Establishing traceability for Infrasound:

Calibration Innovations and Inter-Laboratory Comparisons from the Infra-AUV Project

Erling Sandermann Olsen, HBK

Dominique Rodrigues, LNE

Christoph Kling and Marvin Rust, PTB
Franck Larsonnier and Paul Vincent, CEA
Richard Barham, ASN

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Outline

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2. The Infra-AUV project
3. Traceability
4. Primary calibration methods
5. Secondary calibration methods
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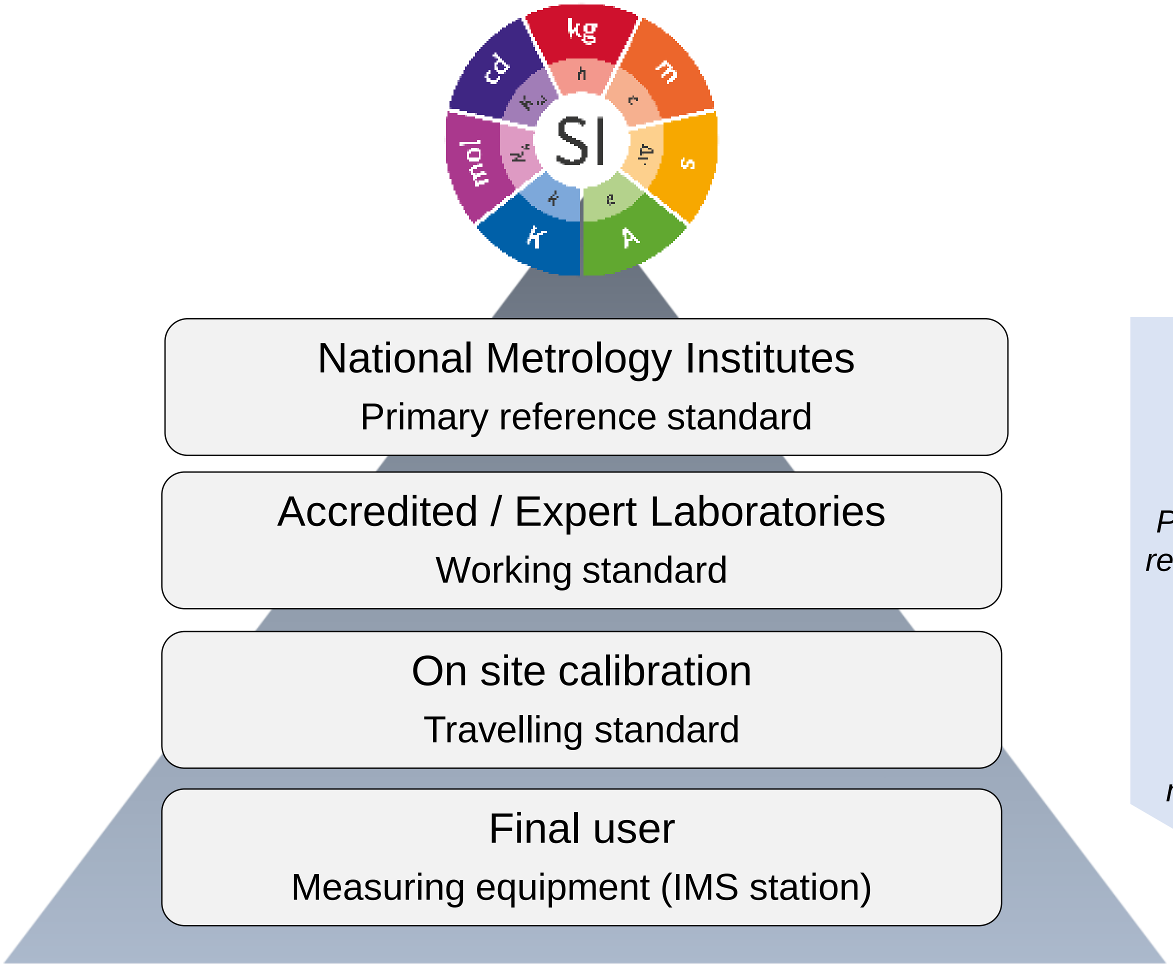
EURAMET EMPIR Infra-AUV project

- Initiated after CTBTO approached CCAUV asking for references traceable to the SI
- and a following meeting with CTBTO and EURAMET members working with infrasound
- Started 1 September 2020, ended ultimo 2023
- Included calibration in the areas of vibration, sound in air and underwater sound
- Intended to establish the basis for traceability of low fequency measurements to the SI
- Independent calibration methods for sound in air
- The goal was 0.01 Hz for vibration, 0.04 Hz for sound in air and 0.5 Hz for underwater sound
- Reference standards for primary and secondary calibrations – including on-site calibrations – should be identified
- Suitable standards were identified, but ambitions on determining environmental parameter influence on the standards had to be reduced
- Comparison calibrations should underpin methods on primary and secondary level

EMPIR Infra-AUV partners

- PTB Physikalisch-Technische Bundesanstalt
- HBK Hottinger, Brüel & Kjaer
- CNAM Conservatoire national des arts et métiers
- DFM Dansk Fundamental Metrologi A/S
- LNE Laboratoire national de métrologie et d'essais
- NPL NPL Management Limited
- TUBITAK Turkiye Bilimsel ve Teknolojik Arastirma Kurumu
- ASN Acoustic Sensor Networks Limited
- BGR Bundesanstalt für Geowissenschaften und Rohstoffe
- CEA Commissariat à l'Energie Atomique et aux Energies Alternatives

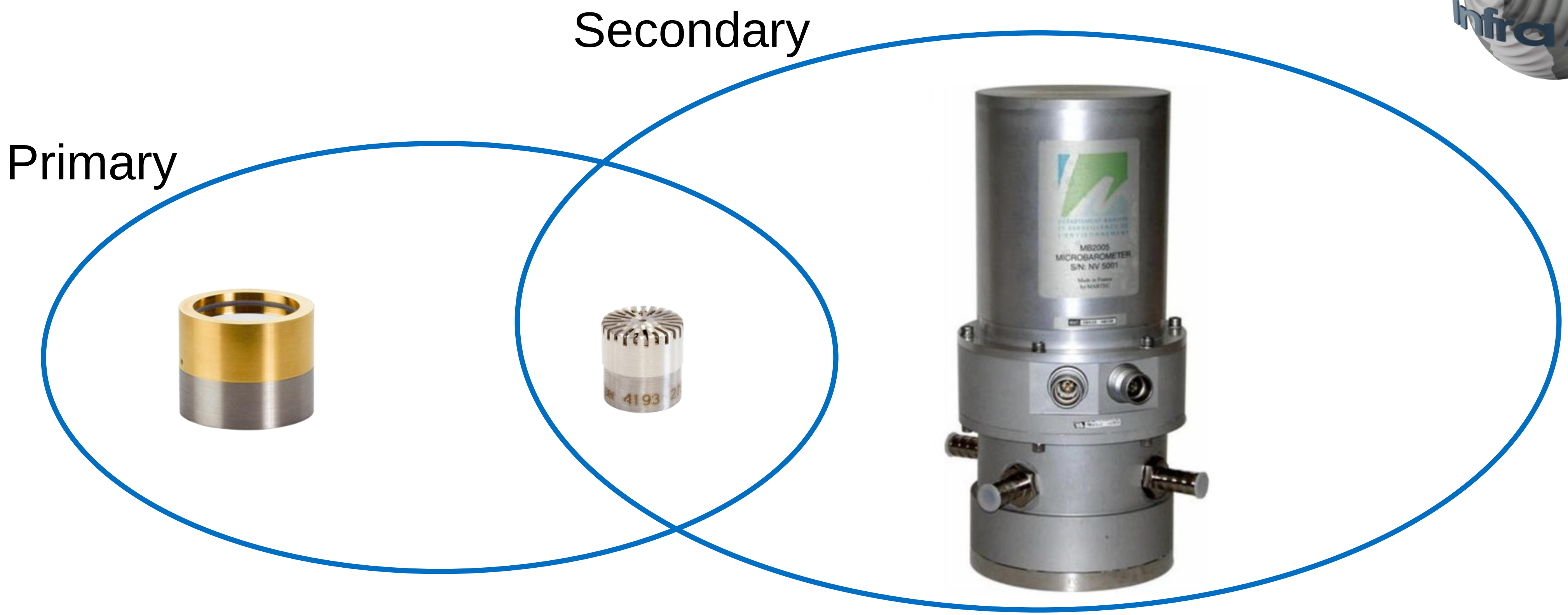
The metrological traceability chain



Metrological traceability

Property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty.

Primary standards and transfer standards for infrasound

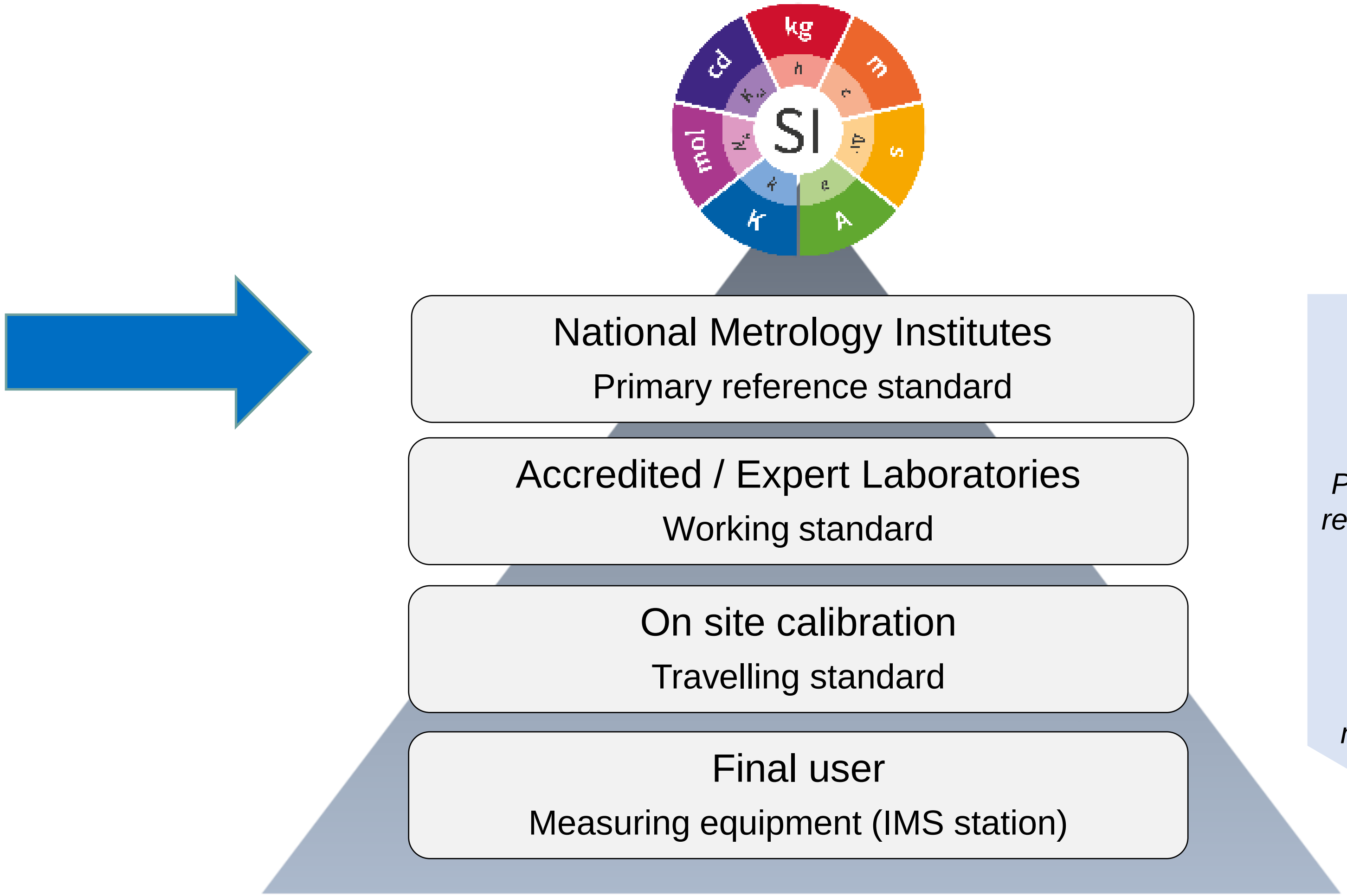


LS1
(Brüel & Kjær 4160)

WS2
(Brüel & Kjær 4193)

Microbarometer
(MB2005)

The metrological traceability chain

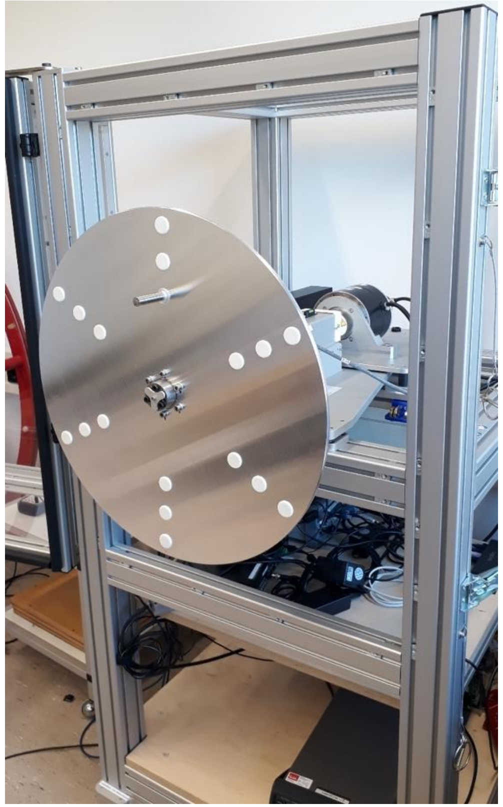


Metrological traceability

Property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty.

Primary calibration methods (1)

LNE (laser)
pistonphone

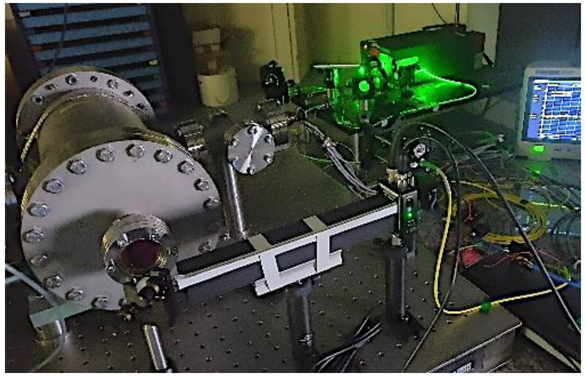


PTB carousel

Brüel & Kjær (HBK)
reciprocity calibration

Primary calibration methods (2)

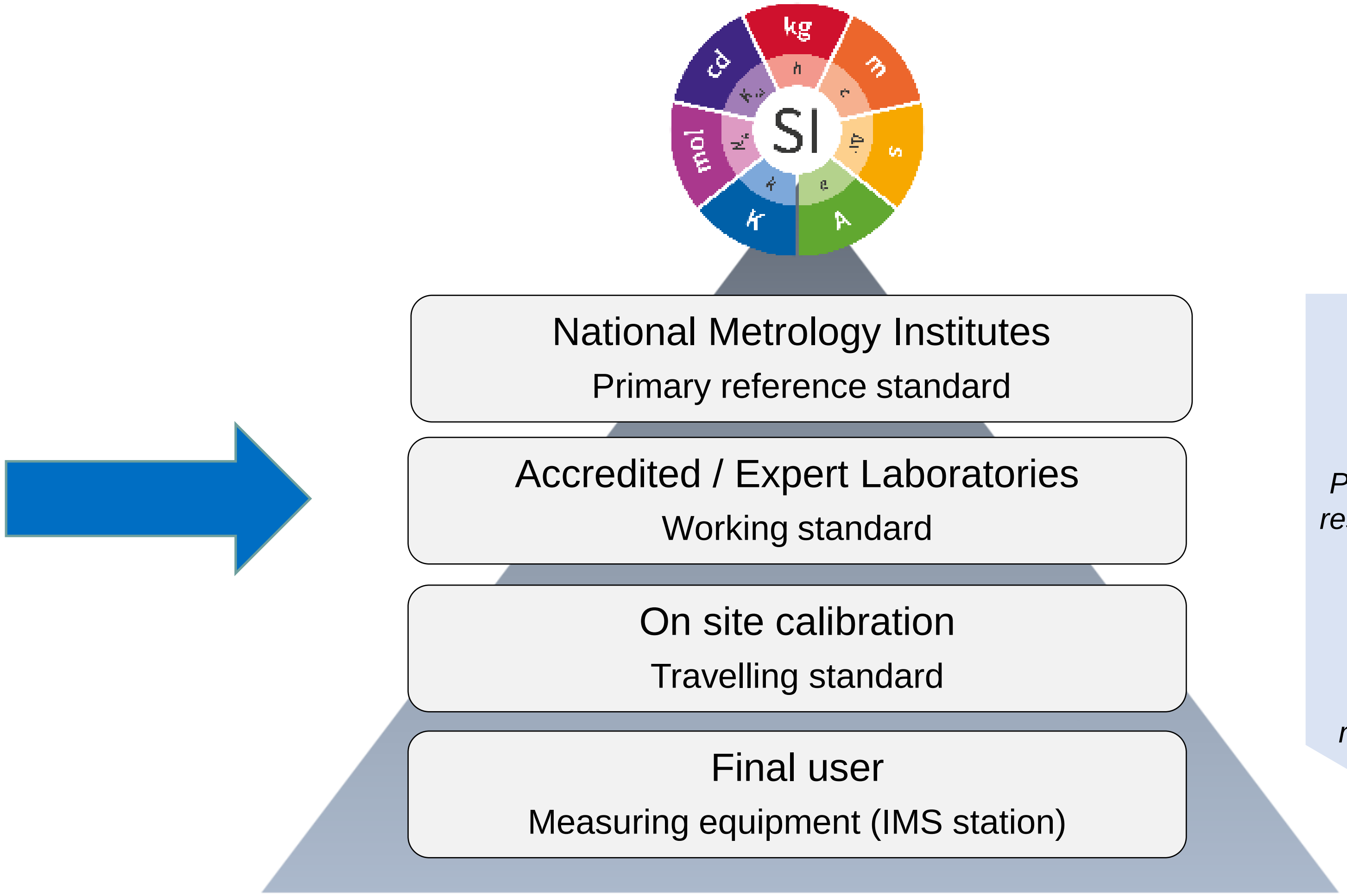
DFM manometric apparatus
(dropped in Infra-AUV)



CNAM Fabry Perot interferometer with infrasound generator

HBK
HOTTINGER BRÜEL & KJÆR

The metrological traceability chain



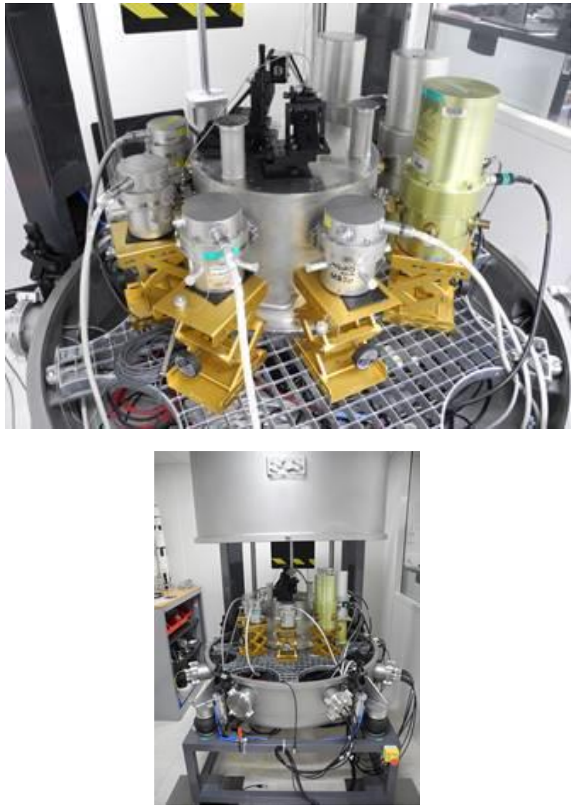
Metrological traceability

Property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty.

Secondary calibration methods

PTB (and DFM)
“sound tubes”

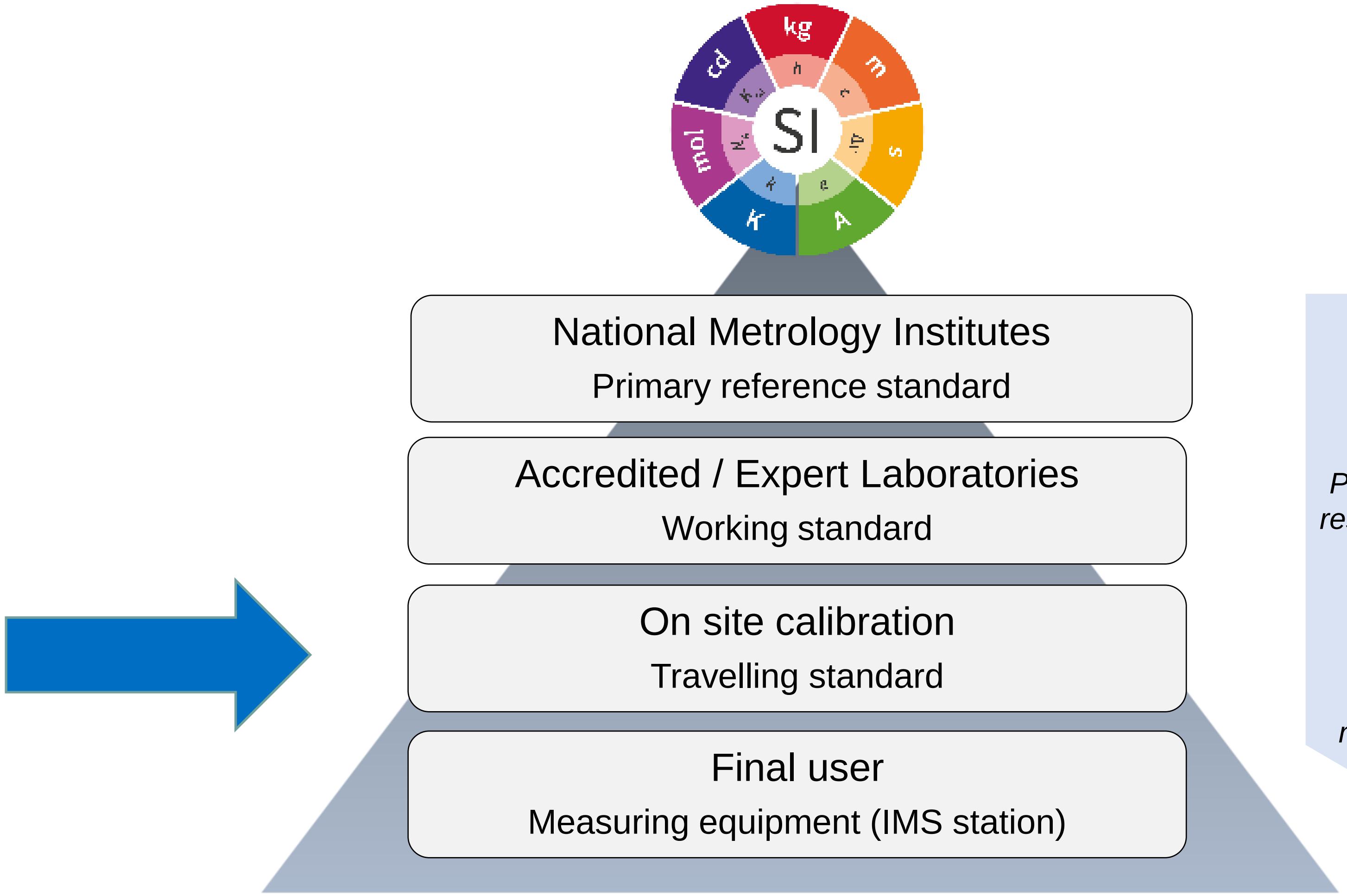
LNE (laser)
pistonphone



CEA “Saturn”
calibration bench

Brüel & Kjær 9757
(not part of Infra-AUV, but used)

The metrological traceability chain



Metrological traceability

Property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty.

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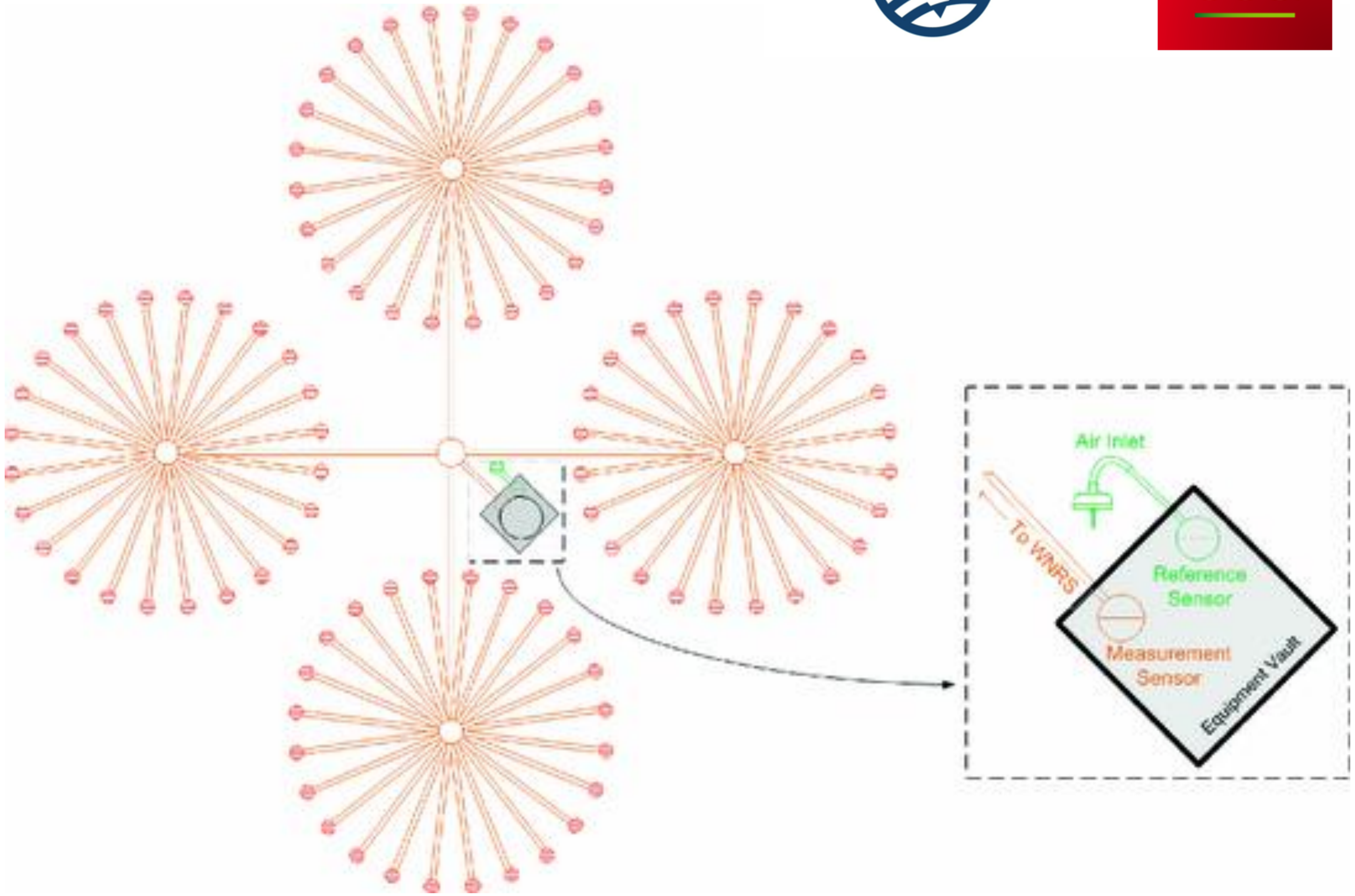
Secondary calibration on-site

GENERAL PRINCIPLE



Secondary calibration on-site

Calibration on-site using correlation techniques

Wind noise reduction system

Reference microbarometer and microbarometer being calibrated

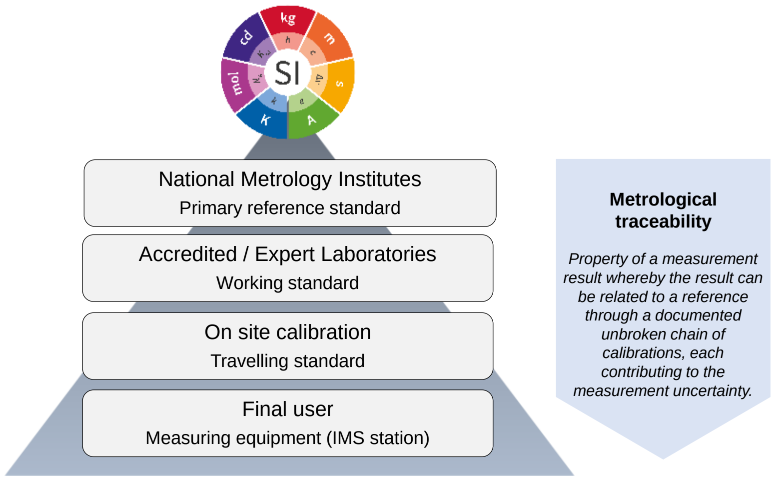
Pictures from Tromsø infrasound monitoring station, Norway. Photographs by Richard Barham

Comparison calibrations – why?

- Traceability is established through an unbroken chain of calibrations
- The uncertainty is evaluated at each stage in the calibration chain

- Comparisons is the only way to ensure that calibrations are consistent within the stated uncertainty of measurement

- Keep in mind – you never know the true value
  - We can agree on methods and calculation principles, but we can only validate that the results are consistent – not whether they are true



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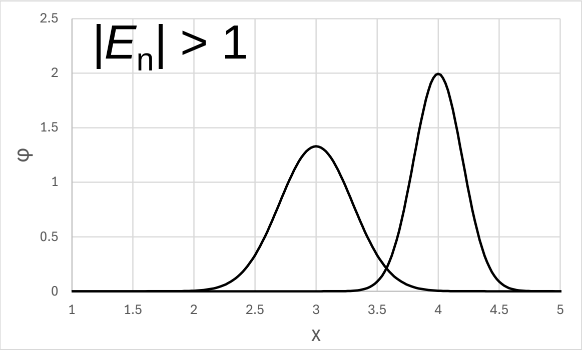
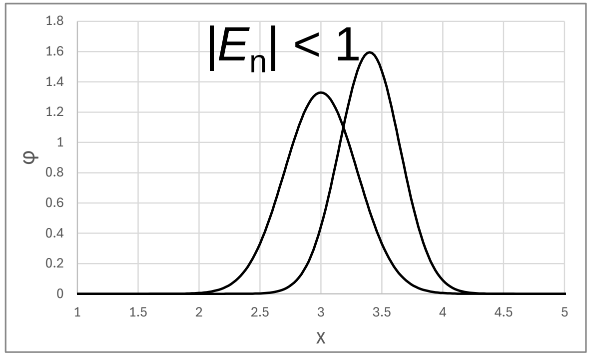
Comparison calibration metrics, E_n

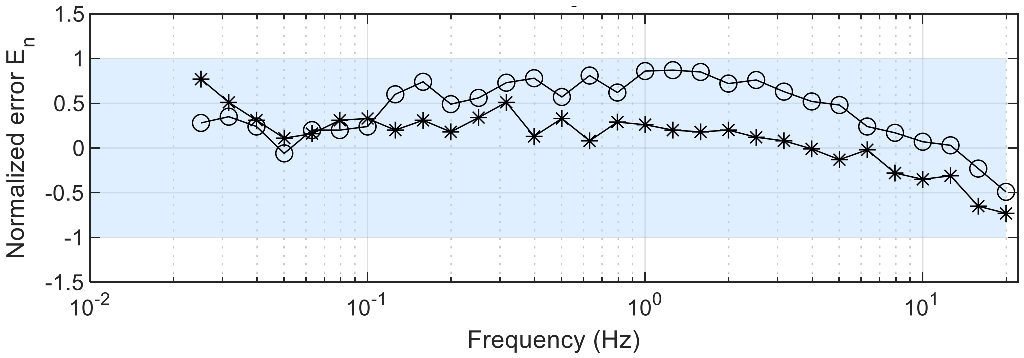
- For the case of two laboratories (the primary calibrations), ”normalized error”, E_n , is calculated.

$$E_n = \frac{x_{lab1} - x_{lab2}}{\sqrt{U_{lab1}^2 + U_{lab2}^2}}$$

- If $|E_n| < 1$, the results can be considered mutually consistent







Comparison calibration metrics, D_{ii}

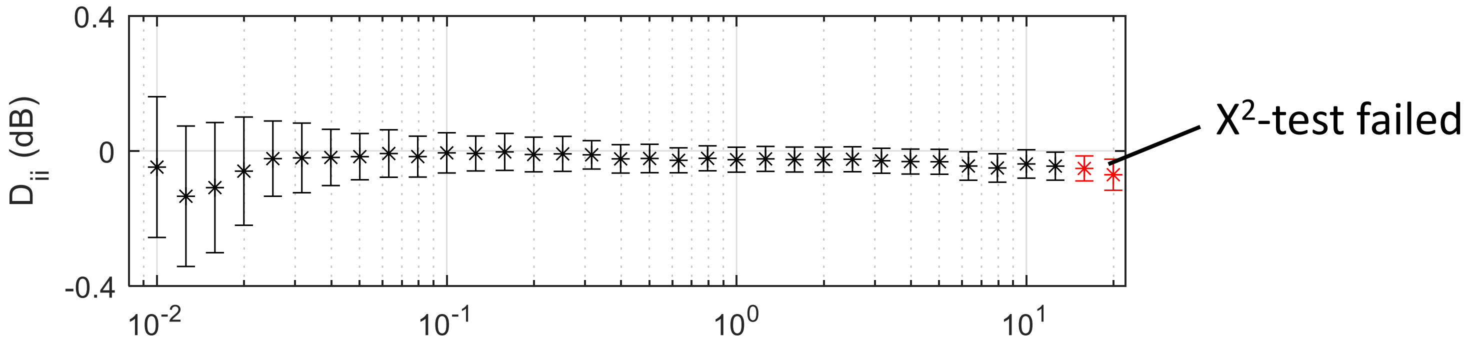
- For the case of more than two laboratories (the secondary comparisons), ”degree of equivalence”, Dii, is calculated
  - The comparison reference value, CRV, is the mean of the results weighted with their uncertainties

$$CRV = \frac{(x_1/u^2(x_1) + \ldots + x_N/u^2(x_N))}{(1/u^2(x_1) + \ldots + 1/u^2(x_N))} \qquad U^2(CRV) = \frac{1}{(1/u^2(x_1) + \ldots + 1/u^2(x_N))}$$

  - Degree of equivalence is the deviation of a result from the CRV (combined for all units)

$$D_{ii} = x_i - y \qquad U_{Dii}^2 = U^2(x_i) - U^2(CRV)$$

  - If 0 is in the confidence interval, the result can be considered consistent with the CRV



HOTTINGER BRÜEL & KJÆR

Sound in air comparisons in Infra-AUV

- Primary calibration of Brüel & Kjær Type 4160
  - HBK-DPLA reciprocity calibration
  - LNE laser pistonphone
- Primary calibration of Brüel & Kjær Type 4193
  - LNE laser pistonphone
  - PTB carousel
- Secondary calibration of microbarometer MB2005
  - CEA pistonphone with barometer and Brüel & Kjær Type 4193 as references
  - LNE laser pistonphone with Brüel & Kjær Type 4160 as reference
  - PTB sound tube with Brüel & Kjær Type 4193 (with GRAS 26AI preamplifier) as reference
- Secondary calibration calibration of Brüel & Kjær Type 4193
  - HBK-DPLA Type 9757 with Brüel & Kjær Type 4160 as reference
  - LNE laser pistonphone with Brüel & Kjær Type 4160 as reference
  - CEA pistonphone with barometer and Brüel & Kjær Type 4193 as references
  - PTB sound tube with Brüel & Kjær Type 4193 (with GRAS 26AI preamplifier) as reference

Primary calibration of 4160, level
HBK-DPLA (reciprocity) and LNE (laser pistonphone)

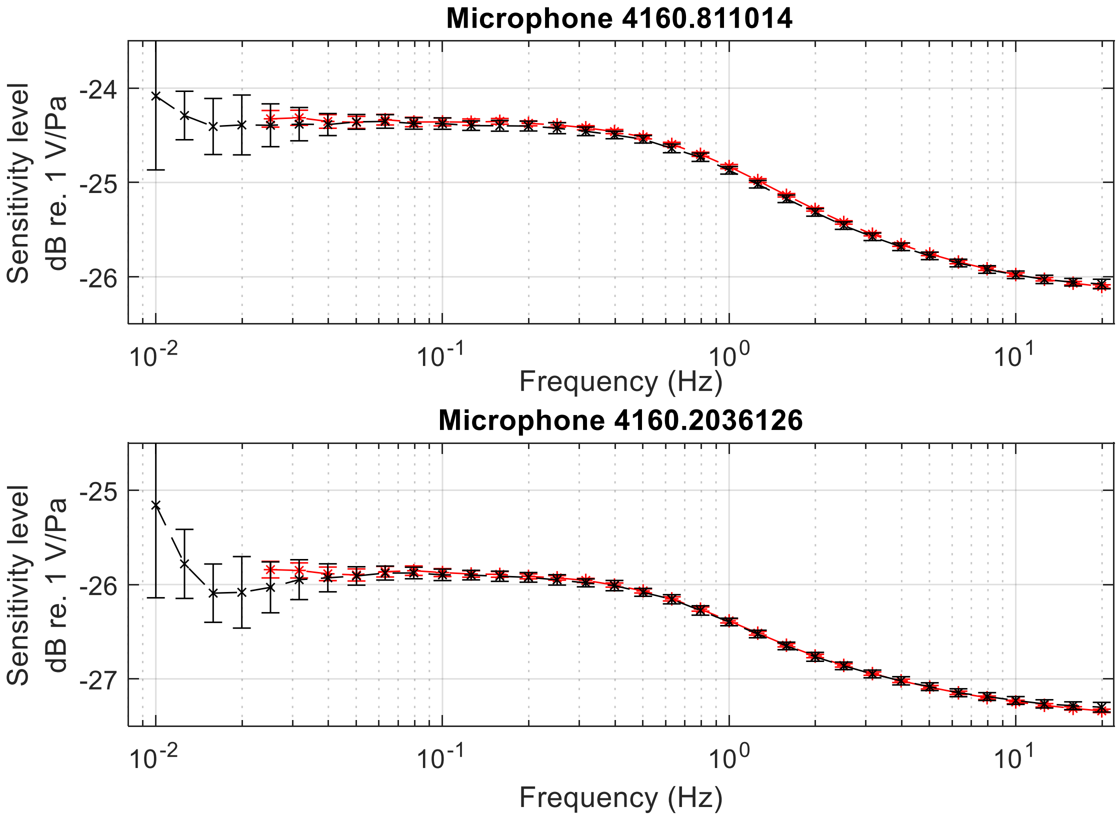


Figure Open circuit pressure sensitivity level in dB re 1 V/Pa and uncertainties in dB of HBK-DPLA (red crosses) and LNE (black stars) for the microphones B&K 4160, corrected to the static pressure of 100kPa.

Primary calibration of 4160, phase

HBK-DPLA (reciprocity) and LNE (laser pistonphone)

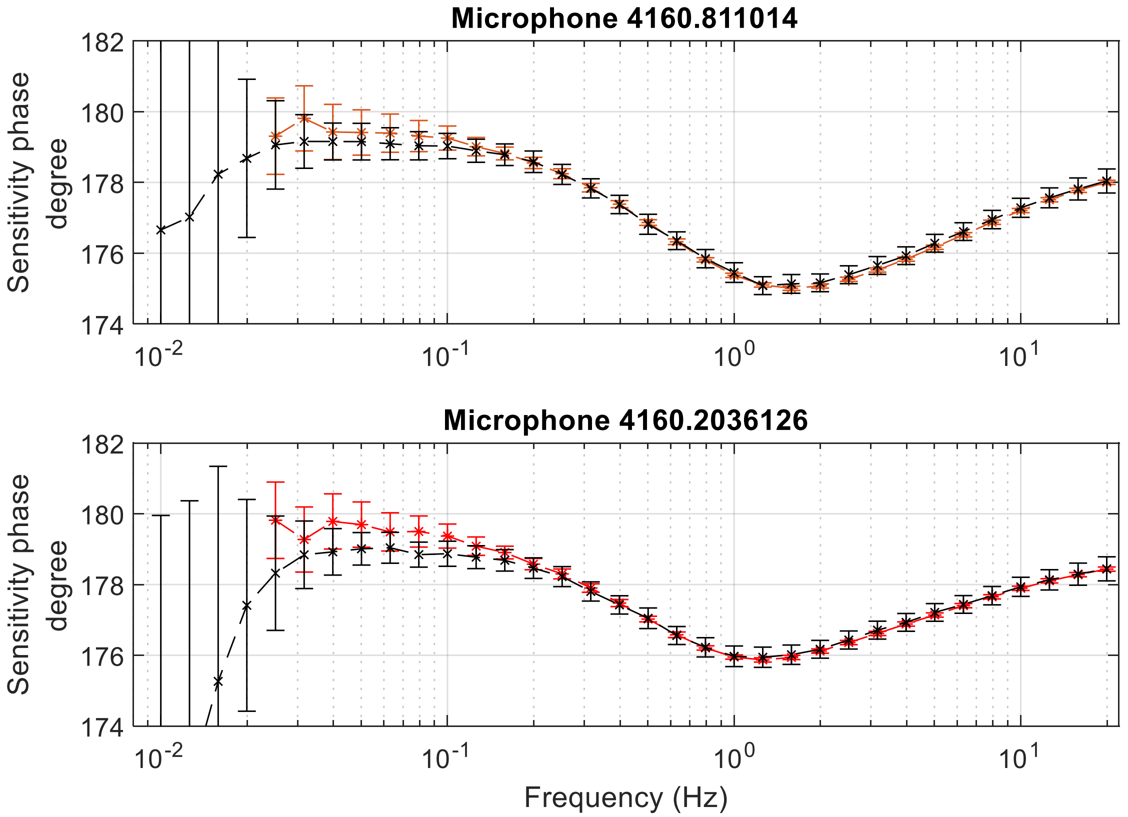


Figure Open circuit pressure sensitivity phase in degree and uncertainties in degree of HBK-DPLA (red crosses) and LNE (black stars) for the microphones B&K 4160, corrected to the static pressure of 100kPa.

Primary calibration of 4160, normalized error E_n

HBK-DPLA (reciprocity) and LNE (laser pistonphone)

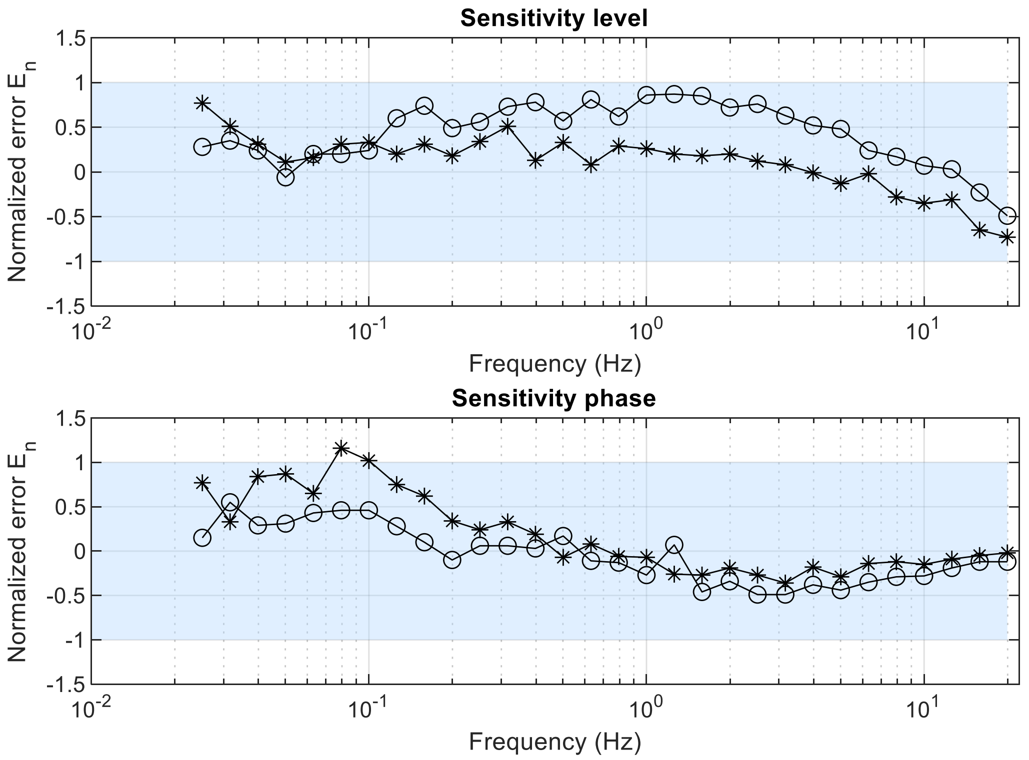


Figure Normalized error (k=2) between HBK-DPLA and LNE for the results of the open circuit sensitivity level (upper chart) and phase (lower chart) of the microphones B&K 4160.811014 (circles) and 4160.2036126 (stars) as a function of frequency. The satisfactory range $[-1, 1]$ of the normalized error is shown in light blue.

Primary calibration of 4193, level

LNE (laser pistonphone) and PTB (carousel)

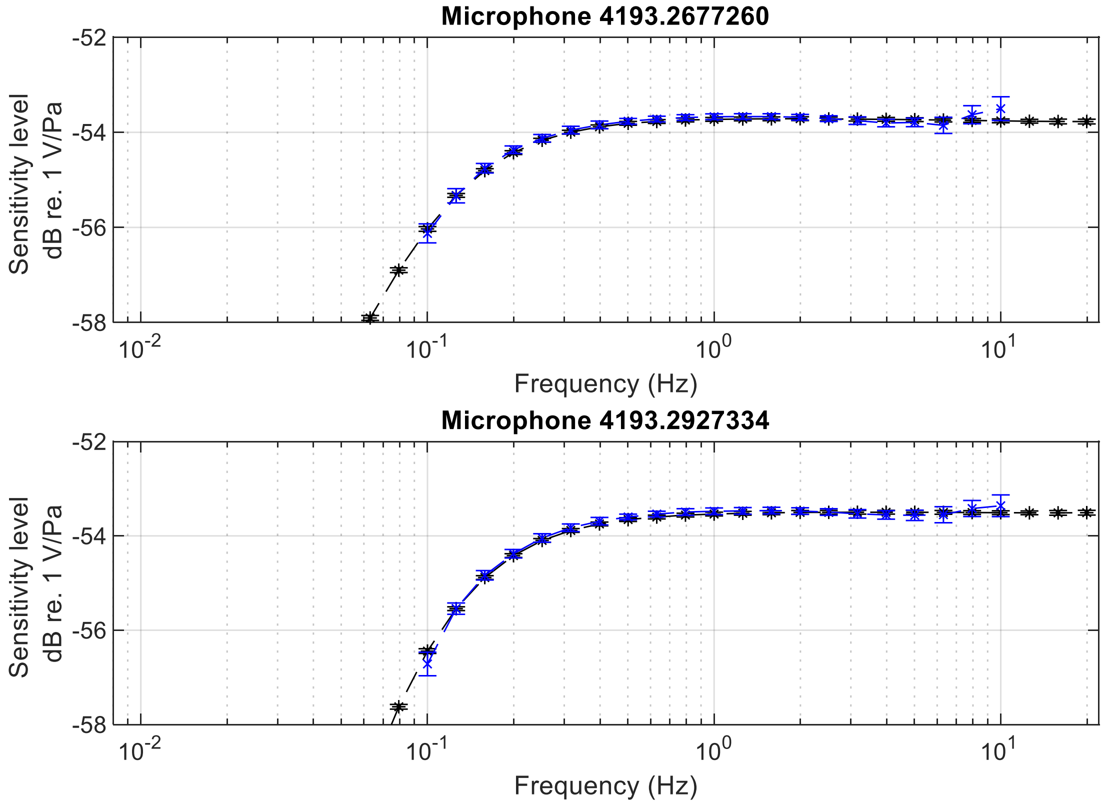


Figure Pressure sensitivity level in dB re 1 V/Pa and uncertainties in dB of LNE (black stars) and PTB (blue crosses) for the microphone units B&K 4193, as declared by the participant laboratories.

Primary calibration of 4193, phase
LNE (laser pistonphone) and PTB (carousel)

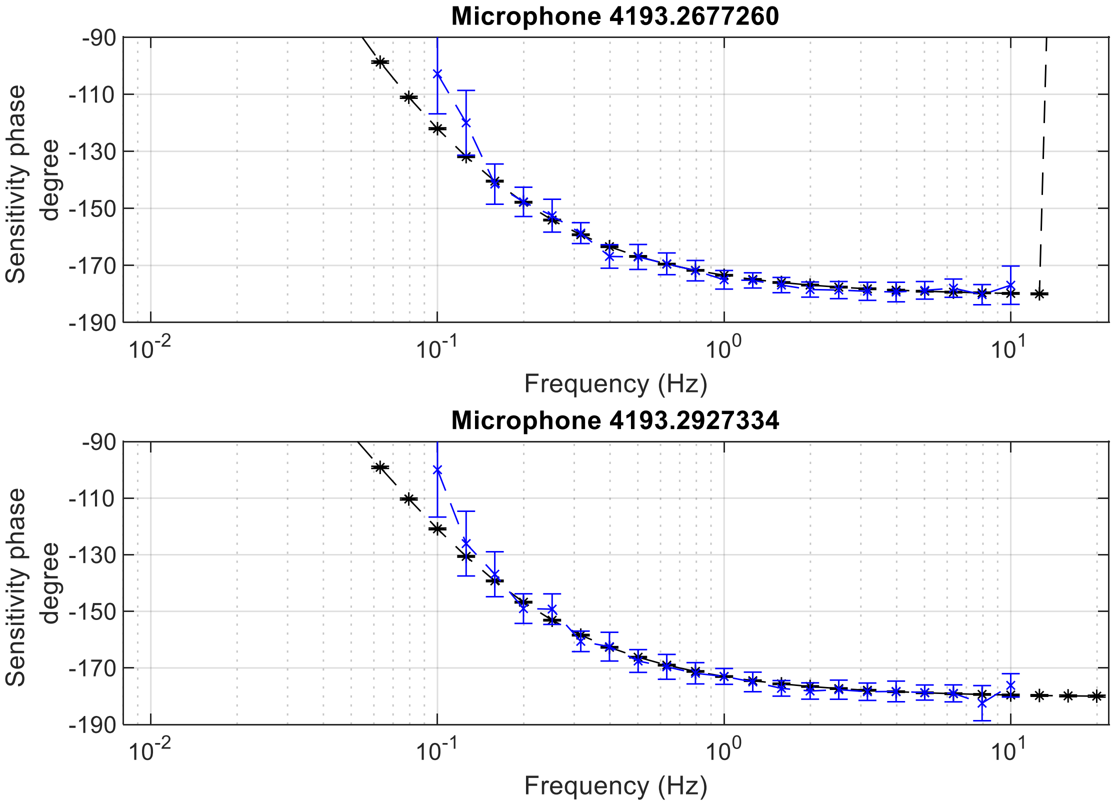


Figure Pressure sensitivity phase in degree and uncertainties in degree of LNE (black stars) and PTB (blue crosses) for the microphone units B&K 4193, as declared by the participant laboratories.

HBK HOTTINGER BRÜEL & KJÆR

Primary calibration of 4193, normalized error E_n

LNE (laser pistonphone) and PTB (carousel)

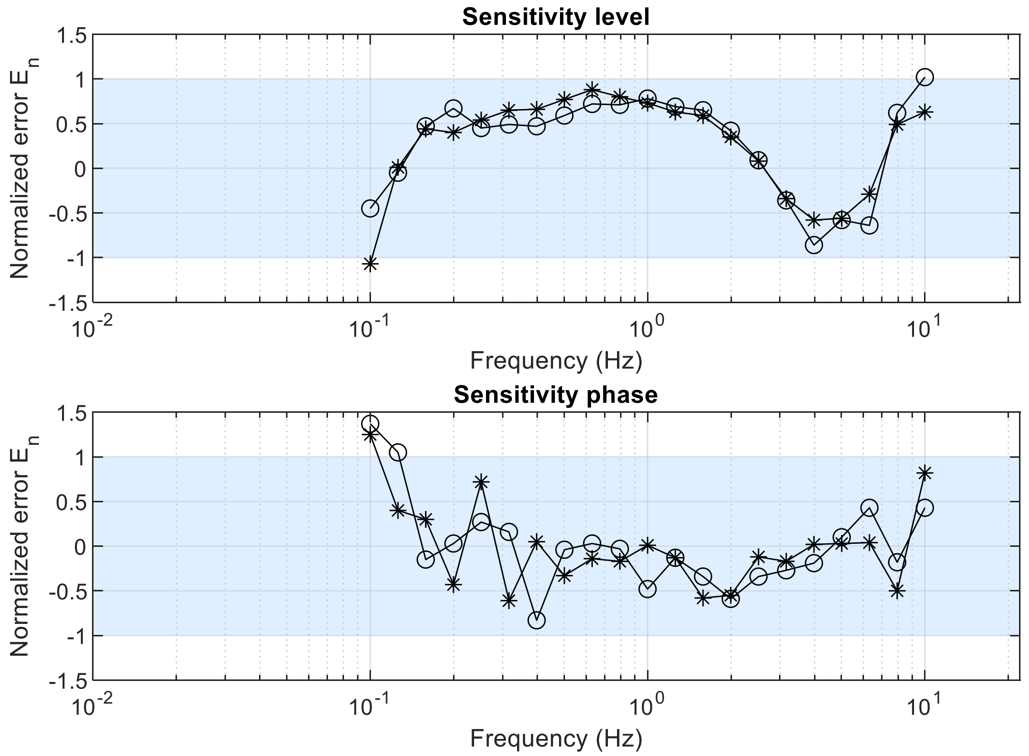


Figure Normalized error (k=2) between LNE and PTB for the results of the sensitivity level (upper chart) and phase (lower chart) of the microphones B&K 4193.2677260 (circles) and 4193.2927334 (stars) as a function of frequency. The satisfactory range $[-1, 1]$ of the normalized error is shown in light blue.

Secondary calibration of MB2005, level
CEA, LNE (laser pistonphone) and PTB (sound tube)

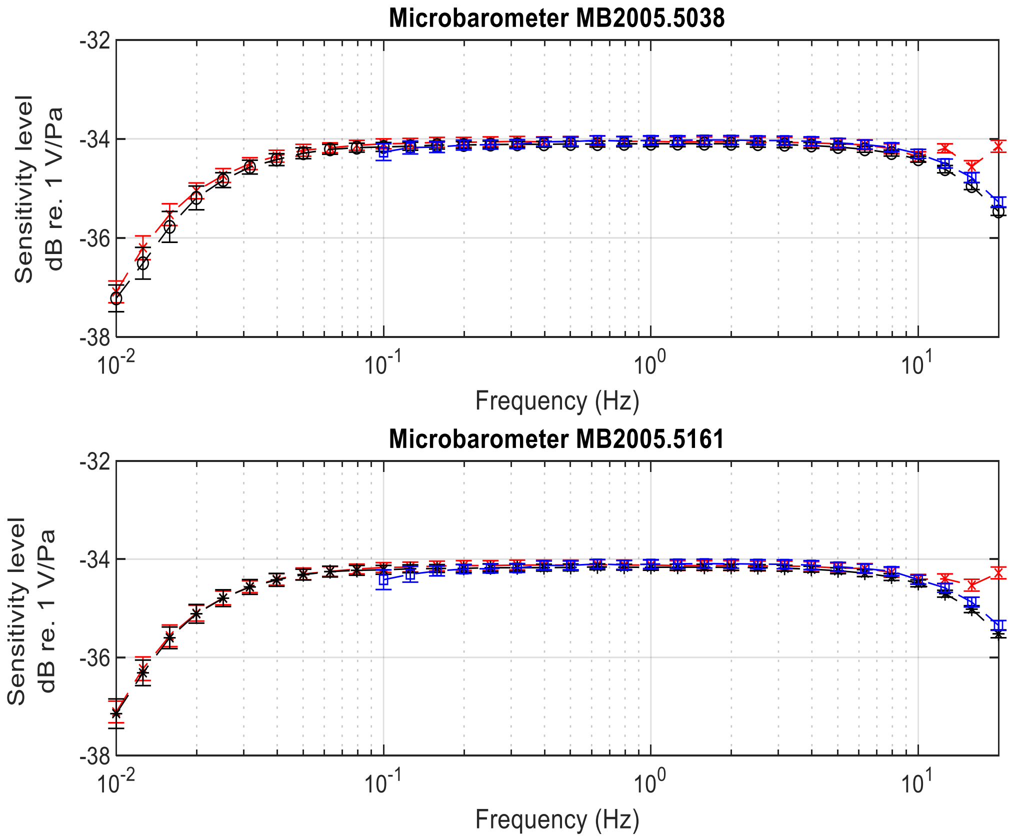


Figure Pressure sensitivity level in dB re. 1 V/Pa and uncertainties in dB of CEA (red crosses), LNE (black stars) and PTB (blue squares) for the microbarometers MB2005, as declared by the participant laboratories.

Secondary calibration of MB2005, phase
CEA, LNE (laser pistonphone) and PTB (sound tube)

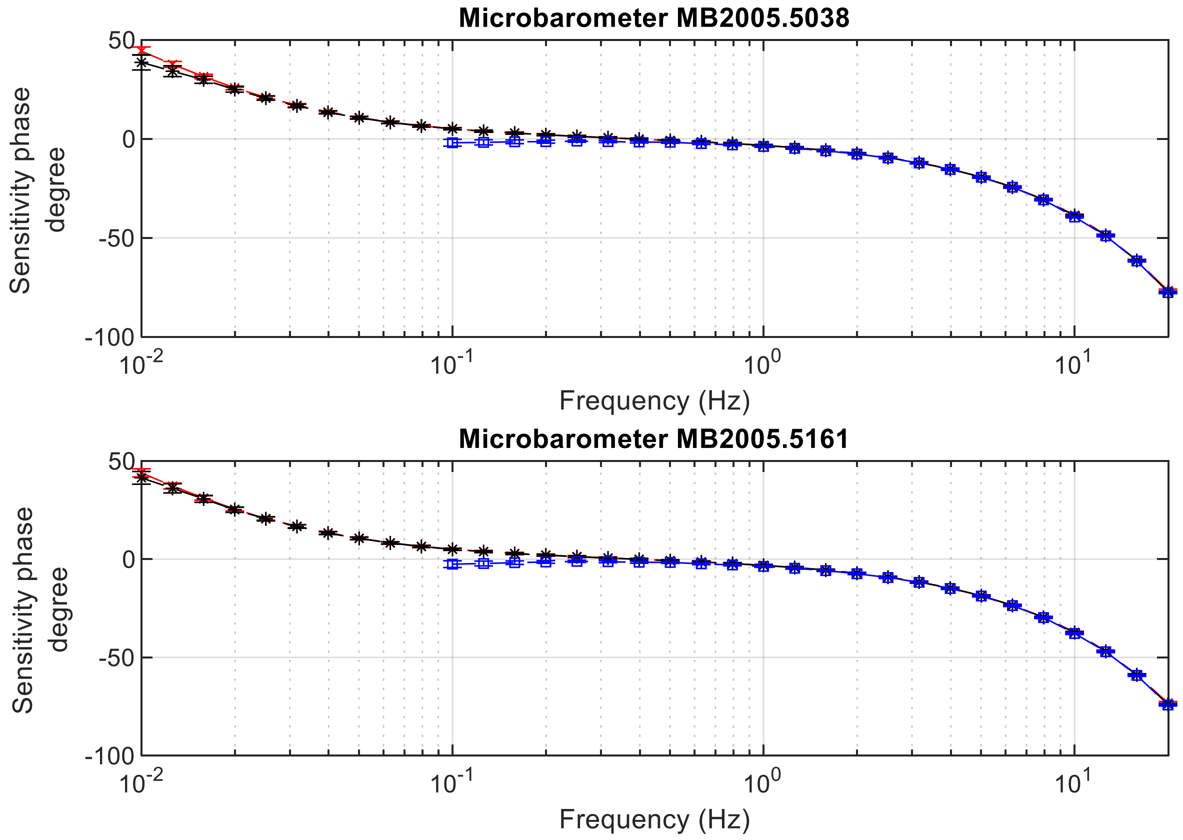


Figure Pressure sensitivity phase in degree and uncertainties in degree of CEA (red crosses), LNE (black stars) and PTB (blue squares) for the microbarometers MB2005, as declared by the participant laboratories.

Secondary calibr. of MB2005, degree of equivalence, level

CEA, LNE (laser pistonphone) and PTB (sound tube)

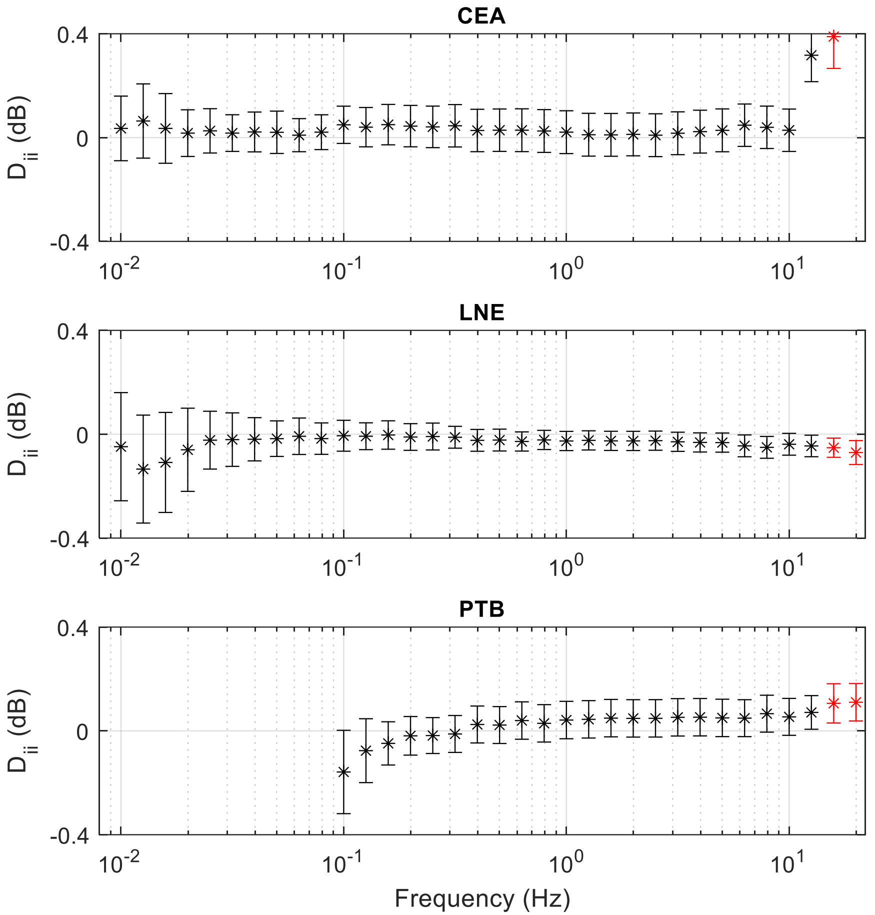


Figure Degrees of equivalence per laboratory for the sensitivity level of the MB2005 microbarometers with uncertainty bars corresponding to coverage factor k=2. The data for which the chi-squared test fails are presented in red.

Secondary calibr. of MB2005, degree of equivalence, phase

CEA, LNE (laser pistonphone) and PTB (sound tube)

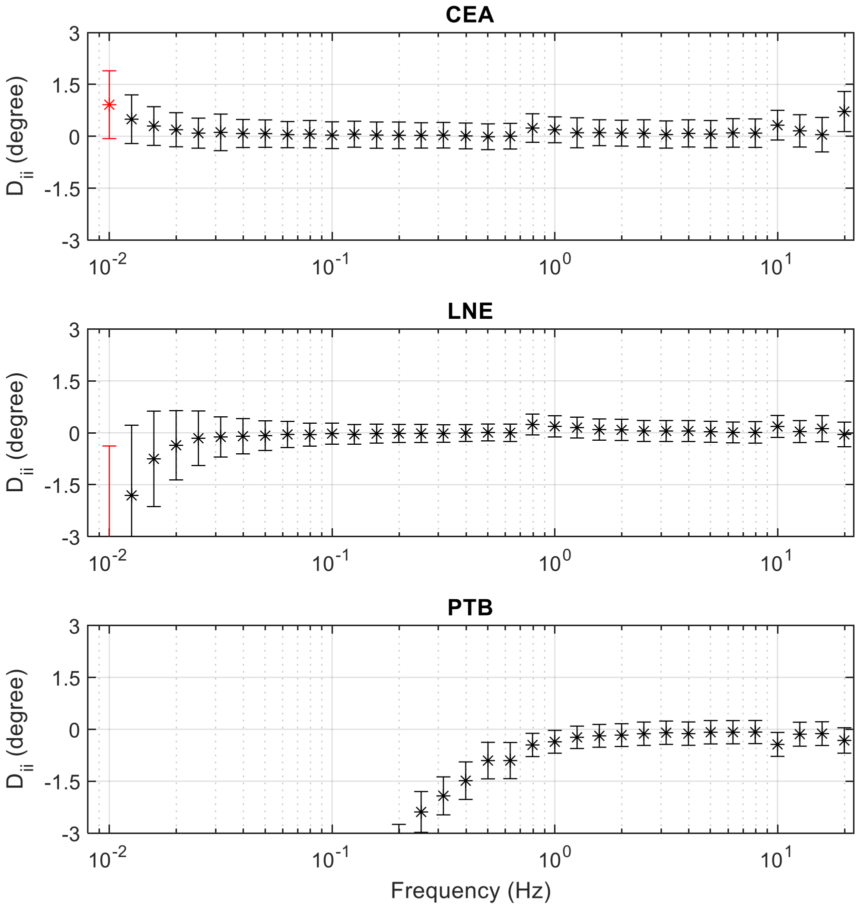


Figure Degrees of equivalence per laboratory for the sensitivity phase of the MB2005 microbarometers with uncertainty bars corresponding to coverage factor k=2. The data for which the chi-squared test fails are presented in red.

Secondary calibration of 4193, level

CEA, LNE (laser pistonphone), HBK-DPLA (coupler) and PTB (sound tube)

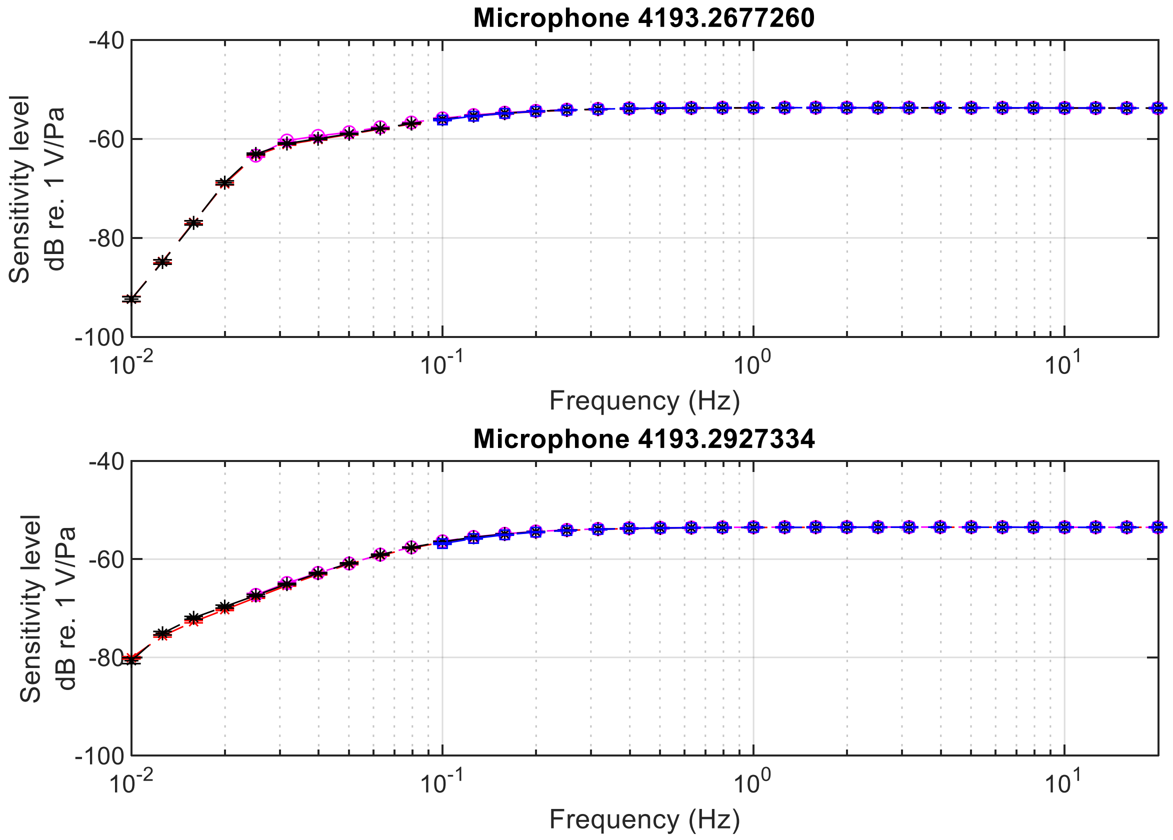


Figure _. Pressure sensitivity level in dB re. 1 V/Pa and uncertainties in dB of CEA (red crosses), HBK-DPLA (magenta circles), LNE (black stars) and PTB (blue squares) for the microphone units B&K 4193, as declared by the participant laboratories.

Secondary calibration of 4193, phase

CEA, LNE (laser pistonphone), HBK-DPLA (coupler) and PTB (sound tube)

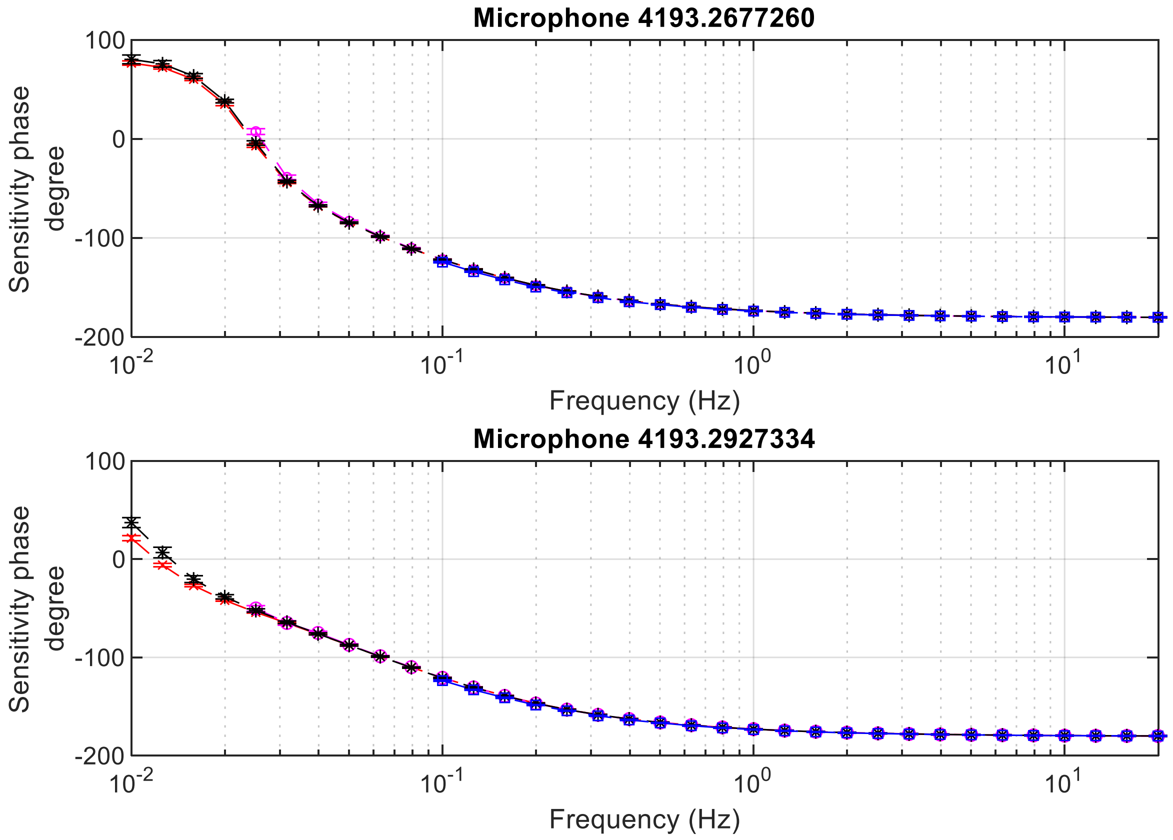


Figure _. Pressure sensitivity phase in degree and uncertainties in degree of CEA (red crosses), HBK-DPLA (magenta circles), LNE (black stars) and PTB (blue squares) for the microphone units B&K 4193, as declared by the participant laboratories.

Secondary calibr. of 4193, degree of equivalence, level
CEA, LNE (laser pistonphone), HBK-DPLA (coupler) and PTB (sound tube)

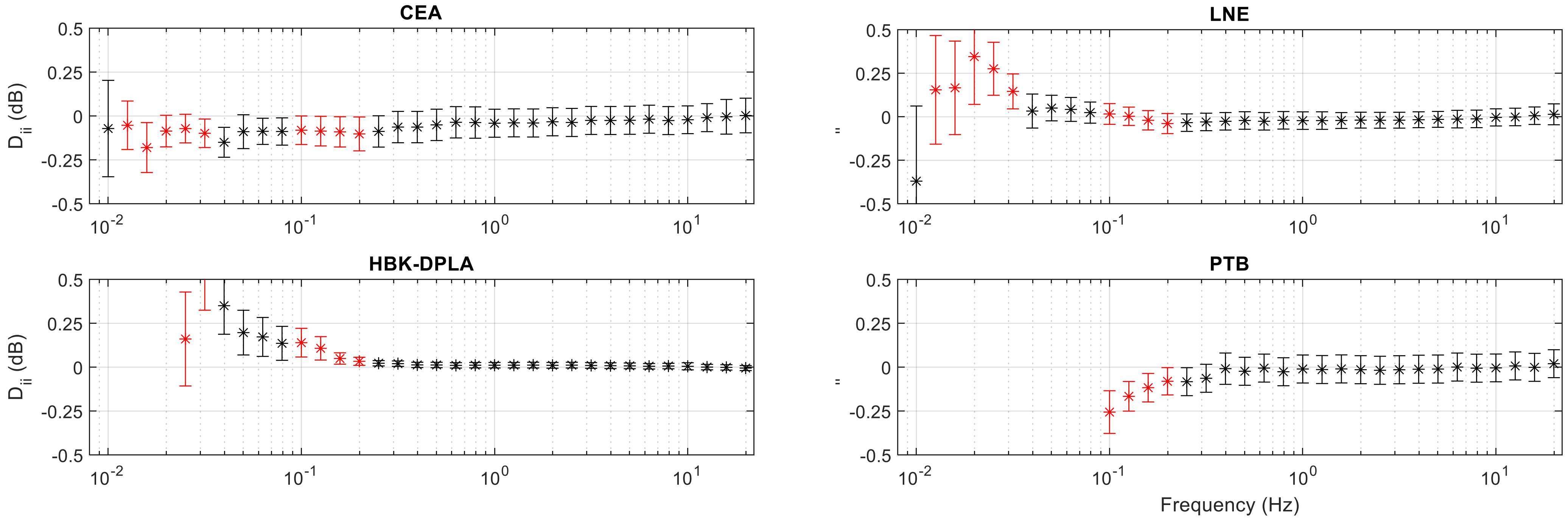


Figure Degrees of equivalence per laboratory for the sensitivity level of the B&K 4193 microphone units with uncertainty bars corresponding to coverage factor k=2. The data for which the chi-squared test fails are presented in red.

Secondary calibr. of 4193, degree of equivalence, phase

CEA, LNE (laser pistonphone), HBK-DPLA (coupler) and PTB (sound tube)

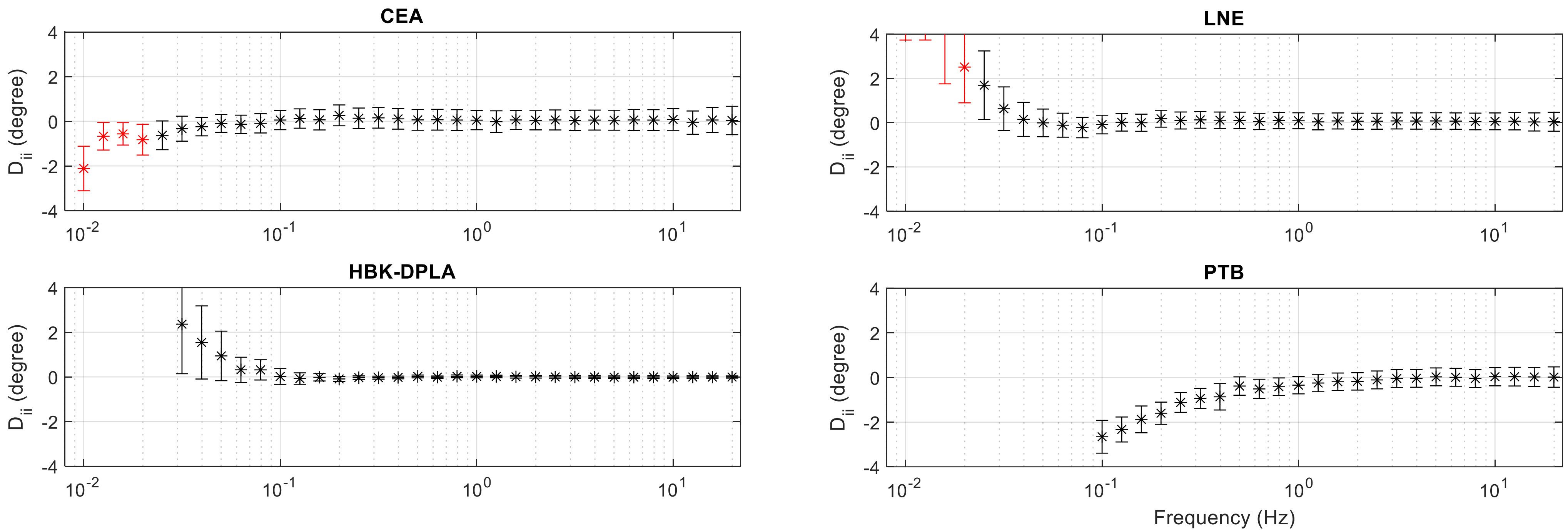


Figure Degrees of equivalence per laboratory for the sensitivity phase of the B&K 4193 microphone unit with uncertainty bars corresponding to coverage factor k=2. The data for which the chi-squared test fails are presented in red.

Comparison result summary

- Apart from the issues mentioned below and a few isolated exceptions, the measurements were shown to be consistent, indicating a robust comparability between the laboratories and the calibration methods

- The combination of the Type 4193 microphones and the power supply provided for the comparison turned out to cause noise and instabilities of the results at frequencies below 0.2 Hz, and results at these frequencies must be intepreted with caution
- The static pressure dependence of the devices in the comparison were only known approximately at the time of the comparison. Hence, corrections applied to some results may cause som additional uncertainty.
- PTB (sound tube) phase results in secondary calibrations were inconsistent with the comparison reference value, CRV, at frequencies below 1 Hz.

Further work

- It is the intention of the laboratories involved to resolve the issues and perform additional comparison measurements as appropriate.

- A consistent combination of Type 4193 microphones and power supply must be identified and verified
- Static pressure and temperature dependence of the standards must be established
- The reason to inconsistent phase mesurements in secondary calibrations must be identified
- Additional comparisons must be performed and results published so as to establish full confidence in the measurements
- Calibration services shall be established and made available for the broader community

Thank you for listening

https://www.ptb.de/empir2020/infra-auv

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