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**INTERCOMPARISON TO VALIDATE CALIBRATION METHODS FOR
HYDROPHONES IN THE FREQUENCY RANGE 10-315 kHz.**

FINAL TECHNICAL REPORT

Contract: MAS2-CT94-0095

Stephen P Robinson and Geraint J Green.

Centre for Ionising Radiation and Acoustics,
National Physical Laboratory,
Teddington, Middlesex,
United Kingdom, TW11 0LW.

ABSTRACT

This document is the Final Report for EC contract number MAS2-CT94-0095 entitled *Intercomparison to validate calibration methods for hydrophones in the frequency range 10-315 kHz*. This two-year project was funded partly by the Directorate-General for Science, Research and Development of the Commission of the European Communities, and partly by the UK DTI. Although the contract has been funded by the EC under the Marine Science and Technology Programme, it was administered through the Standards, Measurement and Testing Programme.

The aim of the project was to carry out a European intercomparison of hydrophone calibrations in the frequency range 10-315 kHz in order to validate existing standards and methods and to identify areas where improvements are required. The intercomparison has been organised radially with the coordinator, NPL, taking a central rôle. A total of 12 participants from 7 European countries have calibrated three reference hydrophones, with NPL performing the coordination, inter-participant checks on the hydrophones, final analysis and reporting of results.

The agreement between the results of participants was such that a majority of the results were within ± 1 dB of the Grand Mean. In general, this is encouraging and reflects well upon the expertise of the participants. Nevertheless, it still means that calibrations originating from two different countries could easily disagree by 2 dB, which could lead to serious and potentially expensive disagreements in measured values when the hydrophones are used in the field. In addition, some large variations were observed which give cause for concern. The uncertainties in the calibrations were typically under-estimated by the participants, with the maximum differences from the Grand Means almost invariably exceeding the quoted overall uncertainties. The report concludes with a discussion of possible further work identified as a result of undertaking the intercomparison.

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

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Approved on behalf of Managing Director, NPL,
by A Marks, Director, Centre for Ionising Radiations and Acoustics.

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1. INTRODUCTION

This is the Final Report for EC contract number MAS2-CT94-0095 entitled *Intercomparison to validate calibration methods for hydrophones in the frequency range 10-315 kHz*. This two-year project has been funded partly by the Directorate-General for Science, Research and Development (DG XII) of the Commission of the European Communities, and partly by the UK DTI. Although the contract was funded by the EC under the Marine Science and Technology Programme, it was administered through the Standards, Measurement and Testing Programme.

1 BACKGROUND

In the field of metrology, intercomparisons are the main method by which the national standards laboratories in different countries can ensure mutual compatibility of their standards. The intercomparisons are conducted by each laboratory calibrating the same devices and comparing the results. Such intercomparisons of standards at the highest echelon between countries provide each country with greater confidence in their own standards, and often lead to the discovery of previously unknown sources of error.

However, the infrastructure of standards for underwater acoustics within Europe is not yet properly developed. This situation is of some concern and is already being addressed by the CEC.¹ In the recent EUROMET Project A73: *Standards for underwater acoustics*, European countries were surveyed to determine the state of standards in this field.² The information obtained showed that traceability to national standards does not generally exist for underwater acoustical measurements within Europe. Of the national standards laboratories, only the National Physical Laboratory in the UK is active in the field. Consequently, any intercomparison must involve establishments other than standards laboratories, such as other government laboratories and private companies.

From the EUROMET survey, it is clear that many hydrophone users simply rely on the manufacturer's calibration. However, of those establishments performing their own in-house calibrations, many expressed the desire to participate in an intercomparison exercise. Some of these establishments are already operating as the *de facto* standards laboratory for underwater acoustics in their country. With interest in the establishment of standards increasing, this has been an appropriate time to conduct such an exercise.

1.2 OBJECTIVES OF THE PROJECT

The aim of the project was to carry out a European intercomparison of hydrophone calibrations in the frequency range 10-315 kHz in order to validate existing standards and methods and to identify areas where improvements are required.

An intercomparison is manifestly of benefit to the participants, for whom it provides a type of quality audit for their calibrations. In addition, a Europe-wide project provides a first step toward the harmonisation of standards and the promotion of common standards across national boundaries. The results of such a project may also identify areas where further work is required

to improve the quality of calibrations. After the intercomparison, the hydrophones used will be useful as reference devices which could be used in the dissemination of standards.

1.3 PROJECT ORGANISATION

The project has been organised on a concerted action basis, which means that each participant takes part on a voluntary basis. There was no contract between the Commission and the participating establishments who performed the calibrations. However, the Commission has provided part-funding for NPL to purchase the test hydrophones and provide project coordination and administration.

The exercise was organised as a radial intercomparison with the coordinator, NPL, at the centre. Each participant received three reference hydrophones to calibrate. In order to cover the required number of participants in the time available, two separate sets of three hydrophones were used with NPL calibrating both sets. The hydrophone sets have been designated as Set A and Set B.

As coordinator, NPL purchased the hydrophones, and prepared and circulated a procedure document describing the measurements required. This procedure document is included as Appendix A of this report. NPL also undertook initial assessment and calibration of the hydrophones to determine their suitability for the project. In addition, NPL performed checks on the hydrophone sensitivities between the calibrations by participants to ensure that the hydrophone sensitivities were stable.

2 THE INTERCOMPARISON PROCEDURE

To provide a guide for the participants, NPL prepared and circulated a procedure document, which provided a description of the measurements required with reference to the appropriate international standards. A copy of the procedure document is included as Appendix A in this report.

2. MEASUREMENTS REQUIRED

Participants were asked to perform a measurement of the end-of-cable free-field sensitivity of each hydrophone using their own in-house methods and procedures for the calibrations. The *free-field* sensitivity of a hydrophone is given by the quotient of the open-circuit voltage at its output terminals to the sound pressure in a plane progressive sound field at the position of the acoustic centre of the hydrophone but in the absence of the hydrophone. The sensitivity can be expressed in microvolts per pascal ($\mu\text{V}/\text{Pa}$), but is more usually stated as a sensitivity level in decibels with reference to $1\text{V}/\mu\text{Pa}$ (dB re $1\text{V}/\mu\text{Pa}$).

For this project, the “left-hand” XYZ coordinate system suggested by IEC 565 - *The calibration of hydrophones*³ has been adopted. In this system, the Z- axis is chosen to be along the axis of the transducer, and the X-axis is perpendicular to the Z-axis in a direction defined by a mark on the hydrophone case. For all calibrations at NPL, the hydrophones were oriented such that the alignment mark pointed in a direction parallel to the direction of propagation of the incoming acoustic wave. In the intercomparison procedure (see Appendix B), each participant was asked to align the hydrophones in this way during their own calibrations.

2.2 ACOUSTIC FREQUENCIES

Calibrations were requested from participants at the third-octave frequencies defined by the International Organization for Standardization (ISO)⁴ in the range 10 to 315 kHz. In practice, this is too coarse a frequency spacing to accurately describe the frequency response of the hydrophones, particularly at frequencies close to or greater than the resonance frequencies of the devices where the response may be changing rapidly with frequency. However, it was necessary to stipulate a standard set of frequencies to enable direct comparisons to be made between the results. This also reduced the effort and time required for calibrations, an important factor in keeping the project on schedule. Nevertheless, some participants were able to provide calibrations at a wider range of frequencies and at greater resolution than third-octave intervals.

2.3 CALIBRATION QUESTIONNAIRE

The procedure also contained a questionnaire, which provided a means for the participants to report the results of measurements and describe the calibration method. This ensured that all participants provided a minimum amount of information regarding the measurement method used, even though the some of the calibration reports produced by participants were more comprehensive than others.

3 THE HYDROPHONES

A total of 12 hydrophones were purchased for the intercomparison. They were purchased from two separate European suppliers of standard measuring hydrophones: namely Brüel and Kjær and RESON A/S. The 12 hydrophones comprise four each of the Brüel and Kjær type 8104, Brüel and Kjær type 8103, and Reson type TC4034. Table 1 gives the nominal specification for each hydrophone, taken from the data provided by the manufacturers.

Nominal specification	B&K 8104	B&K 8103	TC4034
Receive voltage sensitivity (with integral cable) at 250 Hz	56 µV/Pa -205 dB re 1 V/µPa	28 µV/Pa -211 dB re 1 V/µPa	13 µV/Pa -218 dB re 1 V/µPa
Capacitance (pF) including cable	7800	3850	3000
Directivity at 100 kHz: XY (horizontal) XZ (vertical)	±2 dB ±4 dB (@ 50 kHz)	±2 dB ±4 dB	±2 dB ±2 dB
Resonance frequency (kHz)	65	125 and 275	350
Active element type	stack of four 12 mm Ø rings	cylinder (6 mm Ø, 8 mm length)	sphere (6 mm Ø)

Table 1. Nominal specifications for the three types of hydrophone.

Figure 1 is a photograph showing an example of each hydrophone. The hydrophone were divided into four sets of three, with each set containing one of the three hydrophones. Sets A and B have been used in the intercomparison for calibration by participants, set C has been used as a control set to provide a check on the stability of the NPL calibrations, and set D has been used to provide spares in case of breakage. The individual sets were comprised as follows:

Set A:	Set B:
B&K 8104 S/N: 1757063	B&K 8104 S/N: 1757065
B&K 8103 S/N: 1785459	B&K 8103 S/N: 1785461
TC4034 S/N: 426002	TC4034 S/N: 426001
Set C (control set):	Set D (spare set):
B&K 8104 S/N: 1757064	B&K 8104 S/N: 1757066
B&K 8103 S/N: 1785449	B&K 8103 S/N: 1785462
TC4034 S/N: 426003	TC4034 S/N: 426004

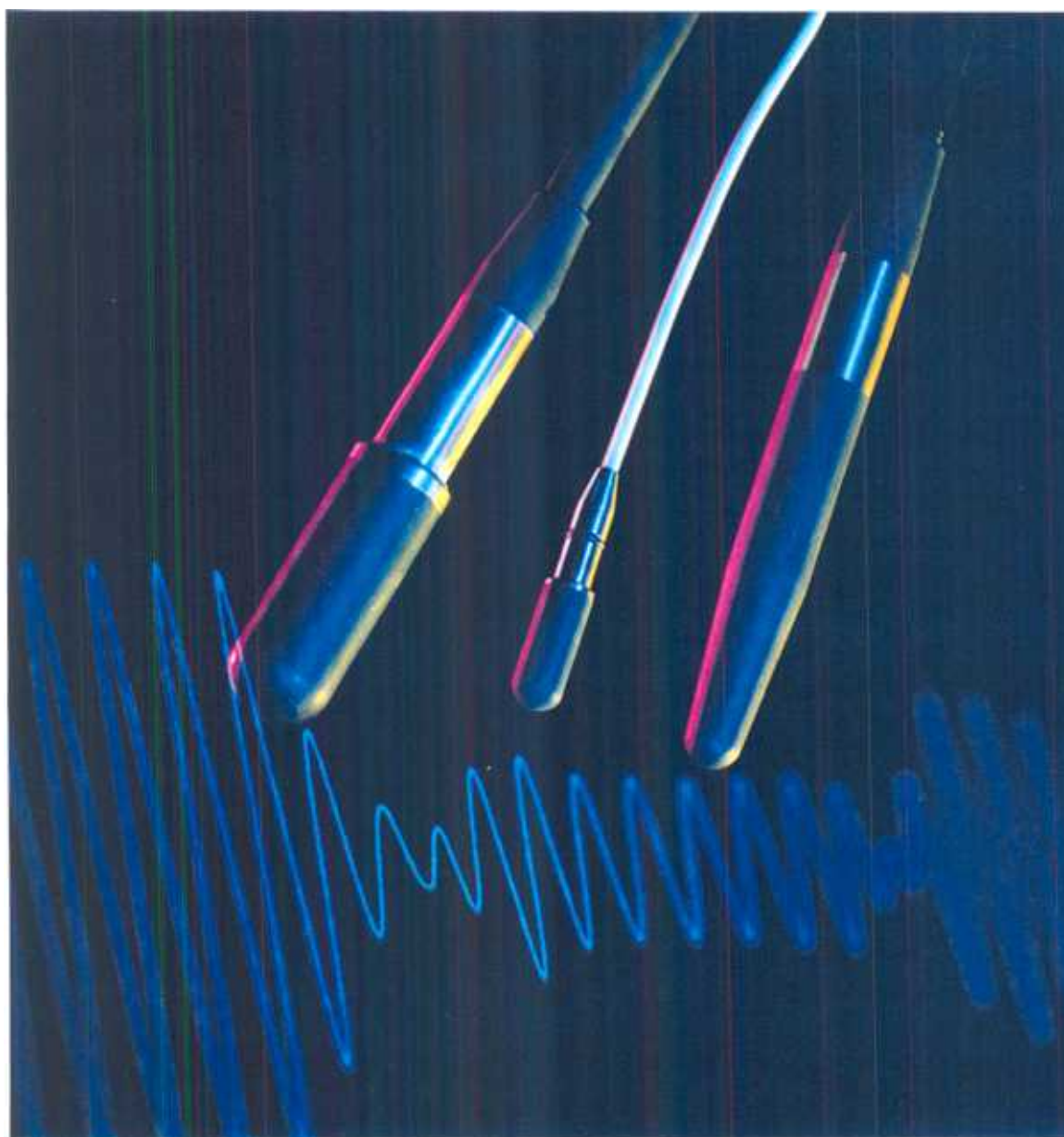


Figure 1

Photograph showing (from left to right) hydrophone types B&K 8104, B&K 8001, and RESON TC 4034.

4 MEASUREMENTS MADE BY COORDINATOR

4.1 INITIAL MEASUREMENTS ON HYDROPHONES

Before the beginning of the calibrations by participants, measurements were made by NPL on all hydrophones to assess their performance. These initial tests included measurements of electrical impedance in the frequency range 1 to 1000 kHz, directional response at selected frequencies in the range 10 to 500 kHz, and free-field sensitivity in the range 10 to 500 kHz. The hydrophones were allocated to each set after initial measurements had been completed on all devices. Although there was little difference in the measured response of the hydrophones, those exhibiting marginally the smoothest frequency response and the least fluctuation in directional response were chosen for set A and B.

The results of these initial calibrations for set A and B only can be seen in Figures 2 and 3. These calibrations were performed by the method of three-transducer spherical-wave reciprocity in conformance with IEC 565 using the NPL tank facility, which is equipped with a precision positioning system. The calibrations were performed at closer frequency intervals than the third-octave intervals used in the intercomparison (5 kHz intervals in the range 10-200 kHz, and 10 kHz intervals in the range 200-500 kHz). The closer frequency spacing allows the frequency response to be seen in greater detail. In particular, the resonances are clearly visible. Reference may be made to these graphs when viewing the results in Section 6 (which are plotted at third-octave frequencies) so that the underlying hydrophone responses can be discriminated.

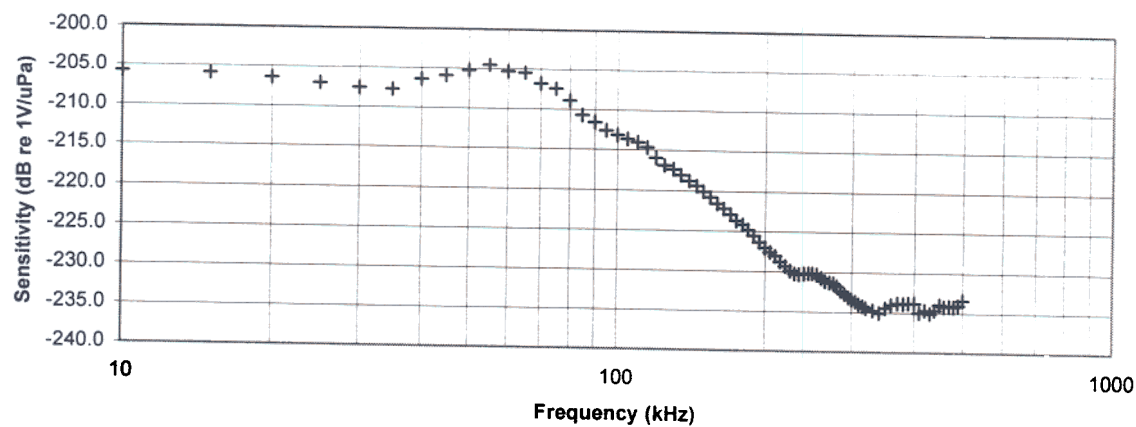
4.2 MEASUREMENTS ON CONTROL HYDROPHONES

At the beginning and end of the intercomparison, the hydrophones of set C were calibrated by NPL. Since the same calibration method was used for both calibrations, the systematic uncertainties should be identical. For each calibration, completely independent repeat measurements were performed with the hydrophones removed from the water, remounted and realigned before each repeated measurement. The two calibrations generally differed by 0.1-0.3 dB which is comparable with the random uncertainties typical in the calibrations, while at a few frequencies, changes of 0.4-0.6 dB were observed. However, by far the biggest observed change was for the RESON TC4034 (s/n 426003) at 315 kHz which changed sensitivity by +1.2 dB. No such change was observed for the two B&K hydrophones in the control set, but a similar change was observed with the TC4034 in set A (see Section 4.3). This strongly suggests that the hydrophone has changed its sensitivity significantly at this frequency. Neglecting this large change, the RMS of the differences between the two calibrations across all frequencies for each hydrophone was: B&K 8104: 0.3 dB, B&K 8103: 0.3 dB, and TC4034: 0.2 dB.

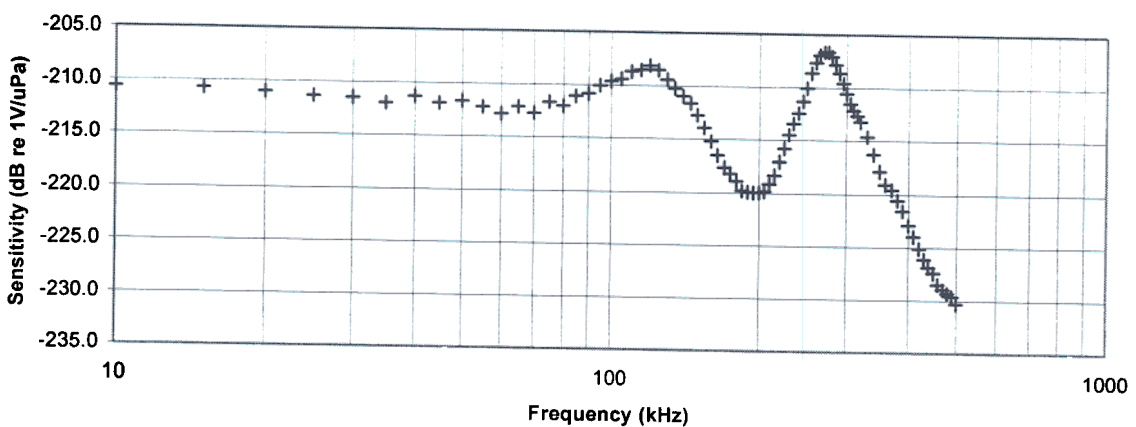
4.3 CHECKS ON HYDROPHONE STABILITY

As a check on the stability of the hydrophones used for the intercomparison, after each participant had completed calibrations, NPL performed check calibrations of Set A and B at the following frequencies: 10, 50, 100, 200 and 315 kHz.

Sensitivity of B&K 8104 SN. 1757063



Sensitivity of B&K 8103 SN. 1785459



Sensitivity of Reson TC4034 SN. 426002

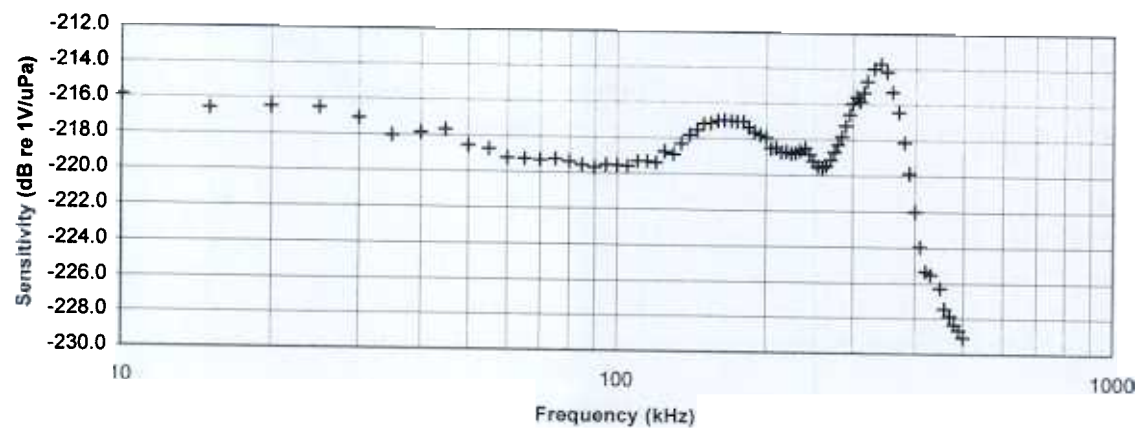
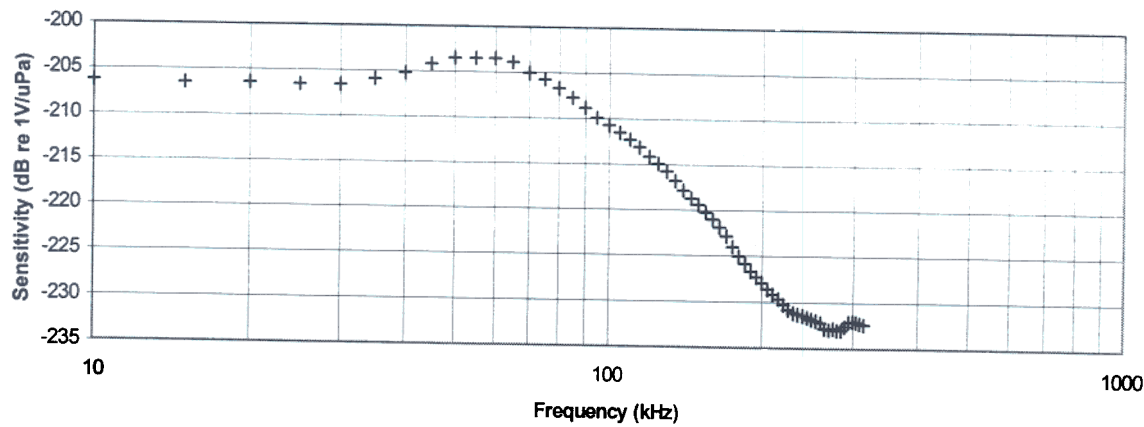
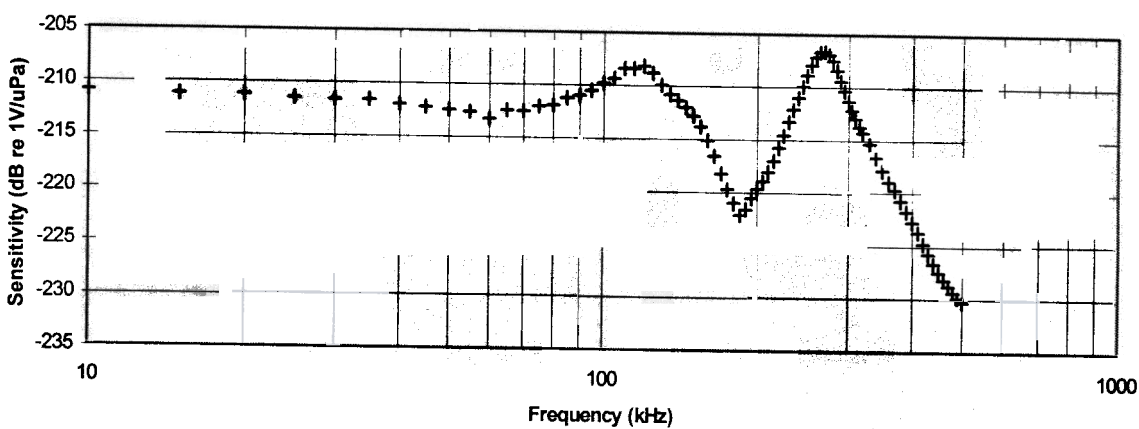


Figure 2 Results of the initial calibration of Set A.

Sensitivity of B&K 8104 SN. 1757065



Sensitivity of B&K 8103 SN. 1785461



Sensitivity of Reson TC4034 SN. 426001

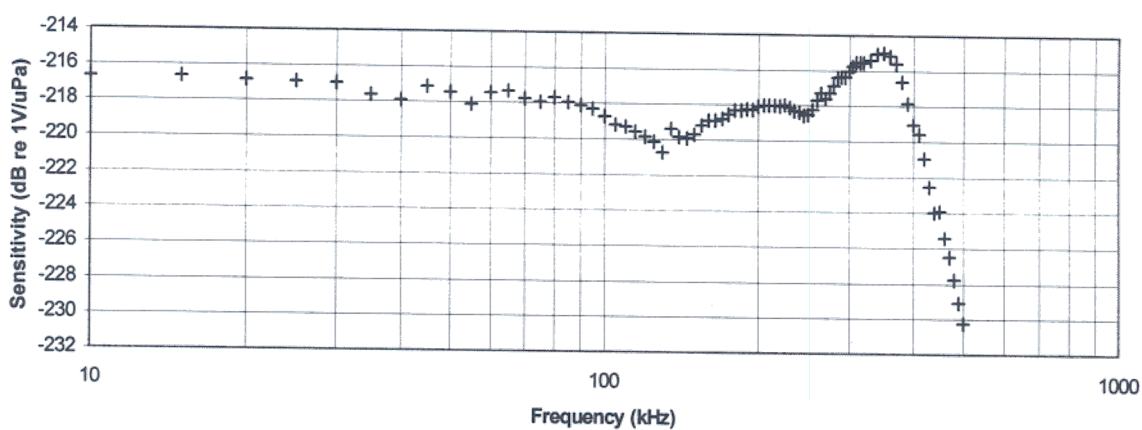


Figure 3 Results of initial calibration of Set B.

Tables 2 and 3 show the variation in the measured sensitivity at the check frequencies for Set A and Set B respectively, during the course of the intercomparison. The variation is expressed in dB for a confidence level of 95% (ie $\pm 2\sigma$ where σ is the standard deviation). The variation is 0.2-0.5 dB for Set B at the lower frequencies, with a larger variation at 200 and 315 kHz for the Brüel & Kjær 8104 hydrophone (which is beyond its usual frequency range at these frequencies). For Set A, in addition to a generally larger variation than for Set B, there are significant changes at 315 kHz for both the B&K8104 and the RESON TC4034. It is clear from the individual measurements on these hydrophones that there has been a gradual change in sensitivity at 315 kHz (a decrease for the 8104 and an increase for the 4034) throughout the time of the intercomparison (a duration of about 18 months). This should be remembered when considering the participants' results for these hydrophones at 315 kHz.

Table 2. Variation in the measured sensitivity of the Set A hydrophones expressed for a confidence level of 95% ($\pm 2\sigma$) in dB.

Frequency (kHz)	Variation in sensitivity (2σ) in dB		
	B&K8104	B&K8103	TC4034
10	0.4	0.1	0.2
50	0.7	0.7	0.3
100	0.8	0.3	0.5
200	0.6	0.4	0.8
315	1.4	0.7	1.4

Table 3. Variation in the measured sensitivity of the Set B hydrophones expressed for a confidence level of 95% ($\pm 2\sigma$) in dB.

Frequency (kHz)	Variation in sensitivity (2σ) in dB		
	B&K8104	B&K8103	TC4034
10	0.2	0.5	0.2
50	0.3	0.5	0.2
100	0.4	0.4	0.2
200	0.9	0.3	0.1
315	0.9	0.8	0.7

An additional point which should be noted is that both B&K 8103 hydrophones developed faulty connectors during the project. In both cases the connector was replaced by the manufacturer, and no significant change in sensitivity was observed by NPL after the new connectors were fitted. Although the fault was usually easily spotted (often leading to a complete loss in signal), it is possible that the fault could have caused a change in electrical

impedance which would have a less significant affect on the sensitivity. Therefore, though it is considered unlikely, it is possible that some of the variation shown in Tables 2 and 3 for the B&K 8103 responses is due to this factor.

The variations reported here are indicative of the variation that may be expected in the hydrophone response during the intercomparison. As such they may be used to inform the assessment of the participant results in Section 7. In particular, they are useful when considering the plots of the difference from the Grand Mean in Section 7.6. Any differences which are significantly greater than those shown in Tables 2 and 3, must be because of systematic differences in the calibrations of the participants.

5 THE PARTICIPANTS

The following 12 organisations participated in the intercomparison (listed in alphabetical order by country). For all the participants, contact names and addresses, telephone and fax numbers are given in Appendix B.

- | | |
|--|----------------|
| • Vrije Universiteit Brussel
(Electrical Measurement Department) | BELGIUM |
| • Brüel & Kjær
(S&V Division) | DENMARK |
| • RESON A/S | DENMARK |
| • DCN
(CTSN/DLSM-Toulon) | FRANCE |
| • Thomson Marconi Sonar | FRANCE |
| • STN Atlas Elektronik GmbH | GERMANY |
| • Wehrtechnische Dienststelle für Schiffe
und Marinewaffen WTD 71
(German Defence Ministry calibration facility) | GERMANY |
| • Istituto di Acustica
CNR-IDAC, "O.M.Corbino", Rome | ITALY |
| • SACLANT URC
(NATO Research Centre, La Spezia) | ITALY |
| • FOA Försvarets Forskningsanstalt
(Swedish Defence Research Agency) | SWEDEN |
| • MOD Wraybury Facility
(Operated by Marine Acoustics Ltd) | UNITED KINGDOM |
| • National Physical Laboratory | UNITED KINGDOM |

6 THE CALIBRATIONS

6.1 CALIBRATION METHODS

The most common primary method of calibration used by participants was the method of three-transducer spherical-wave reciprocity.⁵ This requires the use of three hydrophones, at least one of which must be a reciprocal transducer; that is, its transmitting and receiving sensitivities are related by a constant factor. The hydrophones are paired off in three measurement stages, at each of which one device is used as a transmitter and the other a receiver. For each pair of hydrophones, a measurement is made of the voltage across the terminals of the receiving device to the current driving the transmitting device. By use of the reciprocity principle as applied to the reciprocal transducer, the sensitivity of any one of the three hydrophones can be determined from these purely electrical measurements.

In some cases, relative methods of calibration were also employed. Here, the hydrophone to be calibrated is compared with a reference device which has been calibrated previously by an absolute method. For example, several participants performed a calibration by comparison with a previously-calibrated reference hydrophone, with both hydrophones exposed to the sound field generated by a stable source. Alternatively, a standard projector (previously calibrated by a reciprocity method) was used to provide a known sound field.

For those participants using laboratory tank facilities, tone-burst signals were usually employed, with reflections isolated from the direct-path signal by use of gating and time-windowing techniques. In one case, pulsed signals were used and the resulting waveforms analysed in the frequency domain.

6.2 CALIBRATION FACILITIES

Most commonly, participants used laboratory tank facilities of varying sizes, the largest being 7.5 x 5.5 x 5 metres and the smallest 0.98 x 0.62 x 0.60 metres. Most of the tanks have a framework or positioning system overhead which is used for mounting and positioning the transducers. Two participants used open-water facilities, one a lake and one a reservoir. Here, a laboratory platform is created using either a pier or pontoon based structure, from which transducers may be lowered into the water.

Although not part of the frequency range for this intercomparison, some participants were able to perform a pressure calibration of the hydrophones at low frequencies, for example using a pistonphone at 250 Hz. One participant was able to use a calibrator normally used for line arrays to perform a relative calibration of the hydrophones in the frequency from 30 Hz to 3 kHz.

A more detailed description of the methods used by individual participants is given in Section 7.

7 RESULTS OF CALIBRATIONS BY PARTICIPANTS

7. ANONYMITY OF RESULTS

The results have been presented in an anonymous form such that each set of results is identified by a code letter. Each participant has been informed of the code letter corresponding to his/her results, but not the codes for the other participants.

7.2 CALCULATION OF THE GRAND MEAN

In the next sections, for each hydrophone the results have been compared to the Grand Mean of all calibrations. It should be noted that for all calculations of means and standard deviations, the results were first converted to linear units (eg $\mu\text{V}/\text{Pa}$). After calculation, the values were then converted back to decibels for presentation graphically. Values for the Grand Mean were calculated at the standard third-octave frequencies only. The Grand Means have been calculated from the usual formula for the mean, without any special weighting placed upon any of the results. Use of an unweighted mean has ensured that the calibrations of each participant are treated equally.

With the unweighted mean used here, no account is taken of the uncertainties quoted by participants. When calculating a mean from values with differing uncertainty, it is usual to weight each value inversely with its variance. However, this is really only appropriate when all the measured values are taken from the same overall population. As can be seen from the results, this is clearly not the case here since some of the results show significant systematic differences from the mean. This is to be expected when different participants are using different calibration methods which will have different systematic components of uncertainty. Therefore, this method of weighting has not been used here.

Another method of weighting the mean is to weight each value inversely with its overall uncertainty (including both random and systematic components). Indeed, this method of weighting has been used successfully in other intercomparison projects sponsored by the European Commission.⁶ However, this assumes that the uncertainties have been correctly estimated by the participants. In practice, those participants unfamiliar with metrology may not have identified all the components of uncertainty within the calibration method.

Consequently, the means presented here are unweighted. The values of the Grand Mean sensitivities and the individual values used in their calculation are given in full in Appendix C. This will enable further analysis to be undertaken if required.

7.3 RESULTS FOR SET A

Figures 4 to 6 show the results for the set A hydrophones for the B&K 8104, B&K 8103 and the RESON TC4034 respectively. Also shown in each graph is the overall Grand Mean for that hydrophone.

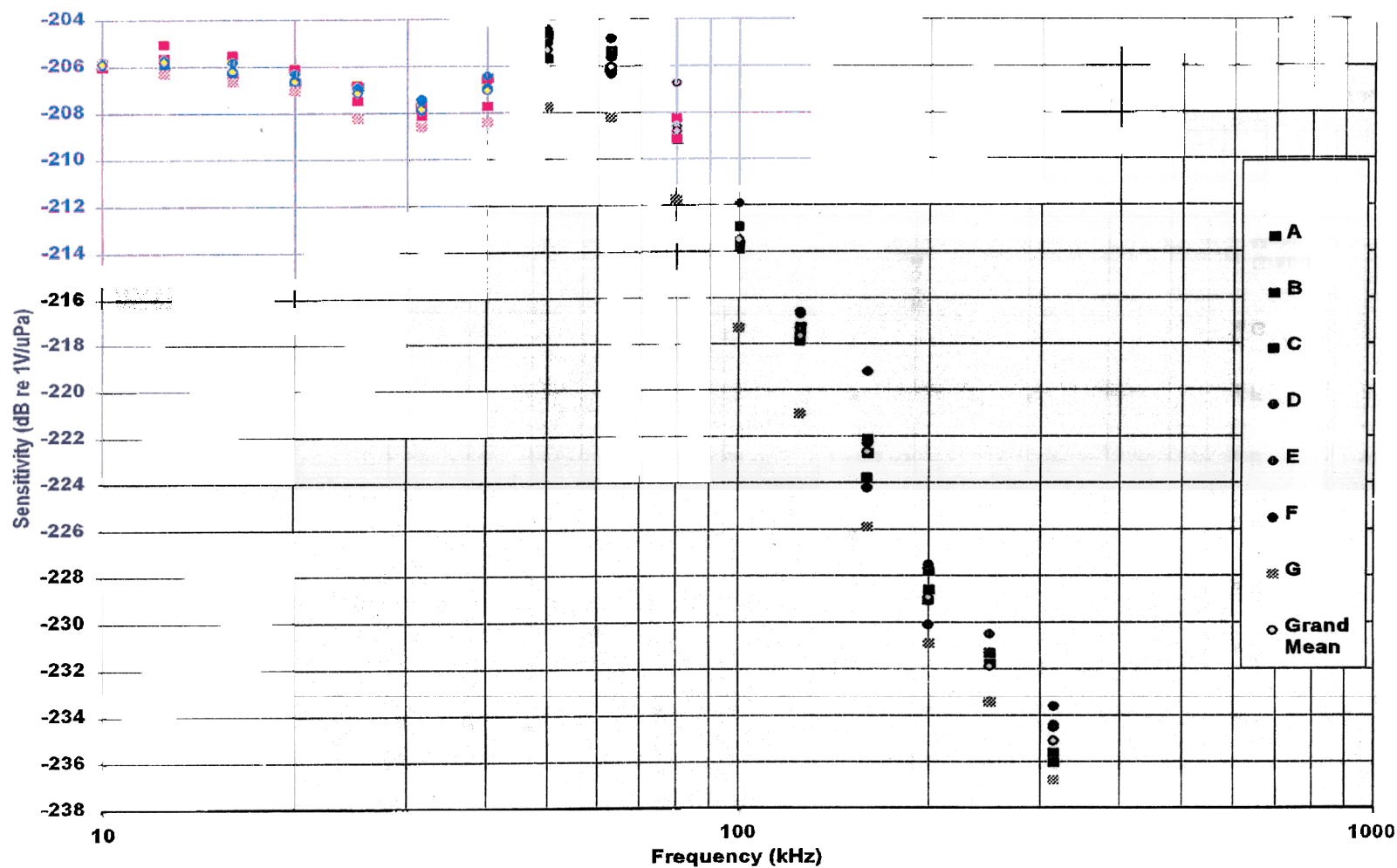


Figure 4 Calibration results for the B&K 8104 hydrophone of Set A.

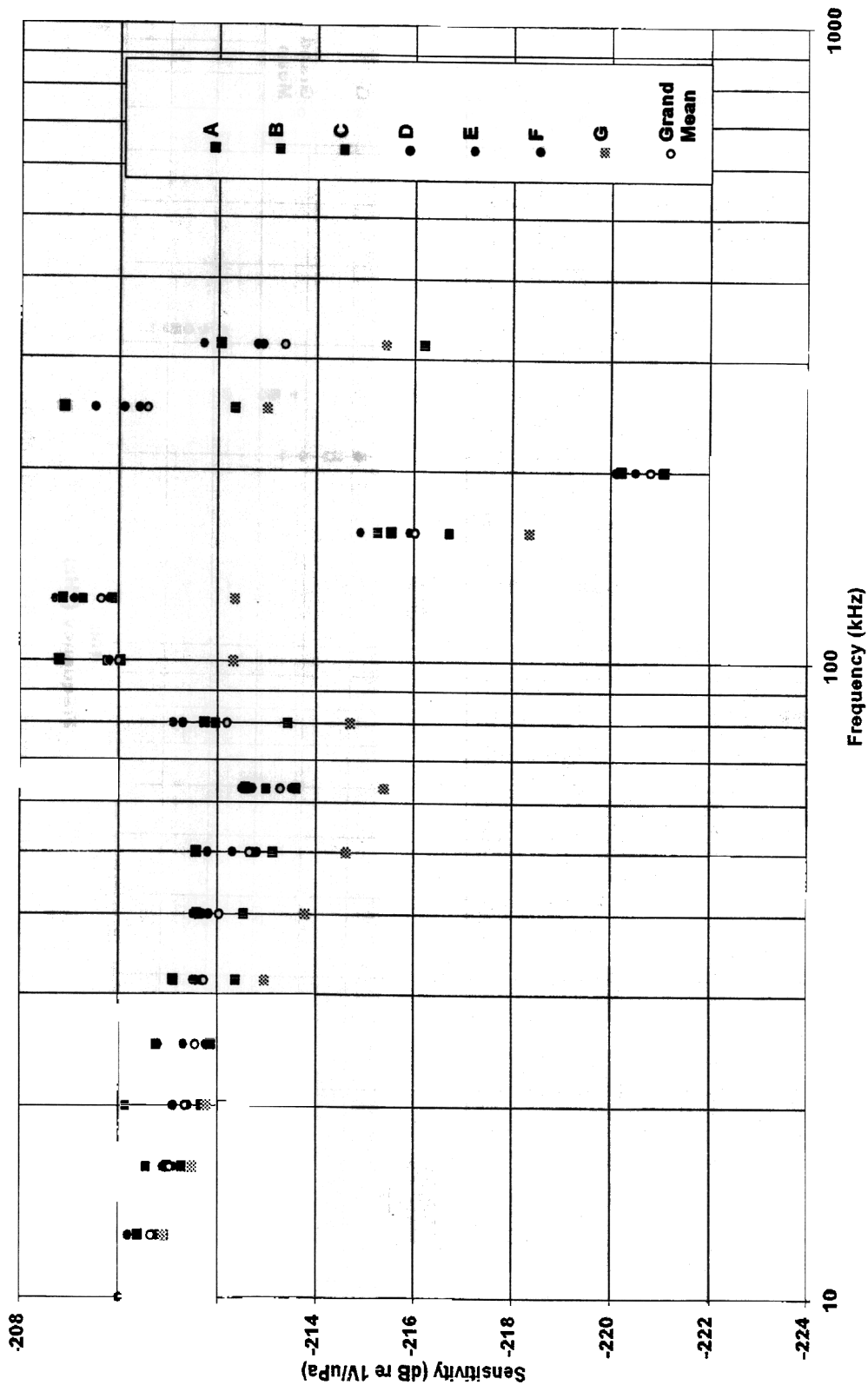


Figure 5 Calibration results for the B&K 8103 hydrophone of Set A.

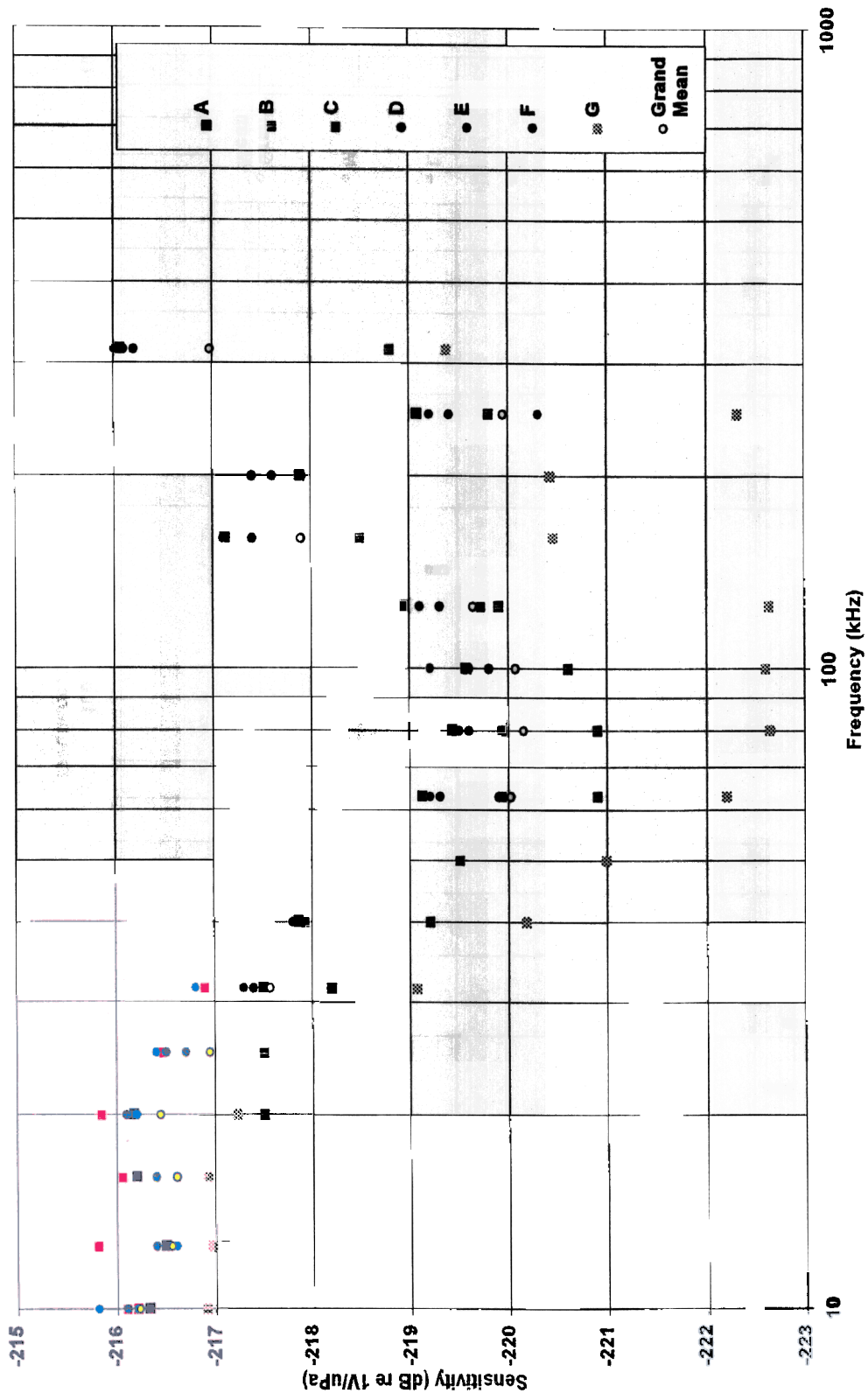


Figure 6 Calibration results for the TC 4034 hydrophone of Set A.

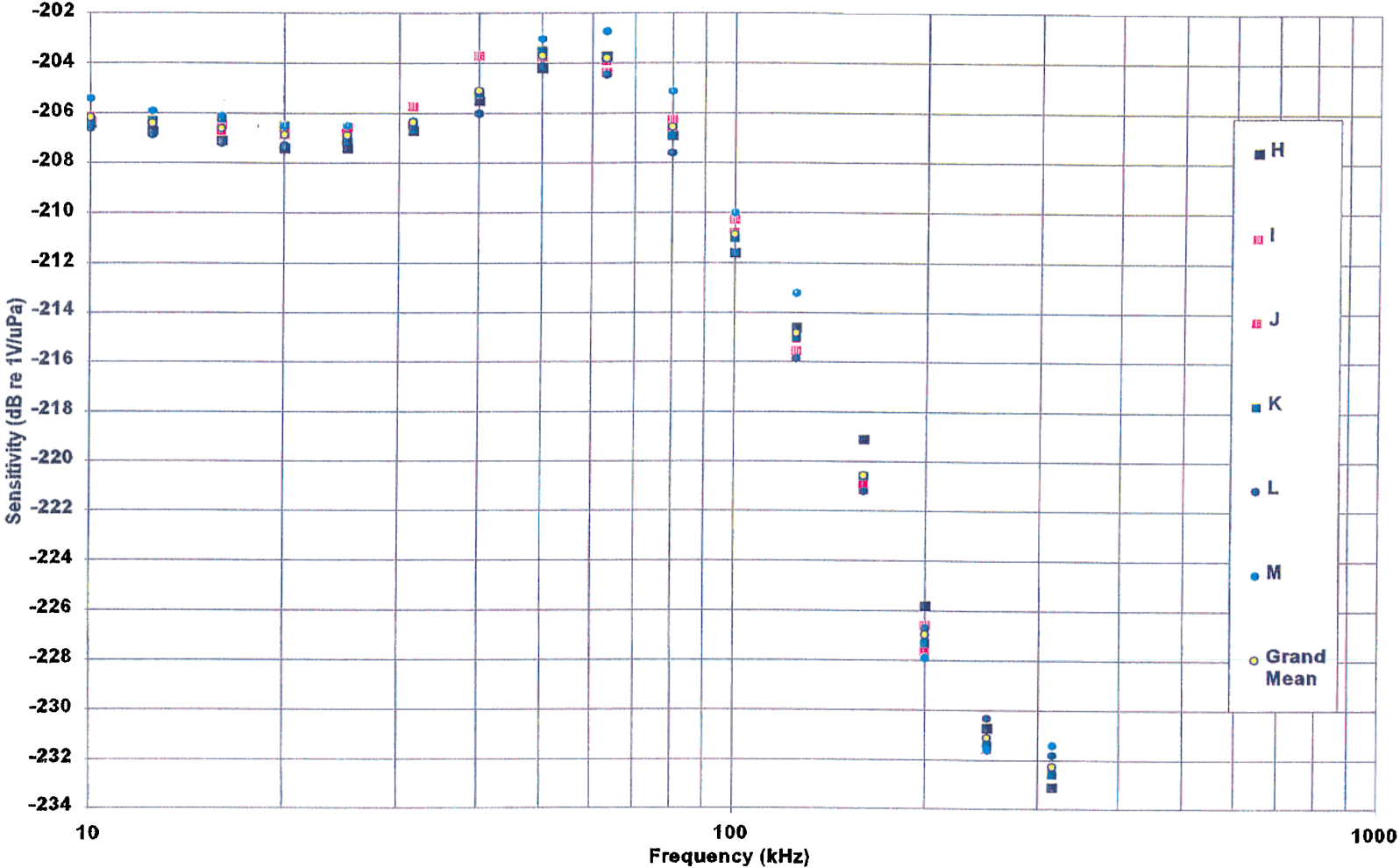


Figure 7 Calibration results for the B&K 8104 hydrophone of Set B.

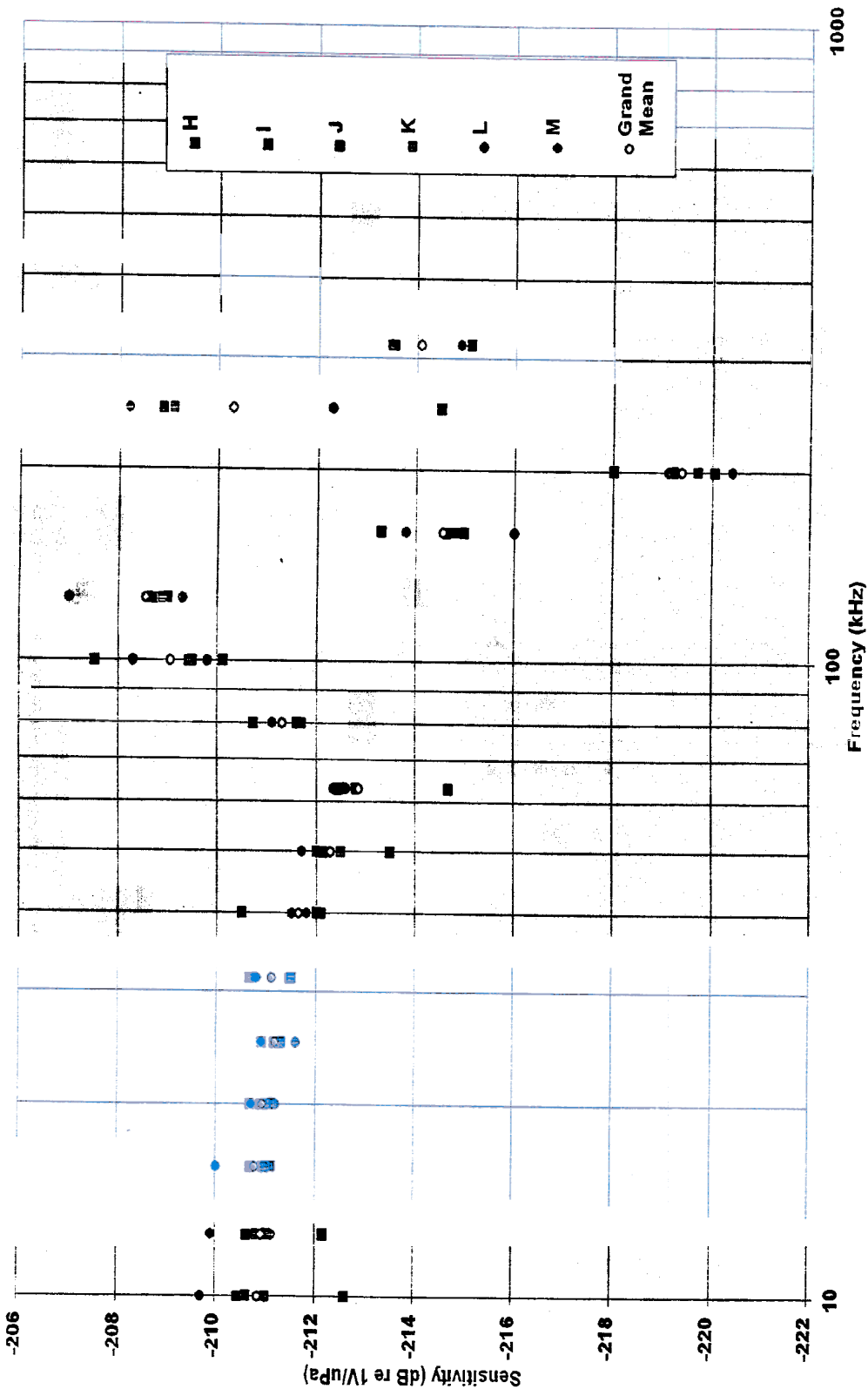


Figure 8 Calibration results for the B&K 8103 hydrophone of Set B.

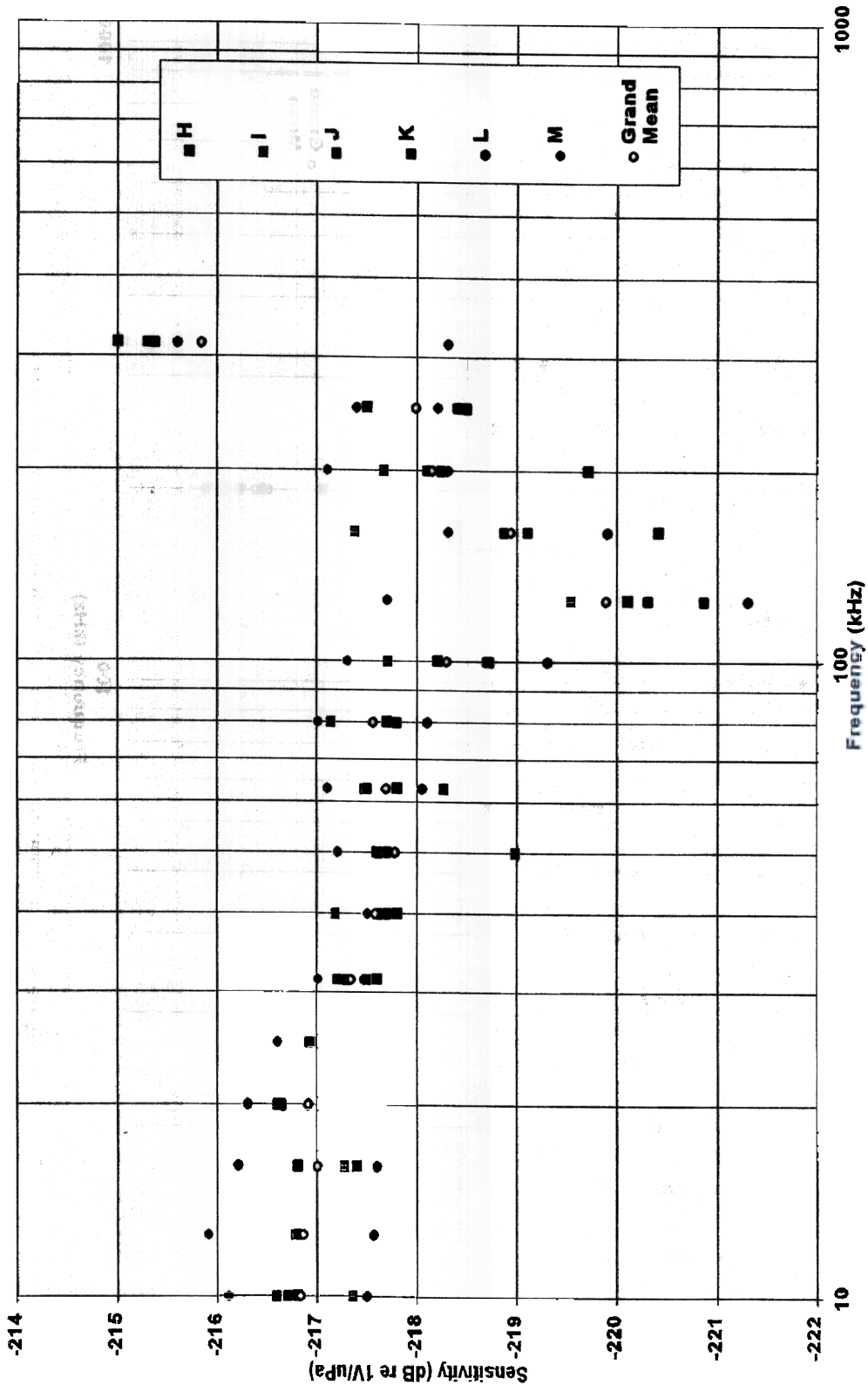


Figure 9 Calibration results for the TC 4034 hydrophone of Set B.

7.4 RESULTS FOR SET B

Figures 7 to 9 show the results for the set B hydrophones for the B&K 8104, B&K 8103 and the RESON TC4034 respectively. Also shown in each graph is the overall Grand Mean for that hydrophone.

7.5 METHODS USED BY PARTICIPANTS

In the following descriptions, the uncertainties quoted are expressed for a confidence interval of 95% unless otherwise stated.

Participant A

This participant used the method of three-transducer spherical-wave reciprocity to calibrate the hydrophones, with in-house hydrophones of known sensitivity used in the calibration procedure as reciprocal transducers. The calibration was performed in two frequency ranges (10-70 kHz and 70-400 kHz) and measurements were made at additional frequencies to the minimum third-octave requirement. The measurements were made in a laboratory tank of dimensions 2.5 x 4.5 x 3.0 m deep, with gated tone-burst signals used to isolate reflections. During calibrations, the transducers were positioned at a depth of 1.3 m and were separated by a distance of 0.6 m, and the water temperature was 22.0 °C. The estimated overall uncertainty was ± 1.1 dB.

Participant B

This participant also used the method of three-transducer spherical-wave reciprocity to calibrate the hydrophones (in conformance with IEC 565). Some measurements were made at additional frequencies to the minimum third-octave requirement. The measurements were made on an open-water facility, a lake 11 m in depth. The calibration laboratory was located on a pier, the pillars of which were at least 3 m away from the hydrophones during measurements. Again, gated tone-burst signals were used to isolate reflections. During calibrations, the transducers were positioned at a depth of 4 m and were separated by a distance of 1 m. The water temperature varied between 12.5 and 15.8 °C. The estimated overall uncertainty varied with frequency, and was stated as: ± 1.1 to 1.5 dB in the frequency range less than 8 kHz; ± 1 dB from 10 to 200 kHz; ± 1.1 -1.2 dB at frequencies greater than 200 kHz.

Participant C

This participant calibrated the hydrophones by comparison with a reference hydrophone which had previously been calibrated by the reciprocity method. The measurements were made in a laboratory tank made of wood and PVC and of dimensions 4 x 3 x 1.8 m deep, with gated tone-burst signals used to isolate reflections. During calibrations, the transducers were positioned at a depth of 0.9 m and were separated by a distance of 0.6 m. The hydrophones were wetted and soaked for 8 hours before calibrations, and were removed from the tank and remounted between each repeated measurement. The water temperature was 24.7 °C. The estimated overall uncertainty was ± 1.4 -1.9 dB, depending on the frequency.

Participant D

This participant also used the method of three-transducer spherical-wave reciprocity to calibrate the hydrophones (in conformance with ANSI S1.20), with in-house hydrophones of

known sensitivity used in the calibration procedure as reciprocal transducers. The measurements were made in a laboratory tank made of steel and of dimensions 4.6 x 3.6 x 2.7 m deep, with gated tone-burst signals used to isolate reflections and a digitising oscilloscope used to measure the electrical signals. During calibrations, the transducers were positioned at a depth of 1.1 m and were mounted on aluminium rods with tie-wraps. The hydrophones were wetted and soaked for a minimum of 30 minutes before calibrations. The water temperature was 21-23 °C. The estimated overall uncertainty was ± 0.3 -0.6 dB, depending on the frequency. In addition, this participant was able to use a calibrator normally used for line arrays to perform a relative calibration of the hydrophones in the frequency range from 30 Hz to 3 kHz.

Participant E

This participant also used the method of three-transducer spherical-wave reciprocity to calibrate the hydrophones (in conformance with IEC 565), with in-house hydrophones of known sensitivity used in the calibration procedure as reciprocal transducers. The measurements were made in a laboratory tank made of polypropylene and steel and of dimensions 1.5 x 2.0 x 1.5 m deep, with gated tone-burst signals used to isolate reflections and a digitising oscilloscope used to measure the electrical signals. During calibrations, the transducers were positioned at a depth of 0.6 m and were mounted using free-flooding aluminium poles. The hydrophones were wetted and soaked overnight before calibrations, and for a minimum of 30 minutes before repeated measurements. The hydrophones were removed from the tank, then remounted and realigned between each repeated measurement, and each repeated calibration was performed at a different separation distance in the range 0.8 to 1.2 m. Extra measurements were also performed to check the reciprocal behaviour of the transducers. The water temperature was 17.5 °C for the first half of the measurements, and was 20.5 °C for the remainder. The estimated overall uncertainty was ± 0.5 dB.

Participant F

This participant also used the method of three-transducer spherical-wave reciprocity to calibrate the hydrophones, with in-house hydrophones of known sensitivity used in the calibration procedure. The measurements were made in a laboratory tank of dimensions 7.5 x 5.5 x 6.0 m deep. During calibrations, the transducers were positioned at a depth of 2 m for frequencies less than 22 kHz, and 1 m for other frequencies. The transducers were separated by a distance of 1.5 m and the water temperature was 22 °C. The estimated overall uncertainty was ± 0.7 dB.

Participant G

This participant also used the method of three-transducer spherical-wave reciprocity to calibrate the hydrophones (in conformance with IEC 565). The measurements were made in a laboratory tank made of steel and PVC and of dimensions 0.98 x 0.62 x 0.60 m deep, with hydrophones mounted using PVC tubes. Gated tone-burst signals were used with the measurements made using a digital oscilloscope. During calibrations, the transducers were positioned at a depth of 0.3 m and were separated by 0.2 m. They were wetted and soaked for 2 hours before measurements. The water temperature was 19.5 °C. The estimated overall uncertainty was ± 0.1 to 0.5 dB.

Participant H

This participant calibrated the hydrophones by use of a standard projector, which had previously been calibrated by the reciprocity method. The measurements were made on an open-water facility, a reservoir of up to 20 m in depth. The calibration laboratory was located on a pontoon barge. Again, gated tone-burst signals were used to isolate reflections. During calibrations, the transducers were positioned at a depth of 5 m and the water temperature was 5 °C. The devices were wetted and soaked for 24 hours before measurements were begun, but no time was available for repeated measurements to be made. Calibrations were performed at close frequency intervals: 0.2 kHz steps at frequencies less than 18 kHz, 1 kHz steps from 18-85 kHz, and 5 kHz steps at higher frequencies. The estimated overall uncertainty was ± 1 dB.

Participant I

This participant calibrated the hydrophones by comparison with a reference hydrophone which had previously been calibrated by the manufacturer. Pulsed signals were used, and spectral analysis performed on the digitised waveforms. This resulted in calibration values at 2.44 kHz intervals. The measurements were made in a laboratory tank made of plexiglass and of dimensions 1 x 1 x 1 m. During calibrations, the transducers were positioned at a depth of 0.36 m. The hydrophones were wetted and soaked for 8 hours before calibrations. They were mounted on poles connected to a positioning system and were removed from the tank and remounted before each repeated measurement. The water temperature was 23.7 °C. The maximum overall uncertainty reported was ± 2.5 dB, but the typical value was between ± 0.5 and 1 dB, depending on the frequency.

Participant J

This participant used the method of three-transducer spherical-wave reciprocity to calibrate the hydrophones (in conformance with ANSI S1.20). The measurements were made in a laboratory tank made of concrete and of dimensions 7 x 3.7 x 3.7 m deep, with gated tone-burst signals used to isolate reflections and a digitising oscilloscope used to measure the electrical signals. During calibrations, the transducers were positioned at a depth of 1.85 m and were allowed to hang without mounting poles, but weighted down with weights attached with thin wire. The water temperature was 20 °C for the measurements and separation distances in the range 1.0-1.3 m were used. The hydrophones were wetted and soaked for 2 hours before measurements were started. The estimated overall uncertainty was ± 0.3 -0.4 dB.

Participant K

This participant also used the method of three-transducer spherical-wave reciprocity to calibrate the hydrophones (in conformance with IEC 565), with in-house hydrophones of known sensitivity used in the calibration procedure as reciprocal transducers. The measurements were made in a laboratory tank made of steel and of dimensions 1.5 x 2.0 x 1.5 m deep, with gated tone-burst signals used to isolate reflections and a digitising oscilloscope used to measure the electrical signals. During calibrations, the transducers were positioned at a depth of 0.6 m and were mounted using free-flooding aluminium poles. The hydrophones were wetted and soaked overnight before calibrations, and for a minimum of 30 minutes before repeated measurements. The hydrophones were removed from the tank, then remounted and realigned between each repeated measurement, and each repeated calibration was performed at a different separation distance in the range 0.8 to 1.2 m. Extra measurements

were also performed to check the reciprocal behaviour of the transducers. The water temperature was 17.5 °C for the first half of the measurements, and was 20.5 °C for the remainder. The estimated overall uncertainty was ± 0.5 dB.

Participant L

This participant calibrated the hydrophones by the method of three-transducer spherical-wave reciprocity in the range 30 to 200 kHz, and by comparison with a reference hydrophone which had previously been calibrated by the reciprocity method at frequencies outside this range (reference was made to the classic text-book by R.J. Bobber⁵). The measurements were made in a laboratory tank made of concrete and of dimensions 4 x 3 x 3.6 m deep, with gated tone-burst signals used to isolate reflections, and a digital oscilloscope and voltmeter used to measure the electrical signals. The hydrophones were mounted using mounting poles which were partly made of fibre-glass and partly made of glass-resin. During calibrations, the transducers were positioned at a depth of 1.8 m and several different separation distances were used. The water temperature was 20 °C. The estimated overall uncertainty was ± 0.7 dB. Calibrations were also made at a frequency of 251 Hz using a commercially available air-pistonphone calibrator.

Participant M

This participant used the method of three-transducer spherical-wave reciprocity to calibrate the hydrophones in conformance with IEC 565 and included in-house hydrophones within the calibration. The measurements were made in an oval water tank which is 5 m deep and has maximum and minimum diameters of 8 and 6 m respectively. Gated tone-burst signals were used to isolate reflections and a digitising oscilloscope used to measure the electrical signals. During calibrations, the transducers were positioned at a depth of 2.5 m and were mounted using a trestle that allows their axes to be directed toward each other. The hydrophones were wetted and soaked for 48 hours before calibrations. The water temperature was 17 °C for the measurements. The estimated overall uncertainty varied according to the acoustic frequency but was generally between ± 0.5 and 2.0 dB.

7.6 DIFFERENCES FROM THE GRAND MEAN

Figures 10 to 12 show the differences from the Grand Mean (in dB) for the B&K 8104, B&K 8103 and the RESON TC4034 of Set A respectively. Figures 13 to 15 show the differences for the B&K 8104, B&K 8103 and the RESON TC4034 of Set B in the same way.

When considering the differences from the mean, notice should be taken of the variations reported in Section 4.3 for the hydrophones in each set. These are indicative of the variation that may be expected in the hydrophone response during the intercomparison. Any differences which are significantly greater than those shown in Tables 2 and 3 of Section 4.3 may be attributed to systematic differences in the calibrations by the participants.

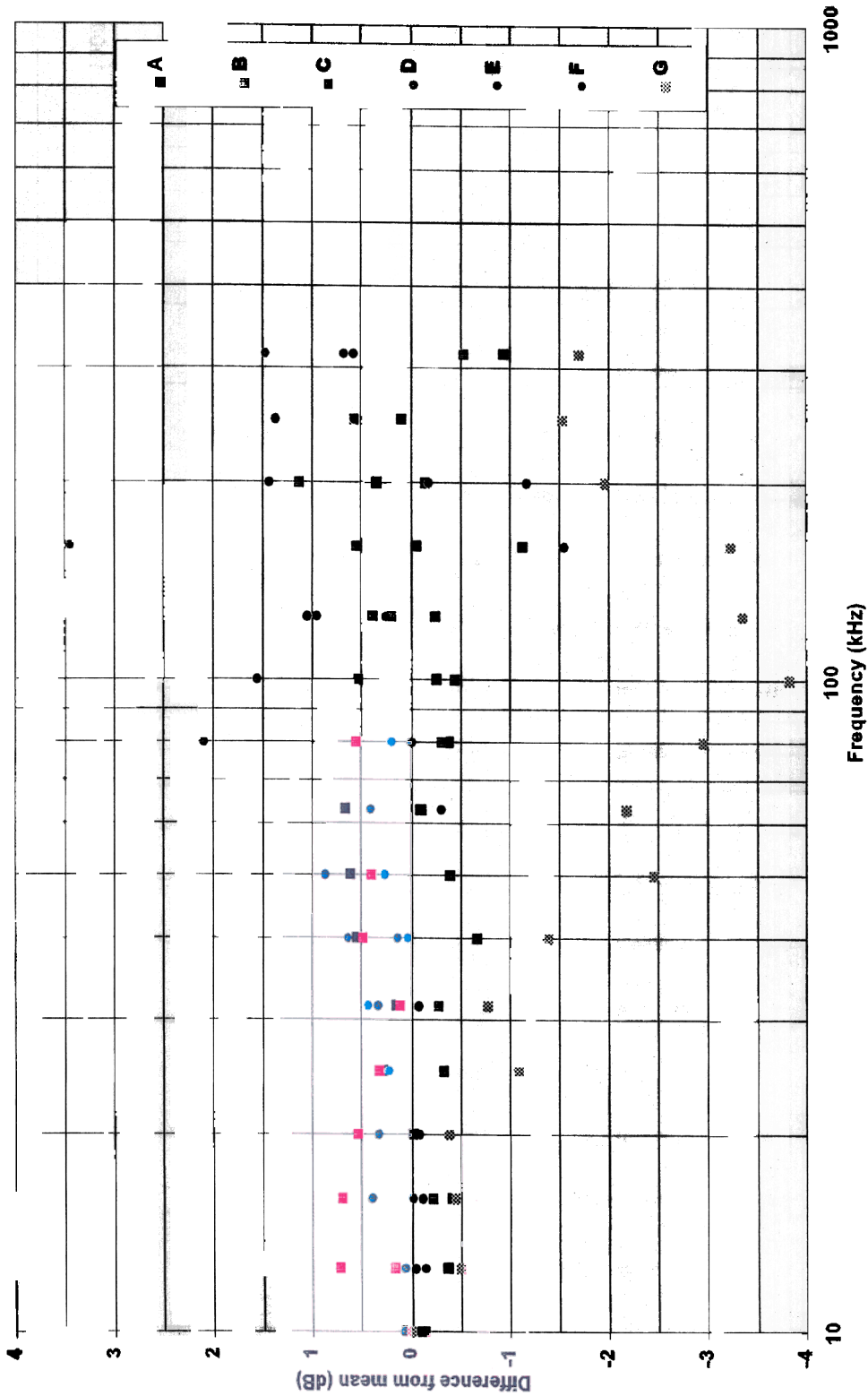


Figure 10 Differences from the Grand Mean for the B&K 8104 hydrophone of Set A.

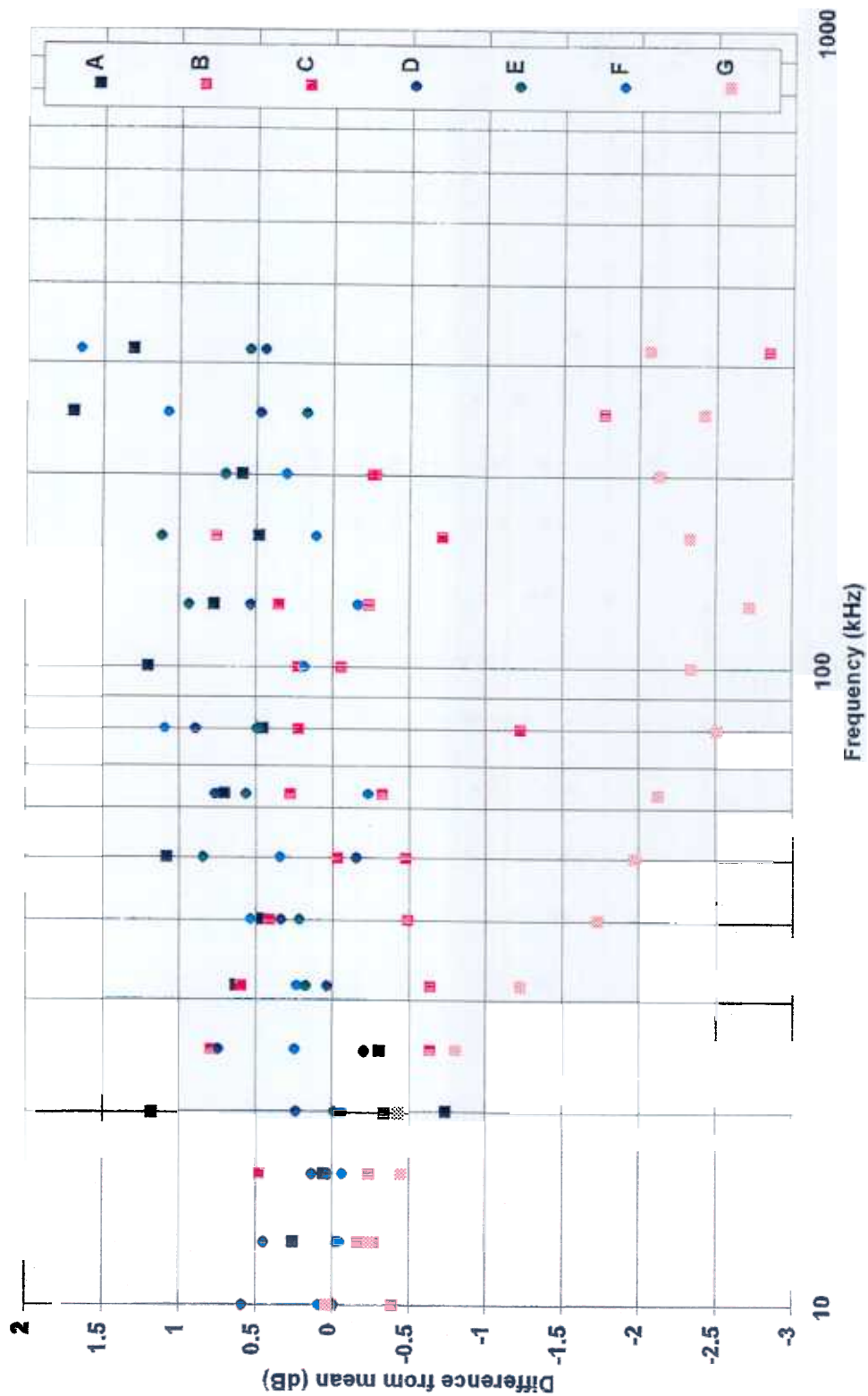


Figure 11 Differences from the Grand Mean for the B&K 8103 hydrophone of Set A.

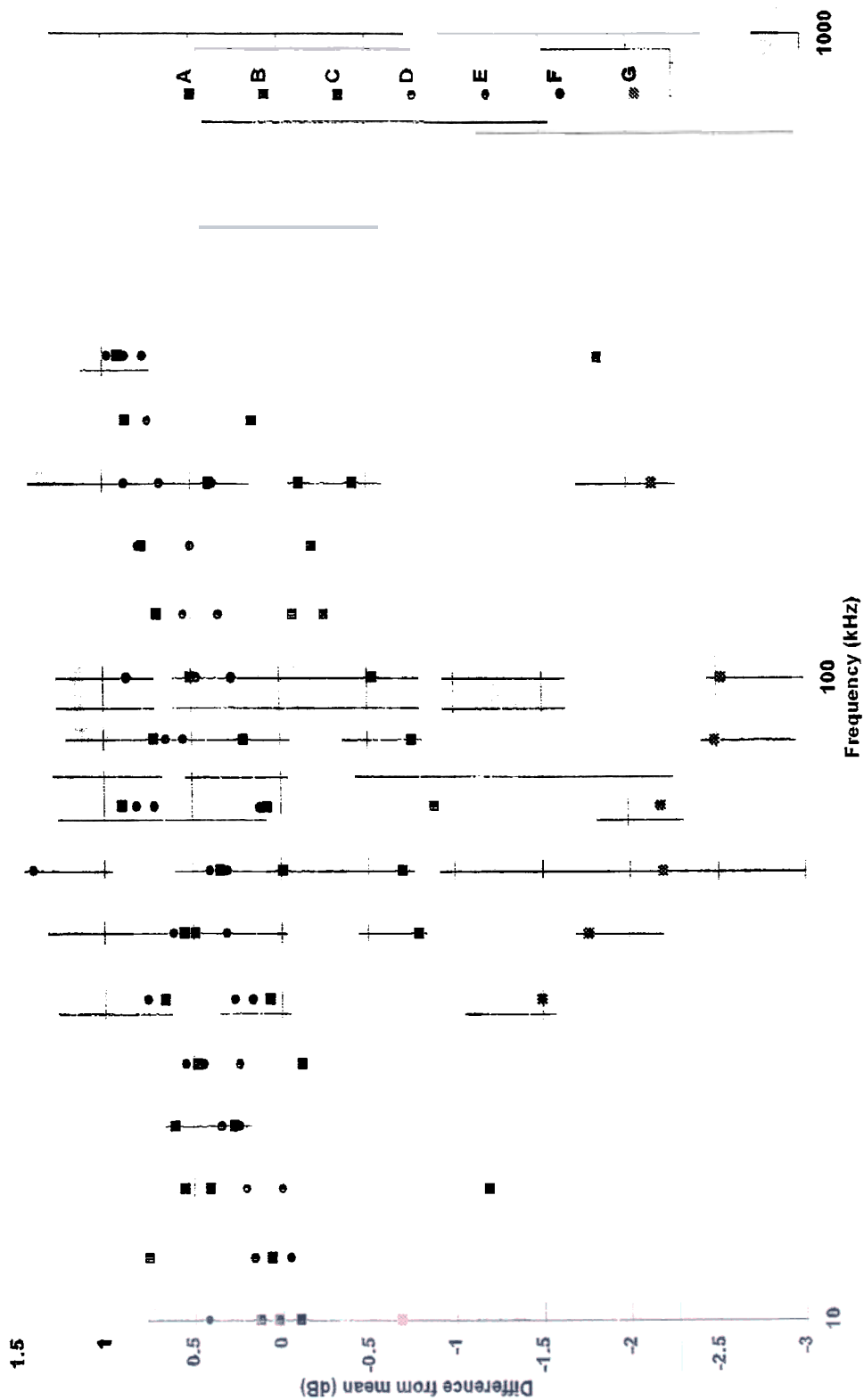


Figure 12 Differences from the Grand Mean for the TC 4034 hydrophone of Set A.

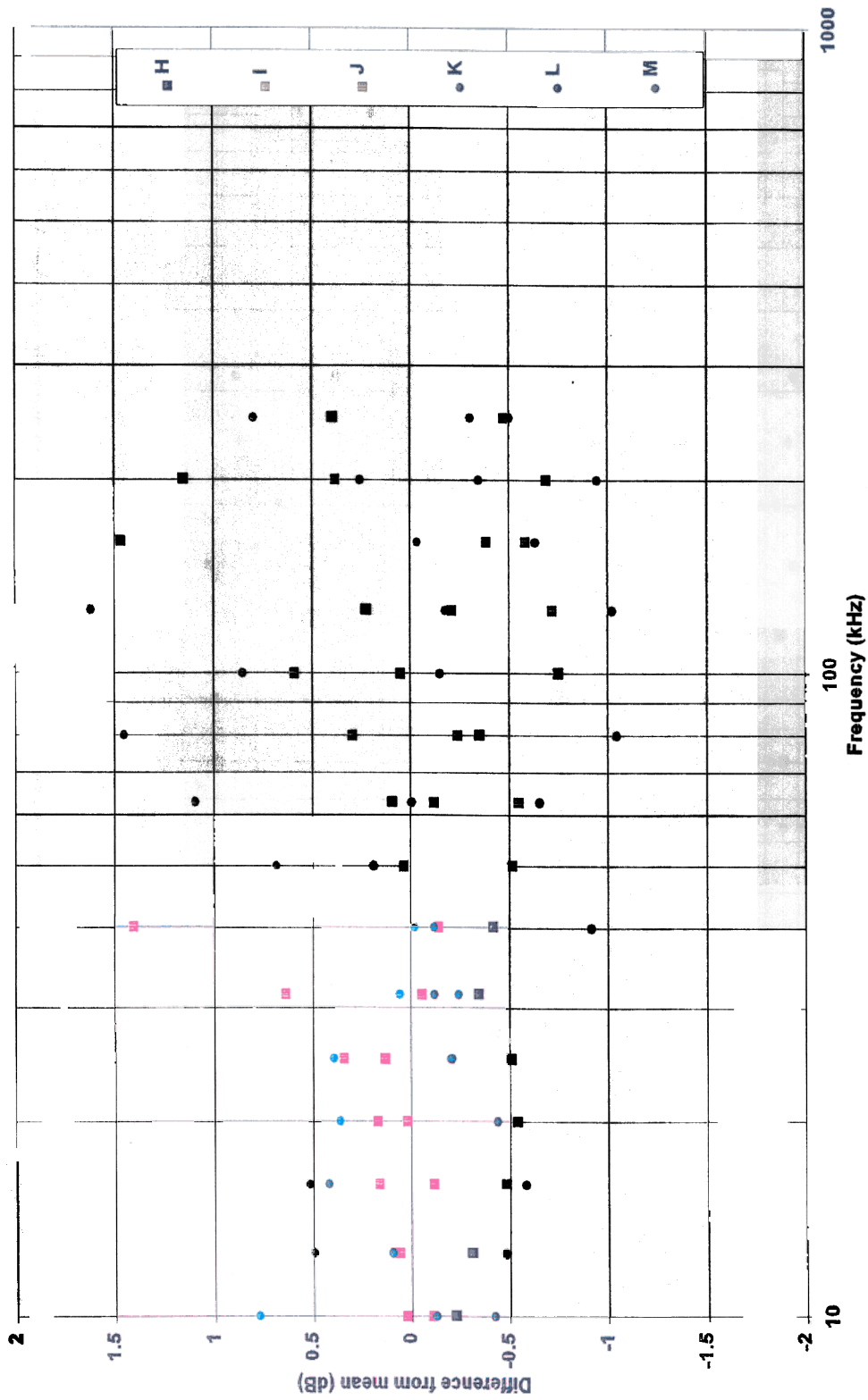


Figure 13 Differences from the Grand Mean for the B&K 8104 hydrophone of Set B.

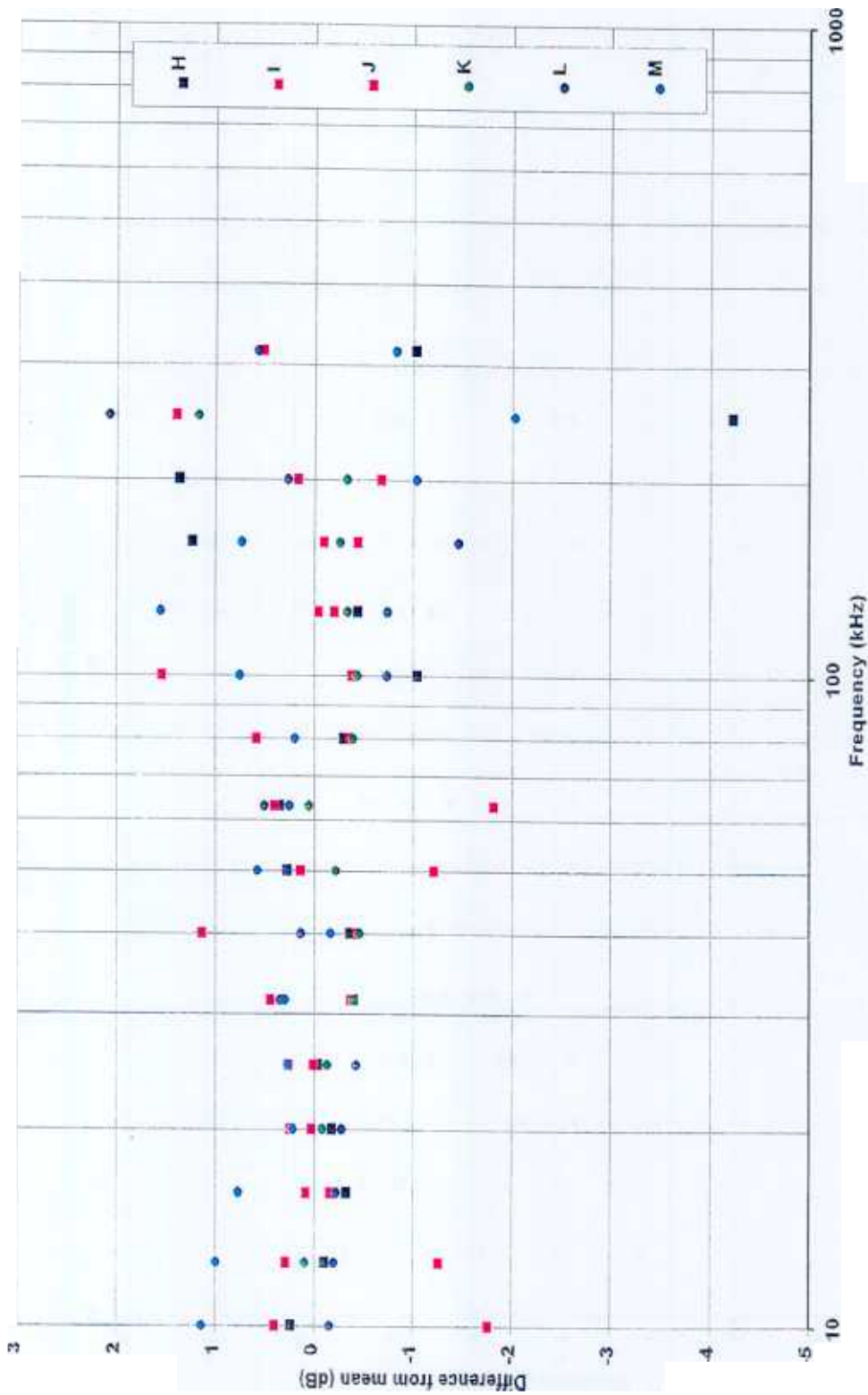


Figure 14 Differences from the Grand Mean for the B&K 8103 hydrophone of Set B

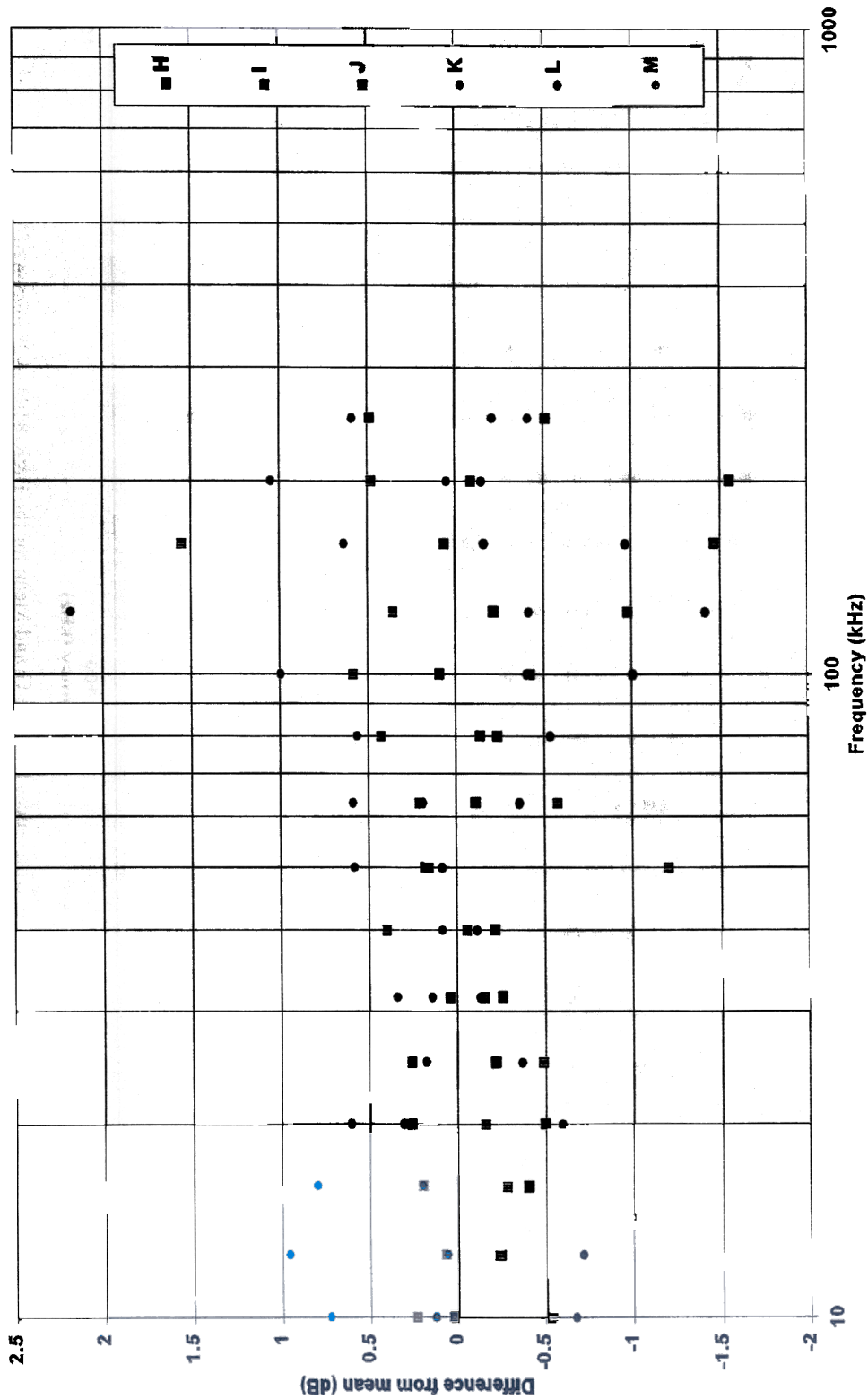


Figure 15 Differences from the Grand Mean for the TC 4034 hydrophone of Set B.

8 DISCUSSION

8 ANALYSIS OF RESULTS

8 Difference from mean averaged over all frequencies

Table 4 and 5 show, for set A and B respectively, the differences from the Grand Mean averaged over all frequencies for each participant calibrating the hydrophones.

Table 4. The differences from the Grand Means for the participants calibrating Set A.

Participant code	Maximum difference (dB)	Mean difference (dB)	RMS difference (dB)	Overall Uncertainty (dB)
B&K8104 (s/n: 1757063)				
A	-0.9	0.04	0.42	1.1
B	1.1	-0.08	0.45	1.0-1.2
C	-1.1	0.18	0.50	1.4-1.9
D	2.1	0.18	0.96	0.3-0.6
E	1.4	0.37	0.53	0.5
F	3.5	0.49	0.88	0.7
G	-3.8	-1.80	2.17	0.1-0.5
B&K8103 (s/n: 1785459)				
A	1.7	0.50	0.74	1.1
B	-2.8	-0.62	1.03	1.0-1.2
C	1.2	0.23	0.49	1.4-1.9
D	0.9	0.40	0.47	0.3-0.6
E	1.1	0.35	0.49	0.5
F	1.6	0.32	0.55	0.7
G	-2.5	-1.63	1.86	0.1-0.5
RESON TC 4034 (s/n: 426002)				
A	0.9	0.45	0.53	1.1
B	-1.8	-0.67	0.82	1.0-1.2
C	0.8	0.28	0.40	1.4-1.9
D	0.9	0.38	0.42	0.3-0.6
E	0.9	0.44	0.49	0.5
F	1.4	0.56	0.66	0.7
G	-3.0	-1.82	2.00	0.1-0.5

Several different measures are given in the tables. Firstly, there is the maximum difference from the Grand Mean, which shows the worst case agreement. Secondly, there is the mean difference, which is an indication of whether the participant’s results are systematically higher or lower than the mean (for results equally spread about the Grand Mean, the mean difference should be zero). And thirdly, there is the RMS difference, which gives an indication of the general disagreement. Finally, the typical overall uncertainty quoted by the participant is stated.

Table 5. The differences from the Grand Means for the participants calibrating Set B.

Participant code	Maximum difference (dB)	Mean difference (dB)	RMS difference (dB)	Overall Uncertainty (dB)
B&K8104 (s/n: 1757065)				
H	1.5	-0.14	0.60	1.0
I	1.4	0.12	0.52	0.5-2.5
J	-0.7	-0.14	0.27	0.3-0.4
K	0.4	-0.08	0.24	0.5
L	-1.0	-0.40	0.63	0.7
M	1.6	0.46	0.74	0.5-2.0
B&K8103 (s/n:1785461)				
H	-4.2	-0.39	1.38	1.0
I	-1.8	-0.22	0.99	0.5-2.5
J	1.4	0.04	0.46	0.3-0.4
K	1.2	-0.10	0.40	0.5
L	2.1	-0.02	0.70	0.7
M	2.0	0.19	0.87	0.5-2.0
RESON TC4034 (s/n: 426001)				
H	-1.6	-0.25	0.64	1.0
I	1.6	-0.01	0.62	0.5-2.5
J	-1.0	-0.03	0.36	0.3-0.4
K	0.5	0.01	0.26	0.5
L	-1.4	-0.43	0.65	0.7
M	-2.5	0.45	0.99	0.5-2.0

As is shown by the above tables, in most cases the maximum difference from the Grand Mean is greater than the uncertainty quoted. This may indicate an error in the measurement, or an under-estimate of the uncertainty. Indeed, in some cases the RMS difference is greater than the uncertainty. It should be noted that the RMS difference is calculated in the manner of a standard deviation (1σ) and so is an optimistic estimate of the variation, whereas the

uncertainty is expressed for a confidence level of 95 % (2σ). It therefore gives some cause for concern that the RMS difference should be larger than the quoted uncertainty. When considering the RMS difference from the Grand Mean, note should be taken of the variation of sensitivity for the hydrophones that was reported in Section 4.3.

8.1.2 Difference from Grand Mean averaged over all participants

Another way of analysing the data is to calculate the RMS difference from the Grand Mean averaged over all participants for each frequency of calibration. This has been done for Set A and B and the results are shown in Figures 16 and 17 respectively.

These graphs give an indication of the variation in the calibrations of the individual hydrophones at each frequency. A general trend may be observed of increasing RMS difference with frequency, a trend which is much more marked for Set A than for Set B. As the frequency increases, the hydrophone responses become more directional, leading to greater sensitivity to mis-alignment during calibration.

8.2 ASSESSMENT OF UNCERTAINTIES

From the comments of participants, it is evident that initially many of them had difficulty assessing and expressing the uncertainty in their calibrations. This was because they were not familiar enough with some of the metrological concepts. One should remember that, with the exception of NPL, there were no national standards laboratories taking part in the project. It was important to ensure that the uncertainties were expressed in a common way, and so NPL provided each participant with a copy of document NIS 3003, edition 8, entitled *The expression of uncertainty and confidence in measurement for calibrations*⁷ which is available from the United Kingdom Accreditation Service (UKAS). The publication contains guidance and requirements applicable to UK calibration laboratories accredited by UKAS, and is consistent with the ISO document *Guide to the Expression of Uncertainty in Measurement*⁸ which has gained world-wide acceptance since its publication in 1993.

Using NIS 3003 for guidance, most participants were able to combine and express their uncertainties in a common way. However, as is evident from the results, some participants appear to have under-estimated their uncertainties. A possible reason for this is the omission of a component of the systematic (Type B) uncertainty. For example, the method of three-transducer spherical-wave reciprocity depends upon certain assumptions, such as the existence of a spherically divergent acoustic field and the reciprocal behaviour of at least one of the transducers. Both of the above can be tested and an uncertainty derived, for example by performing calibrations at different separation distances and checking that the acoustic pressure decreases inversely with distance, or performing additional reciprocity-check measurements. Such checks were not always performed, and uncertainty contributions were rarely included in the overall estimates. Also, at higher frequencies, the responses of the hydrophones become much more directional, making alignment important, particularly in the XZ/YZ (vertical) planes. However, rarely was any estimate made for the potential source of error due to misalignment.

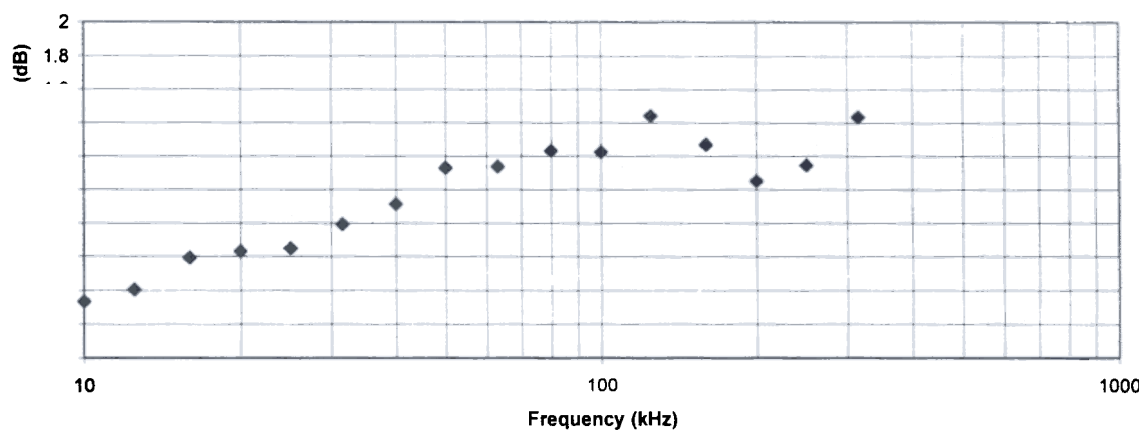
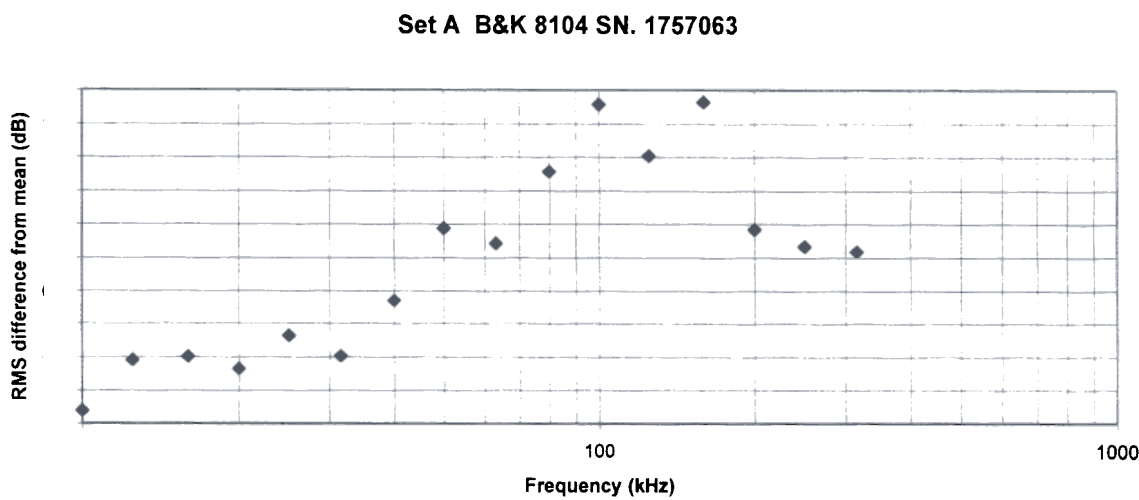
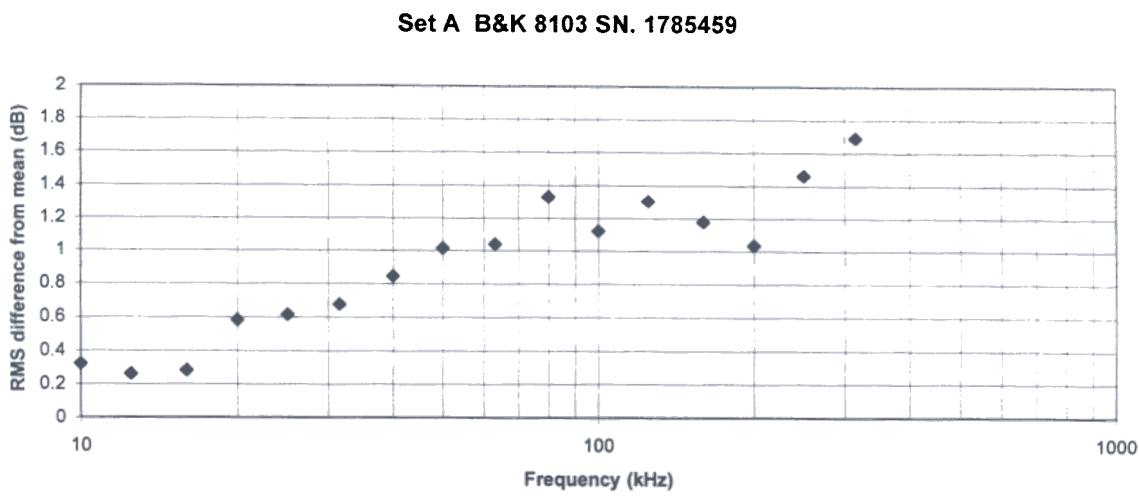


Figure 16 RMS difference from Grand Mean averaged over all participants for Set A.

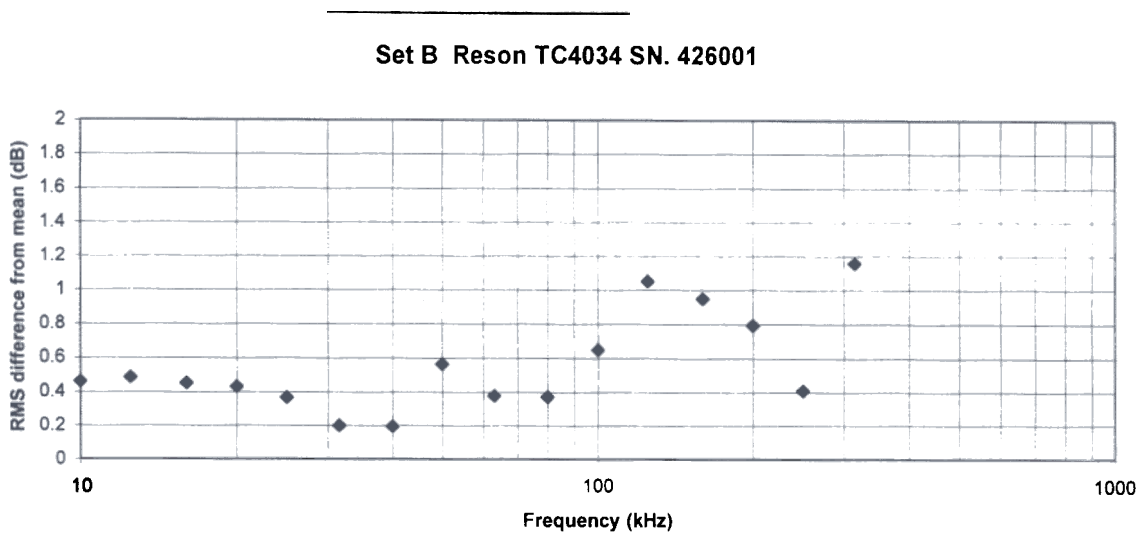
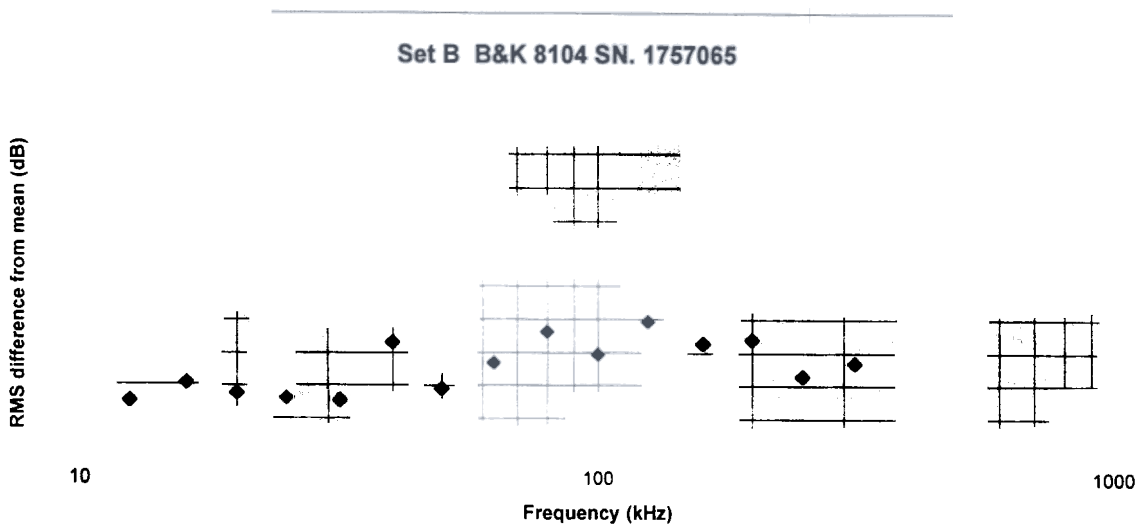
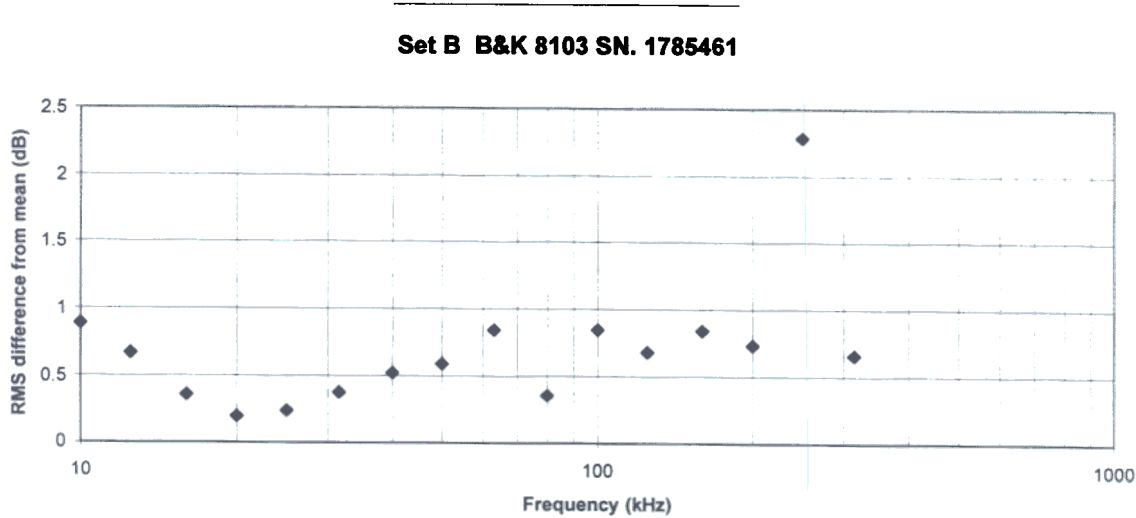


Figure 17 RMS difference from Grand Mean averaged over all participants for Set B

Some participants may have under-estimated the random (Type A) uncertainty in the calibrations. Ideally, for truly independent repeated calibrations, the hydrophones should be removed from the water and remounted between measurements. This allows the influence of variations in mounting and alignment to be assessed. However, not all participants adopted this approach, and this may have led to some optimistic estimates of uncertainty.

8.3 INFLUENCES ON CALIBRATIONS

8.3.1 Water temperature

Given the wide range of facilities used by participants for the calibrations, it was not practicable for NPL to request that calibrations be performed at a standard temperature (eg 20 °C). Whilst it may be possible to control the temperature of the water in a small laboratory tank over a reasonably narrow range, this is not feasible for large tanks or outdoor facilities. As a consequence, the calibrations undertaken by different participants have been performed at different water temperatures. This was envisaged as a potential problem at the beginning of the project. The sensitivity of the hydrophones used in the intercomparison is not believed to vary by more than a maximum of 0.05 dB/°C (according to manufacturer's figures). However, if one participant has performed calibrations outdoors in cold weather at 4-5 °C and another in a small tank situated in a heated laboratory at 25 °C, this could lead to a difference of up to 1 dB. In addition, it is very likely that the magnitude of this variation will change with frequency.

Fortunately, all the participants undertaking calibrations in laboratory tanks were able to perform measurements at water temperatures between 17.5 and 24.5 °C, with most calibrations done between 20 and 23 °C. The participants using open-water facilities necessarily could not control the water temperature, and one participant performed calibrations at 5 °C. The calibration at 5 °C for the B&K 8103 shows a significantly different response in the region of the second resonance (200-300 kHz). From an examination of the intermediate calibration results between the requested third-octave frequencies, it would appear that the second resonance has shifted in frequency. Since the resonance is so sharp, this shift has led to a relatively large change in sensitivity. It is strongly believed that this is due to the temperature difference since the second resonance (the length mode resonance for this cylindrical hydrophone design) is known to be sensitive to boundary conditions (ie the stress applied to the element from the surrounding structure of the hydrophone). These are dependent on material properties which in turn depend on the temperature. The broader radial-mode resonance (at a frequency of 125 kHz) is less sensitive to changes in temperature. Although the effect is most pronounced for the B&K 8103 hydrophone at 5 °C, the temperature difference may also have contributed to a lesser degree to the variation in the calibration results at higher temperatures and for the other two hydrophones, especially around the resonance frequencies.

It should be noted that the check measurements at NPL were performed over a water temperature range of 17.0 to 24.0 °C for Set A and 17.6 to 22.3 °C for Set B, which is a similar range to that of the participants' measurements. It is difficult to make any definitive conclusions regarding trends in this measurement data, but the variations reported in Section 4.3 most likely include

the variations due to this effect over the range of temperatures at which most of the calibrations by participants were performed.

8.3.2 Mounting

It is known that the mounting configuration used can affect the measured sensitivity for some hydrophones, and this may have contributed to the variation in results. Ideally the mount should not cause any reflections or reverberations in the acoustic signal (and so should offer as small an acoustic impedance mismatch as possible), but should be rigid enough to allow precise positioning of the hydrophones. There was 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.

Of course, the hydrophones could have been supplied to participants with a specific mount, but it was felt that it would be better to allow each participant to use their own mount. In fact, there is no “standard” or recommended method of mounting the hydrophones, an issue which may need addressing if substantially increased accuracy were required from hydrophone calibrations.

8.3.3 Alignment (hydrophone directional response)

Although small hydrophones are often described as “omnidirectional”, this is only an approximation valid at very low frequencies and the sensitivity of a hydrophone should not be considered as a single-valued parameter. In fact, the sensitivity of a hydrophone is not just a function of frequency, but also of the angle of incidence of the incoming acoustic wave. The degree of dependence on angle increases as the product ka increases, where k is the wave number (equal to $2\pi/\lambda$ where λ is the acoustic wavelength) and a is the maximum dimension of the hydrophone active element. In practice, this means that the hydrophones become more directional in their response at frequencies around or above their first resonance.

This is particularly true in the vertical orientation (the XZ and YZ planes), where only slight misalignment at the highest frequencies can cause an error in the measurement. The participants were asked to align the hydrophones vertically in the water with their reference alignment marks pointing in the direction of the acoustic source (the most common way for hydrophones to be aligned for calibration). This is difficult to achieve with better accuracy than $\pm 2^\circ$. Consequently, it is thought that misalignment was a contributory factor to the increased variation in the reported results at high frequencies.

8.3.4 Lack of acoustic far-field conditions

The method of three-transducer spherical-wave reciprocity depends upon the assumption of a spherical-wave field. Indeed, this is implicit within the definition of the transmitting response of the transducers. This can only be achieved when operating sufficiently into the acoustic far-field of the transducers, a criterion which is also necessary for accurate comparison calibrations.

To be in the acoustic far-field requires that a large enough separation distance be used between

the transducers under test. Most participants were able to use separation distances of about 1 m which, for such small hydrophones, is sufficient to ensure far-field conditions exist. However, due to the small size of the water tank, participant G used a separation distance of only 20 cm. This is believed to be contributing to the trend in these results which shows good agreement at low frequencies, but increasingly low values relative to the Grand Means as the frequency increases. To test this, at the end of the intercomparison NPL also calibrated two of the hydrophones of Set A at a separation distance of 20 cm. A similar trend in the results was observed, although the magnitudes of the differences were only about half of those shown for participant G.

8.3.5 Wetting and soaking

The length of for which the hydrophones are soaked can have an affect on the calibrations. Soaking for a short time allows the temperature of the hydrophone to equalise with the water and allows any air attached to the surface of the device to dissolve. Wetting with a little detergent can also help to remove trapped air and grease. Most participants seemed familiar with the need for careful wetting and soaking, and adopted appropriate procedures during measurements. However, some problems were reported with air bubbles forming in saturated water, leading to poor reproducibility in measurements. This problem can arise when the water has been stirred up (eg by recirculation), when there is biological or chemical action, or when the water temperature has risen causing gas to come out of solution. This can be a difficult problem to solve, and often it is necessary to wait until the water has settled and stabilised before continuing with measurements.

8.3.6 Interference from acoustic reflections

Most participants used gated tone-burst signals to isolate acoustic reflections. This allows essentially free-field measurements to be made in reverberant environments by making measurements on the steady-state portion of the direct-path signal before the arrival of reflections from boundaries. Care must also be taken to avoid reflections from other structures in the tank such as mounts and other transducers and hydrophones. Although interference from acoustic reflections can be a serious problem, all participants showed a good understanding of the difficulties and took care to avoid making measurements in their presence. Therefore, it is thought unlikely that reflections were a substantial cause of discrepancies in the results.

8.3.7 Transient effects

The use of the gated tone-burst techniques described above means that there is only a finite time during which measurements can be made of the steady-state signal. During this time, the signal at the frequency of interest is contaminated by start-up transients generated due to the resonant nature of the transducers. This effect is worse at low frequencies when there are fewer cycles of the signal available in the echo-free time-window, and also in the presence of high-Q resonances. During the calibrations for this project, most participants seemed to be familiar with the difficulties caused by transient effects. Some difficulties were reported with a small high-Q resonance with the TC4034 hydrophone at 125 kHz which meant that a large number of cycles

were required to achieve steady-state conditions. In addition, some participants commented that they might benefit from better guidelines on the best procedure to use when making measurements on tone-burst signals (eg whether to keep the number of cycles in the measurement window constant as the frequency changes, or whether to use a fixed length of time window and allow the number of cycles to increase as the frequency increases).

8.3.8 Noise

The hydrophones used in the intercomparison are resonant devices, and so when they are used as projectors and are driven off-resonance they exhibit a very poor transmitting response. This can lead to poor signal-to-noise ratio in certain frequency ranges (typically at very low or very high frequencies), and several participants reported problems of this nature. One solution is to use a range of other transducers as projectors (and reciprocal transducers if the reciprocity method is used) so that the signal level is sufficiently high over all frequencies. This procedure was adopted by some participants, although it increases the complexity and effort required for the calibrations.

8.3.9 Electrical loading

The addition of extra cable to the hydrophone can affect the sensitivity due to electrical loading, and corrections must be applied to the results to account for this. Similarly, loading may occur from the input impedance of a preamplifier or oscilloscope. In this project, few participants used extension cables and most participants used preamplifiers with very high input impedances which made the loading corrections insignificant.

8.3.10 Depth of immersion

The sensitivities of the hydrophones used are highly likely to depend on the hydrostatic pressure and therefore on the depth in the water. However, most of the calibrations were undertaken at depths of only a few metres (maximum 5 m) and so it is considered that depth of immersion is unlikely to be a significant cause of variation in the results.

9 CONCLUSIONS

9.1 GENERAL CONCLUSIONS

A number of general conclusions may be drawn from the results of the project.

- The agreement between the results of participants was such that a majority of the results were generally within ± 1 dB of the Grand Mean. In general, this is very encouraging and reflects well upon the expertise of the participants.
- However, this degree of variation means that calibrations originating from laboratories in two different countries could easily disagree by 2 dB, which could lead to serious and potentially expensive disagreements in measured values when the hydrophones are used in the field. In addition, some large variations were observed which must give cause for concern.
- The uncertainties in the calibrations were typically under-estimated by the participants, with the maximum differences from the Grand Mean almost invariably exceeding the quoted overall uncertainties.
- Relatively few participants claimed reference to the relevant international standard: IEC 565 - *The calibration of hydrophones*. This standard now seems dated and it is time for a revision. Indeed, several participants noted that better guidelines were needed for the calibration of hydrophones for underwater acoustics.

9.2 FUTURE WORK

The results of the intercomparison also suggest a number of topics which could be the subject of future work.

- Considerable benefit would be gained by further investigation into some of the large discrepancies in the results of certain participants, either individually or perhaps in collaboration with others.
- Some of the hydrophones used in the intercomparison could now be made available to other interested parties wishing to check their own calibrations. If this were to be done, the hydrophones would need to be maintained in a calibrated state by the coordinator.
- There would be benefit from linking this intercomparison to a similar exercise currently being organised in the United States, perhaps by the coordinators of each project performing calibrations of each others hydrophones.
- Further work could be done to study the sources of uncertainty in calibrations and improve the accuracy of the primary standard, perhaps in conjunction with work to revise the international specification standard. This would provide a greater margin

between the accuracy of primary calibrations and that required for secondary measurements which utilise the calibrated hydrophones. To substantially improve accuracy, work may also be required to:

- (i) standardise the calibration method;
- (ii) standardise the hydrophones used and their manner of mounting;
- (iii) accurately determine the properties of the hydrophones (for example, the variation of sensitivity with temperature).

- Another potential topic of future work is the development of a more accurate method for the primary calibration of hydrophones. This would resolve many of the uncertainties as to the origin of the differences in the calibrations reported in this project. To be useful, the new method would have to be at least 3 times as accurate as the typical ± 1 dB quoted here.
- Several participants noted that the phase response of hydrophones was sometimes required (for example, for phase matching between the elements in arrays). However, the calibration methods are usually employed to measure only the amplitude response. The extension of the calibration methods to cover the measurement of phase could be the subject of future work.
- This project was an intercomparison of calibrations which were performed at essentially atmospheric pressure. Since underwater transducers are required to be used at increasing ocean depth, calibration at elevated static pressure is of great interest. However, there are currently few facilities in which such calibrations may be undertaken.
- There may be scope in the future for parametric modelling of hydrophones and transducers by use of data measured during a calibration.⁹ Such a model could provide amplitude and phase data for transducers at any frequency within the bandwidth of the measurements.

9.3 EXPLOITATION OF RESULTS

Because of the nature of the project, there are no new products or designs originating from it which may be the subject of future commercial exploitation. However, it is planned to disseminate the results of the project in several ways.

- At least one scientific paper will be produced by the coordinator for submission to a European journal within six months of the end of the project. This will help to publicise the results to a wider audience within the scientific community.
- At least one presentation describing the project results will be made by the coordinator at a European conference.
- A project summary has been provided by the coordinator to the European Commission for electronic dissemination on the Internet. This will be updated in due course as

required.

- As stated in the previous section, the hydrophones can now be made available to other interested parties wishing to check the quality of their calibrations, with the coordinator maintaining the devices in a calibrated state.
- The results and recommendations of this project can be used to inform the future work programme of international standards organisations such as the IEC.

10 ACKNOWLEDGEMENTS

The authors acknowledge the support and funding of the Directorate-General for Science, Research and Development of the Commission of the European Communities and the National Measurement System Policy Unit of the UK Department of Trade and Industry.

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2. Robinson, S.P. and Preston, R.C. A survey of European calibration facilities for underwater acoustics. *NPL Report RSA(EXT)32*, April 1992, National Physical Laboratory, UK.
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4. ISO 266: 1975(E). *Acoustics - preferred frequencies for measurements*. International Organization for Standardization, Switzerland.
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APPENDIX A PROCEDURE DOCUMENT

PROCEDURE

EUROPEAN INTERCOMPARISON OF HYDROPHONE CALIBRATIONS IN THE FREQUENCY RANGE 10-315 kHz

MAST Project MAS2-CT94-0095

Authors: Stephen P Robinson and Graham R Doré

APRIL 1995

INTRODUCTION

This document describes the procedure to be used for the European intercomparison of hydrophone calibrations in the frequency range 10 to 315 kHz. The project is sponsored by the Marine Science and Technologies (MAST) programme of the Commission of the European Communities, under contract number MAS2-CT94-0095. The project lasts for 24 months and finishes on 31 October, 1996. The coordinator of the project is the National Physical Laboratory (NPL), UK.

The intercomparison is being run as a *concerted action* project. This means that the Commission will provide funds for project coordination and participants' travel, but not for the actual calibrations to be made. The resource for the calibrations must be provided by the participants themselves, who participate in the project on a voluntary basis.

The following sections provide a description of the project which states the requirements placed upon each participant. Some practical guidance notes are also given on the handling and use of the hydrophones. Finally, a questionnaire is supplied to be completed by each participant during calibrations.

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

National Physical Laboratory
(Division of Radiation Science and Acoustics)
Queens Road
Teddington TW11 0LW
UNITED KINGDOM

Tel: +44 181 977 3222 (switchboard)
Fax: +44 181 943 6161

Project Officer: Stephen P Robinson
Direct telephone: +44 181 943 7152

Additional contacts:	Graham R Doré	Roy C Preston
Direct telephone:	+44 181 943 6695	+44 181 943 6154

2. PROJECT DESCRIPTION

2.1 Organisation and coordination

The intercomparison will be organised radially with the pilot laboratory, the National Physical Laboratory (NPL), coordinating the intercomparison and performing reference calibrations of the hydrophones between the measurements made by the participating laboratories.

Two sets of three hydrophones will be circulated to the participants for calibration, with each participant receiving only one set. Each hydrophone set contains:

- a Brüel & Kjær type 8104,
- a Brüel & Kjær type 8103,
- a Reson System type TC4034.

Another set of hydrophones will be kept at NPL and recalibrated periodically to check the stability of the measurements made at NPL, whilst additional devices will be held in reserve in case the main hydrophones are damaged.

Including NPL, up to twelve participants from at least six countries will take part in the intercomparison. At the end of the project, NPL will circulate a draft project report to all participants and to the Commission, after which there will be a final meeting (held at NPL) attended by representatives of all the participants.

2.2 Calibrations by participants

2.2.1 Measurements required

Each participant is required to provide a calibration of each of the three hydrophones supplied. The quantity which must be reported is the **free-field voltage sensitivity** in reception mode, expressed in units of dB re 1V/ μ Pa. This is the quotient of the open-circuit voltage at the output terminals of the hydrophone to the sound pressure in the undisturbed free field of a plane wave in the position of the acoustic centre of the hydrophone which would exist if the hydrophone were removed from the field. The calibration is required only for the direction indicated by the alignment mark on the hydrophone body.

The sensitivity should be measured for each of the three hydrophones at frequencies between 10 and 315 kHz. The minimum frequencies at which measurements are to be made are the third-octave frequencies recommended by the International Organization for Standardization (ISO),¹ namely 10, 12.5, 16, 20, 25, 31.5, 40, 50, 63, 80, 100, 125, 160, 200, 250 and 315 kHz. Additional measurements may be made at other frequencies (within or outside the 10-315 kHz range) at the discretion of the individual participant.

2.2.2 Calibration method

The calibration method used is at the discretion of the participant. Absolute methods (eg those based on the principle of acoustic reciprocity) or relative methods (eg comparison with a reference hydrophone) may be used. If a relative method is used, some indication must be given as to the traceability of the measurement to the primary standard (eg a reference hydrophone previously calibrated by an absolute method in-house or by another laboratory).

A description must be given of the calibration method used. This may be done by completing the questionnaire contained within this document, or it may be in the form of a short calibration report accompanying the results. If a separate report is provided, it must address all the questions given in the questionnaire. Reference should be made to any specification standards followed during the calibration (eg IEC 565, ANSI S1.20).^{2,3}

2.2.3 Expression of uncertainties

The overall uncertainties for the stated calibration values must be included with the results. The uncertainties should be expressed for a confidence level of 95 %.

The method used to estimate and combine the uncertainty contributions must be described. The random uncertainty (Type A) should be estimated from a minimum of four independent measurements. For the systematic uncertainty (Type B), a breakdown must be given of the individual uncertainty contributions (eg in the form of an uncertainty budget). Reference should be made to any specification standards followed when estimating and combining uncertainties (eg ISO - *Guide to the expression of uncertainty in measurement*).⁴

2.2.4 Scheduling of the calibrations

Each participant must agree the timing of the calibrations with NPL in advance. The hydrophones will then be supplied to the participant by NPL on the appointed date. The participant has a total of **8 weeks** from receipt of the hydrophones to perform the calibrations and return the hydrophones to NPL. The cost of transport of the hydrophones to and from the participants will be borne by the project (ie paid by NPL).

If necessary, NPL staff will visit the participant at the conclusion of measurements to discuss any difficulties with the calibrations. All participants' calibrations should be completed by August 1996.

2.3 List of participants

Including NPL, a maximum of 12 participants will take part in the intercomparison, with at least six European countries represented. NPL will provide all participants with a separate participant list enclosed with this procedure document.

Should any participants be forced to withdraw from the intercomparison due to unforeseen circumstances, NPL will undertake to replace that participant with another where possible.

2.4 Final meeting

At the end of the intercomparison, NPL will circulate a draft final report to all participants and to the Commission for comment. A final meeting will then be held at NPL to discuss the results presented in the report. After the meeting, NPL will make any necessary amendments and then submit the final report to the Commission. All participants will receive a copy of the final report.

All participants will be invited to send a representative to the final meeting. A representative of the Commission may also attend. It is likely that the meeting will be held in October 1996. The cost of travelling to the meeting will be met by the project with a sum of **850 ECU** payable by NPL to each participant.

3 PRACTICAL NOTES

3.1 Manufacturers' data

Table 1 lists the relevant information supplied by the hydrophone manufacturers. This is reproduced here so that acceptance testing may be carried out on each device before full calibration is attempted.

Table 1. Manufacturers' Data

Type	Brüel & Kjær 8104	Brüel & Kjær 8103	Reson TC4034
Nominal voltage sensitivity (250 Hz)	-205 dB re 1V/ μ Pa	-211 dB re 1V/ μ Pa	-218 dB re 1V/ μ Pa
Nominal capacitance	7800 pF	3850 pF	3000 pF
Approximate position of acoustic centre from hydrophone end	16 mm	9.2 mm	5.5 mm
Horizontal directivity (at 100 kHz)	± 2 dB (typical)		
Vertical directivity (over 270°)	± 2 dB (typical) at 50 kHz	± 4 dB (typical) at 100 kHz	± 2 dB (typical) at 100 kHz

3.2 Care of Hydrophones

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

3.3 Wetting and soaking

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

3.4 Mounting

Special care must be taken to ensure that the hydrophone mount does not cause any reflection of the acoustic signal on to the hydrophone. Each hydrophone should be mounted such that it is possible to rotate the hydrophone about its axis (the axis of symmetry passing down the device and through the acoustic centre). Since the method of mounting may influence the

measured sensitivity, a description should be given with the results (ideally, with an accompanying photograph or sketch).

3.5 Alignment

Each hydrophone has an alignment mark on its body. During calibrations, the hydrophone should be oriented such that its alignment mark is parallel to the direction of propagation of the incoming acoustic wave incident on the hydrophone.

3.6 Maximum acoustic pressure levels

An estimate of the maximum acoustic pressure level at the hydrophones during calibration should be made. This should be expressed in dB re $1\mu\text{Pa}$ and stated with the results.

3.7 Electrical loading corrections

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

3.8 Temperature and depth

The hydrophone sensitivity can vary with temperature and depth in the water. Measurements must be made of the water temperature and depth of immersion during calibrations and the values stated with the results. It is not necessary to apply any corrections for either of these effects. However, if the participant wishes to make corrections to their results, then these corrections must be reported separately, along with a description of their derivation.

It has been assumed that all calibrations will be performed under atmospheric conditions. Should any hydrostatic pressure be applied (eg calibrations in a pressurised tank), the value of the static pressure during calibrations must be stated with the calibration results.

3.9 Repeated measurements

The sensitivity values reported should be the mean of at least four measurements. It is important that each repeat measurement is a completely independent measurement (this may require the removal and remounting of the hydrophone between each repeat). In addition to the mean, the standard deviation should be reported, from which the random uncertainty (Type A) may be calculated.

3.10 Transport and delivery of hydrophones

NPL will undertake to arrange for transport of the hydrophones to the participant on the date agreed with the participant. The participant should inform NPL by fax of the safe arrival of

the hydrophones. After calibrations have been completed (or after 8 weeks whichever is the sooner), the hydrophones must be packed away in the transit case and stored along with any associated paperwork. The participant must then inform NPL that the devices are ready for transport, whereupon NPL will arrange for the devices to be collected.

If necessary, the results and questionnaire (or calibration report) may be sent to NPL on an agreed later date, allowing extra time for preparation. However, the hydrophones must be returned after a maximum of 8 weeks to allow the next participant to receive them in good time. If required, a member of staff from NPL will visit the participant to discuss the results and any difficulties encountered.

3.11 Accuracy assessment

The uncertainties present in the measurements must be reported with the results, as described in Section 2.2.3. Any participant not certain of how to properly assess the measurement uncertainties may contact NPL for advice.

4. PROCEDURE DOCUMENT REFERENCES

- 1 ISO 266:1975. *Acoustics - Preferred frequencies for measurements*. International Organization for Standardization, Geneva, Switzerland.
- 2 IEC 565:1977. *The calibration of hydrophones*. International Electrotechnical Commission.
- 3 ANSI S1.20:1988. *Procedures for calibration of underwater electroacoustic transducers*. American National Standards Institute.
- 4 ISO. *Guide to the expression of uncertainty in measurement*. International Organization for Standardization, Geneva, Switzerland. ISBN 92-67-10188-9, First edition 1993.

CALIBRATION QUESTIONNAIRE

This questionnaire must be completed by each participant during their own calibrations, unless a separate written calibration report is to be provided instead. If a separate report is provided, it must address all of the points raised by this questionnaire.

The responses may be hand or type-written, but the language used must be English. When completed, the questionnaire must be returned to NPL along with the hydrophones and the results. If more space is needed to reply to any question, a separate sheet should be used to continue the reply.

PARTICIPANT DETAILS

Participating Institution

Contact person

Date hydrophones received

Dates of calibrations

Date hydrophones dispatched to NPL

Calibration method

Give a description of the method used to calibrate the hydrophones. Specify the type of acoustic field used for the calibration (eg continuous-wave, gated tone-burst, pulsed, noise, etc).

If reference was made to any written standards (eg IEC), give details of how they were applied to this calibration.

2. Give details of any reference transducers used in the calibration. How were these reference transducers calibrated? How was traceability to primary standards achieved?
3. Give a description of how the hydrophones were mounted during the calibrations (a diagram or photograph is desirable).

4. Give a description of the facility in which measurements were made. What are the dimensions of the water tank? What is the tank constructed of? Were any baffles or absorbers used?
5. What was the temperature of the water during measurements? How was the temperature measured?
6. At what depth in the water were the hydrophones during measurements?
7. Specify the length of any extension cable used
8. What is the input impedance of the amplifier used?

9. Were any corrections made for electrical loading? If so, describe how the corrections were calculated.
10. How were the electrical voltages and currents measured during calibrations and to what accuracy?
11. How was the acoustic frequency measured and to what accuracy?
12. How was the separation distance measured and to what accuracy? Were different separation distances used for repeat measurements?
13. Were any other quantities required for the calibration (eg density of water, speed of sound in water)? If so, how were they determined?

14. What were the maximum acoustic pressures that the hydrophones were exposed to during calibrations?
15. How long were the hydrophones immersed in water before the first measurements were taken? Specify the total length of time that the hydrophones were immersed in water. Give details of any wetting agent used on the hydrophones.
16. If it was not possible to comply with the procedures specified in this document, or if there were any in-house procedures used which are considered superior, then the differences should be specified below. Please specify the reasons for the differences if they are not obvious.
17. Does your organisation have any official accreditation or certification for calibration work (eg to ISO 9000, etc)? If so, please give details.

Accuracy assessment

18. How many repeated measurements were made during the calibration? Were the hydrophones removed from the tank and remounted between each calibration? State how the random uncertainty (Type A) was calculated from the results.
19. Give a list of the components which were considered to contribute to the total systematic uncertainty (Type B) for the calibration. The list should include the value of the uncertainty for each contribution and the total expressed for a confidence level of 95%. Specify how the total was calculated from the individual contributions.

- 19 Give a list of the components which were considered to contribute to the total systematic uncertainty (Type B) for the calibration. The list should include the value of the uncertainty for each contribution and the total expressed for a confidence level of 95%. Specify how the total was calculated from the individual contributions.

APPENDIX B: ADDRESSES OF PARTICIPANTS

- | | | |
|----|--|-----------------------|
| 1 | Vrije Universiteit Brussel
Faculteit der Toegepaste Wetenschappen
Pleinlaan 2
B-1050 Brussel
BELGIUM
Tel: +32 2 629 2766 Fax: +32 2 629 2850
E-mail: lpeirlin@vnet3.vub.ac.be | Dr Luc Peirlinckx |
| 2. | Brüel & Kjær (S&V Division)
DK-2850 Nærum
DENMARK
Tel: +45 42 80 05 00 Fax: +45 42 80 14 05 (or +45 45 80 76 21) | Mr Lars Kofoed |
| 3. | Reson System A/S
Fabriksvangen 13
DK-3550 Slangerup
DENMARK
Tel: +45 47 38 00 22 Fax: +45 47 38 00 66 | Mr Christian Skodborg |
| 4. | DCN Toulon
CTSN/DLSM
Chemin de la Gardiole
Le Brusca 83140 SIX-FOURS
FRANCE
Tel: +33 94 34 96 56 Fax: +33 94 34 99 22 | Dr J A Roy |
| 5. | Thomson Marconi Sonar
525 route des Dolines
06561 Valbonne cedex
FRANCE
Tel: +33 92 96 30 30 Fax: +33 92 96 30 66 (or +33 92 96 33 60) | Mr Yvon Mori |
| 6. | STN Atlas Elektronik GmbH
Dept MUA 1
Sebaldsbrücker Heerstr. 235
D-28305 Bremen
GERMANY
Tel: +49 421 457 2246 Fax: +49 421 457 4189 | Mr Axel Brenner |
| 7. | Wehrtechnische Dienststelle für Schiffe
und Marinewaffen WTD 71
Berliner Straße 115
D-2330 Eckernförde, | Mr Dieter Krüger |

GERMANY

Tel: +49 43 51 40 41 389 Fax: +49 43 51 45 400

8. Istituto di Acustica - O.M.Corbino Prof. G.B.Cannelli and Dr Silvano Buogo
Dept. Environmental Acoustics
Via Cassia 1216
00189 Roma
ITALY
Tel: +39 6 303 657 65 Fax: +39 6 303 653 41
E-mail: silvano@idac.rm.cnr.it
9. Saclant URC Mr Luigi Troiano
Electronic and Acoustic Engineering Dept.
Viale S Bartolomeo 400
19138 La Spezia
ITALY
Tel: +39 187 540 319 Fax: +39 187 524 600
E-mail: barbagel@saclantc.nato.int or troiano@saclantc.nato.int
10. FOA Försvarets Forskningsanstalt Mr Claes Runborg
National Defence Research Establishment
Div. 26, Hydroacoustics
S-172 90 Sundbyberg
SWEDEN
Tel: +46 8 706 30 00 Fax: +46 8 706 35 43
E-mail: claesr@sto.foa.se
11. MOD Wraysbury Calibration Facility Mr Gerry Gooch
Wraysbury Reservoir
Coppermill Rd, Wraysbury
Staines TW19 5NW
UNITED KINGDOM
Tel: +44 1784 483 541 Fax: +44 1784 483 541
12. National Physical Laboratory Mr Stephen Robinson
Centre for Ionising Radiation and Acoustics
Queens Road
Teddington TW11 0LW
UNITED KINGDOM
Tel: +44 181 943 7152 Fax: +44 181 943 6161
E-mail: spr@npl.co.uk

APPENDIX C: TABLES OF RESULTS

The following tables contain the results of the calibrations by the participants in the intercomparison for each hydrophone of each set. Results are shown only for the standard third-octave frequencies at which comparisons have been made. It should be noted that some participants provided calibration results at considerably smaller frequency intervals. In a few instances, for example where the participants used some form of spectral analysis, results were not provided at exactly the third-octave frequency requested. In such cases, a linear interpolation was performed to obtain the results at the required frequency. This was considered to be an acceptable approach since in all such cases the two nearest results were very close in frequency to the desired third-octave value.

Also shown in the tables are the Grand Means calculated as described in Section 7.2, along with the standard deviation of the mean values (expressed in dB).

Set A Brüel & Kjær 8104 No. 1757063

Frequency (kHz)	Calibration results of participants (dB re 1V/μPa)							Grand Mean	Standard deviation
	A	B	C	D	E	F	G		
10.0	-205.8	-206.0	-206.0	-205.8	-205.8	-205.9	-205.9	-205.9	0.1
12.5	-206.1	-205.6	-205.0	-205.8	-205.7	-205.9	-206.3	-205.8	0.4
16.0	-206.6	-206.4	-205.5	-206.3	-205.8	-206.2	-206.6	-206.2	0.4
20.0	-206.6	-207.0	-206.1	-206.7	-206.3	-206.7	-207.0	-206.6	0.3
25.0	-206.8	-207.5	-206.8	-206.9	-206.9	-206.9	-208.2	-207.1	0.5
31.5	-207.7	-208.1	-207.7	-207.9	-207.5	-207.4	-208.6	-207.8	0.4
40.0	-206.5	-207.7	-206.6	-206.4	-206.9	-207.0	-208.4	-207.0	0.7
50.0	-204.7	-205.7	-204.9	-204.4	-205.0	-205.0	-207.7	-205.3	1.0
63.0	-205.3	-206.1	-206.1	-204.8	-205.6	-206.3	-208.2	-206.0	1.0
80.0	-209.2	-209.1	-208.2	-206.7	-208.8	-208.6	-211.8	-208.8	1.3
100.0	-213.7	-213.9	-212.9	-211.9	-213.7	-211.9	-217.3	-213.5	1.5
125.0	-217.3	-217.5	-217.9	-216.6	-217.4	-216.7	-221.0	-217.7	1.2
160.0	-222.7	-222.1	-223.8	-224.2	-222.3	-219.2	-225.9	-222.7	2.0
200.0	-228.6	-227.8	-229.1	-230.1	-227.5	-229.1	-230.9	-228.9	1.1
250.0	-231.8	-231.3		-233.4	-230.5	-231.3	-233.4	-231.9	1.1
315.0	-236.0	-235.6		-234.5	-234.4	-233.6	-236.8	-235.1	1.1

Set A Brüel & Kjær 8103 No. 1785459

Frequency (kHz)	Calibration results of participants (dB re 1V/μPa)							Grand Mean	Standard deviation
	A	B	C	D	E	F	G		
10.0	-211.0	-211.0	-210.6	-210.0	-210.6	-210.5	-210.6	-210.6	0.3
12.5	-210.4	-210.8	-210.9	-210.2	-210.7	-210.7	-210.9	-210.7	0.3
16.0	-211.0	-211.3	-210.6	-210.9	-211.0	-211.1	-211.5	-211.0	0.3
20.0	-212.1	-211.7	-210.2	-211.1	-211.4	-211.4	-211.8	-211.3	0.6
25.0	-211.8	-212.2	-210.8	-210.8	-211.8	-211.3	-212.4	-211.5	0.6
31.5	-211.1	-212.4	-211.1	-211.7	-211.6	-211.5	-213.0	-211.7	0.6
40.0	-211.6	-212.5	-211.6	-211.7	-211.8	-211.5	-213.8	-212.0	0.7
50.0	-211.6	-213.1	-212.7	-212.8	-211.8	-212.3	-214.6	-212.6	0.9
63.0	-212.6	-213.6	-213.0	-212.5	-212.7	-213.5	-215.4	-213.3	0.9
80.0	-211.7	-213.4	-212.0	-211.3	-211.7	-211.1	-214.7	-212.2	1.1
100.0	-208.8	-210.0	-209.8	-209.8	-209.8	-209.8	-212.3	-210.0	0.9
125.0	-208.9	-209.9	-209.3	-209.1	-208.7	-209.8	-212.4	-209.6	1.1
160.0	-215.5	-215.3	-216.7	-215.9	-214.9	-215.9	-218.3	-216.0	1.0
200.0	-220.2	-221.1	-221.1	-220.1	-220.1	-220.5	-222.9	-220.8	0.9
250.0	-208.9	-212.3		-210.1	-210.4	-209.5	-213.0	-210.6	1.4
315.0	-212.0	-216.2		-212.9	-212.8	-211.7	-215.4	-213.3	1.6

Set A RESON TC4034 No. 426002

Frequency (kHz)	Calibration results of participants (dB re 1V/μPa)							Grand Mean	Standard deviation
	A	B	C	D	E	F	G		
10.0	-216.3	-216.2	-216.1	-216.1	-216.2	-215.8	-216.9	-216.2	0.3
12.5	-216.5	-217.1	-215.8	-216.4	-216.6	-216.6	-217.0	-216.6	0.4
16.0	-216.2	-217.8	-216.1	-216.4	-216.4	-216.6	-216.9	-216.6	0.5
20.0	-216.2	-217.5	-215.8	-216.1	-216.2	-216.2	-217.2	-216.4	0.6
25.0	-217.1	-217.5	-216.5	-216.5	-216.7	-216.4	-218.1	-216.9	0.6
31.5	-217.5	-218.2	-216.9	-217.4	-217.3	-216.8	-219.1	-217.6	0.7
40.0	-217.9	-219.2	-217.9	-218.1	-218.1	-217.8	-220.2	-218.4	0.8
50.0	-218.5	-219.5	-218.8	-218.5	-218.4	-217.4	-221.0	-218.8	1.0
63.0	-219.1	-220.9	-219.9	-219.9	-219.3	-219.2	-222.2	-220.0	1.0
80.0	-219.4	-220.9	-219.9	-219.5	-219.5	-219.6	-222.6	-220.2	1.0
100.0	-219.6	-220.6	-219.6	-219.8	-219.6	-219.2	-222.6	-220.1	1.0
125.0	-219.0	-219.9	-219.7	-219.3	-219.1	-218.5	-222.6	-219.6	1.1
160.0	-217.1	-218.5	-218.1	-217.4	-217.1	-217.1	-220.5	-217.9	1.1
200.0	-217.9	-218.7	-218.4	-217.4	-217.6	-217.9	-220.4	-218.3	0.9
250.0	-219.1	-219.8		-219.4	-219.2	-220.3	-222.3	-219.9	1.0
315.0	-216.1	-218.8		-216.2	-216.1	-216.0	-219.4	-217.0	1.3

Set B Brüel & Kjær 8104 No. 1757065

Frequency (kHz)	Calibration results of participants (dB re 1V/μPa)						Grand Mean	Standard deviation
	H	I	J	K	L	M		
10.0	-206.4	-206.3	-206.2	-206.3	-206.6	-205.4	-206.2	0.4
12.5	-206.7	-206.3	-206.3	-206.3	-206.9	-205.9	-206.4	0.3
16.0	-207.1	-206.5	-206.7	-206.2	-207.2	-206.1	-206.6	0.4
20.0	-207.4	-206.8	-206.7	-206.5	-207.3	-206.5	-206.9	0.4
25.0	-207.4	-206.5	-206.8	-207.1	-207.1	-206.5	-206.9	0.3
31.5	-206.7	-205.7	-206.4	-206.6	-206.5	-206.3	-206.4	0.3
40.0	-205.5	-203.7	-205.2	-205.2	-206.0	-205.1	-205.1	0.8
50.0	-204.2	-203.7	-203.7	-203.5	-204.1	-203.0	-203.7	0.4
63.0	-203.7	-204.3	-203.9	-203.8	-204.4	-202.7	-203.8	0.6
80.0	-206.9	-206.3	-206.8	-206.9	-207.6	-205.1	-206.6	0.8
100.0	-211.6	-210.3	-210.8	-211.0	-211.6	-210.0	-210.9	0.6
125.0	-214.6	-215.5	-215.0	-215.0	-215.8	-213.2	-214.8	0.9
160.0	-219.1	-221.1	-221.0	-220.6	-221.2	-220.6	-220.6	0.8
200.0	-225.8	-226.6	-227.6	-227.3	-226.7	-227.9	-227.0	0.8
250.0	-230.7		-231.6	-231.4	-230.3	-231.6	-231.1	0.6
315.0	-233.1		-232.4	-232.6	-231.8	-231.4	-232.3	0.7

Set B Brüel & Kjær 8103 No. 1785461

Frequency (kHz)	Calibration results of participants (dB re 1V/μPa)						Grand Mean	Standard deviation
	H	I	J	K	L	M		
10.0	-210.6	-212.6	-210.4	-211.0	-211.0	-209.7	-210.8	0.9
12.5	-211.0	-212.2	-210.6	-210.8	-211.1	-209.9	-210.9	0.7
16.0	-211.1	-210.9	-210.7	-211.0	-211.0	-210.0	-210.8	0.4
20.0	-211.1	-210.7	-210.9	-211.0	-211.2	-210.7	-210.9	0.2
25.0	-211.2	-210.9	-211.2	-211.3	-211.6	-210.9	-211.2	0.3
31.5	-211.5	-210.6	-211.5	-211.5	-210.7	-210.8	-211.1	0.4
40.0	-212.0	-210.5	-212.1	-212.1	-211.5	-211.8	-211.6	0.6
50.0	-212.0	-213.5	-212.1	-212.5	-212.0	-211.7	-212.3	0.6
63.0	-212.5	-214.7	-212.5	-212.8	-212.3	-212.6	-212.9	0.8
80.0	-211.6	-210.7	-211.7	-211.7	-211.1	-211.1	-211.3	0.4
100.0	-210.1	-207.5	-209.4	-209.5	-209.8	-208.3	-209.1	1.0
125.0	-209.0	-208.6	-208.8	-208.9	-209.3	-207.0	-208.6	0.8
160.0	-213.3	-215.0	-214.6	-214.8	-216.0	-213.8	-214.5	0.9
200.0	-218.0	-219.2	-220.1	-219.7	-219.1	-220.4	-219.4	0.8
250.0	-214.5		-208.9	-209.1	-208.2	-212.3	-210.3	2.2
315.0	-215.1		-213.6	-213.5	-213.5	-214.9	-214.1	0.8

Set B **RESON TC4034 No. 426001**

Calibration results of participants (dB re 1V/μPa)								
Frequency (kHz)	H	I	J	K	L	M	Grand Mean	Standard deviation
10.0	-216.8	-217.4	-216.6	-216.7	-217.5	-216.1	-216.8	0.5
12.5	-217.1	-217.1	-216.8	-216.8	-217.6	-215.9	-216.9	0.6
16.0	-217.4	-217.3	-216.8	-216.8	-217.6	-216.2	-217.0	0.5
20.0	-217.4	-217.1	-216.6	-216.6	-217.5	-216.3	-216.9	0.5
25.0	-217.4	-217.7	-216.9	-217.0	-217.5	-216.6	-217.2	0.4
31.5	-217.6	-217.5	-217.3	-217.2	-217.5	-217.0	-217.3	0.2
40.0	-217.8	-217.2	-217.6	-217.7	-217.7	-217.5	-217.6	0.2
50.0	-217.6	-219.0	-217.6	-217.7	-217.7	-217.2	-217.8	0.6
63.0	-217.8	-218.3	-217.5	-217.5	-218.0	-217.1	-217.7	0.4
80.0	-217.7	-217.1	-217.8	-217.7	-218.1	-217.0	-217.6	0.4
100.0	-218.2	-217.7	-218.7	-218.7	-219.3	-217.3	-218.3	0.7
125.0	-220.1	-219.5	-220.9	-220.3	-221.3	-217.7	-219.9	1.3
160.0	-220.4	-217.4	-218.9	-219.1	-219.9	-218.3	-218.9	1.0
200.0	-219.7	-217.7	-218.2	-218.1	-218.3	-217.1	-218.1	0.8
250.0	-217.5		-218.5	-218.4	-217.4	-218.2	-218.0	0.5
315.0	-215.0		-215.4	-215.3	-215.6	-218.3	-215.8	1.1