Final Report
on the Key Comparison

EUROMET-AUV.V-K1.1

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ABSTRACT

This report of the EUROMET.AUV.V-K1.1 comparison presents the final results of the second, follow-up EUROMET comparison in the area of vibration, in this case defined as sinusoidal acceleration. The relation between the results of the participants in this RMO comparison and the results of the first CIPM comparison in the field of vibration CCAUV.V-K1 is calculated via a procedure using one linking laboratory and is fully described. Using this linking, the results of the participants can be directly compared with the results of other comparisons, whether the CCAUV.V-K1 itself or others that are also linked such as the EUROMET.AUV.V-K1. The full uncertainty budgets are given in Appendix A and the Technical Protocol that was used is included as Appendix B.

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1 Introduction

This report presents the results of the second EUROMET comparison in the area of „vibration“, what in this case means sinusoidal acceleration. It is the final report published in the KCDB of the BIPM.

The participants agreed to the results of this report.
Because this is an RMO comparison it is not appropriate to calculate a key comparison reference value (KCRV) from the results of the participants. Instead in this report the relation between the results of the participants and the results of the first CIPM comparison in the field of vibration CCAUV.V-K1 is calculated via a procedure of "linking", which is described in section 8.1. It should be noted, that only one single linking laboratory, i.e. the pilot laboratory, was available for that process. Which is an undesirable situation in general, nevertheless this was obvious already from the technical protocol.

Using the linking the results of the participants can be directly compared to the results of other comparisons, be it CCAUV.V-K1 itself or others, which are linked to it as well.

The Technical Protocol of 14th December 2005[1] (c.f. App. B:) specifies in detail the aim and the task of the comparison, the conditions of measurement, the transfer standards used, measurement instructions, time schedule and other items. A brief survey is given in the following sections.

2 Participants

Five National Metrology Institutes (NMIs) from EUROMET have participated in the comparison EUROMET.AUV.V-K1.1 (c.f. table 1).

Table 1: List of participating institutes

Participant (laboratory name)*	Acronym	Country	Country Code	Calibration period
Physikalisch-Technische Bundesanstalt	PTB	Germany	DE	May 2006
Bulgarian Institute of Metrology, Directorate-General National Centre of Metrology	NCM	Bulgaria	BG	January 2006
Laboratoire National de Métrologie e d'Essais	LNE	France	F	June 2006
Instituto Nacional de Engenharia, Tecnologia e Inovação	INETI	Portugal	PT	August 2006
Bundesamt für Eich- und Vermessungswesen	BEV	Austria	A	July 2006

1 Amended for additional participants on 3rd May 2006, otherwise unchanged.

3 Task and Purpose of the Comparison

This second RMO-level comparison of EUROMET in the field of acceleration was carried out for reasons of different motivations.

- BEV, INETI: The establishment of “calibration and measurement capabilities” (CMC) for primary calibration systems which were only recently implemented and not yet readily available at the time of EUROMET.AUV.V-K1 [1].
- LNE: The re-establishment of CMC after the movement of the laboratory equipment from one location to another and a change in the technical personal.
- NCM: Participation in a EU Phare Project Bulgaria[2]: “Strengthening of the national Conformity Assessment System – Technical Assistance for Standardization and Metrology”, which required a comparison on EUROMET level.

In order to provide the necessary means for a linking of the results to the CIPM comparison CCAUV.V-K1 [2] PTB was requested to volunteer as Pilot- and Linking laboratory.

4 Conditions and Instructions of Measurement

The participating laboratories observed fully or to a large extent the conditions stated in the Technical Protocol, i.e.

- frequencies in Hz:
  40, 80, 160 (reference frequency), 800, 2000, 5000 and additional frequencies up to 10 kHz provided that they are included in the third octave series.
- amplitudes:
  A range of 10 m/s² to 200 m/s² was allowed with 100 m/s² being the preferred value.
- ambient temperature and accelerometer temperature during the calibration:
  23 °C±2 K (actual values should be stated within tolerances of ±0.3 K).
- relative humidity: max. 75%
- mounting torque of the accelerometer: (2±0.1) N·m

The comparison was performed in compliance with the “Guidelines for CIPM key comparisons” [3].

5 Transfer Standards as Artefacts

For the purpose of the comparison the pilot laboratory selected two accelerometers of which monitoring data for a longer period were available and which data were not included in any published international cooperation work. Due to the short preparatory stage of the comparison a designated long term stability monitoring of the artefacts was not possible.

- One transfer standard accelerometer (single-ended), type 8305 WH 2335, S/N 1610168 (manufacturer: Brüel & Kjær) named **SE**-transducer subsequently
- One reference standard accelerometer (back-to-back) type 8305, S/N 2161771 (manufacturer: Brüel & Kjær) named **B2B**-transducer subsequently

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The investigation of the long-term stability was continued throughout the circulation period. The results of the PTB stability measurements and other individual data of the transfer standards are given in Section 7.

6 Circulation of the Artefacts

The circulation Type of this comparison was a star type, i.e. between the measurements at each participant's laboratory the artefacts were checked for stability (c.f. section 7.2) and the state of the mounting surface. If the quality of the mounting surface was degraded the artefacts were re-lapped in order to provide optimum conditions for the following participant.

7 Results of the Measurements

7.1 Transverse Sensitivity

The sensitivity of the accelerometers towards a transverse excitation i.e. in a direction parallel to the mounting surface or orthogonal to their geometric axis was investigated in dedicated measurements.

For this investigation the artefacts were mounted to a mounting block on top off the slip table of PTB's 3-axis vibration exciter. The mounting block was equipped with two reference accelerometers pointing in x- and y-direction which were primary calibrated just before the measurements. Then the x- and y-exciters of the facility were driven synchronously with sinusoidal current of varying amplitude but zero phase difference. The amplitude was varied in a way that with successive runs the slip-table was performing sinusoidal rectilinear motions in different directions with a constant magnitude of acceleration amplitude of 60 m/s² at 40 Hz.

As usual the results are presented here in relative way as a fraction of the nominal sensitivity. The relative uncertainty of this relative transverse sensitivity is estimated to be less than 10 %. Figures 1 and 2 give a graphical view of the results. The values of maximum transverse sensitivity are summarized in table 2.

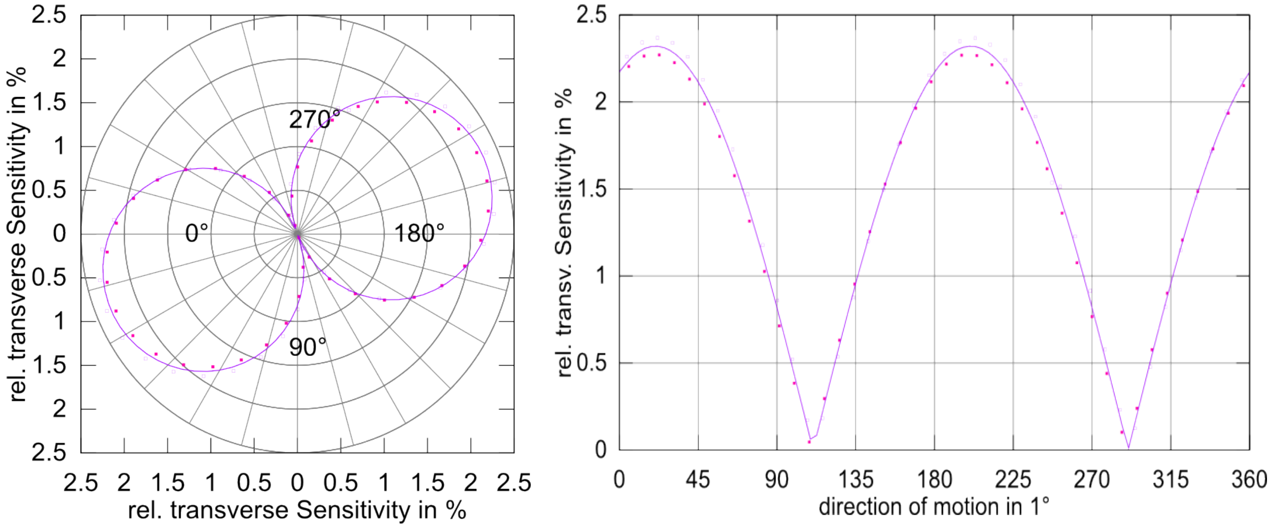

Fig. 1: relative transverse sensitivity of the SE accelerometer in % of the nominal sensitivity, polar representation left, Cartesian representation right.

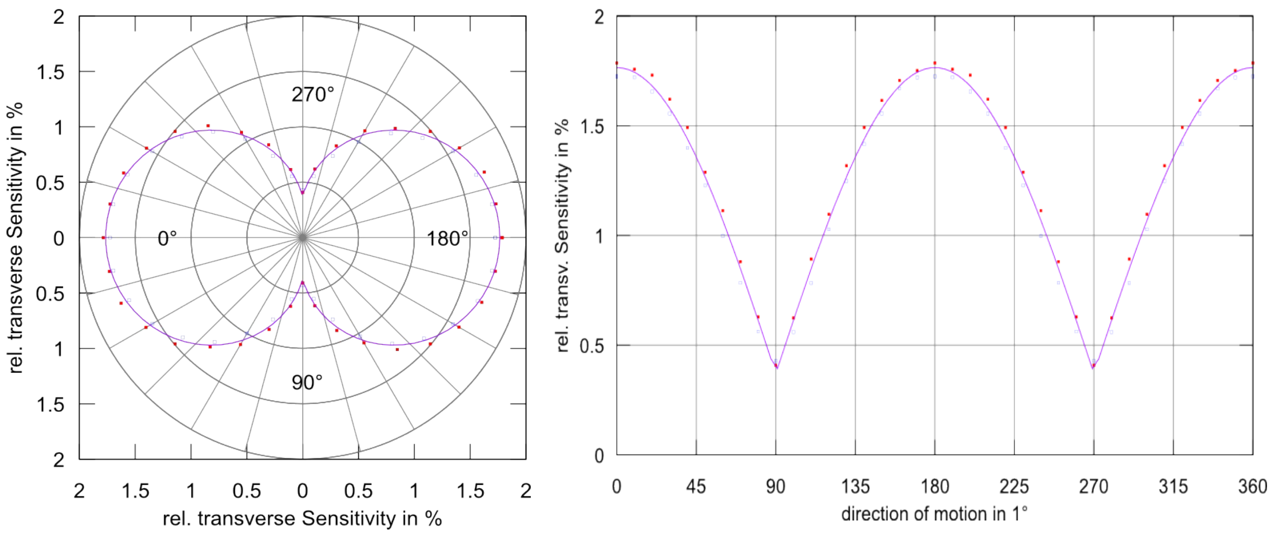

Fig. 2: relative transverse sensitivity of the B2B accelerometer in % of the nominal sensitivity, polar representation left, cartesian representation right.

Table 2: maximum transverse sensitivity of the artefacts a a percentage of the nominal sensitivity

Artefact	max. rel. transverse sensitivity in %
SE	< 2,5
B2B	< 2,0

7.2 Monitoring of stability

Starting with calibration data in autumn 2005 the artefacts were monitored during the period of the comparison by calibrations at those times when they were back at the pilot laboratory. As a representative of the overall change the measurements at reference frequency (160 Hz) are given in the following tables.

Table 3: Charge sensitivities of the SE accelerometer at 160 Hz during the monitoring measurements (rel. std. uncertainty (*k* = 1) *u* = 0,05 %)

Month rel. to 10/2005	S_{qa} in pC/(m/s²)	rel. exp. uncertainty in %
0	0,13069	0,1
2	0,13088	0,1
4	0,13079	0,1
5	0,13066	0,1
7	0,13064	0,1
8	0,13071	0,1
9	0,13065	0,1
11	0,13069	0,1
17	0,13040	0,1
18	0,13046	0,1
19	0,13046	0,1

Table 4: Charge sensitivities of the B2B accelerometer at 160 Hz during the monitoring measurements (rel. std. uncertainty (*k* = 1) *u* = 0,05 %)

Month rel. to 10/2005	S_{qa} in pC/(m/s²)	rel. exp. uncertainty in %
0	0,12489	0,1
1	0,12488	0,1
2	0,12503	0,1
4	0,12514	0,1
7	0,12521	0,1
8	0,12520	0,1
9	0,12518	0,1
11	0,12526	0,1
14	0,12525	0,1
18	0,12540	0,1

This monitoring measurements can in the simplest way be summarized by the following statistical properties. However, a graphical representation (c.f. figs. 3 and 4) may suggest that the stability of the artefacts was not as good as was originally hoped for.

Table 5: mean and standard deviation of the charge sensitivity of the artefacts calculated from the monitoring measurements.

Artefact	long term mean in pC/(m/s²)	rel. std. deviation in %
SE	0,13064	0,11
B2B	0,12514	0,13

7.3 Driftanalysis

From the monitoring data given in section 7.2 it appears that the transducers actual sensitivity might have drifted during the measurement period. In order to take this into account a linear least squares fit was applied to the monitoring data over time. The linear model is described by

$$S(t)=S_0+D\cdot(t-t_0) \qquad (1).$$

The model parameters S0 and D as well as the respective co-variance matrix are fitted according to [4].

In order to check consistency the Chi-squared was calculated for the respective model and compared to the maximum X^2 of $p = 0{,}05$ and the respective degree of freedom ν.

Table 6: Model parameters for the linear drift of the linear drift of the artefacts.

Artefact	S_0 in pC/(m/s²)	s(S0) in pC/(m/s²)	D in (pC/(m/s²)) per month	s(D) in (pC/(m/s²)) per month	ν	χ^2	maximum χ^2	rel. std. dev. in %
SE	0,13082	3.5e-5	-1.94e-5	3.2e-6	9	12,4	16,92	0,056
B2B	0,12495	3.3e-5	2,63e-5	3.6e-6	8	8,96	15,51	0,050

For the SE the drift stated in table 6 converts to a relative value of approx. -0,18 % per year the same conversion results in a drift of approx. 0,24 % per year for the B2B accelerometer. for a direct comparison of the fitted linear drift to the model of constant sensitivity (c.f. table 5) the standard deviation of the measurements with respect to the values estimated by the model is calculated in the last column.

The monitoring data as well as the drift estimate is depicted in the figures 3 and 4 below.

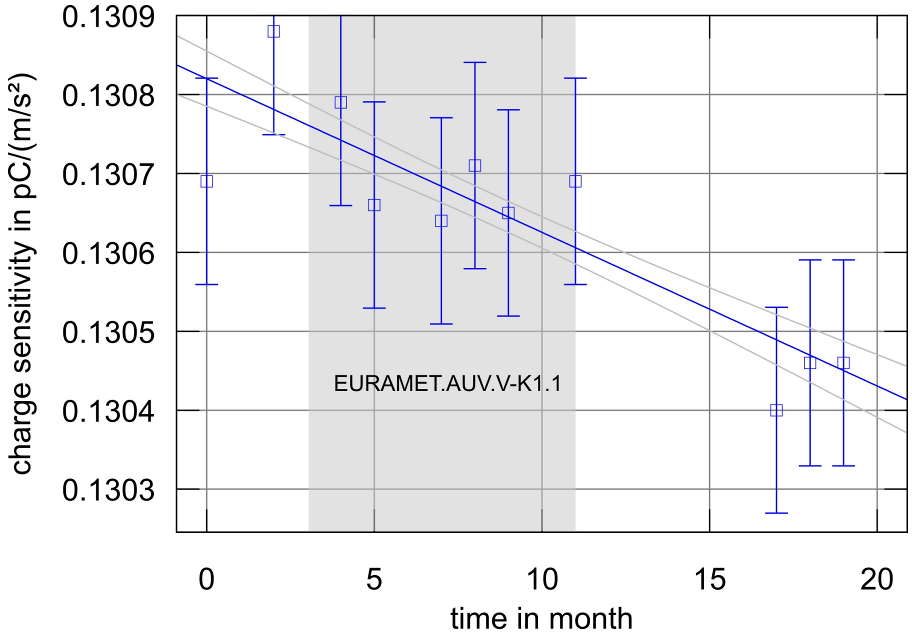

Fig. 3: Charge sensitivities in pC/(m/s²) of the SE accelerometer at 160 Hz over time in months during the monitoring measurements. Uncertainty bars for the exp. uncertainty (*k* = 2). Line (blue) of the fitted drift estimate with the confidence limits of the fit (grey lines) and the period of EURAMET.AUV.V-K1.1 measurements (grey rectangle) when sufficient stability is assumed.

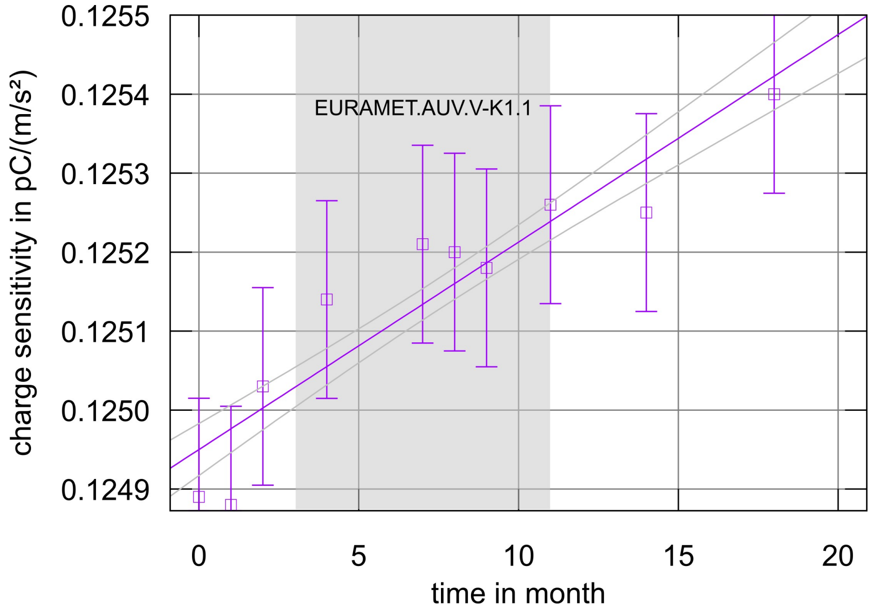

Fig. 4: Charge sensitivities in pC/(m/s²) of the B2B accelerometer at 160 Hz over time in months during the monitoring measurements. Uncertainty bars for the exp. uncertainty (*k* = 2). Line (violet) of the fitted drift estimate with the confidence limits of the fit (grey lines) and the period of EURAMET.AUV.V-K1.1 measurements (grey rectangle) when sufficient stability is assumed.

It was agreed among the participants that a correction of the drift for the measurement period of the EURAMET.AUV.V-K1.1 comparison was not necessary. The artefacts are considered stable during the respective period.

7.4 Results of the Participants

7.4.1 Results of the Single-Ended Accelerometer SN 1610168

Table 7: reported calibration results in pC/(m/s²) of the participants for the SE transducer with expanded relative uncertainty (*k* = 2) in %.

	40 Hz		80 Hz		160 Hz		800 Hz		2 kHz		5 kHz	
	S_{qa} in pC/ (m/s²)	rel. exp. unc. in %	S_{qa} in pC/ (m/s²)	rel. exp. unc. in %	S_{qa} in pC/ (m/s²)	rel. exp. unc. in %	S_{qa} in pC/ (m/s²)	rel. exp. unc. in %	S_{qa} in pC/ (m/s²)	rel. exp. unc. in %	S_{qa} in pC/ (m/s²)	rel. exp. unc. in %
PTB	0,13065	0,10	0,13065	0,10	0,13070	0,10	0,13074	0,10	0,13133	0,10	0,13442	0,10
INETI	0,13110	0,37	0,13090	0,25	0,13090	0,26	0,13190	0,86	0,13400	0,70	0,13590	1,34
BEV	0,13070	0,60	0,13040	0,56	0,13040	0,56	0,13060	0,56	0,13110	0,60	0,13410	0,66
LNE	0,13055	0,60	0,13066	0,60	0,13068	0,60	0,13089	0,60	0,13130	0,60	0,13504	0,60
NCM	0,13078	0,20	0,13076	0,20	0,13065	0,20	0,13067	0,20	0,13146	0,30	0,13426	0,50

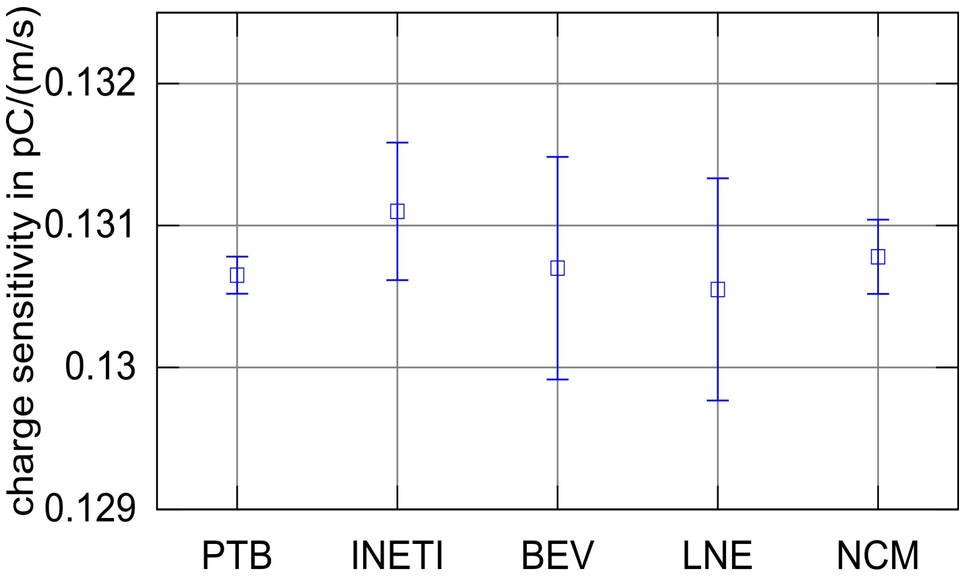

Fig. 5: Charge sensitivity of the SE transducer in pC/(m/s²) reported by the participants for 40 Hz excitation frequency with error bars representing the expanded uncertainty (*k* = 2).

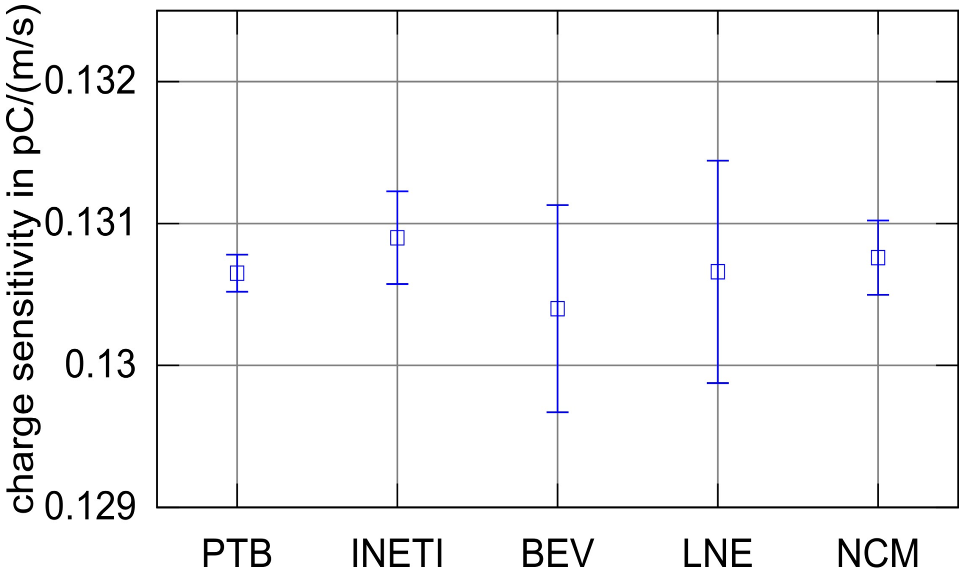

Fig. 6: Charge sensitivity of the SE transducer in pC/(m/s²) reported by the participants for 80 Hz excitation frequency with error bars representing the expanded uncertainty (*k* = 2).

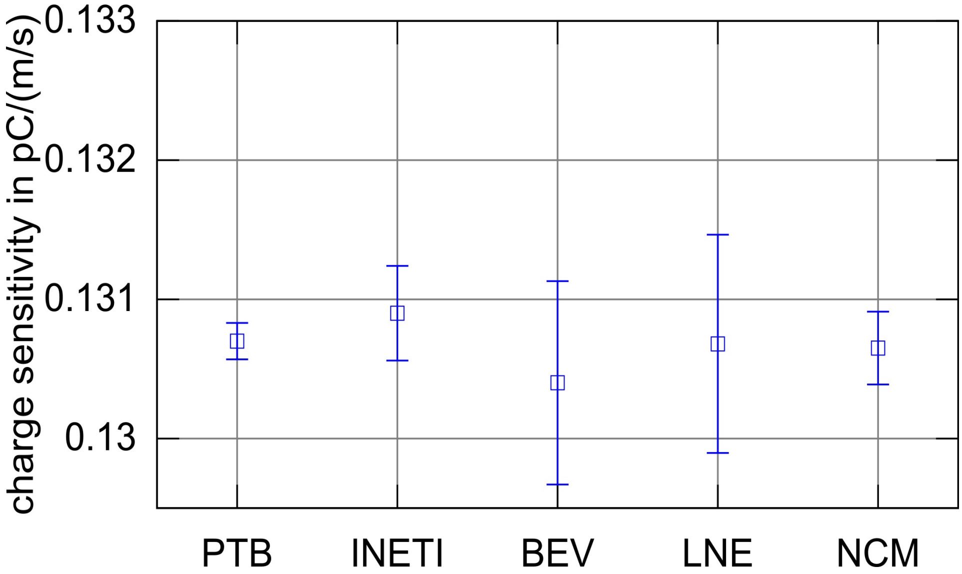

Fig. 7: Charge sensitivity of the SE transducer in pC/(m/s²) reported by the participants for 160 Hz excitation frequency with error bars representing the expanded uncertainty (*k* = 2).

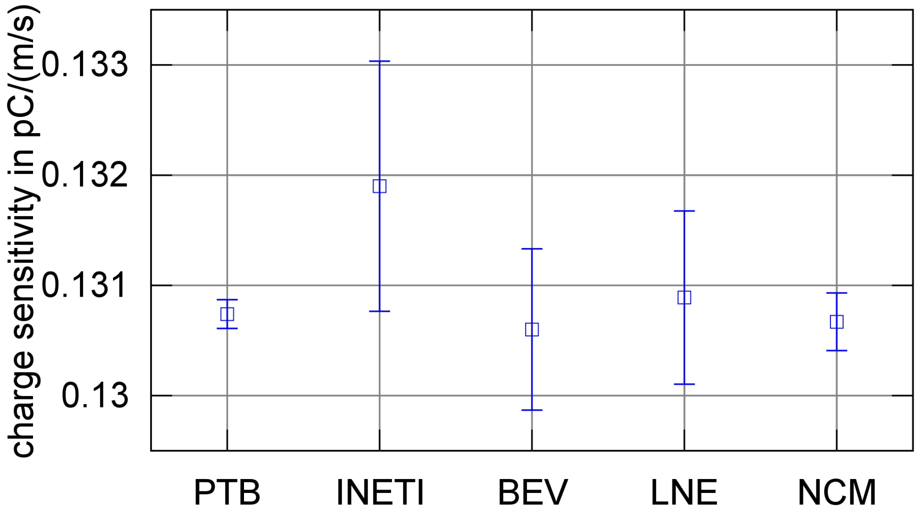

Fig. 8: Charge sensitivity of the SE transducer in pC/(m/s²) reported by the participants for 800 Hz excitation frequency with error bars representing the expanded uncertainty (*k* = 2).

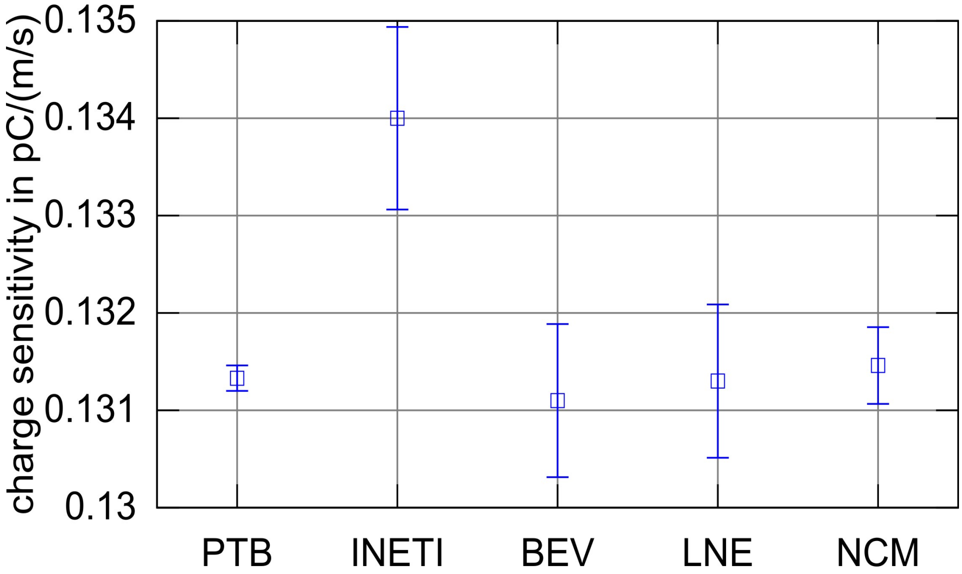

Fig. 9: Charge sensitivity of the SE transducer in pC/(m/s²) reported by the participants for 2 kHz excitation frequency with error bars representing the expanded uncertainty (*k* = 2).

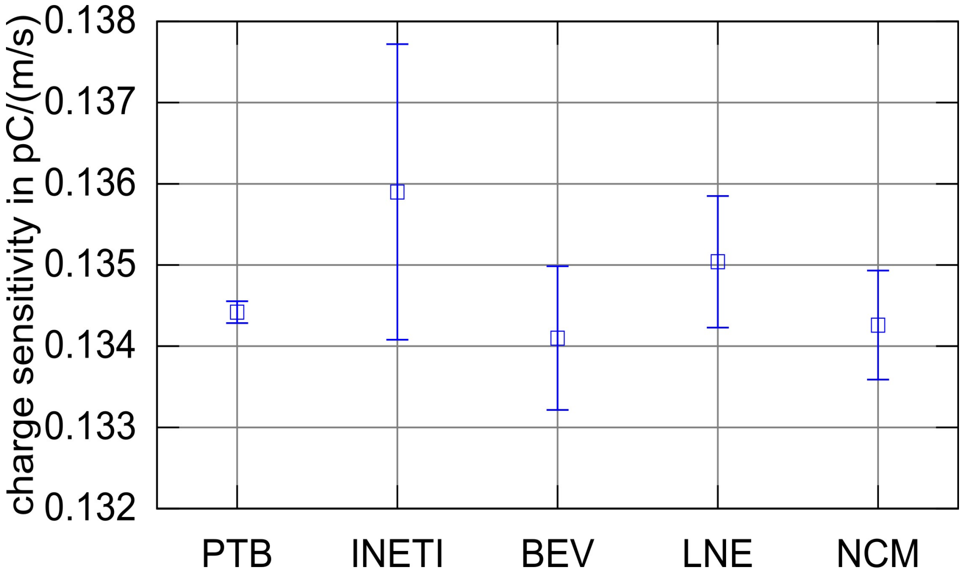

Fig. 10: Charge sensitivity of the SE transducer in pC/(m/s²) reported by the participants for 5 kHz excitation frequency with error bars representing the expanded uncertainty (*k* = 2).

7.4.2 Consistency of the Results for the SE-Accelerometer

In order to check for consistency of the data a Chi-squared test was performed. This test revealed that for 2000 Hz the data were inconsistent if all participants results were included. This was already suggested by the outliers in figure 9, an indication of cause for the inconsistency can be drawn by elimination each laboratory in turn from the chi-squared test and checking for the remaining four participants. The result from this testing are shown in table 8

Table 8: results of the consistency test for the results with the columns: frequency, X^2_{max} limit for 4 degrees of freedom (*df*), X^2 calculated from the reported results, X^2 calculated from the reported results excluding the participant named in the head, X^2_{max} limit for 3 degrees of freedom (*df*)

frequency in Hz	X^2_{max} (*df*=4)	calculated X^2	X^2 without PTB	X^2 without INETI	X^2 without BEV	X^2 without LNE	X^2 without NCM	X^2_{max} (*df*=3)
40	9,49	3,86	3,35	1,1	3,86	3,72	3,42	7,81
80	9,49	2,92	2,55	1,28	2,29	2,92	2,66	7,81
160	9,49	2,22	2,21	0,89	1,52	2,21	2,03	7,81
800	9,49	4,73	4,73	0,54	4,59	4,58	4,48	7,81
2000	9,49	32,5	31,92	1,3	31,99	32,46	32,34	7,81
5000	9,49	5,71	5,69	3,11	5,16	3,45	5,45	7,81

7.4.3 Results of the Back-to-Back Accelerometer S/N 2161771

Table 9: reported calibration results in pC/(m/s²) of the participants for the B2B transducer with expanded relative uncertainty (k = 2) in %.

	40 Hz		80 Hz		160 Hz		800 Hz		2 kHz		5 kHz	
	S_{qa} in pC/ (m/s²)	rel. exp. unc. in %	S_{qa} in pC/ (m/s²)	rel. exp. unc. in %	S_{qa} in pC/ (m/s²)	rel. exp. unc. in %	S_{qa} in pC/ (m/s²)	rel. exp. unc. in %	S_{qa} in pC/ (m/s²)	rel. exp. unc. in %	S_{qa} in pC/ (m/s²)	rel. exp. unc. in %
PTB	0,12505	0,10	0,12511	0,10	0,12521	0,10	0,12537	0,10	0,12576	0,10	0,12791	0,10
INETI	0,12558	0,51	0,12499	0,38	0,12549	0,32	0,12543	0,32	0,12604	0,34	0,12820	0,68
BEV	0,12500	0,60	0,12470	0,56	0,12472	0,56	0,12500	0,56	0,12530	0,60	0,12740	0,66
LNE	0,12502	0,60	0,12518	0,60	0,12526	0,60	0,12540	0,60	0,12572	0,60	0,12741	0,60
NCM	0,12515	0,20	0,12521	0,20	0,12519	0,20	0,12531	0,20	0,12569	0,30	0,12791	0,50

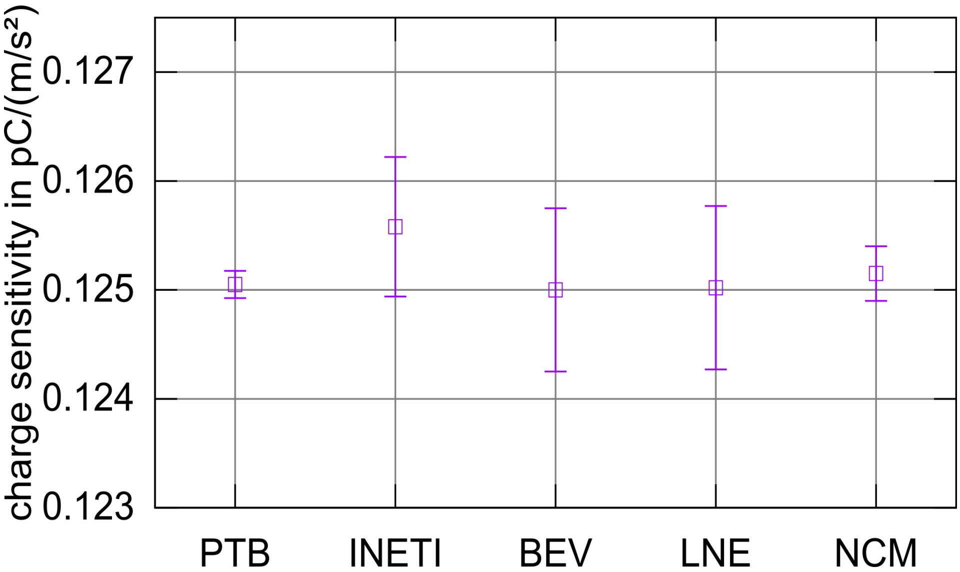

Fig. 11: Charge sensitivity of the B2B transducer in pC/(m/s²) reported by the participants for 40 Hz excitation frequency with error bars representing the expanded uncertainty (k = 2).

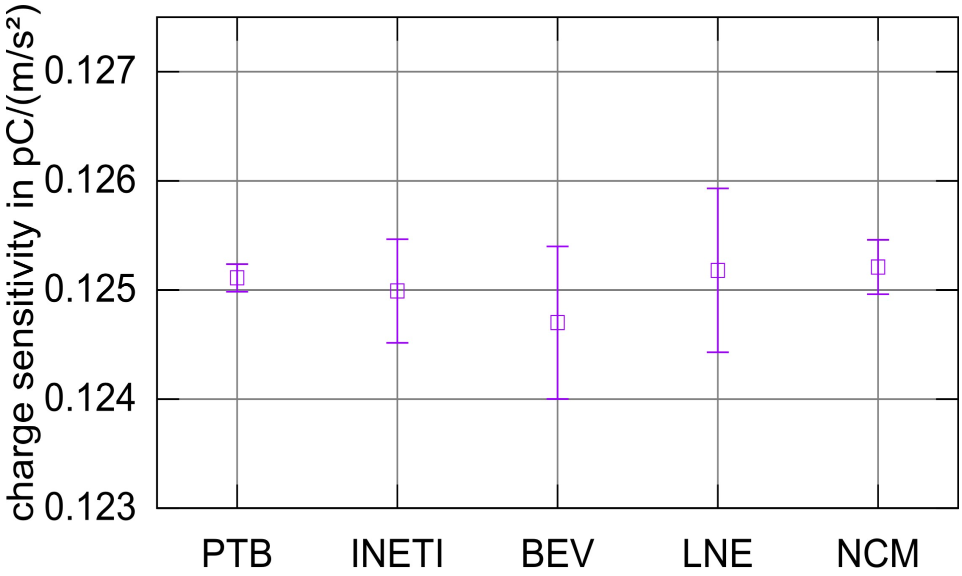

Fig. 12: Charge sensitivity of the B2B transducer in pC/(m/s²) reported by the participants for 80 Hz excitation frequency with error bars representing the expanded uncertainty (*k* = 2).

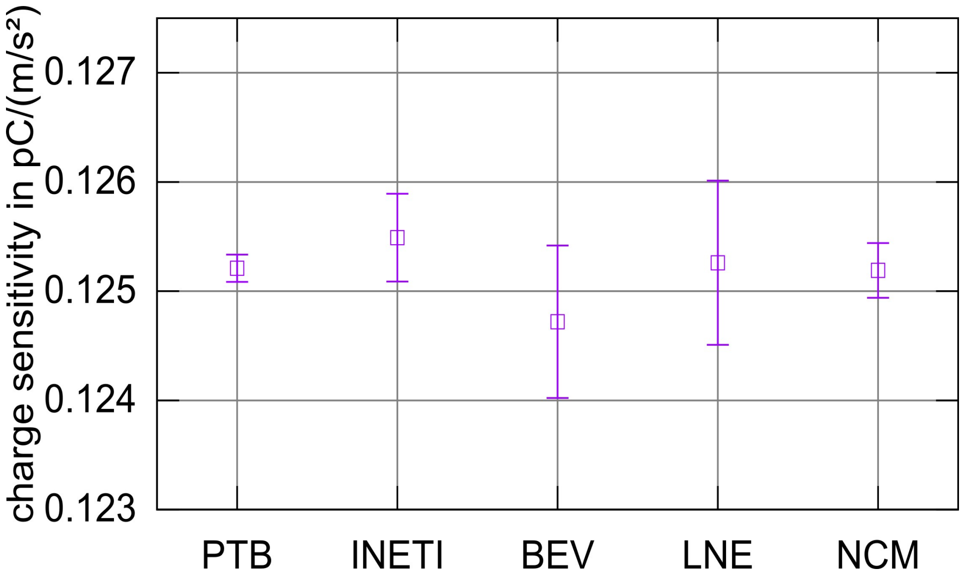

Fig. 13: Charge sensitivity of the B2B transducer in pC/(m/s²) reported by the participants for 160 Hz excitation frequency with error bars representing the expanded uncertainty (*k* = 2).

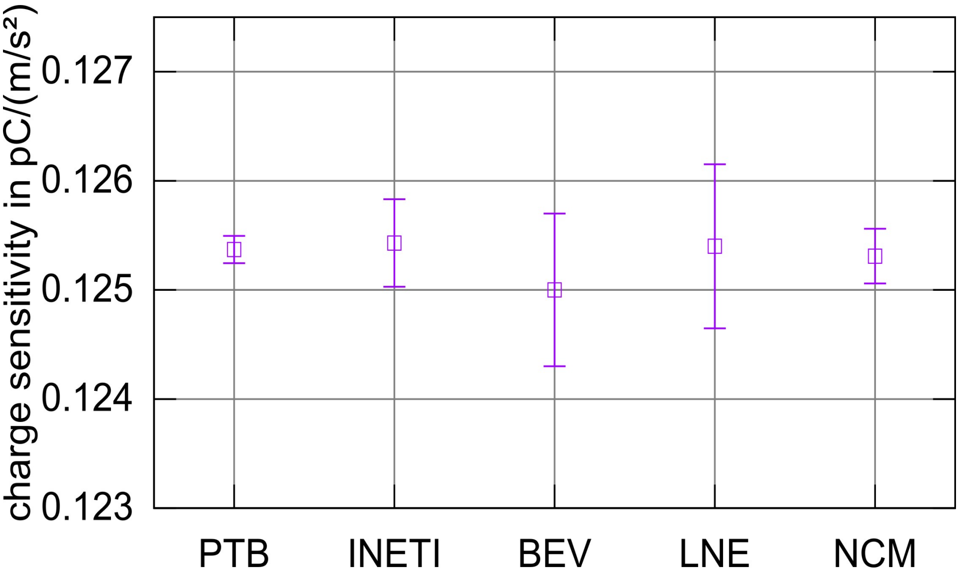

Fig. 14: Charge sensitivity of the B2B transducer in pC/(m/s²) reported by the participants for 800 Hz excitation frequency with error bars representing the expanded uncertainty (*k* = 2).

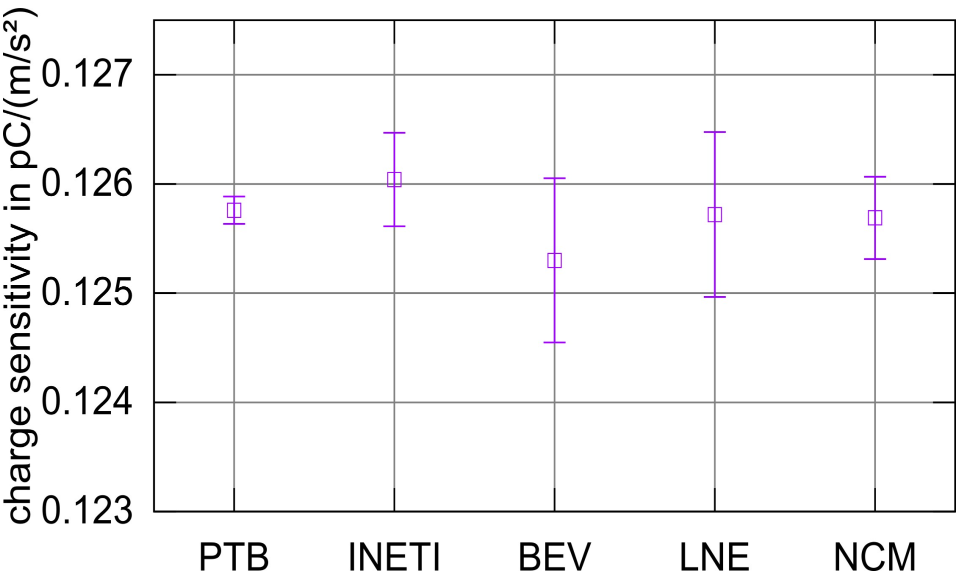

Fig. 15: Charge sensitivity of the B2B transducer in pC/(m/s²) reported by the participants for 2 kHz excitation frequency with error bars representing the expanded uncertainty (*k* = 2).

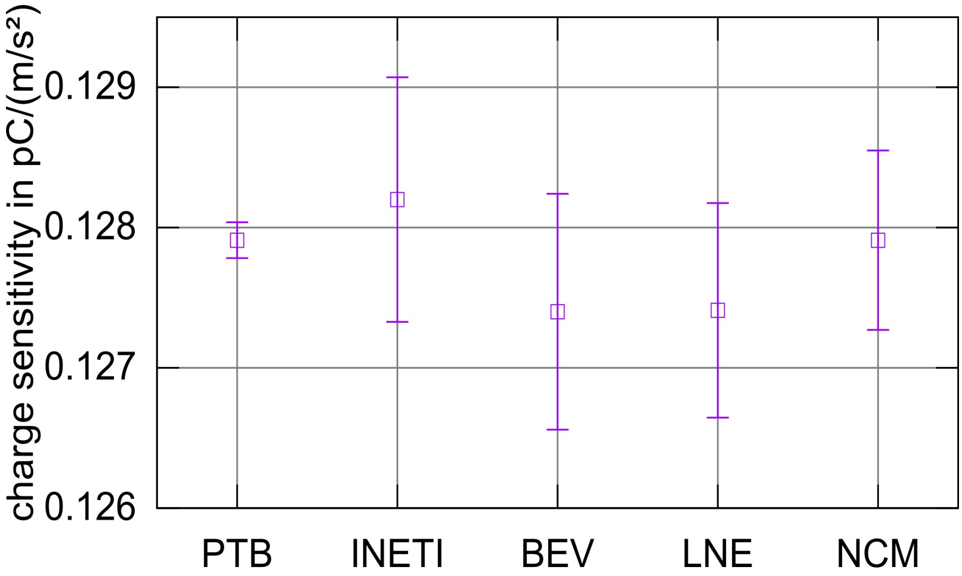

Fig. 16: Charge sensitivity of the B2B transducer in pC/(m/s²) reported by the participants for 5 kHz excitation frequency with error bars representing the expanded uncertainty (*k* = 2).

7.4.4 Consistency of the Results for the B2B-Accelerometer

For first check of the validity of the results the same consistency check was performed as described already in section 7.4.2.

Table 10: results of the consistency test for results with the columns: frequency, X^2_{max} limit for 4 degrees of freedom (*df*), X^2 calculated from the reported results, X^2 calculated from the reported results excluding the participant named in the head, X^2_{max} limit for 3 degrees of freedom (*df*)

frequency in Hz	X^2_{max} (*df*=4)	calculated X^2	X^2 without PTB	X^2 without INETI	X^2 without BEV	X^2 without LNE	X^2 without NCM	X^2_{max} (*df*=3)
40	9,49	2,93	2,71	0,54	2,88	2,9	2,7	7,81
80	9,49	2,27	2,27	2,01	0,88	2,24	1,69	7,81
160	9,49	3,96	3,95	2,07	1,96	3,94	3,91	7,81
800	9,49	1,32	1,28	1,17	0,3	1,3	1,22	7,81
2000	9,49	3,37	3,37	1,69	1,86	3,36	3,21	7,81
5000	9,49	3,54	3,46	3,04	2,17	1,95	3,54	7,81

7.5 Degrees of Equivalence between participants

In order to compare the individual reults of the participating laboratories of this comparison with one another the DoE of pairs of results with respect to a certain frequency were calculated. This DoE are each a pair of values of the difference D_{ij} between the respective participants *i* and *j* and the combined expanded uncertainty U_{ij} of this difference. These values are calculated for each frequency according to:

$$D_{ij} = x_i - x_j \tag{2}$$

$$U_{ij} = k \cdot \sqrt{u^2(x_i) + u^2(x_j)} \tag{3}$$

with a coverage factor of k = 2.

7.5.1 Tables of DoE between participants for the SE

Table 11: degrees of equivalence between the participants for the SE at 40 Hz.

40 Hz	INETI		BEV		LNE		NCM	
i→	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
j↓	in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4	
PTB	-4,5	5,0	-0,5	8,0	1,0	7,9	-1,3	2,9
INETI			4,0	9,2	5,5	9,2	3,2	5,5
BEV					1,5	11,1	-0,8	8,3
LNE							-2,3	8,3

Table 12: degrees of equivalence between the participants for the SE at 80 Hz.

80 Hz	INETI		BEV		LNE		NCM	
i→	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
j↓	in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4	
PTB	-2,5	3,5	2,5	7,4	-0,1	7,9	-1,1	2,9
INETI			5,0	8,0	2,4	8,5	1,4	4,2
BEV					-2,6	10,7	-3,6	7,8
LNE							-1,0	8,3

Table 13: degrees of equivalence between the participants for the SE at 160 Hz.

160 Hz	INETI		BEV		LNE		NCM	
i→	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
j↓	in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4	
PTB	-2,0	3,6	3,0	7,4	0,2	7,9	0,5	2,9
INETI			5,0	8,1	2,2	8,5	2,5	4,3
BEV					-2,8	10,7	-2,5	7,8
LNE							0,3	8,3

Table 14: degrees of equivalence between the participants for the SE at 800 Hz.

800 Hz	INETI		BEV		LNE		NCM	
i→	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
j↓	in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4	
PTB	-11,6	11,4	1,4	7,4	-1,5	8,0	0,7	2,9
INETI			13,0	13,5	10,1	13,8	12,3	11,6
BEV					-2,9	10,7	-0,7	7,8
LNE							2,2	8,3

Table 15: degrees of equivalence between the participants for the SE at 2000 Hz.

2000 Hz	INETI		BEV		LNE		NCM	
i→	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
j↓	in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4	
PTB	-26,7	9,5	2,3	8,0	0,3	8,0	-1,3	4,2
INETI			29,0	12,2	27,0	12,2	25,4	10,2
BEV					-2,0	11,1	-3,6	8,8
LNE							-1,6	8,8

Table 16: degrees of equivalence between the participants for the SE at 5000 Hz.

5000 Hz	INETI		BEV		LNE		NCM	
i→	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
j↓	in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4	
PTB	-14,8	18,3	3,2	9,0	-6,2	8,2	1,6	6,8
INETI			18,0	20,2	8,6	19,9	16,4	19,4
BEV					-9,4	12,0	-1,6	11,1
LNE							7,8	10,5

7.5.2 Tables of DoE between participants for the B2B

Table 17: degrees of equivalence between the participants for the B2B at 40 Hz.

40 Hz	INETI		BEV		LNE		NCM	
i→	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
j↓	in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4	
PTB	-5,3	6,5	0,5	7,6	0,3	7,6	-1,0	2,8
INETI			5,8	9,9	5,6	9,9	4,3	6,9
BEV					-0,2	10,6	-1,5	7,9
LNE							-1,3	7,9

Table 18: degrees of equivalence between the participants for the B2B at 80 Hz.

80 Hz	INETI		BEV		LNE		NCM	
i→	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
j↓	in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4	
PTB	1,2	4,9	4,1	7,1	-0,7	7,6	-1,0	2,8
INETI			2,9	8,4	-1,9	8,9	-2,2	5,4
BEV					-4,8	10,3	-5,1	7,4
LNE							-0,3	7,9

Table 19: degrees of equivalence between the participants for the B2B at 160 Hz.

160 Hz	INETI		BEV		LNE		NCM	
i→	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
j↓	in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4	
PTB	-2,8	4,2	4,9	7,1	-0,5	7,6	0,2	2,8
INETI			7,7	8,1	2,3	8,5	3,0	4,7
BEV					-5,4	10,3	-4,7	7,4
LNE							0,7	7,9

Table 20: degrees of equivalence between the participants for the B2B at 800 Hz.

800 Hz	INETI		BEV		LNE		NCM	
i→	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
j↓	in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4	
PTB	-0,6	4,2	3,7	7,1	-0,3	7,6	0,6	2,8
INETI			4,3	8,1	0,3	8,5	1,2	4,7
BEV					-4,0	10,3	-3,1	7,4
LNE							0,9	7,9

Table 21: degrees of equivalence between the participants for the B2B at 2000 Hz.

2000 Hz	INETI		BEV		LNE		NCM	
i→	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
j↓	in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4	
PTB	-2,8	4,5	4,6	7,6	0,4	7,6	0,7	4,0
INETI			7,4	8,7	3,2	8,7	3,5	5,7
BEV					-4,2	10,6	-3,9	8,4
LNE							0,3	8,4

Table 22: degrees of equivalence between the participants for the B2B at 5000 Hz.

5000 Hz	INETI		BEV		LNE		NCM	
i→	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
j↓	in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4	
PTB	-2,9	8,8	5,1	8,5	5,0	7,8	0,0	6,5
INETI			8,0	12,1	7,9	11,6	2,9	10,8
BEV					-0,1	11,4	-5,1	10,6
LNE							-5,0	10,0

8 Linking

8.1 The Linking Procedure

In contrast to the linking procedure applied for EUROMET.AUV.V-K1, the equivalence between the results of this current RMO KC and the CCAUV.V-K1 was realized via an additive linking procedure. The philosophy for this approach was, to shift the results of the single linking lab (PTB) in EURAMET.AUV.V-K1.1 onto it's results in the CCAUV.V-K1 in order to compensate for the different sensitivities of the devices under test in the two KC. This shift with the associated uncertainty is than applied as an additive term to all other participants in order to make their results comparable to those of all participants of CCAUV.V-K1. This approach corresponds to that taken in [5]

Let $\delta(f)$ be the difference between the results of the linking lab in EURAMET.AUV.V-K1.1 $x_{\mathrm{PTB}}^{\mathrm{EU}}(f)$ and it's results in CCAUV.V-K1.1 $x_{\mathrm{PTB}}^{\mathrm{CC}}(f)$ for any single frequency f

$$\delta(f)=x_{\mathrm{PTB}}^{\mathrm{CC}}(f)-x_{\mathrm{PTB}}^{\mathrm{EU}}(f) \tag{4}$$

Then the uncertainty of this difference is:

$$u_{\delta}^{2}=(u_{\mathrm{PTB}}^{\mathrm{CC}})^{2}+(u_{\mathrm{PTB}}^{\mathrm{EU}})^{2}-2\cdot cov(x_{\mathrm{PTB}}^{\mathrm{CC}},x_{\mathrm{PTB}}^{\mathrm{EU}}) \tag{5}$$

The covariance of the different results of the linking lab is considered negligible. Therefore

$$u_{\delta}^{2}=(u_{\mathrm{PTB}}^{\mathrm{CC}})^{2}+(u_{\mathrm{PTB}}^{\mathrm{EU}})^{2} \tag{6}$$

is used in the analysis.
The degree of equivalence of a participant i of this RMO KC with reference to a participant j of CCAUV.V-K1 is then given by the two values of deviation d_{ij} and uncertainty u_{ij} with

$$d_{ij}=x_{i}^{\mathrm{EU}}+\delta-x_{j}^{CC} \tag{7}$$

$$u_{ij}^{2}=(u_{i}^{\mathrm{EU}})^{2}+u_{\delta}^{2}+(u_{j}^{\mathrm{CC}})^{2}\ . \tag{8}$$

The degree of equivalence with respect to the CCAUV.V-K1 reference value (RV), however, has to consider that the linking lab contributed to the RV and therefore covariance terms occur. This has no influence on the deviation part

$$\begin{aligned} d_{i} &= x_{i}^{\mathrm{EU}}+\delta-x_{\mathrm{RV}}^{\mathrm{CC}} \\ &= x_{i}^{\mathrm{EU}}+(x_{\mathrm{PTB}}^{\mathrm{CC}}-x_{\mathrm{PTB}}^{\mathrm{EU}})-x_{\mathrm{RV}}^{\mathrm{CC}} \end{aligned} \tag{9}$$

but leads to covariance terms in the uncertainty. For participant i of EUROMET the uncertainty is

$$\begin{aligned} u_{i} &= (u_{i}^{\mathrm{EU}})^{2}+(u_{\mathrm{PTB}}^{\mathrm{CC}})^{2}+(u_{\mathrm{PTB}}^{\mathrm{EU}})^{2}+(u_{\mathrm{RV}}^{\mathrm{CC}})^{2}-2\,cov(x_{\mathrm{PTB}}^{\mathrm{CC}},x_{\mathrm{RV}}^{\mathrm{CC}}) \\ &= (u_{i}^{\mathrm{EU}})^{2}+(u_{\delta})^{2}+(u_{\mathrm{RV}}^{\mathrm{CC}})^{2}-2\,cov(x_{\mathrm{PTB}}^{\mathrm{CC}},x_{\mathrm{RV}}^{\mathrm{CC}}) \\ &= (u_{i}^{\mathrm{EU}})^{2}+(u_{\delta})^{2}-(u_{\mathrm{RV}}^{\mathrm{CC}})^{2} \end{aligned} \tag{10}$$

provided that laboratory i is not the linking lab. Eq. (10) makes use of the fact that $x_{\mathrm{RV}}^{\mathrm{CC}}$ was calculated as a weighted mean. The correlation between the results of the linking lab was again considered to be negligible, just like for Eq. (6).

8.2 Degrees of Equivalence to the CCAUV Reference Value

In order to perform a comparison of the participants with the reference value of CCAUV.V-K1 the difference of the linked results z_i and its uncertainty is calculated. This gives the DoE relative to the KCRV. The following tables document this for the two transducers used in this comparison.

Table 23: degrees of equivalence of the participants with respect to the KCRV of CCAUV.V-K1 for the SE.

SE	INETI		BEV		LNE		NCM	
	D_i	$U(D_i)$	D_i	$U(D_i)$	D_i	$U(D_i)$	D_i	$U(D_i)$
	in 10^{-4} pC/(m/s²)		in 10^{-4} pC/(m/s²)		in 10^{-4} pC/(m/s²)		in 10^{-4} pC/(m/s²)	
40 Hz	4,8	5,2	0,8	8,1	-0,7	8	1,6	3,2
80 Hz	2,8	3,8	-2,2	7,5	0,4	8,1	1,4	3,2
160 Hz	2,3	3,9	-2,7	7,5	0,1	8,1	-0,2	3,2
800 Hz	11,3	11,5	-1,7	7,5	1,2	8,1	-1	3,2
2000 Hz	26,7	9,6	-2,3	8,1	-0,3	8,1	1,3	4,4

No DoE for 5000 Hz is available, because there was no reference value calculated beyond 2000 Hz for the single ended accelerometer in CCAUV.V-K1.

Table 24: degrees of equivalence of the participants with respect to the KCRV of CCAUV.V-K1 for the B2B

SE	INETI		BEV		LNE		NCM	
	D_i	$U(D_i)$	D_i	$U(D_i)$	D_i	$U(D_i)$	D_i	$U(D_i)$
	in 10^{-4} pC/(m/s²)		in 10^{-4} pC/(m/s²)		in 10^{-4} pC/(m/s²)		in 10^{-4} pC/(m/s²)	
40 Hz	5,9	6,6	0,1	7,7	0,3	7,7	1,6	3,1
80 Hz	-0,8	5,1	-3,7	7,2	1,1	7,7	1,4	3,1
160 Hz	2,9	4,4	-4,8	7,2	0,6	7,7	-0,1	3,1
800 Hz	0,2	4,4	-4,1	7,2	-0,1	7,7	-1	3,1
2000 Hz	3,1	4,6	-4,3	7,7	-0,1	7,8	-0,4	4,2
5000 Hz	2,7	9,2	-5,3	8,9	-5,2	8,2	-0,2	7,0

8.3 Degrees of Equivalence to the participants of CCAUV.V-K1

8.3.1 Tables of DoE relative to the participants of CCAUV.V-K1 for the SE

Table 25: degrees of equivalence of the participants with respect to the participants of CCAUV.V-K1 for the SE at 40 Hz

40 Hz	INETI		BEV		LNE		NCM	
i→	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
j↓	in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4	
PTB	4,5	5,3	0,5	8,2	-1,0	8,1	1,3	3,4
BNM-CESTA	3,7	8,3	-0,3	10,3	-1,8	10,3	0,5	7,2
CSIRO-NML	3,7	7,3	-0,3	9,6	-1,8	9,6	0,5	6,1
CMI	7,2	7,9	3,2	10,0	1,7	10,0	4,0	6,7
CSIR-NML	-1,3	10,4	-5,3	12,1	-6,8	12,1	-4,5	9,6
CENAM	5,4	8,3	1,4	10,3	-0,1	10,3	2,2	7,2
NRC	7,1	6,5	3,1	8,9	1,6	8,9	3,9	5,0
KRISS	7,5	7,0	3,5	9,3	2,0	9,3	4,3	5,6
NMIJ	9,4	7,5	5,4	9,7	3,9	9,7	6,2	6,3
VNIIM	11,5	7,3	7,5	9,6	6,0	9,5	8,3	6,0
NIST	-1,3	6,5	-5,3	8,9	-6,8	8,9	-4,5	5,0
NMI-VSL	4,2	13,0	0,2	14,3	-1,3	14,3	1,0	12,3

Table 26: degrees of equivalence of the participants with respect to the participants of CCAUV.V-K1 for the SE at 80 Hz

80 Hz	INETI		BEV		LNE		NCM	
i→	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
j↓	in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4	
PTB	2,5	4,0	-2,5	7,6	0,1	8,2	1,1	3,4
BNM-CESTA	-0,4	7,5	-5,4	9,9	-2,8	10,3	-1,8	7,2
CSIRO-NML	3,6	5,4	-1,4	8,5	1,2	8,9	2,2	5,0
CMI	4,1	7,0	-0,9	9,6	1,7	10,0	2,7	6,7
CSIR-NML	0,6	9,8	-4,4	11,8	-1,8	12,1	-0,8	9,6
CENAM	3,1	7,5	-1,9	9,9	0,7	10,3	1,7	7,2
NRC	-1,1	5,4	-6,1	8,5	-3,5	8,9	-2,5	5,0
KRISS	5,3	6,0	0,3	8,8	2,9	9,3	3,9	5,6
NMIJ	4,8	7,2	-0,2	9,7	2,4	10,2	3,4	7,0
VNIIM	6,8	6,4	1,8	9,1	4,4	9,6	5,4	6,1
NIST	2,6	5,4	-2,4	8,5	0,2	8,9	1,2	5,0
NMI-VSL	4,5	4,9	-0,5	8,1	2,1	8,6	3,1	4,4

Table 27: degrees of equivalence of the participants with respect to the participants of CCAUV.V-K1 for the SE at 160 Hz

160 Hz	INETI		BEV		LNE		NCM	
i→	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
j↓	in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4	
PTB	2,0	4,1	-3,0	7,6	-0,2	8,2	-0,5	3,4
BNM-CESTA	-0,8	7,5	-5,8	9,9	-3,0	10,3	-3,3	7,2
CSIRO-NML	3,2	5,5	-1,8	8,5	1,0	8,9	0,7	5,0
CMI	2,2	7,1	-2,8	9,6	0,0	10,0	-0,3	6,7
CSIR-NML	5,2	7,5	0,2	9,9	3,0	10,3	2,7	7,2
CENAM	3,6	7,5	-1,4	9,9	1,4	10,3	1,1	7,2
NRC	0,8	5,5	-4,2	8,5	-1,4	8,9	-1,7	5,0
KRISS	4,2	6,0	-0,8	8,8	2,0	9,3	1,7	5,6
NMIJ	4,4	6,9	-0,6	9,4	2,2	9,8	1,9	6,5
VNIIM	4,0	6,4	-1,0	9,1	1,8	9,6	1,5	6,1
NIST	1,2	5,5	-3,8	8,5	-1,0	8,9	-1,3	5,0
NMI-VSL	2,7	5,8	-2,3	8,7	0,5	9,2	0,2	5,4

Table 28: degrees of equivalence of the participants with respect to the participants of CCAUV.V-K1 for the SE at 800 Hz

800 Hz	INETI		BEV		LNE		NCM	
i→	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
j↓	in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4	
PTB	11,6	11,6	-1,4	7,7	1,5	8,2	-0,7	3,4
BNM-CESTA	8,2	13,2	-4,8	9,9	-1,9	10,3	-4,1	7,2
CSIRO-NML	12,2	12,1	-0,8	8,5	2,1	8,9	-0,1	5,0
CMI	9,2	14,3	-3,8	11,4	-0,9	11,7	-3,1	9,1
CSIR-NML	7,2	13,9	-5,8	10,8	-2,9	11,2	-5,1	8,4
CENAM	10,9	13,2	-2,1	9,9	0,8	10,3	-1,4	7,2
NRC	8,8	12,8	-4,2	9,5	-1,3	9,9	-3,5	6,5
KRISS	13,2	12,4	0,2	8,9	3,1	9,3	0,9	5,6
NMIJ	14,2	14,5	1,2	11,6	4,1	11,9	1,9	9,3
VNIIM	16,0	12,8	3,0	9,4	5,9	9,9	3,7	6,5
NIST	9,2	16,0	-3,8	13,4	-0,9	13,7	-3,1	11,6
NMI-VSL	5,1	12,7	-7,9	9,3	-5,0	9,7	-7,2	6,3

Table 29: degrees of equivalence of the participants with respect to the participants of CCAUV.V-K1 for the SE at 2000 Hz

2000 Hz	INETI		BEV		LNE		NCM	
i→	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
j↓	in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4	
PTB	26,7	9,6	-2,3	8,2	-0,3	8,2	1,3	4,5
BNM-CESTA	26,5	11,6	-2,5	10,4	-0,5	10,4	1,1	7,8
CSIRO-NML	27,5	10,3	-1,5	9	0,5	9	2,1	5,8
CMI	25	12,5	-4	11,4	-2	11,4	-0,4	9,2
CSIR-NML	22,5	12,3	-6,5	11,2	-4,5	11,3	-2,9	8,9
CENAM	26	14,1	-3	13,2	-1	13,2	0,6	11,3
NRC	29,8	12,8	0,8	11,8	2,8	11,8	4,4	9,6
KRISS	30,7	11,4	1,7	10,2	3,7	10,2	5,3	7,6
NMIJ	15,4	11,6	-13,6	10,4	-11,6	10,4	-10	7,9
VNIIM	34,3	11,1	5,3	9,9	7,3	9,9	8,9	7,2
NIST	28,5	13	-0,5	12	1,5	12	3,1	9,8
NMI-VSL	21,4	16	-7,6	15,1	-5,6	15,1	-4	13,5

Table 30: degrees of equivalence of the participants with respect to the participants of CCAUV.V-K1 for the SE at 5000 Hz

5000 Hz	INETI		BEV		LNE		NCM	
i→	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
j↓	in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4	
PTB	14,8	18,6	-3,2	9,7	6,2	9	-1,6	7,8
BNM-CESTA	-	-	-	-	-	-	-	-
CSIRO-NML	12,2	19,2	-5,8	10,8	3,6	10,2	-4,2	9,1
CMI	20,2	21,3	2,2	14,1	11,6	13,7	3,8	12,9
CSIR-NML	-17,8	23	-35,8	16,5	-26,4	16,2	-34,2	15,5
CENAM	27,9	21,3	9,9	14,1	19,3	13,6	11,5	12,9
NRC	27,9	23,3	9,9	17	19,3	16,7	11,5	16
KRISS	29,6	20,4	11,6	12,8	21	12,3	13,2	11,4
NMIJ	-67	28,3	-85	23,5	-75,6	23,2	-83,4	22,7
VNIIM	25,2	20,5	7,2	13	16,6	12,5	8,8	11,6
NIST	12,2	24,4	-5,8	18,6	3,6	18,2	-4,2	17,6
NMI-VSL	-32,8	50,2	-50,8	47,6	-41,4	47,5	-49,2	47,3

8.3.2 Tables of DoE relative to the participants of CCAUV.V-K1 for the B2B

Table 31: degrees of equivalence of the participants with respect to the participants of CCAUV.V-K1 for the B2B at 40 Hz

40 Hz	INETI		BEV		LNE		NCM	
i→	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
j↓	in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4	
PTB	5,3	6,8	-0,5	7,8	-0,3	7,8	1,0	3,3
BNM-CESTA	4,8	9,2	-1,0	10,0	-0,8	10,0	0,5	7,0
CSIRO-NML	4,8	8,4	-1,0	9,2	-0,8	9,2	0,5	5,9
CMI	6,9	8,8	1,1	9,7	1,3	9,7	2,6	6,6
CSIR-NML	-3,2	13,3	-9,0	13,8	-8,8	13,8	-7,5	11,9
CENAM	7,7	9,2	1,9	10,0	2,1	10,0	3,4	7,0
NRC	7,1	7,7	1,3	8,6	1,5	8,6	2,8	4,9
KRISS	7,1	8,1	1,3	9,0	1,5	9,0	2,8	5,5
NMIJ	8,9	8,5	3,1	9,4	3,3	9,4	4,6	6,1
VNIIM	11,4	8,3	5,6	9,2	5,8	9,2	7,1	5,9
NIST	4,8	7,7	-1,0	8,6	-0,8	8,6	0,5	4,9
NMI-VSL	6,8	7,4	1,0	8,4	1,2	8,4	2,5	4,5

Table 32: degrees of equivalence of the participants with respect to the participants of CCAUV.V-K1 for the B2B at 80 Hz

80 Hz	INETI		BEV		LNE		NCM	
i→	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
j↓	in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4	
PTB	-1,2	5,2	-4,1	7,3	0,7	7,8	1,0	3,3
BNM-CESTA	-3,0	8,1	-5,9	9,6	-1,1	10,0	-0,8	7,0
CSIRO-NML	-1,0	6,3	-3,9	8,1	0,9	8,6	1,2	4,9
CMI	-1,0	7,5	-3,9	9,1	0,9	9,5	1,2	6,4
CSIR-NML	4,0	10,2	1,1	11,4	5,9	11,7	6,2	9,3
CENAM	0,3	8,1	-2,6	9,6	2,2	10,0	2,5	7,0
NRC	-4,7	6,3	-7,6	8,2	-2,8	8,6	-2,5	4,9
KRISS	0,3	6,8	-2,6	8,5	2,2	9,0	2,5	5,5
NMIJ	-0,6	7,9	-3,5	9,4	1,3	9,8	1,6	6,8
VNIIM	3,8	7,2	0,9	8,8	5,7	9,2	6,0	5,9
NIST	0,0	6,3	-2,9	8,1	1,9	8,6	2,2	4,9
NMI-VSL	0,9	5,8	-2,0	7,7	2,8	8,2	3,1	4,1

Table 33: degrees of equivalence of the participants with respect to the participants of CCAUV.V-K1 for the B2B at 160 Hz

160 Hz	INETI		BEV		LNE		NCM	
i→	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
j↓	in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4	
PTB	2,8	4,6	-4,9	7,3	0,5	7,8	-0,2	3,3
BNM-CESTA	2,2	7,7	-5,5	9,6	-0,1	10,0	-0,8	7,0
CSIRO-NML	3,2	5,8	-4,5	8,1	0,9	8,6	0,2	4,9
CMI	3,2	7,3	-4,5	9,3	0,9	9,7	0,2	6,6
CSIR-NML	3,2	7,7	-4,5	9,6	0,9	10,0	0,2	7,0
CENAM	3,2	7,7	-4,5	9,6	0,9	10,0	0,2	7,0
NRC	1,7	5,8	-6,0	8,1	-0,6	8,6	-1,3	4,9
KRISS	4,3	6,3	-3,4	8,5	2,0	9,0	1,3	5,5
NMIJ	3,2	7,1	-4,5	9,1	0,9	9,5	0,2	6,4
VNIIM	1,0	6,7	-6,7	8,8	-1,3	9,2	-2,0	5,9
NIST	4,2	5,8	-3,5	8,1	1,9	8,6	1,2	4,9
NMI-VSL	3,2	6,2	-4,5	8,4	0,9	8,8	0,2	5,3

Table 34: degrees of equivalence of the participants with respect to the participants of CCAUV.V-K1 for the B2B at 800 Hz

800 Hz	INETI		BEV		LNE		NCM	
i→	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
j↓	in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4		in pC/(m/s²) · 10^4	
PTB	0,6	4,6	-3,7	7,3	0,3	7,8	-0,6	3,3
BNM-CESTA	-2,5	7,7	-6,8	9,6	-2,8	10,0	-3,7	7,1
CSIRO-NML	0,5	5,8	-3,8	8,2	0,2	8,6	-0,7	4,9
CMI	0,5	8,1	-3,8	9,9	0,2	10,3	-0,7	7,5
CSIR-NML	-1,5	7,7	-5,8	9,6	-1,8	10,0	-2,7	7,1
CENAM	0,8	7,7	-3,5	9,6	0,5	10,0	-0,4	7,0
NRC	-1,2	7,1	-5,5	9,1	-1,5	9,5	-2,4	6,4
KRISS	1,0	6,3	-3,3	8,5	0,7	9,0	-0,2	5,5
NMIJ	1,4	7,9	-2,9	9,8	1,1	10,2	0,2	7,3
VNIIM	-3,3	7,1	-7,6	9,1	-3,6	9,5	-4,5	6,4
NIST	3,5	11,7	-0,8	13,1	3,2	13,3	2,3	11,3
NMI-VSL	-4,6	7,7	-8,9	9,6	-4,9	10,0	-5,8	7,1

Table 35: degrees of equivalence of the participants with respect to the participants of CCAUV.V-K1 for the B2B at 2000 Hz

2000 Hz	INETI		BEV		LNE		NCM	
i→	*D_{ij}*	U_{ij}	*D_{ij}*	U_{ij}	*D_{ij}*	U_{ij}	*D_{ij}*	U_{ij}
j↓	in pC/(m/s²) · 10⁴		in pC/(m/s²) · 10⁴		in pC/(m/s²) · 10⁴		in pC/(m/s²) · 10⁴	
PTB	2,8	4,8	-4,6	7,8	-0,4	7,9	-0,7	4,4
BNM-CESTA	1,4	7,9	-6,0	10,0	-1,8	10,0	-2,1	7,6
CSIRO-NML	3,4	6,0	-4,0	8,6	0,2	8,6	-0,1	5,7
CMI	3,8	7,7	-3,6	9,8	0,6	9,9	0,3	7,4
CSIR-NML	3,4	8,9	-4,0	10,9	0,2	10,9	-0,1	8,7
CENAM	2,3	11,2	-5,1	12,8	-0,9	12,8	-1,2	11,0
NRC	2,4	9,6	-5,0	11,4	-0,8	11,4	-1,1	9,4
KRISS	4,2	6,7	-3,2	9,1	1,0	9,1	0,7	6,4
NMIJ	4,2	7,5	-3,2	9,7	1,0	9,7	0,7	7,2
VNIIM 1)	-14,6	7,3	-22,0	9,6	-17,8	9,6	-18,1	7,0
NIST	7,4	9,8	0,0	11,6	4,2	11,6	3,9	9,6
NMI-VSL	5,2	7,1	-2,2	9,4	2,0	9,4	1,7	6,8

Table 36: degrees of equivalence of the participants with respect to the participants of CCAUV.V-K1 for the B2B at 5000 Hz

5000 Hz	INETI		BEV		LNE		NCM	
i→	*D_{ij}*	U_{ij}	*D_{ij}*	U_{ij}	*D_{ij}*	U_{ij}	*D_{ij}*	U_{ij}
j↓	in pC/(m/s²) · 10⁴		in pC/(m/s²) · 10⁴		in pC/(m/s²) · 10⁴		in pC/(m/s²) · 10⁴	
PTB	2,9	9,5	-5,1	9,3	-5	8,6	0	7,5
BNM-CESTA 1)	-	-	-	-	-	-	-	-
CSIRO-NML	1,3	10,5	-6,7	10,3	-6,6	9,7	-1,6	8,7
CMI	2,8	12	-5,2	11,8	-5,1	11,3	-0,1	10,5
CSIR-NML	4,3	12,9	-3,7	12,7	-3,6	12,2	1,4	11,4
CENAM	3,2	13,8	-4,8	13,6	-4,7	13,2	0,3	12,5
NRC	3,3	16,7	-4,7	16,6	-4,6	16,2	0,4	15,6
KRISS	1,7	10,8	-6,3	10,6	-6,2	10	-1,2	9
NMIJ	3,2	19,4	-4,8	19,2	-4,7	18,9	0,3	18,5
VNIIM 2)	-11,1	12,8	-19,1	12,6	-19	12,1	-14	11,3
NIST	4,3	18	-3,7	17,9	-3,6	17,5	1,4	17
NMI-VSL	3,4	49,7	-4,6	49,7	-4,5	49,6	0,5	49,4

9 Bibliography

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Appendix A: Bilateral results beyond 5 kHz:

As mentioned in the introduction for NCM the Participation in an EU Phare Project was a major motivation for this comparison. In the scope of this project the measurements were performed for an extended frequency range up to 10 kHz. In order to make the results from the high frequencies publicly available they are documented in this Appendix.

The measurement conditions and other regulations are in conformance with those of the main results reported in the main body of this report.

In the mentioned extended frequency range the frequencies 6300 Hz, 8000 Hz and 10 kHz were measured the results compare as follows:

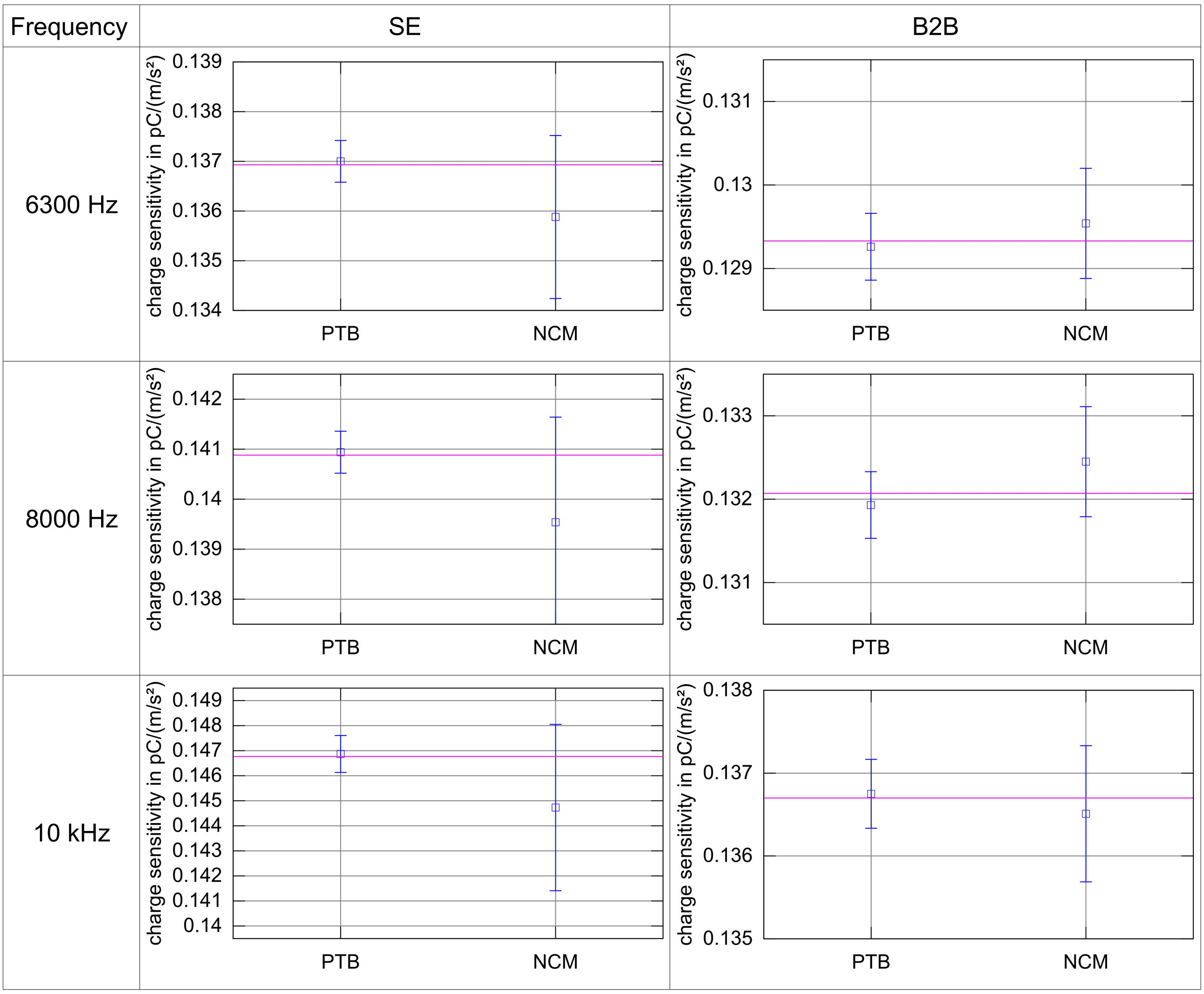

Fig. 17: Charge sensitivity of the SE (left) and B2B (right) transducer in pC/(m/s²) reported by PTB and NCM in the extended range of excitation frequency with error bars representing the expanded uncertainty (*k* = 2). The weighted mean is drawn as a horizontal line.

The quantitative values are given in the tables following. The E_n value was calculated according to the common convention for a coverage factor of k = 2 as

$$E_n = \frac{1}{k} \cdot \frac{x_{lab} - x_{wm}}{\sqrt{u^2(x_{lab}) + u^2(x_{wm})}} \tag{11}$$

where x_{wm} is the weighted mean, x_{lab} the laboratories result and $u(\ldots)$ denotes the absolute standard uncertainty related to the respective value.

Table 37: reported calibration results in pC/(m/s²) of PTB and NCM in the extended frequency range for the B2B transducer with expanded relative uncertainty (k = 2) in %.

	PTB		NCM		weighted mean		NCM	PTB
	S_{qa} in pC/(m/s²)	rel. exp. unc. in %	S_{qa} in pC/(m/s²)	rel. exp. unc. in %	S_{qa} in pC/(m/s²)	rel. exp. unc. in %	E_n	E_n
6300	0,12945	0,30	0,12962	0,50	0,12949	0,26	0,17	-0,09
8000	0,13212	0,30	0,13253	0,50	0,13223	0,26	0,41	-0,21
10000	0,13695	0,30	0,13659	0,60	0,13688	0,27	-0,32	0,13

Table 38: reported calibration results in pC/(m/s²) of PTB and NCM in the extended frequency range for the SE transducer with expanded relative uncertainty (k = 2) in %.

	PTB		NCM		weighted mean		NCM	PTB
	S_{qa} in pC/(m/s²)	rel. exp. unc. in %	S_{qa} in pC/(m/s²)	rel. exp. unc. in %	S_{qa} in pC/(m/s²)	rel. exp. unc. in %	E_n	E_n
6300	0,13686	0,30	0,13582	1,20	0,13679	0,29	-0,58	0,11
8000	0,14079	0,30	0,13948	1,50	0,14074	0,29	-0,59	0,09
10000	0,14672	0,50	0,14467	2,30	0,14662	0,49	-0,57	0,09

Appendix B: Technical Protocol

Physikalisch-Technische-Bundesanstalt (PTB)

3rd May, 2006 (participants revised)
Dr. Thomas Bruns

Technical protocol of the Complementary Comparison on the measurement of vibration acceleration
EUROMET Project 897 (proposed).

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Introduction

The **Technical Protocol** specifies in detail the aim and the task of the comparison, the conditions of measurement, the transfer standards used, measurement instructions, time schedule and other items. A brief survey is given in the following sections.

Aim and task of the comparison

The principal task of each laboratory of the comparison is the measurement of the charge sensitivity of two accelerometer standards (one of back-to-back design and one of single-ended design) at frequencies and acceleration amplitudes specified in clause 4. The charge sensitivity shall be calculated as the ratio of the amplitude of the output charge of the accelerometer to the amplitude of the acceleration at its reference surface. The reference surface is the base or mounting surface of the accelerometer of single-ended design, and the top surface of the accelerometer of back-to-back design. The charge sensitivity shall be given in pico coulombs per metres per second squared: pC/(m/s²), for the different measurement conditions specified below.

To calibrate two accelerometers, Primary vibration calibration by laser interferometry in accordance with **ISO 16063-11** shall be used.

To measure the output charge of the accelerometer standards, a calibrated charge amplifier shall be used. For the calibration of the charge amplifier, see clause 5.

Recommendation: expanded uncertainty of measurement (coverage factor $k = 2$) determined by the participating laboratories should be in the approximate range of

- 0,5 % to 1 % or smaller

Note: The participating laboratories shall report the measurement results of the charge sensitivity and the associated uncertainties individually as they were calculated for any specified measurement condition (in particular, for a given frequency), without applying any curve fitting procedure which is frequently used to suppress deviations from a "flat" frequency response.

Only Sinusoidal excitation is to be applied to the transfer standards.

Conditions of measurement

- frequencies in Hz :
  40 Hz, 80 Hz, 160 Hz, 800 Hz, 2 kHz and 5 kHz (160 Hz is reference frequency)
  (Optionally the lab can measure at other frequencies provided they are included in the third-oktave frequency series).
  Calibrations at these frequencies are mandatory. Optionally, other frequencies may be measured in addition.
- amplitudes:
  prefferred value 100 m/s². A range of 10 ms² to 200 m/s² should be complied with. If needed, up to 300 m/s² will be accepted.
- ambient temperature and accelerometer temperature during the calibration:
  23°C ± 3 K (actual values to be stated within tolerances of ±0,5 K).
- relative humidity: max. 75%.
- mounting torque of the accelerometer: (2 ± 0,1) N·m.

Transfer standards

As transfer standars, two typs of piezoelectric accelerometers are to be used: standard accelerometer (back-to-back) type 8305 (**Accelerometer A**) and standard accelerometer (single-ended) type 8305 WH2335 (**Accelerometer B**) (manufacturer Brüel & Kjaer).

Specifications of Accelerometer A: reference standard accelerometer (back-to-back) type 8305 (manufacturer Brüel & Kjær), weight: 40 grams, length: 29 mm, width over flats of hexagonal faces: 16 mm, mounting thread: 10 - 32 UNF - 2B, electrical connector: coaxial 10 – 32 UNF - 2A thread, accelerometer capacitance: ≈ 75 pF, sensitivity: ≈ 0,13 pC/(m/s²).

Specifications of Accelerometer B transfer standard accelerometer (single ended), type 8305 WH 2335 (manufacturer Brüel & Kjær); weight: 26 grams, length: 22 mm, width over flats of hexagonal faces: 16 mm, mounting thread: 10-32 UNF-2B, electrical connector: coaxial 10-32 UNF-2A thread, accelerometer capacitance: ≈ 75 pF, sensitivity:≈ 0,13 pC/(m/s²).

Time schedule and transportation

The transfer standards are transported in a closed box by an international transportation agency (e.g. TNT).

Receipt of the accelerometers has to be confirmed immediately by Fax. with the accompanying form.

The schedule of transportation and calibration is given in the table below.

NMI/Country	Transportation to Specified lab. i	Calibration
NCM/Bulgaria	26.12.-30.12.2006	02.01.2005-06.02.2006
PTB	13.02.-17.02.2006	08.05.-19.05.2006
LNE/FR	22.05.-26.05.2006	29.05.-09.06.2006
PTB	12.06.-16.06.2006	19.06.-30.06.2006
BEV/AU	03.07.-07.07.2006	10.07.-21.07.2006
PTB	24.07.-28.07.2006	31.07.-11.08.2006
INETI/P	14.08.-18.08.2006	21.08-01.09.2006
PTB	04.09.-08.09.2006	11.09.-22.09.2006

Measurement instructions

The measurand is the magnitude of the complex charge sensitivity.

- **Primary calibration of BB accelerometer (A) by laser interferometry:** The motion is to be sensed at the top surface (polished) without any dummy mass; no reflector (e.g. corner cube) must be attached to the top surface. The reflectivity of the polished top surface will be 80 % or higher, and the flatness over the top surface in the order of 1 µm.
- **Primary calibration of SE accelerometer (B) by laser interferometry**:

  The reference surface for acceleration measurement is by definition the base or mounting surface of the accelerometer. If this surface is covered during the calibration, the motion is to be sensed on the moving part close to the accelerometer. Alternatively, the motion can be sensed at the mounting surface of the accelerometer via longitudinal holes in the moving part of the vibration exciter. ISO 16063-11 is to be observed.
- The **charge amplifier** used in the laboratory should be calibrated using a standard capacitor and standard voltmeter, both traceable to national standards. The calibration of the charge amplifier was to be carried out shortly before the calibration, using values of the electric quantities similar to those found in accelerometer calibration.
- In order to suppress the effect of any non-rectilinearity of the motion, the displacement

should be measured at least at three different points. These points should be equally spaced on the top surface of the back-to-back accelerometer or on the base surface of the single-ended accelerometer.

- The mounting surfaces of the accelerometer and the moving part of the vibration exciter shall be slightly lubricated before mounting.

For each of two accelerometers, carry out the calibration in accordance with the usual procedure of your laboratory.

Communication of the results to the pilot laboratory

The calibration report shall be submitted to the pilot laboratory within 6 weeks after the calibration and contain detailed descriptions of:

- the calibration equipment
- the calibration method(s) used
- the ambient conditions
- the mounting technique
- the calibration results
- the uncertainty budget(s)

In addition to the calibration report, the measurement results should be submitted to the pilot laboratory on a diskette formatted to be compatible with a 3.5 inch PC disk drive or on a CD, and in advance by electronic mail, with the data in *Excel* or ASCII text format.

For reporting the calibration results, clause 10 of ISO 16063-11:1999 shall be taken into account. For uncertainty, the following instructions were given:

The list(s) of the principal components of the uncertainty budget shall be in accordance with ISO 16063-11:1999, Annex A for the primary calibration by laser interferometry according to method 1 ("fringe-counting method"), method 2 ("minimum-point method") and/or method 3 ("sine-approximation method").

Clause 10 and Annex A of ISO 16063-11:99 is formal part of clause 6 of the technical protocol.

Appendix C: Uncertainty Budgets of the participants

PTB:

Measurement uncertainties applicable for the fringe counting method used in EURAMET.AUV.V-K1.1 from 40 Hz to 800 Hz:

DUT	B&K 8305 or 8305-001	+ B&K 2650				
acceleration:	100 m/s²					
Voltage	typic. 1V				std. uncert. combined frequency ranges	
Disturbing Component	**comment**	**typical width**	**distribution**	**factor**	**10 Hz to 40 Hz**	**to 800Hz**
nominal Frequency	Generator accuracy	5,00E-05	rectangular	1,73	2,89E-05	2,89E-05
Accelerometer Voltage	DVM calibration (200mV to 900 mV)	5,00E-05	rectangular	1,73	2,89E-05	2,89E-05
Acceleration Ampl. by FC	optical misalignment, Heydeman correction, Wavelngth	1,00E-04	rectangular	1,73	5,77E-05	5,77E-05
harmonic distortion on Voltage measurement	estimated < 6e-5 max at 63 Hz		single point	2	3,00E-05	3,00E-05
Humm	50 Hz, ~0,7mV RMS	1,23E-05	single point	2,00	6,13E-06	3,83E-07
Noise	1,7mV RMS	0,00007225	single point	2	3,61E-05	2,26E-06
Transverse motion	1 % transv. Sensitivity @ 4% transv. Excitation		complex		1,14E-04	1,14E-04
Base Strain sensitivity	S = 0,005m/s² / µ€ € < 0,1 µm/m	depending on acc. Level	rectangular	1,73	2,89E-05	5,77E-06
Mounting torque	S = 6e-4/Nm; dM = 0,2 Nm	0,00012	rectangular	1,73	6,93E-05	6,93E-05
temperature sensitivity	S=2,5e-4 /K dT = 0,3 K	0,000075	rectangular	1,73	4,33E-05	4,33E-05
magnetic sensitivity	S=1/a *(m/s²)/T B < 0,03mT	depending on acc. Level	rectangular	1,73	1,73E-06	3,46E-07
airborne sound	S=0,008 m/s² at 154 dB max sound level 88 dB	8,00E-08	rectangular	1,73	4,62E-08	4,62E-08
quantization	suppressed by known phase-disturbance	1,00E-05	U-type	1,41	7,07E-06	7,07E-06
phase disturbance	Depending on ratio of stoch. Veloc. to stat. Veloc.	Stoch. Veloc. RMS 30µm/s	Steiner	1	1,78E-08	1,78E-08
trigger hysteresis	set hysteresis value 20 mV system. Dev. Corrected	est. remaining dev. < 1e-6		1	1,00E-06	1,00E-06
Low pass of photo detector voltage	f_c (-3db) 3 MHz	1,00E-07	rectangular	1,73	5,77E-08	5,77E-08
foto electric noise	RMS 2,5mV		Steiner	1	1,30E-05	2,00E-05
harmonical distortion	rectangular distrib. of relat. Phase. Only 1st harmonic essential, ampl. ratio 0,0012	1,33E-04	U-type	1,41	9,43E-05	9,43E-05
humm (50 Hz)	humm acc. 0,08m/s²	1,77E-05	rectangular	1,73	1,02E-05	1,60E-04
asynchronous measurement	voltage/acceleration/voltage	1,00E-04	rectangular	1,73	5,77E-05	5,77E-05
residual influences		1,00E-04	normal	1,41	7,07E-05	7,07E-05
exp. std. deviation		1,70E-04	normal	1,41	1,20E-04	1,20E-04
Charge Amplifier calibration		4,24E-04	normal	2	2,12E-04	2,12E-04
rel. std. uncertainty	**in %**				**0,0324**	**0,0358**
rel. comb. exp. Uncertainty (k=2)	**in %**				**0,0647**	**0,0716**
stated rel. comb. exp. Uncertainty	**in %**				**0,1000**	**0,1000**

Measurement uncertainties applicable for the sine approximation method method used in EURAMET.AUV.V-K1.1 from 1 kHz to 10 kHz:

DUT	B&K 8305 or 8305-001	+ B&K 2650				
acceleration:	100 m/s²					
Voltage	typic. 1V					
Sample rate	10 MS/s	@ 12 Bit				
					std. uncert. combined frequency ranges	
Disturbing Component	**comment**	**95% value**	**distribution**	**factor**	**500 Hz to 5 kHz**	**to 10 kHz**
frequency of SAM	deviation of sample clock from generator clock	1,00E-04	rectangular	1,73	5,77E-05	5,77E-05
Accelerometer Voltage	sampling of HP3458A	5,00E-04	rectangular	1,73	2,89E-04	2,89E-04
Velocity amplitude	wave length, optical adjustment, deviation between the two beams	1,16E-05	normal	2,00	5,80E-06	5,80E-06
harmon. Distortion	mainly 1st harmonic		Steiner	1,00	7,84E-06	7,84E-06
Humm on Voltage	typical 1mV	5,00E-07	Steiner	1,00	5,00E-07	5,00E-07
Noise on Voltage	MC on influence to SAM duration 20ms, Un=1,0mV	6,60E-06	normal	1,00	3,30E-06	3,30E-06
Transverse Motion	S(transv) = 0,7% a(transv) < 4%		u-type	1,41	1,98E-04	1,98E-04
Base strain sensitivity	S = 0,005m/s² / µ€ € < 0,1 µm/m	5,00E-06	rectangular	1,73	2,89E-06	2,89E-06
mounting	S = 6e-4/Nm; dM = 0,2 Nm	1,20E-04	rectangular	1,73	6,93E-05	6,93E-05
Temperature	S=2,5e-4 /K dT = 0,3 K	7,50E-05	rectangular	1,73	4,33E-05	4,33E-05
Magnetic field	S=1/a *(m/s²)/T B < 0,03mT	3,00E-07	rectangular	1,73	1,73E-07	1,73E-07
Airborne acoustics	S=0,008 m/s² at 154 dB max sound level 88 dB	8,00E-08	rectangular	1,73	4,62E-08	4,62E-08
Noise on Interferom.	noise level equiv. of 2 nm after demodulation, Monte Carlo		normal	1,00	1,10E-04	3,00E-04
a-synchronous Measurement	voltage/acceleration/voltage	1,00E-04	rectangular	1,73	5,77E-05	5,77E-05
charge ampl. calibration		4,24E-04	normal	2,00	2,12E-04	2,12E-04
resid. influences		1,00E-04	normal	1,41	7,07E-05	7,07E-05
exp. std. dev					2,30E-05	1,60E-04
rel. std. uncertainty	**in %**				**0,0446**	**0,0549**
rel. comb. exp. Uncertainty (k=2)	**in %**				**0,0891**	**0,1098**
stated rel. comb. exp. Uncertainty	**in %**				**0,1000**	**0,3000**

INETI:

(extract from the report)

5.2. Uncertainty Budget

The calculation of the uncertainty was made in accordance with *GUM – "Guide to the Expression of Uncertainty in Measurement"*. In the tables 3 and 4 is include an example of the uncertainty budget, respectively, for the 160 Hz and 2 kHz. For each uncertainty component the type of evaluation (A or B), probability distribution, standard uncertainty and sensitivity coefficients are also indicated. Finally is presented the coverage factor and the associated expanded uncertainty of the measurement.

f = 160 Hz

Quantity	Estimate		Type of evaluation (A or B) / Probability Distribution	Standard Uncertainty [u (xi)]	Sensitivity Coefficient [ci]			[ci *u (xi)]2	
Uncertainty for the accelerometer voltmeter output	1,60E-04	V	B / rectangular	9,24E-05	0,20264/(l*f*ff)	1,005E-02	1/Hz2*m	8,62439E-13	$[V/m*s\text{-}2]^2$
Experimental standard deviation of the mean of V	2,44E-04	V	A / normal	2,44E-04	0,20264/(l*f*ff)	1,005E-02	1/Hz2*m	6,00524E-12	$[V/m*s\text{-}2]^2$
Experimental Standard deviation of the mean of the acceleration	3,64E-01	m*s-2	A / normal	3,64E-01	-V/(a^2)	-1,011E-04	V/m*s-2	1,35634E-09	$[V/m*s\text{-}2]^2$
Uncertainty of l laser	1,00E-10	m	B / rectangular	5,77E-11	-0,20264*V/(l^2*f*ff)	-1,589E+04	-V/(Hz^2*m2)	8,41351E-13	$[V/m*s\text{-}2]^2$
Uncertainty for the frequency of the vibrator	1,00E-06	Hz	B / rectangular	5,77E-07	-0,20264*V/(f^2*ff*l)	-6,283E-05	-V/(Hz3*m)	1,31604E-21	$[V/m*s\text{-}2]^2$
Uncertainty for the fringe frequency	2,01E+01	Hz	B / rectangular	1,16E+01	-0,20264*V/(f*ff^2*l)	-5,050E-08	-V/(Hz3*m)	3,42548E-13	$[V/m*s\text{-}2]^2$
							Σ	**1,36E-09**	

Standard uncertainty, Uc (y) =	3,69E-05	V/m*s-2
Coverage Factor, k =	2	
Expanded uncertainty of measurement, U =	7,39E-05	V/m*s-2
Expanded uncertainty of measurement, U =	**0,74**	**%**

Table 3 – Budget uncertainty of the Accelerometer B

B&K 8305 WH2335, Single-ended, with f=160 Hz and a=100 m*s^{-2}.

f = 2000 Hz

Quantity	Estimate		Type of evaluation (A or B) / Probability Distribution	Standard Uncertatiny [u (xi)]	Sensitivity Coefficient [ci]			[ci *u (xi)]^2	
Uncertainty for the accelerometer voltmeter output	1,60E-04	V	B / rectangular	9,24E-05	13/(l*famp*p*f^2)	1,26E-01	pC/(V*m*Hz^2)	1,36E-10	[pC/(m*s^-2)]^2
Experimental standard deviation of the mean of V	8,96E-06	V	A / normal	8,96E-06	13/(l*famp*p*f^2)	1,26E-01	pC/(V*m*Hz^2)	1,28E-12	[pC/(m*s^-2)]^2
Uncertainty for the phase amplitude measurement	1,00E-02	rad	B / rectangular	5,77E-03	13*V/(l*famp^2*p*f^2	-9,75E-03	pC/(m*Hz^2)	3,17E-09	[pC/(m*s^-2)]^2
Standard deviation of the pha	2,03E-02	rad	A / normal	2,03E-02	13*V/(l*famp^2*p*f^2	-9,75E-03	pC/(m*Hz^2)	3,91E-08	[pC/(m*s^-2)]^2
Uncertainty of l laser (in air)	1,00E-10	m	B / rectangular	5,77E-11	13*V/(l^2*famp*p*f^2	-2,00E+05	pC/(m^2*Hz^2)	1,33E-10	[pC/(m*s^-2)]^2
Uncertainty for the frequency of the vibrator	1,00E-06	Hz	B / rectangular	5,77E-07	-26*V/(l*famp*p*f^3)	-1,26E-04	pC/(m*Hz^3)	5,31E-21	[pC/(m*s^-2)]^2
							Σ	**4,26E-08**	

Standard uncertainty, Uc (y) =	2,1E-04	pC/(m*s^-2)
Coverage Factor, k =	2	
Expanded uncertainty of measurement, U =	**4,1E-04**	pC/(m*s^-2)
Expanded uncertainty of measurement, U =	**0,33**	**%**

Table 4 – Budget uncertainty of the accelerometer A

B&K 8305, back-to-back, with *f=2 kHz* and *a=100 m*s*$^{-2}$.

BEV:

Measurement uncertainties as reported by the laboratory

Accelerometer, type 8305 WH 2335, series nr. 1610168
Uncertainty in %

			Frequency/Hz					
Nr.	Abbreviation	Source of uncertainty	40	80	160	800	2000	5000
1	$u(u_V)$	volmeter & chargeamlifier	0,06	0,06	0,06	0,06	0,06	0,06
2	$u(d_u)$	total distortion	0,10	0,09	0,09	0,09	0,10	0,10
3	$u(u_T)$	transverse motion & Tilting	0,16	0,16	0,16	0,17	0,18	0,22
4	$u(S_Q)$	displacement quantization	0,08	0,08	0,08	0,08	0,09	0,10
5	$u(S_H)$	trigger hystresis	0,02	0,02	0,02	0,02	0,02	0,02
6	$u(S_F)$	filtering effect	0,07	0,06	0,06	0,06	0,06	0,06
7	$u(S_{VD})$	voltage disturbance	0,00	0,00	0,00	0,00	0,00	0,00
8	$u(S_{MD})$	motion disturbance	0,10	0,09	0,09	0,09	0,09	0,09
9	$u(S_{PD})$	phase noise	0,14	0,12	0,12	0,12	0,12	0,12
10	$u(a_{re})$	interferometer function	0,06	0,06	0,06	0,06	0,06	0,06
11	$u(a_{fg})$	vibration frequency	0,05	0,05	0,05	0,05	0,05	0,05
12	$u(A)$	standard deviation of amean	0,03	0,03	0,03	0,03	0,07	0,08
		combined uncertainty	0,30	0,28	0,28	0,28	0,30	0,33
		overall uncertainty (k=2)	0,59	0,56	0,56	0,57	0,61	0,67

Accelerometer, type 8305 (back to back), series nr. 2161771
Uncertainty in %

			Frequency/Hz					
Nr.	Abbreviation	Source of uncertainty	40	80	160	800	2000	5000
1	$u(u_V)$	volmeter & chargeamlifier	0,06	0,06	0,06	0,06	0,06	0,06
2	$u(d_u)$	total distortion	0,11	0,09	0,09	0,09	0,12	0,16
3	$u(u_T)$	transverse motion & tilting	0,17	0,16	0,16	0,17	0,20	0,24
4	$u(S_Q)$	displacement quantization	0,09	0,08	0,08	0,08	0,09	0,11
5	$u(S_H)$	trigger hystresis	0,02	0,02	0,02	0,02	0,02	0,03
6	$u(S_F)$	filtering effect	0,07	0,06	0,06	0,06	0,07	0,08
7	$u(S_{VD})$	voltag disturbance	0,00	0,00	0,00	0,00	0,00	0,00
8	$u(S_{MD})$	motion disturbance	0,11	0,09	0,09	0,09	0,11	0,14
9	$u(S_{PD})$	phase noise	0,14	0,12	0,12	0,12	0,12	0,13
10	$u(a_{re})$	interferometer function	0,07	0,06	0,06	0,06	0,07	0,09
11	$u(a_{fg})$	vibration frequency	0,05	0,05	0,05	0,05	0,05	0,05
12	$u(A)$	standard deviation of arithmetic mean	0,05	0,03	0,03	0,03	0,09	0,15
		combined uncertainty	0,32	0,28	0,28	0,28	0,34	0,42
		overall uncertainty (k=2)	0,63	0,56	0,56	0,57	0,67	0,84

LNE

Measurement uncertainties as reported by the laboratory

Method 1 (for method 2 see next tab)

i	component	source of uncertainty	contribution (%)
1	$u(\hat{u}_V)$	accelerometer output voltage measurement	0,102
1a	$u(S_a)$	calibration factor for reference charge amplifier	0,143
2	$u(\hat{u}_D)$	effect of total distortion on accelerometer output voltage measurement	0,110
3	$u(\hat{u}_T)$	effect of transverse, rocking, and bending acceleration on accelerometer output voltage measurement (transverse sensitivity)	0,070
4	$u(s_Q)$	effect of displacement quantization on displacement measurement (fringe counting error)	0,124
5	$u(s_H)$	effect of hysteresis on displacement measurement	0,030
6	$u(s_F)$	filtering effect on displacement measurement (frequency band limitation)	not applicable
7	$u(s_{VD})$	effect of voltage disturbance on displacement measurement (eg random noise in the photoelectric measuring chain)	0,030
8	$u(s_{MD})$	effect of motion disturbance on displacement measurement (e.g. relative motion between the accelerometer reference surface and the spot sensed byt he interferometer)	0,140
9	$u(s_{PD})$	effect of phase disturbance on displacement measurement (e.g. phase noise of the interferometer signal)	not applicable
10	$u(s_{RE})$	residual interferometric effects on displacement measurement (e.g. interferometer function)	0,042
11	$u(f_{FG})$	vibration frequency measurement (frequency generator and indicator)	0,032
12	$u(S_{RE})$	residual effects on sensitivity measurement (e.g. random effects in repeat measurements, experimental deviation of arithmetic mean, temperature)	0,036
	$u_{rel}(S)$	*uncertainty (%) for accelerometer sensitivity (standard unc k=1)*	0,30
		uncertainty (%) for accelerometer sensitivty S at 95% conf level (k=2)	***0,60***

Method 2 (for method 1 see previous tab).

i	component	source of uncertainty	contribution (%)
1	$u(\hat{u}_V)$	accelerometer output voltage measurement	0,102
1a	$u(S_a)$	calibration factor for reference charge amplifier	0,143
2	$u(\hat{u}_D)$	effect of total distortion on accelerometer output voltage measurement	0,150
3	$u(\hat{u}_T)$	effect of transverse, rocking, and bending acceleration on accelerometer output voltage measurement (transverse sensitivity)	0,070
4	$u(s_Z)$	effect of minimum-point resolution on displacement measurement	0,070
5	$u(s_{VD})$	effect of voltage disturbance on displacement measurement (eg hum and noise)	0,070
6	$u(s_{MD})$	effect of motion disturbance on displacement measurement (e.g. relative motion between the accelerometer reference surface and the spot sensed by the interferometer)	0,140
7	$u(s_{RE})$	residual interferometrics effects on displacement measurement (interferometer function)	0,030
8	$u(f_{FG})$	vibration frequency measurement (frequency generator and indicator)	0,032
9	$u(S_{RE})$	residual effects on sensitivity measurement (e.g. random effects in repeat measurements, experimental deviation of arithmetic mean, temperature)	0,036
	$u_{rel}(S)$	*uncertainty (%) for accelerometer sensitivity (standard unc k=1)*	0,30
		uncertainty (%) for accelerometer sensitivty S at 95% conf level (k=2)	***0,60***

NCM

Measurement uncertainties as reported by the laboratory

Table 3 Uncertainty Components Taken into Account for Uncertainty Calculation for Method 1 – Fringe Counting

i	Standard uncertainty component $u(x_i)$	Source of uncertainty	Uncertainty contribution $u_i(y)$
1	$u(\hat{u}_V)$	accelerometer output charge measurement (conditioning amplifier and voltmeter)	$u_1(S)$
2	$u(\hat{u}_D)$	effect of total distortion on accelerometer output voltage measurement	$u_2(S)$
3	$u(\hat{u}_T)$	effect of transverse, rocking and bending acceleration on accelerometer output voltage measurement (transverse sensitivity)	$u_3(S)$
4	$u(\hat{s}_Q)$	effect of displacement quantization on displacement measurement	$u_4(S)$
5	$u(\hat{s}_H)$	effect of trigger hysteresis on displacement measurement	$u_5(S)$
6	$u(\hat{s}_F)$	filtering effect on displacement measurement (frequency band limitation)	$u_6(S)$
7	$u(\hat{s}_{VD})$	effect of voltage disturbance on displacement measurement (e.g. random noise in the photoelectric measuring chain)	$u_7(S)$
8	$u(\hat{s}_{MD})$	effect of motion disturbance on displacement measurement (e.g. total distortion; relative motion between the accelerometer reference surface and the spot sensed by the interferometer)	$u_8(S)$
9	$u(\hat{s}_{PD})$	effect of phase disturbance on displacement measurement (e.g. phase noise of the interferometer signal)	$u_9(S)$
10	$u(\hat{s}_{RE})$	residual interferometric effects on displacement measurement (interferometer function)	$u_{10}(S)$
11	$u(f_{FG})$	vibration frequency measurement (frequency generator and indicator)	$u_{11}(S)$
12	$u(S_{RE})$	residual effects on sensitivity measurement (e.g. random effect in repeat measurements; experimental standard deviation of arithmetic mean)	$u_{12}(S)$

Table 4 Uncertainty Components Taken into Account for Uncertainty Calculation for Method 2 – Minimum Points of Bessel Function J_1

i	Standard uncertainty component $u(x_i)$	Source of uncertainty	Uncertainty contribution $u_i(y)$
1	$u(\hat{u}_V)$	accelerometer output charge measurement (conditioning amplifier and voltmeter)	$u_1(S)$
2	$u(\hat{u}_D)$	effect of total distortion on accelerometer output voltage measurement	$u_2(S)$
3	$u(\hat{u}_T)$	effect of transverse, rocking and bending acceleration on accelerometer output voltage measurement (transverse sensitivity)	$u_3(S)$
4	$u(\hat{s}_Z)$	effect of minimum-point resolution on displacement measurement	$u_4(S)$
5	$u(\hat{s}_{VD})$	effect of voltage disturbance on displacement measurement (e.g. hum and noise)	$u_5(S)$
6	$u(\hat{s}_{MD})$	effect of motion disturbance on displacement measurement (e.g. relative motion between the accelerometer reference surface and the spot sensed by the interferometer)	$u_6(S)$
7	$u(\hat{s}_{RE})$	residual interferometric effects on displacement measurement (interferometer function)	$u_7(S)$
8	$u(f_{FG})$	vibration frequency measurement (frequency generator and indicator)	$u_8(S)$
9	$u(S_{RE})$	residual effects on sensitivity measurement (e.g. random effect in repeat measurements; experimental standard deviation of arithmetic mean)	$u_9(S)$

Table 5 Uncertainty Components Taken into Account for Uncertainty Calculation for Method 3 – Laser Heterodyne Interferometer

i	Standard uncertainty component $u(x_i)$	Source of uncertainty	Uncertainty contribution $u_i(y)$
1	$u(\hat{u}_V)$	accelerometer output charge measurement	$u_1(S)$
2	$u(\hat{u}_F)$	voltage filtering effect on accelerometer output amplitude measurement	$u_2(S)$
3	$u(\hat{u}_D)$	effect of voltage disturbance on accelerometer output voltage measurement (e.g. hum and noise)	$u_3(S)$
4	$u(\hat{u}_T)$	effect of transverse, rocking and bending acceleration on accelerometer output voltage measurement (transverse sensitivity)	$u_4(S)$
5	$u(\hat{\varphi}_{M,Q})$	effect of interferometer quadrature output signal disturbance on phase amplitude measurement (e.g. offsets, voltage amplitude deviation, deviation from 90° nominal angle difference)	$u_5(S)$
6	$u(\hat{\varphi}_{M,F})$	interferometer signal filtering effect on phase amplitude measurement (frequency band limitation)	$u_6(S)$
7	$u(\hat{\varphi}_{M,VD})$	effect of voltage disturbance on phase amplitude measurement (e.g. random noise in the photoelectric measuring chains)	$u_7(S)$
8	$u(\hat{\varphi}_{M,MD})$	effect of motion disturbance on phase amplitude measurement (e.g. drift; relative motion between the accelerometer reference surface and the spot sensed by the interferometer)	$u_8(S)$
9	$u(\hat{\varphi}_{M,PD})$	effect of phase disturbance on phase amplitude measurement (e.g. phase noise of the interferometer signals)	$u_9(S)$
10	$u(\hat{\varphi}_{M,RE})$	residual interferometric effects on phase amplitude measurement (interferometer function)	$u_{10}(S)$
11	$u(f_{FG})$	vibration frequency measurement (frequency generator and indicator)	$u_{11}(S)$
12	$u(S_{RE})$	residual effects on sensitivity measurement (e.g. random effect in repeat measurements; experimental standard deviation of arithmetic mean)	$u_{12}(S)$

Table 6 Uncertainty Budget in Calibration of Accelerometer Standard Type 8305 Ser. No 2161771, Method 1 – Fringe Counting

f [Hz]	***A*** [m/s²]	S_q [pC/(m/s²)]	U_{rel} [%]	Uncertainty contributions $u_i(y)$ (Table 3) [10^{-2} %]											
				1	2	3	4	5	6	7	8	9	10	11	12
40	50	0,12516	0,12	3,2	0,5	2,5	0,1	0,3	0,1	0,3	3,5	0,5	1,4	0,4	0,1
80	100	0,12525	0,12	3,2	0,5	2,5	0,1	0,3	0,1	0,3	3,5	0,5	1,4	0,3	0,1
160	100	0,12519	0,12	3,2	0,5	2,5	0,1	0,3	0,1	0,3	3,5	0,5	1,4	0,2	0,1
800	200	0,12538	0,12	3,2	0,5	2,5	0,5	0,3	0,1	0,3	3,5	0,8	1,4	0,2	0,5

Table 7 Uncertainty Budget in Calibration of Accelerometer Standard Type 8305 Ser. No 2161771, Method 2 – Bessel J1

f [Hz]	***a*** [m/s²]	S_q [pC/(m/s²)]	U_{rel} [%]	Uncertainty contributions $u_i(y)$ (Table 4) [10^{-2} %]								
				1	2	3	4	5	6	7	8	9
1000	20	0,12540	0,11	3,2	0,5	2,5	2,5	0,3	0,5	1,4	1,3	0,4
1250	50	0,12559	0,11	3,2	0,5	2,5	2,5	0,3	0,5	1,4	1,3	0,1
1600	98	0,12584	0,11	3,2	0,5	2,5	2,5	0,3	0,5	1,4	0,5	0,1
2000	103	0,12569	0,11	3,2	0,5	2,5	2,5	0,3	0,5	1,4	0,3	0,3
2500	102	0,12593	0,11	3,2	0,5	2,5	2,5	0,3	0,5	1,4	0,2	0,1
3150	101	0,12634	0,11	3,2	0,5	2,5	2,5	0,3	0,5	1,4	0,2	0,4
4000	112	0,12689	0,11	3,2	0,5	2,5	2,5	0,3	0,5	1,4	0,2	0,4
5000	95	0,12791	0,11	3,2	0,5	2,5	2,5	0,3	0,5	1,4	0,2	0,2
6300	151	0,12962	0,14	3,2	0,5	5,0	2,5	0,3	0,5	1,4	0,2	0,5
8000	244	0,13253	0,26	3,2	0,5	12	2,5	0,3	0,5	1,4	0,2	0,3
10000	382	0,13659	0,37	3,2	0,5	18	2,5	0,3	0,5	1,4	0,2	0,3
12500	596	0,14422	0,41	3,2	0,5	20	2,5	0,3	0,5	1,4	0,2	0,6

Table 8 Uncertainty Budget in Calibration of Accelerometer Standard Type 8305 Ser. No 2161771, Method 3 – hp5529A

f [Hz]	***a*** [m/s²]	S_q [pC/(m/s²)]	U_{rel} [%]	Uncertainty contributions $u_i(y)$ (Table 5) [10^{-2} %]											
				1	2	3	4	5	6	7	8	9	10	11	12
5	10	0,12512	0,15	5,2	0,5	0,5	2,5	0,5	0,1	0,3	4,0	0,1	0,5	0,5	1,8
10	10	0,12519	0,20	3,2	1,0	0,5	2,5	0,5	0,1	0,3	9,0	0,1	1,4	0,5	0,7
20	20	0,12515	0,19	3,2	0,9	0,5	2,5	0,5	0,1	0,3	8,1	0,1	1,4	0,5	0,3
40	50	0,12513	0,13	3,2	0,6	0,5	2,5	0,5	0,1	0,3	4,5	0,1	1,4	0,4	0,6
50	50	0,12520	0,12	3,2	0,5	0,5	2,5	0,5	0,1	0,3	3,5	0,1	1,4	0,3	0,7
63	100	0,12520	0,12	3,2	0,5	0,5	2,5	0,5	0,1	0,3	3,5	0,1	1,4	0,3	0,4
80	100	0,12517	0,12	3,2	0,5	0,5	2,5	0,5	0,1	0,3	3,5	0,1	1,4	0,3	0,8
100	100	0,12521	0,12	3,2	0,5	0,5	2,5	0,5	0,1	0,3	3,5	0,1	1,4	0,2	1,1
125	100	0,12523	0,12	3,2	0,5	0,5	2,5	0,5	0,1	0,3	3,5	0,1	1,4	0,2	1,1
160	100	0,12519	0,12	3,2	0,5	0,5	2,5	0,5	0,1	0,3	3,5	0,1	1,4	0,2	1,1
200	100	0,12523	0,12	3,2	0,5	0,5	2,5	0,5	0,1	0,3	3,5	0,1	1,4	0,2	1,4
250	100	0,12522	0,12	3,2	0,5	0,5	2,5	0,5	0,1	0,3	3,5	0,1	1,4	0,2	1,5
315	100	0,12515	0,12	3,2	0,5	0,5	2,5	0,5	0,1	0,3	3,5	0,3	1,4	0,2	1,6
400	100	0,12519	0,13	3,2	0,5	0,5	2,5	0,5	0,1	0,3	3,5	0,4	1,4	0,2	2,8
500	100	0,12522	0,13	3,2	0,5	0,5	2,5	0,5	0,1	0,3	3,5	0,6	1,4	0,2	3,0
630	100	0,12519	0,13	3,2	0,5	0,5	2,5	1,0	0,1	0,3	3,5	0,9	1,4	0,2	2,8
800	200	0,12538	0,16	3,2	0,5	0,5	2,5	1,5	0,1	0,3	3,5	0,7	1,4	0,2	4,9
1000	200	0,12529	0,16	3,2	0,5	0,5	2,5	2,0	0,1	0,3	3,5	1,1	1,4	0,2	5,3

Table 9 Uncertainty Budget in Calibration of Accelerometer Standard Type 8305 WH2335 Ser. No 1610168, Method 2 – Bessel J1

f [Hz]	***a*** [m/s²]	S_q [pC/(m/s²)]	U_{rel} [%]	Uncertainty contributions $u_i(y)$ (Table 4) [10^{-2} %]								
				1	2	3	4	5	6	7	8	9
1000	20	0,13090	0,11	3,2	0,5	2,5	2,5	0,5	1,0	1,4	1,3	0,4
1250	50	0,13096	0,11	3,2	0,5	2,5	2,5	0,5	1,5	1,4	1,3	0,1
1600	98	0,13083	0,11	3,2	0,5	2,5	2,5	0,5	2,0	1,4	0,5	0,1
2000	103	0,13146	0,12	3,2	0,5	2,5	2,5	0,5	3,0	1,4	0,3	0,3
2500	102	0,13148	0,13	3,2	0,5	2,5	2,5	0,5	4,0	1,4	0,2	0,1
3150	101	0,13222	0,15	3,2	0,5	2,5	2,5	0,5	5,0	1,4	0,2	0,4
4000	112	0,13273	0,16	3,2	0,5	2,5	2,5	0,5	6,0	1,4	0,2	0,4
5000	95	0,13426	0,19	3,2	0,5	2,5	2,5	0,5	8,0	1,4	0,2	0,2
6300	151	0,13582	0,46	3,2	0,5	4,0	2,5	0,3	22	1,4	0,2	0,3
8000	244	0,13948	0,74	3,2	0,5	8,0	2,5	0,3	36	1,4	0,2	0,3
10000	382	0,14467	1,2	3,2	0,5	9,0	2,5	0,3	60	1,4	0,2	0,4
12500	596	0,15246	2,0	3,2	0,5	10	2,5	0,3	100	1,4	0,2	0,4

Table 10 Uncertainty Budget in Calibration of Accelerometer Standard Type 8305 WH2335 Ser. No 1610168, Method 3 – hp5529A

f [Hz]	***a*** [m/s²]	S_q [pC/(m/s²)]	U_{rel} [%]	Uncertainty contributions $u_i(y)$ (Table 5) [10^{-2} %]											
				1	2	3	4	5	6	7	8	9	10	11	12
5	10	0,13071	0,15	5,2	0,5	0,5	2,5	0,5	0,1	0,3	4,0	0,1	0,5	0,5	1,4
10	10	0,13062	0,20	3,2	1,0	0,5	2,5	0,5	0,1	0,3	9,0	0,1	1,4	0,5	0,8
20	20	0,13064	0,19	3,2	0,9	0,5	2,5	0,5	0,1	0,3	8,1	0,1	1,4	0,5	0,4
40	50	0,13078	0,13	3,2	0,6	0,5	2,5	0,5	0,1	0,3	4,5	0,1	1,4	0,4	0,4
80	100	0,13076	0,12	3,2	0,5	0,5	2,5	0,5	0,1	0,3	3,5	0,1	1,4	0,3	0,8
160	100	0,13065	0,12	3,2	0,5	0,5	2,5	0,5	0,1	0,3	3,5	0,1	1,4	0,2	1,0
315	100	0,13066	0,12	3,2	0,5	0,5	2,5	0,5	0,1	0,3	3,5	0,3	1,4	0,2	0,9
630	100	0,13054	0,13	3,2	0,5	0,5	2,5	1,0	0,1	0,3	3,5	0,9	1,4	0,2	2,7
800	200	0,13067	0,13	3,2	0,5	0,5	2,5	1,5	0,1	0,3	3,5	0,7	1,4	0,2	2,8