICIPANTS

Knud Rasmussen
Danish Primary Laboratory for Acoustics
c/o Dept of Acoustic Technology
Building 352
Danmarks Tekniske Universitet
DK-2880 Lyngby
Denmark

Claudio Guglielmone
Istituto Elettrotecnico Nazionale
"Galileo Ferraris"
Strada delle Cacce 91
I-10135 Torino
Italy

Peter Hanes
Centre for Mechanical and Acoustical Metrology
National Physical Laboratory
Teddington
Middlesex
United Kingdom TW11 0LW

Utz Richter
Physikalisch Teknische Bundesanstalt
Postfach 33 45
38023 Braunschweig
Germany

APPENDIX 2. PROTOCOL FOR MEASUREMENTS

PART 1: CALIBRATION OF WS1F MICROPHONES

Measurement method.
The free-field sensitivity of the supplied type WS1F (Brüel & Kjær 4145) microphone shall be determined using the method normally used by your laboratory for comparison calibrations, and by any other comparison method that you wish to employ.

Reference microphones.
The sensitivity of the WS1F microphone should be determined by comparison with reference microphones of types LS1P and LS2P. It is anticipated that these reference microphones will have been calibrated by pressure reciprocity method; the free-field sensitivity levels for the reference microphones shall be calculated using the following corrections to the pressure sensitivity level:

Frequency (kHz)	Free-field/pressure sensitivity level differences (dB)		Uncertainty (95 % confidence) (dB)
	Type LS1P	Type LS2P	
0.500	0.07	0.00	± 0.10
0.630	0.11	0.00	± 0.10
0.800	0.17	0.00	± 0.10
1.000	0.24	0.00	± 0.10
1.250	0.41	0.00	± 0.10
1.600	0.67	0.00	± 0.10
2.000	0.99	0.20	± 0.10
2.500	1.60	0.34	± 0.10
3.150	2.37	0.56	± 0.10
4.000	3.59	0.95	± 0.10
5.000	5.01	1.49	± 0.10
6.300	6.86	2.39	± 0.20
8.000	8.35	3.61	± 0.20
10.000	9.17	5.06	± 0.20
12.500	8.93	6.79	± 0.20
16.000	-	8.31	± 0.20
20.000	-	8.59	± 0.20

Note: At frequencies below 0.5 kHz, no correction should be made. For this project, the differences listed in the table shall be used, in order to facilitate the comparison of results obtained from the various participating laboratories. [Free-field/pressure sensitivity level differences will be standardised in the future in a new part of IEC 61094.]

Results to be reported.
Free-field sensitivity levels with the associated expanded uncertainties for a level of confidence of 95 %, calculated according to the *Guide to the expression of uncertainty in measurement* (ISO Information Publication:1995, ISBN 92-67-10188-9). Include free-field sensitivity levels at octave-band centre frequencies from 125 Hz to 8 kHz, plus 12.5 kHz. Sensitivity levels at other frequencies should be reported if measured.

Comments to be reported.
The following details should be submitted with the results of the measurements:

- the chamber(s) in which the work was performed (dimensions, construction, anechoic lining, previously-determined performance of chamber etc)
- reference microphones (type, model, serial number, calibrated pressure sensitivity levels etc)
- instrumentation used (function, type, interconnections, software etc)
- the noise source (loudspeaker type, positioning etc)
- the microphone positions relative to the noise source
- the sound pressure levels at the microphone position
- environmental conditions (air temperature, static pressure and relative humidity) prevalent during the measurements
- other experimental information (number of replications performed, problems, criteria for accepting results, other checks of results etc)
- source and magnitude of contributions (systematic and random) to measurement uncertainty

Preferred format for submitted results and comments.
Microsoft Word- or Excel-compatible file formats are preferred for the submission of results and comments.

PART 2: EVALUATION OF PERFORMANCE OF FREE-FIELD ROOM

One important factor in the accuracy of the comparison calibrations is the quality of free-field in which the measurements are performed. It will be useful to have an indication of the performance of the free-field rooms used by the participating laboratories.

Measurement method.
In the absence of a standardised method for assessing the performance of a free-field room, the following method shall be used to determine the root mean square deviation (rmsd) from ideal free-field conditions. This quantity is a single figure for the performance of the room at a particular frequency. To determine the rmsd, a WS2F microphone is moved to different positions along a straight line path from the sound source in the free-field room, and the (amplified) output of the microphone at each position in response to a constant level signal from the sound source is recorded. The straight line path is that on which the microphone is positioned during the comparison calibration of microphones, and is usually along the axis of the sound source. It shall cover at least the positions at which the microphones are positioned during the comparison calibrations. The line of best fit for the inverse of the measured pressure versus the distance along the path is calculated, allowing for the effect of air attenuation. At each distance, the deviation between this line and the measured value is calculated. The rms value of the deviations can then be calculated.

In order to keep constant the level from the sound source the use of another microphone, positioned close to the source, is recommended. This could be used as an independent monitor of the output from the sound source, or as part of a compressor/feedback system for maintaining a constant level from the sound source.

The microphone may be traversed continually or in discrete steps along the straight line path. In either case, readings of the signal from the microphone should be taken at intervals of no greater than 2 cm along the straight line path. At the end of the traverse, the microphone should be returned to the first point on the path, and its output compared with that measured earlier at the same point: the dB difference between the two measurements should be noted. If the difference is greater than 0.1 dB, the experimental arrangement should be reviewed to see whether the positioning system or stability of signal level can be improved, and the traverse repeated.

Results to be reported.
The supplied Microsoft Excel workbook contains separate worksheets for each frequency under investigation. The frequencies at which measurements should be made are the same as those in part 1 of this protocol. The worksheets can be copied to allow measurements at additional frequencies. The results for each frequency should be entered into the cells with green backgrounds in the first two columns of the appropriate worksheet. The data to be entered are the signal frequency, static pressure, air temperature and relative humidity measured within the chamber, and the sound pressure signal as a voltage versus the distance from the sound source. Additional rows for the data in columns A-H shall be copied to include the results from every measurement position along the straight line path.

All calculations are performed within the workbook, and the full spreadsheet should be returned to NPL at the end of the work.

Comments to be reported.
The following details should be submitted with the results of the measurements:

- any changes to the chamber(s), instrumentation, noise source as described in Part 1
- microphones used (type, model, serial number)
- the microphone positions, relative to the noise source, at which your laboratory would permit comparison calibrations to be performed
- other experimental information (problems, number of measurements performed, criteria for accepting results, other checks of results etc)

Preferred format for submitted comments.
For information additional to that supplied on the pre-formatted spreadsheets, Microsoft Word-compatible file formats are preferred for the submission of comments.

APPENDIX 3. FACILITIES

DPLA

DPLA/DTU possesses a large (1000 m^3) anechoic chamber, in which experimental setups have been tested in the past. Mechanical problems in obtaining an exact positioning of source and test microphones during measurements, as well as the stability over time of the source and the environmental conditions were found. These problems have meant that it has not been possible to develop in the large chamber a comparison calibration technique for which:

- the calibrations are easy to perform
- the measurement period is short enough to avoid stability problems
- the reproducibility is 0.05 dB or better

The free-field correction below 1 kHz can be predicted/calculated with an uncertainty equal to or smaller than obtained by a comparison calibration, and so DPLA is giving priority to comparison calibrations at 1 kHz and higher. Therefore, measurements were carried out in a small anechoic room (free space 1.8 m^3) designed for free-field reciprocity calibrations and located in a temperature-controlled room. The free dimensions of the chamber are $0.85 \times 1.20 \times 1.75$ m. The room is lined with mineral wool wedges with base of 70×70 mm^2 and a length of 300 mm. The pressure reflection factor of the wedges is less than -30 dB above 1 kHz for perpendicular incidence. Two vertical telescopic rods of 12.5 mm diameter house the receiver preamplifier and the transmitter driver for use in free-field reciprocity. The source and microphone can be located within 0.1 mm.

IEN

The room used for free-field calibration is not a conventional anechoic room for research purposes: it is mainly a semi-anechoic room for sound power measurements, over whose floor a sound absorbing floor made of fibreglass wedges can be placed. Obviously this solution is a compromise: the height of the room, adequate for the semi-anechoic configuration, becomes too small. It is not possible to set solid posts to fix loudspeakers or microphones etc on the removable floor. Therefore threaded steel bars from the ceiling are used to suspend microphones or other light equipment. The walls are 40 cm thick and are made of solid bricks and the room floor perimeter rests on omega-shaped steel springs for insulation from vibration. The typical noise floor is around 20 dB SPL.

The floor of the room is partly (around 20%) covered by aluminium grids resting on steel frames that encircle four wedges: all the grids except the one under the source tripod were removed for the measurements and room evaluation. The dimensions of the room (at wedge tips) are 10.32 m (length) × 6.70 m (width) × 3.75 m (height). The wedges are 1.00 m long with a solid base of 0.4 m × 0.4 m × 0.25 m and are made of glass fibre; unfortunately the outer part is made of a much denser material then that of the inner core, thus providing non-optimal impedance adaptation.

The sound source used was a co-axial loudspeaker system KEF Uni-Q type KAR 160 Q mounted in a 40 litre box. The unit is made of a 160 mm woofer and of a co-axial 25 mm tweeter mounted at the apex of the woofer cone.

The microphone was positioned on a Brüel & Kjær type 2645 insert voltage preamplifier inserted in a stainless steel pipe 1.2 m long and of the same diameter of the preamplifier. The pipe was suspended to the ceiling by a system of nylon wires and a threaded steel bar. The position of the microphones was checked by using the beams of two laser diodes. The centre of the diaphragm or of the protection grid was positioned at the crossing of the two beams. The repeatability of the positioning is estimated to be 1 mm.

A monitor microphone Brüel & Kjær type 4134 1430138 was placed 0.05 m from the woofer suspension plane in front of the centre of the loudspeaker. This microphone was used to monitor the acoustical output of the source and hence compensate for any drift due to voice coil heating. The power to the loudspeaker was held constant at 1 W.

Sound pressure levels at the microphone generally increased with frequency from 63 dB at 125 Hz to 82 dB at 12.5 kHz. The outputs of the two microphones (monitor and reference or test) were fed to a Brüel & Kjær type 2133 third-octave analyser. The connection of the monitor microphone was direct via a Brüel & Kjær type 2639 preamplifier; the reference/test microphone was connected to a insert voltage preamplifier Brüel & Kjær type 2645 to a IEN switching box that enabled the insertion of a voltage from a Keithley 3930A generator and then the Brüel & Kjær analyser.

The sensitivity of the two channels was approximately adjusted by calibrating the two channels by means of a Brüel & Kjær type 4228 pistonphone: the results do not depend on the accuracy of this calibration since the output of the reference/test microphone were determined by the insert voltage technique and the reference microphone provided data to compensate for the drift in the output of the loudspeaker during the two phases of the calibration. The only purpose of the calibration was to determine the SPL at the two microphone positions.

NPL

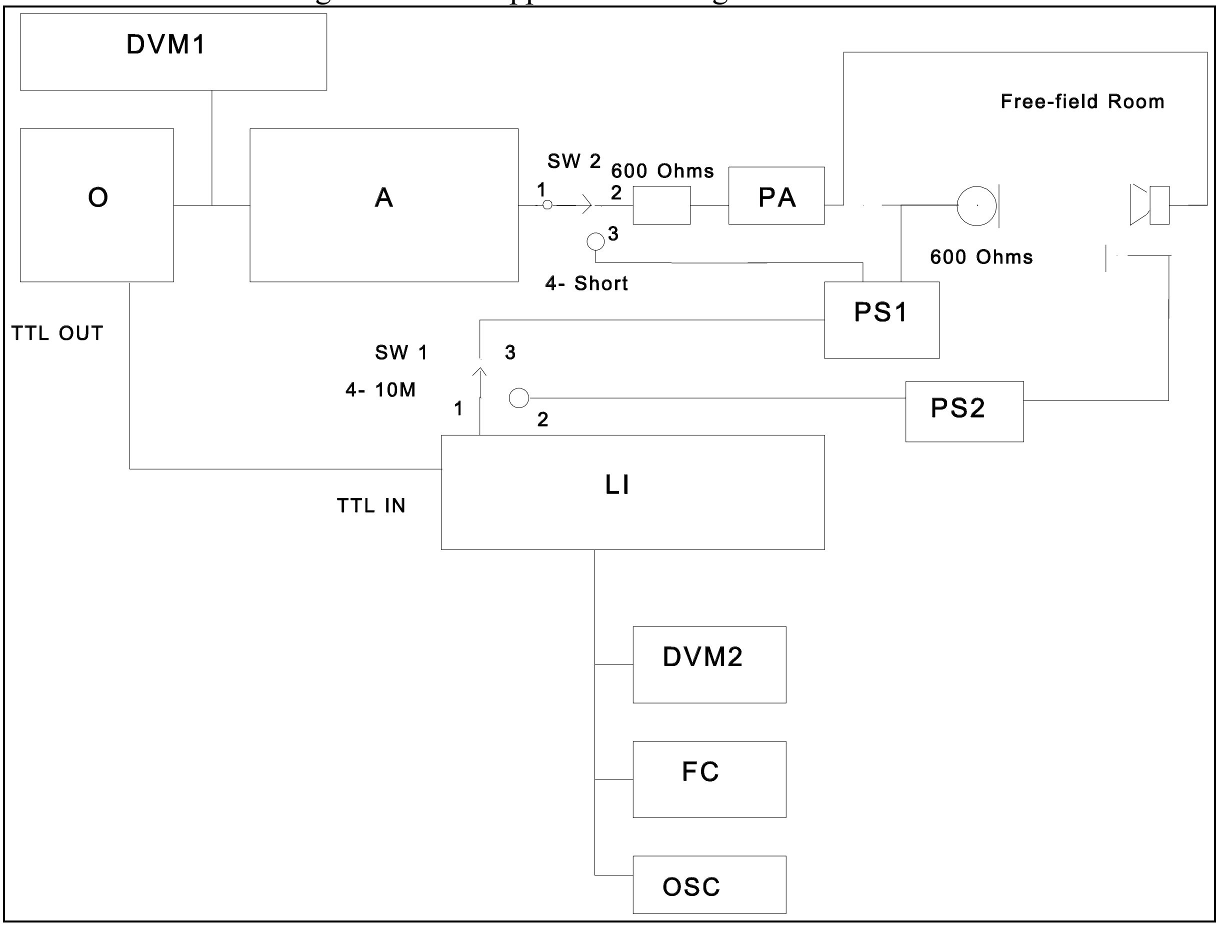
The calibrations were performed in a free-field room of dimensions 5.8 m × 6.1 m × 4.7 m (166 m^3 volume). On most wall surfaces the wedges are 0.85 m long with a solid base of 0.3 m × 0.3 m × 0.2 m; smaller wedges are used on the part of the ceiling covering the traverse, with dimensions 0.42 m long and a solid base of 0.14 m × 0.14 m × 0.12 m. The wedges consist of 48 $kg.m^{-3}$ density glass fibre totally enclosed in white glass tissue. A working space of 2.4 m × 2.7 m × 1.3 m in the centre of the room is achieved with this arrangement. The room is intended to approximate free-field conditions at frequencies above 100 Hz.

A 10 cm diameter loudspeaker provides the sound source in the room. It was mounted in a rigid box which in turn was mounted on a 0.61 m × 0.61 m board to provide an ‘infinite’ baffle that ensures that the loudspeaker does not radiate from the rear. To reduce reflections from the surface of the board it is covered in a 2.5 cm layer of rockwool.

NPL also maintains facilities for measuring the sensitivity level of microphones in a rigid-walled duct at 250 Hz and below. In this facility measurements of the pressure response of the microphone are performed. Although at these low frequencies the pressure sensitivity levels of measurement microphones can be assumed to be very nearly the same as the free-field sensitivity levels, the duct method is not described in this report.

The method used is one of sequential comparison of the microphone under test with an LS1P reference microphone. The true free-field sound pressure level is set up using the reference microphone (using the insert voltage method). The free-field sound pressure level is then duplicated when the reference microphone is replaced by the microphone under test. This is achieved by referring to the output voltage of a monitor microphone placed near the sound source (for frequencies below 4 kHz), or by applying the same driving voltage to the sound source as was applied when the reference microphone was in position (for 4 kHz and above). The free-field sensitivity level is calculated by measuring the output voltage of the microphone under test. The equipment is shown in Figure 10, with the following abbreviations: DVM (digital voltmeter), O (oscillator), A (attenuator), PA (power amplifier), PS (microphone power supply), LI (lock-in amplifier), FC (frequency counter), OSC (oscilloscope).

Figure 10. NPL apparatus with signal connections



The microphone was positioned at six different distances in the range 1.0 m to 1.25 m from the loudspeaker along the axis of the loudspeaker. At each position the output of the reference microphone was measured first, followed by the output of the microphone under test. The nominal sound pressure level at the microphone is 74 dB (frequencies below 2 kHz) or 84 dB (2 kHz and above).

The performance of the reference microphone system was verified prior to the measurement of each microphone by:

- applying a calibrated pistonphone and a calibrated sound calibrator to the reference microphone, and ensuring the measured level agreed, within 0.07 dB for the pistonphone and 0.1 dB for the sound calibrator, with the known values for these devices
- running a ‘self-check’ of the system by calibrating the reference microphone against itself.

The repeatability of the sensitivity levels was typically ≤ 0.02 dB at frequencies up to 6.3 kHz and ≤ 0.041 dB from 8 kHz to 20 kHz.

PTB

The calibrations were carried out in an anechoic room of 8 m × 9 m × 6 m (430 m^3 volume), containing wedges 0.8 m long. The lower limiting frequency of the room is estimated at 95 Hz. The sound source comprised coaxial loudspeakers - an Isophon unit (25 Hz to 2500 Hz) together with a Visaton unit DSM 25 FFL (2500 Hz to 20000 Hz) - mounted in the wall of the anechoic room. Measurement points were located on the loudspeaker axis at 1 m from the loudspeaker housing, with the microphone diaphragm facing the loudspeaker. The microphone was screwed onto a metal tube 1.4 m in length and of the same diameter of the microphone for at least 40 cm away from the microphone.

A sequential comparison method was used. Block diagrams of the test equipment are shown in Figure 11 and Figure 12. Free-field sensitivity levels of the reference microphones were calculated from their pressure sensitivity levels determined at PTB and the free-field corrections supplied in the measurement protocol. The test signals employed were pure tones at one-third-octave intervals from 100 Hz up to either 12.5 kHz or 20 kHz, with levels of 84 dB.

Measurements were performed on five different days. Each day the measurement of the reference microphone was made both before and after the measurement with the microphone under test. Results were only accepted where the two results performed with the reference microphone differed by 0.1 dB or less. Differences between the pair of measurements with the reference microphone of greater than 0.1 dB occurred mainly in the vicinity of 6 kHz.

Figure 11. PTB apparatus (generation of the test signal)

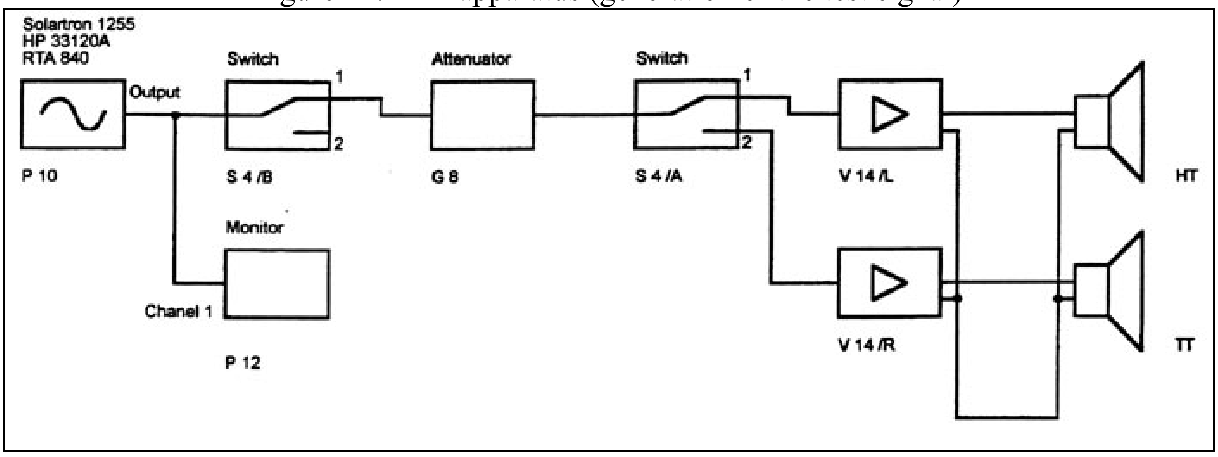
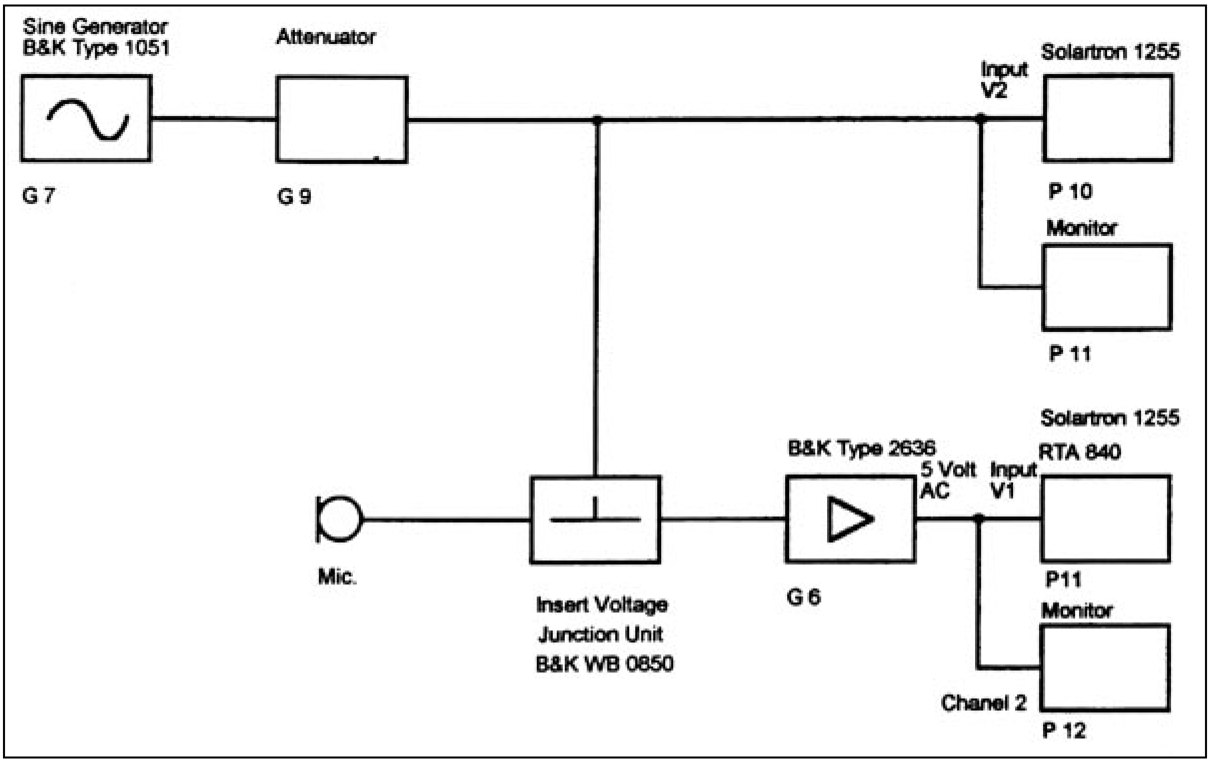


Figure 12. PTB apparatus (measurement of microphone output by insert voltage technique)



APPENDIX 4. MEASUREMENT UNCERTAINTY BUDGETS

DPLA

The influence of standing waves in the room are estimated at less than 0.1 dB above 1 kHz. For a comparison calibration the influence on the calibration result is much smaller, provided the directivity pattern and the position of the acoustic centres for the reference microphone and the microphone under test are the same. For this reason, the calibrations of the WS1F microphone were performed only with LS1P reference microphones.

Table 2. DPLA uncertainty contributions

Source of uncertainty	Magnitude (dB)
Pressure calibration of LS1P reference microphone (frequency dependent, up to 10 kHz)	0.03 - 0.12
Influence of standing waves in room	<< 0.1
Analyser averaging of frequency response measurements	0.01
Difference in position of acoustic centres (frequency dependent)	under investigation
Repeatability standard deviation (frequency dependent)	0.008 - 0.056

IEN

The following estimate of the measurement uncertainty was evaluated from the repeatability of the measurements and from the systematic differences from the data obtained using two different reference standards. The characteristics of the anechoic room at IEN stress the problem of calibrating microphones whose directivity pattern is different to those of the reference microphone. It is difficult to establish the nature of the sound field on the microphone: the room and the sound source characteristics are difficult to describe, being subject both to space (reflections, directivity) and time (drifts, variations of the speed of sound) variations.

The uncertainties in the free-field corrections were those supplied in the measurement protocol. The contribution from the calibration of the reference microphone has a gaussian distribution. The contribution for source stability includes monitor microphone gain variations. The contribution for field non-uniformity was introduced to account for systematic difference found when using the two different reference standard microphones. The contribution from positioning of the microphone was derived from the level difference (dB) measured over 2 mm along the steepest slope of curves of room evaluation, and was interpolated if not available. An additional component due to field non-uniformity has been introduced: it accounts for the different sensitivity of the two different reference microphones to a sound field that is not a plane progressive wave.

The large values for repeatability were thought to be due to variations in the speed of sound in the room between the replications. The repeatability estimate was based on an assumption of three replications being performed (as in calibrations for customers). At some frequencies, the repeatability (Type A uncertainty component) is so high relative to the calculated combined uncertainty that the effective number of degrees of freedom of the combined uncertainty is below 100. In these cases, the coverage factors k necessary to maintain a level of confidence of about 95 % exceed 2.0 and have been recalculated for Table 3 and Table 4 from the IEN figures.

Table 3. IEN uncertainty budget (low frequencies)

Source	Uncertainty contributions (dB) at each frequency (Hz)									
	125	160	200	250	315	400	501.2	631	794.3	1000
Free-field correction	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0500	0.0500	0.0500	0.0500
Calibration of reference microphone	0.0250	0.0250	0.0250	0.0250	0.0250	0.0250	0.0250	0.0250	0.0250	0.0250
Source stability	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100
Field non-uniformity	0.0124	0.0100	0.0207	0.0126	0.0100	0.0272	0.0011	0.0170	0.0233	0.0367
Positioning	0.0030	0.0040	0.0040	0.0050	0.0100	0.0150	0.0180	0.0180	0.0180	0.0200
Insert Voltage repeatability	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025
Repeatability	0.0154	0.0186	0.0292	0.0123	0.0077	0.0119	0.0170	0.0128	0.0662	0.0486
Combined uncertainty	0.0336	0.0345	0.0450	0.0327	0.0315	0.0429	0.0620	0.0633	0.0921	0.0857
Veff	43	23	11	92	457	309	339	1111	7.5	19
Coverage factor, k	2.00	2.13	2.28	2.00	2.00	2.00	2.00	2.00	2.43	2.15
Expanded Uncertainty	0.07	0.07	0.10	0.07	0.06	0.09	0.12	0.13	0.22	0.18

Table 4. IEN uncertainty budget (high frequencies)

Source	Uncertainty contributions (dB) at each frequency (Hz)										
	1259	1585	1995	2512	3162	3981	5012	6310	7943	10000	12590
Free-field correction	0.0500	0.0500	0.0500	0.0500	0.0500	0.0500	0.0500	0.1000	0.1000	0.1000	0.1000
Calibration of reference microphone	0.0250	0.0250	0.0250	0.0250	0.0250	0.0250	0.0250	0.0250	0.0250	0.0400	0.0600
Source stability	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100
Field non-uniformity	0.0100	0.1857	0.0135	0.1146	0.0287	0.0305	0.0797	0.1070	0.2450	0.1063	0.2521
Positioning	0.0250	0.0300	0.0430	0.0500	0.0550	0.0600	0.0650	0.0700	0.0800	0.0700	0.0600
Insert Voltage repeatability	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025
Repeatability	0.0562	0.0459	0.0294	0.0358	0.1238	0.0386	0.0599	0.2237	0.1387	0.2164	0.0748
Combined uncertainty	0.0843	0.2018	0.0783	0.1419	0.1497	0.0962	0.1319	0.2777	0.3105	0.2734	0.2940
Veff	10	743	99	489	4.3	76	47	4.8	50	5.1	476
Coverage factor, k	2.28	2.00	2.00	2.00	2.87	2.00	2.00	2.87	2.00	2.65	2.00
Expanded Uncertainty	**0.19**	**0.40**	**0.16**	**0.28**	**0.43**	**0.19**	**0.26**	**0.80**	**0.62**	**0.72**	**0.59**

NPL

The largest contributions are from the uncertainty in the free-field correction, the error introduced in rounding of the final result to one decimal place and resetting the drive signal.

The uncertainty due to the influence of atmospheric pressure and temperature on the reference microphone is calculated from the data in Annex D of IEC 61094-2:1992. Uncertainties in measurement of attenuation and calibration of the attenuator were derived from the attenuator's calibration certificate. The uncertainty in resetting the level of the drive signal of the sound source is equal to the limit of error allowed in the pre-calibration 'self-check' test. Uncertainties in measurement of voltage are based on the rounding error in reading the insert voltage to three decimal places.

The contributions for static pressure, air temperature, and pressure sensitivity and free-field correction of reference microphone vary with frequency. The uncertainty in the pressure sensitivity level of the LS1P reference microphone increases to 0.22 dB at 12.5 kHz, while that of the LS2P reference microphone increases to 0.17 dB at 20 kHz.

Table 5. NPL uncertainty budget (LS1P reference microphone)

Source of uncertainty	Contribution (± dB) at frequency (Hz) 125	250	500	1000	2000	4000	8000	10000	12500
Resetting drive signal to sound source	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029
Measurement of insert voltage (ref. mic.)	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Measurement of attenuation (ref. mic.)	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017
Static pressure (ref. mic.)	0.017	0.017	0.017	0.017	0.017	0.012	0.012	0.035	0.046
Air temperature (ref. mic.)	0.017	0.017	0.017	0.017	0.023	0.040	0.046	0.017	0.023
Measurement of insert voltage (test mic.)	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Measurement of attenuation (test mic.)	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017
Pressure sensitivity level of ref. mic.	0.015	0.015	0.015	0.015	0.015	0.020	0.025	0.045	0.110
Free-field correction	0.000	0.000	0.050	0.050	0.050	0.050	0.100	0.100	0.100
Calibration of attenuators	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025
Repeatability (typical)	0.020	0.020	0.020	0.020	0.020	0.020	0.041	0.041	0.041
Combined uncertainty	0.057	0.057	0.076	0.076	0.078	0.084	0.129	0.131	0.169
Expanded uncertainty (k=2)	0.12	0.12	0.16	0.16	0.16	0.17	0.26	0.27	0.34

Table 6. NPL uncertainty budget (LS2P reference microphone)

Source of uncertainty	Contribution (± dB) at frequency (Hz) 125	250	500	1000	2000	4000	8000	10000	12500	16000	20000
Resetting drive signal to sound source	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.046
Measurement of insert voltage (ref. mic.)	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Measurement of attenuation (ref. mic.)	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017
Static pressure (ref. mic.)	0.017	0.017	0.006	0.006	0.006	0.006	0.006	0.012	0.012	0.006	0.035
Air temperature (ref. mic.)	0.017	0.017	0.017	0.017	0.017	0.035	0.035	0.046	0.052	0.052	0.017
Measurement of insert voltage (test mic.)	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Measurement of attenuation (test mic.)	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017
Pressure sensitivity level of ref. mic.	0.025	0.025	0.025	0.025	0.025	0.025	0.030	0.035	0.040	0.045	0.085
Free-field correction	0.000	0.000	0.050	0.050	0.050	0.050	0.100	0.100	0.100	0.100	0.100
Calibration of attenuators	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025
Repeatability (typical)	0.020	0.020	0.020	0.020	0.020	0.020	0.041	0.041	0.041	0.041	0.041
Combined uncertainty	0.061	0.061	0.077	0.077	0.077	0.083	0.126	0.131	0.135	0.136	0.154
Expanded uncertainty (k=2)	0.13	0.13	0.16	0.16	0.16	0.17	0.26	0.27	0.27	0.28	0.31

PTB

Estimates for contributions to measurement uncertainties provided by PTB are listed in Table 7. The uncertainty budgets for calibration using LS1P and LS2P as the reference microphone are given in Table 8 and Table 9 respectively. The major difference is the inclusion of a contribution for difference in acoustic centre where the LS2P reference microphone was used. The largest contributions are uncertainties in the pressure sensitivity level of the reference microphone and its free-field correction. The calculations were performed in pressure units before conversion to dB.

Table 7. Uncertainty contributions estimated by PTB

Source of uncertainty	Range of contributions (dB)
Free-field correction (frequency dependent)	0.0 - 0.2
Pressure calibration of reference microphone (frequency dependent)	0.03 - 0.05 (LS1P) 0.04 - 0.08 (LS2P)
Quotient of test microphone voltage to reference microphone voltage (frequency dependent)	0.02 - 0.06
Influence of temperature and static pressure	negligible
Free-field interference	0.04 - 0.10
Difference in position of acoustic centres (frequency dependent)	0.00 - 0.03
Rounding	0.005
Repeatability (frequency dependent)	0.02 - 0.05

Table 8. PTB uncertainty budget (LS1P reference microphone)

Source of uncertainty	Uncertainty contributions by frequency range (Hz)						
	100 - 250	315 - 400	400- 2000	>2000- 4000	>4000- 5000	>5000- 8000	>8000- 12500
Free-field correction	0.00000	0.00230	0.00570	0.00570	0.00570	0.01140	0.01140
Pressure calibration of LS1P	0.00170	0.00170	0.00170	0.00170	0.00290	0.00290	0.00290
Quotient of microphone voltages	0.00115	0.00115	0.00115	0.00230	0.00230	0.00230	0.00350
Free-field interference	0.00230	0.00230	0.00230	0.00460	0.00460	0.00460	0.00570
Rounding	0.00035	0.00035	0.00035	0.00035	0.00035	0.00035	0.00035
Repeatability (Type A)	0.00230	0.00230	0.00230	0.00230	0.00570	0.00570	0.00350
Combined uncertainty	0.00386	0.00449	0.00689	0.00820	0.01000	0.01405	0.01398
Combined uncertainty (dB)	0.033	0.039	0.060	0.071	0.086	0.122	0.121
Expanded uncertainty (dB)	0.07	0.08	0.12	0.14	0.17	0.24	0.24

Table 9. PTB uncertainty budget for calibration (LS2P reference microphone)

Source of uncertainty	Uncertainty contributions by frequency range (Hz)						
	100 - 250	315 - 400	400- 2000	>2000- 4000	>4000- 5000	>5000- 8000	>8000- 12500
Free-field correction	0.00000	0.00230	0.00570	0.00570	0.00570	0.01140	0.01140
Pressure calibration of LS2P	0.00230	0.00230	0.00230	0.00230	0.00350	0.00350	0.00460
Quotient of microphone voltages	0.00115	0.00115	0.00115	0.00230	0.00230	0.00230	0.00350
Free-field interference	0.00230	0.00230	0.00230	0.00460	0.00460	0.00460	0.00570
Acoustic centre	0.00350	0.00350	0.00350	0.00230	0.00115	0.00115	0.00000
Rounding	0.00035	0.00035	0.00035	0.00035	0.00035	0.00035	0.00035
Repeatability (Type A)	0.00230	0.00230	0.00230	0.00230	0.00230	0.00460	0.00460
Combined uncertainty	0.00544	0.00590	0.00788	0.00866	0.00883	0.01383	0.01419
Combined uncertainty (dB)	0.047	0.051	0.068	0.075	0.076	0.119	0.122
Expanded uncertainty (dB)	0.09	0.10	0.14	0.15	0.15	0.24	0.24

The magnitude of the Type A uncertainty for six repeats of the positioning of the microphone was investigated separately. Six repeated measurements of sound pressure level at three different points (0.85 m, 1.00 m and 1.15 m) resulted in standard deviations of less than 0.03 dB.

The repeatabilities of three different types of test signal were also investigated. Pure tones (duration 8.2 s), broadband pink noise (duration 60 s) and an MLS pseudo-random noise signal (duration 8.2 s) were played through the wall-mounted loudspeaker source; levels of about 70 dB were measured with an LS1P microphone positioned 1 m from the source. Six repeats of each signal resulted in standard deviations of 0.01 dB or less at each frequency (200 Hz to 20 kHz) for the pure tones and for the MLS signal, while standard deviations for the pink noise signal were between 0.01 dB and 0.03 dB (1250 Hz and higher frequencies) and between 0.02 dB and 0.09 dB (200 Hz to 1000 Hz). The shorter duration and better repeatability indicate that use of pure tones or MLS signals is preferable to use of broadband pink noise.

APPENDIX 5. PERFORMANCE OF FREE-FIELD ROOMS

DPLA

Deviations from ideal free-field had been measured in the course of previous work. The measurements were performed at steps of one-tenth wavelength. From these measurements, the optimum source-microphone distance of 0.48 m was selected. The data was used to calculate the rmsd and the calculated values are given in Table 10.

Table 10. Rmsd in DPLA free-field room

Frequency (kHz)	rmsd (dB) over range 0.2 m - 0.6 m
0.63	0.065
0.80	0.052
1.00	0.083
1.25	0.037
1.60	0.032
2.00	0.032
2.50	0.027
3.15	0.076
4.00	0.032
5.00	0.016
6.30	0.012
8.00	0.009
10.00	0.009
12.50	0.009
16.00	0.010
20.00	0.009

DPLA point out that rmsd is not suitable for use as an uncertainty contribution for the comparison calibration method used, especially when the comparison measurement is made at fixed positions. The influence of standing waves for this project is estimated at less than 0.1 dB above 1 kHz.

IEN

A previous evaluation of the room in the semi anechoic configuration was made according to ISO 3745[1]. By the criteria of that standard (maximum allowable difference from ideal free-field of ± 2.0 dB, ± 2.5 dB or ± 3.0 dB dependent on frequency band) the room was found capable of providing a semi-anechoic field at frequencies down to 100 Hz. The requirements of this ISO standard are not very severe and obviously are not applicable for comparison calibrations.

The instrumentation for room evaluation was slightly different from that used for the calibrations: instead of the Brüel & Kjær Type 2133 real time analyser, two HP type 3458A multimeters were used to measure the output of the monitor and measuring microphone. The

[1] International Standardization Organisation, ISO 3745:1977, *Acoustics - Determination of sound power levels of noise sources - Precision methods for anechoic and semi-anechoic rooms*.

two microphone channels were amplified by a Brüel & Kjær Type 2636 measuring amplifier and a Brüel & Kjær Type 5935 microphone supply respectively.

No difference is expected due to the use of two different measuring chains: the uncertainty of the electrical part being negligible compared to the acoustical sources. The choice of the second chain was due to the possibility to perform the large number of measurements in a shorter time automatically. Moreover there was no need to use the insert voltage technique or to monitor the actual SPL level. The room evaluation was performed using the same sound source used for the comparison calibrations: it is far from being a spherical source and this can partly explain the large deviation obtained in the evaluation. On the other hand a source of spherical waves commonly used for room evaluation is generally too narrow-band to be of practical use for a large band of frequency calibration and was not considered for this project since at least three sound sources would have had to be used.

The measured values of rmsd are provided in Table 11. The deviations are rather large: they may partly be due to diffraction around the edges of the box of the sound source.

Table 11. Rmsd in IEN free-field room

Frequency (kHz)	rmsd (dB) over range 1.595 m - 1.795 m
0.125	0.02
0.25	0.05
0.50	0.15
1.00	0.23
2.00	0.18
4.00	0.19
8.00	0.16
12.50	0.16

NPL

The performance of the free-field room in which the calibrations took place has been investigated and reported by Stephen Watkins. A WS2F (Brüel & Kjær type 4165) microphone was mounted on a semi-infinite rod which could be traversed away from the loudspeaker along the nominal axis of the loudspeaker. The microphone was traversed from 10 cm to 3 m away from the loudspeaker, taking approximately 11 minutes. The output V of the microphone was measured and stored every few seconds, and 1/V was plotted against distance r, with the expectation that a perfect, free field would result in a linear relationship.

The measurements were made with sine waves at frequencies from 125 Hz to 20 kHz. The sine wave signals were measured with a Datron 1061 voltmeter, taking readings of the microphone output once a second. The root mean square deviations (with air attenuation corrections assuming atmospheric conditions of 101.3 kPa, 20 °C and 65 % RH) are listed in Table 12, calculated for distances from the source of 0.5 m to 2.5 m and 1.0 m to 1.25 m. The former range is the practical working area of the room, and the latter range is that used in calibration of the WS1F microphones described above. The rmsd for the calibration range is no greater than 0.06 dB at all frequencies.

Table 12. Rmsd in NPL free-field room

Frequency (kHz)	Air attenuation ($\times10^{-3}$ dB.m^{-1})	rmsd (dB) over range 0.5 m - 2.5 m	1.0 m - 1.25 m
0.125	0.0	0.31	0.06
0.25	0.0	0.34	0.01
0.50	3.2	0.13	0.04
1.00	4.8	0.13	0.02
2.00	8.6	0.09	0.04
4.00	23	0.07	0.05
8.00	79	0.06	0.06
10.00	120	0.06	0.05
12.50	183	0.06	0.02
16.00	289	0.07	0.09
20.00	431	0.09	0.02

PTB

During the calibrations, a discrepancy of 0.02 dB was observed in the free-field frequency response of the WS1F microphone at 160 Hz. This discrepancy was probably caused by a standing wave between the loudspeaker housing and the surface of the larger reference microphone at a distance of 1 m (corresponding to half a wavelength at 171 Hz).

To investigate the room performance, the sound pressure level was measured with an LS1P microphone at small intervals over the range 0.85 m to 1.00 m along the axis of the wall-mounted loudspeaker source used in the calibrations, and also at the points 1.00 m ± 0.15 m and 1.5 m ± 0.25 m from the source. The sound pressure level at 1 m distance was 84 dB.

PTB considered that the twin-loudspeaker used cannot be regarded as a point source, and therefore the exact value of its acoustic centre is not known. A series of curves showing the change in sound pressure level over the range 0.85 m to 1.00 m were drawn for each frequency of test signal (25 Hz to 20 kHz), but no calculation of rmsd was performed. It was assumed that the largest part of the obvious non-linear behaviour between 630 Hz and 10 kHz is due to the loudspeaker housing and arrangement, that a smaller part is due to the influence of the mounting arrangement of the microphone, and only a small part is due to the characteristics of the room (known from former measurements with point sources).

The sound pressure levels at the points 1.00 m ± 0.15 m and 1.5 m ± 0.25 m were measured and compared with the levels predicted by the effects of the inverse square law and the absorption of sound in air. The results for the frequency range 200 Hz to 20 kHz are listed in Table 13.

Table 13. Difference between measured and ideal free-field levels in PTB free-field room

Frequency (Hz)	Measured difference (dB) from level at 1.00 m		Measured difference (dB) from level at 1.50 m	
	0.85 m	1.15 m	1.25 m	1.75 m
200	0.08	-0.08	0.17	-0.11
250	-0.02	-0.09	0.03	-0.16
315	0.07	-0.10	0.11	0.08
400	-0.08	-0.02	0.25	0.00
500	-0.05	0.12	-0.20	-0.23
630	-0.23	-0.04	0.09	0.18
800	-0.15	-0.05	-0.22	0.25
1000	-0.28	-0.02	0.13	0.49
1250	-0.19	-0.21	-0.05	-0.12
1600	0.04	-0.07	0.13	-0.09
2000	-0.07	-0.09	0.07	-0.03
2500	-0.04	-0.04	0.10	0.00
3150	-0.16	0.02	-0.25	-0.03
4000	-0.22	0.02	-0.01	-0.07
5000	0.02	-0.20	0.01	-0.18
6300	-0.36	-0.13	-0.22	-0.02
8000	-0.13	0.01	-0.23	0.14
10000	-0.03	0.06	0.00	0.11
12500	-0.11	0.10	-0.18	-0.01
16000	-0.03	0.01	-0.04	0.18
20000	-0.06	-0.09	0.11	-0.15

PTB conclude that there is still no suitable criterion to decide what deviation from an ideal free field is acceptable, when both the reference microphone and the microphone under test are measured at the same point, and that the agreed test procedure was unsuitable for specification of a minimum performance criterion for the free-field room.

The test of inverse distance law was repeated at the four individual distances used above along the axis of a loudspeaker mounted on a rod in the centre of the anechoic room. The preliminary results show no advantage to this arrangement over the wall-mounted sound source.

APPENDIX 6. ACOUSTIC CENTRE

Table 14 contains the data used in the discussion of acoustic centre described in Section 4.1.5.

Table 14. Calculation of correction for difference in acoustic centre between reference microphones

Frequency (Hz)	Acoustic centre of 4160 (mm)	Acoustic centre of 4180 (mm)	Difference in acoustic centre (mm)	Change of SPL at test point (dB.mm^{-1})	Correction of 4180 results to acoustic centre of 4160 (dB)
100				-0.007	-0.03
125				-0.007	-0.03
160				-0.008	-0.03
200				-0.008	-0.03
250				-0.007	-0.03
315				-0.009	-0.03
400				-0.006	-0.03
500				-0.009	-0.03
630	9.0			0.000	0.00
800	8.7			-0.007	-0.03
1000	9.0	4.6	4.4	-0.004	-0.02
1250	8.1	4.6	3.5	-0.007	-0.02
1600	8.0	4.5	3.5	-0.003	-0.01
2000	7.3	4.2	3.1	-0.007	-0.02
2500	6.4	4.2	2.2	-0.007	-0.02
3150	5.7	3.8	1.9	0.003	0.01
4000	5.4	3.8	1.6	-0.009	-0.01
5000	4.9	3.5	1.4	-0.009	-0.01
6300	4.2	3.1	1.1	0.000	0.00
8000	3.0	2.3	0.7	-0.035	-0.02
10000	2.2	2.3	-0.1	-0.008	0.00
12500		1.7		0.000	0.00
16000				0.003	0.00
20000					0.00

APPENDIX 7. FREE-FIELD CORRECTIONS $\Delta_{f,p}$ FOR LABORATORY STANDARD MICROPHONES

Alternative values of $\Delta_{f,p}$ were calculated by PTB. For the LS1P microphone, the mean values of the free-field corrections determined in a previous exercise by DPLA, LNE (France), NPL and PTB were used for the frequency range from 1 kHz to 10 kHz. The values at 500 Hz to 800 Hz and at 12.5 kHz were retained from the measurement protocol. PTB also determined corrections for frequencies down to 250 Hz by interpolation.

For the LS2P microphone, the NPL values at 6.3 kHz and above were retained. At lower frequencies, the corrections were calculated by assuming that the correction reduces with frequency by the same factor as the LS1P correction reduces at frequencies an octave lower. It was found the corrections determined using this octave difference (corresponding to the ratio of the diameters of the diaphragms of the two microphones) were better than those obtained using a 9/10-octave difference (corresponding to the ratio of the diameters of the microphones).

Table 15. Free-field corrections $\Delta_{f,p}$ of LS microphones, recalculated by PTB

Frequency (Hz)	Recalculated $\Delta_{f,p}$ (dB)	
	LS1P	LS2P
100	0.00	0.00
125	0.00	0.00
160	0.00	0.00
200	0.00	0.00
250	0.01	0.00
315	0.02	0.00
400	0.04	0.00
500	0.07	0.01
630	0.11	0.02
800	0.17	0.04
1000	0.28	0.07
1250	0.43	0.11
1600	0.68	0.17
2000	1.01	0.29
2500	1.56	0.44
3150	2.34	0.69
4000	3.53	1.03
5000	5.06	1.59
6300	6.86	2.39
8000	8.41	3.61
10000	9.29	5.06
12500	8.93	6.79
16000	-	8.31
20000	-	8.59

The values of L_{Mf} reported by the participants, after correction for environmental effects, were recalculated using the PTB values of $\Delta_{f,p}$. The effect of using the PTB values of $\Delta_{f,p}$ on the differences between the values of L_{Mf} measured with the two different reference microphone types is shown in Figure 13 to Figure 16.

Figure 13. Difference between L_{Mf} of 4145 2071917 measured with different reference microphone types (PTB results)

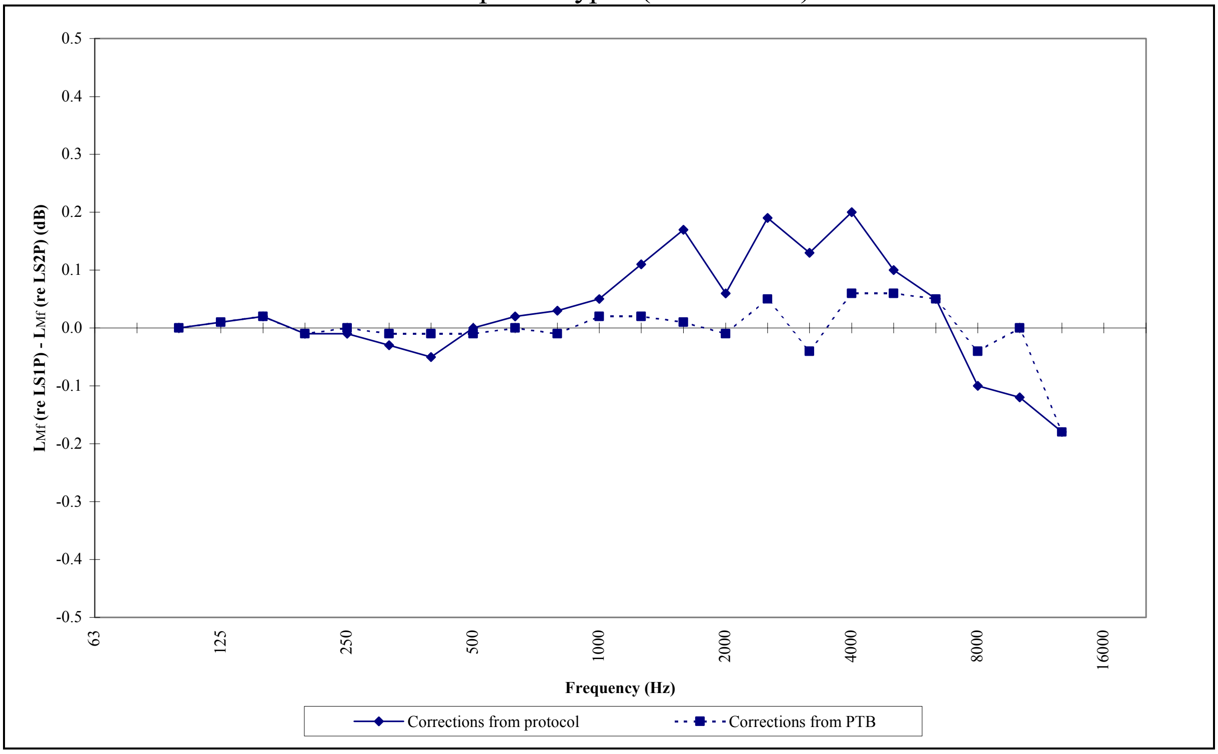


Figure 14. Difference between L_{Mf} of 4145 2071917 measured with different reference microphone types (NPL results)

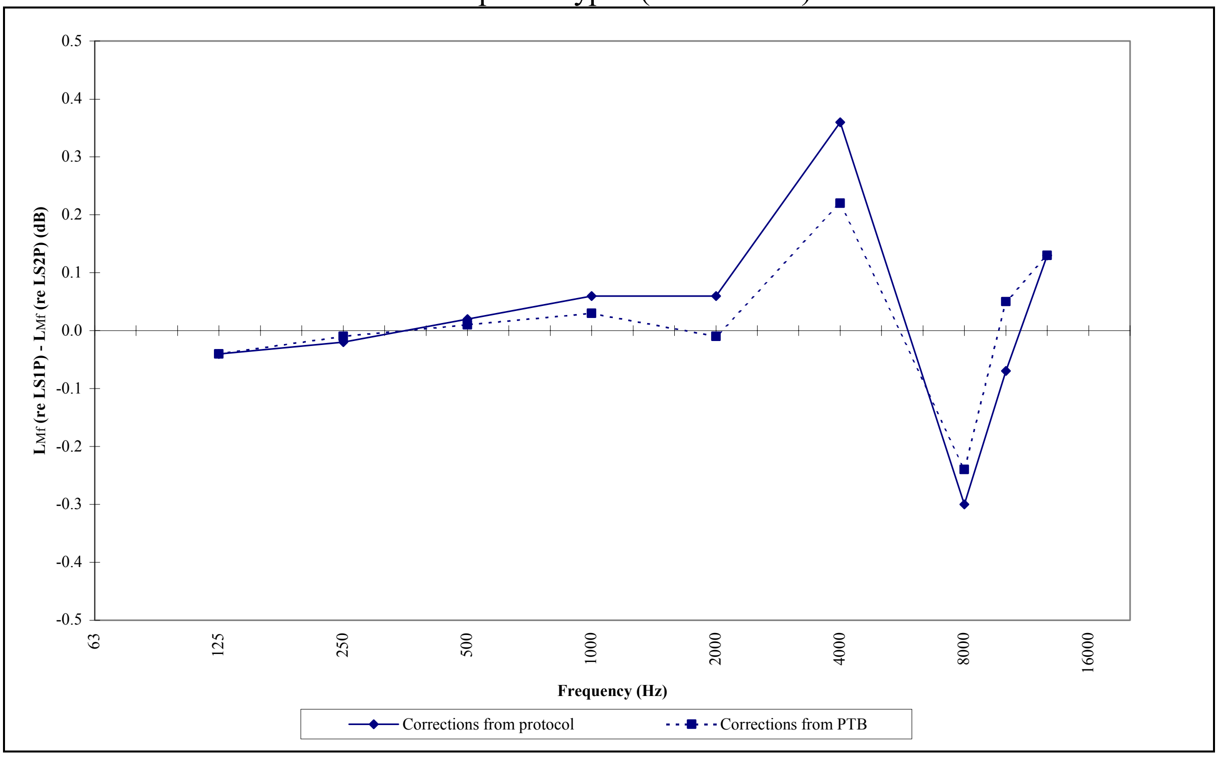


Figure 15. Difference between L_{Mf} of 4145 2071918 measured with different reference microphone types (IEN results)

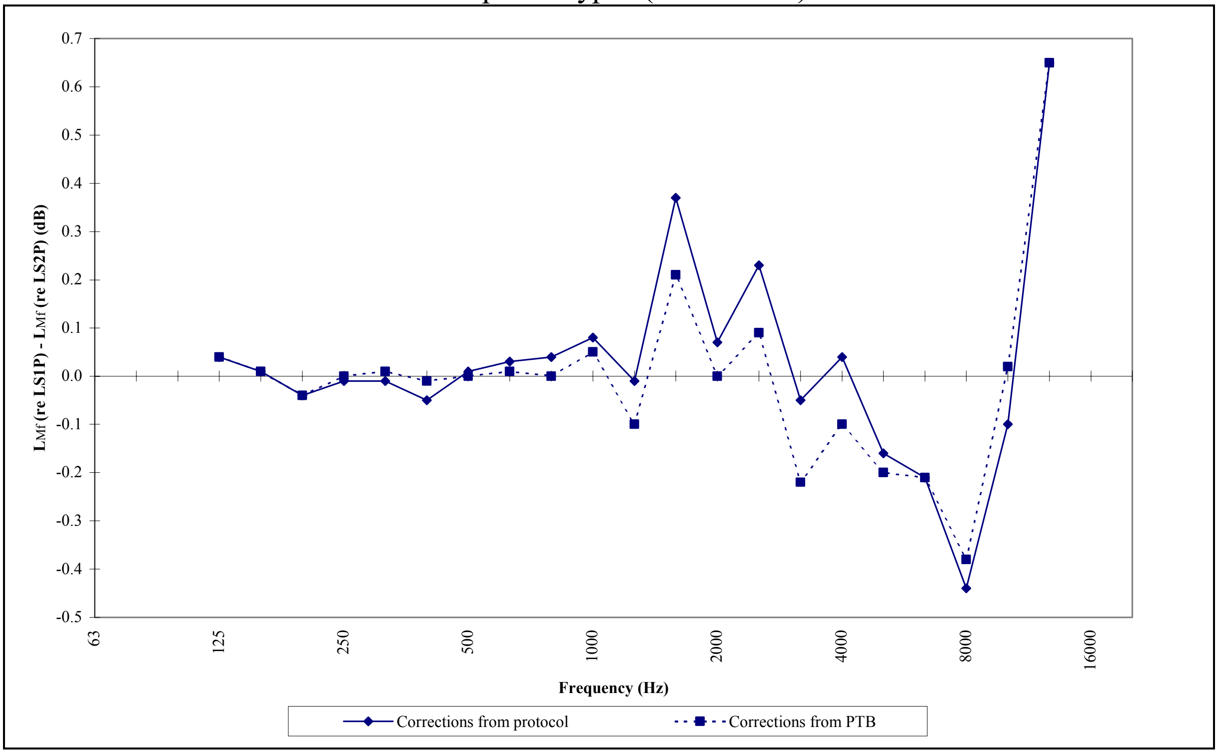


Figure 16. Difference between L_{Mf} of 4145 2071918 measured with different reference microphone types (NPL results)