Final Report on the

Supplementary comparison

EURAMET.AUV.V-S1

Summary

The Supplementary comparison EURAMET.AUV.V-S1 has been carried out within the framework of the CIPM MRA. The specific task of this comparison is the measurement of the magnitude and phase of the sensitivity of single-ended accelerometers in the medium frequency domain (10 to 10 000 Hz). The sensitivity is calculated as the ratio of the amplitude of the output of the accelerometer to the amplitude of the acceleration at its reference surface with secondary means in accordance with ISO 16063-21 "Methods for the calibration of vibration and shock transducers - Part 21: Vibration calibration by comparison to a reference transducer" [1]. The participating NMIs are BEV (Austria), BIM (Bulgaria), CMI (Czech Republic), IPQ (Portugal), KEBS (Kenya), METAS (Switzerland) and MIKES (Finland). BEV (Austria) was the pilot laboratory of the comparison. The measurements took place between October 2019 and February 2021. Three single-ended accelerometers were circulated. This report includes the measurement results from the participants, information about their calibration methods, and the analysis leading to the assignation of equivalence degrees.

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Table of Contents

1 Introduction ... 3
2 Scope ... 3
3 Stability of travelling standards ... 4
4 Calibration methods ... 7
  4.1 Overview ... 7
  4.2 BEV ... 8
  4.3 BIM ... 8
  4.4 CMI ... 9
  4.5 IPQ ... 9
  4.6 KEBS ... 10
  4.7 MIKES ... 10
  4.8 METAS ... 10
5 Results ... 10
  5.1 Sensitivity Magnitude 8305-001 ... 11
  5.2 Sensitivity Magnitude 2270M8 ... 13
  5.3 Sensitivity Phase 8305-001 ... 15
  5.4 Sensitivity Phase 2270M8 ... 17
6 Analysis of the results ... 19
  6.1 Degrees of equivalence ... 19
  6.2 DoE of Sensitivity Magnitude 8305-001 ... 20
  6.3 DoE of Sensitivity Magnitude 2270M8 ... 24
  6.4 DoE of Sensitivity Phase 8305-001 ... 28
  6.5 DoE of Sensitivity Phase 2270M8 ... 29
7 Conclusions ... 30
8 References ... 31
Appendix A - Results of accelerometer 4371-V ... 32
Appendix B - Uncertainty budgets ... 36
  a) BEV ... 36
  b) BIM ... 37
  c) CMI ... 44
  d) IPQ ... 48
  e) KEBS ... 52
  f) MIKES ... 53
  g) METAS ... 62
Appendix C - Technical protocol ... 64
Appendix D - Technical note ... 68

1 Introduction

The EURAMET.AUV.V-S1 is a supplementary comparison realised under the auspices of the EURAMET TC-AUV in the framework of the CIPM MRA.

Three standards were circulated among the laboratories. The accelerometers were calibrated for magnitude and phase (optional) of their complex charge sensitivity according to those procedures and conditions implemented by the NMI in conformance with ISO 16063-21 [1]. The frequency range of the measurements was agreed to be from 10 Hz to 10 kHz.

Seven National Metrology Institutes took part and BEV (Austria) piloted the comparison. The participants are listed in Table 1. The measurements took place between October 2019 and February 2021. This report includes the measurement results from the participants, information about their calibration methods, and the analysis leading to the assignation of equivalence degrees.

Table 1. List of participating institutes

Participant (alphabetical order)	Acronym	Country	Country code
Bundesamt für Eich- und Vermessungswesen	BEV	Austria	AT
Bulgarian Institute of Metrology	BIM	Bulgaria	BG
Czech Metrology Institute	CMI	Czech Republic	CZ
Instituto Português da Qualidade	IPQ	Portugal	PT
Kenya Bureau of Standards	KEBS	Kenya	KE
Eidgenössisches Institut für Metrologie	METAS	Switzerland	CH
Mittatekniikan Keskus	MIKES	Finland	FI

2 Scope

The technical protocol for the supplementary comparison EURAMET.AUV.V-S1 was approved by all participants (Appendix C). Further Instructions about handling of the transfer standards were given in a technical note (Appendix D).

The specific task of this RMO comparison is to measure the magnitude and phase (optional) of the charge sensitivity of three different accelerometers at specified frequencies with secondary means according to ISO 16063-21 “Methods for the calibration of vibration and shock transducers - Part 21: Vibration calibration by comparison to a reference transducer” [1]. The accelerometers were also sent to METAS for primary calibration according to ISO 16063-11 “Methods for the calibration of vibration and shock transducers - Part 11: Primary vibration calibration by laser interferometry” [2]. The results of the METAS calibration provide the reference values for phase and magnitude. The reported sensitivities and associated uncertainties are used for the calculation of the DoE between the participating NMI and the primary calibration value of METAS.

Three piezoelectric accelerometers were circulated among the participating laboratories. The individual transducers are:

- Brüel & Kjær 8305-001 (SN: 2423435) “single ended” (SE) type, 0.126 pC/(m/s^2)
- Brüel & Kjær 4371V (SN: 2046745) “single ended” (SE) type, 1 pC/(m/s^2)
- Endevco 2270M8 (SN: 16198) “single ended” (SE) type, 0.22 pC/(m/s^2)

B&K 8305-001

B&K 4371-V

Endevco 2270M8

In the following these transducers are referred to as “8305-001”, “4371-V” and “2270M8”, respectively.

The frequency range of the measurements was agreed to be from 10 Hz to 10 kHz. Specifically, the laboratories were supposed to measure at the following frequencies (all values in Hz).

10, 12.5, 16, 20, 25, 31.5, 40, 63, 80, 100, 125, 160, 200, 250, 315, 400, 500, 630, 800, 1 000, 1 250, 1 600, 2 000, 2 500, 3 150, 4 000, 5 000, 6 300, 8 000, 10 000

Note: this set does deviate from the standard frequencies of ISO 266.

Specific conditions for the measurements of this comparison were:

- Acceleration amplitudes: preferably 50 m/s^2 to 100 m/s^2, a range of 2 m/s^2 to 200 m/s^2 was admissible.
- Ambient temperature during the calibration:
  (23 ± 2) °C (actual values to be stated within tolerances of ± 0.3 °C).
- Relative humidity: max. 75 %rh
- Mounting torque of the accelerometer: (2.0 ± 0.1) N·m

3 Stability of travelling standards

BEV has monitored the transfer accelerometers since the beginning of the comparison. The monitoring consisted of magnitude calibrations according to ISO 16063-21 [1]. The measurement schedule was:

BEV → IPQ → MIKES → BEV → CMI → BIM → BEV → METAS→ BEV→ KEBS→ BEV

According to ISO 16063-21 a rectangular probability distribution is assumed for the quantity “drift of the magnitude of an accelerometer”. At each frequency f, the estimator for the mean $\bar{S}(f)$ of the magnitude of all monitoring measurements is then given as:

$$\bar{S}(f) = \frac{S_{max}(f) + S_{min}(f)}{2}$$

Where $S_{max}(f)$ and $S_{min}(f)$ are the maximum and minimum of all monitoring measurements at each frequency. To deduce a significant drift of an accelerometer for each monitoring measurement an ε_i number is defined as:

$$\varepsilon_i(f) = \frac{|S_i(f) - \bar{S}(f)|}{U_{S_i}(f)}$$

Where $S_i(f)$ is the magnitude of a single monitoring measurement i and $U_{S_i}(f)$ is the expanded uncertainty of $S_i(f)$. Similar as in [3] this omits the uncertainty of $\bar{S}(f)$ for good reason, since the aim of ε_i is the deduction of drift. As long as $\varepsilon_i(f) \leq 1$, $\forall i$, $\forall f$ is valid, no significant drift can be deduced by the means of the pilot laboratory. For starters, it is sufficient to calculate $\varepsilon_{max}(f) = \max_i \varepsilon_i(f)$ for each frequency and check, if $\varepsilon_{max}(f) \leq 1$.

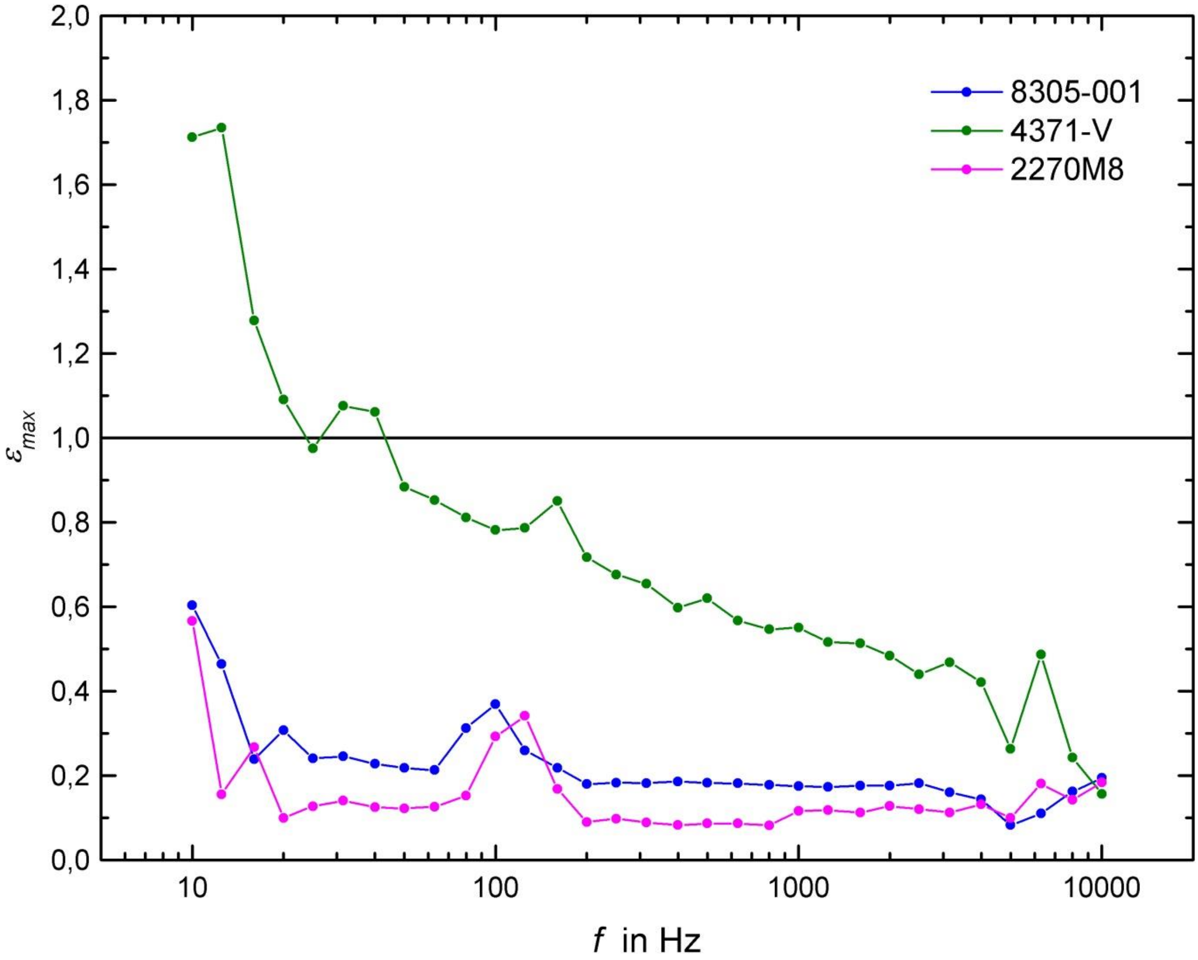


Figure 1. Maximum values of ε for all frequencies f and all accelerometers.

Fig. 1 clearly indicates some drift of accelerometer 4371-V in comparison with the remaining two transducers. For a more detailed view, the differences of the measured magnitudes ΔS were calculated for selected frequencies.

$$\Delta S = 100 \cdot \frac{S_i(f) - \bar{S}(f)}{\bar{S}(f)}\,\%$$

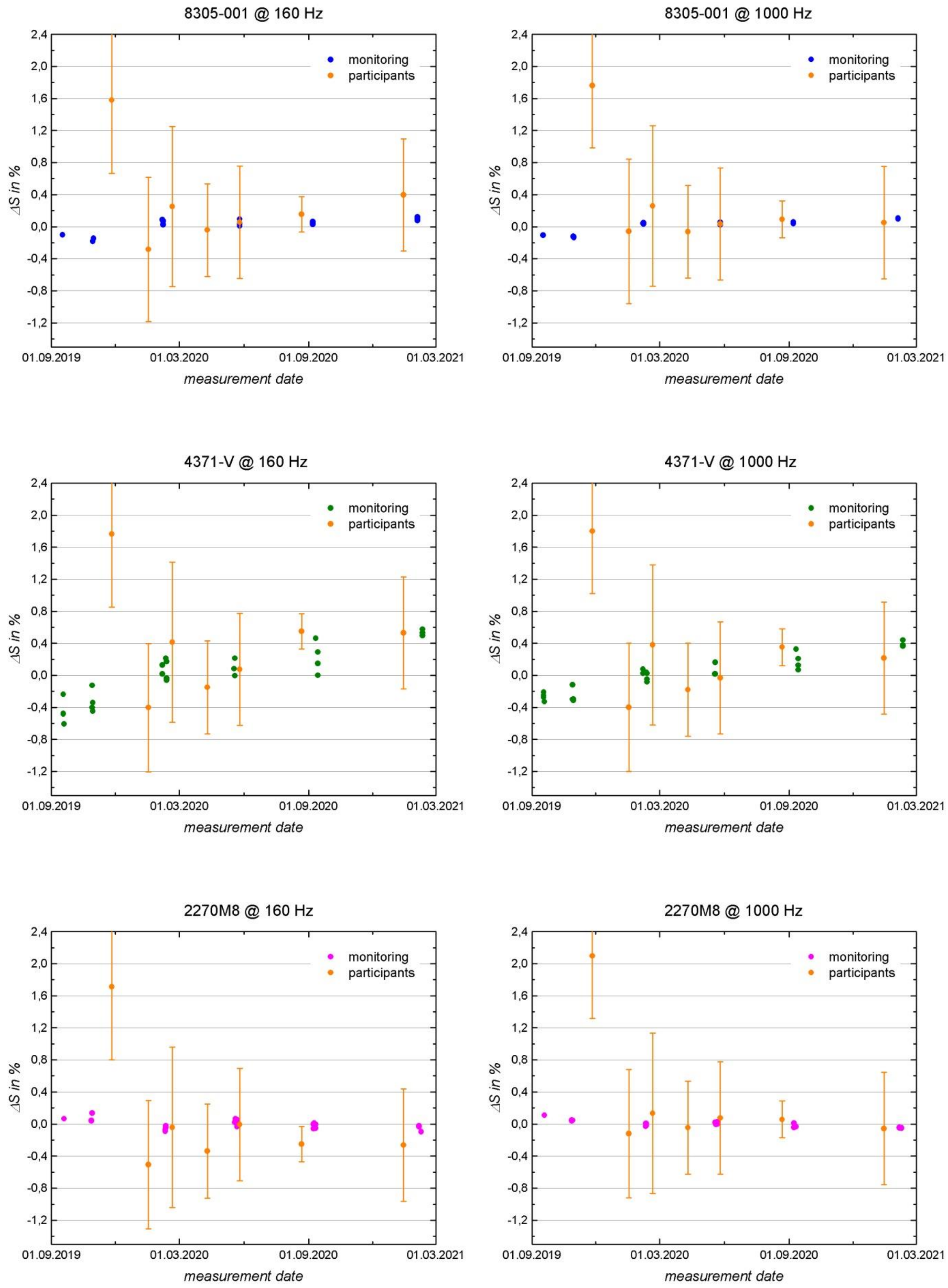


Figure 2. **Differences in magnitude ΔS for the frequencies 160 Hz and 1000 Hz for all accelerometers. For convenience, the results of the participants are also presented in graphs.**

While the accelerometers 8305-001 and 2270M8 are sufficiently stable, 4371-V shows again a considerable drift as can be seen from the Fig. 2. The drift of 4371-V is also reflected by the results of the participants. As Fig. 1 already indicates, this drift increases with decreasing frequency.

It was therefore decided, to exclude the results of 4371-V from the analysis of the comparison. The results of 4371-V are given in Appendix A only.

Remark about transportation

An automatic data logger type MSR 145 was packed inside the transport case of the transfer standards. It recorded 3 axis acceleration, temperature, humidity and air pressure. All shipments were done commercially, except for the personal transport from BEV to METAS and back. The recorded data show similar shock values for all commercial shipments, but the shock values of the personal transport are about three times smaller than for commercial shipment. Therefore, it has to be emphasized again, that during a comparison transportation should be done personally, whenever possible.

4 Calibration methods

4.1 Overview

Table 2. Measurement instrumentation of all participants. BB (back-to-back) means the reference sensor of the measurement system, while SE (single ended) stands for the transfer standards.

	BEV	BIM	CMI	IPQ	KEBS	MIKES	METAS
Reference Transducer BB	B&K 8305	B&K 8305	PCB M353B17	B&K 8305	B&K 8305	B&K 8305	n/a
Traceability BB	PTB	PTB	CMI primary system	IPQ primary system	NMISA	DPLA	primary
Recalibration Interval BB	3 years	5 years	1 year	2 years	4 years	1,5 years	n/a
Shaker	SPEKTRA SE-09	B&K 4805	SPEKTRA SE-10	B&K 4809	B&K 4809	Homemade air bearing shaker	SPEKTRA SE-10
Power Amplifier	SPEKTRA PA 14-500	B&K 2707	SPEKTRA PA 14-180	B&K 2718	SPEKTRA BAA 80	Homemade power amplifier	SPEKTRA PA 14-180
Shaker Source	HP 33120A	Agilent 33220A	SPEKTRA SRS-35	B&K 1051	SPEKTRA SRS-35	NI PXI-4461	SPEKTRA SRS-35
Mounting Technique BB	Screw	Screw	shaker Internal reference	Screw	Screw	Screw	n/a
Mounting Technique SE	Screw	Screw	Screw	Screw	Screw	Screw	Screw
Grease*	slightly greased	slightly greased	slightly greased	slightly greased	slightly greased	slightly greased	slightly greased
Torque	2 N·m	2 N·m	2 N·m	2 N·m	BB 2,5 N·m SE 2 N·m	2 N·m	2 N·m
Charge Amp. BB	B&K 2635	B&K 2635	SPEKTRA SRS-35	B&K NEXUS 2692 A	SPEKTRA SRS-35	B&K NEXUS 2692 OS	n/a

	BEV	BIM	CMI	IPQ	KEBS	MIKES	METAS
Charge Amp. SE	B&K 2525	B&K 2626	SPEKTRA SRS-35	B&K NEXUS 2692 A	SPEKTRA SRS-35	B&K NEXUS 2692 OS	SPEKTRA SRS-35
Voltmeter BB	NI PXI-6124	Fluke 8506A	SPEKTRA SRS-35	HP 3458A	SPEKTRA SRS-35	NI PXI-4461	n/a
Voltmeter SE	NI PXI-6124	Fluke 8506A	SPEKTRA SRS-35	HP 3458A	SPEKTRA SRS-35	NI PXI-4461	SPEKTRA SRS-35

*Institutes employing a back-to-back transducer as reference use grease on both surfaces of the back-to-back transducer.

A description of the calibration methods of each laboratory is given below as submitted by each participant. Minor editing of the contents and a small amount of reformatting has been performed.

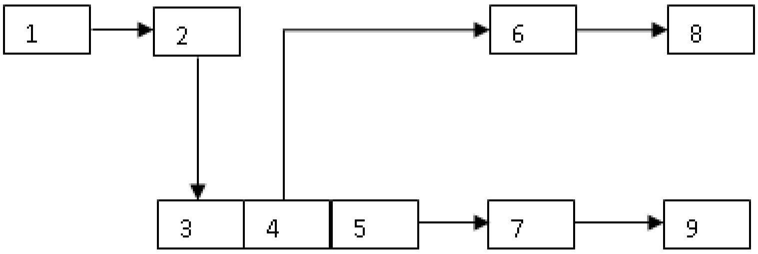
4.2 BEV

Measurements were done according to ISO 16063-21. Table 2 shows details about instrumentation.

4.3 BIM

Measurement set-up

The block diagram of the measurement set-up using comparison method is shown in Fig. 3.



1	Sine wave voltage generator
2	Power amplifier
3	Electrodynamic vibration exciter
4	Reference standard accelerometer
5	Accelerometer for calibration
6	Preamplifier for standard accelerometer
7	Preamplifier for calibration accelerometer
8, 9	Digital voltmeters

Figure 3. BIM block diagram for calibration

Electrodynamic vibrator (3) is supplied from generator (1) and power amplifier (2). The reference standard accelerometer (Back-to-Back) (4) is fixed on vibrational table. The accelerometer for calibration (5) is mounted on the top of surface of a reference standard accelerometer as illustrated in Figure 4. The output signal of the standard accelerometer is applied to the input of the charge preamplifier (6). The output signal of the calibrated accelerometer (5) is applied to the input of the charge preamplifier (7). The output signals of both preamplifiers are measured with two voltmeters (8 and 9).

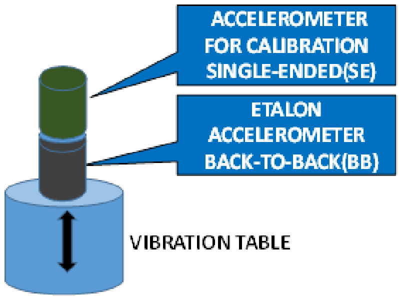


Figure 4. BIM mounting schematic of accelerometer Single Ended (SE) for calibration and Reference standard accelerometer Back-to-Back (BB).

Preliminary check and preparation

The measurement devices and the components of standard measurement system are connected according to the block diagram presented in Fig. 3 and the corresponding technical documentation. The electrical connections and grounding are checked.

The calibrated accelerometer (SE) is connected and operated according to the related technical specifications. The reference standard accelerometer (BB) is mounted on the vibration exciter table (after a slight oiling) by using a standard wrench, with applied torque value according to manufacturer's data. The surfaces of the accelerometers being in contact are separated with mica washer. The thin layer of special grease is applied between the accelerometers. Fix the signal cables of accelerometers to avoid signal distortions.

It is important to wait until the warm-up time is up before starting any measurements, as noted in the technical specs, according to the metrological requirements.

The functionality of the standard measuring systems is tested for consistency after the warm-up time is up. The relation between the vibration quantities and time should produce harmonic output signal with insignificant distortions, within the frequency and amplitude range used. If necessary, the acceleration distortion factor is monitored by Distortion meter or Frequency Analyser.

4.4 CMI

Measurements were done according to ISO 16063-21. Table 2 shows details about instrumentation.

4.5 IPQ

The measurement setup was implemented around:

- A reference accelerometer - Brüel & Kjær – 8305S characterized by the IPQ primary interferometric system;
- A signal source - Brüel & Kjær - 1051;
- An amplifier - Brüel & Kjær - 2718;
- An exciter - Brüel & Kjær - 4809-W-001;
- Accelerometer conditioners - Brüel & Kjær - NEXUS 2692 A 0I4;
- Two sampling voltmeters – Agilent 3458A;
- An in-house developed *LabView* routine to control the voltmeters readings and store all acquired data;
- An in-house developed *LabView* routine with the ability to process the stored data in offline mode.

4.6 KEBS

Calibration was performed using procedure MET/15/CP/01 Vibration Sensor Calibration. The procedure makes use of the following instruments.

- Automated measurement control unit Spektra SRS 35 S/No. 200511 with a standard uncertainty of approximately 0.25% over the selected frequency range of calibration.
- B&K 8305 back-to-back reference accelerometer S/No. 2519460 with a standard uncertainty of 0.25 % from 10 Hz to 1 kHz, 0.35 % from frequencies > 1 kHz to 5 kHz, 0.5 % from frequencies > 5 kHz to 7.5 kHz and 0.75 % from frequencies > 7.5 kHz to 10 kHz.
- Vibration exciter 4809 with amplifier BAA 80 capable of a maximum payload of 390 grams at 100 m/s^2.

Back-to-back mounting of the sensors was done by screwing. The coupling surfaces of the reference accelerometer and the DUT were slightly greased. A torque of 2.5 N·m was applied on the screwed connection between vibration exciter and reference accelerometer. A torque of 2 N·m was applied between the reference accelerometer and the DUT. All cables were appropriately secured using double sided tape.
Calibration was repeated over multiple days and times within the allocated measurement period.

4.7 MIKES

Measurements were done according to ISO 16063-21. Table 2 shows details about instrumentation.

4.8 METAS

Measurements were done according to ISO 16063-11. Table 2 shows details about instrumentation.

5 Results

The following tables and figures show the reported results of the participants for transducers 8305-001 and 2270M8. Due to its stability issues, the results of 4371-V are given in Appendix A. The uncertainty budgets of each participant are presented in Appendix B. Table 3 explains the quantities and symbols of the results tables.

Table 3. Quantities of results tables

Quantity	Symbol	Unit	Representation
Sensitivity magnitude	S	$\mathrm{pC/(m\ s^{-2})}$	x.xxxxx
Expanded relative Uncertainty	U_S	%	x.xx
Sensitivity Phase	φ	1°	x.xx
Expanded Uncertainty	U_φ	1°	x.xx

5.1 Sensitivity Magnitude 8305-001

Table 4. Sensitivity magnitude and expanded relative uncertainty for accelerometer 8305-001, part 1.

f Hz	BEV		BIM		CMI		IPQ	
	S in $\frac{\mathrm{pC}}{(\mathrm{m\,s^{-2}})}$	U_S in %	S in $\frac{\mathrm{pC}}{(\mathrm{m\,s^{-2}})}$	U_S in %	S in $\frac{\mathrm{pC}}{(\mathrm{m\,s^{-2}})}$	U_S in %	S in $\frac{\mathrm{pC}}{(\mathrm{m\,s^{-2}})}$	U_S in %
10.0	0.12601	0.90	0.12563	0.82	0.12663	1.00		
12.5	0.12607	0.90	0.12557	0.83	0.12624	1.00		
16.0	0.12625	0.90	0.12556	0.75	0.12648	1.00		
20.0	0.12627	0.90	0.12565	0.68	0.12615	1.00		
25.0	0.12613	0.90	0.12564	0.64	0.12614	1.00	0.12736	1.10
31.5	0.12610	0.70	0.12567	0.64	0.12631	1.00		
40.0	0.12610	0.70	0.12573	0.63	0.12614	1.00	0.12778	0.94
63.0	0.12610	0.70	0.12582	0.58	0.12626	1.00	0.12781	0.97
80.0	0.12609	0.70	0.12581	0.59	0.12607	1.00	0.12779	0.93
100	0.12590	0.70	0.12584	0.59	0.12599	1.00	0.12785	0.92
125	0.12585	0.70	0.12581	0.59	0.12621	1.00		
160	0.12593	0.70	0.12580	0.58	0.12617	1.00	0.12786	0.91
200	0.12595	0.70	0.12583	0.58	0.12622	1.00	0.12786	0.90
250	0.12595	0.70	0.12582	0.58	0.12633	1.00	0.12801	0.89
315	0.12596	0.70	0.12583	0.58	0.12621	1.00	0.12805	0.88
400	0.12605	0.70	0.12585	0.58	0.12620	1.00	0.12813	0.86
500	0.12605	0.70	0.12589	0.58	0.12619	1.00	0.12819	0.85
630	0.12603	0.70	0.12591	0.58	0.12623	1.00	0.12823	0.83
800	0.12613	0.70	0.12594	0.58	0.12624	1.00	0.12829	0.80
1000	0.12612	0.70	0.12599	0.58	0.12640	1.00	0.12831	0.78
1250	0.12621	0.70	0.12612	0.58	0.12643	1.00	0.12823	0.75
1600	0.12632	0.70	0.12633	0.62	0.12650	1.00	0.12800	0.73
2000	0.12655	0.70	0.12654	0.63	0.12669	1.00	0.12764	0.73
2500	0.12680	0.70	0.12692	0.63	0.12701	1.00	0.12704	0.75
3150	0.12728	0.70	0.12746	0.64	0.12727	1.00	0.12666	0.82
4000	0.12796	0.70	0.12839	0.63	0.12830	1.00	0.12528	0.99
5000	0.13005	1.20	0.12966	0.69	0.12956	1.00	0.12775	1.30
6300	0.13181	1.20	0.13175	0.68	0.13164	1.50		
8000	0.13593	1.20	0.13502	0.72	0.13491	1.50		
10000	0.14109	1.20	0.14125	0.81	0.14086	1.50		

Table 5. Sensitivity magnitude and expanded relative uncertainty for accelerometer 8305-001, part 2.

f Hz	KEBS		MIKES		METAS	
	S in $\frac{\mathrm{pC}}{(\mathrm{m\,s^{-2}})}$	U_S in %	S in $\frac{\mathrm{pC}}{(\mathrm{m\,s^{-2}})}$	U_S in %	S in $\frac{\mathrm{pC}}{(\mathrm{m\,s^{-2}})}$	U_S in %
10.0	0.12677	0.70	0.12600	0.90	0.12711	0.22
12.5	0.12666	0.70	0.12590	0.90	0.12668	0.22
16.0	0.12651	0.70	0.12590	0.90	0.12654	0.22
20.0	0.12640	0.70	0.12590	0.90	0.12638	0.19
25.0	0.12625	0.70	0.12590	0.90	0.12625	0.19
31.5	0.12631	0.70	0.12600	0.90	0.12617	0.19
40.0	0.12622	0.70	0.12590	0.90	0.12608	0.19

f Hz	KEBS		MIKES		METAS	
	S in $\frac{\mathrm{pC}}{(\mathrm{m\,s^{-2}})}$	U_S in %	S in $\frac{\mathrm{pC}}{(\mathrm{m\,s^{-2}})}$	U_S in %	S in $\frac{\mathrm{pC}}{(\mathrm{m\,s^{-2}})}$	U_S in %
63.0	0.12619	0.70	0.12590	0.90	0.12604	0.22
80.0	0.12619	0.70	0.12590	0.90	0.12603	0.22
100	0.12611	0.70	0.12570	0.90	0.12599	0.22
125	0.12599	0.70	0.12590	0.90	0.12599	0.22
160	0.12636	0.70	0.12550	0.90	0.12605	0.22
200	0.12579	0.70	0.12560	0.90	0.12604	0.22
250	0.12602	0.70	0.12540	0.90	0.12615	0.22
315	0.12592	0.70	0.12590	0.90	0.12612	0.22
400	0.12602	0.70	0.12580	0.90	0.12620	0.22
500	0.12603	0.70	0.12580	0.90	0.12607	0.22
630	0.12610	0.70	0.12590	0.90	0.12611	0.22
800	0.12610	0.70	0.12580	0.90	0.12617	0.22
1000	0.12614	0.70	0.12600	0.90	0.12619	0.23
1250	0.12621	1.00	0.12590	1.30	0.12629	0.23
1600	0.12643	1.00	0.12620	1.30	0.12642	0.23
2000	0.12660	1.00	0.12640	1.30	0.12659	0.23
2500	0.12688	1.00	0.12660	1.30	0.12693	0.23
3150	0.12742	1.00	0.12730	1.30	0.12736	0.23
4000	0.12863	1.00	0.12810	1.30	0.12814	0.23
5000	0.12908	1.00	0.12990	1.90	0.12930	0.70
6300	0.13005	1.30	0.13160	1.90	0.13120	0.70
8000	0.14461	2.20	0.13480	1.90	0.13460	0.70
10000	0.14611	2.20	0.13760	1.90	0.14000	0.70

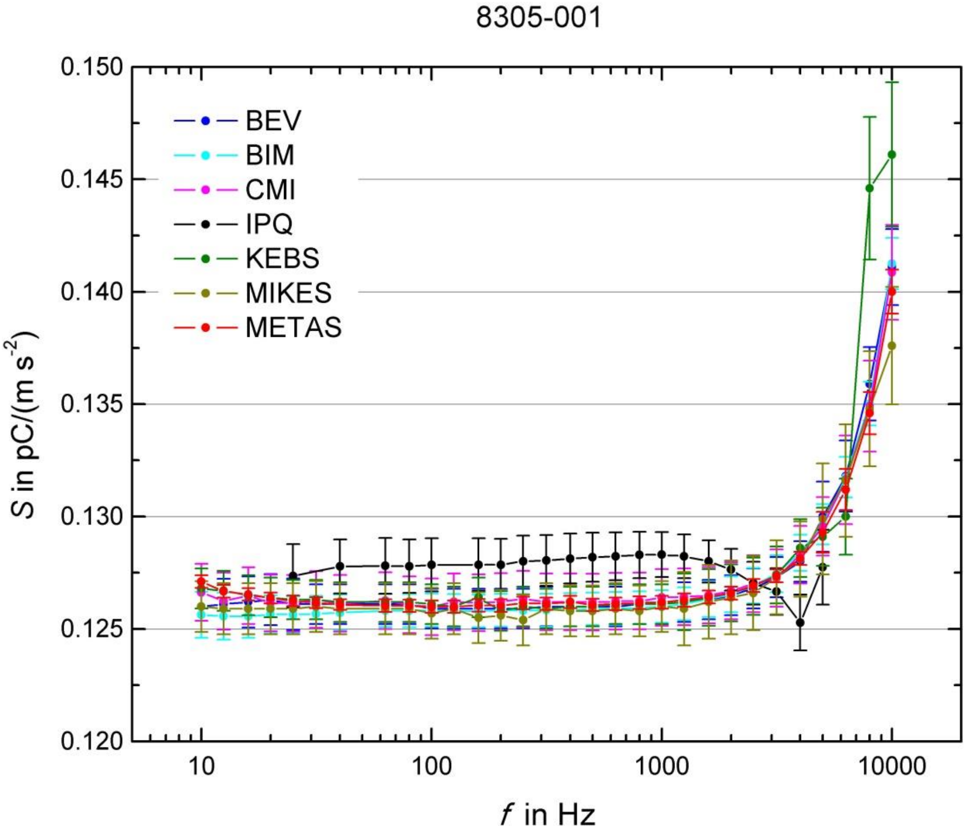


Figure 5. Sensitivity magnitude, accelerometer 8305-001

5.2 Sensitivity Magnitude 2270M8

Table 6. Sensitivity magnitude and expanded relative uncertainty for accelerometer 2270M8, part 1.

f Hz	BEV		BIM		CMI		IPQ	
	S in $\frac{\mathrm{pC}}{(\mathrm{m\,s^{-2}})}$	U_S in %	S in $\frac{\mathrm{pC}}{(\mathrm{m\,s^{-2}})}$	U_S in %	S in $\frac{\mathrm{pC}}{(\mathrm{m\,s^{-2}})}$	U_S in %	S in $\frac{\mathrm{pC}}{(\mathrm{m\,s^{-2}})}$	U_S in %
10.0	0.20904	0.90	0.20794	0.91	0.20845	1.00		
12.5	0.20916	0.90	0.20804	0.85	0.20849	1.00		
16.0	0.20930	0.90	0.20801	0.76	0.20871	1.00	0.21240	0.97
20.0	0.20927	0.90	0.20811	0.67	0.20879	1.00		
25.0	0.20924	0.90	0.20818	0.64	0.20886	1.00	0.21271	0.94
31.5	0.20916	0.70	0.20811	0.63	0.20895	1.00	0.21243	0.94
40.0	0.20909	0.70	0.20820	0.63	0.20884	1.00	0.21233	0.94
63.0	0.20891	0.70	0.20821	0.58	0.20874	1.00	0.21274	0.93
80.0	0.20859	0.70	0.20820	0.58	0.20860	1.00	0.21264	0.93
100	0.20877	0.70	0.20821	0.59	0.20848	1.00	0.21240	0.92
125	0.20852	0.70	0.20823	0.59	0.20868	1.00	0.21232	0.92
160	0.20884	0.70	0.20815	0.59	0.20877	1.00	0.21246	0.91
200	0.20869	0.70	0.20815	0.58	0.20847	1.00	0.21246	0.90
250	0.20859	0.70	0.20811	0.58	0.20857	1.00	0.21273	0.91
315	0.20848	0.70	0.20808	0.59	0.20849	1.00	0.21212	0.88
400	0.20855	0.70	0.20807	0.59	0.20846	1.00	0.21231	0.86
500	0.20846	0.70	0.20811	0.58	0.20837	1.00	0.21246	0.85
630	0.20838	0.70	0.20813	0.58	0.20844	1.00	0.21255	0.83
800	0.20845	0.70	0.20805	0.58	0.20830	1.00	0.21265	0.80
1000	0.20831	0.70	0.20806	0.58	0.20843	1.00	0.21256	0.78
1250	0.20836	0.70	0.20808	0.58	0.20843	1.00	0.21231	0.75
1600	0.20839	0.70	0.20817	0.63	0.20832	1.00	0.21177	0.73
2000	0.20851	0.70	0.20824	0.63	0.20837	1.00	0.21089	0.73
2500	0.20857	0.70	0.20831	0.63	0.20856	1.00	0.20960	0.75
3150	0.20890	0.70	0.20841	0.64	0.20864	1.00	0.20815	0.82
4000	0.20942	0.70	0.20879	0.63	0.20917	1.00	0.20672	0.99
5000	0.21041	1.20	0.20946	0.68	0.20986	1.00	0.20779	1.30
6300	0.21136	1.20	0.21023	0.68	0.21092	1.50		
8000	0.21360	1.20	0.21222	0.68	0.21260	1.50		
10000	0.21654	1.20	0.21484	0.77	0.21520	1.50		

Table 7. Sensitivity magnitude and expanded relative uncertainty for accelerometer 2270M8, part 2.

f Hz	KEBS		MIKES		METAS	
	S in $\frac{\mathrm{pC}}{(\mathrm{m\,s^{-2}})}$	U_S in %	S in $\frac{\mathrm{pC}}{(\mathrm{m\,s^{-2}})}$	U_S in %	S in $\frac{\mathrm{pC}}{(\mathrm{m\,s^{-2}})}$	U_S in %
10.0	0.20834	0.70	0.20840	0.80	0.20829	0.22
12.5	0.20862	0.70	0.20830	0.80	0.20843	0.22
16.0	0.20881	0.70	0.20830	0.80	0.20863	0.22
20.0	0.20883	0.70	0.20840	0.80	0.20866	0.19
25.0	0.20866	0.70	0.20830	0.80	0.20864	0.19
31.5	0.20871	0.70	0.20840	0.80	0.20860	0.19
40.0	0.20853	0.70	0.20840	0.80	0.20860	0.19

f Hz	KEBS		MIKES		METAS	
	S in $\frac{\mathrm{pC}}{(\mathrm{m\,s^{-2}})}$	U_S in %	S in $\frac{\mathrm{pC}}{(\mathrm{m\,s^{-2}})}$	U_S in %	S in $\frac{\mathrm{pC}}{(\mathrm{m\,s^{-2}})}$	U_S in %
63.0	0.20862	0.70	0.20810	0.80	0.20852	0.22
80.0	0.20849	0.70	0.20830	0.80	0.20852	0.22
100	0.20837	0.70	0.20780	0.80	0.20847	0.22
125	0.20806	0.70	0.20780	0.80	0.20836	0.22
160	0.20831	0.70	0.20780	0.80	0.20833	0.22
200	0.20825	0.70	0.20770	0.80	0.20830	0.22
250	0.20836	0.70	0.20790	0.80	0.20825	0.22
315	0.20799	0.70	0.20790	0.80	0.20820	0.22
400	0.20824	0.70	0.20790	0.80	0.20858	0.22
500	0.20804	0.70	0.20780	0.80	0.20834	0.22
630	0.20814	0.70	0.20780	0.80	0.20833	0.22
800	0.20805	0.70	0.20770	0.80	0.20829	0.22
1000	0.20803	0.70	0.20790	0.80	0.20827	0.23
1250	0.20805	1.00	0.20790	1.30	0.20834	0.23
1600	0.20820	1.00	0.20800	1.30	0.20841	0.23
2000	0.20825	1.00	0.20810	1.30	0.20848	0.23
2500	0.20830	1.00	0.20820	1.30	0.20877	0.23
3150	0.20825	1.00	0.20840	1.30	0.20904	0.23
4000	0.20976	1.00	0.20860	1.30	0.20955	0.23
5000	0.21004	1.00	0.20980	1.70	0.21060	0.70
6300	0.20979	1.30	0.21040	1.70	0.21170	0.70
8000	0.21942	2.20	0.21260	1.70	0.21400	0.70
10000	0.22256	2.20	0.21580	1.70	0.21660	0.70

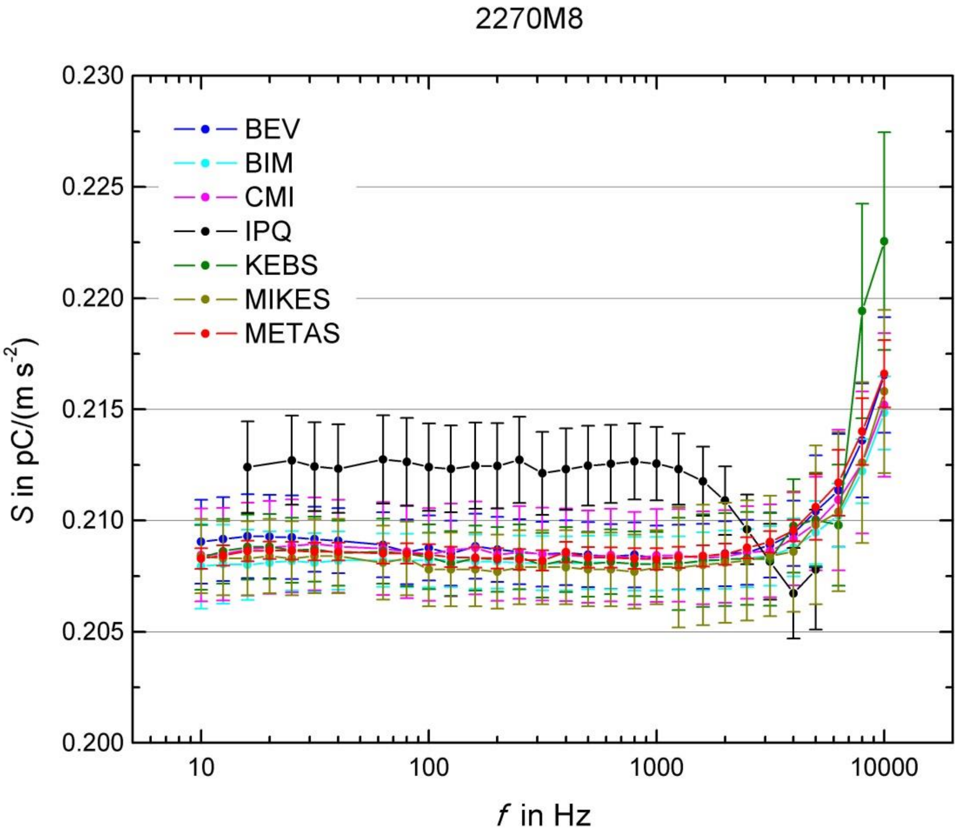


Figure 6. Sensitivity magnitude, accelerometer 2270M8

5.3 Sensitivity Phase 8305-001

Table 8. Sensitivity phase and expanded uncertainty for accelerometer 8305-001.

f Hz	CMI		MIKES		METAS	
	φ in °	U_φ in °	φ in °	U_φ in °	φ in °	U_φ in °
10.0	0.22	0.70	-0.08	0.90	-0.08	0.40
12.5	0.08	0.70	-0.07	0.90	-0.06	0.40
16.0	0.57	0.70	-0.03	0.90	0.01	0.40
20.0	0.35	0.70	-0.02	0.90	-0.03	0.38
25.0	0.12	0.70	-0.05	0.90	-0.01	0.38
31.5	0.07	0.70	-0.02	0.90	-0.01	0.38
40.0	0.08	0.70	-0.03	0.90	-0.02	0.38
63.0	0.25	0.70	-0.04	0.90	-0.03	0.39
80.0	0.04	0.70	-0.08	0.90	-0.04	0.39
100	0.01	0.70	-0.09	0.90	-0.04	0.39
125	0.02	0.70	-0.06	0.90	-0.02	0.39
160	0.06	0.70	-0.06	0.90	-0.08	0.39
200	0.31	0.70	-0.04	0.90	0.06	0.39
250	0.13	0.70	0.05	0.90	0.04	0.39
315	0.09	0.70	0.05	0.90	0.03	0.39
400	0.05	0.70	0.03	0.90	0.00	0.39
500	0.03	0.70	0.10	0.90	-0.01	0.39
630	0.04	0.70	-0.14	0.90	0.02	0.39
800	0.03	0.70	-0.04	0.90	0.01	0.39
1000	0.08	0.70	0.02	0.90	0.06	0.47
1250	0.04	1.50	-0.04	1.40	0.06	0.47
1600	0.03	1.50	0.00	1.40	0.07	0.47
2000	0.03	1.50	-0.04	1.40	0.08	0.47
2500	0.02	1.50	-0.07	1.40	0.10	0.47
3150	-0.01	1.50	-0.09	1.40	0.10	0.47
4000	0.02	1.50	-0.19	1.40	0.13	0.47
5000	0.00	1.50	-0.20	2.30	0.10	0.90
6300	0.01	2.00	-0.22	2.30	0.10	0.90
8000	-0.06	2.00	-0.62	2.30	0.10	0.90
10000	-0.08	2.00	-1.69	2.30	0.00	0.90

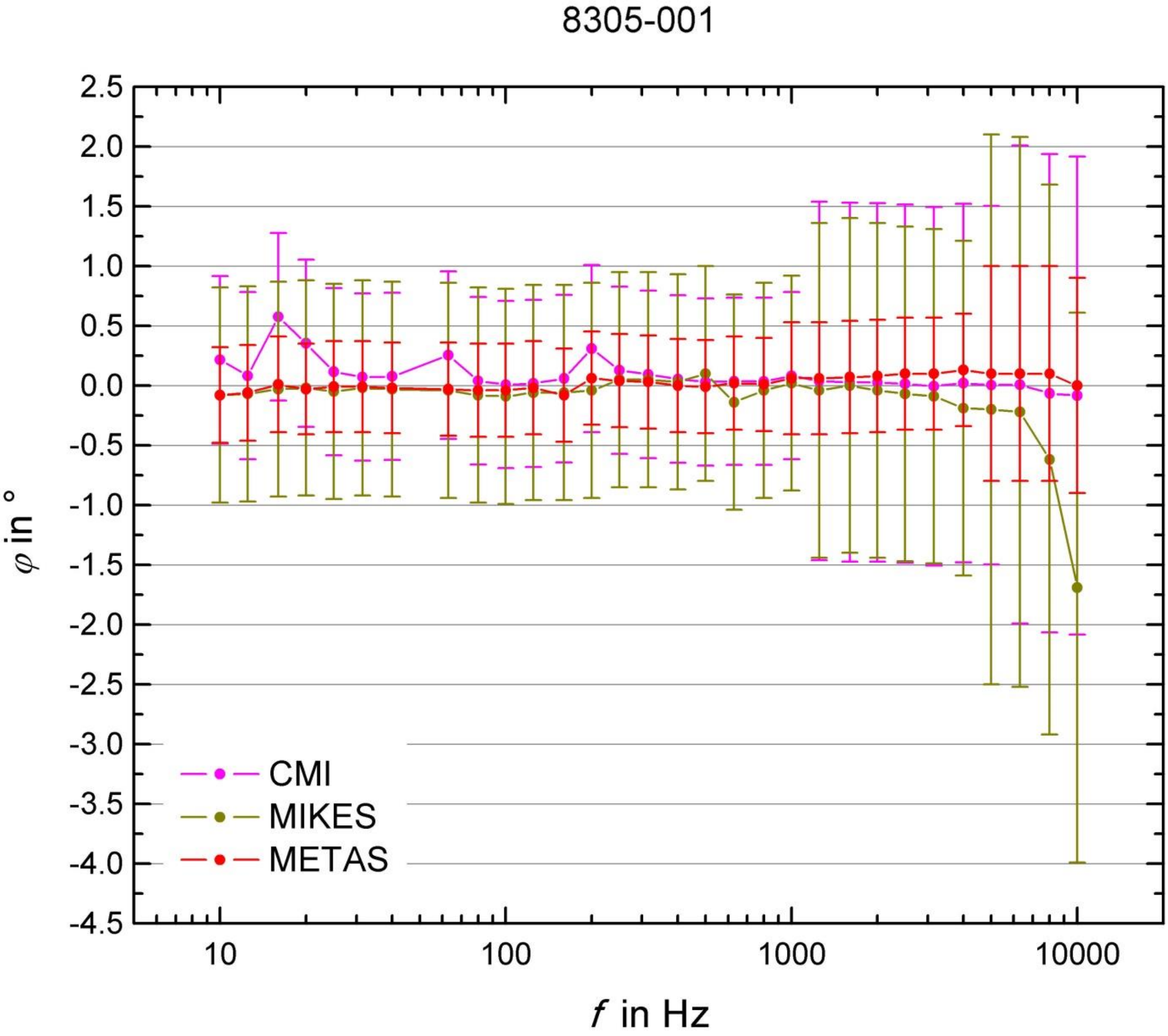


Figure 7. Sensitivity phase, accelerometer 8305-001

5.4 Sensitivity Phase 2270M8

Table 9. Sensitivity phase and expanded uncertainty for accelerometer 2270M8.

f Hz	CMI		MIKES		METAS	
	φ in °	U_{φ} in °	φ in °	U_{φ} in °	φ in °	U_{φ} in °
10.0	-0.02	0.70	-0.12	0.80	0.06	0.40
12.5	-0.01	0.70	-0.12	0.80	0.04	0.40
16.0	-0.02	0.70	-0.09	0.80	0.02	0.40
20.0	0.06	0.70	-0.07	0.80	0.01	0.38
25.0	0.01	0.70	-0.12	0.80	-0.01	0.38
31.5	-0.01	0.70	-0.09	0.80	-0.02	0.38
40.0	-0.02	0.70	-0.04	0.80	-0.04	0.38
63.0	-0.04	0.70	-0.14	0.80	-0.06	0.39
80.0	-0.04	0.70	-0.12	0.80	-0.08	0.39
100	-0.07	0.70	-0.09	0.80	-0.11	0.39
125	-0.03	0.70	-0.12	0.80	-0.13	0.39
160	-0.11	0.70	-0.09	0.80	-0.15	0.39
200	-0.12	0.70	-0.03	0.80	-0.04	0.39
250	-0.06	0.70	-0.04	0.80	-0.03	0.39
315	-0.09	0.70	-0.13	0.80	0.00	0.39
400	-0.04	0.70	-0.10	0.80	-0.02	0.39
500	-0.05	0.70	-0.10	0.80	-0.06	0.39
630	-0.07	0.70	-0.18	0.80	-0.06	0.39
800	-0.05	0.70	-0.16	0.80	-0.07	0.39
1000	-0.03	0.70	-0.20	0.80	-0.02	0.47
1250	0.02	1.50	-0.27	1.40	-0.04	0.47
1600	-0.05	1.50	-0.33	1.40	-0.02	0.47
2000	-0.05	1.50	-0.41	1.40	-0.03	0.47
2500	-0.02	1.50	-0.51	1.40	-0.01	0.47
3150	-0.06	1.50	-0.60	1.40	-0.03	0.47
4000	-0.03	1.50	-0.73	1.40	0.00	0.47
5000	-0.04	1.50	-0.93	2.10	0.10	0.90
6300	-0.08	2.00	-1.15	2.10	-0.10	0.90
8000	-0.09	2.00	-1.55	2.10	0.00	0.90
10000	-0.15	2.00	-2.61	2.10	0.00	0.90

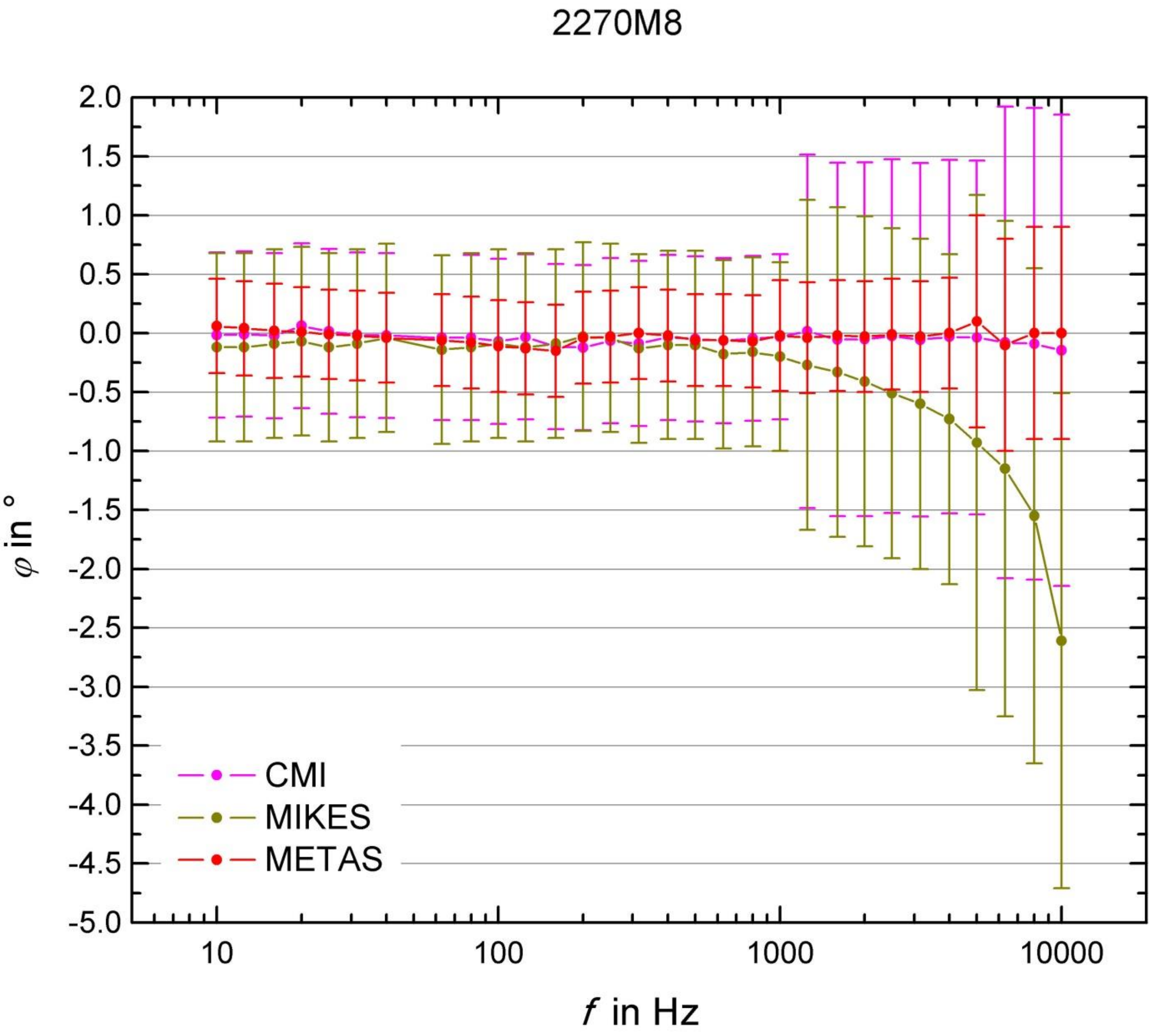


Figure 8. Sensitivity phase, accelerometer 2270M8

6 Analysis of the results

6.1 Degrees of equivalence

As decided in the protocol (Appendix C) and according to [4] the primary measurements at METAS are used as reference values of this comparison for the six remaining participants. Degrees of equivalence (DoE) D were calculated at each frequency f for sensitivity magnitude S and sensitivity phase φ, respectively:

$$D_{S,j}(f) = S_j(f) - S_{METAS}(f)$$
$$D_{\varphi,j}(f) = \varphi_j(f) - \varphi_{METAS}(f)$$

Where the index j stands for one of the participants, except METAS.

Since none of the other participants is traceable to METAS, no correlations have to be taken into account for uncertainty calculations of DoE. Principally, one must not do uncertainty calculations with expanded uncertainties, but under the present circumstances the simplest way to gain the expanded uncertainties of the DoE is:

$$U_{D_{S,j}}(f) = \frac{1}{100} \cdot \sqrt{S_j^2 U_{S_j}^2(f) + S_{METAS}^2 U_{S_{METAS}}^2(f)}$$

$$U_{D_{\varphi,j}}(f) = \sqrt{U_{\varphi_j}^2(f) + U_{\varphi_{METAS}}^2(f)}$$

Where $U_{S_j}(f)$ and $U_{S_{METAS}}(f)$ are relative uncertainties in %.

Due to the stability issues of transducer 4371-V, DoE are only calculated for transducers 8305-001 and 2270M8. The calculations were done without any intermediate rounding. In the following DoE tables results with $|D_j(f)| > U_{D_j}(f)$ are marked by a yellow background. Table 10 explains the quantities and symbols presented in the DoE tables.

Table 10. Quantities of DoE tables

Quantity	Symbol	Unit	Representation
DoE of Sensitivity magnitude	D_S	$\mathrm{fC/(m\ s^{-2})}$	x.xx
Expanded Uncertainty	U_{D_S}	$\mathrm{fC/(m\ s^{-2})}$	x.xx
DoE of Sensitivity Phase	D_φ	1°	x.xx
Expanded Uncertainty	U_{D_φ}	1°	x.xx

6.2 DoE of Sensitivity Magnitude 8305-001

Table 11. DoE of sensitivity magnitude and expanded uncertainty for accelerometer 8305-001, part 1.

f Hz	BEV		BIM		CMI	
	D_S in $\frac{\text{fC}}{(\text{m s}^{-2})}$	U_{D_S} in $\frac{\text{fC}}{(\text{m s}^{-2})}$	D_S in $\frac{\text{fC}}{(\text{m s}^{-2})}$	U_{D_S} in $\frac{\text{fC}}{(\text{m s}^{-2})}$	D_S in $\frac{\text{fC}}{(\text{m s}^{-2})}$	U_{D_S} in $\frac{\text{fC}}{(\text{m s}^{-2})}$
10.0	-1.10	1.17	-1.48	1.06	-0.48	1.30
12.5	-0.61	1.17	-1.11	1.08	-0.44	1.29
16.0	-0.29	1.17	-0.98	0.98	-0.06	1.30
20.0	-0.11	1.16	-0.73	0.89	-0.23	1.28
25.0	-0.12	1.16	-0.61	0.84	-0.11	1.28
31.5	-0.07	0.91	-0.50	0.84	0.14	1.29
40.0	0.02	0.91	-0.35	0.83	0.06	1.28
63.0	0.06	0.93	-0.22	0.78	0.22	1.29
80.0	0.06	0.93	-0.22	0.79	0.04	1.29
100	-0.09	0.92	-0.15	0.79	0.00	1.29
125	-0.14	0.92	-0.18	0.79	0.22	1.29
160	-0.12	0.92	-0.25	0.78	0.12	1.29
200	-0.09	0.92	-0.21	0.78	0.18	1.29
250	-0.20	0.92	-0.33	0.78	0.18	1.29
315	-0.16	0.92	-0.29	0.78	0.09	1.29
400	-0.15	0.92	-0.35	0.79	0.00	1.29
500	-0.02	0.92	-0.18	0.78	0.12	1.29
630	-0.08	0.92	-0.20	0.78	0.12	1.29
800	-0.04	0.93	-0.23	0.78	0.07	1.29
1000	-0.07	0.93	-0.20	0.78	0.21	1.30
1250	-0.08	0.93	-0.17	0.78	0.14	1.30
1600	-0.10	0.93	-0.09	0.84	0.08	1.30
2000	-0.04	0.93	-0.05	0.85	0.10	1.30
2500	-0.13	0.93	-0.01	0.85	0.08	1.30
3150	-0.08	0.94	0.10	0.87	-0.09	1.31
4000	-0.18	0.94	0.25	0.86	0.16	1.32
5000	0.75	1.80	0.36	1.27	0.26	1.58
6300	0.61	1.83	0.55	1.28	0.44	2.18
8000	1.33	1.88	0.42	1.35	0.31	2.23
10000	1.09	1.96	1.25	1.51	0.86	2.33

Table 12. DoE of sensitivity magnitude and expanded uncertainty for accelerometer 8305-001, part 2.

f Hz	IPQ		KEBS		MIKES	
	D_S in $\frac{\text{fC}}{(\text{m s}^{-2})}$	U_{D_S} in $\frac{\text{fC}}{(\text{m s}^{-2})}$	D_S in $\frac{\text{fC}}{(\text{m s}^{-2})}$	U_{D_S} in $\frac{\text{fC}}{(\text{m s}^{-2})}$	D_S in $\frac{\text{fC}}{(\text{m s}^{-2})}$	U_{D_S} in $\frac{\text{fC}}{(\text{m s}^{-2})}$
10.0			-0.34	0.93	-1.11	1.17
12.5			-0.02	0.93	-0.78	1.17
16.0			-0.03	0.93	-0.64	1.17
20.0			0.02	0.92	-0.48	1.16
25.0	1.11	1.43	0.00	0.92	-0.35	1.16
31.5			0.14	0.92	-0.17	1.16
40.0	1.70	1.22	0.14	0.92	-0.18	1.16

f Hz	IPQ		KEBS		MIKES	
	D_S in $\frac{\text{fC}}{(\text{m s}^{-2})}$	U_{D_S} in $\frac{\text{fC}}{(\text{m s}^{-2})}$	D_S in $\frac{\text{fC}}{(\text{m s}^{-2})}$	U_{D_S} in $\frac{\text{fC}}{(\text{m s}^{-2})}$	D_S in $\frac{\text{fC}}{(\text{m s}^{-2})}$	U_{D_S} in $\frac{\text{fC}}{(\text{m s}^{-2})}$
63.0	1.77	1.27	0.15	0.93	-0.14	1.17
80.0	1.76	1.22	0.16	0.93	-0.13	1.17
100	1.86	1.21	0.12	0.93	-0.29	1.16
125			0.00	0.92	-0.09	1.17
160	1.81	1.20	0.31	0.93	-0.55	1.16
200	1.82	1.19	-0.26	0.92	-0.44	1.16
250	1.86	1.18	-0.13	0.92	-0.75	1.16
315	1.93	1.16	-0.20	0.92	-0.22	1.17
400	1.93	1.14	-0.18	0.92	-0.40	1.17
500	2.12	1.12	-0.04	0.92	-0.27	1.17
630	2.12	1.09	-0.01	0.93	-0.21	1.17
800	2.12	1.07	-0.07	0.93	-0.37	1.17
1000	2.12	1.04	-0.05	0.93	-0.19	1.17
1250	1.94	1.01	-0.08	1.30	-0.39	1.66
1600	1.58	0.98	0.01	1.30	-0.22	1.67
2000	1.05	0.97	0.01	1.30	-0.19	1.67
2500	0.11	0.99	-0.05	1.30	-0.33	1.67
3150	-0.70	1.08	0.05	1.31	-0.06	1.68
4000	-2.86	1.27	0.49	1.32	-0.04	1.69
5000	-1.55	1.89	-0.23	1.58	0.60	2.63
6300			-1.15	1.92	0.40	2.66
8000			10.01	3.32	0.20	2.73
10000			6.11	3.36	-2.40	2.79

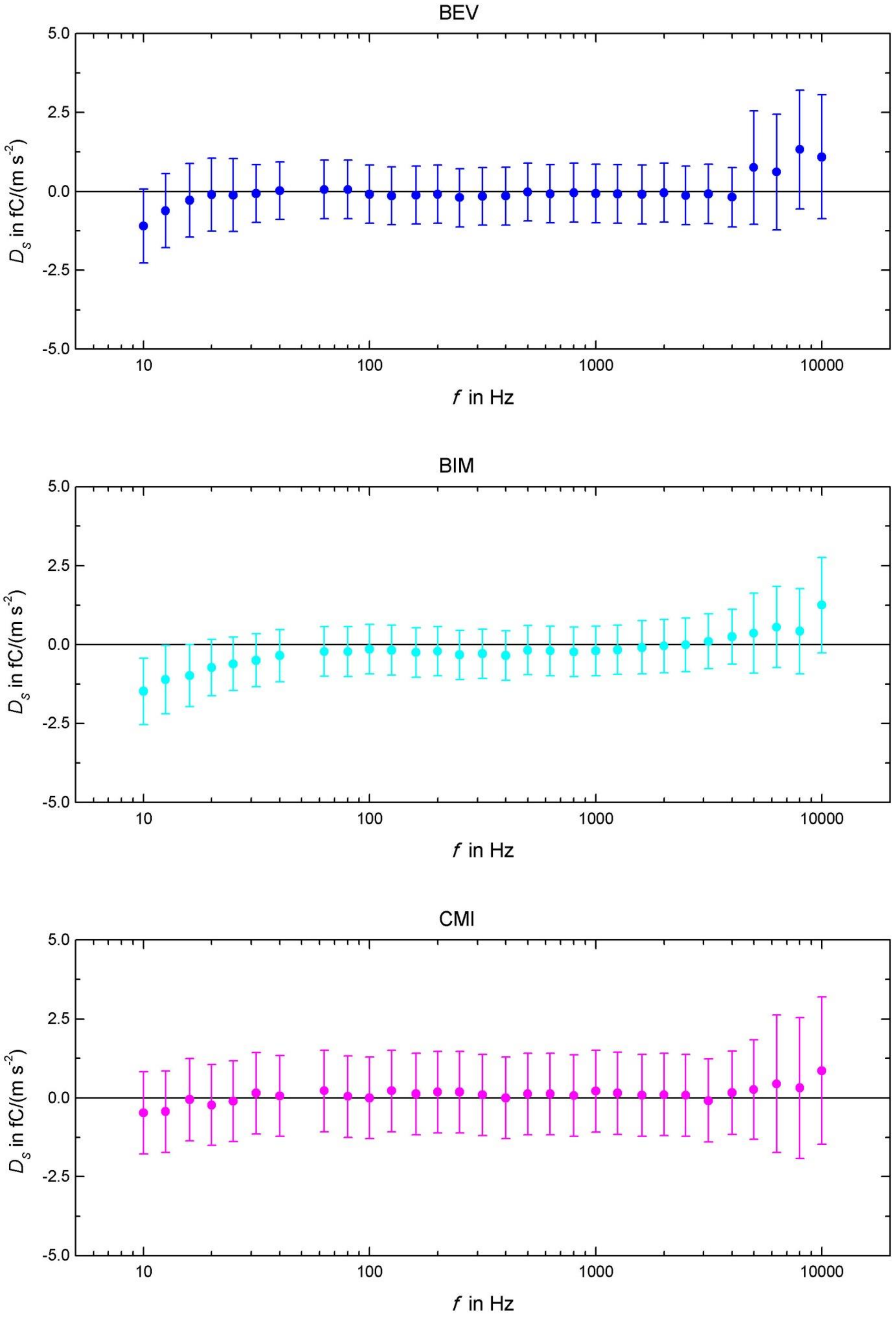


Figure 9. DoE of sensitivity magnitude, accelerometer 8305-001, part 1

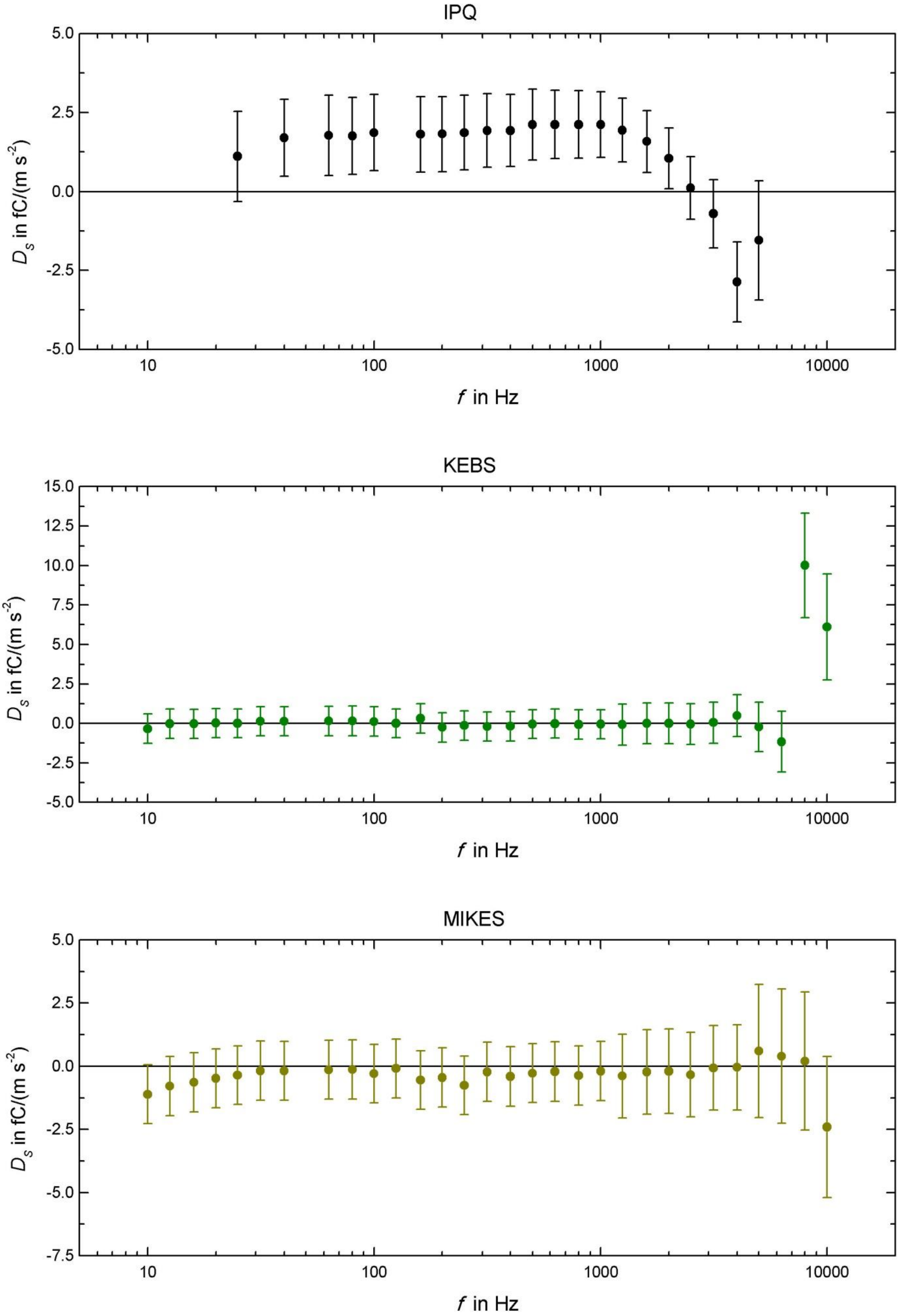


Figure 10. DoE of sensitivity magnitude, accelerometer 8305-001, part 2

6.3 DoE of Sensitivity Magnitude 2270M8

Table 13. DoE of sensitivity magnitude and expanded uncertainty for accelerometer 2270M8, part 1.

f Hz	BEV		BIM		CMI	
	D_S in $\frac{\text{fC}}{(\text{m s}^{-2})}$	U_{D_S} in $\frac{\text{fC}}{(\text{m s}^{-2})}$	D_S in $\frac{\text{fC}}{(\text{m s}^{-2})}$	U_{D_S} in $\frac{\text{fC}}{(\text{m s}^{-2})}$	D_S in $\frac{\text{fC}}{(\text{m s}^{-2})}$	U_{D_S} in $\frac{\text{fC}}{(\text{m s}^{-2})}$
10.0	0.75	1.94	-0.35	1.95	0.16	2.13
12.5	0.73	1.94	-0.39	1.84	0.06	2.13
16.0	0.67	1.94	-0.62	1.64	0.08	2.14
20.0	0.61	1.92	-0.55	1.46	0.13	2.13
25.0	0.60	1.92	-0.46	1.40	0.22	2.13
31.5	0.56	1.52	-0.49	1.38	0.35	2.13
40.0	0.49	1.52	-0.40	1.37	0.24	2.13
63.0	0.39	1.53	-0.31	1.28	0.22	2.14
80.0	0.07	1.53	-0.32	1.29	0.08	2.14
100	0.30	1.53	-0.26	1.31	0.01	2.13
125	0.16	1.53	-0.13	1.31	0.32	2.14
160	0.51	1.53	-0.18	1.31	0.44	2.14
200	0.39	1.53	-0.15	1.30	0.17	2.13
250	0.34	1.53	-0.14	1.30	0.32	2.14
315	0.28	1.53	-0.12	1.30	0.29	2.13
400	-0.03	1.53	-0.51	1.30	-0.12	2.13
500	0.12	1.53	-0.23	1.29	0.03	2.13
630	0.05	1.53	-0.20	1.29	0.11	2.13
800	0.16	1.53	-0.24	1.29	0.01	2.13
1000	0.04	1.53	-0.21	1.30	0.16	2.14
1250	0.02	1.54	-0.26	1.30	0.09	2.14
1600	-0.02	1.54	-0.24	1.39	-0.09	2.14
2000	0.03	1.54	-0.24	1.39	-0.11	2.14
2500	-0.20	1.54	-0.46	1.39	-0.21	2.14
3150	-0.14	1.54	-0.63	1.42	-0.40	2.14
4000	-0.13	1.54	-0.76	1.39	-0.38	2.15
5000	-0.19	2.92	-1.14	2.05	-0.74	2.56
6300	-0.34	2.94	-1.47	2.06	-0.78	3.49
8000	-0.40	2.97	-1.78	2.08	-1.40	3.52
10000	-0.06	3.01	-1.76	2.24	-1.40	3.57

Table 14. DoE of sensitivity magnitude and expanded uncertainty for accelerometer 2270M8, part 2.

f Hz	IPQ		KEBS		MIKES	
	D_S in $\frac{\text{fC}}{(\text{m s}^{-2})}$	U_{D_S} in $\frac{\text{fC}}{(\text{m s}^{-2})}$	D_S in $\frac{\text{fC}}{(\text{m s}^{-2})}$	U_{D_S} in $\frac{\text{fC}}{(\text{m s}^{-2})}$	D_S in $\frac{\text{fC}}{(\text{m s}^{-2})}$	U_{D_S} in $\frac{\text{fC}}{(\text{m s}^{-2})}$
10.0			0.05	1.53	0.11	1.73
12.5			0.19	1.53	-0.13	1.73
16.0	3.77	2.10	0.17	1.53	-0.33	1.73
20.0			0.17	1.51	-0.26	1.71
25.0	4.07	2.04	0.02	1.51	-0.34	1.71
31.5	3.83	2.03	0.11	1.51	-0.20	1.71
40.0	3.73	2.03	-0.07	1.51	-0.20	1.71

f Hz	IPQ		KEBS		MIKES	
	D_S in $\frac{\mathrm{fC}}{(\mathrm{m\,s^{-2}})}$	U_{D_S} in $\frac{\mathrm{fC}}{(\mathrm{m\,s^{-2}})}$	D_S in $\frac{\mathrm{fC}}{(\mathrm{m\,s^{-2}})}$	U_{D_S} in $\frac{\mathrm{fC}}{(\mathrm{m\,s^{-2}})}$	D_S in $\frac{\mathrm{fC}}{(\mathrm{m\,s^{-2}})}$	U_{D_S} in $\frac{\mathrm{fC}}{(\mathrm{m\,s^{-2}})}$
63.0	4.22	2.04	0.10	1.53	-0.42	1.73
80.0	4.12	2.03	-0.03	1.53	-0.22	1.73
100	3.93	2.02	-0.10	1.53	-0.67	1.72
125	3.96	2.00	-0.30	1.53	-0.56	1.72
160	4.13	1.99	-0.02	1.53	-0.53	1.72
200	4.16	1.97	-0.05	1.53	-0.60	1.72
250	4.48	1.99	0.11	1.53	-0.35	1.73
315	3.92	1.92	-0.21	1.53	-0.30	1.73
400	3.73	1.89	-0.34	1.53	-0.68	1.73
500	4.12	1.86	-0.31	1.53	-0.54	1.72
630	4.22	1.81	-0.19	1.53	-0.53	1.72
800	4.36	1.77	-0.24	1.53	-0.59	1.72
1000	4.29	1.72	-0.24	1.53	-0.37	1.73
1250	3.97	1.67	-0.29	2.13	-0.44	2.74
1600	3.36	1.62	-0.21	2.14	-0.41	2.75
2000	2.41	1.61	-0.23	2.14	-0.38	2.75
2500	0.83	1.64	-0.48	2.14	-0.57	2.75
3150	-0.89	1.77	-0.79	2.14	-0.64	2.75
4000	-2.83	2.10	0.21	2.15	-0.95	2.75
5000	-2.81	3.07	-0.56	2.57	-0.80	3.86
6300			-1.91	3.10	-1.30	3.87
8000			5.42	5.05	-1.40	3.91
10000			5.96	5.13	-0.80	3.97

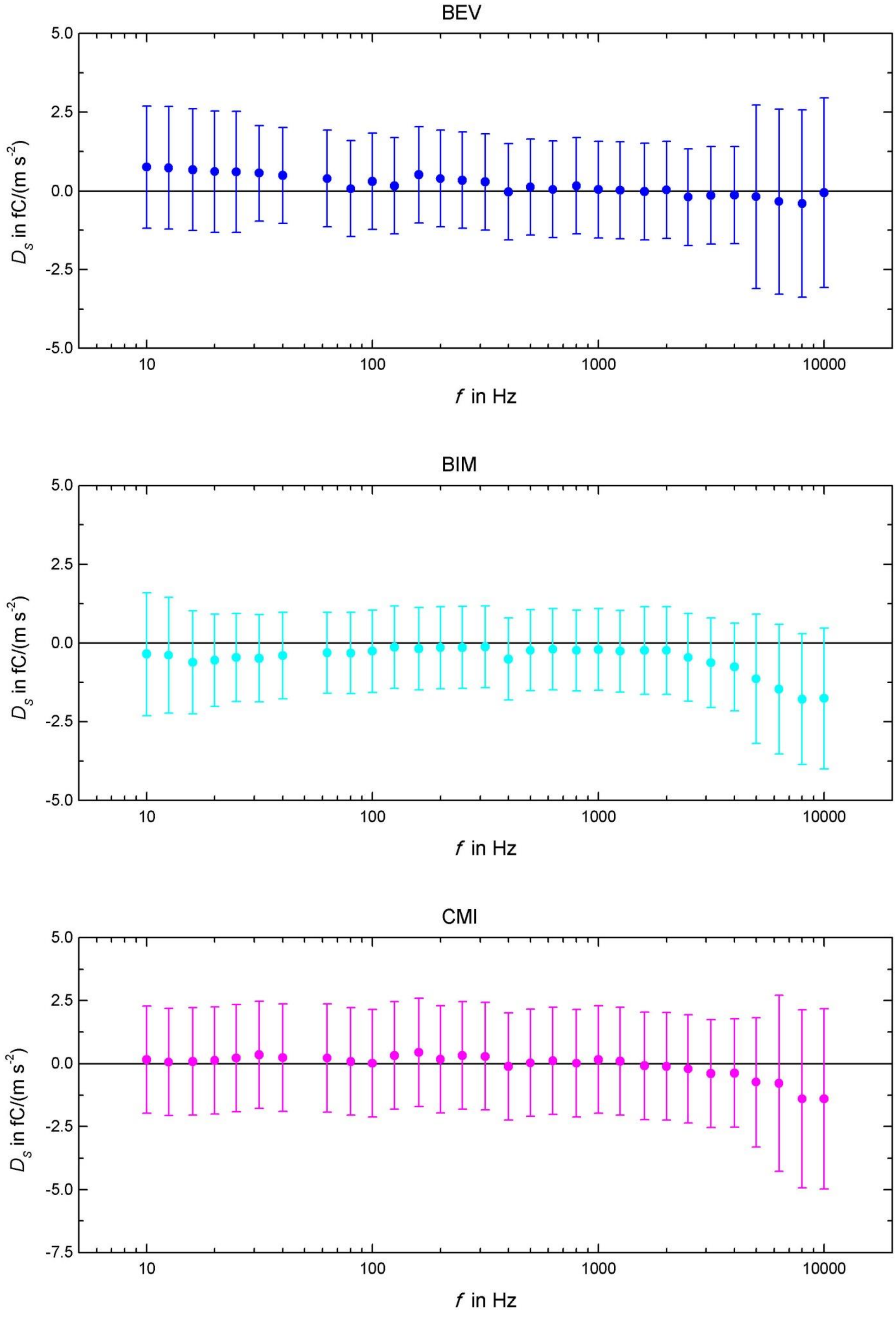


Figure 11. DoE of sensitivity magnitude, accelerometer 2270M8, part 1

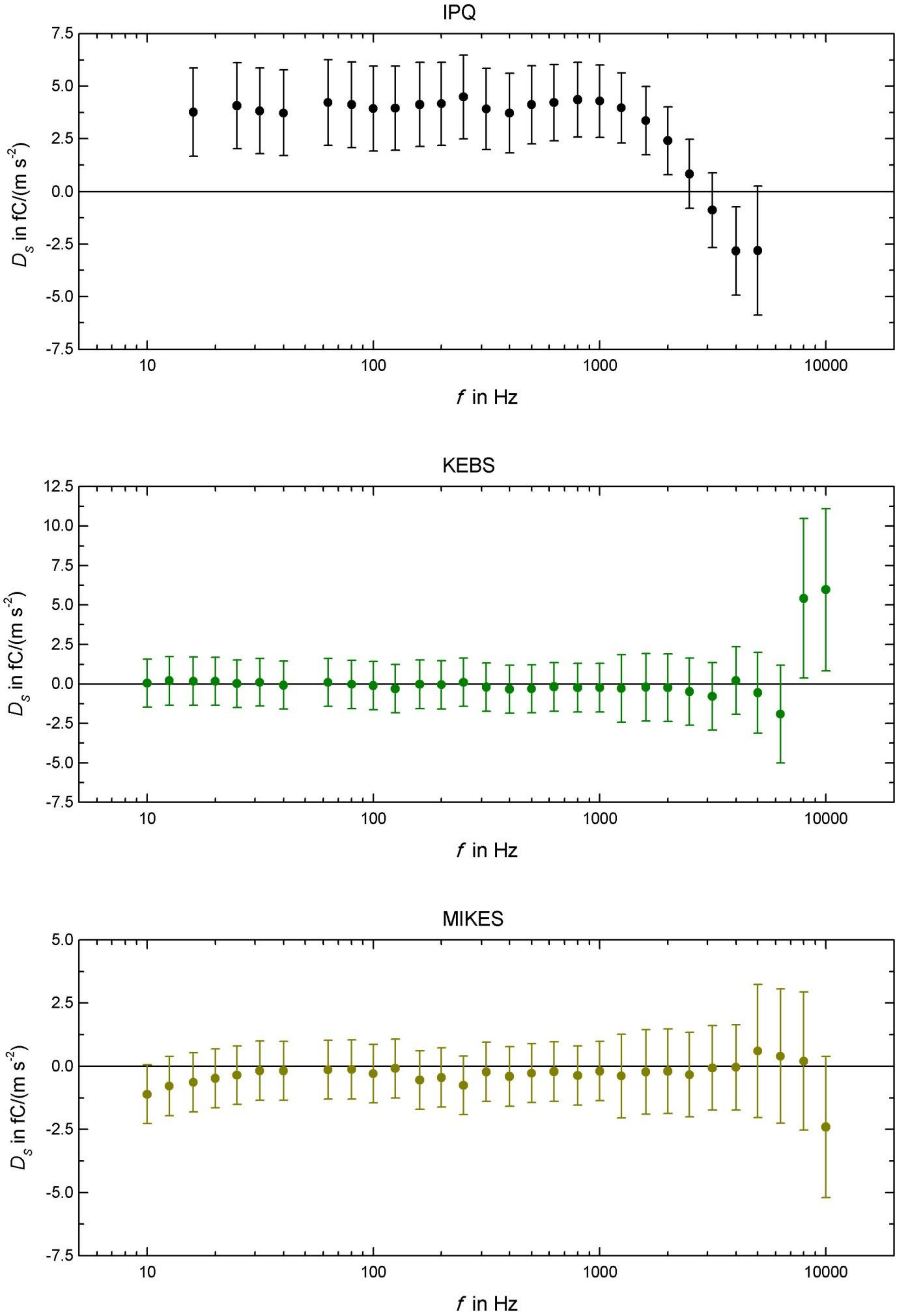


Figure 12. DoE of sensitivity magnitude, accelerometer 2270M8, part 2

6.4 DoE of Sensitivity Phase 8305-001

Table 15. DoE of sensitivity phase and expanded uncertainty for accelerometer 8305-001.

f Hz	CMI		MIKES		f Hz	CMI		MIKES	
	D_φ in °	U_{D_φ} in °	D_φ in °	U_{D_φ} in °		D_φ in °	U_{D_φ} in °	D_φ in °	U_{D_φ} in °
10.0	0.30	0.81	0.00	0.98	400	0.05	0.80	0.03	0.98
12.5	0.14	0.81	-0.01	0.98	500	0.04	0.80	0.11	0.98
16.0	0.56	0.81	-0.04	0.98	630	0.02	0.80	-0.16	0.98
20.0	0.38	0.80	0.01	0.98	800	0.02	0.80	-0.05	0.98
25.0	0.13	0.80	-0.04	0.98	1000	0.02	0.84	-0.04	1.02
31.5	0.08	0.80	-0.01	0.98	1250	-0.02	1.57	-0.10	1.48
40.0	0.10	0.80	-0.01	0.98	1600	-0.04	1.57	-0.07	1.48
63.0	0.28	0.80	-0.01	0.98	2000	-0.05	1.57	-0.12	1.48
80.0	0.08	0.80	-0.04	0.98	2500	-0.08	1.57	-0.17	1.48
100	0.05	0.80	-0.05	0.98	3150	-0.11	1.57	-0.19	1.48
125	0.04	0.80	-0.04	0.98	4000	-0.11	1.57	-0.32	1.48
160	0.14	0.80	0.02	0.98	5000	-0.10	1.75	-0.30	2.47
200	0.25	0.80	-0.10	0.98	6300	-0.09	2.19	-0.32	2.47
250	0.09	0.80	0.01	0.98	8000	-0.16	2.19	-0.72	2.47
315	0.06	0.80	0.02	0.98	10000	-0.08	2.19	-1.69	2.47

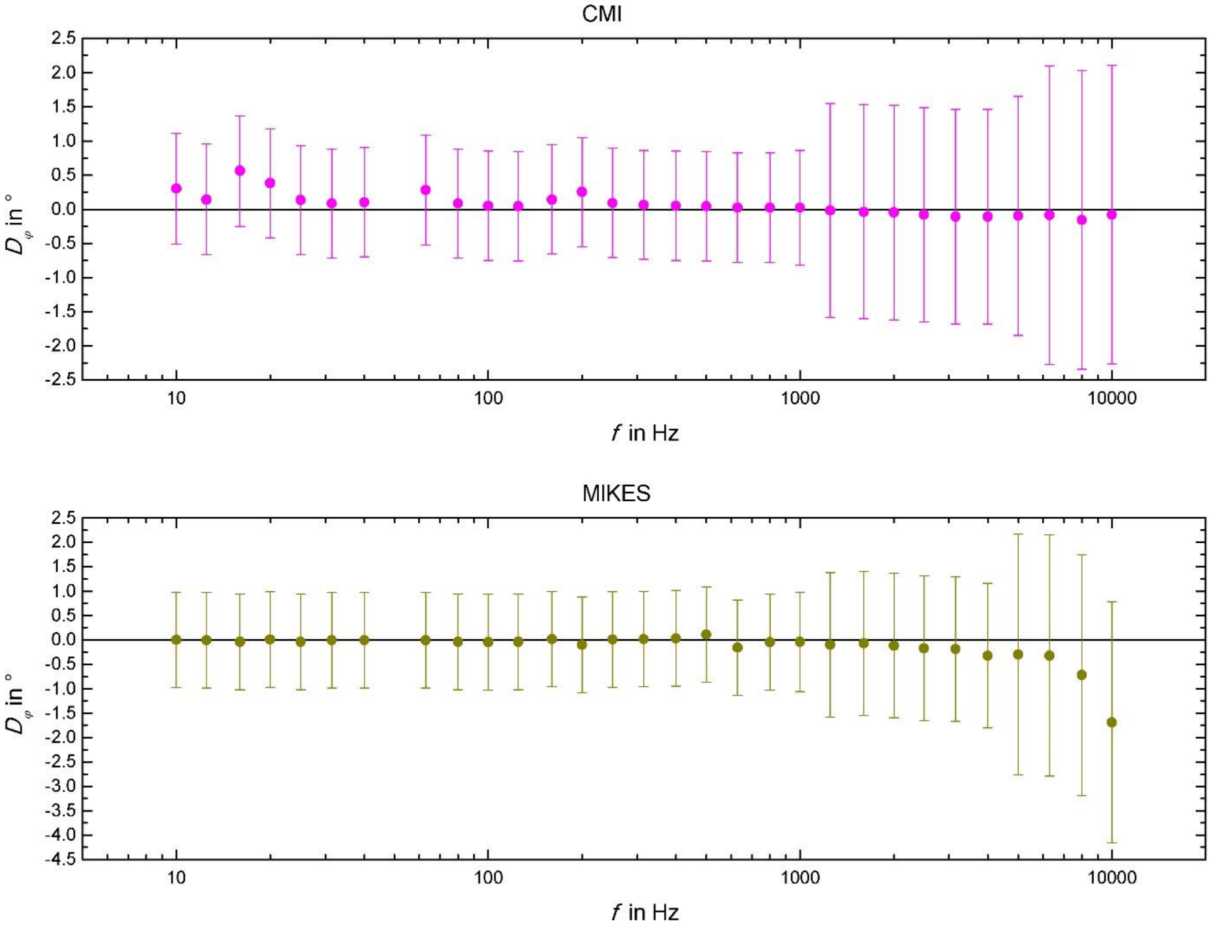


Figure 13. DoE of sensitivity phase, accelerometer 8305-001

6.5 DoE of Sensitivity Phase 2270M8

Table 16. DoE of sensitivity phase and expanded uncertainty for accelerometer 2270M8.

f Hz	CMI		MIKES		*f* Hz	CMI		MIKES	
	D_φ in °	U_{D_φ} in °	D_φ in °	U_{D_φ} in °		D_φ in °	U_{D_φ} in °	D_φ in °	U_{D_φ} in °
10.0	-0.08	0.81	-0.18	0.89	400	-0.02	0.80	-0.08	0.89
12.5	-0.05	0.81	-0.16	0.89	500	0.01	0.80	-0.04	0.89
16.0	-0.04	0.81	-0.11	0.89	630	-0.01	0.80	-0.12	0.89
20.0	0.05	0.80	-0.08	0.89	800	0.02	0.80	-0.09	0.89
25.0	0.02	0.80	-0.11	0.89	1000	-0.01	0.84	-0.18	0.93
31.5	0.01	0.80	-0.07	0.89	1250	0.06	1.57	-0.23	1.48
40.0	0.02	0.80	0.00	0.89	1600	-0.03	1.57	-0.31	1.48
63.0	0.02	0.80	-0.08	0.89	2000	-0.02	1.57	-0.38	1.48
80.0	0.04	0.80	-0.04	0.89	2500	-0.01	1.57	-0.50	1.48
100	0.04	0.80	0.02	0.89	3150	-0.03	1.57	-0.57	1.48
125	0.10	0.80	0.01	0.89	4000	-0.03	1.57	-0.73	1.48
160	0.04	0.80	0.06	0.89	5000	-0.14	1.75	-1.03	2.28
200	-0.08	0.80	0.01	0.89	6300	0.02	2.19	-1.05	2.28
250	-0.03	0.80	-0.01	0.89	8000	-0.09	2.19	-1.55	2.28
315	-0.09	0.80	-0.13	0.89	10000	-0.15	2.19	-2.61	2.28

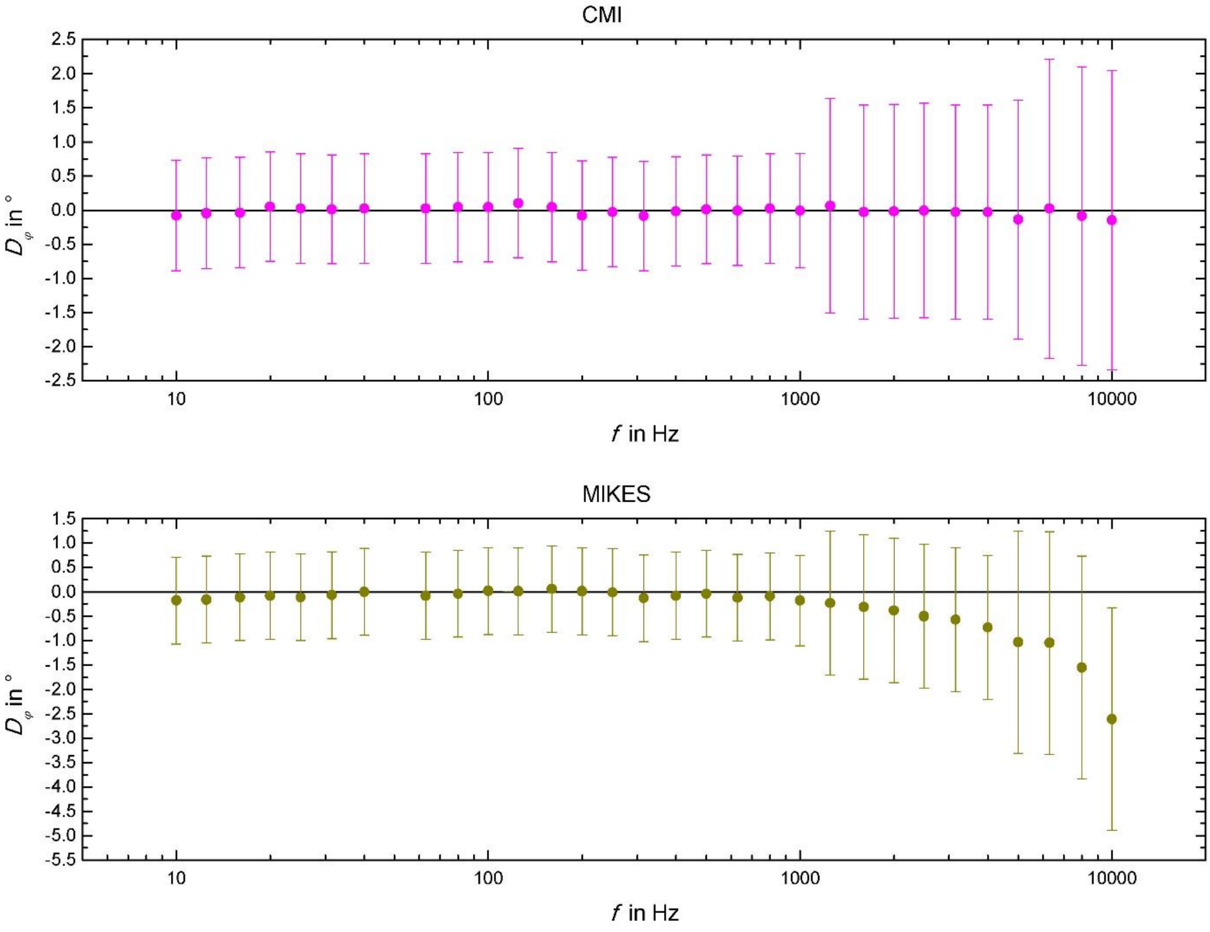


Figure 14. DoE of sensitivity phase, accelerometer 2270M8

7 Conclusions

The aim of the supplementary comparison EURAMET.AUV.V-S1 is to establish reliable equivalence between national metrology institutes for the calibration of accelerometers with secondary means according to ISO 16063-21 [1]. Three single ended accelerometers were circulated among the participants. Due to its poor stability, one accelerometer had to be excluded from the analysis of the results. The results of primary calibrations according to ISO 16063-11 [2] at METAS were used as reference values for the analysis of the results of the secondary calibrations.

There are two typical issues of the method of secondary calibration of accelerometers:

At high frequencies, relative movements can occur and disturb the calibration results. This effect is called payload effect or mass loading effect. The relative movement results in an apparent change of the sensitivity of the reference transducer. This effect increases with increasing mass load and frequency. It especially affects external back-to-back reference transducers. Typically, for frequencies above 5 kHz, it can result in significant deviations of the calibration results.

At low frequencies (< 20 Hz), increased harmonic distortions and signal noise can occur and disturb the calibration results. The signal-to-noise ratios of the transducer to be calibrated and the reference transducer have to be observed and considered. In addition, large displacements may induce cable-noise via the triboelectric effect of the bending cable.

One aspect of the comparison task was the complementation of the measurement chain with a local charge amplifier calibrated by the participant. Due to this requirement the consistency of the SC results of most participants demonstrates the associated capability of calibration of magnitude and/or phase of the complex transfer function of charge amplifiers. In addition, this capability could be expected to be valid for other kinds of measuring amplifiers as well, including voltage amplifiers.

Overall, the supplementary comparison EURAMET.AUV.V-S1 can be considered successful for most of the participants. The calibration of accelerometers with secondary means according to ISO 16063-21 [1] is still offered by several metrology institutes. Its technical challenges may be less demanding compared to primary calibration, but the results of EURAMET.AUV.V-S1 show, that the method of secondary calibration is worthwhile to be addressed by a metrology-level comparison. After all, secondary calibration is the most common calibration method in accredited laboratories worldwide.

The authors wish to thank Gustavo Ripper (INMETRO Brazil) and Stephen Robinson (NPL, United Kingdom) for their valuable help.

8 References

[1] ISO 16063-21:2003 Methods for the calibration of vibration and shock transducers - Part 21: Vibration calibration by comparison to a reference transducer

[2] ISO 16063-11:1999 Methods for the calibration of vibration and shock transducers - Part 11: Primary vibration calibration by laser interferometry

[3] Th Bruns, G P Ripper and A Täubner: Final Report on the CIPM Key Comparison CCAUV.V-K2, Metrologia 2014 51 Tech. Suppl. 09002

[4] ISO/IEC 17043:2010 Conformity assessment - General requirements for proficiency testing

Appendix A - Results of accelerometer 4371-V

Table 16. Sensitivity magnitude and expanded relative uncertainty for accelerometer 4371-V, part 1.

f Hz	BEV		BIM		CMI		IPQ	
	S in $\frac{\mathrm{pC}}{(\mathrm{m\,s^{-2}})}$	U_S in %	S in $\frac{\mathrm{pC}}{(\mathrm{m\,s^{-2}})}$	U_S in %	S in $\frac{\mathrm{pC}}{(\mathrm{m\,s^{-2}})}$	U_S in %	S in $\frac{\mathrm{pC}}{(\mathrm{m\,s^{-2}})}$	U_S in %
10.0	1.03121	0.90	1.02135	0.82	1.03574	1.00		
12.5	1.02899	0.90	1.02039	0.77	1.03204	1.00		
16.0	1.02669	0.90	1.01888	0.70	1.02936	1.00	1.04351	0.98
20.0	1.02438	0.90	1.01841	0.64	1.02733	1.00	1.04371	0.94
25.0	1.02320	0.90	1.01750	0.64	1.02556	1.00	1.04039	0.94
31.5	1.02101	0.70	1.01656	0.63	1.02423	1.00	1.03805	0.94
40.0	1.01917	0.70	1.01557	0.62	1.02141	1.00	1.03557	0.94
63.0	1.01577	0.70	1.01316	0.58	1.01973	1.00	1.03140	0.93
80.0	1.01331	0.70	1.01146	0.58	1.01687	1.00	1.03082	0.93
100	1.01149	0.70	1.00986	0.58	1.01499	1.00	1.02899	0.92
125	1.01139	0.70	1.00899	0.59	1.01464	1.00	1.02809	0.92
160	1.00881	0.70	1.00654	0.58	1.01224	1.00	1.02598	0.91
200	1.00738	0.70	1.00517	0.58	1.01187	1.00	1.02464	0.90
250	1.00567	0.70	1.00388	0.59	1.01059	1.00	1.02307	0.89
315	1.00411	0.70	1.00255	0.59	1.00826	1.00	1.02115	0.88
400	1.00318	0.70	1.00157	0.59	1.00646	1.00	1.02063	0.86
500	1.00121	0.70	1.00015	0.58	1.00469	1.00	1.01933	0.85
630	0.99947	0.70	0.99825	0.59	1.00332	1.00	1.01844	0.83
800	0.99846	0.70	0.99695	0.59	1.00150	1.00	1.01685	0.80
1000	0.99667	0.70	0.99520	0.58	1.00078	1.00	1.01508	0.78
1250	0.99691	0.70	0.99387	0.59	0.99911	1.00	1.01243	0.75
1600	0.99597	0.70	0.99275	0.63	0.99719	1.00	1.00824	0.73
2000	0.99595	0.70	0.99130	0.63	0.99618	1.00	1.00270	0.73
2500	0.99543	0.70	0.99013	0.64	0.99569	1.00	0.99547	0.75
3150	0.99596	0.70	0.99071	0.65	0.99548	1.00	0.98697	0.82
4000	0.99770	0.70	0.99287	0.63	0.99676	1.00	0.97884	0.99
5000	1.00327	1.20	0.99617	0.68	1.00020	1.00	0.98393	1.30
6300	1.02063	1.20	1.00301	0.68	1.00596	1.50		
8000	1.02499	1.20	1.01515	0.68	1.01328	1.50		
10000	1.04403	1.20	1.03718	0.78	1.03584	1.50		

Table 17. Sensitivity magnitude and expanded relative uncertainty for accelerometer 4371-V, part 2.

f Hz	KEBS		MIKES		METAS	
	S in $\frac{\mathrm{pC}}{(\mathrm{m\,s^{-2}})}$	U_S in %	S in $\frac{\mathrm{pC}}{(\mathrm{m\,s^{-2}})}$	U_S in %	S in $\frac{\mathrm{pC}}{(\mathrm{m\,s^{-2}})}$	U_S in %
10.0	1.03207	0.70	1.02500	0.80	1.03760	0.22
12.5	1.03055	0.70	1.02200	0.80	1.03520	0.22
16.0	1.02971	0.70	1.02000	0.80	1.03420	0.22
20.0	1.02760	0.70	1.01800	0.80	1.03000	0.19
25.0	1.02482	0.70	1.01600	0.80	1.03220	0.19
31.5	1.02452	0.70	1.01500	0.80	1.02650	0.19
40.0	1.02206	0.70	1.01300	0.80	1.02440	0.19

f Hz	KEBS		MIKES		METAS	
	S in $\frac{\mathrm{pC}}{(\mathrm{m\,s^{-2}})}$	U_S in %	S in $\frac{\mathrm{pC}}{(\mathrm{m\,s^{-2}})}$	U_S in %	S in $\frac{\mathrm{pC}}{(\mathrm{m\,s^{-2}})}$	U_S in %
63.0	1.01970	0.70	1.01000	0.80	1.02100	0.22
80.0	1.01784	0.70	1.00900	0.80	1.01920	0.22
100	1.01578	0.70	1.00700	0.80	1.01730	0.22
125	1.01317	0.70	1.00700	0.80	1.01550	0.22
160	1.01340	0.70	1.00400	0.80	1.01360	0.22
200	1.01307	0.70	1.00300	0.80	1.01190	0.22
250	1.00832	0.70	0.99900	0.80	1.01090	0.22
315	1.00595	0.70	1.00000	0.80	1.00920	0.22
400	1.00536	0.70	0.99900	0.80	1.00830	0.22
500	1.00354	0.70	0.99700	0.80	1.00570	0.22
630	1.00256	0.70	0.99500	0.80	1.00380	0.22
800	1.00048	0.70	0.99400	0.80	1.00240	0.22
1000	0.99912	0.70	0.99300	0.80	1.00050	0.23
1250	0.99775	1.00	0.99100	1.30	0.99930	0.23
1600	0.99712	1.00	0.99000	1.30	0.99790	0.23
2000	0.99598	1.00	0.99000	1.30	0.99690	0.23
2500	0.99517	1.00	0.98900	1.30	0.99690	0.23
3150	0.99592	1.00	0.98900	1.30	0.99700	0.23
4000	1.00444	1.00	0.98900	1.30	0.99840	0.23
5000	1.00040	1.00	0.99400	1.70	1.00300	0.70
6300	1.00398	1.30	1.00000	1.70	1.00900	0.70
8000	1.04477	2.20	1.01300	1.70	1.02100	0.70
10000	1.07719	2.20	1.03600	1.70	1.04400	0.70

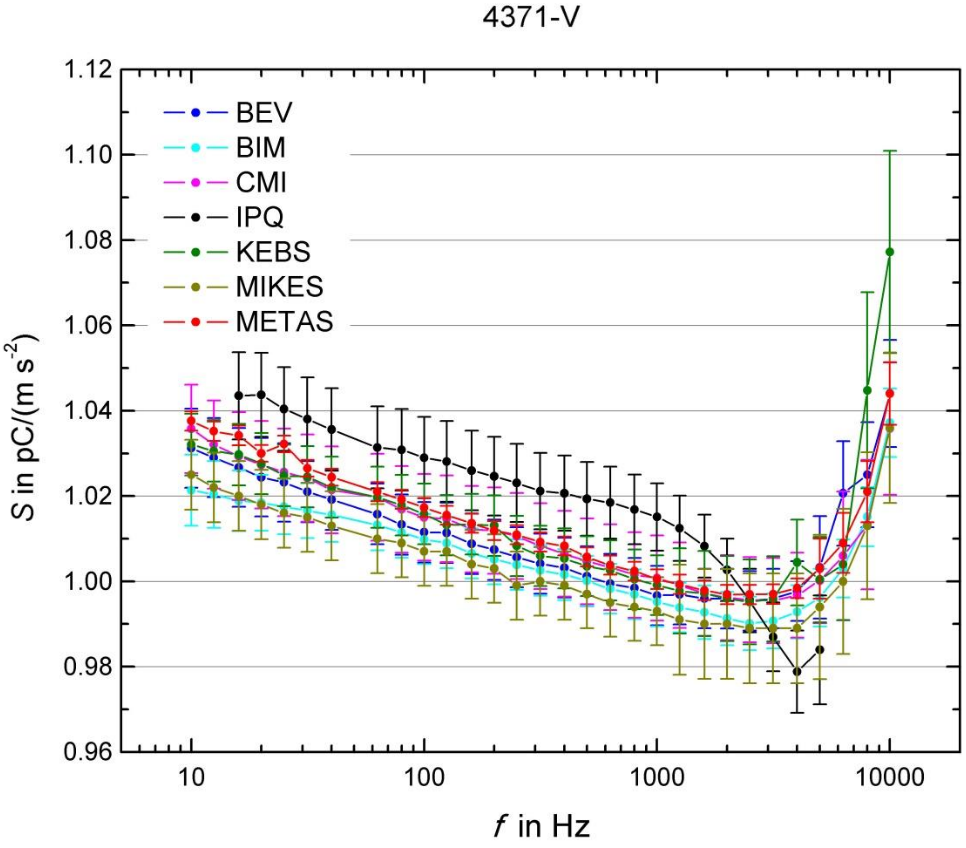


Figure 15. Sensitivity magnitude, accelerometer 4371-V

Table 18. Sensitivity phase and expanded uncertainty for accelerometer 4371-V.

f Hz	CMI		MIKES		METAS	
	φ in °	U_{φ} in °	φ in °	U_{φ} in °	φ in °	U_{φ} in °
10.0	-0.42	0.70	-0.53	0.80	-0.43	0.40
12.5	-0.46	0.70	-0.54	0.80	-0.47	0.40
16.0	-0.48	0.70	-0.52	0.80	-0.50	0.40
20.0	-0.50	0.70	-0.52	0.80	-0.53	0.38
25.0	-0.50	0.70	-0.57	0.80	-0.46	0.38
31.5	-0.52	0.70	-0.55	0.80	-0.57	0.38
40.0	-0.54	0.70	-0.56	0.80	-0.59	0.38
63.0	-0.55	0.70	-0.58	0.80	-0.63	0.39
80.0	-0.54	0.70	-0.56	0.80	-0.65	0.39
100	-0.57	0.70	-0.60	0.80	-0.67	0.39
125	-0.58	0.70	-0.53	0.80	-0.70	0.39
160	-0.63	0.70	-0.67	0.80	-0.73	0.39
200	-0.48	0.70	-0.58	0.80	-0.60	0.39
250	-0.60	0.70	-0.65	0.80	-0.59	0.39
315	-0.61	0.70	-0.61	0.80	-0.61	0.39
400	-0.63	0.70	-0.64	0.80	-0.65	0.39
500	-0.63	0.70	-0.67	0.80	-0.67	0.39
630	-0.67	0.70	-0.73	0.80	-0.67	0.39
800	-0.65	0.70	-0.73	0.80	-0.69	0.39
1000	-0.64	0.70	-0.77	0.80	-0.65	0.47
1250	-0.65	1.50	-0.83	1.40	-0.66	0.47
1600	-0.70	1.50	-0.90	1.40	-0.66	0.47
2000	-0.71	1.50	-0.96	1.40	-0.67	0.47
2500	-0.72	1.50	-1.06	1.40	-0.65	0.47
3150	-0.76	1.50	-1.14	1.40	-0.68	0.47
4000	-0.75	1.50	-1.20	1.40	-0.66	0.47
5000	-0.77	1.50	-1.43	2.10	-0.60	0.90
6300	-0.83	2.00	-1.47	2.10	-0.70	0.90
8000	-0.92	2.00	-1.81	2.10	-0.70	0.90
10000	-0.94	2.00	-2.92	2.10	-0.70	0.90

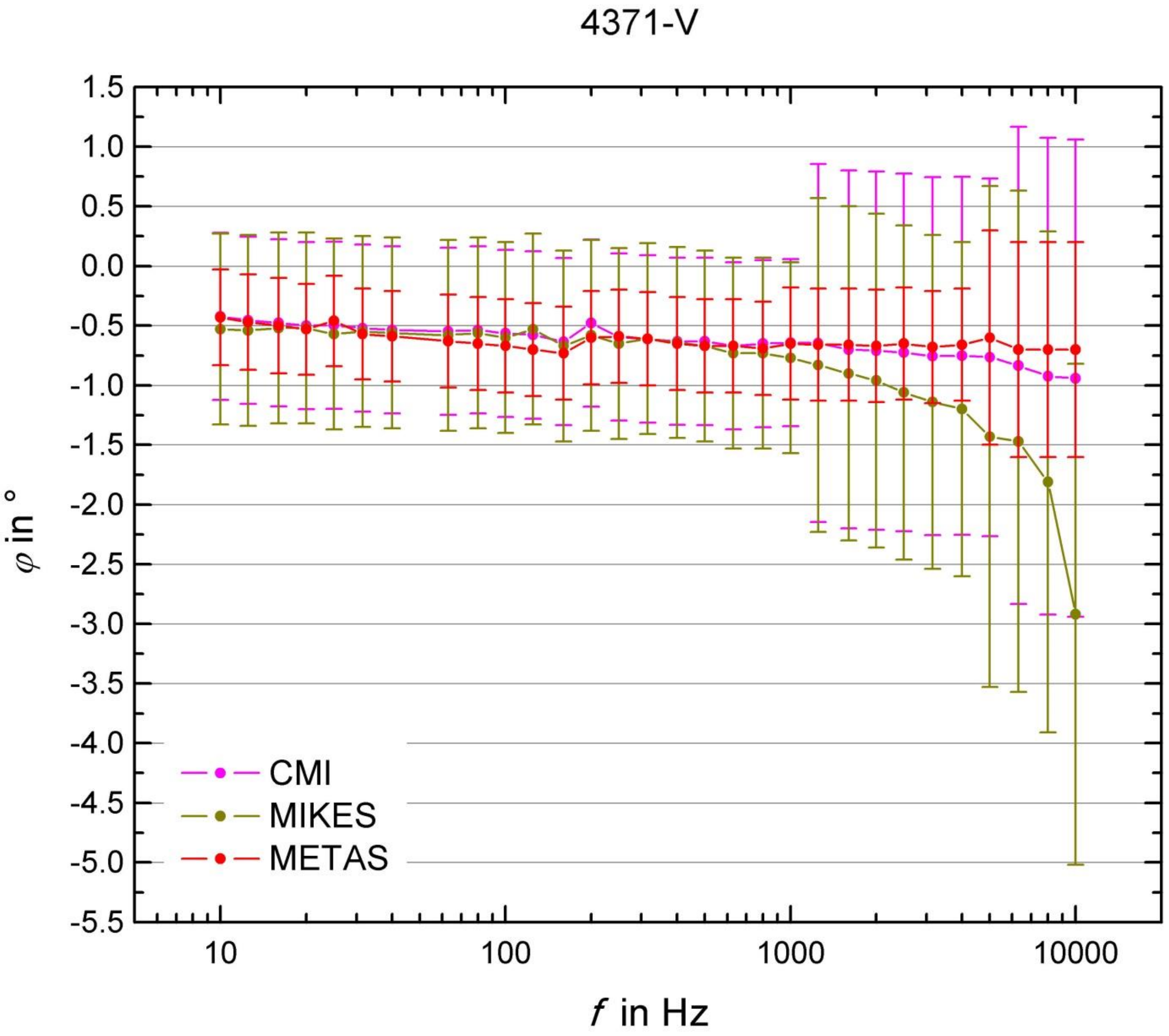


Figure 16. Sensitivity phase, accelerometer 4371-V

Appendix B - Uncertainty budgets

The uncertainty budgets of each laboratory are given below as submitted by each participant. Minor editing of the contents and a small amount of reformatting has been performed.

a) BEV

Measurement uncertainty sensitivity magnitude S		Frequency range			
Uncertainty contribution	Distribution	10 Hz ≤ f ≤ 25 Hz	25 Hz < f ≤ 1 kHz	1 kHz < f ≤ 4 kHz	4 kHz < f ≤ 10 kHz
Combined uncertainty of reference transducer	normal	0.100	0.100	0.150	0.200
Reference transducer drift over 3 years	rect	0.020	0.020	0.020	0.030
Charge amplifier amplification ratio	normal	0.141	0.141	0.141	0.141
Charge amplifier drift	rect	0.071	0.071	0.071	0.071
Voltage ratio	normal	0.007	0.007	0.007	0.007
Voltmeter drift	rect	0.014	0.014	0.014	0.014
Effect of Hum&noise	rect	0.040	0.012	0.012	0.012
Effect of distortion	rect	0.115	0.058	0.058	0.058
Effect of transverse, rocking and bending vibration	rect	0.029	0.029	0.087	0.231
Effect of base strain	rect	0.029	0.029	0.029	0.029
Effect of mounting parameters (torque, cable fixing, etc.)	rect	0.346	0.173	0.173	0.404
Effect of relative motion	rect	0.058	0.029	0.029	0.029
Effect of temperature	rect	0.115	0.115	0.115	0.115
Effect of acceleration stability during measurement	rect	0.058	0.058	0.058	0.058
Effect of gravitation	rect	0.029	0.029	0.029	0.029
Effect of magnetic field from exciter	rect	0.029	0.029	0.029	0.029
Effect of other environmental parameters	rect	0.029	0.029	0.029	0.029
Residual effects (e.g. random effect in repeated measurements; etc.)	rect	0.029	0.029	0.029	0.029
Relative uncertainty u_S %		0.442	0.303	0.333	0.555
Expanded relative uncertainty U_S %		**0.9**	**0.7**	**0.7**	**1.2**

b) BIM

Measurements

The acceleration value a_{et} (in m/s^2) is controlled by the standard chain for each frequency by measuring the output voltage V_{et} (in mV) of the reference standard accelerometer preamplifier. The relationship between a_{et} and V_{et} is given by the equation:

$$V_{et} = S_{et}.a_{et}$$

where

S_{et} is the sensitivity of reference standard acceleration measuring chain for the current frequency, according to the calibration certificate (in mV/(m/s^2)).

The calibrated accelerometer will be subject to the same vibration acceleration:

$$a_{et} = a_{cal} = \frac{V_{cal}}{S_{cal.}.S_A}$$

where

S_{cal} is the sensitivity of calibrated accelerometer, (in pC/(m/s^2);

V_{cal} is output voltage of calibrated accelerometer preamplifier for current frequency (in mV);

S_A is the sensitivity of preamplifier used with calibrated accelerometer, (in mV/pC).

The sensitivity of the calibrated accelerometer is obtained by comparing the outputs of the two accelerometers. The charge amplifier used for the measurements of the calibrated accelerometers is calibrated with traceable equipment according to the national measurement standards. The measurements results are obtained from measurements series carried out at different days under the same conditions.

Uncertainty of measurement

The sensitivity S_{cal} of the calibrated accelerometer is calculated by:

$$S_{cal} = \frac{V_{cal}}{V_{et}}.\frac{S_{et}.}{S_A}.\prod_{i=1}^{18} K_i$$

where

K_i are quantities that have influence over sensitivity with expected value equal to 1.

The input quantities are shown in the following table.

Input quantities

Symbol	**Description**	**Relative standard uncertainty, %**
S_{et}	Sensitivity of national standard Uncertainty is estimated on the bases of calibration certificate; normal distribution	$u_1(S_{et}) = \frac{U_{Set}}{2}$
V_{et}	Voltage measurements for reference standard measuring chain Uncertainty of voltmeter is estimated on the bases of calibration certificate; normal distribution	$u_2(V_{et}) = \frac{U_{Vet}}{2}$
V_{cal}	Voltage measurements for calibrated accelerometer Uncertainty of voltmeter is estimated on the bases of calibration certificate; normal distribution	$u_3(V_{cal}) = \frac{U_{Vcal}}{2}$
S_A	Sensitivity of preamplifier used for calibrated accelerometer Uncertainty is determined at settings used during the calibration; normal distribution	$u_4(S_A) = \frac{U_A}{2}$
K_1	Correction due to the dispersion of results Relative standard uncertainty $\frac{u(\hat{S}_{cal})}{\hat{S}_{cal}}$ of the average value $\hat{S}_{cal}$ is estimated on the basis of the results from n=15 repetition measurements; normal distribution.	$u_5(K_1) = \frac{u(\hat{S}_{cal})}{\hat{S}_{cal}}$ $= \frac{1}{\hat{S}_{cal}} \cdot \sqrt{\frac{\sum_1^n (S_i - \hat{S}_{cal})^2}{n.(n-1)}}$
K_2	Correction due to the resolution of voltmeter for reference standard measuring chain Uncertainty is estimated on the basis of resolution of digital scale ($\Delta_{rs\text{-}et}$); rectangular distribution.	$u_6(K_2) = \frac{\Delta_{rs-et}}{\sqrt{3}}$
K_3	Correction due to the resolution of voltmeter for calibrated accelerometer Uncertainty is estimated on the basis of resolution of digital scale ($\Delta_{rs\text{-}cal}$); rectangular distribution.	$u_7(K_3) = \frac{\Delta_{rs-cal}}{\sqrt{3}}$

Symbol	**Description**	**Relative standard uncertainty, %**
K_4	Correction due to the drift of standard sensitivity S_{et} Uncertainty is estimated on the basis of the results between the last two certificates; rectangular distribution.	$u_8(K_4) = \frac{\Delta_{dr}}{\sqrt{3}}$
K_5	Correction due to the influence of mounting of the reference transducer; rectangular distribution.	$u_9(K_5) = \frac{0{,}05}{\sqrt{3}}$
K_6	Correction due to the influence of change of temperature on reference sensitivity Uncertainty is estimated according to the technical specification given by the manufacturer, rectangular distribution	$u_{10}(K_6) = \frac{\Delta_t}{\sqrt{3}}.5℃$
K_7	Correction due to the influence of change of temperature on sensitivity of calibration accelerometer Uncertainty is estimated according to the technical specification given by the manufacturer, rectangular distribution	$u_{11}(K_7) = \frac{\Delta_t}{\sqrt{3}}.5℃$
K_8	Correction due to the changes of acceleration during the measurement. Uncertainty is estimated; rectangular distribution.	$u_{12}(K_8) = \frac{0{,}1}{\sqrt{3}}$
K_9	Correction due to the influence of mounting of the calibration transducer Uncertainty is estimated; rectangular distribution.	5 Hz÷ 10 Hz $u_{13}(K_9) = \frac{0{,}3}{\sqrt{3}}$ 12,5 Hz÷ 40 Hz $u_{13}(K_9) = \frac{0{,}2}{\sqrt{3}}$ 50 Hz ÷ 10 000 Hz $u_{13}(K_9) = \frac{0{,}05}{\sqrt{3}}$
K_{10}	Correction due to the influence of nonlinear distortions Uncertainty is estimated on the basis of the measured nonlinear distortion factor d (in %) of output signal from amplifier in the reference path for vibrations with accelerations and frequencies during the calibration); rectangular distribution.	$u_{14}(K_{10}) = \frac{0{,}5.(0{,}01.d)^2}{\sqrt{3}}.100$ d - distortion factor

Symbol	Description	Relative standard uncertainty, %
K_{11}	Correction due to the influence of transverse motion Uncertainty is estimated based on the acceleration of transverse vibration of exciter (a_t) and maximum relative transverse sensitivity of transducers (S_{et} , S_{cal}) according to the specification; special distribution.	$u_{15}(K_{11}) = \frac{(S_{et}^2 + S_{cal}^2).a_\tau^2}{\sqrt{18}}.100$
K_{12}	Correction due to the base strain Uncertainty is estimated; rectangular distribution.	$u_{16}(K_{12}) = \frac{0,05}{\sqrt{3}}$
K_{13}	Correction due to the relative motion Uncertainty is estimated; rectangular distribution.	$u_{17}(K_{13}) = \frac{0,05}{\sqrt{3}}$
K_{14}	Correction due to the hum and noise Uncertainty is estimated; rectangular distribution.	$u_{18}(K_{14}) = \frac{\Delta_n}{\sqrt{3}}$ $a=5\div10$ m/s^2, Δ_n=0,05 % $a > 10$ m/s^2, Δ_n=0,01 %
K_{15}	Correction due to the Earth gravity Uncertainty is estimated; rectangular distribution.	$u_{19}(K_{15}) = \frac{0,03}{\sqrt{3}}$
K_{16}	Correction due to the magnetic field of exciter Uncertainty is estimated; rectangular distribution.	$u_{20}(K_{16}) = \frac{0,03}{\sqrt{3}}$
K_{17}	Correction due to the residual environmental influences Uncertainty is estimated; rectangular distribution.	$u_{21}(K_{17}) = \frac{0,03}{\sqrt{3}}$
K_{18}	Correction due to 2 voltmeters used Uncertainty is estimated on the basis of calibration certificates; rectangular distribution.	$u_{22}(K_{18}) = \frac{\Delta_V}{\sqrt{3}}$

Uncertainty budgets

Uncertainty budget for the accelerometer type BK 8305-001, SN 2423435

Uncertainty in %	**u_1**	**u_2**	**u_3**	**u_4**	**u_5**	**u_6**	**u_7**	**u_8**	**u_9**	**u_{10}**	**u_{11}**	**u_{12}**	**u_{13}**	**u_{14}**	**u_{15}**	**u_{16}**	**u_{17}**	**u_{18}**	**u_{19}**	**u_{20}**	**u_{21}**	**u_{22}**	**u_{rel}**
distribution	normal	normal	normal	normal	normal	rectang.	rectang.	rectang.	rectang.	rectang.	rectang.	rectang.	rectang.	rectang.	special	rectang.	rectang.	rectang.	rectang.	rectang.	rectang.	rectang.	
f, Hz																							
10	0,1000	0,0183	0,0255	0,2000	0,0498	0,0866	0,0866	0,0460	0,0289	0,0577	0,1443	0,0577	0,1732	0,1848	0,0085	0,0289	0,0289	0,0289	0,0173	0,0173	0,0173	0,0254	0,41
12,5	0,1000	0,0183	0,0255	0,2000	0,1619	0,0866	0,0866	0,0230	0,0289	0,0577	0,1443	0,0577	0,1155	0,1848	0,0085	0,0289	0,0289	0,0289	0,0173	0,0173	0,0173	0,0318	0,42
16	0,1000	0,0167	0,0245	0,2000	0,1463	0,0866	0,0866	0,0460	0,0289	0,0577	0,1443	0,0577	0,1155	0,0722	0,0085	0,0289	0,0289	0,0289	0,0173	0,0173	0,0173	0,0398	0,38
20	0,1000	0,0150	0,0245	0,2000	0,1070	0,0009	0,0009	0,0460	0,0289	0,0577	0,1443	0,0577	0,1155	0,0509	0,0085	0,0289	0,0289	0,0289	0,0173	0,0173	0,0173	0,0525	0,34
25	0,1000	0,0150	0,0245	0,2000	0,0590	0,0009	0,0009	0,0230	0,0289	0,0577	0,1443	0,0577	0,1155	0,0462	0,0085	0,0289	0,0289	0,0289	0,0173	0,0173	0,0173	0,0421	0,32
31,5	0,1000	0,0057	0,0070	0,2000	0,0593	0,0009	0,0009	0,0230	0,0289	0,0577	0,1443	0,0577	0,1155	0,0354	0,0085	0,0289	0,0289	0,0289	0,0173	0,0173	0,0173	0,0277	0,32
40	0,1000	0,0057	0,0070	0,2000	0,0483	0,0009	0,0009	0,0230	0,0289	0,0577	0,1443	0,0577	0,1155	0,0260	0,0085	0,0289	0,0289	0,0289	0,0173	0,0173	0,0173	0,0092	0,31
63	0,1000	0,0048	0,0057	0,2000	0,0424	0,0009	0,0009	0,0230	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0104	0,0289	0,0289	0,0060	0,0173	0,0173	0,0173	0,0165	0,29
80	0,1000	0,0048	0,0067	0,2000	0,0550	0,0009	0,0009	0,0230	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0104	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0157	0,29
100	0,1000	0,0048	0,0067	0,2000	0,0421	0,0009	0,0009	0,0460	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0130	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0148	0,29
125	0,1000	0,0048	0,0067	0,2000	0,0370	0,0009	0,0009	0,0460	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0260	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0140	0,29
160	0,1000	0,0048	0,0067	0,2000	0,0225	0,0009	0,0009	0,0230	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0260	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0134	0,29
200	0,1000	0,0048	0,0067	0,2000	0,0228	0,0009	0,0009	0,0230	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0260	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0135	0,29
250	0,1000	0,0048	0,0067	0,2000	0,0281	0,0009	0,0009	0,0230	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0260	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0135	0,29
315	0,1000	0,0048	0,0067	0,2000	0,0293	0,0009	0,0009	0,0230	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0390	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0136	0,29
400	0,1000	0,0048	0,0067	0,2000	0,0167	0,0009	0,0009	0,0461	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0286	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0137	0,29
500	0,1000	0,0028	0,0045	0,2000	0,0205	0,0009	0,0009	0,0230	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0098	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0139	0,29
630	0,1000	0,0028	0,0045	0,2000	0,0194	0,0009	0,0009	0,0460	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0130	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0140	0,29
800	0,1000	0,0028	0,0045	0,2000	0,0146	0,0009	0,0009	0,0460	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0130	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0142	0,29
1000	0,1000	0,0028	0,0045	0,2000	0,0103	0,0009	0,0009	0,0230	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0163	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0144	0,29
1250	0,1000	0,0028	0,0045	0,2000	0,0086	0,0009	0,0009	0,0230	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0293	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0140	0,29
1600	0,1500	0,0028	0,0045	0,2000	0,0056	0,0009	0,0009	0,0460	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0293	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0133	0,31
2000	0,1500	0,0028	0,0045	0,2000	0,0290	0,0009	0,0009	0,0459	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0293	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0125	0,31
2500	0,1500	0,0035	0,0042	0,2000	0,0215	0,0009	0,0009	0,0458	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0325	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0115	0,31
3150	0,1500	0,0035	0,0042	0,2000	0,0252	0,0009	0,0009	0,0914	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0195	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0103	0,32
4000	0,1500	0,0035	0,0042	0,2000	0,0339	0,0009	0,0009	0,0455	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0260	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0135	0,31
5000	0,2000	0,0035	0,0042	0,2000	0,0622	0,0009	0,0009	0,0451	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0195	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0173	0,34
6300	0,2000	0,0035	0,0042	0,2000	0,0366	0,0009	0,0009	0,0447	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0130	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0223	0,34
8000	0,2000	0,0035	0,0042	0,2000	0,1233	0,0009	0,0009	0,0219	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0260	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0288	0,36
10000	0,2000	0,0035	0,0042	0,2000	0,1472	0,0009	0,0009	0,1693	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0455	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0364	0,41

Uncertainty budget for the accelerometer type BK 4371-V, SN 2046745

Uncertainty in %	u_1	u_2	u_3	u_4	u_5	u_6	u_7	u_8	u_9	u_{10}	u_{11}	u_{12}	u_{13}	u_{14}	u_{15}	u_{16}	u_{17}	u_{18}	u_{19}	u_{20}	u_{21}	u_{22}	u_{rel}
distribution	normal	normal	normal	normal	normal	rectang.	rectang.	rectang.	rectang.	rectang.	rectang.	rectang.	rectang.	rectang.	special	rectang.	rectang.	rectang.	rectang.	rectang.	rectang.	rectang.	
f, Hz																							
10	0,1000	0,0183	0,0167	0,2000	0,0474	0,0866	0,0866	0,0460	0,0289	0,0577	0,1443	0,0577	0,1732	0,1848	0,0136	0,0289	0,0289	0,0289	0,0173	0,0173	0,0173	0,0254	0,41
12,5	0,1000	0,0183	0,0167	0,2000	0,0320	0,0866	0,0866	0,0230	0,0289	0,0577	0,1443	0,0577	0,1155	0,1848	0,0136	0,0289	0,0289	0,0289	0,0173	0,0173	0,0173	0,0224	0,38
16	0,1000	0,0167	0,0167	0,2000	0,0587	0,0866	0,0866	0,0460	0,0289	0,0577	0,1443	0,0577	0,1155	0,0722	0,0136	0,0289	0,0289	0,0289	0,0173	0,0173	0,0173	0,0182	0,35
20	0,1000	0,0150	0,0150	0,2000	0,0561	0,0009	0,0009	0,0460	0,0289	0,0577	0,1443	0,0577	0,1155	0,0509	0,0136	0,0289	0,0289	0,0289	0,0173	0,0173	0,0173	0,0173	0,32
25	0,1000	0,0150	0,0150	0,2000	0,0479	0,0009	0,0009	0,0230	0,0289	0,0577	0,1443	0,0577	0,1155	0,0462	0,0136	0,0289	0,0289	0,0289	0,0173	0,0173	0,0173	0,0159	0,32
31,5	0,1000	0,0057	0,0057	0,2000	0,0399	0,0009	0,0009	0,0230	0,0289	0,0577	0,1443	0,0577	0,1155	0,0354	0,0136	0,0289	0,0289	0,0289	0,0173	0,0173	0,0173	0,0142	0,31
40	0,1000	0,0057	0,0057	0,2000	0,0289	0,0009	0,0009	0,0230	0,0289	0,0577	0,1443	0,0577	0,1155	0,0260	0,0136	0,0289	0,0289	0,0289	0,0173	0,0173	0,0173	0,0118	0,31
63	0,1000	0,0048	0,0048	0,2000	0,0382	0,0009	0,0009	0,0230	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0167	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0086	0,29
80	0,1000	0,0048	0,0048	0,2000	0,0457	0,0009	0,0009	0,0230	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0167	0,0289	0,0289	0,0060	0,0173	0,0173	0,0173	0,0079	0,29
100	0,1000	0,0048	0,0048	0,2000	0,0196	0,0009	0,0009	0,0460	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0209	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0069	0,29
125	0,1000	0,0048	0,0048	0,2000	0,0179	0,0009	0,0009	0,0460	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0418	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0062	0,29
160	0,1000	0,0048	0,0048	0,2000	0,0133	0,0009	0,0009	0,0230	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0418	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0057	0,29
200	0,1000	0,0048	0,0048	0,2000	0,0154	0,0009	0,0009	0,0230	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0418	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0057	0,29
250	0,1000	0,0048	0,0048	0,2000	0,0525	0,0009	0,0009	0,0230	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0418	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0058	0,29
315	0,1000	0,0048	0,0048	0,2000	0,0441	0,0009	0,0009	0,0230	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0626	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0060	0,30
400	0,1000	0,0048	0,0048	0,2000	0,0457	0,0009	0,0009	0,0461	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0459	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0062	0,30
500	0,1000	0,0028	0,0028	0,2000	0,0437	0,0009	0,0009	0,0230	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0261	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0064	0,29
630	0,1000	0,0028	0,0028	0,2000	0,0391	0,0009	0,0009	0,0460	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0209	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0067	0,29
800	0,1000	0,0028	0,0028	0,2000	0,0400	0,0009	0,0009	0,0460	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0209	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0070	0,29
1000	0,1000	0,0028	0,0028	0,2000	0,0365	0,0009	0,0009	0,0230	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0261	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0075	0,29
1250	0,1000	0,0028	0,0028	0,2000	0,0333	0,0009	0,0009	0,0230	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0470	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0072	0,29
1600	0,1500	0,0028	0,0028	0,2000	0,0311	0,0009	0,0009	0,0460	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0470	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0068	0,32
2000	0,1500	0,0028	0,0028	0,2000	0,0218	0,0009	0,0009	0,0459	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0470	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0062	0,31
2500	0,1500	0,0035	0,0035	0,2000	0,0408	0,0009	0,0009	0,0458	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0522	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0056	0,32
3150	0,1500	0,0035	0,0035	0,2000	0,0354	0,0009	0,0009	0,0914	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0313	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0048	0,32
4000	0,1500	0,0035	0,0035	0,2000	0,0340	0,0009	0,0009	0,0455	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0418	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0086	0,32
5000	0,2000	0,0035	0,0035	0,2000	0,0244	0,0009	0,0009	0,0451	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0313	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0131	0,34
6300	0,2000	0,0035	0,0035	0,2000	0,0267	0,0009	0,0009	0,0447	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0209	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0189	0,34
8000	0,2000	0,0035	0,0035	0,2000	0,0430	0,0009	0,0009	0,0219	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0418	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0266	0,34
10000	0,2000	0,0035	0,0035	0,2000	0,0557	0,0009	0,0009	0,1693	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0731	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0356	0,39

Uncertainty budget for the accelerometer type EN 2270M8, SN 16198

Uncertainty in %	u_1	u_2	u_3	u_4	u_5	u_6	u_7	u_8	u_9	u_{10}	u_{11}	u_{12}	u_{13}	u_{14}	u_{15}	u_{16}	u_{17}	u_{18}	u_{19}	u_{20}	u_{21}	u_{22}	u_{rel}
distribution	normal	normal	normal	normal	normal	rectang.	rectang.	rectang.	rectang.	rectang.	rectang.	rectang.	rectang.	rectang.	special	rectang.	rectang.	rectang.	rectang.	rectang.	rectang.	rectang.	
f, Hz																							
10	0,1000	0,0183	0,0255	0,2000	0,2096	0,0866	0,0866	0,0460	0,0289	0,0577	0,1443	0,0577	0,1732	0,1848	0,0109	0,0289	0,0289	0,0289	0,0173	0,0173	0,0173	0,0254	0,46
12,5	0,1000	0,0183	0,0255	0,2000	0,1887	0,0866	0,0866	0,0230	0,0289	0,0577	0,1443	0,0577	0,1155	0,1848	0,0109	0,0289	0,0289	0,0289	0,0173	0,0173	0,0173	0,0318	0,43
16	0,1000	0,0167	0,0245	0,2000	0,1540	0,0866	0,0866	0,0460	0,0289	0,0577	0,1443	0,0577	0,1155	0,0722	0,0109	0,0289	0,0289	0,0289	0,0173	0,0173	0,0173	0,0398	0,38
20	0,1000	0,0150	0,0245	0,2000	0,1013	0,0009	0,0009	0,0460	0,0289	0,0577	0,1443	0,0577	0,1155	0,0509	0,0109	0,0289	0,0289	0,0289	0,0173	0,0173	0,0173	0,0525	0,34
25	0,1000	0,0150	0,0245	0,2000	0,0586	0,0009	0,0009	0,0230	0,0289	0,0577	0,1443	0,0577	0,1155	0,0462	0,0109	0,0289	0,0289	0,0289	0,0173	0,0173	0,0173	0,0421	0,32
31,5	0,1000	0,0057	0,0070	0,2000	0,0477	0,0009	0,0009	0,0230	0,0289	0,0577	0,1443	0,0577	0,1155	0,0354	0,0109	0,0289	0,0289	0,0289	0,0173	0,0173	0,0173	0,0277	0,32
40	0,1000	0,0057	0,0070	0,2000	0,0575	0,0009	0,0009	0,0230	0,0289	0,0577	0,1443	0,0577	0,1155	0,0260	0,0109	0,0289	0,0289	0,0289	0,0173	0,0173	0,0173	0,0092	0,32
63	0,1000	0,0048	0,0057	0,2000	0,0154	0,0009	0,0009	0,0230	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0134	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0165	0,29
80	0,1000	0,0048	0,0145	0,2000	0,0149	0,0009	0,0009	0,0230	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0134	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0157	0,29
100	0,1000	0,0048	0,0145	0,2000	0,0410	0,0009	0,0009	0,0460	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0167	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0141	0,29
125	0,1000	0,0048	0,0145	0,2000	0,0382	0,0009	0,0009	0,0460	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0335	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0135	0,29
160	0,1000	0,0048	0,0145	0,2000	0,0492	0,0009	0,0009	0,0230	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0335	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0128	0,29
200	0,1000	0,0048	0,0145	0,2000	0,0315	0,0009	0,0009	0,0230	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0335	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0128	0,29
250	0,1000	0,0048	0,0145	0,2000	0,0330	0,0009	0,0009	0,0230	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0335	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0128	0,29
315	0,1000	0,0048	0,0145	0,2000	0,0194	0,0009	0,0009	0,0230	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0502	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0129	0,29
400	0,1000	0,0048	0,0145	0,2000	0,0223	0,0009	0,0009	0,0461	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0368	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0129	0,29
500	0,1000	0,0028	0,0025	0,2000	0,0257	0,0009	0,0009	0,0230	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0126	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0130	0,29
630	0,1000	0,0028	0,0025	0,2000	0,0149	0,0009	0,0009	0,0460	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0167	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0130	0,29
800	0,1000	0,0028	0,0025	0,2000	0,0131	0,0009	0,0009	0,0460	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0167	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0132	0,29
1000	0,1000	0,0028	0,0025	0,2000	0,0107	0,0009	0,0009	0,0230	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0418	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0133	0,29
1250	0,1000	0,0028	0,0025	0,2000	0,0093	0,0009	0,0009	0,0230	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0377	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0128	0,29
1600	0,1500	0,0028	0,0025	0,2000	0,0074	0,0009	0,0009	0,0460	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0377	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0121	0,31
2000	0,1500	0,0028	0,0025	0,2000	0,0260	0,0009	0,0009	0,0459	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0377	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0114	0,31
2500	0,1500	0,0035	0,0105	0,2000	0,0154	0,0009	0,0009	0,0458	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0418	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0105	0,31
3150	0,1500	0,0035	0,0105	0,2000	0,0065	0,0009	0,0009	0,0914	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0251	0,0289	0,0289	0,0060	0,0173	0,0173	0,0173	0,0092	0,32
4000	0,1500	0,0035	0,0105	0,2000	0,0060	0,0009	0,0009	0,0455	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0335	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0125	0,31
5000	0,2000	0,0035	0,0105	0,2000	0,0179	0,0009	0,0009	0,0451	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0251	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0164	0,34
6300	0,2000	0,0035	0,0025	0,2000	0,0126	0,0009	0,0009	0,0447	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0167	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0215	0,34
8000	0,2000	0,0035	0,0025	0,2000	0,0297	0,0009	0,0009	0,0219	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0335	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0281	0,34
10000	0,2000	0,0035	0,0025	0,2000	0,0352	0,0009	0,0009	0,1693	0,0289	0,0577	0,1443	0,0577	0,0289	0,0029	0,0586	0,0289	0,0289	0,0058	0,0173	0,0173	0,0173	0,0358	0,38

c) CMI

CMI - Budget of uncertainty - Calibration of an accelerometer at frequency range from 10 Hz to 5 kHz and 10 m/s^2 on the secondary level (back-to-back) according ISO 16063-21

Quantity	Description	Relative expanded uncertainty or bounds of estimated error components %	Probability distribution model	Factor x_i	Sensitivity coefficient c_i	Relative contribution $u_{\mathrm{rel},i}(y)$ %
S_1	Calibration of reference transducer set	0,48	Normal ($k = 2$)	1/2	1	0,240
$S_{1,\mathrm{s}}$	Drift for 3 years, manufacturer specification < 0,05 % per year	0,2	Rectangular	$1/\sqrt{3}$	1	0,115
$S_{\mathrm{A,Cal}}$	Sensitivity of conditioning amplifier calibration, specification	0,3	Rectangular	$1/\sqrt{3}$	–1	0,173
V_R	Voltage ratio, specification	0,15	Rectangular	$1/\sqrt{3}$	1	0,087
$I(V_{R,\mathrm{T}})$	Influence on V_R measurement from temperature variation. Reference transducer sensitivity, (23 ± 3) °C, < 0,02 % per °C Transducer to be calibrated, (23 ± 3) °C, < 0,1 % per °C	0,36	Rectangular	$1/\sqrt{3}$	1	0,208
$I(V_{R,\mathrm{s}})$	Maximum allowed difference between the reference level before and after the measurement, 0,2 %	0,2	Rectangular	$1/\sqrt{3}$	1	0,115
$I(V_{R,\mathrm{N}})$	Influence of mounting parameters on transducer to be calibrated, cable, plug and torque, maximum 0,05 %	0,2	Rectangular	$1/\sqrt{3}$	1	0,115
$I(V_{R,\mathrm{d}})$	Influence on V_R measurement from acceleration distortion Difference in frequency slopes between transducer to be calibrated (PZT) and reference transducer (quartz) typically −2 % per decade of frequency Dominating 3rd harmonic less than 5 %. Assuming rectangular distribution	0,002 4 See Note 2	Rectangular	$1/\sqrt{3}$	1	0,001
$I(V_{R,\mathrm{v}})$	Influence on V_R measurement from transverse acceleration Transverse vibration a_T for vibrator maximum 10 % Transverse sensitivity, reference transducer, $S_{v,1}$, max. 2 % Transverse sensitivity, transducer to be calibrated, $S_{v,2}$, max. 5 %	$\sqrt{(S_{v,2}^2 + S_{v,1}^2)\,a_\mathrm{T}^2} = 0{,}51$ See Note 3 and refs. [4] and [5] for explanation of the formula	Special	$\sqrt{\frac{1}{18}}$ See Note 3 and refs. [4] and [5] for explanation of the factor 1/18	1	0,120
$I(V_{R,\mathrm{e}})$	Influence on V_R measurement from base strain. Estimated to be less than	0,1	Rectangular	$1/\sqrt{3}$	1	0,058
$I(V_{R,\mathrm{r}})$	Influence on V_R measurement from relative motion. Estimated to be less than	0,1	Rectangular	$1/\sqrt{3}$	1	0,058
$I(V_{R,\mathrm{L}})$	Influence on V_R measurement from non-linearity of transducers. Estimated to be less than	0,09	Rectangular	$1/\sqrt{3}$	1	0,052
$I(V_{R,\mathrm{l}})$	Influence on V_R measurement from non-linearity of amplifiers. Estimated to be less than	0,09	Rectangular	$1/\sqrt{3}$	1	0,052

Quantity	Description	Relative expanded uncertainty or bounds of estimated error components %	Probability distribution model	Factor x_i	Sensitivity coefficient c_i	Relative contribution $u_{\mathrm{rel},i}(y)$ %
$I(V_{R,\mathrm{G}})$	Influence on V_R measurement from gravity. Estimated to be less than	0,00	Rectangular	$1/\sqrt{3}$	1	0,00
$I(V_{R,\mathrm{B}})$	Influence on V_R measurement from magnetic field from exciter. Estimated to be less than	0,05	Rectangular	$1/\sqrt{3}$	1	0,029
$I(V_{R,\mathrm{E}})$	Influence on V_R measurement from other environmental effects. Estimated to be less than	0,05	Rectangular	$1/\sqrt{3}$	1	0,029
$I(V_{R,\mathrm{RE}})$	Influence on V_R measurement from residual effects (e.g. random effect in repeated measurements; experimental standard deviation of arithmetic mean). Estimated to be less than	0,05	Rectangular	$1/\sqrt{3}$	1	0,029
$u_{\mathrm{rel}}(S_2)$	Uncertainty for accelerometer sensitivity S_2		Relative expanded uncertainty ($k = 2$)			0,91 **(~1,0)**

NOTE 1 The uncertainties involved in the measurements by comparison are listed with their estimated magnitudes. The uncertainties are converted to a standard deviation in the last column using the appropriate distribution model, e.g. rectangular. All the calculated values $u_{\mathrm{rel},i}(y)$ are standard uncertainties ($k = 1$ values).

NOTE 2 The output from the two channels can be described by $u_1^2 = S_1^2(f_{\mathrm{ref}})(a_{\mathrm{ref}}^2 + a_3^2)$ d $u_2^2 = S_A^2(S_2^2(f_{\mathrm{ref}})a_{\mathrm{ref}}^2 + S_2^2(3f_{\mathrm{ref}})a_3^2)$ llowing the comments in the text with no dependence on frequency for the reference and following the formula in the text for the transducer to be calibrated, a sensitivity at the third harmonic of 0,99 times the sensitivity at the reference frequency is obtained. Using $a_3 = 0{,}05$, this gives an error as calculated above on the ratio of the square roots of the squared outputs. The amplifier is assumed to have a flat response (S_A constant).

NOTE 3 If the transverse sensitivity directions of the two transducers and the exciter transverse direction are known, but their relative directions are unknown, an integration over 360° gives the resulting variance $\sigma^2 = \frac{1}{2}(S_{v,2}^2 + S_{v,1}^2)a_T^2$, where $S_{v,2}$, $S_{v,1}$ and a_T are the transverse sensitivities and the transverse vibration respectively.
If all three are assumed to be unknown but rectangularly distributed with the bounds as the values used as known above, it is necessary to normalize by $1/\sqrt{3}$, yielding $\sigma^2 = \frac{1}{2}(\frac{1}{3}S_{v,2}^2 + \frac{1}{3}S_{v,1}^2) \times \frac{1}{3}a_T^2 = \frac{1}{18}(S_{v,2}^2 + S_{v,1}^2)a_T^2.$

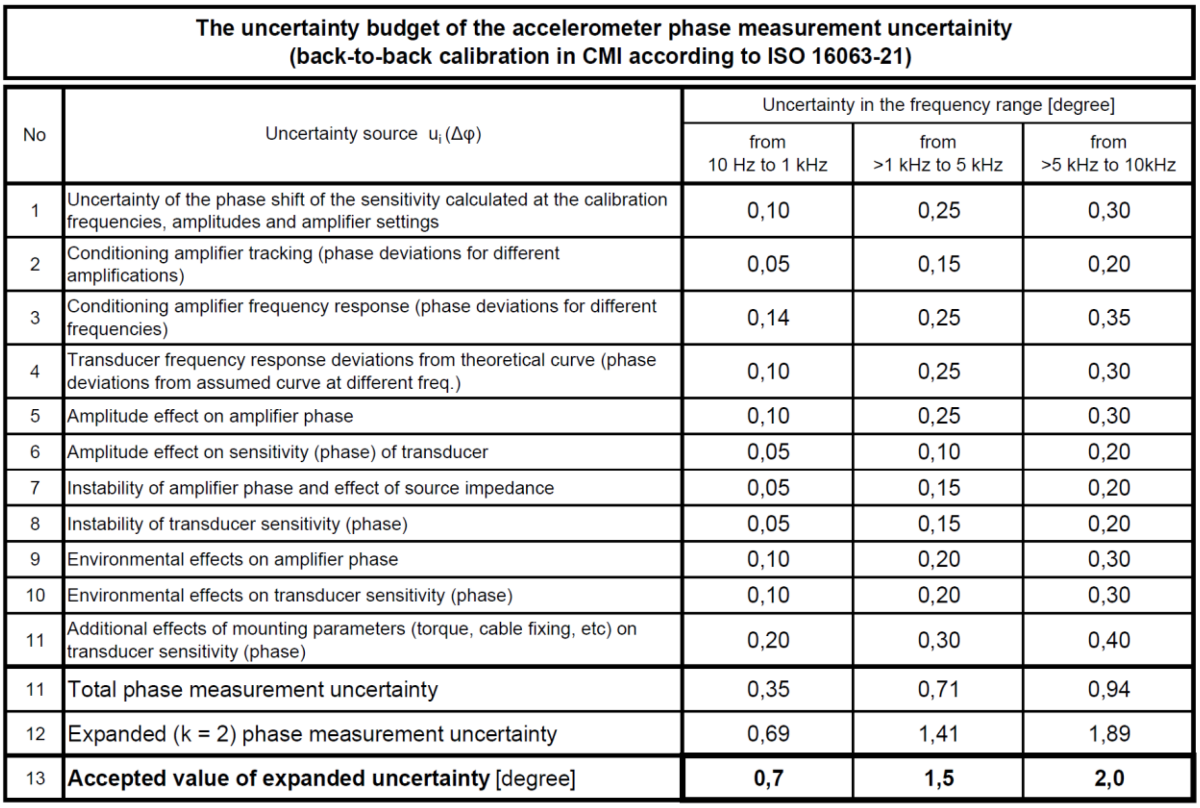
CMI - Budget of uncertainty - Calibration of an accelerometer at frequency range from 5 kHz to 10 kHz and 10 m/s^2 on the secondary level (back-to-back) according ISO 16063-21

Quantity	Description	Relative expanded uncertainty or bounds of estimated error components %	Probability distribution model	Factor x_i	Sensitivity coefficient c_i	Relative contribution $u_{\mathrm{rel},i}(y)$ %
S_1	Calibration of reference transducer set	1,0	Normal ($k = 2$)	1/2	1	0,5
$S_{1,\mathrm{s}}$	Drift for 3 years, manufacturer specification < 0,05 % per year	0,2	Rectangular	$1/\sqrt{3}$	1	0,115
$S_{\mathrm{A,Cal}}$	Sensitivity of conditioning amplifier calibration, specification	0,4	Rectangular	$1/\sqrt{3}$	–1	0,231
V_R	Voltage ratio, specification	0,2	Rectangular	$1/\sqrt{3}$	1	0,115
$I(V_{R,\mathrm{T}})$	Influence on V_R measurement from temperature variation. Reference transducer sensitivity, (23 ± 3) °C, < 0,02 % per °C Transducer to be calibrated, (23 ± 3) °C, < 0,1 % per °C	0,36	Rectangular	$1/\sqrt{3}$	1	0,208
$I(V_{R,\mathrm{s}})$	Maximum allowed difference between the reference level before and after the measurement, 0,3 %	0,3	Rectangular	$1/\sqrt{3}$	1	0,173
$I(V_{R,\mathrm{N}})$	Influence of mounting parameters on transducer to be calibrated, cable, plug and torque, maximum 0,3 %	0,4	Rectangular	$1/\sqrt{3}$	1	0,231
$I(V_{R,\mathrm{d}})$	Influence on V_R measurement from acceleration distortion Difference in frequency slopes between transducer to be calibrated (PZT) and reference transducer (quartz) typically −2 % per decade of frequency Dominating 3rd harmonic less than 5 %. Assuming rectangular distribution	0,002 4 See Note 2	Rectangular	$1/\sqrt{3}$	1	0,001
$I(V_{R,\mathrm{v}})$	Influence on V_R measurement from transverse acceleration Transverse vibration a_{T} for vibrator maximum 10 % Transverse sensitivity, reference transducer, $S_{v,1}$, max. 2 % Transverse sensitivity, transducer to be calibrated, $S_{v,2}$, max. 5 %	$\sqrt{(S_{v,2}^2 + S_{v,1}^2)\,a_{\mathrm{T}}^2} = 0{,}51$ See Note 3 and refs. [4] and [5] for explanation of the formula	Special	$\sqrt{\frac{1}{18}}$ See Note 3 and refs. [4] and [5] for explanation of the factor 1/18	1	0,120
$I(V_{R,\mathrm{e}})$	Influence on V_R measurement from base strain. Estimated to be less than	0,3	Rectangular	$1/\sqrt{3}$	1	0,173
$I(V_{R,\mathrm{r}})$	Influence on V_R measurement from relative motion. Estimated to be less than	0,2	Rectangular	$1/\sqrt{3}$	1	0,115
$I(V_{R,\mathrm{L}})$	Influence on V_R measurement from non-linearity of transducers. Estimated to be less than	0,09	Rectangular	$1/\sqrt{3}$	1	0,052
$I(V_{R,\mathrm{l}})$	Influence on V_R measurement from non-linearity of amplifiers. Estimated to be less than	0,09	Rectangular	$1/\sqrt{3}$	1	0,052
$I(V_{R,\mathrm{G}})$	Influence on V_R measurement from gravity. Estimated to be less than	0,00	Rectangular	$1/\sqrt{3}$	1	0,00

Quantity	**Description**	**Relative expanded uncertainty or bounds of estimated error components%**	**Probability distribution model**	**Factor** x_i	**Sensitivity coefficient** c_i	**Relative contribution** $u_{\mathrm{rel},i}(y)$ %
$I(V_{R,\ \mathrm{B}})$	Influence on V_R measurement from magnetic field from exciter. Estimated to be less than	0,05	Rectangular	$1/\sqrt{3}$	1	0,029
$I(V_{R,\ \mathrm{E}})$	Influence on V_R measurement from other environmental effects. Estimated to be less than	0,1	Rectangular	$1/\sqrt{3}$	1	0,058
$I(V_{R,\ \mathrm{RE}})$	Influence on V_R measurement from residual effects (e.g. random effect in repeated measurements; experimental standard deviation of arithmetic mean). Estimated to be less than	0,1	Rectangular	$1/\sqrt{3}$	1	0,058
$u_{\mathrm{rel}}(S_2)$	Uncertainty for accelerometer sensitivity S_2		Relative expanded uncertainty ($k = 2$)			1,45 **(~1,5)**

NOTE 1 The uncertainties involved in the measurements by comparison are listed with their estimated magnitudes. The uncertainties are converted to a standard deviation in the last column using the appropriate distribution model, e.g. rectangular. All the calculated values $u_{\mathrm{rel},i}(y)$ are standard uncertainties ($k = 1$ values).

NOTE 2 The output from the two channels can be described by $u_1{}^2 = S_1{}^2(f_{\mathrm{ref}})(a_{\mathrm{ref}}{}^2 + a_3{}^2)$ and $u_2{}^2 = S_{\mathrm{A}}{}^2(S_2{}^2(f_{\mathrm{ref}})a_{\mathrm{ref}}{}^2 + S_2{}^2(3f_{\mathrm{ref}})a_3{}^2)$ following the comments in the text with no dependence on frequency for the reference and following the formula in the text for the transducer to be calibrated, a sensitivity at the third harmonic of 0,99 times the sensitivity at the reference frequency is obtained. Using $a_3 = 0{,}05$, this gives an error as calculated above on the ratio of the square roots of the squared outputs. The amplifier is assumed to have a flat response (S_{A} constant).
NOTE 3 If the transverse sensitivity directions of the two transducers and the exciter transverse direction are known, but their relative directions are unknown, an integration over 360° gives the resulting variance $\sigma^2 = \frac{1}{2}(S_{v,2}^2 + S_{v,1}^2)\,a_{\mathrm{T}}^2$, where $S_{v,\ 2}$, $S_{v,\ 1}$ and a_{T} are the transverse sensitivities and the transverse vibration respectively.
If all three are assumed to be unknown but rectangularly distributed with the bounds as the values used as known above, it is necessary to normalize by $1/\sqrt{3}$, yielding $\sigma^2 = \frac{1}{2}(\frac{1}{3}S_{v,2}^2 + \frac{1}{3}S_{v,1}^2) \times \frac{1}{3}a_{\mathrm{T}}^2 = \frac{1}{18}(S_{v,2}^2 + S_{v,1}^2)\,a_{\mathrm{T}}^2.$



The uncertainty budget of the accelerometer phase measurement uncertainity (back-to-back calibration in CMI according to ISO 16063-21)

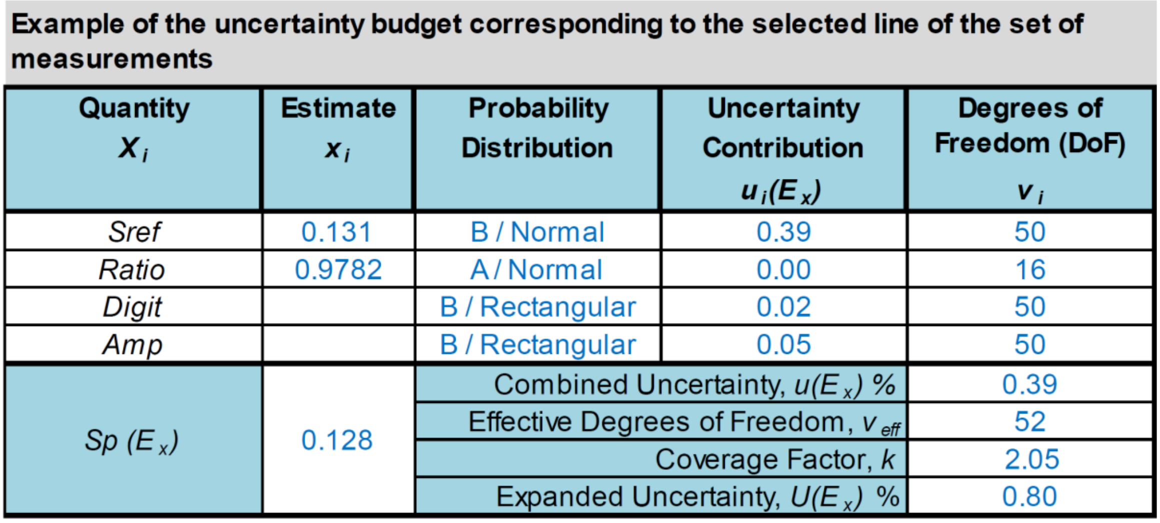
No	Uncertainty source $u_i(\Delta\varphi)$	Uncertainty in the frequency range [degree]		
		from 10 Hz to 1 kHz	from >1 kHz to 5 kHz	from >5 kHz to 10kHz
1	Uncertainty of the phase shift of the sensitivity calculated at the calibration frequencies, amplitudes and amplifier settings	0,10	0,25	0,30
2	Conditioning amplifier tracking (phase deviations for different amplifications)	0,05	0,15	0,20
3	Conditioning amplifier frequency response (phase deviations for different frequencies)	0,14	0,25	0,35
4	Transducer frequency response deviations from theoretical curve (phase deviations from assumed curve at different freq.)	0,10	0,25	0,30
5	Amplitude effect on amplifier phase	0,10	0,25	0,30
6	Amplitude effect on sensitivity (phase) of transducer	0,05	0,10	0,20
7	Instability of amplifier phase and effect of source impedance	0,05	0,15	0,20
8	Instability of transducer sensitivity (phase)	0,05	0,15	0,20
9	Environmental effects on amplifier phase	0,10	0,20	0,30
10	Environmental effects on transducer sensitivity (phase)	0,10	0,20	0,30
11	Additional effects of mounting parameters (torque, cable fixing, etc) on transducer sensitivity (phase)	0,20	0,30	0,40
11	Total phase measurement uncertainty	0,35	0,71	0,94
12	Expanded (k = 2) phase measurement uncertainty	0,69	1,41	1,89
13	**Accepted value of expanded uncertainty** [degree]	**0,7**	**1,5**	**2,0**

d) IPQ

The calculation of the uncertainty was made in accordance with *GUM – "Guide to the Expression of Uncertainty in Measurement "*.

For each of those final entry lines an uncertainty budget is presented assuming the combined uncertainty calculated (standard error, u(Ex)), the effective degrees of freedom, the coverage factor, k, and the expanded uncertainty, U(Ex), determined.

The following table shows an example of those calculations that can be reached by choosing the observation line in the corresponding separate spreadsheet file.



Example of the uncertainty budget corresponding to the selected line of the set of measurements

Quantity X_i	**Estimate** x_i	**Probability Distribution**	**Uncertainty Contribution** $u_i(E_x)$	**Degrees of Freedom (DoF)** v_i
Sref	0.131	B / Normal	0.39	50
Ratio	0.9782	A / Normal	0.00	16
Digit		B / Rectangular	0.02	50
Amp		B / Rectangular	0.05	50
Sp (E_x)	0.128	Combined Uncertainty, $u(E_x)$ %		0.39
		Effective Degrees of Freedom, v_{eff}		52
		Coverage Factor, k		2.05
		Expanded Uncertainty, $U(E_x)$ %		0.80

IPQ uncertainty budget Brüel & Kjær 8305-001 (SN: 2423435) “single ended”

measurement ID				*amb temp*		*amb press*		*amb rel hum*		*Sref (IPQ-8305S)*			*measured ratio*				*digitizing capacity (3458A)*		*accelerometer conditioning (NEXUS)*		*result*				
date	*accelero meter*	*nominal acel (m s^{-2})*	*nominal freq (Hz)*	*amb temp (ºC)*	*unc amb temp (ºC)*	*amb press (hPa)*	*unc amb press (hPa)*	*amb hum (%)*	*unc amb hum (%)*	sensib (pC/m·s^{-2})	*standard unc $u(x_i)$ %*	*deg freed*	*measured ratio*	*comb std dev*	*standard unc $u(x_i)$ %*	*deg freed*	*standard unc $u(x_i)$ %*	*deg freed*	*standard unc $u(x_i)$ %*	*deg freed*	*Sp (E_x)*	*comb unc $u(E_x)$ %*	*V eff*	*k*	*expand unc $U(E_x)$ %*
2019-11-26 14:53	8305	30	25	22,9	0,5	1002	10	67	3,0	0,1303	0,456	> 50	0,9774	2,8E-03	0,288	16	0,02	> 50	0,05	> 50	0,1274	0,54	67	2,04	1,10
2019-11-26 15:05	8305	30	40	22,9	0,5	1002	10	67	3,0	0,1303	0,454	> 50	0,9804	2,2E-04	0,022	16	0,02	> 50	0,05	> 50	0,1278	0,46	52	2,05	0,94
2019-11-26 15:17	8305	30	63	22,9	0,5	1002	10	67	3,0	0,1304	0,452	> 50	0,9802	1,4E-03	0,142	16	0,02	> 50	0,05	> 50	0,1278	0,48	60	2,04	0,97
2019-11-26 15:30	8305	30	80	22,9	0,5	1002	10	66	3,0	0,1304	0,450	> 50	0,9799	4,4E-05	0,004	16	0,02	> 50	0,05	> 50	0,1278	0,45	51	2,05	0,93
2019-11-26 15:41	8305	30	100	22,9	0,5	1002	10	66	3,0	0,1305	0,448	> 50	0,9800	5,9E-05	0,006	16	0,02	> 50	0,05	> 50	0,1278	0,45	51	2,05	0,92
2019-11-26 15:49	8305	30	160	22,9	0,5	1002	10	67	3,0	0,1306	0,441	> 50	0,9793	4,6E-05	0,005	16	0,02	> 50	0,05	> 50	0,1279	0,44	52	2,05	0,91
2019-11-26 15:59	8305	31	200	22,6	0,5	1002	10	68	3,0	0,1306	0,437	> 50	0,9788	1,2E-05	0,001	16	0,02	> 50	0,05	> 50	0,1279	0,44	52	2,05	0,90
2019-11-26 16:17	8305	30	250	22,3	0,5	1003	10	69	3,0	0,1307	0,432	> 50	0,9794	1,1E-04	0,011	16	0,02	> 50	0,05	> 50	0,1280	0,44	52	2,05	0,89
2019-11-26 16:25	8305	30	315	22,2	0,5	1002	10	69	3,0	0,1308	0,426	> 50	0,9791	6,7E-06	0,001	16	0,02	> 50	0,05	> 50	0,1281	0,43	52	2,05	0,88
2019-11-26 16:30	8305	30	400	22,2	0,5	1002	10	69	3,0	0,1309	0,418	> 50	0,9789	4,7E-06	0,000	16	0,02	> 50	0,05	> 50	0,1281	0,42	52	2,05	0,86
2019-11-26 16:38	8305	30	500	22,2	0,5	1002	10	70	3,0	0,1310	0,410	> 50	0,9786	5,3E-06	0,001	16	0,02	> 50	0,05	> 50	0,1282	0,41	52	2,05	0,85
2019-11-26 16:45	8305	30	630	22,2	0,5	1002	10	70	3,0	0,1311	0,399	> 50	0,9782	5,8E-06	0,001	16	0,02	> 50	0,05	> 50	0,1282	0,40	52	2,05	0,83
2019-11-26 16:54	8305	30	800	22,1	0,5	1003	10	70	3,0	0,1311	0,387	> 50	0,9782	3,8E-06	0,000	16	0,02	> 50	0,05	> 50	0,1283	0,39	52	2,05	0,80
2019-11-26 17:00	8305	30	1000	22,1	0,5	1002	10	70	3,0	0,1312	0,375	> 50	0,9783	4,1E-06	0,000	16	0,02	> 50	0,05	> 50	0,1283	0,38	52	2,05	0,78
2019-11-26 17:29	8305	30	1250	22,0	0,5	1003	10	69	3,0	0,1311	0,364	> 50	0,9783	7,2E-05	0,007	16	0,02	> 50	0,05	> 50	0,1282	0,37	52	2,05	0,75
2019-11-27 11:49	8305	30	1600	22,5	0,5	1008	10	59	3,0	0,1308	0,353	> 50	0,9785	6,6E-05	0,007	16	0,02	> 50	0,05	> 50	0,1280	0,36	52	2,05	0,73
2019-11-27 12:08	8305	30	2000	22,5	0,5	1008	10	59	3,0	0,1303	0,351	> 50	0,9792	7,1E-05	0,007	16	0,02	> 50	0,05	> 50	0,1276	0,35	52	2,05	0,73
2019-11-27 12:19	8305	29	2500	22,5	0,5	1007	10	59	3,0	0,1297	0,361	> 50	0,9798	8,2E-05	0,008	16	0,02	> 50	0,05	> 50	0,1270	0,36	52	2,05	0,75
2019-11-27 12:30	8305	31	3150	22,5	0,5	1007	10	59	3,0	0,1288	0,395	> 50	0,9835	6,2E-05	0,006	16	0,02	> 50	0,05	> 50	0,1267	0,40	52	2,05	0,82
2019-11-27 17:53	8305	31	4000	23,1	0,5	1006	10	56	3,0	0,1281	0,478	> 50	0,9777	6,3E-05	0,006	16	0,02	> 50	0,05	> 50	0,1253	0,48	51	2,05	0,99
2019-11-27 18:01	8305	30	5000	23,1	0,5	1006	10	56	3,0	0,1290	0,630	> 50	0,9903	3,7E-05	0,004	16	0,02	> 50	0,05	> 50	0,1278	0,63	51	2,05	1,30

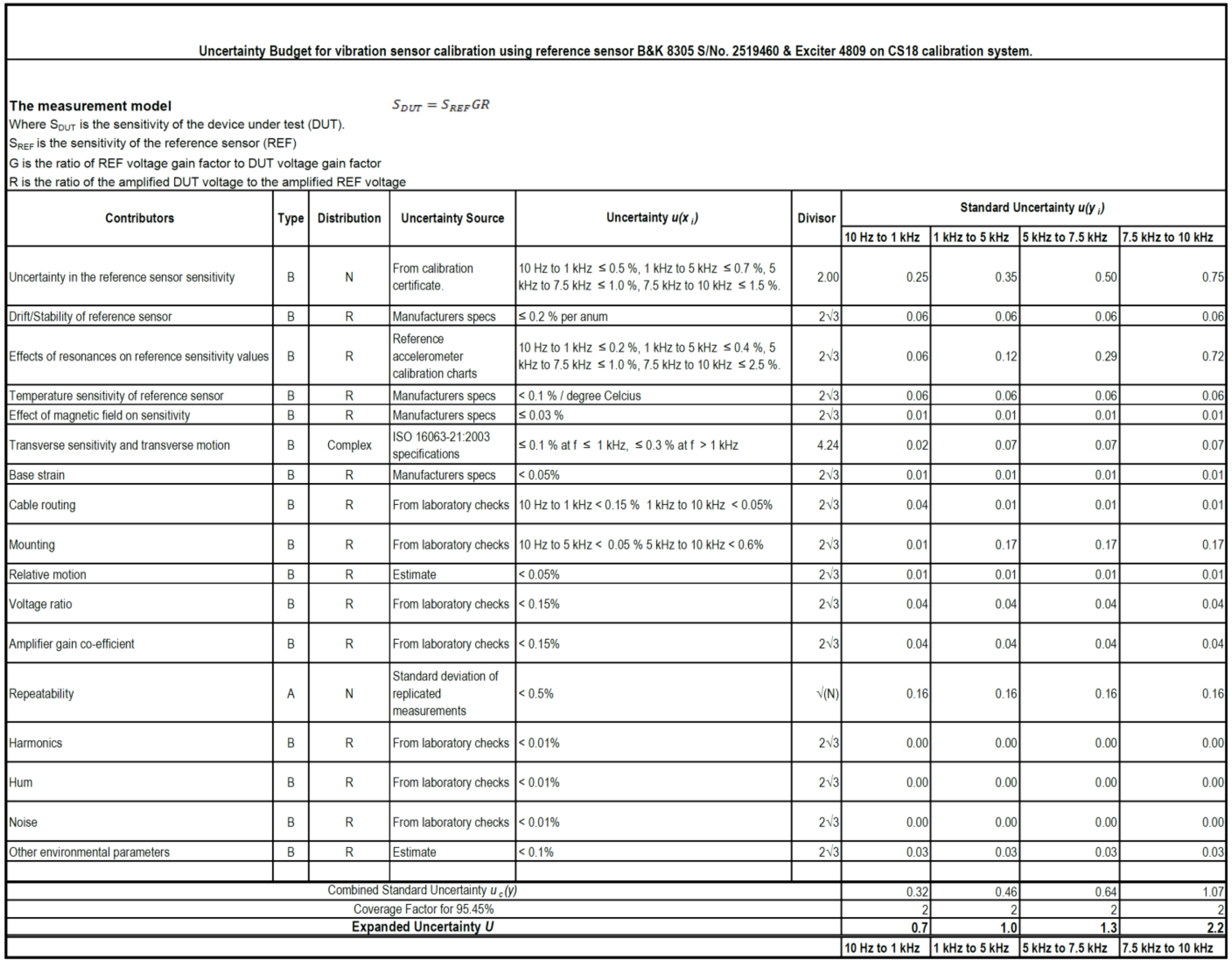
IPQ uncertainty budget Brüel & Kjær 4371-V (SN: 2046745) “single ended”

measurement ID				amb temp		amb press		amb rel hum		Sref (IPQ-8305S)			measured ratio				digitizing capacity (3458A)		accelerometer conditioning (NEXUS)		result				
date	accelero meter	nominal acel (m s^{-2})	nominal freq (Hz)	amb temp (ºC)	unc amb temp (ºC)	amb press (hPa)	unc amb press (hPa)	amb hum (%)	unc amb hum (%)	sensib (pC/m·s^{-2})	standard unc $u(x_i)$ %	deg freed	measured ratio	comb std dev	standard unc $u(x_i)$ %	deg freed	standard unc $u(x_i)$ %	deg freed	standard unc $u(x_i)$ %	deg freed	Sp (E_x)	comb unc $u(E_x)$ %	V eff	k	expand unc $U(E_x)$ %
2019-11-28 08:14	4371	20	16	22,5	0,5	1008	10	60	3,0	0,1303	0,457	> 50	8,0092	1,1E-02	0,135	16	0,02	> 50	0,05	> 50	1,0435	0,48	59	2,04	0,98
2019-11-28 08:27	4371	26	20	22,5	0,5	1008	10	61	3,0	0,1303	0,456	> 50	8,0102	6,7E-04	0,008	16	0,02	> 50	0,05	> 50	1,0437	0,46	51	2,05	0,94
2019-11-28 08:36	4371	30	25	22,5	0,5	1008	10	61	3,0	0,1303	0,456	> 50	7,9841	2,6E-04	0,003	16	0,02	> 50	0,05	> 50	1,0404	0,46	51	2,05	0,94
2019-11-28 08:44	4371	35	32	22,5	0,5	1008	10	61	3,0	0,1303	0,455	> 50	7,9653	5,1E-04	0,006	16	0,02	> 50	0,05	> 50	1,0380	0,46	51	2,05	0,94
2019-11-28 09:14	4371	30	40	22,4	0,5	1008	10	62	3,0	0,1303	0,454	> 50	7,9453	1,4E-04	0,002	16	0,02	> 50	0,05	> 50	1,0356	0,46	51	2,05	0,94
2019-11-28 09:26	4371	32	63	22,3	0,5	1009	10	62	3,0	0,1304	0,452	> 50	7,9105	6,9E-05	0,001	16	0,02	> 50	0,05	> 50	1,0314	0,45	51	2,05	0,93
2019-11-28 09:36	4371	34	80	22,3	0,5	1009	10	62	3,0	0,1304	0,450	> 50	7,9040	7,9E-05	0,001	16	0,02	> 50	0,05	> 50	1,0308	0,45	51	2,05	0,93
2019-11-28 09:42	4371	36	100	22,3	0,5	1009	10	62	3,0	0,1305	0,448	> 50	7,8877	1,6E-04	0,002	16	0,02	> 50	0,05	> 50	1,0290	0,45	51	2,05	0,92
2019-11-28 10:12	4371	35	125	22,6	0,5	1009	10	61	3,0	0,1305	0,445	> 50	7,8781	4,3E-04	0,005	16	0,02	> 50	0,05	> 50	1,0281	0,45	51	2,05	0,92
2019-11-28 10:18	4371	35	160	22,8	0,5	1009	10	61	3,0	0,1306	0,441	> 50	7,8583	1,5E-04	0,002	16	0,02	> 50	0,05	> 50	1,0260	0,44	51	2,05	0,91
2019-11-28 10:27	4371	33	200	22,8	0,5	1009	10	61	3,0	0,1306	0,437	> 50	7,8440	1,3E-04	0,002	16	0,02	> 50	0,05	> 50	1,0246	0,44	52	2,05	0,90
2019-11-28 10:33	4371	30	250	22,8	0,5	1009	10	61	3,0	0,1307	0,432	> 50	7,8275	3,6E-04	0,005	16	0,02	> 50	0,05	> 50	1,0231	0,44	52	2,05	0,89
2019-11-28 10:39	4371	30	315	22,7	0,5	1009	10	61	3,0	0,1308	0,426	> 50	7,8075	8,5E-05	0,001	16	0,02	> 50	0,05	> 50	1,0212	0,43	52	2,05	0,88
2019-11-28 10:47	4371	30	400	22,5	0,5	1009	10	62	3,0	0,1309	0,418	> 50	7,7975	1,9E-04	0,002	16	0,02	> 50	0,05	> 50	1,0206	0,42	52	2,05	0,86
2019-11-28 10:53	4371	30	500	22,4	0,5	1009	10	62	3,0	0,1310	0,410	> 50	7,7818	5,1E-05	0,001	16	0,02	> 50	0,05	> 50	1,0193	0,41	52	2,05	0,85
2019-11-28 11:02	4371	30	630	22,3	0,5	1010	10	62	3,0	0,1311	0,399	> 50	7,7695	6,0E-05	0,001	16	0,02	> 50	0,05	> 50	1,0184	0,40	52	2,05	0,83
2019-11-28 11:08	4371	30	800	22,3	0,5	1010	10	63	3,0	0,1311	0,387	> 50	7,7534	5,0E-05	0,001	16	0,02	> 50	0,05	> 50	1,0168	0,39	52	2,05	0,80
2019-11-28 11:13	4371	30	1000	22,3	0,5	1010	10	63	3,0	0,1312	0,375	> 50	7,7395	6,0E-05	0,001	16	0,02	> 50	0,05	> 50	1,0151	0,38	52	2,05	0,78
2019-11-28 11:23	4371	31	1250	22,2	0,5	1010	10	63	3,0	0,1311	0,364	> 50	7,7244	6,0E-05	0,001	16	0,02	> 50	0,05	> 50	1,0124	0,37	52	2,05	0,75
2019-11-28 11:31	4371	31	1600	22,2	0,5	1010	10	63	3,0	0,1308	0,353	> 50	7,7080	6,9E-05	0,001	16	0,02	> 50	0,05	> 50	1,0082	0,36	52	2,05	0,73
2019-11-28 11:36	4371	31	2000	22,2	0,5	1010	10	63	3,0	0,1303	0,351	> 50	7,6925	4,3E-05	0,001	16	0,02	> 50	0,05	> 50	1,0027	0,35	52	2,05	0,73
2019-11-28 11:43	4371	30	2500	22,2	0,5	1009	10	63	3,0	0,1297	0,361	> 50	7,6777	6,0E-05	0,001	16	0,02	> 50	0,05	> 50	0,9955	0,36	52	2,05	0,75
2019-11-28 11:51	4371	30	3150	22,2	0,5	1009	10	63	3,0	0,1288	0,395	> 50	7,6641	8,2E-05	0,001	16	0,02	> 50	0,05	> 50	0,9870	0,40	52	2,05	0,82
2019-11-28 12:03	4371	30	4000	22,2	0,5	1010	10	63	3,0	0,1281	0,478	> 50	7,6388	8,6E-05	0,001	16	0,02	> 50	0,05	> 50	0,9788	0,48	51	2,05	0,99
2019-11-28 12:13	4371	30	5000	22,2	0,5	1010	10	63	3,0	0,1290	0,630	> 50	7,6271	7,1E-05	0,001	16	0,02	> 50	0,05	> 50	0,9839	0,63	51	2,05	1,30

IPQ uncertainty budget Endevco 2270M8 (SN: 16198) “single ended”

measurement ID				amb temp		amb press		amb rel hum		Sref (IPQ-8305S)			measured ratio				digitizing capacity (3458A)		accelerometer conditioning (NEXUS)		result				
date	accelero meter	nominal acel (m s^{-2})	nominal freq (Hz)	amb temp (ºC)	unc amb temp (ºC)	amb press (hPa)	unc amb press (hPa)	amb hum (%)	unc amb hum (%)	sensib (pC/m·s^{-2})	standard unc $u(x_i)$ %	deg freed	measured ratio	comb std dev	standard unc $u(x_i)$ %	deg freed	standard unc $u(x_i)$ %	deg freed	standard unc $u(x_i)$ %	deg freed	Sp (E_x)	comb unc $u(E_x)$ %	V eff	k	expand unc $U(E_x)$ %
2019-11-28 15:46	2270	20	16	22,5	0,5	1008	10	65	3,0	0,1303	0,457	> 50	1,6302	1,7E-03	0,106	16	0,02	> 50	0,05	> 50	0,2124	0,47	56	2,05	0,97
2019-11-28 16:12	2270	33	25	22,4	0,5	1009	10	66	3,0	0,1303	0,456	> 50	1,6324	7,1E-05	0,004	16	0,02	> 50	0,05	> 50	0,2127	0,46	51	2,05	0,94
2019-11-28 16:23	2270	30	31	22,4	0,5	1008	10	66	3,0	0,1303	0,455	> 50	1,6300	5,0E-05	0,003	16	0,02	> 50	0,05	> 50	0,2124	0,46	51	2,05	0,94
2019-11-28 16:37	2270	30	40	22,3	0,5	1008	10	66	3,0	0,1303	0,454	> 50	1,6291	6,6E-05	0,004	16	0,02	> 50	0,05	> 50	0,2123	0,46	51	2,05	0,94
2019-11-28 16:50	2270	30	63	22,3	0,5	1009	10	66	3,0	0,1304	0,452	> 50	1,6317	6,5E-05	0,004	16	0,02	> 50	0,05	> 50	0,2127	0,45	51	2,05	0,93
2019-11-28 16:56	2270	33	80	22,3	0,5	1008	10	66	3,0	0,1304	0,450	> 50	1,6305	4,6E-04	0,028	16	0,02	> 50	0,05	> 50	0,2126	0,45	52	2,05	0,93
2019-11-28 17:06	2270	34	100	22,3	0,5	1009	10	66	3,0	0,1305	0,448	> 50	1,6282	5,6E-05	0,003	16	0,02	> 50	0,05	> 50	0,2124	0,45	51	2,05	0,92
2019-11-29 08:18	2270	32	125	22,7	0,5	1011	10	65	3,0	0,1305	0,445	> 50	1,6270	2,0E-04	0,012	16	0,02	> 50	0,05	> 50	0,2123	0,45	52	2,05	0,92
2019-11-29 08:28	2270	31	160	22,7	0,5	1011	10	65	3,0	0,1306	0,441	> 50	1,6273	7,8E-05	0,005	16	0,02	> 50	0,05	> 50	0,2125	0,44	52	2,05	0,91
2019-11-29 08:35	2270	31	200	22,7	0,5	1011	10	65	3,0	0,1306	0,437	> 50	1,6264	4,9E-05	0,003	16	0,02	> 50	0,05	> 50	0,2125	0,44	52	2,05	0,90
2019-11-29 08:43	2270	30	250	22,7	0,5	1011	10	65	3,0	0,1307	0,432	> 50	1,6276	1,5E-03	0,091	16	0,02	> 50	0,05	> 50	0,2127	0,44	56	2,05	0,91
2019-11-29 09:18	2270	32	315	22,3	0,5	1011	10	67	3,0	0,1308	0,426	> 50	1,6218	7,6E-05	0,005	16	0,02	> 50	0,05	> 50	0,2121	0,43	52	2,05	0,88
2019-11-29 09:25	2270	30	400	22,2	0,5	1012	10	68	3,0	0,1309	0,418	> 50	1,6220	4,6E-05	0,003	16	0,02	> 50	0,05	> 50	0,2123	0,42	52	2,05	0,86
2019-11-29 09:33	2270	29	500	22,1	0,5	1012	10	68	3,0	0,1310	0,410	> 50	1,6220	5,9E-05	0,004	16	0,02	> 50	0,05	> 50	0,2125	0,41	52	2,05	0,85
2019-11-29 09:47	2270	27	630	22,0	0,5	1012	10	69	3,0	0,1311	0,399	> 50	1,6215	5,2E-05	0,003	16	0,02	> 50	0,05	> 50	0,2125	0,40	52	2,05	0,83
2019-11-29 09:57	2270	28	800	22,2	0,5	1012	10	68	3,0	0,1311	0,387	> 50	1,6215	3,8E-04	0,024	16	0,02	> 50	0,05	> 50	0,2127	0,39	52	2,05	0,80
2019-11-29 10:22	2270	28	1000	22,3	0,5	1012	10	68	3,0	0,1312	0,375	> 50	1,6207	4,7E-05	0,003	16	0,02	> 50	0,05	> 50	0,2126	0,38	52	2,05	0,78
2019-11-29 10:29	2270	27	1250	22,1	0,5	1012	10	69	3,0	0,1311	0,364	> 50	1,6199	1,5E-04	0,009	16	0,02	> 50	0,05	> 50	0,2123	0,37	52	2,05	0,75
2019-11-29 10:39	2270	28	1600	22,0	0,5	1012	10	69	3,0	0,1308	0,353	> 50	1,6190	4,7E-05	0,003	16	0,02	> 50	0,05	> 50	0,2118	0,36	52	2,05	0,73
2019-11-29 10:53	2270	29	2000	21,9	0,5	1013	10	70	3,0	0,1303	0,351	> 50	1,6179	5,8E-05	0,004	16	0,02	> 50	0,05	> 50	0,2109	0,35	52	2,05	0,73
2019-11-29 11:00	2270	29	2500	21,9	0,5	1013	10	70	3,0	0,1297	0,361	> 50	1,6166	5,5E-05	0,003	16	0,02	> 50	0,05	> 50	0,2096	0,36	52	2,05	0,75
2019-11-29 11:13	2270	28	3150	21,8	0,5	1013	10	70	3,0	0,1288	0,395	> 50	1,6163	5,0E-05	0,003	16	0,02	> 50	0,05	> 50	0,2081	0,40	52	2,05	0,82
2019-11-29 11:22	2270	29	4000	21,8	0,5	1013	10	70	3,0	0,1281	0,478	> 50	1,6132	6,8E-05	0,004	16	0,02	> 50	0,05	> 50	0,2067	0,48	51	2,05	0,99
2019-11-29 11:44	2270	31	5000	21,7	0,5	1013	10	71	3,0	0,1290	0,630	> 50	1,6107	8,6E-05	0,005	16	0,02	> 50	0,05	> 50	0,2078	0,63	51	2,05	1,30

e) KEBS



Uncertainty Budget for vibration sensor calibration using reference sensor B&K 8305 S/No. 2519460 & Exciter 4809 on CS18 calibration system.

The measurement model $S_{DUT} = S_{REF}GR$

Where S_{DUT} is the sensitivity of the device under test (DUT).
S_{REF} is the sensitivity of the reference sensor (REF)
G is the ratio of REF voltage gain factor to DUT voltage gain factor
R is the ratio of the amplified DUT voltage to the amplified REF voltage

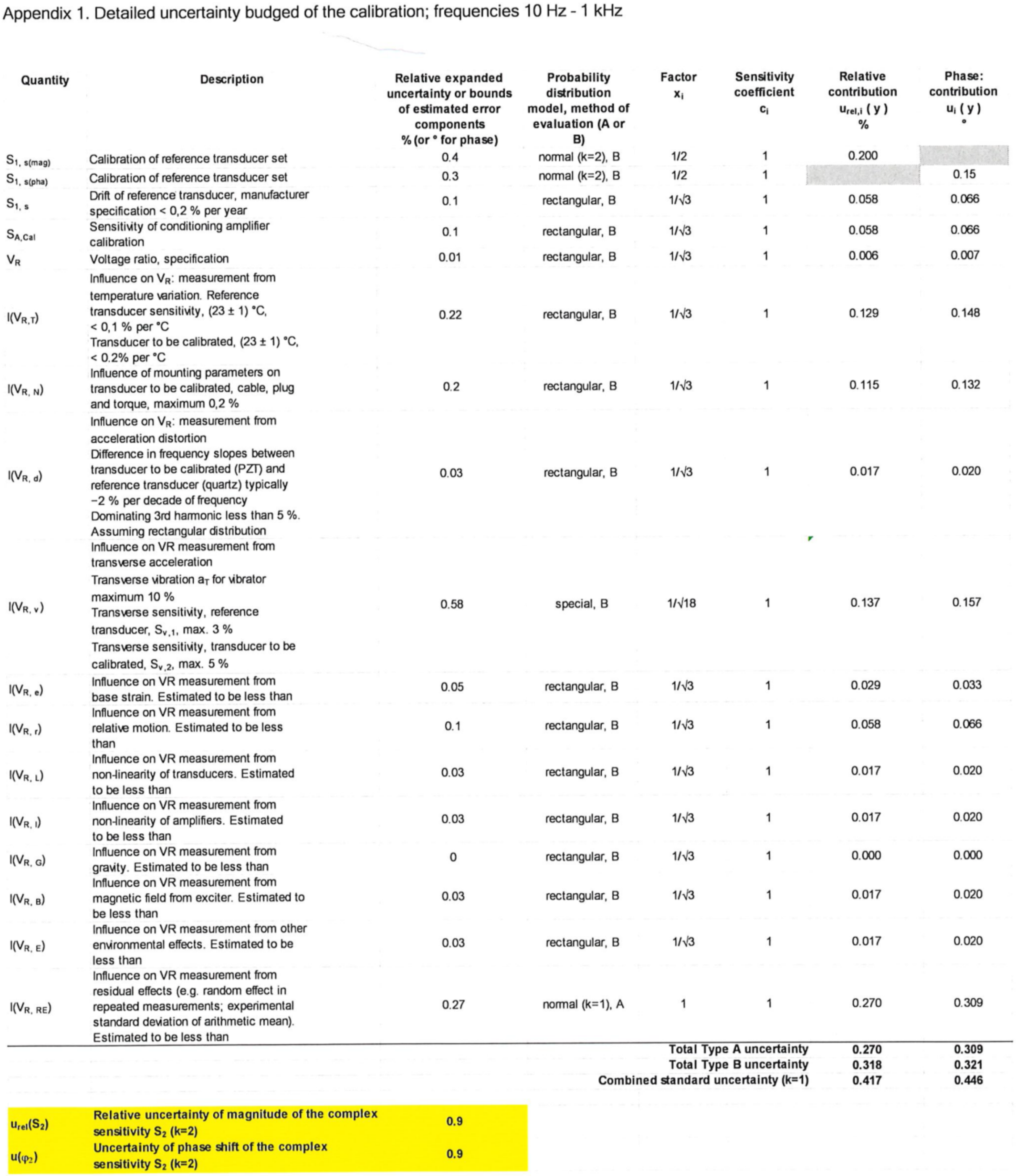
Contributors	**Type**	**Distribution**	**Uncertainty Source**	**Uncertainty *u(x $_i$)***	**Divisor**	**Standard Uncertainty *u(y $_i$)***			
						10 Hz to 1 kHz	**1 kHz to 5 kHz**	**5 kHz to 7.5 kHz**	**7.5 kHz to 10 kHz**
Uncertainty in the reference sensor sensitivity	B	N	From calibration certificate.	10 Hz to 1 kHz ≤ 0.5 %, 1 kHz to 5 kHz ≤ 0.7 %, 5 kHz to 7.5 kHz ≤ 1.0 %, 7.5 kHz to 10 kHz ≤ 1.5 %.	2.00	0.25	0.35	0.50	0.75
Drift/Stability of reference sensor	B	R	Manufacturers specs	≤ 0.2 % per anum	2√3	0.06	0.06	0.06	0.06
Effects of resonances on reference sensitivity values	B	R	Reference accelerometer calibration charts	10 Hz to 1 kHz ≤ 0.2 %, 1 kHz to 5 kHz ≤ 0.4 %, 5 kHz to 7.5 kHz ≤ 1.0 %, 7.5 kHz to 10 kHz ≤ 2.5 %.	2√3	0.06	0.12	0.29	0.72
Temperature sensitivity of reference sensor	B	R	Manufacturers specs	< 0.1 % / degree Celcius	2√3	0.06	0.06	0.06	0.06
Effect of magnetic field on sensitivity	B	R	Manufacturers specs	≤ 0.03 %	2√3	0.01	0.01	0.01	0.01
Transverse sensitivity and transverse motion	B	Complex	ISO 16063-21:2003 specifications	≤ 0.1 % at f ≤ 1 kHz, ≤ 0.3 % at f > 1 kHz	4.24	0.02	0.07	0.07	0.07
Base strain	B	R	Manufacturers specs	< 0.05%	2√3	0.01	0.01	0.01	0.01
Cable routing	B	R	From laboratory checks	10 Hz to 1 kHz < 0.15 % 1 kHz to 10 kHz < 0.05%	2√3	0.04	0.01	0.01	0.01
Mounting	B	R	From laboratory checks	10 Hz to 5 kHz < 0.05 % 5 kHz to 10 kHz < 0.6%	2√3	0.01	0.17	0.17	0.17
Relative motion	B	R	Estimate	< 0.05%	2√3	0.01	0.01	0.01	0.01
Voltage ratio	B	R	From laboratory checks	< 0.15%	2√3	0.04	0.04	0.04	0.04
Amplifier gain co-efficient	B	R	From laboratory checks	< 0.15%	2√3	0.04	0.04	0.04	0.04
Repeatability	A	N	Standard deviation of replicated measurements	< 0.5%	√(N)	0.16	0.16	0.16	0.16
Harmonics	B	R	From laboratory checks	< 0.01%	2√3	0.00	0.00	0.00	0.00
Hum	B	R	From laboratory checks	< 0.01%	2√3	0.00	0.00	0.00	0.00
Noise	B	R	From laboratory checks	< 0.01%	2√3	0.00	0.00	0.00	0.00
Other environmental parameters	B	R	Estimate	< 0.1%	2√3	0.03	0.03	0.03	0.03
Combined Standard Uncertainty *u $_c$(y)*						0.32	0.46	0.64	1.07
Coverage Factor for 95.45%						2	2	2	2
Expanded Uncertainty *U*						**0.7**	**1.0**	**1.3**	**2.2**
						10 Hz to 1 kHz	**1 kHz to 5 kHz**	**5 kHz to 7.5 kHz**	**7.5 kHz to 10 kHz**

u $_c$(y) is the combined standard uncertainty and is given by $\sqrt{(u(y)_1{}^2 + u(y)_2{}^2 + \cdots + u(y)_n{}^2)}$

The expanded uncertainty ***U*** is then given by multiplying the standard uncertainty ***u $_c$(y)*** by a coverage factor of **2**.

f) *MIKES*

MIKES uncertainty budget for transducer 8305-001



Appendix 1. Detailed uncertainty budged of the calibration; frequencies 10 Hz - 1 kHz

Quantity	Description	Relative expanded uncertainty or bounds of estimated error components % (or ° for phase)	Probability distribution model, method of evaluation (A or B)	Factor x_i	Sensitivity coefficient c_i	Relative contribution $u_{rel,i}(y)$ %	Phase: contribution $u_i(y)$ °
$S_{1,s(mag)}$	Calibration of reference transducer set	0.4	normal (k=2), B	1/2	1	0.200	
$S_{1,s(pha)}$	Calibration of reference transducer set	0.3	normal (k=2), B	1/2	1		0.15
$S_{1,s}$	Drift of reference transducer, manufacturer specification < 0,2 % per year	0.1	rectangular, B	1/√3	1	0.058	0.066
$S_{A,Cal}$	Sensitivity of conditioning amplifier calibration	0.1	rectangular, B	1/√3	1	0.058	0.066
V_R	Voltage ratio, specification	0.01	rectangular, B	1/√3	1	0.006	0.007
$I(V_{R,T})$	Influence on V_R: measurement from temperature variation. Reference transducer sensitivity, (23 ± 1) °C, < 0,1 % per °C Transducer to be calibrated, (23 ± 1) °C, < 0.2% per °C	0.22	rectangular, B	1/√3	1	0.129	0.148
$I(V_{R,N})$	Influence of mounting parameters on transducer to be calibrated, cable, plug and torque, maximum 0,2 %	0.2	rectangular, B	1/√3	1	0.115	0.132
$I(V_{R,d})$	Influence on V_R: measurement from acceleration distortion Difference in frequency slopes between transducer to be calibrated (PZT) and reference transducer (quartz) typically −2 % per decade of frequency Dominating 3rd harmonic less than 5 %. Assuming rectangular distribution	0.03	rectangular, B	1/√3	1	0.017	0.020
$I(V_{R,v})$	Influence on VR measurement from transverse acceleration Transverse vibration a_T for vibrator maximum 10 % Transverse sensitivity, reference transducer, $S_{v,1}$, max. 3 % Transverse sensitivity, transducer to be calibrated, $S_{v,2}$, max. 5 %	0.58	special, B	1/√18	1	0.137	0.157
$I(V_{R,e})$	Influence on VR measurement from base strain. Estimated to be less than	0.05	rectangular, B	1/√3	1	0.029	0.033
$I(V_{R,r})$	Influence on VR measurement from relative motion. Estimated to be less than	0.1	rectangular, B	1/√3	1	0.058	0.066
$I(V_{R,L})$	Influence on VR measurement from non-linearity of transducers. Estimated to be less than	0.03	rectangular, B	1/√3	1	0.017	0.020
$I(V_{R,I})$	Influence on VR measurement from non-linearity of amplifiers. Estimated to be less than	0.03	rectangular, B	1/√3	1	0.017	0.020
$I(V_{R,G})$	Influence on VR measurement from gravity. Estimated to be less than	0	rectangular, B	1/√3	1	0.000	0.000
$I(V_{R,B})$	Influence on VR measurement from magnetic field from exciter. Estimated to be less than	0.03	rectangular, B	1/√3	1	0.017	0.020
$I(V_{R,E})$	Influence on VR measurement from other environmental effects. Estimated to be less than	0.03	rectangular, B	1/√3	1	0.017	0.020
$I(V_{R,RE})$	Influence on VR measurement from residual effects (e.g. random effect in repeated measurements; experimental standard deviation of arithmetic mean). Estimated to be less than	0.27	normal (k=1), A	1	1	0.270	0.309
					Total Type A uncertainty	**0.270**	**0.309**
					Total Type B uncertainty	**0.318**	**0.321**
					Combined standard uncertainty (k=1)	**0.417**	**0.446**

$u_{rel}(S_2)$	**Relative uncertainty of magnitude of the complex sensitivity S_2 (k=2)**	**0.9**
$u(\varphi_2)$	**Uncertainty of phase shift of the complex sensitivity S_2 (k=2)**	**0.9**

Appendix 1. Detailed uncertainty budged of the calibration; frequencies 1.25 kHz - 4.5 kHz

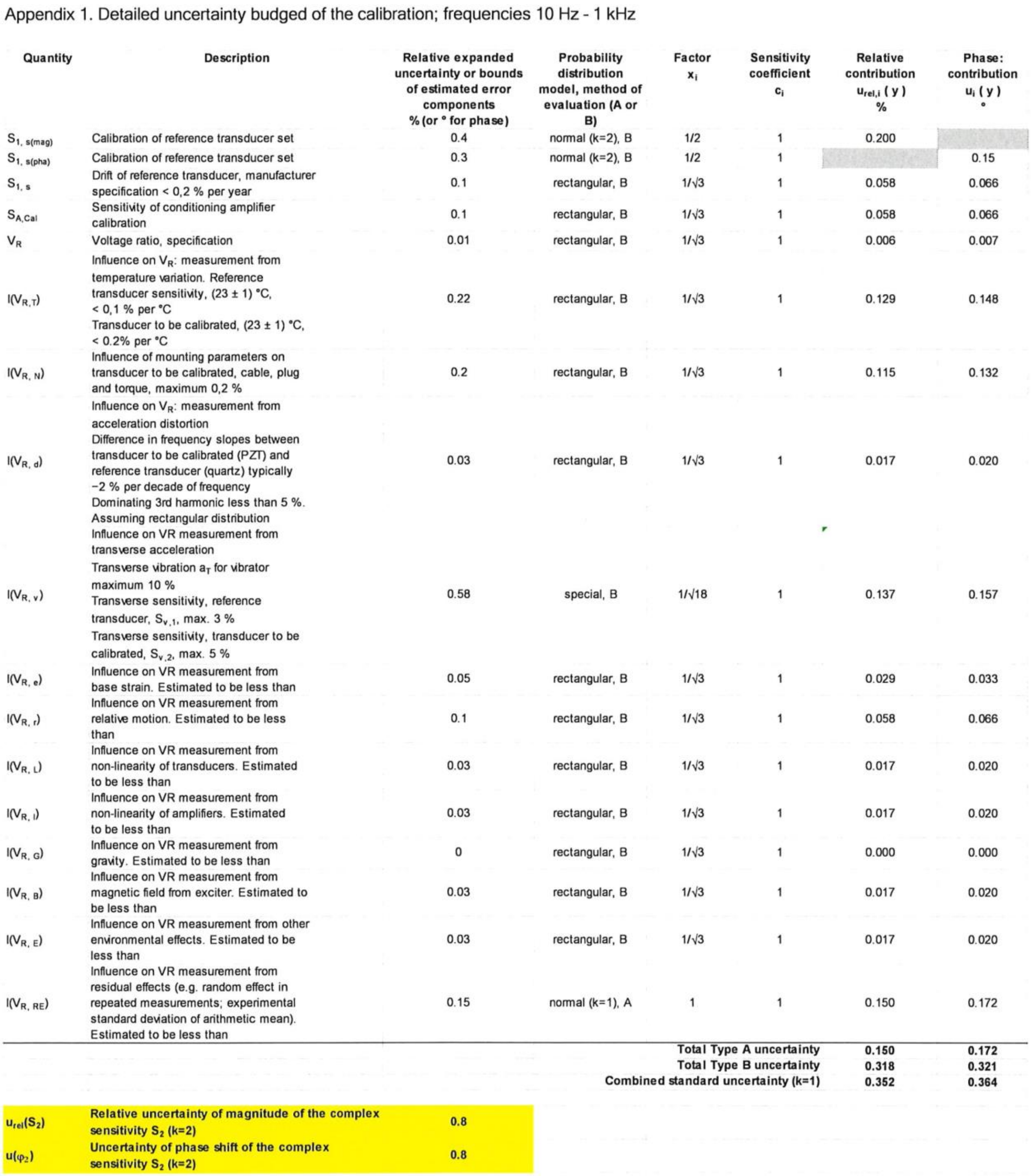
Quantity	Description	Relative expanded uncertainty or bounds of estimated error components % (or ° for phase)	Probability distribution model, method of evaluation (A or B)	Factor x_i	Sensitivity coefficient c_i	Relative contribution $u_{rel,i}(y)$ %	Phase: contribution $u_i(y)$ °
$S_{1, s(mag)}$	Calibration of reference transducer set	0.4	normal (k=2), B	1/2	1	0.200	
$S_{1, s(pha)}$	Calibration of reference transducer set	0.3	normal (k=2), B	1/2	1		0.15
$S_{1, s}$	Drift of reference transducer, manufacturer specification < 0,2 % per year	0.1	rectangular, B	1/√3	1	0.058	0.066
$S_{A,Cal}$	Sensitivity of conditioning amplifier calibration	0.1	rectangular, B	1/√3	1	0.058	0.066
V_R	Voltage ratio, specification	0.01	rectangular, B	1/√3	1	0.006	0.007
$I(V_{R,T})$	Influence on V_R: measurement from temperature variation. Reference transducer sensitivity, (23 ± 1) °C, < 0,1 % per °C Transducer to be calibrated, (23 ± 1) °C, < 0.2% per °C	0.22	rectangular, B	1/√3	1	0.129	0.148
$I(V_{R, N})$	Influence of mounting parameters on transducer to be calibrated, cable, plug and torque, maximum 0,2 %	0.2	rectangular, B	1/√3	1	0.115	0.132
$I(V_{R, d})$	Influence on V_R: measurement from acceleration distortion Difference in frequency slopes between transducer to be calibrated (PZT) and reference transducer (quartz) typically −2 % per decade of frequency Dominating 3rd harmonic less than 5 %. Assuming rectangular distribution	0.03	rectangular, B	1/√3	1	0.017	0.020
$I(V_{R, v})$	Influence on VR measurement from transverse acceleration Transverse vibration a_T for vibrator maximum 20 % Transverse sensitivity, reference transducer, $S_{v,1}$, max. 3 % Transverse sensitivity, transducer to be calibrated, $S_{v,2}$, max. 5 %	1.17	special, B	1/√18	1	0.275	0.315
$I(V_{R, e})$	Influence on VR measurement from base strain. Estimated to be less than	0.05	rectangular, B	1/√3	1	0.029	0.033
$I(V_{R, r})$	Influence on VR measurement from relative motion. Estimated to be less than	0.8	rectangular, B	1/√3	1	0.462	0.529
$I(V_{R, L})$	Influence on VR measurement from non-linearity of transducers. Estimated to be less than	0.03	rectangular, B	1/√3	1	0.017	0.020
$I(V_{R, l})$	Influence on VR measurement from non-linearity of amplifiers. Estimated to be less than	0.03	rectangular, B	1/√3	1	0.017	0.020
$I(V_{R, G})$	Influence on VR measurement from gravity. Estimated to be less than	0	rectangular, B	1/√3	1	0.000	0.000
$I(V_{R, B})$	Influence on VR measurement from magnetic field from exciter. Estimated to be less than	0.03	rectangular, B	1/√3	1	0.017	0.020
$I(V_{R, E})$	Influence on VR measurement from other environmental effects. Estimated to be less than	0.03	rectangular, B	1/√3	1	0.017	0.020
$I(V_{R, RE})$	Influence on VR measurement from residual effects (e.g. random effect in repeated measurements; experimental standard deviation of arithmetic mean). Estimated to be less than	0.11	normal (k=1), A	1	1	0.110	0.126
					Total Type A uncertainty	**0.110**	**0.126**
					Total Type B uncertainty	**0.607**	**0.673**
					Combined standard uncertainty (k=1)	**0.616**	**0.685**

$u_{rel}(S_2)$	**Relative uncertainty of magnitude of the complex sensitivity S_2 (k=2)**	**1.3**
$u(\varphi_2)$	**Uncertainty of phase shift of the complex sensitivity S_2 (k=2)**	**1.4**

Appendix 1. Detailed uncertainty budged of the calibration; frequencies 5 kHz - 10 kHz

Quantity	Description	Relative expanded uncertainty or bounds of estimated error components % (or ° for phase)	Probability distribution model, method of evaluation (A or B)	Factor x_i	Sensitivity coefficient c_i	Relative contribution $u_{rel,i}(y)$ %	Phase: contribution $u_i(y)$ °
$S_{1,\,s(mag)}$	Calibration of reference transducer set	0.6	normal (k=2), B	1/2	1	0.300	
$S_{1,\,s(pha)}$	Calibration of reference transducer set	1	normal (k=2), B	1/2	1		0.5
$S_{1,\,s}$	Drift of reference transducer, manufacturer specification < 0,2 % per year	0.1	rectangular, B	1/√3	1	0.058	0.066
$S_{A,Cal}$	Sensitivity of conditioning amplifier calibration	0.1	rectangular, B	1/√3	1	0.058	0.066
V_R	Voltage ratio, specification	0.01	rectangular, B	1/√3	1	0.006	0.007
$I(V_{R,T})$	Influence on V_R: measurement from temperature variation. Reference transducer sensitivity, (23 ± 1) °C, < 0,1 % per °C Transducer to be calibrated, (23 ± 1) °C, < 0.2% per °C	0.22	rectangular, B	1/√3	1	0.129	0.148
$I(V_{R,\,N})$	Influence of mounting parameters on transducer to be calibrated, cable, plug and torque, maximum 0,3 %	0.3	rectangular, B	1/√3	1	0.173	0.198
$I(V_{R,\,d})$	Influence on V_R: measurement from acceleration distortion Difference in frequency slopes between transducer to be calibrated (PZT) and reference transducer (quartz) typically −2 % per decade of frequency Dominating 3rd harmonic less than 5 %. Assuming rectangular distribution	0.03	rectangular, B	1/√3	1	0.017	0.020
$I(V_{R,\,v})$	Influence on VR measurement from transverse acceleration Transverse vibration a_T for vibrator maximum 25 % Transverse sensitivity, reference transducer, $S_{v,1}$, max. 3 % Transverse sensitivity, transducer to be calibrated, $S_{v,2}$, max. 5 %	1.46	special, B	1/√18	1	0.344	0.394
$I(V_{R,\,e})$	Influence on VR measurement from base strain. Estimated to be less than	0.05	rectangular, B	1/√3	1	0.029	0.033
$I(V_{R,\,r})$	Influence on VR measurement from relative motion. Estimated to be less than	1.1	rectangular, B	1/√3	1	0.635	0.728
$I(V_{R,\,L})$	Influence on VR measurement from non-linearity of transducers. Estimated to be less than	0.03	rectangular, B	1/√3	1	0.017	0.020
$I(V_{R,\,I})$	Influence on VR measurement from non-linearity of amplifiers. Estimated to be less than	0.03	rectangular, B	1/√3	1	0.017	0.020
$I(V_{R,\,G})$	Influence on VR measurement from gravity. Estimated to be less than	0	rectangular, B	1/√3	1	0.000	0.000
$I(V_{R,\,B})$	Influence on VR measurement from magnetic field from exciter. Estimated to be less than	0.03	rectangular, B	1/√3	1	0.017	0.020
$I(V_{R,\,E})$	Influence on VR measurement from other environmental effects. Estimated to be less than	0.03	rectangular, B	1/√3	1	0.017	0.020
$I(V_{R,\,RE})$	Influence on VR measurement from residual effects (e.g. random effect in repeated measurements; experimental standard deviation of arithmetic mean). Estimated to be less than	0.42	normal (k=1), A	1	1	0.420	0.481
			Total Type A uncertainty			**0.420**	**0.481**
			Total Type B uncertainty			**0.817**	**1.004**
			Combined standard uncertainty (k=1)			**0.918**	**1.113**
$u_{rel}(S_2)$	**Relative uncertainty of magnitude of the complex sensitivity S_2 (k=2)**	**1.9**					
$u(\varphi_2)$	**Uncertainty of phase shift of the complex sensitivity S_2 (k=2)**	**2.3**					

MIKES uncertainty budget for transducer 4371-V



Appendix 1. Detailed uncertainty budged of the calibration; frequencies 10 Hz - 1 kHz

Quantity	Description	Relative expanded uncertainty or bounds of estimated error components % (or ° for phase)	Probability distribution model, method of evaluation (A or B)	Factor x_i	Sensitivity coefficient c_i	Relative contribution $u_{rel,i}(y)$ %	Phase: contribution $u_i(y)$ °
$S_{1,\ s(mag)}$	Calibration of reference transducer set	0.4	normal (k=2), B	1/2	1	0.200	
$S_{1,\ s(pha)}$	Calibration of reference transducer set	0.3	normal (k=2), B	1/2	1		0.15
$S_{1,\ s}$	Drift of reference transducer, manufacturer specification < 0,2 % per year	0.1	rectangular, B	1/√3	1	0.058	0.066
$S_{A,Cal}$	Sensitivity of conditioning amplifier calibration	0.1	rectangular, B	1/√3	1	0.058	0.066
V_R	Voltage ratio, specification	0.01	rectangular, B	1/√3	1	0.006	0.007
$I(V_{R,T})$	Influence on V_R: measurement from temperature variation. Reference transducer sensitivity, (23 ± 1) °C, < 0,1 % per °C Transducer to be calibrated, (23 ± 1) °C, < 0.2% per °C	0.22	rectangular, B	1/√3	1	0.129	0.148
$I(V_{R,\ N})$	Influence of mounting parameters on transducer to be calibrated, cable, plug and torque, maximum 0,2 %	0.2	rectangular, B	1/√3	1	0.115	0.132
$I(V_{R,\ d})$	Influence on V_R: measurement from acceleration distortion Difference in frequency slopes between transducer to be calibrated (PZT) and reference transducer (quartz) typically −2 % per decade of frequency Dominating 3rd harmonic less than 5 %. Assuming rectangular distribution	0.03	rectangular, B	1/√3	1	0.017	0.020
$I(V_{R,\ v})$	Influence on VR measurement from transverse acceleration Transverse vibration a_T for vibrator maximum 10 % Transverse sensitivity, reference transducer, $S_{v,1}$, max. 3 % Transverse sensitivity, transducer to be calibrated, $S_{v,2}$, max. 5 %	0.58	special, B	1/√18	1	0.137	0.157
$I(V_{R,\ e})$	Influence on VR measurement from base strain. Estimated to be less than	0.05	rectangular, B	1/√3	1	0.029	0.033
$I(V_{R,\ r})$	Influence on VR measurement from relative motion. Estimated to be less than	0.1	rectangular, B	1/√3	1	0.058	0.066
$I(V_{R,\ L})$	Influence on VR measurement from non-linearity of transducers. Estimated to be less than	0.03	rectangular, B	1/√3	1	0.017	0.020
$I(V_{R,\ i})$	Influence on VR measurement from non-linearity of amplifiers. Estimated to be less than	0.03	rectangular, B	1/√3	1	0.017	0.020
$I(V_{R,\ G})$	Influence on VR measurement from gravity. Estimated to be less than	0	rectangular, B	1/√3	1	0.000	0.000
$I(V_{R,\ B})$	Influence on VR measurement from magnetic field from exciter. Estimated to be less than	0.03	rectangular, B	1/√3	1	0.017	0.020
$I(V_{R,\ E})$	Influence on VR measurement from other environmental effects. Estimated to be less than	0.03	rectangular, B	1/√3	1	0.017	0.020
$I(V_{R,\ RE})$	Influence on VR measurement from residual effects (e.g. random effect in repeated measurements; experimental standard deviation of arithmetic mean). Estimated to be less than	0.15	normal (k=1), A	1	1	0.150	0.172
					Total Type A uncertainty	**0.150**	**0.172**
					Total Type B uncertainty	**0.318**	**0.321**
					Combined standard uncertainty (k=1)	**0.352**	**0.364**

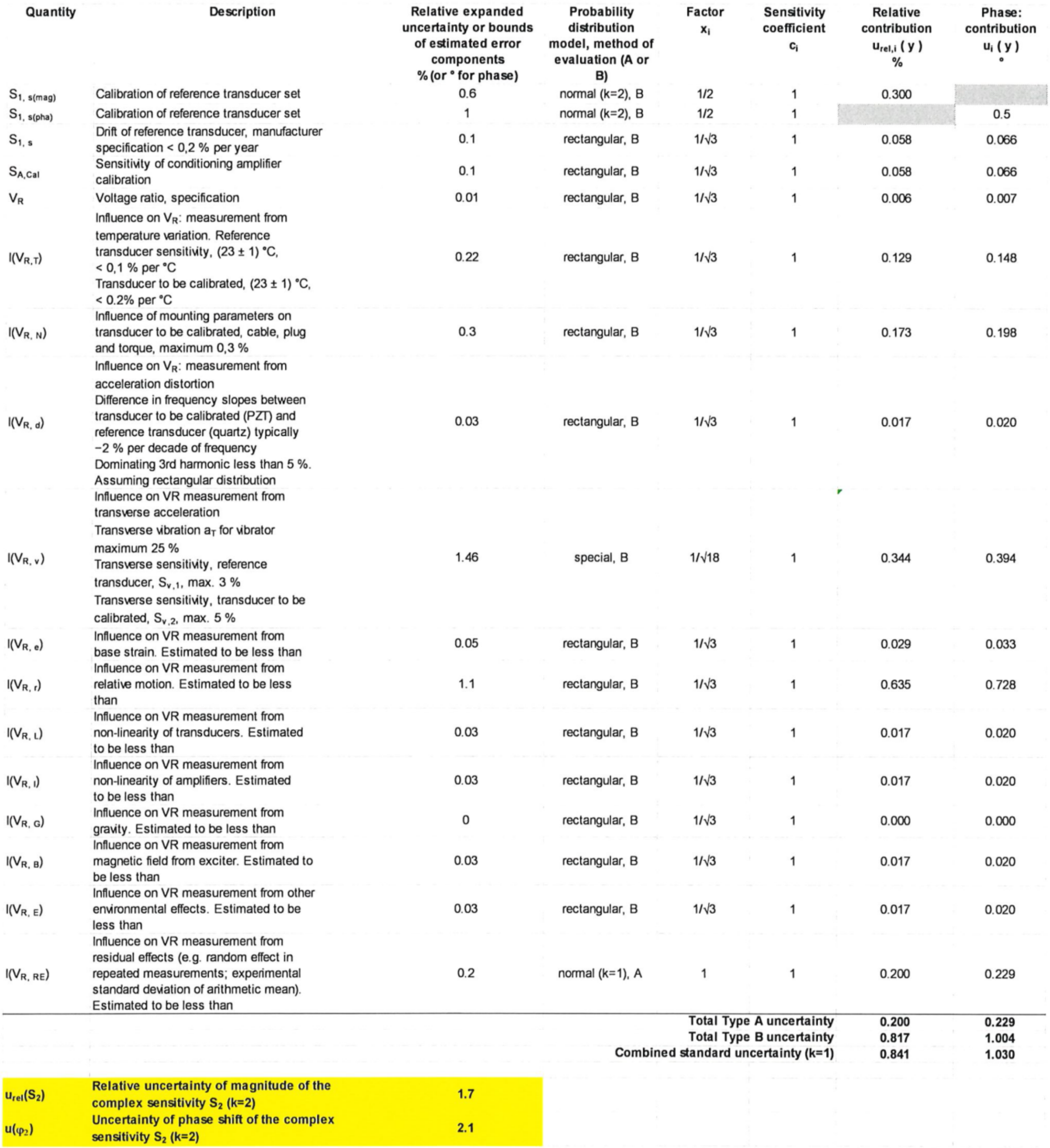
$u_{rel}(S_2)$	**Relative uncertainty of magnitude of the complex sensitivity S_2 (k=2)**	**0.8**
$u(\varphi_2)$	**Uncertainty of phase shift of the complex sensitivity S_2 (k=2)**	**0.8**

Appendix 1. Detailed uncertainty budged of the calibration; frequencies 1.25 kHz - 4.5 kHz

Quantity	Description	Relative expanded uncertainty or bounds of estimated error components % (or ° for phase)	Probability distribution model, method of evaluation (A or B)	Factor x_i	Sensitivity coefficient c_i	Relative contribution $u_{rel,i}(y)$ %	Phase: contribution $u_i(y)$ °
$S_{1,\ s(mag)}$	Calibration of reference transducer set	0.4	normal (k=2), B	1/2	1	0.200	
$S_{1,\ s(pha)}$	Calibration of reference transducer set	0.3	normal (k=2), B	1/2	1		0.15
$S_{1,\ s}$	Drift of reference transducer, manufacturer specification < 0,2 % per year	0.1	rectangular, B	1/√3	1	0.058	0.066
$S_{A,Cal}$	Sensitivity of conditioning amplifier calibration	0.1	rectangular, B	1/√3	1	0.058	0.066
V_R	Voltage ratio, specification	0.01	rectangular, B	1/√3	1	0.006	0.007
$I(V_{R,T})$	Influence on V_R: measurement from temperature variation. Reference transducer sensitivity, (23 ± 1) °C, < 0,1 % per °C Transducer to be calibrated, (23 ± 1) °C, < 0.2% per °C	0.22	rectangular, B	1/√3	1	0.129	0.148
$I(V_{R,\ N})$	Influence of mounting parameters on transducer to be calibrated, cable, plug and torque, maximum 0,2 %	0.2	rectangular, B	1/√3	1	0.115	0.132
$I(V_{R,\ d})$	Influence on V_R: measurement from acceleration distortion Difference in frequency slopes between transducer to be calibrated (PZT) and reference transducer (quartz) typically −2 % per decade of frequency Dominating 3rd harmonic less than 5 %. Assuming rectangular distribution	0.03	rectangular, B	1/√3	1	0.017	0.020
$I(V_{R,\ v})$	Influence on VR measurement from transverse acceleration Transverse vibration a_T for vibrator maximum 20 % Transverse sensitivity, reference transducer, $S_{v,1}$, max. 3 % Transverse sensitivity, transducer to be calibrated, $S_{v,2}$, max. 5 %	1.17	special, B	1/√18	1	0.275	0.315
$I(V_{R,\ e})$	Influence on VR measurement from base strain. Estimated to be less than	0.05	rectangular, B	1/√3	1	0.029	0.033
$I(V_{R,\ r})$	Influence on VR measurement from relative motion. Estimated to be less than	0.8	rectangular, B	1/√3	1	0.462	0.529
$I(V_{R,\ L})$	Influence on VR measurement from non-linearity of transducers. Estimated to be less than	0.03	rectangular, B	1/√3	1	0.017	0.020
$I(V_{R,\ I})$	Influence on VR measurement from non-linearity of amplifiers. Estimated to be less than	0.03	rectangular, B	1/√3	1	0.017	0.020
$I(V_{R,\ G})$	Influence on VR measurement from gravity. Estimated to be less than	0	rectangular, B	1/√3	1	0.000	0.000
$I(V_{R,\ B})$	Influence on VR measurement from magnetic field from exciter. Estimated to be less than	0.03	rectangular, B	1/√3	1	0.017	0.020
$I(V_{R,\ E})$	Influence on VR measurement from other environmental effects. Estimated to be less than	0.03	rectangular, B	1/√3	1	0.017	0.020
$I(V_{R,\ RE})$	Influence on VR measurement from residual effects (e.g. random effect in repeated measurements; experimental standard deviation of arithmetic mean). Estimated to be less than	0.15	normal (k=1), A	1	1	0.150	0.172
					Total Type A uncertainty	**0.150**	**0.172**
					Total Type B uncertainty	**0.607**	**0.673**
					Combined standard uncertainty (k=1)	**0.625**	**0.695**

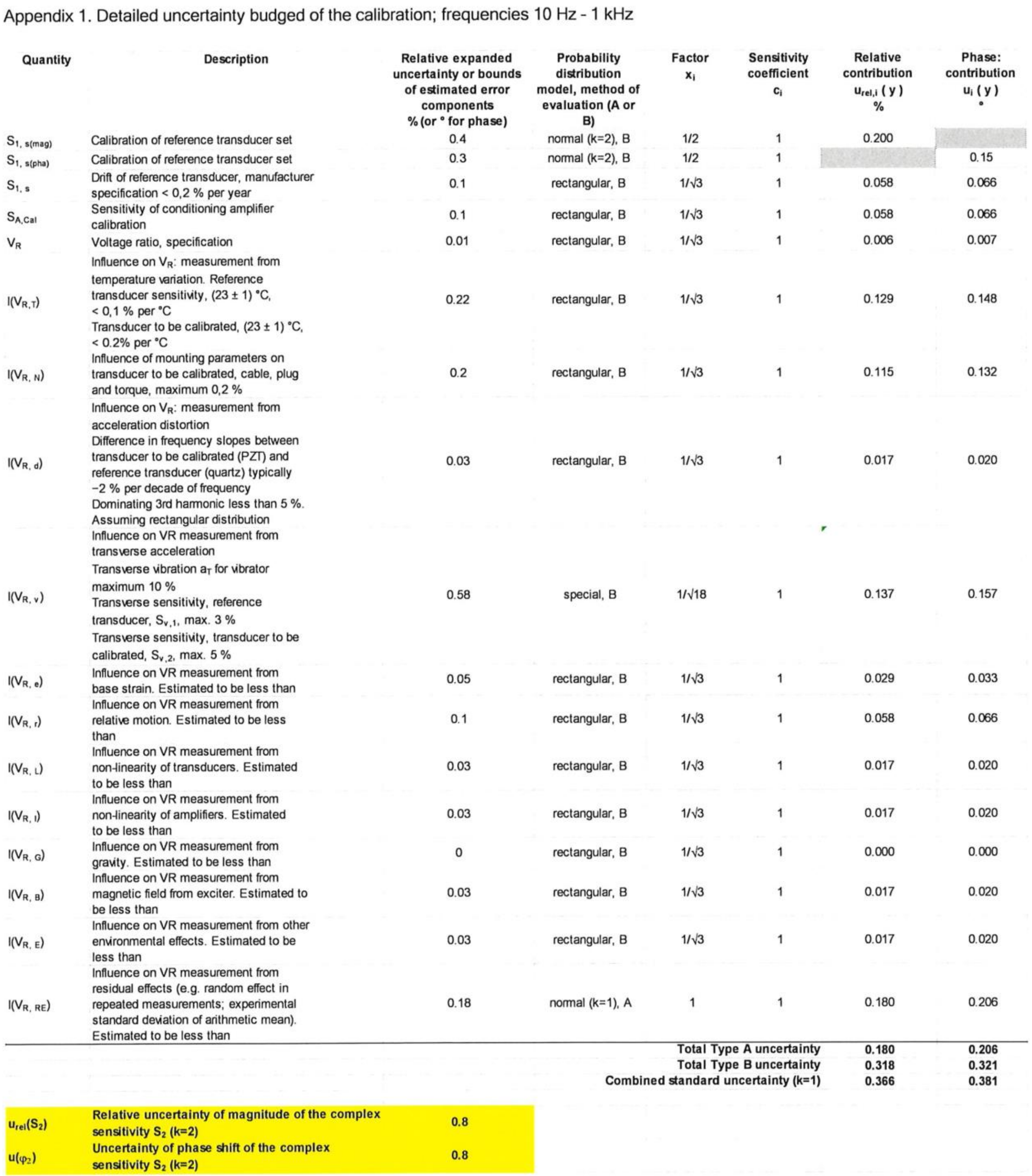
$u_{rel}(S_2)$	**Relative uncertainty of magnitude of the complex sensitivity S_2 (k=2)**	**1.3**
$u(\varphi_2)$	**Uncertainty of phase shift of the complex sensitivity S_2 (k=2)**	**1.4**

Appendix 1. Detailed uncertainty budged of the calibration; frequencies 5 kHz - 10 kHz



Quantity	Description	Relative expanded uncertainty or bounds of estimated error components % (or ° for phase)	Probability distribution model, method of evaluation (A or B)	Factor x_i	Sensitivity coefficient c_i	Relative contribution $u_{rel,i}$ (y) %	Phase: contribution u_i (y) °
$S_{1,s(mag)}$	Calibration of reference transducer set	0.6	normal (k=2), B	1/2	1	0.300	
$S_{1,s(pha)}$	Calibration of reference transducer set	1	normal (k=2), B	1/2	1		0.5
$S_{1,s}$	Drift of reference transducer, manufacturer specification < 0,2 % per year	0.1	rectangular, B	1/√3	1	0.058	0.066
$S_{A,Cal}$	Sensitivity of conditioning amplifier calibration	0.1	rectangular, B	1/√3	1	0.058	0.066
V_R	Voltage ratio, specification	0.01	rectangular, B	1/√3	1	0.006	0.007
$I(V_{R,T})$	Influence on V_R: measurement from temperature variation. Reference transducer sensitivity, (23 ± 1) °C, < 0,1 % per °C Transducer to be calibrated, (23 ± 1) °C, < 0.2% per °C	0.22	rectangular, B	1/√3	1	0.129	0.148
$I(V_{R,N})$	Influence of mounting parameters on transducer to be calibrated, cable, plug and torque, maximum 0,3 %	0.3	rectangular, B	1/√3	1	0.173	0.198
$I(V_{R,d})$	Influence on V_R: measurement from acceleration distortion Difference in frequency slopes between transducer to be calibrated (PZT) and reference transducer (quartz) typically −2 % per decade of frequency Dominating 3rd harmonic less than 5 %. Assuming rectangular distribution	0.03	rectangular, B	1/√3	1	0.017	0.020
$I(V_{R,v})$	Influence on VR measurement from transverse acceleration Transverse vibration a_T for vibrator maximum 25 % Transverse sensitivity, reference transducer, $S_{v,1}$, max. 3 % Transverse sensitivity, transducer to be calibrated, $S_{v,2}$, max. 5 %	1.46	special, B	1/√18	1	0.344	0.394
$I(V_{R,e})$	Influence on VR measurement from base strain. Estimated to be less than	0.05	rectangular, B	1/√3	1	0.029	0.033
$I(V_{R,r})$	Influence on VR measurement from relative motion. Estimated to be less than	1.1	rectangular, B	1/√3	1	0.635	0.728
$I(V_{R,L})$	Influence on VR measurement from non-linearity of transducers. Estimated to be less than	0.03	rectangular, B	1/√3	1	0.017	0.020
$I(V_{R,l})$	Influence on VR measurement from non-linearity of amplifiers. Estimated to be less than	0.03	rectangular, B	1/√3	1	0.017	0.020
$I(V_{R,G})$	Influence on VR measurement from gravity. Estimated to be less than	0	rectangular, B	1/√3	1	0.000	0.000
$I(V_{R,B})$	Influence on VR measurement from magnetic field from exciter. Estimated to be less than	0.03	rectangular, B	1/√3	1	0.017	0.020
$I(V_{R,E})$	Influence on VR measurement from other environmental effects. Estimated to be less than	0.03	rectangular, B	1/√3	1	0.017	0.020
$I(V_{R,RE})$	Influence on VR measurement from residual effects (e.g. random effect in repeated measurements; experimental standard deviation of arithmetic mean). Estimated to be less than	0.2	normal (k=1), A	1	1	0.200	0.229
					Total Type A uncertainty	**0.200**	**0.229**
					Total Type B uncertainty	**0.817**	**1.004**
					Combined standard uncertainty (k=1)	**0.841**	**1.030**
$u_{rel}(S_2)$	**Relative uncertainty of magnitude of the complex sensitivity S_2 (k=2)**	**1.7**					
$u(\varphi_2)$	**Uncertainty of phase shift of the complex sensitivity S_2 (k=2)**	**2.1**					

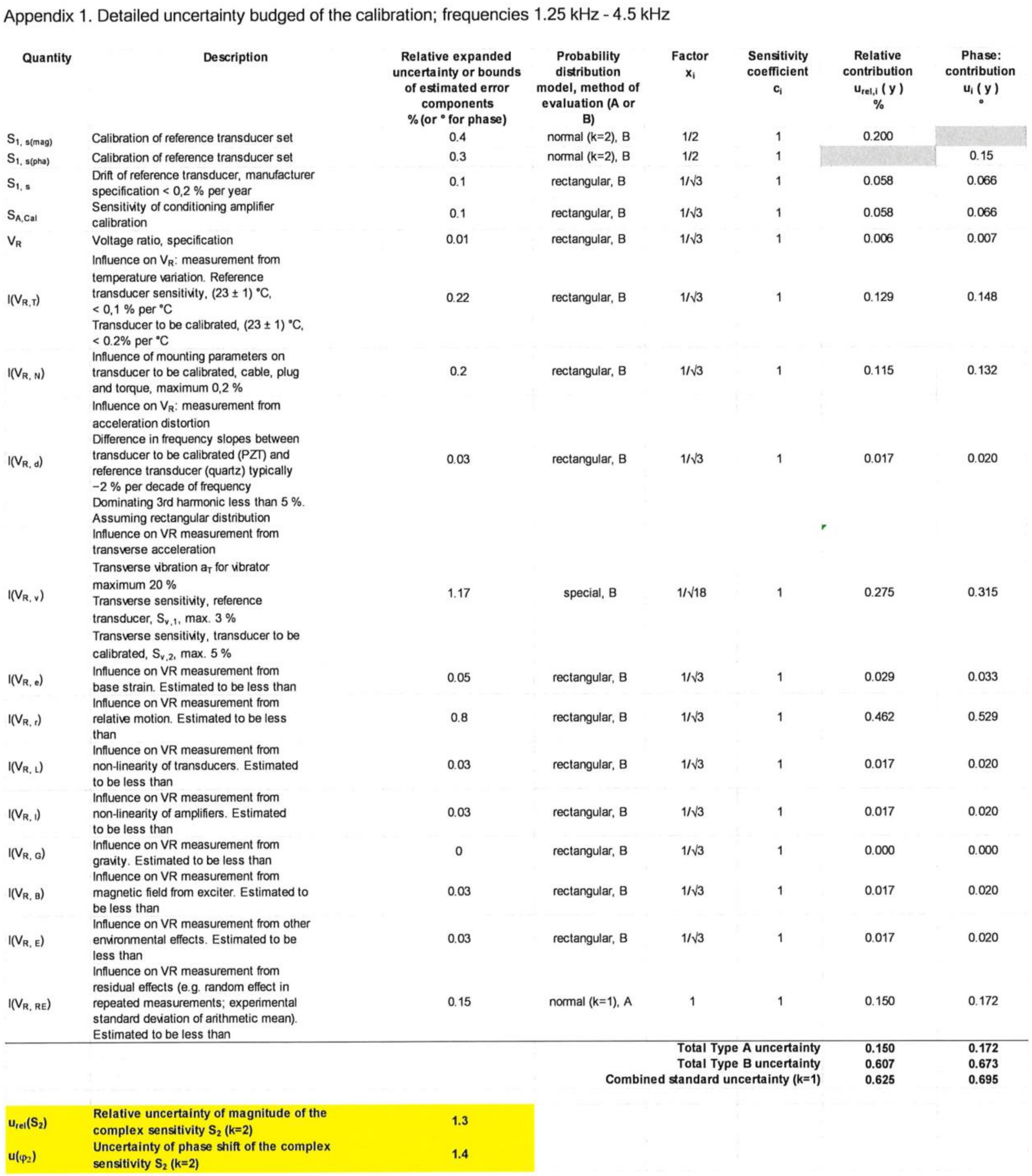
MIKES uncertainty budget for transducer 2270M8



Appendix 1. Detailed uncertainty budged of the calibration; frequencies 10 Hz - 1 kHz

Quantity	**Description**	**Relative expanded uncertainty or bounds of estimated error components % (or ° for phase)**	**Probability distribution model, method of evaluation (A or B)**	**Factor x_i**	**Sensitivity coefficient c_i**	**Relative contribution $u_{rel,i}(y)$ %**	**Phase: contribution $u_i(y)$ °**
$S_{1,\ s(mag)}$	Calibration of reference transducer set	0.4	normal (k=2), B	1/2	1	0.200	
$S_{1,\ s(pha)}$	Calibration of reference transducer set	0.3	normal (k=2), B	1/2	1		0.15
$S_{1,\ s}$	Drift of reference transducer, manufacturer specification < 0,2 % per year	0.1	rectangular, B	1/√3	1	0.058	0.066
$S_{A,Cal}$	Sensitivity of conditioning amplifier calibration	0.1	rectangular, B	1/√3	1	0.058	0.066
V_R	Voltage ratio, specification	0.01	rectangular, B	1/√3	1	0.006	0.007
$I(V_{R,T})$	Influence on V_R: measurement from temperature variation. Reference transducer sensitivity, (23 ± 1) °C, < 0,1 % per °C Transducer to be calibrated, (23 ± 1) °C, < 0.2% per °C	0.22	rectangular, B	1/√3	1	0.129	0.148
$I(V_{R,\ N})$	Influence of mounting parameters on transducer to be calibrated, cable, plug and torque, maximum 0,2 %	0.2	rectangular, B	1/√3	1	0.115	0.132
$I(V_{R,\ d})$	Influence on V_R: measurement from acceleration distortion Difference in frequency slopes between transducer to be calibrated (PZT) and reference transducer (quartz) typically −2 % per decade of frequency Dominating 3rd harmonic less than 5 %. Assuming rectangular distribution	0.03	rectangular, B	1/√3	1	0.017	0.020
$I(V_{R,\ v})$	Influence on VR measurement from transverse acceleration Transverse vibration a_T for vibrator maximum 10 % Transverse sensitivity, reference transducer, $S_{v,1}$, max. 3 % Transverse sensitivity, transducer to be calibrated, $S_{v,2}$, max. 5 %	0.58	special, B	1/√18	1	0.137	0.157
$I(V_{R,\ e})$	Influence on VR measurement from base strain. Estimated to be less than	0.05	rectangular, B	1/√3	1	0.029	0.033
$I(V_{R,\ r})$	Influence on VR measurement from relative motion. Estimated to be less than	0.1	rectangular, B	1/√3	1	0.058	0.066
$I(V_{R,\ L})$	Influence on VR measurement from non-linearity of transducers. Estimated to be less than	0.03	rectangular, B	1/√3	1	0.017	0.020
$I(V_{R,\ l})$	Influence on VR measurement from non-linearity of amplifiers. Estimated to be less than	0.03	rectangular, B	1/√3	1	0.017	0.020
$I(V_{R,\ G})$	Influence on VR measurement from gravity. Estimated to be less than	0	rectangular, B	1/√3	1	0.000	0.000
$I(V_{R,\ B})$	Influence on VR measurement from magnetic field from exciter. Estimated to be less than	0.03	rectangular, B	1/√3	1	0.017	0.020
$I(V_{R,\ E})$	Influence on VR measurement from other environmental effects. Estimated to be less than	0.03	rectangular, B	1/√3	1	0.017	0.020
$I(V_{R,\ RE})$	Influence on VR measurement from residual effects (e.g. random effect in repeated measurements; experimental standard deviation of arithmetic mean). Estimated to be less than	0.18	normal (k=1), A	1	1	0.180	0.206
					Total Type A uncertainty	**0.180**	**0.206**
					Total Type B uncertainty	**0.318**	**0.321**
					Combined standard uncertainty (k=1)	**0.366**	**0.381**

$u_{rel}(S_2)$	**Relative uncertainty of magnitude of the complex sensitivity S_2 (k=2)**	**0.8**
$u(\varphi_2)$	**Uncertainty of phase shift of the complex sensitivity S_2 (k=2)**	**0.8**



Appendix 1. Detailed uncertainty budged of the calibration; frequencies 1.25 kHz - 4.5 kHz

Quantity	Description	Relative expanded uncertainty or bounds of estimated error components % (or ° for phase)	Probability distribution model, method of evaluation (A or B)	Factor x_i	Sensitivity coefficient c_i	Relative contribution $u_{rel,i}(y)$ %	Phase: contribution $u_i(y)$ °
$S_{1,\ s(mag)}$	Calibration of reference transducer set	0.4	normal (k=2), B	1/2	1	0.200	
$S_{1,\ s(pha)}$	Calibration of reference transducer set	0.3	normal (k=2), B	1/2	1		0.15
$S_{1,\ s}$	Drift of reference transducer, manufacturer specification < 0,2 % per year	0.1	rectangular, B	1/√3	1	0.058	0.066
$S_{A,Cal}$	Sensitivity of conditioning amplifier calibration	0.1	rectangular, B	1/√3	1	0.058	0.066
V_R	Voltage ratio, specification	0.01	rectangular, B	1/√3	1	0.006	0.007
$I(V_{R,T})$	Influence on V_R: measurement from temperature variation. Reference transducer sensitivity, (23 ± 1) °C, < 0,1 % per °C Transducer to be calibrated, (23 ± 1) °C, < 0.2% per °C	0.22	rectangular, B	1/√3	1	0.129	0.148
$I(V_{R,\ N})$	Influence of mounting parameters on transducer to be calibrated, cable, plug and torque, maximum 0,2 %	0.2	rectangular, B	1/√3	1	0.115	0.132
$I(V_{R,\ d})$	Influence on V_R: measurement from acceleration distortion Difference in frequency slopes between transducer to be calibrated (PZT) and reference transducer (quartz) typically −2 % per decade of frequency Dominating 3rd harmonic less than 5 %. Assuming rectangular distribution	0.03	rectangular, B	1/√3	1	0.017	0.020
$I(V_{R,\ v})$	Influence on VR measurement from transverse acceleration Transverse vibration a_T for vibrator maximum 20 % Transverse sensitivity, reference transducer, $S_{v,1}$, max. 3 % Transverse sensitivity, transducer to be calibrated, $S_{v,2}$, max. 5 %	1.17	special, B	1/√18	1	0.275	0.315
$I(V_{R,\ e})$	Influence on VR measurement from base strain. Estimated to be less than	0.05	rectangular, B	1/√3	1	0.029	0.033
$I(V_{R,\ r})$	Influence on VR measurement from relative motion. Estimated to be less than	0.8	rectangular, B	1/√3	1	0.462	0.529
$I(V_{R,\ L})$	Influence on VR measurement from non-linearity of transducers. Estimated to be less than	0.03	rectangular, B	1/√3	1	0.017	0.020
$I(V_{R,\ l})$	Influence on VR measurement from non-linearity of amplifiers. Estimated to be less than	0.03	rectangular, B	1/√3	1	0.017	0.020
$I(V_{R,\ G})$	Influence on VR measurement from gravity. Estimated to be less than	0	rectangular, B	1/√3	1	0.000	0.000
$I(V_{R,\ B})$	Influence on VR measurement from magnetic field from exciter. Estimated to be less than	0.03	rectangular, B	1/√3	1	0.017	0.020
$I(V_{R,\ E})$	Influence on VR measurement from other environmental effects. Estimated to be less than	0.03	rectangular, B	1/√3	1	0.017	0.020
$I(V_{R,\ RE})$	Influence on VR measurement from residual effects (e.g. random effect in repeated measurements; experimental standard deviation of arithmetic mean). Estimated to be less than	0.15	normal (k=1), A	1	1	0.150	0.172
					Total Type A uncertainty	**0.150**	**0.172**
					Total Type B uncertainty	**0.607**	**0.673**
					Combined standard uncertainty (k=1)	**0.625**	**0.695**
$u_{rel}(S_2)$	**Relative uncertainty of magnitude of the complex sensitivity S_2 (k=2)**	**1.3**					
$u(\varphi_2)$	**Uncertainty of phase shift of the complex sensitivity S_2 (k=2)**	**1.4**					

Appendix 1. Detailed uncertainty budged of the calibration; frequencies 5 kHz - 10 kHz

Quantity	Description	Relative expanded uncertainty or bounds of estimated error components % (or ° for phase)	Probability distribution model, method of evaluation (A or B)	Factor x_i	Sensitivity coefficient c_i	Relative contribution $u_{rel,i}(y)$ %	Phase: contribution $u_i(y)$ °
$S_{1,\ s(mag)}$	Calibration of reference transducer set	0.6	normal (k=2), B	1/2	1	0.300	
$S_{1,\ s(pha)}$	Calibration of reference transducer set	1	normal (k=2), B	1/2	1		0.5
$S_{1,\ s}$	Drift of reference transducer, manufacturer specification < 0,2 % per year	0.1	rectangular, B	1/√3	1	0.058	0.066
$S_{A,Cal}$	Sensitivity of conditioning amplifier calibration	0.1	rectangular, B	1/√3	1	0.058	0.066
V_R	Voltage ratio, specification	0.01	rectangular, B	1/√3	1	0.006	0.007
$I(V_{R,T})$	Influence on V_R: measurement from temperature variation. Reference transducer sensitivity, (23 ± 1) °C, < 0,1 % per °C Transducer to be calibrated, (23 ± 1) °C, < 0.2% per °C	0.22	rectangular, B	1/√3	1	0.129	0.148
$I(V_{R,\ N})$	Influence of mounting parameters on transducer to be calibrated, cable, plug and torque, maximum 0,3 %	0.3	rectangular, B	1/√3	1	0.173	0.198
$I(V_{R,\ d})$	Influence on V_R: measurement from acceleration distortion Difference in frequency slopes between transducer to be calibrated (PZT) and reference transducer (quartz) typically −2 % per decade of frequency Dominating 3rd harmonic less than 5 %. Assuming rectangular distribution	0.03	rectangular, B	1/√3	1	0.017	0.020
$I(V_{R,\ v})$	Influence on VR measurement from transverse acceleration Transverse vibration a_T for vibrator maximum 25 % Transverse sensitivity, reference transducer, $S_{v,1}$, max. 3 % Transverse sensitivity, transducer to be calibrated, $S_{v,2}$, max. 5 %	1.46	special, B	1/√18	1	0.344	0.394
$I(V_{R,\ e})$	Influence on VR measurement from base strain. Estimated to be less than	0.05	rectangular, B	1/√3	1	0.029	0.033
$I(V_{R,\ r})$	Influence on VR measurement from relative motion. Estimated to be less than	1.1	rectangular, B	1/√3	1	0.635	0.728
$I(V_{R,\ L})$	Influence on VR measurement from non-linearity of transducers. Estimated to be less than	0.03	rectangular, B	1/√3	1	0.017	0.020
$I(V_{R,\ l})$	Influence on VR measurement from non-linearity of amplifiers. Estimated to be less than	0.03	rectangular, B	1/√3	1	0.017	0.020
$I(V_{R,\ G})$	Influence on VR measurement from gravity. Estimated to be less than	0	rectangular, B	1/√3	1	0.000	0.000
$I(V_{R,\ B})$	Influence on VR measurement from magnetic field from exciter. Estimated to be less than	0.03	rectangular, B	1/√3	1	0.017	0.020
$I(V_{R,\ E})$	Influence on VR measurement from other environmental effects. Estimated to be less than	0.03	rectangular, B	1/√3	1	0.017	0.020
$I(V_{R,\ RE})$	Influence on VR measurement from residual effects (e.g. random effect in repeated measurements; experimental standard deviation of arithmetic mean). Estimated to be less than	0.2	normal (k=1), A	1	1	0.200	0.229
					Total Type A uncertainty	**0.200**	**0.229**
					Total Type B uncertainty	**0.817**	**1.004**
					Combined standard uncertainty (k=1)	**0.841**	**1.030**
$u_{rel}(S_2)$	**Relative uncertainty of magnitude of the complex sensitivity S_2 (k=2)**	**1.7**					
$u(\varphi_2)$	**Uncertainty of phase shift of the complex sensitivity S_2 (k=2)**	**2.1**					

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Measurement uncertainty budget for the primary calibration of accelerometers, type B&K 8305, single ended, (amplitude)

uncertainty contribution					frequency range / Hz						
					5 - < 20	20 - < 63	63 - < 1 k	1 k - < 5 k	5 k - 10 k	>10 k - 15 k	>15 k - 10 k
Component		Distribution	Factor	Evaluation Type	contribution	contribution	contribution	contribution	contribution	contribution	contribution
electrical measurement	including charge amplifier calibration	normal	2.00	Type B	3.00E-04	3.00E-04	3.00E-04	3.00E-04	3.00E-04	5.00E-04	5.00E-04
frequency	including the influence of speed to acceleration conversion	rectangular	1.73	Type B	1.00E-05	1.00E-05	1.00E-05	1.00E-05	1.00E-05	1.00E-05	1.00E-05
signal conditioner gain	including level non-linearity	normal	2.00	Type B	2.00E-04	2.00E-04	2.00E-04	2.00E-04	2.00E-04	2.00E-04	2.00E-04
signal conditioner frequency response	including frequency non-linearity	normal	2.00	Type B	5.00E-04	5.00E-04	5.00E-04	5.00E-04	2.00E-03	4.00E-03	4.00E-03
transverse motion	typical values for 8305-type of transducer	rectangular	1.73	Type B	1.40E-04	1.40E-04	1.40E-04	7.00E-04	2.50E-03	7.00E-03	7.00E-03
contribution of harmonics	nonlinearities affecting mechanical excitation	rectangular	1.73	Type B	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
hum	max. tolerated contribution of powerline hum	rectangular	1.73	Type B	1.00E-04	1.00E-04	1.00E-04	1.00E-04	1.00E-04	1.00E-04	1.00E-04
noise	broadband noise (including DUT, mechanical, electrical contributions)	normal	2.00	Type B	1.00E-05	1.00E-05	1.00E-05	1.00E-05	1.00E-05	1.00E-05	1.00E-05
position dependence	reproducibility and averaging from different measurement positions * (determined for each calibration)	rectangular	1.73	Type A*	2.10E-05	2.94E-05	5.22E-04	2.70E-04	4.30E-04	4.65E-04	1.96E-03
transducer mounting	including reproducibility of mounting torque	rectangular	1.73	Type A	7.00E-05	7.00E-05	1.40E-04	5.00E-04	1.00E-03	2.00E-03	2.00E-03
cable fixture	including connector strain and triboelectric effects	rectangular	1.73	Type B	9.00E-04	7.00E-04	7.00E-04	3.50E-04	0.00E+00	0.00E+00	0.00E+00
relative motion	including imperfections of the laser vibration isolation	rectangular	1.73	Type B	1.00E-04	1.00E-05	1.00E-05	1.00E-05	1.00E-05	1.00E-05	1.00E-05
thermal stability	combinde effect on laser reference, signal acquisition and DUT	rectangular	1.73	Type B	1.50E-05	1.50E-05	1.50E-05	1.50E-05	1.50E-05	1.50E-05	1.50E-05
linearity	additional effects of non-linearity	rectangular	1.73	Type B	1.00E-05	1.00E-05	1.00E-05	1.00E-05	1.00E-05	1.00E-05	1.00E-05
reference signal	instabilities affecting the velocity signal after demodulation	rectangular	1.73	Type B	1.00E-05	1.00E-05	1.00E-05	1.00E-05	1.00E-05	1.00E-05	1.00E-05
residual components		rectangular	1.73	Type B	1.00E-04	1.00E-04	1.00E-04	1.00E-04	1.00E-04	1.00E-04	1.00E-04
relative standard uncertainty					1.12E-03	9.57E-04	1.10E-03	1.16E-03	3.40E-03	8.34E-03	8.55E-03
expanded uncertainty					2.23E-03	1.91E-03	2.19E-03	2.31E-03	6.81E-03	1.67E-02	1.71E-02
expanded uncertainty (%)					**0.22**	**0.19**	**0.22**	**0.23**	**0.7**	**1.7**	**1.7**

Measurement uncertainty budget for the primary calibration of accelerometers, type B&K 8305, single ended, (phase)

uncertainty contribution					frequency range / Hz						
					5 - < 20	20 - < 63	63 - < 1 k	1 k - 5 k	5 k - 10 k	>10 k - 15 k	>15 k - 10 k
Component		Distribution	Factor	Evaluation Type	contribution	contribution	contribution	contribution	contribution	contribution	contribution
electrical measurement	including charge amplifier calibration	normal	2.00	Type B	5.00E-02	5.00E-02	5.00E-02	5.00E-02	5.00E-02	1.00E-01	1.00E-01
frequency	including the influence of speed to acceleration conversion	rectangular	1.73	Type B	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
signal conditioner gain	including level non-linearity	normal	2.00	Type B	1.00E-01	1.00E-01	1.00E-01	1.00E-01	1.00E-01	2.00E-01	2.00E-01
signal conditioner frequency response	including frequency non-linearity	normal	2.00	Type B	1.00E-01	1.00E-01	1.00E-01	1.00E-01	2.00E-01	4.00E-01	4.00E-01
transverse motion	typical values for 8305-type of transducer	rectangular	1.73	Type B	7.00E-02	7.00E-02	7.00E-02	1.40E-01	3.00E-01	6.00E-01	6.00E-01
contribution of harmonics	nonlinearities affecting mechanical excitation	rectangular	1.73	Type B	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
hum	max. tolerated contribution of powerline hum	rectangular	1.73	Type B	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	2.00E-02	2.00E-02
noise	broadband noise (including DUT, mechanical, electrical contributions)	normal	2.00	Type B	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	2.00E-02	2.00E-02
position dependence	reproducibility and averaging from different measurement positions * (determined for each calibration)	rectangular	1.73	Type A*	1.04E-03	4.96E-04	4.71E-02	3.67E-03	6.22E-03	4.19E-02	8.64E-02
transducer mounting	including reproducibility of mounting torque	rectangular	1.73	Type A	5.00E-02	5.00E-02	5.00E-02	1.00E-01	2.00E-01	4.00E-01	4.00E-01
cable fixture	including connector strain and triboelectric effects	rectangular	1.73	Type B	7.00E-02	5.00E-02	5.00E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
relative motion	including imperfections of the laser vibration isolation	rectangular	1.73	Type B	5.00E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
thermal stability	combinde effect on laser reference, signal acquisition and DUT	rectangular	1.73	Type B	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	2.00E-02	2.00E-02
linearity	additional effects of non-linearity	rectangular	1.73	Type B	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	2.00E-02	2.00E-02
reference signal	instabilities affecting the velocity signal after demodulation	rectangular	1.73	Type B	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	2.00E-02	2.00E-02
residual components		rectangular	1.73	Type B	5.00E-02	5.00E-02	5.00E-02	5.00E-02	5.00E-02	1.00E-01	1.00E-01
relative standard uncertainty					2.01E-01	1.88E-01	1.94E-01	2.35E-01	4.31E-01	8.62E-01	8.66E-01
expanded uncertainty (°)					**0.40**	**0.38**	**0.39**	**0.47**	**0.9**	**1.7**	**1.7**

Appendix C - Technical protocol

Task and Purpose of the Comparison

According to the rules set up by the CIPM MRA the consultative committees of the CIPM have the responsibility to establish “degrees of equivalence” (DoE) between the different measurement standards operated by the national NMIs.

The specific task of this RMO comparison is to measure the magnitude of the charge sensitivity of three different accelerometers at specified frequencies with secondary means *i.e.* according to ISO 16063-21 “Methods for the calibration of vibration and shock transducers - Part 21: Vibration calibration by comparison to a reference transducer”. The accelerometers are also sent to METAS (participant of CCAUV.V-K5) for primary calibration according to ISO 16063-11 “Methods for the calibration of vibration and shock transducers - Part 11: Primary vibration calibration by laser interferometry”. The results of the METAS calibration will provide the reference value. The reported sensitivities and associated uncertainties are then supposed to be used for the calculation of the DoE between the participating NMI and the primary calibration value of METAS.

Pilot and Co Pilot Laboratories

Pilot laboratory for this RMO Comparison is

BEV, Austria
Arltgasse 35
1160 Wien, Austria

This is the delivery address for the set of artifacts and the written and signed reports.
Contact Person:

Peter Rosenkranz
Phone: +43 1 21110 826515
Email: peter.rosenkranz@bev.gv.at

Terms of participation

All laboratories from EURAMET (and others RMOs) can participate to this RMO comparison.
Following this recommendation, this technical protocol is distributed to the chairman of the technical committees of Acoustics, Ultrasound and Vibration (AUV) of GULFMET and AFRIMET and of course EURAMET.

Devices under Test and Measurement Conditions

For the calibration task of this KC a set of three piezoelectric accelerometers will be circulated among the participating laboratories. The individual transducers are:

- Brüel & Kjær 8305-001 (SN: 2423435) “single ended” (SE) type, 0.126 pC/m/s^2
- Brüel & Kjær 4371-V (SN: 2046745) “single ended” (SE) type, 1 pC/m/s^2
- Endevco 2270M8 (SN: 16198) “single ended” (SE) type, 0.22 pC/m/s^2

B&K 8305-001

B&K 4371-V

Endevco 2270M8

The accelerometers are to be calibrated for magnitude of their complex charge sensitivity according to those procedures and conditions implemented by the NMI in conformance with ISO 16063-21. If phase calibration is desired, it may be included since METAS will perform a primary calibration according to ISO 16063-11, including phase calibration. The pilot does not perform phase calibration. For monitoring the stability of the transfer sensors, the measurement of magnitude should be sufficient. The sensitivities reported shall be for the accelerometers alone, excluding any effects from the charge amplifier. The frequency range of the measurements was agreed to be from 10 Hz to 10 kHz. Specifically, the laboratories are supposed to measure at the following frequencies (all values in Hz).

10, 12.5, 16, 20, 25, 31.5, 40, 63, 80, 100, 125, 160, 200, 250, 315, 400, 500, 630, 800, 1 000, 1 250, 1 600, 2 000, 2 500, 3 150, 4 000, 5 000, 6 300, 8 000, 10 000

Note: this set does deviate from the standard frequencies of ISO 266.

The charge amplifier (CA) used for the calibration is not provided within the set of the artifacts, it must therefore be provided by the individual participant.
The measurement condition should be kept according to the laboratory's standard conditions for calibration of customer accelerometers for claiming their best measurement capability or CMC where applicable. This presumes that these conditions comply with those defined by the applicable ISO documentary standards [1, 3], simultaneously.
Specific conditions for the measurements of this comparison are:

- Acceleration amplitudes: preferably 50 m/s^2 to 100 m/s^2, a range of 2 m/s^2 to 200 m/s^2 is admissible.
- Ambient temperature during the calibration:
  (23 ± 2) °C (actual values to be stated within tolerances of ± 0.3 °C).
- Relative humidity: max. 75 %RH
- Mounting torque of the accelerometer: (2.0 ± 0.1) N·m

Circulation Type, Schedule and Transportation

The transducers are circulated in a flower type fashion with a measurement period of two weeks provided for each participant. In between two subsequent measurements at any participant's laboratory the transducers are measured at the pilot lab in order to monitor the long-term stability. The schedule is planned as follows:

BEV → IPQ → VTT → BEV → CMI → BIM → BEV → METAS→ BEV→ KEBS→ BEV

For transportation, the artifacts are packed in a protective aluminum box, which in turn is put into a card-board container. The cost of transportation to the next participating laboratory shall be covered by the participating laboratory. The accelerometers have to be sent by an international logistic service providing a tracking system. The transportation has to include an insurance covering a total value of € 18.000, - in case the set of accelerometers gets damaged or lost during transportation. As an alternative the artifact may be hand carried by a member of the participating laboratory.

Handling, Measurement and Analysis Instructions

The participating laboratories have to observe the following instructions:

- Any instrument used for the measurement of the accelerometer's response has to be calibrated with equipment traceable to national measurement standards.
- The mounting surface of the BB accelerometer or the adapters in case of the SE accelerometers and the moving part of the exciter must be slightly lubricated before mounting.
- The cable between accelerometer and charge amplifier must be a B&K, 10-32 UNF (M) to 10-32 UNF (M) 1,2 m cable. Such a cable comes with each transfer standard.

Note:
In contrast to almost simultaneously performed CCAUV.V-K5 no mechanical adapter is provided and none should be used for the single-ended accelerometer calibration. This is, because, opposed to the Laser measurement in primary calibration the accuracy of the secondary calibration relies on the direct proximity of the reference surfaces of reference accelerometer and device under test. Where, for single ended calibration the reference surface is typically given by a back-to-back reference or by an instrumented and calibrated shaker armature.

Communication of the Results to the Pilot Laboratory

Each participating laboratory will submit one printed and signed calibration report for all accelerometers to the pilot laboratory including the following:

- a description of the calibration systems used and the mounting techniques for the accelerometer,
- a description of the calibration methods used,
- a description of the mounting method (simple screw, tripod, etc.) of the transfer standards to the reference sensor and the type of reference sensor (back-to-back sensor, built-in sensor of the shaker, etc.)
- a documented record of the ambient conditions during measurements,
- the calibration results, including the relative expanded measurement uncertainty, and the applied coverage factor for each value,
- a detailed uncertainty budget for the system covering all components of measurement uncertainty (calculated according to GUM, [3, 4]). Including among others information on the type of uncertainty (A or B), assumed distribution function and repeatability component.
- A record of the traceability chain of the laboratories' used reference accelerometers up to the primary source of acceleration traceability.

In addition, each participating laboratory will receive an electronic spreadsheet prepared by the pilot laboratory, where the calibration results have to be filled in following the structure given in the files. The use of the electronic spreadsheet for reporting is mandatory. The consistency between the results in electronic form and the printed and signed calibration report is the responsibility of the participating laboratory. The data submitted in the electronic spreadsheet shall be deemed the official results submitted for the comparison.

The results have to be submitted to the pilot laboratory within six weeks after the measurements.

Remarks on the Post Processing

- Presuming consistency of the results, calculation of the results will be done according to EN ISO 17043:2010, Annex B.3.1.3 e), formula B.5. The report will include the DoE to the primary calibration value of METAS.
- In case of damage or loss of any of the artifacts the comparison will be evaluated as far in the schedule as possible, all further action concerning continuation will be decided in coordination with the participants.

[1] ISO 16063-21:2003 "Methods for the calibration of vibration and shock transducers - Part 21: Vibration calibration by comparison to a reference transducer"

[2] ISO/IEC 17025:2017 "General requirements for the competence of testing and calibration laboratories"

[3] ISO/IEC Guide 98-3:2008 "Uncertainty of measurement
Part 3: Guide to the expression of uncertainty in measurement (GUM: 1995)

[4] ISO/IEC Guide 98-3:2008/Suppl. 1:2008 "Propagation of distributions using a Monte Carlo method"

[5] ISO/IEC 17043:2010 "Conformity assessment –General requirements for proficiency testing"

Appendix D - Technical note

Grounding and Shielding Considerations

For EURAMET Project Nr. 1481 the following accelerometers are used as transfer standards:

- Brüel & Kjær 8305-001 (SN: 2423435) SE type
- Brüel & Kjær 4371-V (SN: 2046745) SE type
- Endevco 2270M8 (SN: 16198) SE type.

Figure 1. Accelerometer transfer standards

The Shield Configuration differs between manufacturers. The B&K devices 8305-001 and 4371-V have the metallic housing connected to the connector thread and hence there is a continuous shield from accelerometer metallic housing over shielded measurement cable shield to charge amplifier input terminal. The Endevco accelerometer metallic housing is isolated from connector thread and hence from the sensor electric interface and cable shield. This allows for flexibility in grounding. If the metallic housing or the measurement cable shield is not connected to a ground potential, this means that the accelerometer or the connected measurement cable is sensitive to power line hum and coupling from electrical fields.

The following common practices and recommendations should be applied for low noise and hum measurements:

- There shall be a shield over accelerometer housing and measurement cables to the charge amplifiers input terminals.
- To make this shield effective, it shall be connected to ground.
- In order to avoid ground loops, the devices for accelerometer measurement, consisting of shaker, 2 accelerometers and 2 charge amplifiers shall be connected to ground/PE only by one common star point.

At the BEV vibration laboratory, the basic ground configuration is like this:

- Shaker tables where accelerometers are mounted are floating and isolated from PE (protective earth).
- One charge amplifier (B&K 2525) is powered from mains power line with chassis, signal input and output GND connected to PE (protective earth)
- One charge amplifier (B&K 2635) is floating and isolated form PE Chassis while Signal input and output GND are connected (manufacturers default state at delivery).

The following setups have been used with these devices with good results following above principles:

- Setup 1: Two B&K accelerometers both back-to-back and single ended.
  Both accelerometers are mounted by means of metallic screws on shaker and measurement cables are connected to charge amplifier input terminals. No additional ground connections are established by means of wires or cables.
- Setup 2: B&K back-to-back accelerometer and Endevco accelerometer.
  Both accelerometers are mounted by means of metallic screws on shaker and measurement cables are connected to charge amplifier input terminals. The Endevco accelerometer metallic housing is connected to connector thread by thin stranded and twisted copper wires as shown on Figure 2 below. These wires are pulled through the shown holes and are stretched by twisting both ends. Hence the metallic housing is connected to the attached measurement cable shield.

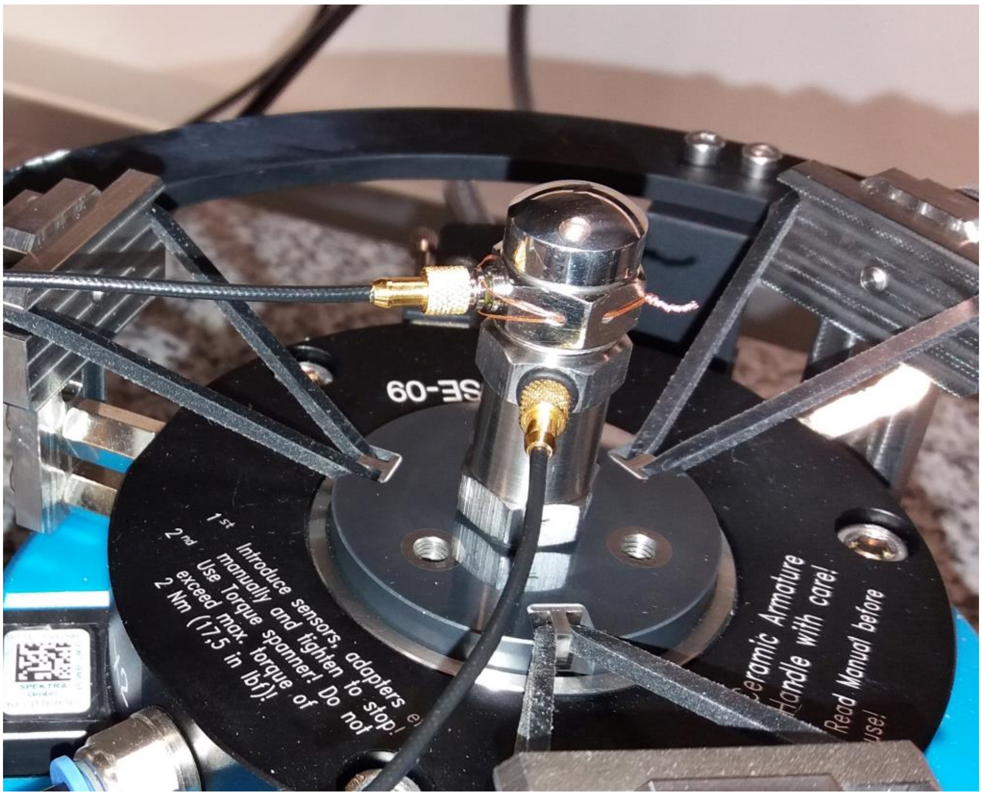

Figure 2. Endevco accelerometer mounted on top of a B&K 8305 accelerometer

- Setup 3: B&K back-to-back accelerometer and Endevco accelerometer.
  Both accelerometers are mounted with metallic crews on shaker and measurement cables are connected to charge amplifier input terminals. The two B&K charge amplifiers both have 4 mm banana sockets providing GND potential of each device. These sockets on the two charge amplifiers are connected by means of banana plug cable with 4 mm^2 cross section and about 50 cm long and.

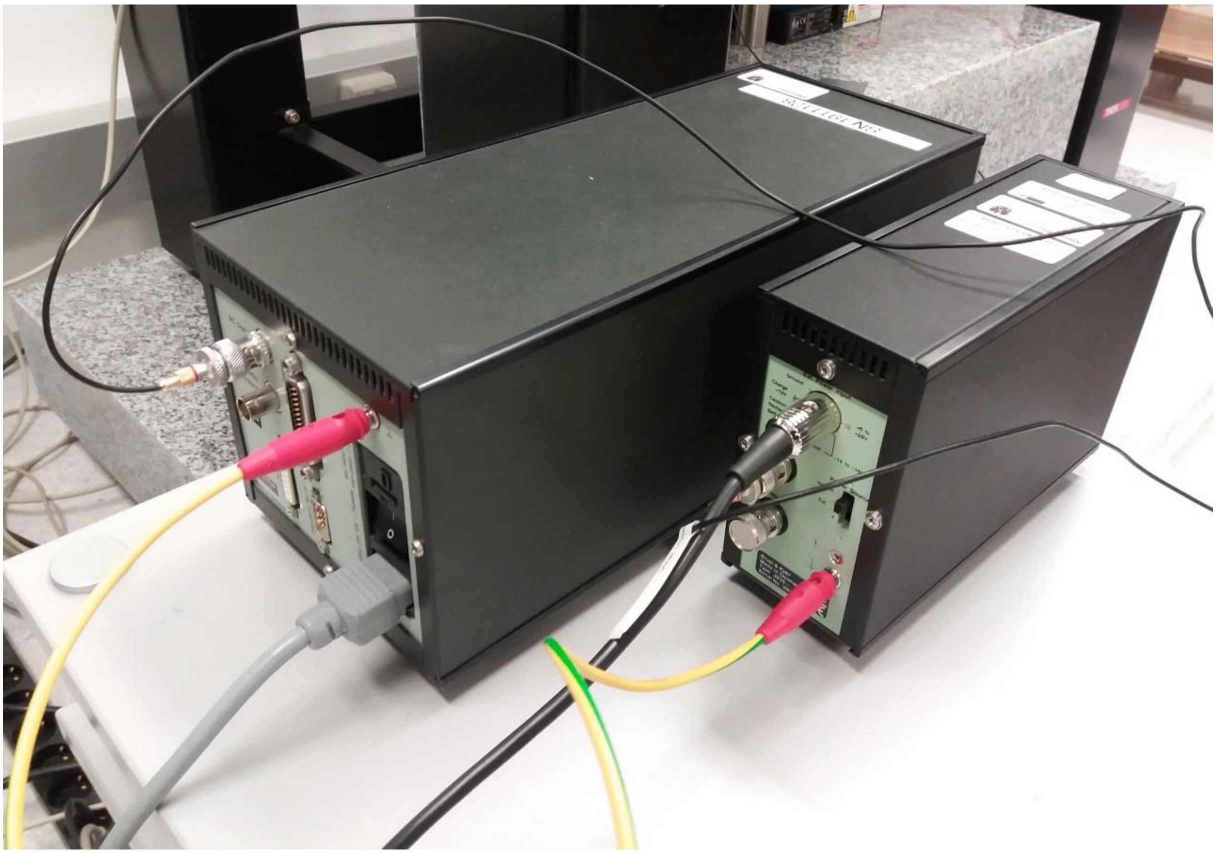
Figure 3. Ground wire connecting the two charge amplifiers

All setups provide good and equivalent results concerning noise and hum interference. Considering the mechanical motion applied on the accelerometers one might assume that setup 3 could provide a more reliable ground connection compared to setup 2 in the long term. The Endevco transfer standard is circulated without the stranded wires installed.

Capacitance measurements

The capacitances of all transfer standards and the measurement cable have been measured using an LCR Meter. It is recommended to measure the capacitances of the transfer standards prior to calibration to check for any damage during transport. However, such measurements are not part of the protocol and therefore not mandatory.

Item	Capacitance pF	*U* (k=2) %
Meas. Cable	123.07	0.5
BK 4371-V	1154.43	0.7
BK 8305-001	75.06	0.5
Endevco 2270M8	1661.39	0.5

Shipment procedure

To minimize risk of damage of the transfer standards the following measures have been taken:

- All transfer standards are packed in small original manufacturers boxes with top cover of soft foam.
- These accelerometer boxes are packed in a rugged plastic transport suitcase filled with soft foam.

- An automatic data logger type MSR 145 is packed inside this transport suitcase. It records 3 axis acceleration, temperature humidity and air pressure.
- The plastic transport suitcase is packed inside bubble wrap and packed in a cardboard box filled with soft foam and polystyrene chips.
- The cardboard box is marked with appropriate shipping labels.
- The transport includes an insurance for loss or damage of € 18.000.

Figure 4. Manufacturers boxes in the transport suitcase and the cardboard box