Final Report of CCAUV.V-K4:
Key comparison in the field of acceleration on low intensity shock sensitivity

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1. Introduction

This report presents the results of the first CCAUV comparison in the area of low intensity shock, which in this case means low intensity linear shock acceleration.

The participants have reached consensus and considered the weighted mean as the most appropriate method for this particular comparison to compute the key comparison reference values (KCRVs) and the degrees of equivalence (DoEs). Detailed analysis and application of the method for use of the weighted mean in comparisons in the field of vibration, is documented in the CCAUV.V-K1 report [1]. The calculation of the KCRVs is also in accordance with the Guidelines for CIPM key comparisons [2].

The Technical Protocol, published in 2016 [3], specifies in detail the aim, the task of the comparison, the conditions for the measurements, the transfer standard used, measurement instructions, time schedule and other items. A brief survey of the Technical Protocol is given in the following sections. Refer to Annex A for details of the TP.

2. Participants

Nine metrology institutes (NMIs) from five Regional Metrology Organizations (RMOs) participated in the comparison. They are listed in chronological order of measurement in Table 2.1.

Table 2.1: List of participants and schedule of CCAUV.V-K4

No.	Participant Laboratory	Acronym	Country	RMO	Calibration period (week/year)
1	National Institute of Metrology, China	NIM	China	APMP	12/2017 to 14/2017
2	Instituto Nacional de Metrologia, Qualidade e Tecnologia	INMETRO	Brazil	SIM	17/2017 to 19/2017
3	Centro Nacional de Metrologia	CENAM	Mexico	SIM	22/2017 to 24/2017
4	National Metrology Institute of Japan	NMIJ	Japan	APMP	27/2017 to 29/2017
5	D.I. Mendeleyev Institute for Metrology	VNIIM	Russia Federation	COOMET	12/2017 to 14/2017
6	National Metrology Institute of South Africa	NMISA	South Africa	AFRIMETS	07/2018 to 09/2018

7	Physikalisch-Technische Bundesanstalt	PTB	Germany	EURAMET	12/2018 to 14/2018
8	National Measurement Institute of Australia	NMIA	Australia	APMP	17/2018 to 19/2018
9	Korea Research Institute of Standards and Science	KRISS	Republic of Korea	APMP	22/2018 to 24/2018

3. Task and purpose of the comparison

According to the rules set up by the CIPM MRA [4], the consultative committees of the CIPM have the responsibility to establish Degrees of Equivalence (DoEs) between the different measurement standards operated by the NMIs. This is done by conducting key comparisons (KCs) on different levels of the international metrological infrastructure.

However, in the sub-field of shock, there has been no formal key or supplementary comparison either at Consultative Committee (CC) level or Regional Metrology Organization Technical Committee (RMO TC) level at the time of this proposed comparison. Therefore during the 10th meeting of CCAUV in November 2015, the decision was taken to make preparations for a further key comparison targeted at low shock acceleration.

In the field of accelerometer shock calibration, this key comparison is organized in order to compare primary measurements of Gaussian, half-sine or half-sine squared linear shock accelerations in the range from 500 m/s^2 to 5 000 m/s^2. It is the task of the comparison to measure the voltage shock sensitivity of an accelerometer measuring chain including a standard accelerometer (of back-to-back type) with a charge amplifier and the charge shock sensitivity of an accelerometer (of single-ended type) at different peak acceleration values with associated pulse durations as specified in section 3. The results of this key comparison will, after approval of equivalence, serve as the foundation at low intensity shock for the registration of ‘calibration and measurement capabilities’ (CMCs) in the framework of the CIPM MRA [4].

The results of this comparison are expected to provide direct support to CMCs related to the primary calibration of voltage shock sensitivity of acceleration measuring chains and charge shock sensitivity of accelerometers at low intensity acceleration.

For the calibration of the accelerometer chain and the accelerometer, laser interferometry in compliance with a method described in the international standard ISO 16063-13:2001 has to be applied. Specifically, the voltage shock sensitivity shall be given in milli-volt per meter per second squared (mV/(m/s^2)) and the charge shock sensitivity shall be given in pico-coulomb per meter per second squared (pC/(m/s^2)) for the different measurement conditions specified in section 4.

The reported shock sensitivities and associated uncertainties are then supposed to be used for the calculation of the weighted mean as the key comparison reference value (KCRV) and the DoE between the participating NMI and the KCRV.

4. Transfer standard as artefacts

For the purpose of the comparison the pilot laboratory selected one accelerometer measuring chain and one accelerometer of which monitoring data for six months were available and not included in any published international cooperation work.

- One transfer standard Accelerometer Chain of a standard accelerometer of back-to-back type, ENDEVCO 2270, S/N 14155 and a charge amplifier, Brüel & Kjær 2692, S/N 2752215.
- One transfer standard accelerometer (single-ended), PCB 357B03, S/N LW50432.

The investigation of the long-term stability was continued throughout the circulation period. The results of the NIM stability measurements and other individual data of the transfer standards are given in Section 6.

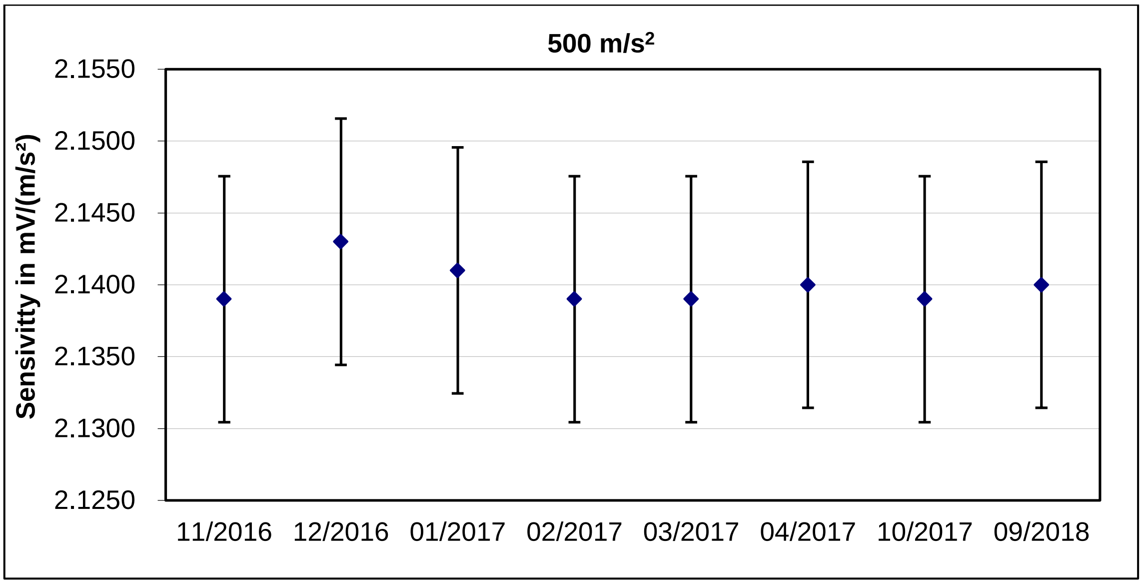
5. Circulation of the artefacts

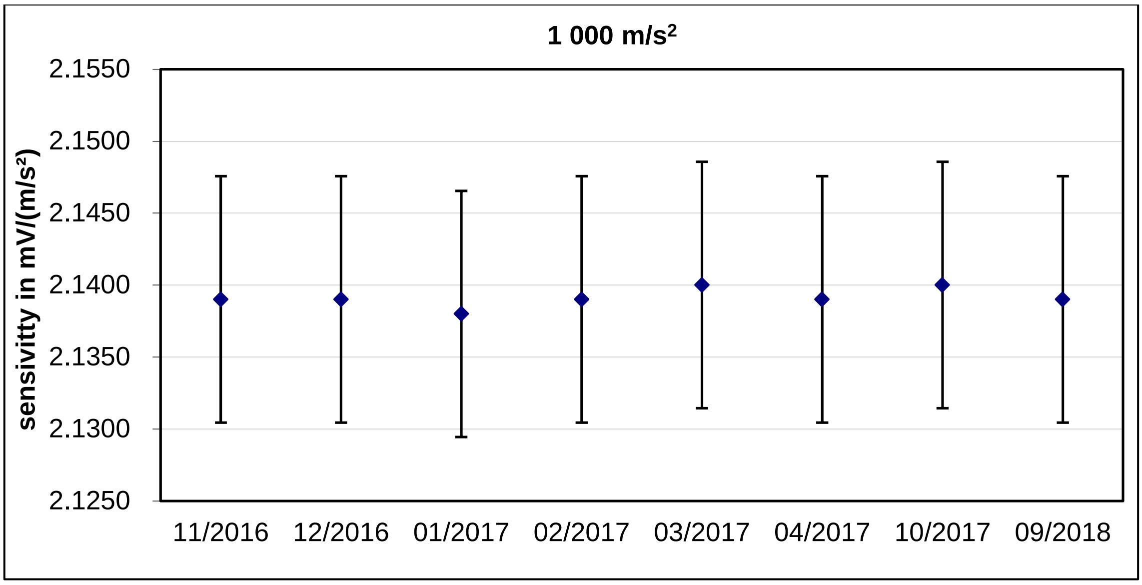
The artefacts were circulated in two loops with a measurement period of three weeks provided for each participating laboratory. At the beginning and the end of the circulation as well as between certain subsequent measurements of participating laboratories, the artefacts were measured by the pilot laboratory in order to monitor the stability of the transfer standard.

6. Results of the monitoring measurements

Starting with calibration data in November 2016, the artefacts were monitored during the preparation period and the intervals of the comparison when they were back at the pilot laboratory. The measurements at all peak acceleration values are presented in Figure 6.1 and Figure 6.2. These figures depict the stability of the artefacts over time for the duration of the comparison.

Figure 6.1 Monitoring of the voltage shock sensitivity over the comparison period

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sensivitty in mV/(m/s²)
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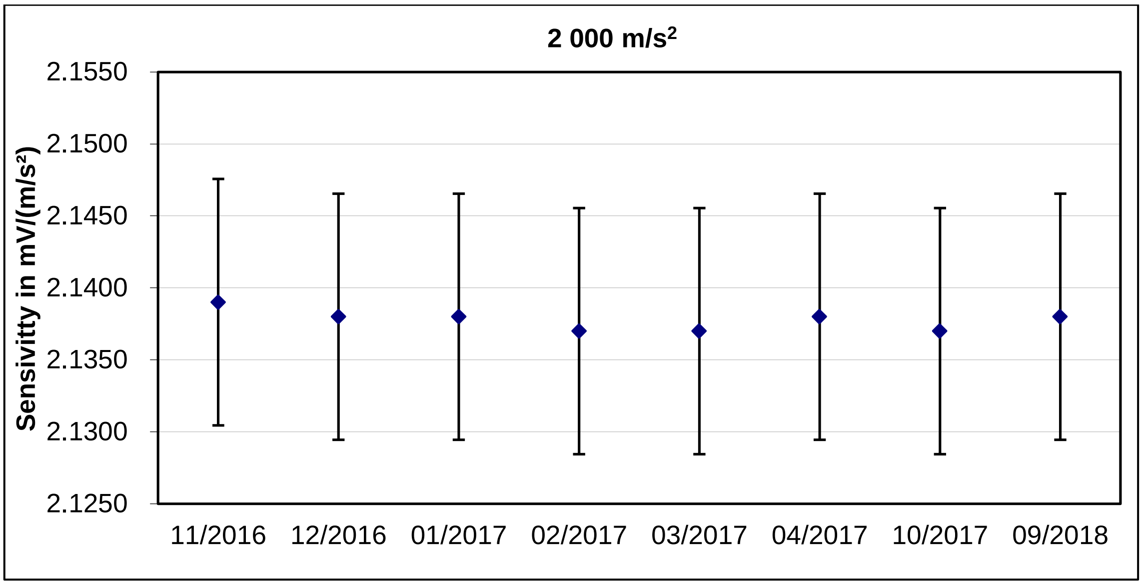
2.1500
2.1450
2.1400
2.1350
2.1300
2.1250
11/2016
12/2016
01/2017
02/2017
03/2017
04/2017
10/2017
09/2018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Sensivitty in mV/(m/s²)
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2.1500
2.1450
2.1400
2.1350
2.1300
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12/2016
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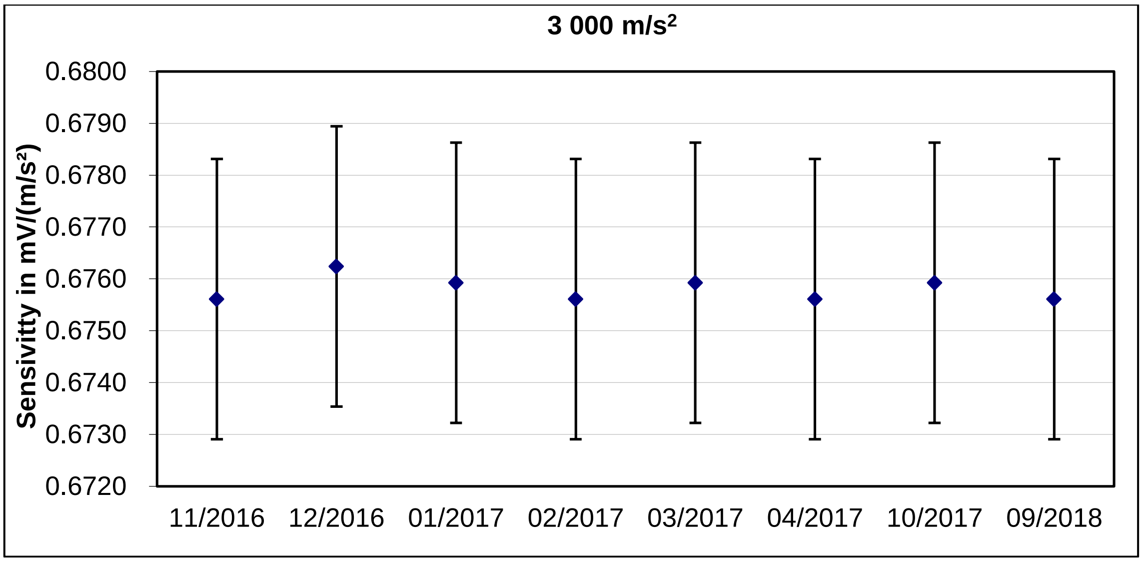
04/2017
10/2017
09/2018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Sensivitty in mV/(m/s²)
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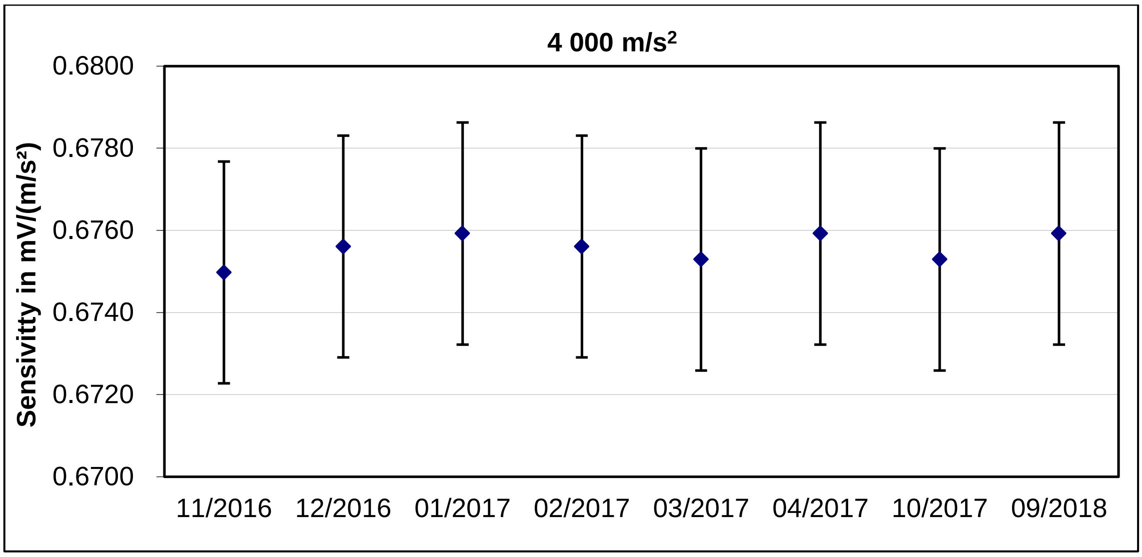
0.6780
0.6770
0.6760
0.6750
0.6740
0.6730
0.6720
11/2016
12/2016
01/2017
02/2017
03/2017
04/2017
10/2017
09/2018



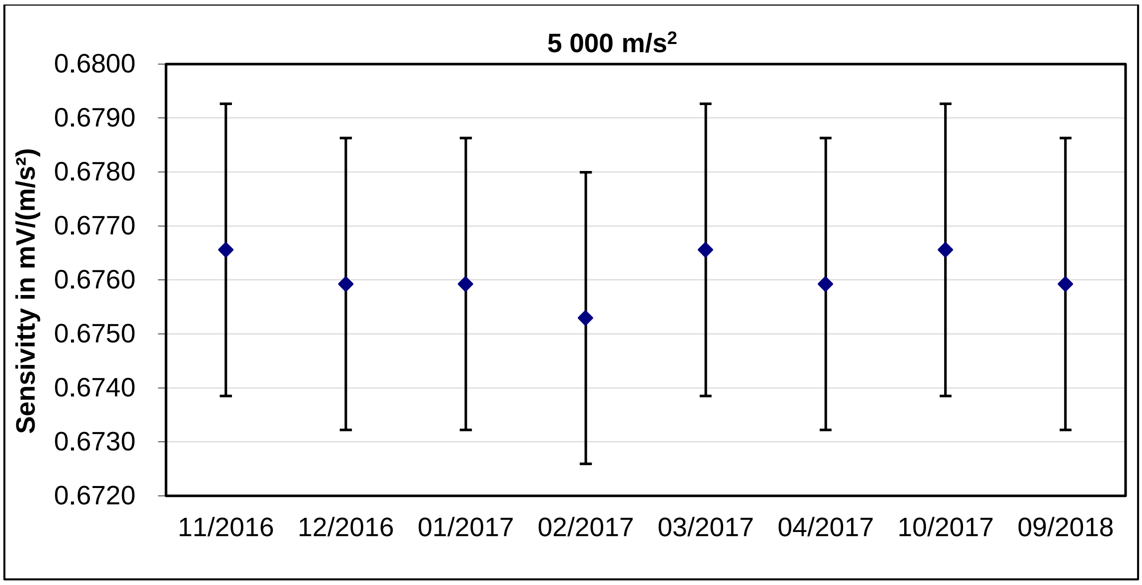
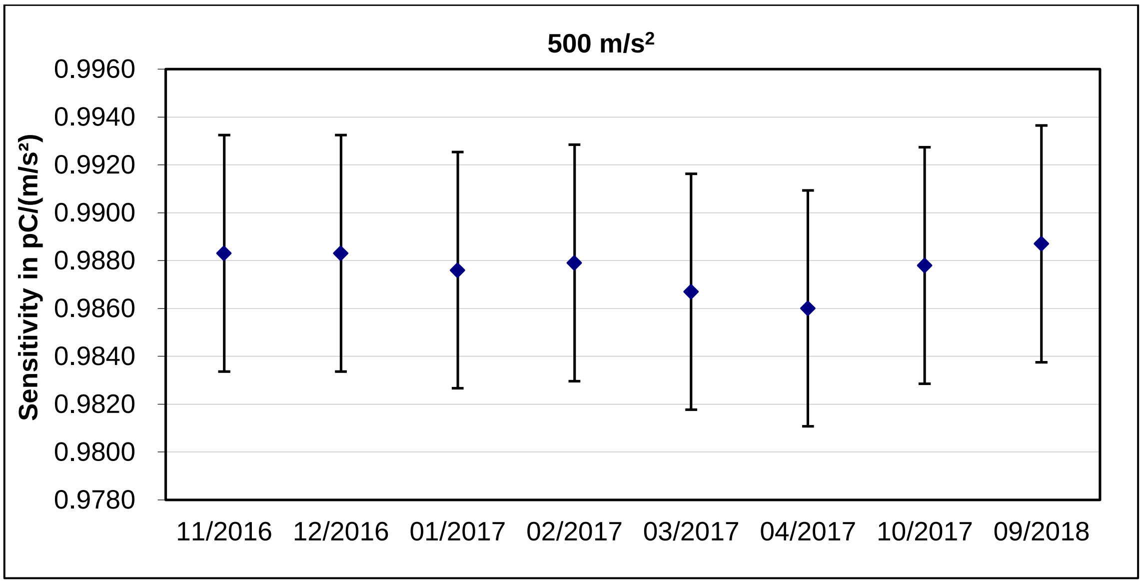
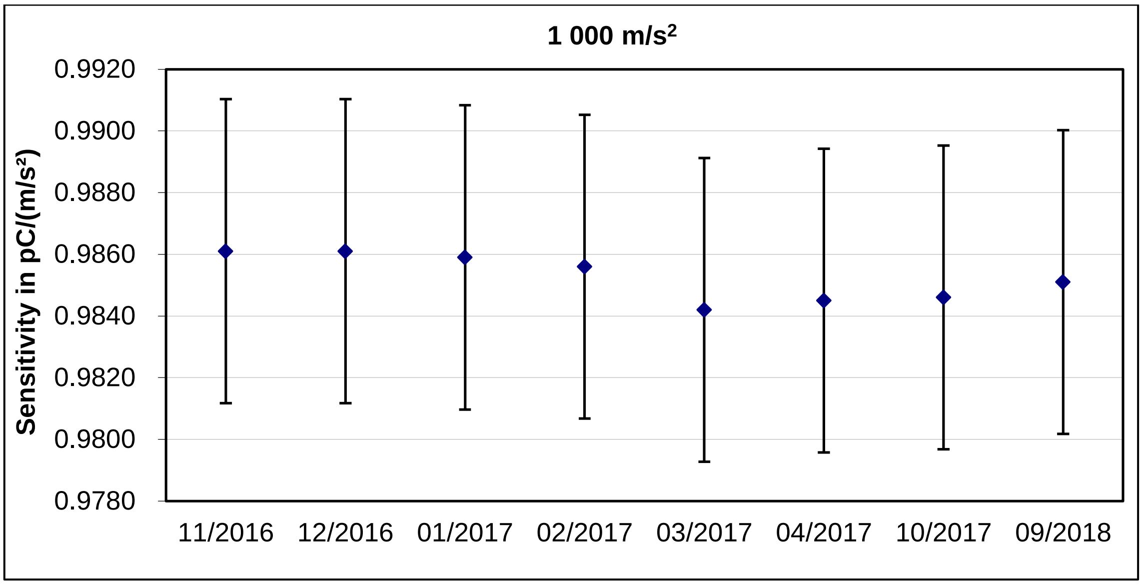


Figure 6.2 Monitoring of the charge shock sensitivity over the comparison period




1 000 m/s²
Sensitivity in pC/(m/s²)
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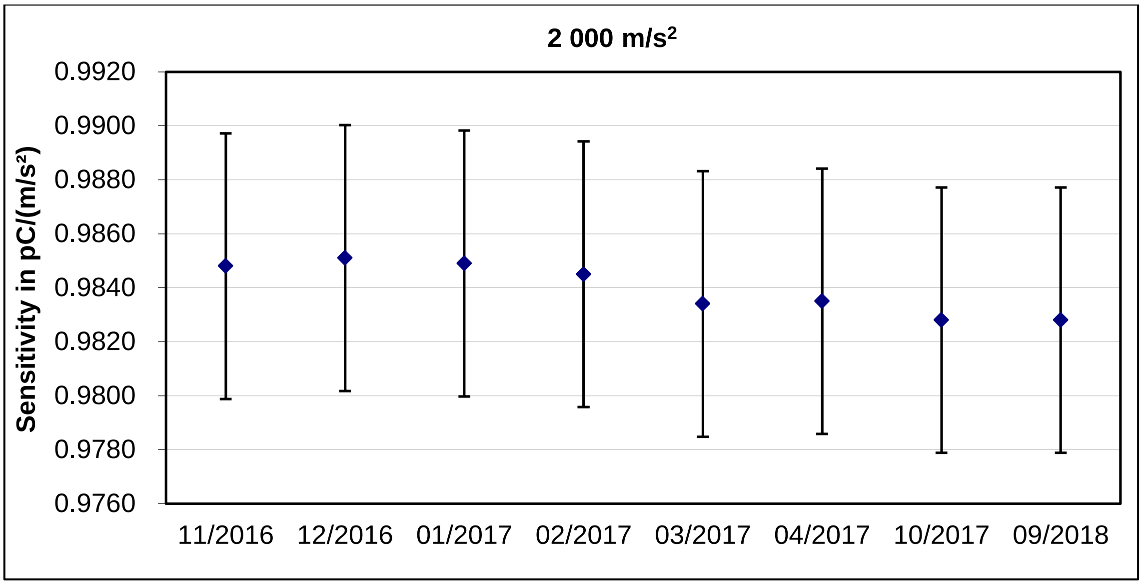
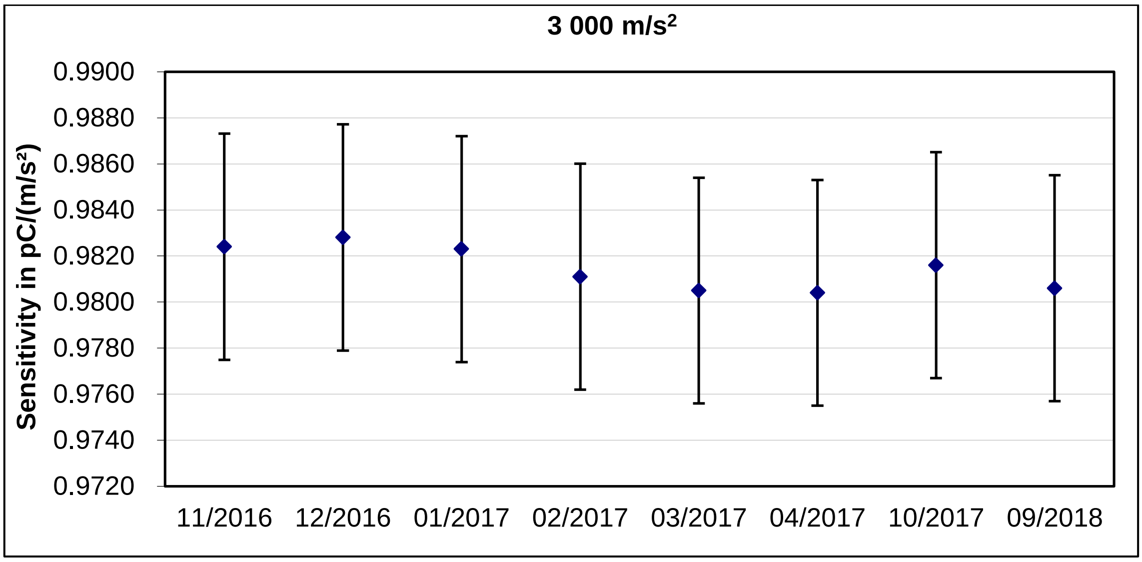
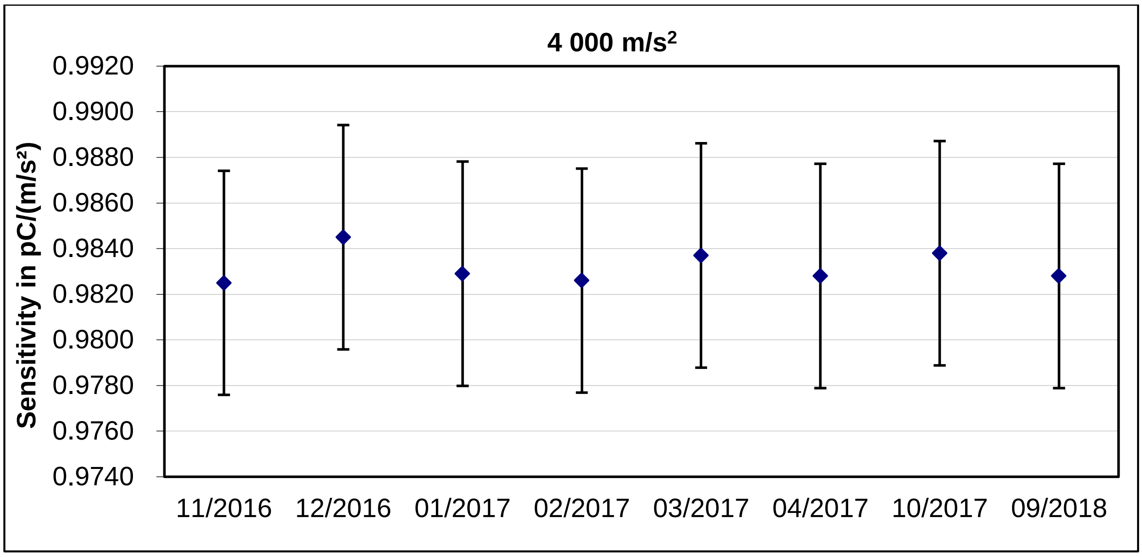
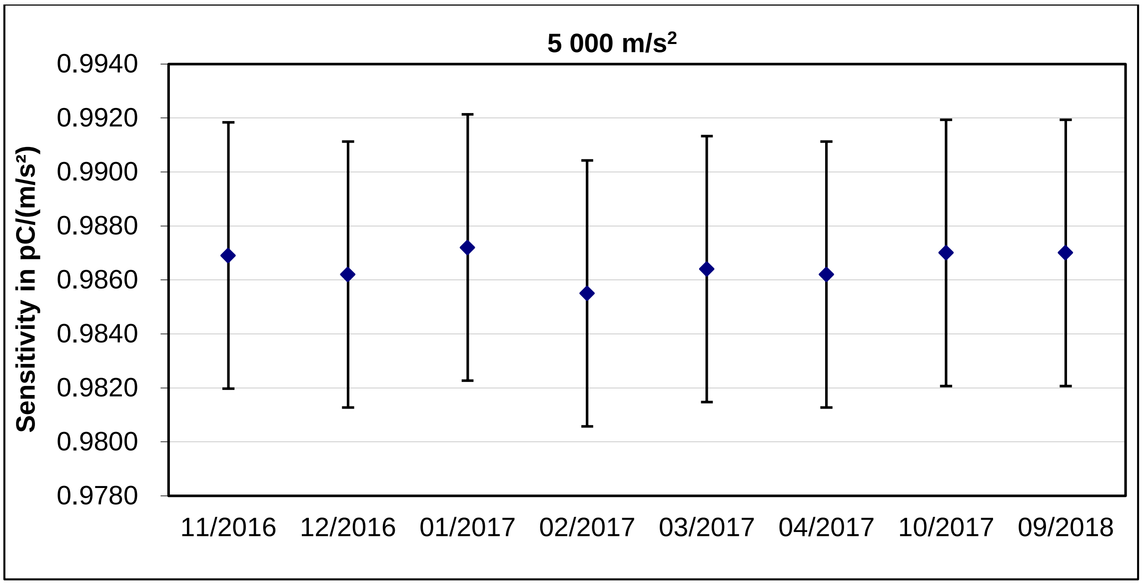
0.9900
0.9880
0.9860
0.9840
0.9820
0.9800
0.9780
11/2016
12/2016
01/2017
02/2017
03/2017
04/2017
10/2017
09/2018


2 000 m/s²
Sensitivity in pC/(m/s²)
0.9920
0.9900
0.9880
0.9860
0.9840
0.9820
0.9800
0.9780
0.9760
11/2016
12/2016
01/2017
02/2017
03/2017
04/2017
10/2017
09/2018


3 000 m/s²
Sensitivity in pC/(m/s²)
0.9900
0.9880
0.9860
0.9840
0.9820
0.9800
0.9780
0.9760
0.9740
0.9720
11/2016
12/2016
01/2017
02/2017
03/2017
04/2017
10/2017
09/2018





A visual inspection of the above results indicates that the artefacts were sufficiently stable during the whole period of the comparison.

7. Results of the participants

The following sections report the results submitted by the participants for the comparison to the pilot laboratory using the mandatory report spreadsheet. The results presented are in mV/(m/s²) for the voltage shock sensitivity and and in pC/(m/s²) for the charge shock sensitivity.

Note that PTB did not submit its results for charge shock sensitivity.

7.1 Results for the voltage shock sensitivity

Table 7.1.a: Reported participants' results for the voltage shock sensitivity of the accelerometer chain with relative expanded uncertainties (k = 2)

	NIM		INMETRO		CENAM		NMIJ		VNIIM	
peak acceleration	voltage shock sensitivity	rel. exp. Unc.	voltage shock sensitivity	rel. exp. Unc.	voltage shock sensitivity	rel. exp. Unc.	voltage shock sensitivity	rel. exp. Unc.	voltage shock sensitivity	rel. exp. Unc.
in m/s²	mV/(m/s²)	%	mV/(m/s²)	%	mV/(m/s²)	%	mV/(m/s²)	%	mV/(m/s²)	%
500	2.140	0.4	2.1399	0.40	2.1388	0.8	2.138	0.2	0.2154	1.5
1000	2.139	0.4	2.1390	0.40	2.1387	0.6	2.137	0.2	0.2130	1.5
2000	2.138	0.4	2.1381	0.40	2.1387	0.6	2.136	0.2	0.2122	1.5
3000	0.6756	0.4	0.67582	0.40	2.1391	0.6	0.6753	0.2	0.2158	1.5
4000	0.6759	0.4	0.67556	0.40	2.1383	0.6	0.6746	0.2	0.2158	1.5
5000	0.6759	0.4	0.67531	0.40	0.21384	0.8	0.6738	0.2	0.2120	1.5

	NMISA		PTB		NMIA		KRISS	
peak acceleration	voltage shock sensitivity	rel. exp. Unc.	voltage shock sensitivity	rel. exp. Unc.	voltage shock sensitivity	rel. exp. Unc.	voltage shock sensitivity	rel. exp. Unc.
in m/s²	mV/(m/s²)	%	mV/(m/s²)	%	mV/(m/s²)	%	mV/(m/s²)	%
500	2.1377	1.0	2.1362	0.25	2.1363	0.5	2.150	1.1
1000	2.1383	1.0	2.1362	0.25	2.1352	0.5	2.145	1.1
2000	2.1323	1.0	2.1359	0.25	2.1348	0.5	2.141	1.1
3000	0.6755	1.1	0.6750	0.25	0.6744	0.5	0.6780	1.1
4000	0.6754	1.1	0.6749	0.25	0.6743	0.5	0.6768	1.1
5000	0.6754	1.1	0.6750	0.25	0.6737	0.5	0.6783	1.1

In table 7.1.a, it should be noted that the results marked using a yellow background are reported measurement values of VNIIM and CENAM using different gain settings from specifications of the mandatory report spreadsheet. Refer to Annex B for detailed information.

Table 7.1.b: Corrected participants' results for the voltage shock sensitivity of the accelerometer chain with relative expanded uncertainties (k = 2)

	NIM		INMETRO		CENAM		NMIJ		VNIIM	
peak acceleration	voltage shock sensitivity	rel. exp. Unc.	voltage shock sensitivity	rel. exp. Unc.	voltage shock sensitivity	rel. exp. Unc.	voltage shock sensitivity	rel. exp. Unc.	voltage shock sensitivity	rel. exp. Unc.
in m/s²	mV/(m/s²)	%	mV/(m/s²)	%	mV/(m/s²)	%	mV/(m/s²)	%	mV/(m/s²)	%
500	2.140	0.4	2.1399	0.40	2.1388	0.8	2.138	0.2	2.154	1.5
1000	2.139	0.4	2.1390	0.40	2.1387	0.6	2.137	0.2	2.130	1.5
2000	2.138	0.4	2.1381	0.40	2.1387	0.6	2.136	0.2	2.122	1.5
3000	0.6756	0.4	0.67582	0.40	0.67596	0.6	0.6753	0.2	0.6819	1.5
4000	0.6759	0.4	0.67556	0.40	0.67570	0.6	0.6746	0.2	0.6819	1.5
5000	0.6759	0.4	0.67531	0.40	0.67573	0.8	0.6738	0.2	0.6699	1.5

	NMISA		PTB		NMIA		KRISS	
peak acceleration	voltage shock sensitivity	rel. exp. Unc.	voltage shock sensitivity	rel. exp. Unc.	voltage shock sensitivity	rel. exp. Unc.	voltage shock sensitivity	rel. exp. Unc.
in m/s²	mV/(m/s²)	%	mV/(m/s²)	%	mV/(m/s²)	%	mV/(m/s²)	%
500	2.1377	1.0	2.1362	0.25	2.1363	0.5	2.150	1.1
1000	2.1383	1.0	2.1362	0.25	2.1352	0.5	2.145	1.1
2000	2.1323	1.0	2.1359	0.25	2.1348	0.5	2.141	1.1
3000	0.6755	1.1	0.6750	0.25	0.6744	0.5	0.6780	1.1
4000	0.6754	1.1	0.6749	0.25	0.6743	0.5	0.6768	1.1
5000	0.6754	1.1	0.6750	0.25	0.6737	0.5	0.6783	1.1

Table 7.1.b presents the corrected results for the subsequent calculation of DoE and KCRVs. In this table, the corrections for different gain settings were applied as follows:

- Corrected measurement values of CENAM at 3 000 and 4 000 m/s^2 were multiplied by the factor of 0.316.
- Corrected measurement values of CENAM at 5 000 m/s^2 was multiplied by the factor of 3.16.
- Corrected measurement values of VNIIM at 500, 1 000 and 2 000 m/s^2 were multiplied by the factor of 10.
- Corrected measurement values of VNIIM at 3 000, 4 000 and 5 000 m/s^2 were multiplied by the factor of 3.16.

7.2 Results for the charge shock sensitivity

Table 7.2: Reported participants' results for the charge shock sensitivity of the accelerometer with relative expanded uncertainties (k = 2)

	NIM		INMETRO		CENAM		NMIJ		VNIIM	
peak acceleration	charge shock sensitivity	rel. exp. Unc.	charge shock sensitivity	rel. exp. Unc.	charge shock sensitivity	rel. exp. Unc.	charge shock sensitivity	rel. exp. Unc.	charge shock sensitivity	rel. exp. Unc.
in m/s²	pC/(m/s²)	%	pC/(m/s²)	%	pC/(m/s²)	%	pC/(m/s²)	%	pC/(m/s²)	%
500	0.9860	0.5	0.98734	0.45	0.99101	0.8	0.9885	0.4	1.0022	1.5
1000	0.9845	0.5	0.98460	0.45	0.98844	0.6	0.9868	0.4	1.0032	1.5
2000	0.9835	0.5	0.98270	0.45	0.98742	0.6	0.9843	0.4	1.0031	1.5
3000	0.9804	0.5	0.98193	0.45	0.98360	0.6	0.9808	0.4	1.0017	1.5
4000	0.9828	0.5	0.98160	0.45	0.98323	0.6	0.9813	0.4	0.9974	1.5
5000	0.9862	0.5	0.97994	0.45	0.97998	0.8	0.9852	0.4	0.9894	1.5

	NMISA		PTB		NMIA		KRISS	
peak acceleration	charge shock sensitivity	rel. exp. Unc.	charge shock sensitivity	rel. exp. Unc.	charge shock sensitivity	rel. exp. Unc.	charge shock sensitivity	rel. exp. Unc.
in m/s²	pC/(m/s²)	%	pC/(m/s²)	%	pC/(m/s²)	%	pC/(m/s²)	%
500	0.9897	1.1			0.9858	0.6	0.9886	1.1
1000	0.9888	1.1			0.9823	0.6	0.9884	1.1
2000	0.9878	1.1			0.9810	0.6	0.9853	1.1
3000	0.9759	1.2			0.9785	0.6	0.9838	1.1
4000	0.9768	1.2			0.9773	0.6	0.9838	1.1
5000	0.9761	1.2			0.9746 (*)	0.6 (*)	0.9840	1.1

8. Degrees of equivalence with respect to the weighted mean

The evaluation of the results was performed using a weighted mean computed with the following equations:

$$x_{WM}(a) = \sum \frac{X_i(a)}{u_i^2(a)} \cdot \left(\sum \frac{1}{u_i^2(a)}\right)^{-1} \quad (1)$$

$$u_{WM}(a) = \left(\sum \frac{1}{u_i^2(a)}\right)^{-1/2} \quad (2)$$

where the WM was calculated using the results of the participants according to [1]. In the equations above the following symbols were used:

$x_i(a)$	result of participant *i* at peak acceleration *a*
$u_i(a)$	absolute standard uncertainty of participant *i* at peak acceleration *a*
$x_{WM}(a)$	best estimate of the weighted mean (WM) sensitivity at peak acceleration *a*
$u_{WM}(a)$	estimated absolute standard uncertainty for the weighted mean (WM) at peak acceleration *a*

Consistency checks were performed for the voltage and charge shock sensitivities. The test defined by Cox in [5, 6] was applied in order to determine the participants that are members of the largest consistent subset (LCS).

The key comparison reference values (KCRVs) were finally determined by the WM using the participants that are members of the largest consistent subset (MoCS):

$x_{KCRV}(a)$	best estimate of the KCRV at peak acceleration *a*
$u_{KCRV}(a)$	estimated absolute standard uncertainty of the KCRV at peak acceleration *a*

Table 8.1, 8.2, 8.3 and 8.4 present the results of the consistency test for the voltage and charge shock sensitivity results. Cell is highlighted in yellow when $X^2obs > X^2(nu)$.

Table 8.1: Results of the consistency test applied to all the results reported by the participants for shock voltage sensitivities

Acceleration in m/s²	number of participants	number of degrees of freedom	X²obs	X²(nu) with P < 0.05
500	9	8	2.99	15.51
1000	9	8	1.35	15.51
2000	9	8	1.70	15.51
3000	9	8	4.53	15.51
4000	9	8	5.65	15.51
5000	9	8	7.37	15.51

Table 8.2: Results of the consistency test applied to all the results reported by the participants for shock charge sensitivities

Acceleration in m/s²	number of participants	number of degrees of freedom	X²obs	X²(nu) with P < 0.05
500	8	7	5.61	14.07
1000	8	7	8.61	14.07
2000	8	7	9.27	14.07
3000	8	7	9.35	14.07
4000	8	7	7.34	14.07
5000	8	7	14.15	14.07

Table 8.3: Results of the consistency test applied to all the results reported by the largest consistent subset for shock voltage sensitivities

Acceleration in m/s²	number of participants	number of degrees of freedom	X²obs	X²(nu) with P < 0.05
500	9	8	2.99	15.51
1000	9	8	1.35	15.51
2000	9	8	1.70	15.51
3000	9	8	4.53	15.51
4000	9	8	5.65	15.51
5000	9	8	7.37	15.51

Table 8.4: Results of the consistency test applied to all the results reported by the largest consistent subset for shock charge sensitivities

Acceleration in m/s²	number of participants	number of degrees of freedom	X²obs	X²(nu) with P < 0.05
500	8	7	5.61	14.07
1000	8	7	8.61	14.07
2000	8	7	9.27	14.07
3000	8	7	9.35	14.07
4000	8	7	7.34	14.07
5000	7	6	6.05	12.59

The results presented in tables 7.2 marked with an asterisk (*) were considered as not within the LCS and were excluded from the calculation of the KCRV.

For the further evaluation of the comparison, the unilateral degrees of equivalence with respect to the KCRVs were calculated according to:

$$d_{i,KCRV}(a) = x_i(a) - x_{KCRV}(a) \quad (3)$$

$$u^2{}_{i,KCRV}(a) = \begin{cases} u^2{}_i(a) - u^2{}_{KCRV}(a) & \text{for results within the LCS} \\ u^2{}_i(a) + u^2{}_{KCRV}(a) & \text{for results not within the LCS} \end{cases} \quad (4)$$

These formulas were applied for both voltage and charge shock sensitivity results. In the subsequent tables 8.5 and 8.6, $U_i = 2u_i$ and the results are marked using a light brown background where $|d_{i,KCRV}(a)| > 2 \cdot u_{i,KCRV}(a)$.

Unilateral DoEs obtained from results which were excluded from the largest consistent subset and which therefore did not contribute to the calculation of the KCRV are marked with an asterisk (*) in table 8.6.

Note that :

- PTB presented differences higher than 10 % of the recommended pulse durations for all peak accelerations.
- NMISA presented differences higher than 10 % of the recommended pulse durations for all peak accelerations except 500 m/s^2.
- NMIA presented differences higher than 10 % of the recommended pulse durations for the peak accelerations of 4 000 m/s^2 and 5 000 m/s^2.
- VNIIM presented a 10% difference of the recommended pulse duration at peak acceleration of 500 m/s^2.

Refer to Annex B for detailed information.

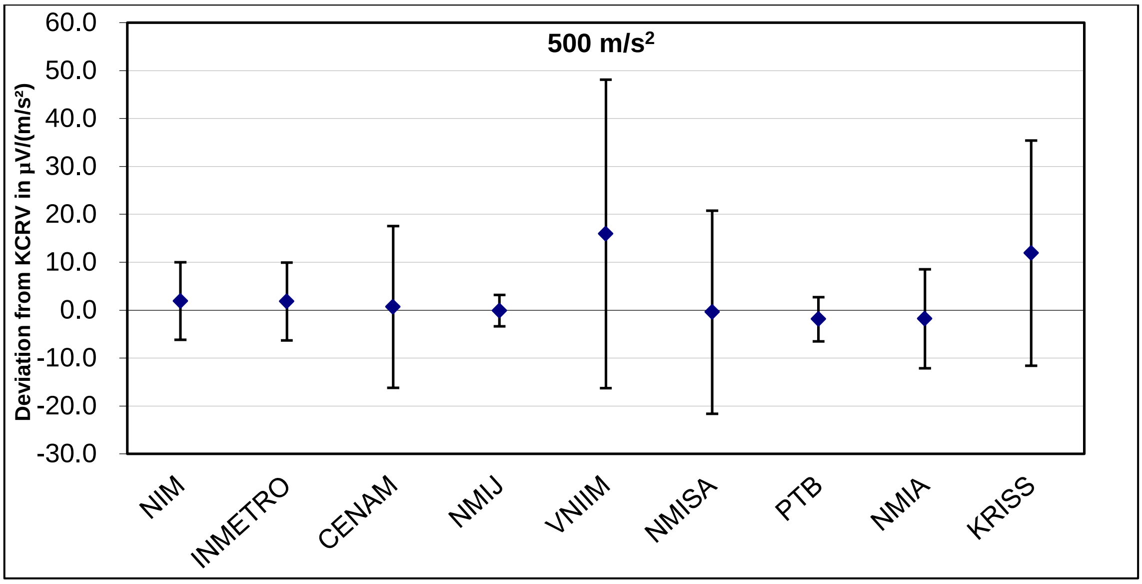
8.1 Results for the voltage shock sensitivity

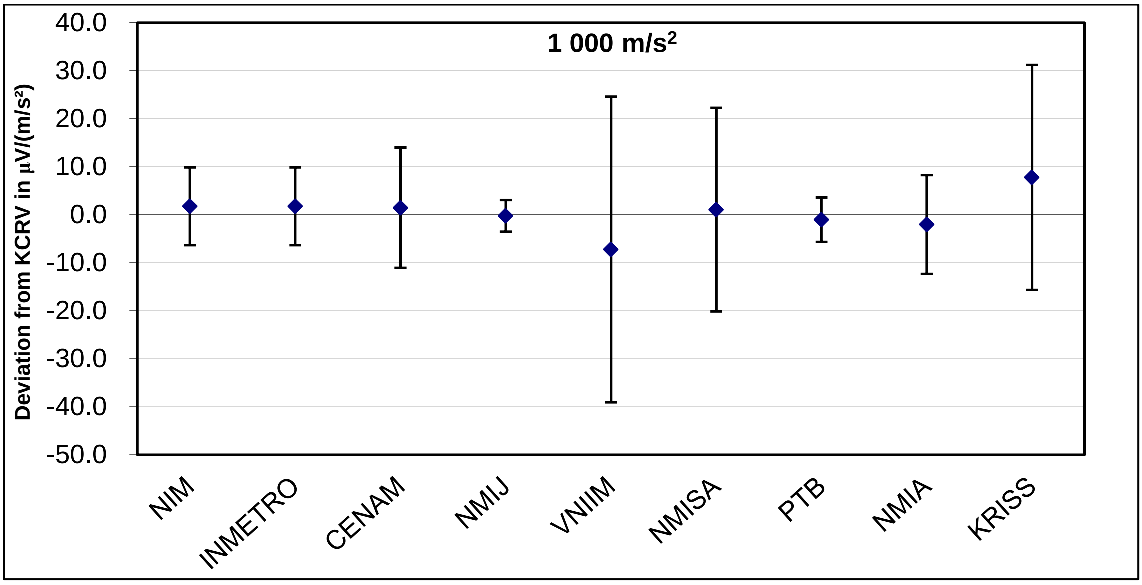
Table 8.5: Unilateral degrees of equivalence for the voltage shock sensitivity with absolute expanded uncertainties (k = 2)

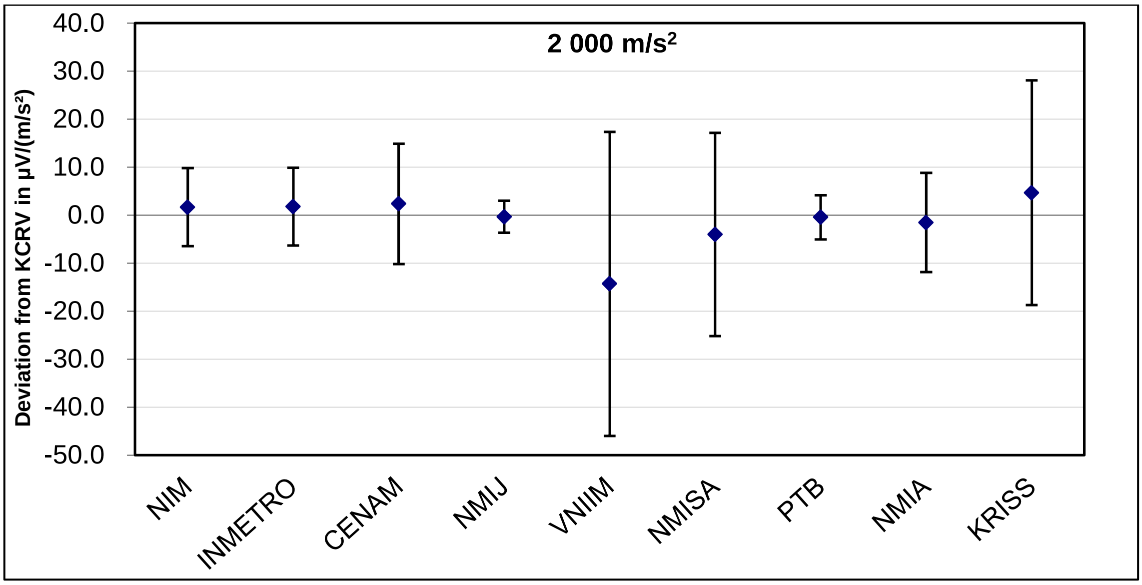
	KCRV		NIM		INMETRO		CENAM		NMIJ		VNIIM	
peak acceleration	X_{KCRV}	U_{KCRV}	$d_{i,KCRV}$	$U_{i,KCRV}$	$d_{i,KCRV}$	$U_{i,KCRV}$	$d_{i,KCRV}$	$U_{i,KCRV}$	$d_{i,KCRV}$	$U_{i,KCRV}$	$d_{i,KCRV}$	$U_{i,KCRV}$
in m/s²	mV/(m/s²)		mV/(m/s²)		mV/(m/s²)		mV/(m/s²)		mV/(m/s²)		mV/(m/s²)	
500	2.13810	0.00273	0.00190	0.00811	0.00180	0.00811	0.00070	0.01689	-0.00010	0.00329	0.01590	0.03219
1000	2.13723	0.00270	0.00177	0.00812	0.00177	0.00812	0.00147	0.01254	-0.00023	0.00331	-0.00723	0.03184
2000	2.13633	0.00270	0.00167	0.00811	0.00177	0.00811	0.00237	0.01254	-0.00033	0.00331	-0.01433	0.03172
3000	0.67536	0.00086	0.00024	0.00256	0.00046	0.00256	0.00059	0.00396	-0.00006	0.00105	0.00657	0.01019
4000	0.67502	0.00085	0.00088	0.00256	0.00054	0.00256	0.00068	0.00396	-0.00042	0.00104	0.00690	0.01019
5000	0.67458	0.00086	0.00132	0.00256	0.00073	0.00256	0.00116	0.00534	-0.00078	0.00104	-0.00466	0.01001

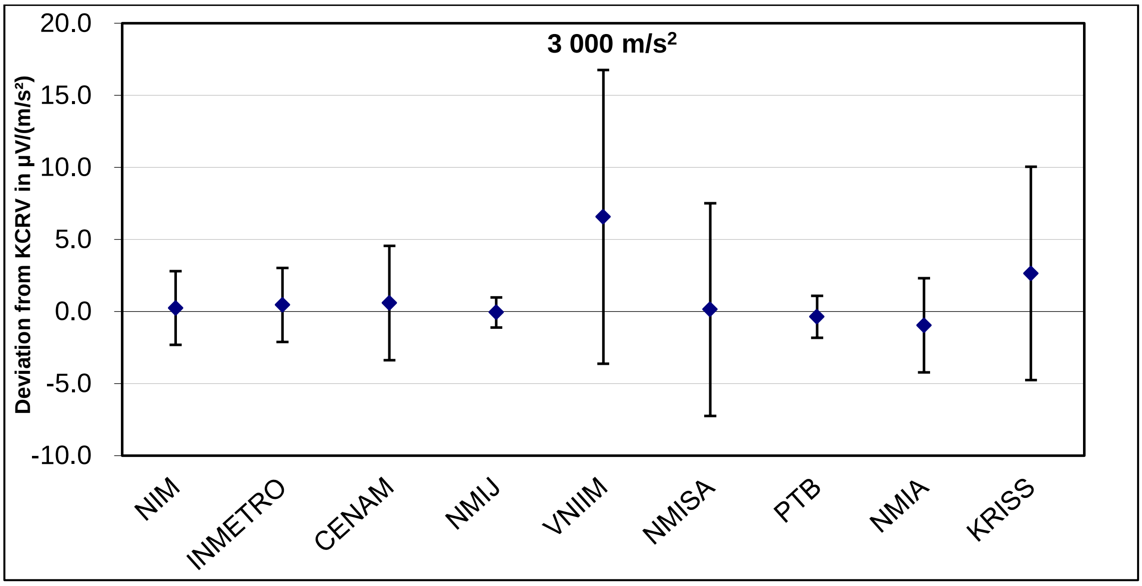
	KCRV		NMISA		PTB		NMIA		KRISS	
peak acceleration	X_{KCRV}	U_{KCRV}	$d_{i,KCRV}$	$U_{i,KCRV}$	$d_{i,KCRV}$	$U_{i,KCRV}$	$d_{i,KCRV}$	$U_{i,KCRV}$	$d_{i,KCRV}$	$U_{i,KCRV}$
in m/s²	mV/(m/s²)		mV/(m/s²)		mV/(m/s²)		mV/(m/s²)		mV/(m/s²)	
500	2.13810	0.00273	-0.00040	0.02120	-0.00190	0.00459	-0.00180	0.01033	0.01190	0.02349
1000	2.13723	0.00270	0.00107	0.02121	-0.00103	0.00461	-0.00203	0.01033	0.00777	0.02344
2000	2.13633	0.00270	-0.00403	0.02115	-0.00043	0.00461	-0.00153	0.01033	0.00467	0.02340
3000	0.67536	0.00086	0.00014	0.00738	-0.00036	0.00145	-0.00096	0.00326	0.00264	0.00741
4000	0.67502	0.00085	0.00038	0.00738	-0.00012	0.00145	-0.00072	0.00326	0.00178	0.00740
5000	0.67458	0.00086	0.00082	0.00738	0.00042	0.00145	-0.00088	0.00326	0.00372	0.00741

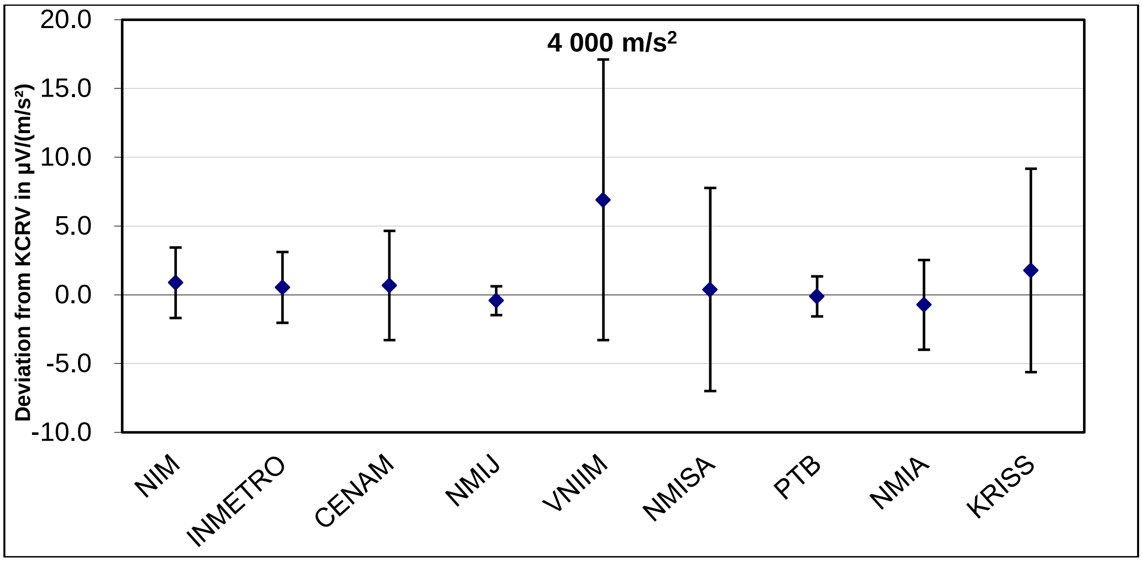
Figure 8.1 : Deviation of the voltage shock sensitivity from the KCRV for all peak accelerations of the comparison with expanded uncertainties $U_{i,KCRV}$ (k = 2)

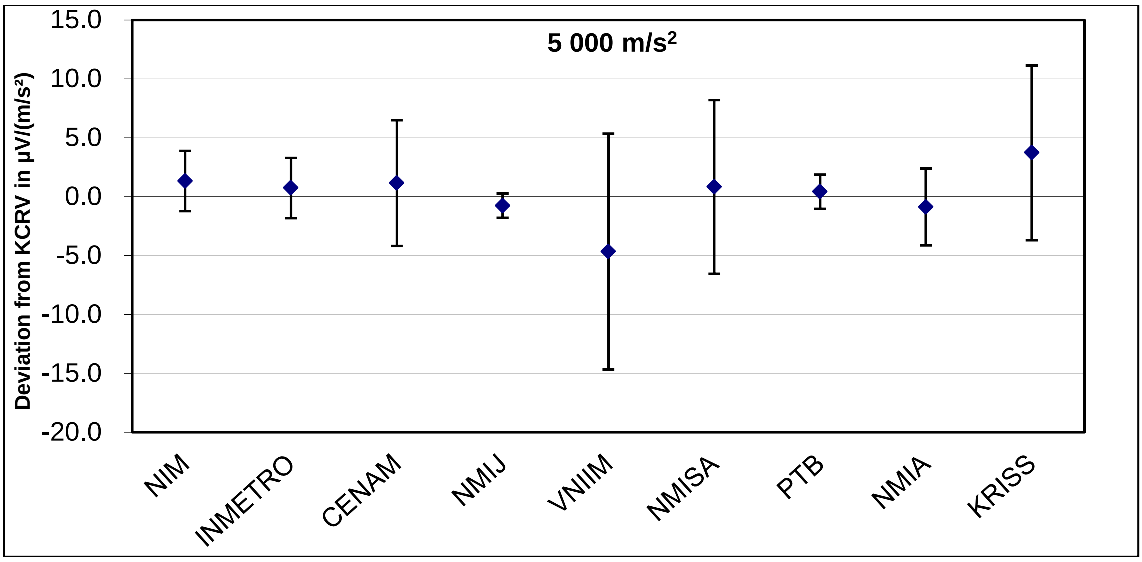



1 000 m/s²
Deviation from KCRV in µV/(m/s²)
40.0
30.0
20.0
10.0
0.0
-10.0
-20.0
-30.0
-40.0
-50.0
NIM
INMETRO
CENAM
NMIJ
VNIIM
NMISA
PTB
NMIA
KRISS


2 000 m/s²
Deviation from KCRV in µV/(m/s²)
40.0
30.0
20.0
10.0
0.0
-10.0
-20.0
-30.0
-40.0
-50.0
NIM
INMETRO
CENAM
NMIJ
VNIIM
NMISA
PTB
NMIA
KRISS


3 000 m/s²
Deviation from KCRV in µV/(m/s²)
20.0
15.0
10.0
5.0
0.0
-5.0
-10.0
NIM
INMETRO
CENAM
NMIJ
VNIIM
NMISA
PTB
NMIA
KRISS





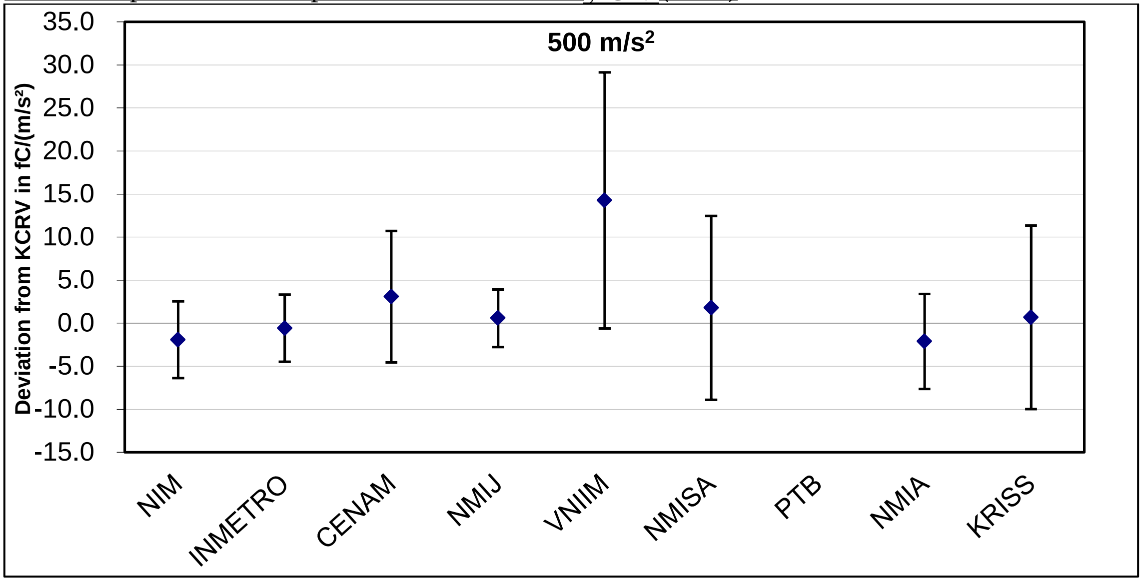
8.2 Results for the charge shock sensitivity

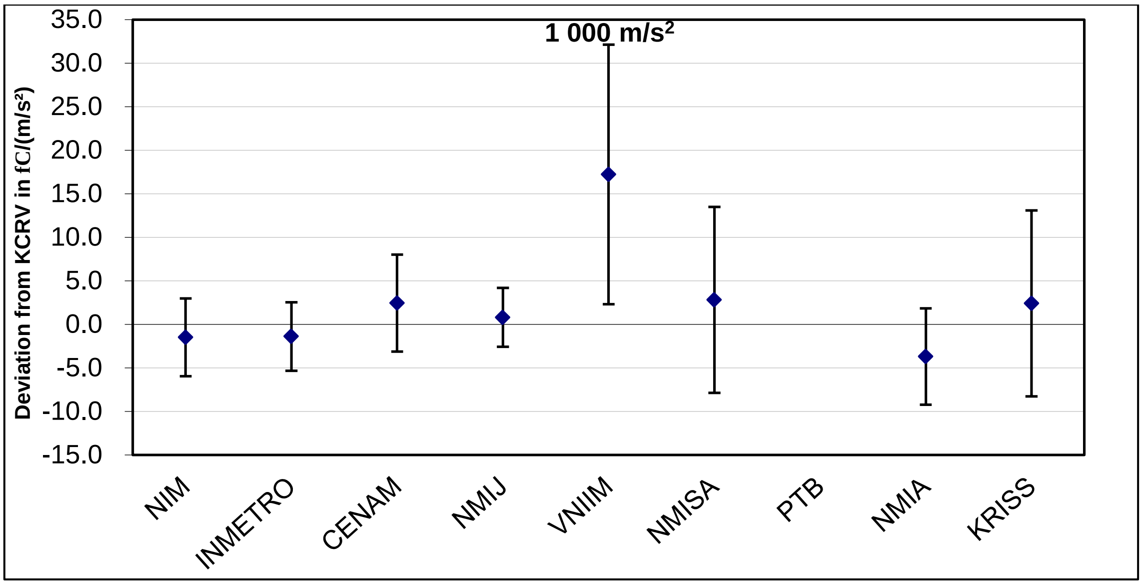
Table 8.6: Unilateral degrees of equivalence for the charge shock sensitivity with absolute expanded uncertainties (k = 2)

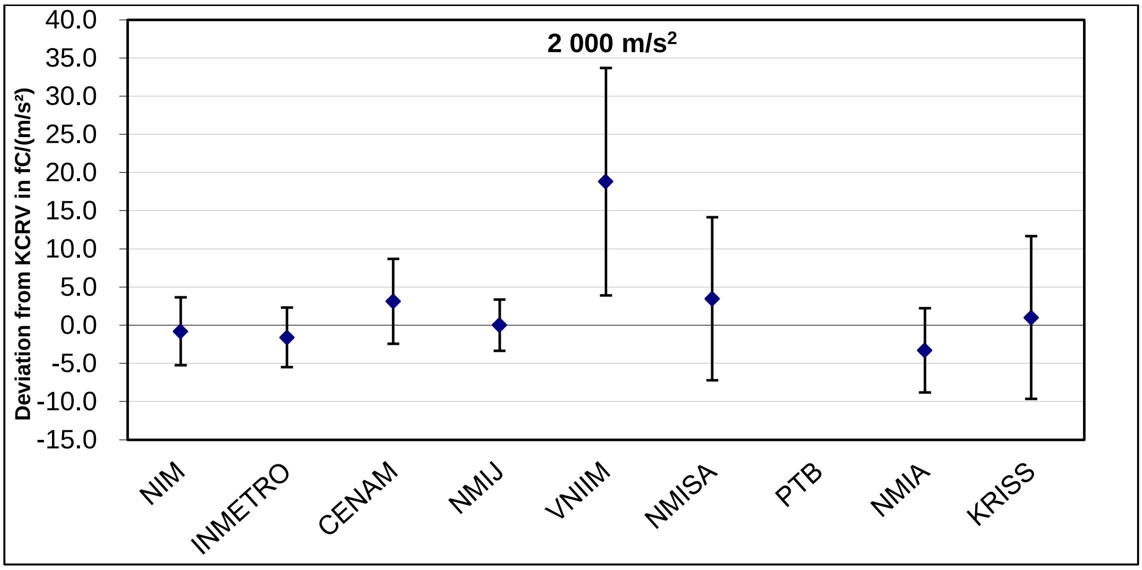
	KCRV		NIM		INMETRO		CENAM		NMIJ		VNIIM	
peak acceleration	X_{KCRV}	U_{KCRV}	$d_{I,KCRV}$	$U_{I,KCRV}$	$d_{I,KCRV}$	$U_{I,KCRV}$	$d_{I,KCRV}$	$U_{I,KCRV}$	$d_{I,KCRV}$	$U_{I,KCRV}$	$d_{I,KCRV}$	$U_{I,KCRV}$
in m/s²	pC/(m/s²)		pC/(m/s²)		pC/(m/s²)		pC/(m/s²)		pC/(m/s²)		pC/(m/s²)	
500	0.98793	0.00212	-0.00193	0.00445	-0.00059	0.00390	0.00308	0.00764	0.00057	0.00333	0.01427	0.01488
1000	0.98600	0.00206	-0.00150	0.00447	-0.00140	0.00392	0.00244	0.00556	0.00080	0.00337	0.01720	0.01491
2000	0.98430	0.00206	-0.00080	0.00447	-0.00160	0.00391	0.00312	0.00556	0.00000	0.00336	0.01880	0.01490
3000	0.98138	0.00206	-0.00098	0.00445	0.00055	0.00391	0.00222	0.00553	-0.00058	0.00334	0.02032	0.01488
4000	0.98163	0.00206	0.00117	0.00446	-0.00003	0.00391	0.00160	0.00553	-0.00033	0.00334	0.01577	0.01482
5000	0.98328	0.00227	0.00292	0.00438	-0.00334	0.00378	-0.00330	0.00750	0.00192	0.00322	0.00612	0.01467

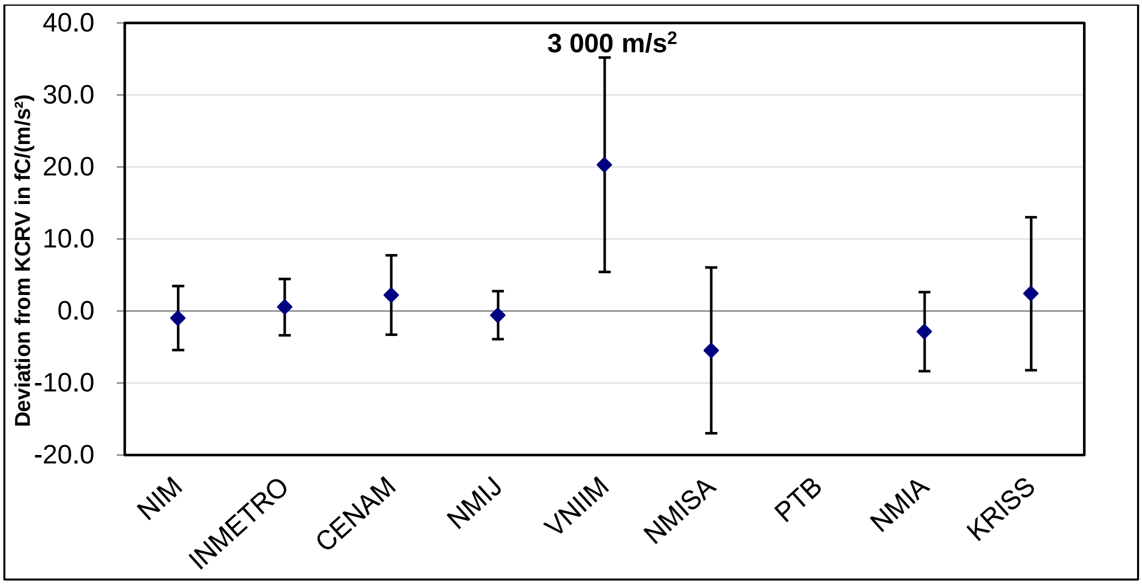
	KCRV		NMISA		PTB		NMIA		KRISS	
peak acceleration	X_{KCRV}	U_{KCRV}	$d_{I,KCRV}$	$U_{I,KCRV}$	$d_{I,KCRV}$	$U_{I,KCRV}$	$d_{I,KCRV}$	$U_{I,KCRV}$	$d_{I,KCRV}$	$U_{I,KCRV}$
in m/s²	pC/(m/s²)		pC/(m/s²)		pC/(m/s²)		pC/(m/s²)		pC/(m/s²)	
500	0.98793	0.00212	0.00177	0.01068			-0.00213	0.00552	0.00067	0.01067
1000	0.98600	0.00206	0.00280	0.01068			-0.00370	0.00552	0.00240	0.01067
2000	0.98430	0.00206	0.00350	0.01067			-0.00330	0.00551	0.00100	0.01064
3000	0.98138	0.00206	-0.00548	0.01153			-0.00288	0.00550	0.00242	0.01062
4000	0.98163	0.00206	-0.00483	0.01154			-0.00433	0.00549	0.00217	0.01062
5000	0.98328	0.00227	-0.00718	0.01149			-0.00868 (*)	0.00627 (*)	0.00072	0.01058

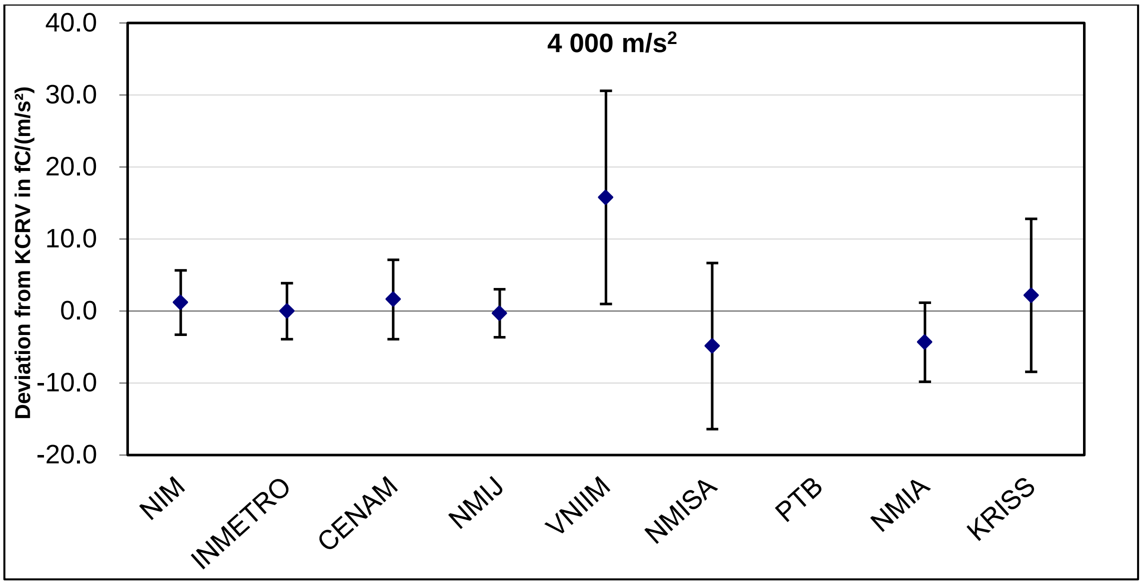
Figure 8.2 : Deviation of the charge shock sensitivity from the KCRV for all peak accelerations of the comparison with expanded uncertainties $U_{i,KCRV}$ (k = 2)

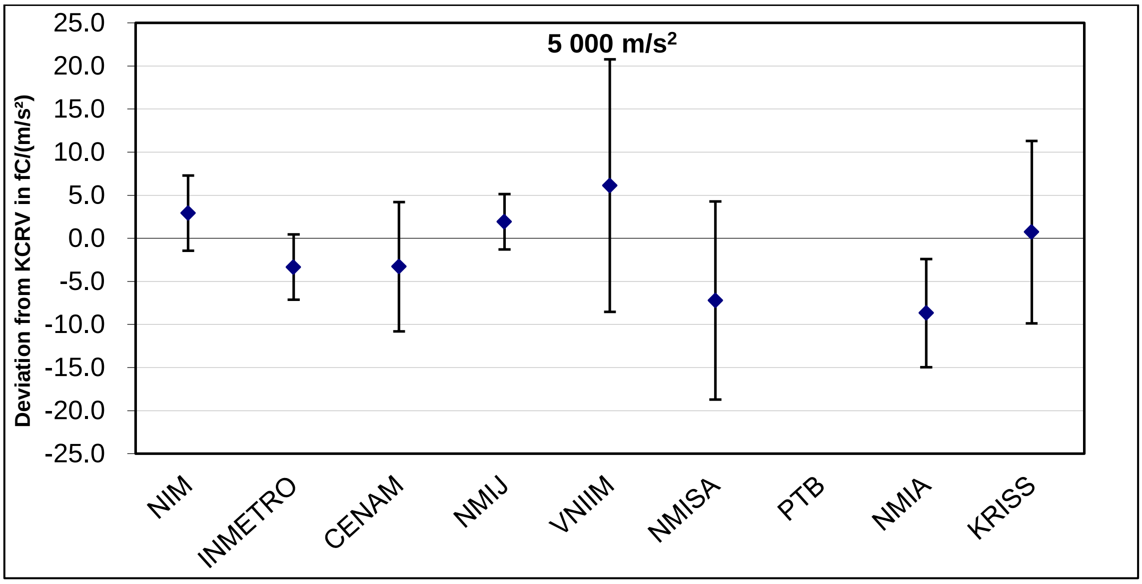







3 000 m/s²
Deviation from KCRV in fC/(m/s²)
40.0
30.0
20.0
10.0
0.0
-10.0
-20.0
NIM
INMETRO
CENAM
NMIJ
VNIIM
NMISA
PTB
NMIA
KRISS


4 000 m/s²
Deviation from KCRV in fC/(m/s²)
40.0
30.0
20.0
10.0
0.0
-10.0
-20.0
NIM
INMETRO
CENAM
NMIJ
VNIIM
NMISA
PTB
NMIA
KRISS


5 000 m/s²
Deviation from KCRV in fC/(m/s²)
25.0
20.0
15.0
10.0
5.0
0.0
-5.0
-10.0
-15.0
-20.0
-25.0
NIM
INMETRO
CENAM
NMIJ
VNIIM
NMISA
PTB
NMIA
KRISS

9. Conclusion

The first low intensity shock CIPM key comparison CCAUV.V-K4 revealed the current calibration capabilities of the 9 participants of five RMOs.
All the participating laboratories provided their calibration results, which were all consistent within their declared expanded uncertainties for the voltage shock sensitivity results. All participants contributed to the KCRVs calculated for six peak acceleration comparison values.
For charge shock sensitivity, the situation was notably worse. One participant failed to contribute to the calculation of the KCRV at 5 000 m/s^2. Two participating laboratories were not consistent within their declared expanded uncertainties at a total of five peak acceleration comparison values. Further improvements of their calibration devices and uncertainty evaluations will provide more accurate and reliable measurement results in the future.

10. Acknowledgment

The authors gratefully acknowledge all the participating institutes for their cooperation and supports.

Bibliography

[1] von Martens, H.-J. et al., Final report on key comparison CCAUV.V-K1, 2003, Metrologia, 40, Tech. Suppl. 09001.

[2] Guidelines for CIPM key comparisons (Appendix F to the "Mutual recognition of national measurements standards and of measurement certificates issued by national metrology institutes" (MRA)). March 1, 1999.

[3] Technical Protocol of the CCAUV Key comparison CCAUV.V-K4. NIM, Qiao Sun, 2016.

[4] Guide to the implementation of the CIPM MRA CIPM-MRA-G-01 VERSION 1.2. June, 2013.

[5] M.G. Cox, The evaluation of key comparison data, Metrologia, 2002, volume 39, p 589-595.

[6] M.G. Cox, The evaluation of key comparison data: determining a largest consistent subset, Metrologia, 2007, 44, 187-200.

Annex A - Technical protocol

Technical Protocol of CIPM Key Comparison CCAUV.V-K4

1 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. This is done by conducting key comparisons (KC) at different levels of the international metrological infrastructure.

However, in the sub-field of shock, there has been no formal key or supplementary comparison either at Consultative Committee (CC) level or Regional Metrology Organization Technical Committee (RMO TC) level at the time of this proposed comparison. Therefore during the 10th meeting of CCAUV in November 2015, the decision was taken to make preparations for a further key comparison targeted at low shock acceleration.

In the field of accelerometer shock calibration, this key comparison is organized in order to compare primary measurements of Gaussian, half-sine or half-sine squared linear shock accelerations in the range from 500 m/s^2 to 5 000 m/s^2. It is the task of the comparison to measure the shock sensitivity of an accelerometer measuring chain (a standard accelerometer (of back-to-back type) with a charge amplifier) (Accelerometer Chain) and an accelerometer (of single-ended type) at different peak acceleration values with associated pulse durations as specified in section 3. The results of this key comparison will, after approval of equivalence, serve as the foundation at low intensity shock for the registration of 'calibration and measurement capabilities' (CMC) in the framework of the CIPM MRA.

The voltage sensitivity shall be calculated as the ratio of the peak value of the Accelerometer Chain output voltage to the peak value of the input acceleration at its reference surface. The shock voltage sensitivity shall be given in milli-volt per meter per second squared (mV/(m/s^2)) for the different measurement conditions specified in section 4. In addition, the charge sensitivity shall be calculated as the ratio of the peak value of the accelerometer output charge to the peak value of the input acceleration at its reference surface. The shock charge sensitivity shall be given in pico-coulomb per meter per second squared (pC/(m/s^2)) for the different measurement conditions specified in section 4.

For the calibration of the accelerometer chain and the accelerometer, laser interferometry in compliance with method of the international standard ISO 16063-13:2001 has to be applied.

The reported shock sensitivities and associated uncertainties are then supposed to be used for the calculation of the weighted mean as the key comparison reference value (KCRV) and the DoE between the participating NMI and the KCRV.

2 Pilot Laboratory

Pilot laboratory for this key comparison is

Vibration and Gravity Section
Mechanics and Acoustics Metrology Division
National Institute of Metrology, P.R. China
BeiSanHuanDongLu 18, ChaoYang District, 100029 Beijing, P.R. China

This is the delivery address for the artefacts.

Contact Persons are

SUN Qiao	HU Hongbo
Tel.: +86 10 64524623	Tel.: +86 10 64524607
e-mail: sunq@nim.ac.cn	e-mail: huhb@nim.ac.cn
Fax: +86 10 64218628	

Co-Pilot laboratory for this key comparison is

Vibration and Hardness Standards Group
Research Institute for Engineering Measurement
National Metrology Institute of Japan
Tukuba Central 3, 1-1 Umezono, Tsukuba, Ibaraki 305-8563 Japan

Contact Persons are

Akihiro Ota	Hideaki Nozato
Tel.: +81 29 8614366	Tel.: +81 29 8614329
e-mail: a-oota@aist.go.jp	e-mail: hideaki.nozato@aist.go.jp
Fax: +81 29 8614047	

3 Devices under Test and Measurement Conditions

For the calibration task of this comparison, one Accelerometer Chain and one accelerometer will be circulated between the participating laboratories. The Accelerometer Chain is a ‘back-to-back’ (BB) type, namely an ENDEVCO 2270 (SN: *to be confirmed in the ‘spreadsheet BB’*), with a charge amplifier, namely Brüel & Kjær 2692 (SN: *to be confirmed in the ‘spreadsheet BB’*). The accelerometer is a ‘single-ended’ (SE) type, namely a PCB 357B03 (SN: *to be confirmed in the ‘spreadsheet SE’*).

The voltage sensitivity of the accelerometer chain as compulsory of the measurement and the charge sensitivity of the accelerometer as optional of the measurement are to be calibrated according to those procedures and conditions implemented by the laboratory in conformance with ISO 16063-13 which provides sensitivity information of the accelerometer. The voltage sensitivities reported shall be for the accelerometer chain, including all effects from the signal conditioner. The charge sensitivities reported shall be for the accelerometer, without any effect from the signal conditioner.

The peak acceleration range of the measurements was agreed to be from 500 m/s² to 5 000 m/s². Specifically, the laboratories are supposed to measure at the following acceleration levels (all values in m/s²) and pulse duration (time width between rising edge point and falling edge point at 10 % level of peak acceleration). These are nominal values and should be met by participants' best calibration capability.

500 @ 3 ms, 1 000 @ 2 ms, 2 000 @ 1.5 ms, 3 000 @ 1 ms, 4 000 @ 0.8 ms, 5 000 @ 0.5 ms.

The frequency contents of the calibration signals should be limited to below 10 kHz by low pass filtering or peak fitting in conformance with ISO 16063-13. The applied filter cut-off frequency shall be noted in the calibration report.

The measurement conditions should be kept according to the laboratory's standard conditions for calibration of customers' accelerometers for claiming their CMC where applicable. This presumes that these conditions comply with those defined by the applicable ISO documentary standards [1,2,3], simultaneously.

Specific conditions for the measurements of this comparison are:

- ambient temperature and accelerometer temperature during the calibration: (23 ± 3) ºC (actual values to be stated within tolerances of ± 0.3 ºC).
- relative humidity: max. 75 % RH
- mounting torque of the accelerometer: (2.0 ± 0.1) N·m

4 Circulation Type, Schedule and Transportation

The artifacts are circulated in a two-loop fashion with a measurement period of three weeks provided for each participating laboratory. At the beginning and the end of the circulation as well as between certain subsequent measurements of participating laboratories, the accelerometer chain and the accelerometer are measured at the pilot laboratory in order to monitor their stability.

The schedule is planned as follows:

Participant	Measurement (calendar week)	Transportation (calendar week)
NIM	12-14/2017	15-16/2017
INMETRO	17-19/2017	20-21/2017
CENAM	22-24/2017	25-26/2017
NMIJ	27-29/2017	30-31/2017
VNIIM	32-34/2017	35-36/2017
NIM	37-39/2017	05-06/2018
NMISA	07-09/2018	10-11/2018
PTB	12-14/2018	15-16/2018
NMIA	17-19/2018	20-21/2018
KRISS	22-24/2018	25-26/2018
NIM	27-29/2018	

* 12/2017 refers to the period from March 20th to 26th, 2017.

* 05/2018 refers to the period from January 29th to February 4th, 2018.

The cost of transportation to the next laboratory shall be covered by the participating laboratory. The artifacts are recommended to be sent hand-carried with great caution. In case the artifacts get damaged or lost during transportation, the participating laboratory for delivery should pay USD 5 000 to pilot laboratory.

5 Measurement and Analysis Instructions

The participating laboratories have to observe the following instructions:

- The motion of the BB accelerometer should be measured at the center of the top surface of the dummy mass applied for BB type. The motion of the SE accelerometer should be measured close to the accelerometer's mounting surface, since the mounting (reference) surface is usually not directly accessible.
- The mounting surface of the accelerometer and the end surface of the airborne anvil must be slightly lubricated before mounting.
- The cable between accelerometer and signal conditioner should be taken from the delivery to the laboratory.
- The dummy mass should be taken from the delivery to the laboratory. It is 20 g and the mounting torque applied is (2.0 ± 0.1) N·m. The mounting surface of the dummy mass and the end surface of the accelerometer must be slightly lubricated before mounting.
- It is advised that the measurement results should be compiled from complete measurement series carried out at different days under nominally the same conditions, except that the accelerometer is remounted and the cable re-attached. The standard deviation of the subsequent measurements should be included in the report.

6 Communication of the Results to Pilot Laboratory

Each participating laboratory will submit a scanned version of the printed and signed calibration report(s) to the pilot laboratory including the following:

- a description of the calibration system used for the comparison with photo(s) of the system, preferably when the accelerometer is installed,
- a description of the calibration method used and the mounting techniques for the accelerometer,
- documented records of the ambient conditions during measurements,
- 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 [4,5]). Including, among others, information on the type of uncertainty (A or B), assumed distribution function and repeatability component [6].

In addition, the use of the electronic spreadsheets named as ‘spreadsheet SE’ and ‘spreadsheet BB’ for reporting is mandatory. The spreadsheets include serial numbers of the comparison artefacts and setting information of the charge amplifier. The spreadsheets should be circulated to all the participants before week 17 of 2017. The consistency between the results in electronic form and a scanned version of the printed and signed calibration report(s) is the responsibility of the participating laboratories. The data submitted in the electronic spreadsheet shall be deemed as official results submitted for the comparison.

The results have to be submitted to the pilot laboratory within four weeks after the measurements have been completed.

References

[1] ISO 16063-1:1998 'Methods for the calibration of vibration and shock transducers -- Part 1: Basic concepts

[2] ISO 16063-13:2001 'Methods for the calibration of vibration and shock transducers-- Part 13: Primary shock calibration using laser interferometry'

[3] ISO/IEC 17025:2005 'General requirements for the competence of testing and calibration laboratories'

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

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

[6] Qiao Sun, HongBo Hu. "Final Report on Pilot Comparison of Low Intensity Shock APMP.AUV.V-P1". Metrologia Tech. Suppl., 2015, 52: 09002.

Results sheet for CCAUV.V-K4

'Spreadsheet BB' for BB 2270(14155)+2692(2752215)

Results sheet for CCAUV.V-K4

NMI		☐ I confirm that the data reported here has been checked against the data reported in the NMI certificate issued for the acceleration measuring chain
Contact Person		
email		

Please return the completed form to sunq@nim.ac.cn

No.	Recommended conditions for comparison				Actual conditions for calibration			Calibration results		Comments (Filter setting,etc)
	Peak Acceleration	Pulse Duration	Transducer set-up	Gain Setting	Peak Acceleration	Pulse Duration	Gain Setting	Voltage Sensitivity	Rel. Expanded Uncertainty	
	in m/s^2	in ms	in pC/(m/s^2)	in mV/(m/s^2)	in m/s^2	in ms	in mV/(m/s^2)	in mV/(m/s^2)	in %(k=2)	
1	500	3.0	1.0	10						
2	1000	2.0	1.0	10						
3	2000	1.5	1.0	10						
4	3000	1.0	1.0	3.16						
5	4000	0.8	1.0	3.16						
6	5000	0.5	1.0	3.16						

Note1: Peak Acceleration and Pulse Duration with deviation less than ±10% are recommended.

Note2: Lower Freq. Limit of 0.1 Hz and Upper Freq. Limit of 100 kHz are recommended for charge amplifier 2692.

Note3: Voltage sensitivity with 4 digits shall be provided.

Note4: The estimated peak voltage at peak acceleration of 2000 m/s^2 is about 4 V under the measurement condition as the above-specified transducer set-up and gain setting.

'Spreadsheet SE' for SE 357B03(LW50432)

Results sheet for CCAUV.V-K4

NMI Contact Person email		☐ I confirm that the data reported here has been checked against the data reported in the NMI certificate issued for the accelerometer

Please return the completed form to sunq@nim.ac.cn

No.	Recommended conditions for comparison		Actual conditions for calibration		Calibration results		Comments (Filter setting,etc)
	Peak Acceleration	Pulse Duration	Peak Acceleration	Pulse Duration	Charge Sensitivity	Rel. Expanded Uncertainty	
	in m/s^2	in ms	in m/s^2	in ms	in pC/(m/s^2)	in % (k=2)	
1	500	3.0					
2	1000	2.0					
3	2000	1.5					
4	3000	1.0					
5	4000	0.8					
6	5000	0.5					

Note1: Peak Acceleration and Pulse Duration with deviation less than ±10% are recommended.

Note2: Lower Freq. Limit of 0.1 Hz and Upper Freq. Limit of 100 kHz are recommended for charge amplifier.

Note3: Charge sensitivity with 4 digits shall be provided.

Annex B : Measurement conditions and results

1 – NIM

Voltage shock sensitivity

Actual conditions for calibration			Calibration results	
Peak Acceleration	Pulse Duration	Gain Setting	Voltage Sensitivity	Rel. Expanded Uncertainty
in m/s^2	in ms	in $mV/(m/s^2)$	in $mV/(m/s^2)$	in % (k=2)
525	3.11	10	2.140	0.4
1071	2.08	10	2.139	0.4
2008	1.43	10	2.138	0.4
3206	1.07	3.16	0.6756	0.4
4085	0.81	3.16	0.6759	0.4
5151	0.53	3.16	0.6759	0.4

Charge shock sensitivity

Actual conditions for calibration		Calibration results	
Peak Acceleration	Pulse Duration	Charge Sensitivity	Rel. Expanded Uncertainty
in m/s^2	in ms	in $pC/(m/s^2)$	in % (k=2)
490	2.86	0.9860	0.5
1017	1.97	0.9845	0.5
2082	1.52	0.9835	0.5
3150	1.04	0.9804	0.5
4140	0.81	0.9828	0.5
5247	0.52	0.9862	0.5

2 –INMETRO

Voltage shock sensitivity

Actual conditions for calibration			Calibration results	
Peak Acceleration	Pulse Duration	Gain Setting	Voltage Sensitivity	Rel. Expanded Uncertainty
in m/s^2	in ms	in $mV/(m/s^2)$	in $mV/(m/s^2)$	in % (k=2)
509	3.1	10	2.1399	0.40
1037	2.1	10	2.1390	0.40
2002	1.5	10	2.1381	0.40
2975	1.0	3.16	0.67582	0.40
4037	0.8	3.16	0.67556	0.40
5069	0.5	3.16	0.67531	0.40

Charge shock sensitivity

Actual conditions for calibration		Calibration results	
Peak Acceleration	Pulse Duration	Charge Sensitivity	Rel. Expanded Uncertainty
in m/s^2	in ms	in $pC/(m/s^2)$	in % (k=2)
508	3.1	0.98734	0.45
1008	2.1	0.98460	0.45
1996	1.5	0.98270	0.45
3019	1.0	0.98193	0.45
4056	0.8	0.98160	0.45
5045	0.5	0.97994	0.45

3 –CENAM

Voltage shock sensitivity

Actual conditions for calibration			Calibration results	
Peak Acceleration	Pulse Duration	Gain Setting	Voltage Sensitivity	Rel. Expanded Uncertainty
in m/s^2	in ms	in $mV/(m/s^2)$	in $mV/(m/s^2)$	in % (k=2)
524	3.01	10	2.1388	0.8
1001	2.05	10	2.1387	0.6
1886	1.49	10	2.1387	0.6
2714	1.02	10	2.1391	0.6
3783	0.79	10	2.1383	0.6
4875	0.51	1	0.21384	0.8

Charge shock sensitivity

Actual conditions for calibration		Calibration results	
Peak Acceleration	Pulse Duration	Charge Sensitivity	Rel. Expanded Uncertainty
in m/s^2	in ms	in $pC/(m/s^2)$	in % (k=2)
516	3.03	0.99101	0.8
975	1.98	0.98844	0.6
1890	1.48	0.98742	0.6
2821	1.04	0.98360	0.6
3760	0.81	0.98323	0.6
5214	0.51	0.97998	0.8

4 –NMIJ

Voltage shock sensitivity

Actual conditions for calibration			Calibration results	
Peak Acceleration in m/s²	Pulse Duration in ms	Gain Setting in mV/(m/s²)	Voltage Sensitivity in mV/(m/s²)	Rel. Expanded Uncertainty in % (*k*=2)
511	3.04	10	2.138	0.2
1015	1.91	10	2.137	0.2
2039	1.54	10	2.136	0.2
2951	1.05	3.16	0.6753	0.2
3786	0.83	3.16	0.6746	0.2
5041	0.46	3.16	0.6738	0.2

Charge shock sensitivity

Actual conditions for calibration		Calibration results	
Peak Acceleration in m/s²	Pulse Duration in ms	Charge Sensitivity in pC/(m/s²)	Rel. Expanded Uncertainty in % (*k*=2)
506	3.00	0.9885	0.4
1006	1.93	0.9868	0.4
2009	1.53	0.9843	0.4
2987	1.03	0.9808	0.4
3869	0.77	0.9813	0.4
5027	0.48	0.9852	0.4

5 –VNIIM

Voltage shock sensitivity

Actual conditions for calibration			Calibration results	
Peak Acceleration	Pulse Duration	Gain Setting	Voltage Sensitivity	Rel. Expanded Uncertainty
in m/s^2	in ms	in $mV/(m/s^2)$	in $mV/(m/s^2)$	in % (k=2)
487.0	2.7	10	0.2154	1.5
1123.0	2.1	10	0.2130	1.5
1997.0	1.4	10	0.2122	1.5
3119.0	1.0	3.16	0.2158	1.5
4085.0	0.8	3.16	0.2158	1.5
4870.0	0.5	3.16	0.2120	1.5

Charge shock sensitivity

Actual conditions for calibration		Calibration results	
Peak Acceleration	Pulse Duration	Charge Sensitivity	Rel. Expanded Uncertainty
in m/s^2	in ms	in $pC/(m/s^2)$	in % (k=2)
507.0	2.9	1.0022	1.5
1040.0	1.9	1.0032	1.5
2087.0	1.4	1.0031	1.5
3084.0	0.9	1.0017	1.5
4136.0	0.7	0.9974	1.5
5141.0	0.5	0.9894	1.5

6 –NMISA

Voltage shock sensitivity

Actual conditions for calibration			Calibration results	
Peak Acceleration	Pulse Duration	Gain Setting	Voltage Sensitivity	Rel. Expanded Uncertainty
in m/s^2	in ms	in $mV/(m/s^2)$	in $mV/(m/s^2)$	in % (k=2)
502.9	3.00	10	2.1377	1.0
988.6	2.56	10	2.1383	1.0
1985.2	2.02	10	2.1323	1.0
3019.1	0.33	3.16	0.6755	1.1
4041.2	0.31	3.16	0.6754	1.1
5034.4	0.29	3.16	0.6754	1.1

Charge shock sensitivity

Actual conditions for calibration		Calibration results	
Peak Acceleration	Pulse Duration	Charge Sensitivity	Rel. Expanded Uncertainty
in m/s^2	in ms	in $pC/(m/s^2)$	in % (k=2)
511.1	3.0	0.9897	1.1
1014.2	2.5	0.9888	1.1
2000.3	2.0	0.9878	1.1
2984.3	0.3	0.9759	1.2
3986.4	0.3	0.9768	1.2
5027.9	0.2	0.9761	1.2

7 –PTB

Voltage shock sensitivity

Actual conditions for calibration			Calibration results	
Peak Acceleration	Pulse Duration	Gain Setting	Voltage Sensitivity	Rel. Expanded Uncertainty
in m/s^2	in ms	in $mV/(m/s^2)$	in $mV/(m/s^2)$	in % (k=2)
507	3.5	10	2.1362	0.25
1026	2.5	10	2.1362	0.25
2008	1.8	10	2.1359	0.25
2990	1.4	3.16	0.6750	0.25
4023	1.2	3.16	0.6749	0.25
5005	1.1	3.16	0.6750	0.25

8 –NMIA

Voltage shock sensitivity

Actual conditions for calibration			Calibration results	
Peak Acceleration	Pulse Duration	Gain Setting	Voltage Sensitivity	Rel. Expanded Uncertainty
in m/s^2	in ms	in mV/(m/s^2)	in mV/(m/s^2)	in % (k=2)
506	3.1	10.0	2.1363	0.5
1028	1.9	10.0	2.1352	0.5
1982	1.4	10.0	2.1348	0.5
2923	1.0	3.16	0.6744	0.5
4004	0.7	3.16	0.6743	0.5
5041	0.4	3.16	0.6737	0.5

Charge shock sensitivity

Actual conditions for calibration		Calibration results	
Peak Acceleration	Pulse Duration	Charge Sensitivity	Rel. Expanded Uncertainty
in m/s^2	in ms	in pC/(m/s^2)	in % (k=2)
503	3.0	0.9858	0.6
1000	1.9	0.9823	0.6
2009	1.4	0.9810	0.6
3004	0.9	0.9785	0.6
3999	0.7	0.9773	0.6
4993	0.4	0.9746	0.6

9 –KRISS

Voltage shock sensitivity

Actual conditions for calibration			Calibration results	
Peak Acceleration in m/s²	Pulse Duration in ms	Gain Setting in mV/(m/s²)	Voltage Sensitivity in mV/(m/s²)	Rel. Expanded Uncertainty in % (k=2)
510	3.08	10	2.150	1.1
1003	1.99	10	2.145	1.1
1991	1.49	10	2.141	1.1
2903	0.96	3.16	0.6780	1.1
3977	0.79	3.16	0.6768	1.1
4918	0.50	3.16	0.6783	1.1

Charge shock sensitivity

Actual conditions for calibration		Calibration results	
Peak Acceleration in m/s²	Pulse Duration in ms	Charge Sensitivity in pC/(m/s²)	Rel. Expanded Uncertainty in % (k=2)
501	2.96	0.9886	1.1
1008	2.01	0.9884	1.1
1966	1.48	0.9853	1.1
2990	0.99	0.9838	1.1
4009	0.79	0.9838	1.1
4995	0.51	0.9840	1.1

Annex C : Measurement uncertainty Budget (MUB)

1 – NIM

Source of Uncertainty	Symbol	U or (semi-range)%	Probability distribution model	k factor	Type	Standard uncertainty %
Accelerometer output voltage peak value measurement	u_1	0.06	Rectangular	$\sqrt{3}$	B	0.04
Voltage filtering effect on accelerometer output voltage peak value	u_2	0.10	Normal	2	B	0.05
Effect of voltage disturbance on accelerometer output voltage peak value	u_3	0.05	Normal	2	B	0.03
Influence of resonant vibration on anvil for accelerometer	u_4	0.15	Rectangular	$\sqrt{3}$	B	0.09
Effect of transverse, rocking and bending acceleration on accelerometer output voltage peak value	u_5	0.05	Normal	2	B	0.03
Zero voltage Uncertainty	u_6	0.10	Normal	2	A	0.05
Effect of interferometer quadrature output signal disturbance on acceleration peak value	u_7	0.05	Normal	2	B	0.03
Effect of interferometer quadrature output signal disturbance on acceleration peak value	u_8	0.10	Rectangular	$\sqrt{3}$	B	0.06
Influence of resonant vibration on anvil for acceleration	u_9	0.15	Rectangular	$\sqrt{3}$	B	0.09
Interferometer signal filtering effect on acceleration peak value	u_{10}	0.10	Rectangular	$\sqrt{3}$	B	0.06
Effect of voltage disturbance on acceleration peak value	u_{11}	0.05	Normal	2	B	0.03
Effect of motion disturbance on acceleration peak value	u_{12}	0.08	Normal	2	B	0.04

Residual interferometric effects on acceleration peak value	u_{13}	0.01	Normal	2	B	0.01
Effect of errors associated with zero acceleration	u_{14}	0.10	Normal	2	B	0.05
Calibration of charge amplifier and cable (only for charge sensitivity)	u_{15}	0.15	Rectangular	$\sqrt{3}$	B	0.09
Combined uncertainty	u_c	**For voltage sensitivity**				0.19
	u_c	**For charge sensitivity**				0.22
Coverage factor				2		
Expended uncertainty U_c		**For voltage sensitivity**				0.38
		For charge sensitivity				0.44
Stated expended uncertainty		**For voltage sensitivity**				0.40
		For charge sensitivity				0.50

2 –INMETRO

Voltage shock sensitivity

	i	Standard uncertainty component $u(x_i)$	Source of uncertainty	description	Probability distribution model	Factor x_i	Sens. factor c_i	Relative expanded uncertainty or bounds of estimated error components (%)	Relative uncertainty contribution $u_{rel}(y)$ (%)
Accelerometer output voltage peak value measurement	1	$u(V_{peak,VC})$	accelerometer output voltage peak value measurement (DAQ calibration, traceability)	DAQ calibration / check	normal (k=2)	0.5	1	0.150	0.075
	2	$u(V_{peak,VR})$	accelerometer output voltage peak value measurement (DAQ resolution)	Resolution of A/D converter = 16-bit	retangular	0.58	1	0.005	0.003
	3	$u(V_{peak,VD})$	accelerometer output voltage peak value measurement (DAQ drift)	drift for 1 year, estimated to be = 0,05 % per year	retangular	0.58	1	0.004	0.002
	4	$u(V_{peak,F})$	voltage filtering effect on accelerometer output voltage peak (frequency band limitation)	residual effect on sensitivity estimated to be less than (same digital filter is applied to numerator and denominator)	retangular	0.58	1	0.050	0.029
	5	$u(V_{peak,E,AR})$	effect of voltage disturbance on accelerometer output voltage peak value (disturbance by anvil resonance)	residual effect after filtering and LS curve fitting	normal (k=1)	1	1	0.080	0.080
	6	$u(V_{peak,E,N})$	effect of voltage disturbance on accelerometer output voltage peak value (effect of noise on shock peak region, and baseline)	residual effect after filtering and LS curve fitting	normal (k=1)	1	1	0.050	0.050
	7	$u(V_{peak,T})$	effect of transverse acceleration on accelerometer output voltage peak value (transverse sensitivity)	transverse accel = 2%, Stl max 1%	special	0.24	1	0.020	0.005
	8	$u(V_{peak,RE})$	effect of rocking acceleration on accelerometer output voltage peak value	Estimated to be less than, considering the air bearing guidance	retangular	0.58	1	0.020	0.012
	9	$u(V_{peak,MP})$	effect of mounting parameters (torque, cable, etc) on accelerometer output voltage peak value	Estimated to be less than	retangular	0.58	1	0.020	0.012
	10	$u(V_{peak,BS})$	effect of base strain on accelerometer output voltage peak value	Estimated to be less than	retangular	0.58	1	0.020	0.012
Interferometric measurement of reference acceleration peak value	11	$u(a_{peak,Q})$	acceleration peak value (e.g. effects, voltage amplitude deviation from 90°)	Estimated to be less than (heterodyne interferometer is used and I&Q are obtained digitally)	retangular	0.58	1	0.050	0.029
	12	$u(a_{peak,F})$	interferometer signal filtering effect on acceleration peak value (frequency band limitation)	residual filtering effect already considered in item 4	retangular	0.58	1	0.000	0.000
	13	$u(a_{peak,VD})$	effect of voltage disturbance on acceleration peak value (e.g. random noise in the photoelectric measuring chain)	estimated to be less than	retangular	0.58	1	0.050	0.029
	14	$u(a_{peak,VC})$	effect of voltage disturbance on acceleration peak value measurement (DAQ calibration, traceability)	DAQ calibration / check	normal (k=2)	0.5	1	0.150	0.075
	15	$u(a_{peak,VR})$	effect of voltage disturbance on acceleration peak value measurement (DAQ resolution)	Effect of resolution of A/D converter = 14-bit and 100 MHz sample rate	retangular	0.58	1	0.050	0.029
	16	$u(a_{peak,VD})$	accelerometer output voltage peak value measurement (DAQ drift)	drift for 1 year, estimated to be = 0,05 % per year	retangular	0.58	1	0.004	0.002
	17	$u(a_{peak,MD,RS})$	effect of motion disturbance on acceleration peak value (relative motion between the accelerometer reference surface and the spot sensed by the interferometer)	Not aplicable for the KC, Technical protocol reguired measurement at the centre of dummy mass	retangular	0.58	1	0.050	0.029
	18	$u(a_{peak,MD,DS})$	effect of motion disturbance on acceleration peak value (relative motion between different spots sensed by the interferometer)	Not aplicable for the KC, Technical protocol reguired measurement at the centre of dummy mass	retangular	0.58	1	0.050	0.029
	19	$u(a_{peak,PD})$	effect of phase disturbance on acceleration peak value (e.g. phase noise of the interferometer signal)	estimated to be less than	retangular	0.58	1	0.030	0.017
	20	$u(a_{peak,RE})$	residual interferometric effects on acceleration peak value (interferometer function)	estimated to be less than	retangular	0.58	1	0.030	0.017
	21	$u(a_{peak,\lambda})$	uncertainty due to traceability of non-stabilised laser wavelength	calibration of laser + bandwidth (1200 MHz)	normal (k=2)	0.5	1	0.0002	0.000
	22	$u(a_{peak,ME})$	environmental effects on laser wavelength. Estimated to be less than (dT =+/- 3 C, dP = +/- 70 hPa, dU = +/- 20 %)	Estimated to be less than (Temp range from 21 to 25 degrees)	retangular	0.58	1	0.001	0.000
Residual effects on the shock sensitivity	23	$u(S_{sh,RE})$	residual effects on shock sensitivity measurement (effect of resonance excitation in the transducer or shock machine)	estimated to be less than	retangular	0.58	1	0.050	0.029
	24	$u(S_{sh,RE,rep})$	residual effects on shock sensitivity measurement (random effect in repeat measurements)	measured (for N=6, std dev of the mean)	normal (k=1)	1.00	1	0.050	0.050
	25	$u(S_{sh,RE,exp})$	residual effects on shock sensitivity measurement (experimental standard deviation of arithmetic mean)	measured (for N=10, std dev of the mean)	normal (k=1)	1.00	1	0.030	0.030
Extra components for charge shock sensitivity of an accelerometer	26	$u(V_{peak,GC})$	calibration of reference amplifier gain	calibration of charge amplifier	normal (k=2)	0.5	0	0.050	0.000
	27	$u(V_{peak,GL})$	amplitude linearity deviation of reference amplifier	estimated to be less than	retangular	0.58	0	0.020	0.000
	28	$u(V_{peak,GI})$	instability of reference amplifier gain, drift and effect of source impedance on gain and phase shift	drift for 1 year, estimated to be = 0,05 % per year and instability of 0,02 %	retangular	0.58	0	0.024	0.000
	29	$u(V_{peak,GE})$	environmental effects on gain and phase shift of reference amplifier (temperature effects during calibration)	estimated to be less than	retangular	0.58	0	0.010	0.000
Effects due to the DUT during the calibration	30	$u(V_{peak,SI})$	instability of accelerometer sensitivity during period of calibration (magnitude and phase shift)	estimated to be less than (2270 manufacturer spec: non-linearity of + 0.1%/1000g)	retangular	0.58	1	0.050	0.029
	31	$u(V_{peak,SF})$	frequency dependence of accelerometer sensitivity	estimated to be less than	retangular	0.58	1	0.050	0.029
	32	$u(V_{peak,SE})$	environmental effects on reference accelerometer sensitivity (magnitude and phase shift)	temperature variation: (23 +/- 1)°C; S_{temp} = 0,03% per°C	retangular	0.58	1	0.030	0.017

$u_{rel}(S_{sh})$ Estimated Uncertainty for acelerometer sensitivity (k=1)	0.18
$u_{rel}(S_{sh})$ Estimated Uncertainty for acelerometer sensitivity (k=2)	0.36

Charge shock sensitivity

Group	i	Standard uncertainty component $u(x_i)$	Source of uncertainty	description	Probability distribution model	Factor x_i	Sens. factor d	Relative expanded uncertainty or bounds of estimated error components (%)	Relative uncertainty contribution $u_{rel}(y)$ (%)
Accelerometer output voltage peak value measurement	1	$u(V_{peak,V,C})$	accelerometer output voltage peak value measurement (DAQ calibration, traceability)	DAQ calibration / check	normal (k=2)	0.5	1	0.150	0.075
	2	$u(V_{peak,V,R})$	accelerometer output voltage peak value measurement (DAQ resolution)	Resolution of A/D converter = 16-bit	rectangular	0.58	1	0.005	0.003
	3	$u(V_{peak,V,D})$	accelerometer output voltage peak value measurement (DAQ drift)	drift for 1 year, estimated to be = 0,05 % per year	rectangular	0.58	1	0.004	0.002
	4	$u(V_{peak,F})$	voltage filtering effect on accelerometer output voltage peak (frequency band limitation)	residual effect on sensitivity estimated to be less than (same digital filter is applied to numerator and denominator)	rectangular	0.58	1	0.050	0.029
	5	$u(V_{peak,QAN})$	effect of voltage disturbance on accelerometer output voltage peak value (disturbance by anvil resonance)	residual effect after filtering and LS curve fitting	normal (k=1)	1	1	0.080	0.080
	6	$u(V_{peak,QN})$	effect of voltage disturbance on accelerometer output voltage peak value (effect of noise on shock peak region, and baseline)	residual effect after filtering and LS curve fitting	normal (k=1)	1	1	0.050	0.050
	7	$u(V_{peak,T})$	effect of transverse acceleration on accelerometer output voltage peak value (transverse sensitivity)	transverse accel = 2%, St1 max 1%	special	0.24	1	0.020	0.005
	8	$u(V_{peak,RE})$	effect of rocking acceleration on accelerometer output voltage peak value	Estimated to be less than, considering the air bearing guidance	rectangular	0.58	1	0.020	0.012
	9	$u(V_{peak,MP})$	effect of mounting parameters (torque, cable, etc) on accelerometer output voltage peak value	Estimated to be less than	rectangular	0.58	1	0.020	0.012
	10	$u(V_{peak,BS})$	effect of base strain on accelerometer output voltage peak value	Estimated to be less than	rectangular	0.58	1	0.020	0.012
Interferometric measurement of reference acceleration peak value	11	$u(a_{peak,a})$	acceleration peak value (e.g. offsets, voltage amplitude deviation from 90°)	Estimated to be less than (heterodyne interferometer is used and I&Q are obtained digitally)	rectangular	0.58	1	0.050	0.029
	12	$u(a_{peak,F})$	interferometer signal filtering effect on acceleration peak value (frequency band limitation)	residual filtering effect already considered in item 4	rectangular	0.58	1	0.000	0.000
	13	$u(a_{peak,VD})$	effect of voltage disturbance on acceleration peak value (e.g. random noise in the photoelectric measuring chain)	estimated to be less than	rectangular	0.58	1	0.050	0.029
	14	$u(a_{peak,V,C})$	effect of voltage disturbance on acceleration peak value measurement (DAQ calibration, traceability)	DAQ calibration / check	normal (k=2)	0.5	1	0.150	0.075
	15	$u(a_{peak,V,R})$	effect of voltage disturbance on acceleration peak value measurement (DAQ resolution)	Effect of resolution of A/D converter = 14-bit and 100 MHz sample rate	rectangular	0.58	1	0.050	0.029
	16	$u(a_{peak,V,D})$	accelerometer output voltage peak value measurement (DAQ drift)	drift for 1 year, estimated to be = 0,05 % per year	rectangular	0.58	1	0.004	0.002
	17	$u(a_{peak,MD,RS})$	effect of motion disturbance on acceleration peak value (relative motion between the accelerometer reference surface and the spot sensed by the interferometer)	estimated to be less than	rectangular	0.58	1	0.050	0.029
	18	$u(a_{peak,MD,SD})$	effect of motion disturbance on acceleration peak value (relative motion between different spots sensed by the interferometer)	estimated to be less than	rectangular	0.58	1	0.050	0.029
	19	$u(a_{peak,PD})$	effect of phase disturbance on acceleration peak value (e.g. phase noise of the interferometer signal)	estimated to be less than	rectangular	0.58	1	0.030	0.017
	20	$u(a_{peak,RE})$	residual interferometric effects on acceleration peak value (interferometer function)	estimated to be less than	rectangular	0.58	1	0.030	0.017
	21	$u(a_{peak,a})$	uncertainty due to traceability of nonstabilized laser wavelength	calibration of laser + bandwidth (1200 MHz)	normal (k=2)	0.5	1	0.0002	0.000
	22	$u(a_{peak,RE})$	environmental effects on laser wavelength. Estimated to be less than (dT =+/- 3 C, dF = +/- 70 MHz, dU = +/- 20 %)	Estimated to be less than (Temp range from 21 to 25 degrees)	rectangular	0.58	1	0.001	0.000
Residual effects on the shock sensitivity	23	$u(S_{sh,RE})$	residual effects on shock sensitivity measurement (effect of resonance excitation in the transducer or shock machine)	estimated to be less than	rectangular	0.58	1	0.050	0.029
	24	$u(S_{sh,RE,rep})$	residual effects on shock sensitivity measurement (random effect in repeat measurements)	measured (for N=5, std dev of the mean)	normal (k=1)	1.00	1	0.050	0.050
	25	$u(S_{sh,RE,std})$	residual effects on shock sensitivity measurement (experimental standard deviation of arithmetic mean)	measured (for N=10, std dev of the mean)	normal (k=1)	1.00	1	0.030	0.030
Extra components for charge shock sensitivity of an accelerometer	26	$u(V_{peak,g})$	calibration of reference amplifier gain	calibration of chargeamplifier	normal (k=2)	0.5	1	0.050	0.025
	27	$u(V_{peak,g})$	amplitude linearity deviation of reference amplifier	estimated to be less than	rectangular	0.58	1	0.020	0.012
	28	$u(V_{peak,g})$	instability of reference amplifier gain, drift and effect of source impedance on gain and phase shift	drift for 1 year, estimated to be = 0,05 % per year and instability of 0,02 %	rectangular	0.58	1	0.024	0.014
	29	$u(V_{peak,g})$	environmental effects on gain and phase shift of reference amplifier (temperature effects during calibration)	estimated to be less than	rectangular	0.58	1	0.010	0.006
Effects due to the DUT during the calibration	30	$u(V_{peak,s})$	instability of accelerometer sensitivity during period of calibration (magnitude and phase shift)	estimated to be less than	rectangular	0.58	1	0.050	0.029
	31	$u(V_{peak,s})$	frequency dependence of accelerometer sensitivity	estimated to be less than	rectangular	0.58	1	0.050	0.029
	32	$u(V_{peak,s})$	environmental effects on reference accelerometer sensitivity (magnitude and phase shift)	temperature variation: (23 +/- 1)°C, S_{temp} = 0,1 % per °C	rectangular	0.58	1	0.100	0.058

$u_{rel}(S_{S})$ Estimated Uncertainty for accelerometer sensitivity (k=1)	0.19
$u_{rel}(S_{S})$ Estimated Uncertainty for accelerometer sensitivity (k=2)	0.38
Reported Uncertainty for accelerometer sensitivity (k=2)	0.45

3 –CENAM

Source of uncertainty	Distribution	Type	Uncertainty contribution (500 & 5 000 m/s^2)	Uncertainty contribution (1000, 2000, 3000 & 4000 m/s^2)
				1.900E-01
Quantization peak voltaje	Normal	A	2.30E-01	8.81E-03
Resolution of data adquisition	Rectangular	B	8.81E-03	1.48E-03
Voltage disturbance	Rectangular	B	1.48E-03	1.00E-01
Offset voltage	Normal	A	1.00E-01	
				0.19
Quantization peak aceleration	Normal	A	2.30E-01	1.48E-03
Aceleration disturbance	Rectangular	B	1.48E-03	1.58E-05
Laser wavelength	Rectangular	B	1.58E-05	5.00E-05
Sampling frequency of data adquisition	Rectangular	B	5.00E-05	5.00E-02
Charge amplifier	Rectangular	B	5.000E-02	
				8.000E-02
Randon effect in repeat measurements	Normal	B	2.000E-01	
Relative cobined standard uncertainty [%]			0.40	0.30
Relative expanded standard uncertainty [%]			0.80	0.60

4 –NMIJ

Voltage shock sensitivity

Indetification code	CCAUV.V-K4								
Device under test	Endevco 2270, BK 2692								
Calibration period	3rd to 21th July 2017								
Uncertainty components	Comment	Type	Distribution	500 m/s^2	1000 m/s^2	2000 m/s^2	3000 m/s^2	4000 m/s^2	5000 m/s^2
Voltage standard	voltage accuracy	B	normal	3.00E-04	3.00E-04	3.00E-04	3.00E-04	3.00E-04	3.00E-04
Digitizer calibration	voltage correction	B	normal	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02
Digitizer quantizaton error	accelerometer output	B	rectangular	1.03E-03	4.98E-04	2.55E-04	5.51E-04	4.32E-04	3.30E-04
Peak voltage	anvil's resonance	B	normal	7.50E-03	7.50E-03	7.50E-03	7.50E-03	7.50E-03	7.50E-03
Zero voltage		A	normal	6.33E-04	3.24E-04	1.62E-04	2.25E-03	2.79E-04	2.45E-04
Transverse motion	3 % trans. Sens. 2 % trans. Motion	B	rectangular	4.24E-02	4.24E-02	4.24E-02	4.24E-02	4.24E-02	4.24E-02
Digitizer quantizaton error	acceleration measurement	B	normal	6.00E-02	6.00E-02	6.00E-02	6.00E-02	6.00E-02	6.00E-02
Laser wavelength	unstabilized He-Ne laser	B	normal	1.60E-03	1.60E-03	1.60E-03	1.60E-03	1.60E-03	1.60E-03
Peak acceleration	anvil's resonance	B	normal	7.50E-03	7.50E-03	7.50E-03	7.50E-03	7.50E-03	7.50E-03
Zero acceleration	±0.1 m/s^2	B	normal	4.00E-02	1.93E-02	9.91E-03	6.76E-03	5.29E-03	4.03E-03
Sampling frequency	10 MHz accuracy	B	normal	5.80E-08	5.80E-08	5.80E-08	5.80E-08	5.80E-08	5.80E-08
Relative motion	exciter and laser interferometer	B	normal	2.00E-04	9.67E-05	4.95E-05	3.38E-05	2.64E-05	2.02E-05
Residual influences		A	normal	1.32E-02	6.67E-03	7.52E-03	1.80E-02	1.39E-02	6.27E-03
Repeatability	different days	A	normal	2.90E-02	8.59E-03	1.06E-02	5.61E-02	1.81E-02	4.01E-02
Zero voltage shift	Zero voltage compensation	B	rectangular	2.00E-02	2.00E-02	2.00E-02	2.00E-02	2.00E-02	2.00E-02
comb. Std. uncertainty	in %			0.093	0.081	0.079	0.098	0.081	0.088
expanded uncertainty (k=2)	in %			0.186	0.161	0.159	0.195	0.162	0.175
stated expanded Uncertainty	in %			0.200	0.200	0.200	0.200	0.200	0.200

Charge shock sensitivity

Indetification code	CCAUV.V-K4								
Device under test	PCB 357B03								
Calibration period	3rd to 21th July 2017								
Uncertainty components	**Comment**	**Type**	**Distribution**	**500 m/s²**	**1000 m/s²**	**2000 m/s²**	**3000 m/s²**	**4000 m/s²**	**5000 m/s²**
Voltage standard	voltage accuracy	B	normal	3.00E-04	3.00E-04	3.00E-04	3.00E-04	3.00E-04	3.00E-04
Digitizer calibration	voltage correction	B	normal	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02
Digitizer quantizaton error	accelerometer output	B	rectangular	1.03E-03	4.98E-04	2.55E-04	5.51E-04	4.32E-04	3.30E-04
Peak voltage	accelerometer resonance (3KHz)	B	normal	9.81E-02	9.81E-02	9.81E-02	9.81E-02	9.81E-02	9.81E-02
Zero voltage		A	normal	6.33E-04	3.24E-04	1.62E-04	2.25E-03	2.79E-04	2.45E-04
Transverse motion	3 % trans. Sens. 2 % trans. Motion	B	rectangular	4.24E-02	4.24E-02	4.24E-02	4.24E-02	4.24E-02	4.24E-02
Digitizer quantizaton error	acceleration measurement	B	normal	6.00E-02	6.00E-02	6.00E-02	6.00E-02	6.00E-02	6.00E-02
Laser wavelength	unstabilized He-Ne laser	B	normal	1.60E-03	1.60E-03	1.60E-03	1.60E-03	1.60E-03	1.60E-03
Peak acceleration	accelerometer resonance (3KHz)	B	normal	9.81E-02	9.81E-02	9.81E-02	9.81E-02	9.81E-02	9.81E-02
Zero acceleration	±0.1 m/s²	B	normal	4.00E-02	1.93E-02	9.91E-03	6.76E-03	5.29E-03	4.03E-03
Sampling frequency	10 MHz accuracy	B	normal	5.80E-08	5.80E-08	5.80E-08	5.80E-08	5.80E-08	5.80E-08
Relative motion	exciter and laser interferometer	B	normal	2.00E-04	9.67E-05	4.95E-05	3.38E-05	2.64E-05	2.02E-05
Residual influences		A	normal	1.32E-02	6.67E-03	7.52E-03	1.80E-02	1.39E-02	6.27E-03
Repeatability	different days	A	normal	1.10E-01	4.41E-02	1.11E-01	5.73E-02	3.22E-02	3.49E-02
charge amplifier calibration	deconvolution	B	rectangular	2.00E-02	2.00E-02	2.00E-02	2.00E-02	2.00E-02	2.00E-02
comb. Std. uncertainty	in %			0.198	0.166	0.194	0.170	0.163	0.163
expanded uncertainty (k=2)	in %			0.396	0.332	0.388	0.340	0.325	0.325
stated expanded Uncertainty	in %			0.400	0.400	0.400	0.400	0.400	0.400

5 –VNIIM

i	Standard uncertainty	Source of uncertainty	Probability distribution	Factor	Type of uncertainty	Relative standard uncertainty, %
1	u(upeak,V)	accelerometer output voltage peak value measurement (waveform recorder; e.g. ADC-resolution)	rectangular	1.732	B	0.1
2	u(upeak,F)	voltage filtering effect on accelerometer output voltage peak value (frequency band limitation)	rectangular	1.732	B	0.25
3	u(upeak,D)	effect of voltage disturbance on accelerometer output voltage peak value (e.g. hum and noise)	rectangular	1.732	B	0.1
4	u(upeak,T)	effect of transverse, rocking and bending acceleration on accelerometer output voltage peak value (transverse sensitivity)	Normal	2.000	A	0.25
5	u(apeak,Q)	effect of interferometer quadrature output signal disturbance on acceleration peak value (e.g. offsets, voltage amplitude deviation, deviation from 90	rectangular	1.732	B	0.2
6	u(apeak,F)	interferometer signal filtering effect on acceleration peak value (frequency band limitation)	rectangular	1.732	B	0.2
7	u(apeak,VD)	effect of voltage disturbance on acceleration peak value (e.g. random noise in the photoelectric measuring chain)	rectangular	1.732	B	0.2
8	u(apeak,MD)	effect of motion disturbance on acceleration peak value (e.g. drift; relative motion between the accelerometer reference surface and the spot sensed	rectangular	1.732	B	0.2
9	u(apeak,PD)	effect of phase disturbance on acceleration peak value (e.g. phase noise of the interferometer signal)	rectangular	1.732	B	0.2
10	u(apeak,RE)	residual interferometric effects on acceleration peak value (interferometer function)	Normal	2.000	A	0.2
11	u(Ssh,RE)	residual effects on shock sensitivity measurement (e.g. effect of resonance excitation in the transducer or shock machine, random effect in repeat measurements; experimental standard deviation of arithmetic mean)	Normal	2.000	A	0.4
		Standard uncertainty				**0.74**
		The relative expanded uncertainty of measurement of the shock sensitiv				**1.48**

6 –NMISA

Voltage shock sensitivity

UNCERTAINTY BUDGET MATRIX (UBM)

Certificate No: AV\VS-3619
Procedure No: AV\VS-0019

Reference: Guide to the Expression of Uncertainty in Measurement, issued by BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML - ISO 1995 (ISBN 92-67-10188-9)

Description: Shock sensitivity calibration (modulus) as per ISO 16063-13
Make & model: Brüel & Kjær / Endevco / PCB
Serial number: 0
Range: 500 m/s² to 2 000 m/s²; 1,5 ms to 4,5 ms
Metrologist: Ian Veldman

Mathematical Model: $S = \frac{\hat{u}}{\hat{a}} = \frac{\hat{u}}{\hat{s}}$

Symbol	Input Quantity (Source of Uncertainty)	Estimated Uncertainty		Probability Distribution	k	Divisor factor	Standard Uncertainty	Sensitivity Coefficient		Standard Uncertainty Contribution $U_i(y)$	Reliability	Degrees of Freedom	Remarks
u	▼ Standards and Reference Equipment (Uncorrelated) ▼	(Xi)	Unit	(N, R, T, U)	▼	▼	u(xi)	Ci	Unit	%	%	v	
$a_{peak\,Q}$	Effect of interferometer quadrature output signal disturbance on acceleration peak value	0,1	%	Rectangular √3	2,00	1,73	0,058	1	%	0,058	100	infinite	e.g. offsets, voltage amplitude deviations, quadrature <> 90°
$a_{peak\,F}$	Effect of interferometer signal filtering effect on acceleration peak value	0,3	%	Rectangular √3	2,00	1,73	0,173	1	%	0,173	100	infinite	Frequency and band limitation
$a_{peak\,VD}$	Effect of voltage disturbance on acceleration peak value	0,1	%	Rectangular √3	2,00	1,73	0,058	1	%	0,058	100	infinite	e.g. random noise in the photoelectric measuring chain
$a_{peak\,MD}$	Effect of motion disturbance on acceleration peak value	0,3	%	Rectangular √3	2,00	1,73	0,173	1	%	0,173	100	infinite	e.g. drift; relative motion between accelerometer reference surface and spot sensed by the interferometer
$a_{peak\,PD}$	Effect of phase disturbance on acceleration peak value	0,1	%	Rectangular √3	2,00	1,73	0,058	1	%	0,058	100	infinite	e.g. phase noise in the interferometer signal
$a_{peak\,EDP}$	Acceleration peak determination accuracy	0,4	%	Rectangular √3	2,00	1,73	0,231	1	%	0,231	100	infinite	Double differentiation and peak detection accuracy
$S_{sh,RE}$	Residual effects on shock sensitivity measurement	0,3	%	Rectangular √3	2,00	1,73	0,173	1	%	0,173	100	infinite	e.g. effect of resonance excitation in the transducer or shock machine
	Resolution of Standard / Equipment (If applicable)										100		
	▼ Unit Under Test / Calibration (Uncorrelated) ▼							NOTE! ONLY CHANGE BLUE CELLS - All OTHER CELLS (WHITE) ARE PROTECTED					
$u_{peak\,V}$	Accelerometer output voltage peak measurement	0,1	%	Triangular √6		1,73	0,058	1	%	0,058	100	infinite	NI PXI-5922 Specifications (0,5 % of input + 50 µV)
$u_{peak\,V}$	Accelerometer output voltage peak fit	0,15	%	Normal k = 3		2,00	0,075	1	%	0,075	100	infinite	Closeness fof fit to measured pulse (e.g. r² value)
$u_{peak\,V}$	Effect of filtering & residual charge on sensitivity measurement	0,4	%	Triangular √6		1,73	0,231	1	%	0,231	100	infinite	Filtering effect is small as the same filter is applied to both signals. (Ratio of accelerometer output voltage
$u_{peak\,V}$	Effect of voltage disturbance on accelerometer output voltage peak measurement	0,05	%	Normal k = 2,576		1,00	0,050	1	%	0,050	100	infinite	Distortion in accelerometer output peak voltage and residual charge effect correction
$u_{peak\,V}$	Effect of transverse motion on accelerometer output voltage peak measurement	2	%			1,73	1,155	0,03	%	0,035	100	infinite	Transverse motion in the presence of transverse sensitivity. Taken 3 % transverse sensitivity.
$u_{amp\,G}$	Uncertainty in conditioning amplifier gain calibration	0,00	%			2,00	0,000	1	%	0,000	100	infinite	σ of gain values over selected frequency span (typically 10 Hz to 10 kHz)
	Resolution of UUT / Equipment (If applicable)										100		
	Data - Type "B" Evaluation Range of the results (Rectangular)										100		
	Data - Type "A" Evaluation Exp Std Dev of the Mean (ESDM)	0,15	%	Normal k = 1		1,73	0,087	1	%	0,087		9	No of Readings 10
Short UBM	TOTAL COMBINED UNCERTAINTY									%			

Best Measurement Capability (Excluding UUT contribution)	Combined Uncertainty (Normal)	▼ Level of Confidence ▼	0,392	V_{eff}	infinite	Checked and Approved By:
	Expanded Uncertainty	95,45 % K = 2	0,78	k =	2,00	
Uncertainty of Measurement (Including UUT contribution)	Combined Uncertainty (Normal)	▼ Level of Confidence ▼	0,476	V_{eff}	infinite	
	Expanded Uncertainty	95,45 % K = 2	0,95	k =	2,00	

UNCERTAINTY BUDGET MATRIX (UBM)

Certificate No:	AV\VS-3619	Procedure No:	AV\VS-0019

Reference: Guide to the Expression of Uncertainty in Measurement, issued by BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML - ISO 1995 (ISBN 92-67-10188-9)

Description:	Shock sensitivity calibration (modulus) as per ISO 16063-13	Make & model:	Brüel & Kjær / Endevco / PCB	Range:	> 2 km/s² to 10 km/s² 0,1 ms to 1,0 ms	Metrologist
		Serial number:	0			Ian Veldman

Mathematical Model: $S = \frac{\hat{u}}{\hat{a}} = \frac{\hat{u}}{\hat{s}}$

Symbol	Input Quantity (Source of Uncertainty)	Estimated Uncertainty		Probability Distribution	k	Divisor factor	Standard Uncertainty	Sensitivity Coefficient		Standard Uncertainty Contribution Ui(y)	Reliability	Degrees of Freedom	Remarks
u	▼ Standards and Reference Equipment (Uncorrelated) ▼	(Xi)	Unit	(N, R, T, U)	▼	▼	U(Xi)	Ci	Unit	%	%	ν	
$a_{peak,Q}$	Effect of interferometer quadrature output signal disturbance on acceleration peak value	0,1	%	Rectangular √3	2,00	1,73	0,058	1	%	0,058	100	infinite	e.g. offsets, voltage amplitude deviations, quadrature <> 90°
$a_{peak,F}$	Effect of interferometer signal filtering effect on acceleration peak value	0,3	%	Rectangular √3	2,00	1,73	0,173	1	%	0,173	100	infinite	Frequency and band limitation
$a_{peak,VD}$	Effect of voltage disturbance on acceleration peak value	0,1	%	Rectangular √3	2,00	1,73	3,358	1	%	0,058	100	infinite	e.g. random noise in the photoelectric measuring chain
$a_{peak,MD}$	Effect of motion disturbance on acceleration peak value	0,4	%	Rectangular √3	2,00	1,73	0,231	1	%	0,231	100	infinite	e.g. drift; relative motion between accelerometer reference surface and spot sensed by the interferometer
$a_{peak,PD}$	Effect of phase disturbance on acceleration peak value	0,1	%	Rectangular √3	2,00	1,73	0,058	1	%	0,058	100	infinite	e.g. phase noise in the interferometer signal
$a_{peak,DSP}$	Acceleration peak determination accuracy	0,4	%	Rectangular √3	2,00	1,73	0,231	1	%	0,231	100	infinite	Double differentiation and peak detection accuracy
$S_{sh,RE}$	Residual effects on shock sensitivity measurement	0,3	%	Rectangular √3	2,00	1,73	0,173	1	%	0,173	100	infinite	e.g. effect of resonance excitation in the transducer or shock machine
	Resolution of Standard / Equipment (If applicable)										100		
	▼ Unit Under Test / Calibration (Uncorrelated) ▼					NOTE! ONLY CHANGE BLUE CELLS - All OTHER CELLS (WHITE) ARE PROTECTED							
$u_{peak,V}$	Accelerometer output voltage peak measurement	0,1	%	Triangular √6		1,73	0,058	1	%	0,058	100	infinite	NI PXI-5922 Specifications (0,5 % of input + 50 µV)
$u_{peak,V}$	Accelerometer output voltage peak fit	0,15	%	Normal k = 3		2,00	0,075	1	%	0,075	100	infinite	Closeness fof fit to measured pulse (e.g. r² value)
$u_{peak,V}$	Effect of filtering & residual charge on sensitivity measurement	0,4	%	Triangular √6		1,73	0,231	1	%	0,231	100	infinite	Filtering effect is small as the same filer is applied to both signals. (Ratio of accelerometer output voltage
$u_{peak,V}$	Effect of voltage disturbance on accelerometer output voltage peak measurement	0,05	%	Normal k = 2,576		1,00	0,050	1	%	0,050	100	infinite	Distortion in accelerometer output peak voltage
$u_{peak,V}$	Effect of transverse motion on accelerometer output voltage peak measurement	5	%			1,73	2,887	0,03	%	0,087	100	infinite	Transverse motion in the presence of transverse sensitivity. Taken 3 % transverse sensitivity.
$u_{amp,G}$	Uncertainty in conditioning amplifier gain calibration	0,00	%			2,00	0,000	1	%	0,000	100	infinite	σ of gain values over selected frequency span (typically 10 Hz to 10 kHz)
	Resolution of UUT / Equipment (If applicable)										100		
	Data - Type "B" Evaluation Range of the results (Rectangular)										100		
	Data - Type "A" Evaluation Exp Std Dev of the Mean (ESDM)	0,25	%	Normal k = 1		1,73	0,144	1	%	0,144		9	No of Readings 10
[illegible] UBM	TOTAL COMBINED UNCERTAINTY									%			

Best Measurement Capability (Excluding UUT contribution)	Combined Uncertainty (Normal)	▼ Level of Confidence ▼	0,420	V_{eff}	infinite	Checked and Approved By:
	Expanded Uncertainty	95,45 % K = 2	0,84	k =	2,00	
Uncertainty of Measurement (Including UUT contribution)	Combined Uncertainty (Normal)	▼ Level of Confidence ▼	0,519	V_{eff}	infinite	
	Expanded Uncertainty	95,45 % K = 2	1,04	k =	2,00	

Charge shock sensitivity

UNCERTAINTY BUDGET MATRIX (UBM)

Certificate No	AV\VS-3618
Procedure No	AV\VS-0019

Reference: Guide to the Expression of Uncertainty in Measurement, issued by BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML - ISO 1995 (ISBN 92-67-10188-9)

Description:	Shock sensitivty calibration (modulus) as per ISO 16063-13	Make & model:	Brüel & Kjær / Endevco / PCB	Range:	500 m/s² to 2 000 m/s² 1,5 ms to 4,5 ms	Metrologist
		Serial number:	0			Ian Veldman

Mathematical Model: $S = \frac{\hat{u}}{\hat{a}} = \frac{\hat{q}}{\hat{s}}$

Symbol	Input Quantity (Source of Uncertainty)	Estimated Uncertainty		Probability Distribution	k	Divisor factor	Standard Uncertainty	Sensitivity Coefficient		Standard Uncertainty Contribution Ui(y)	Reliability	Degrees of Freedom	Remarks
u	▼ Standards and Reference Equipment (Uncorrelated) ▼	(Xi)	Unit	(N, R, T, U)	▼	▼	U(Xi)	Ci	Unit	%	%	v	
$a_{peak,Q}$	Effect of Interferometer quadrature output signal disturbance on acceleration peak value	0,1	%	Rectangular √3	2,00	1,73	0,058	1	%	0,058	100	infinite	e.g. offsets, voltage amplitude deviations, quadrature <> 90°
$a_{peak,F}$	Effect of interferometer signal filtering effect on acceleration peak value	0,3	%	Rectangular √3	2,00	1,73	0,173	1	%	0,173	100	infinite	Frequency and band limitation
$a_{peak,VD}$	Effect of voltage disturbance on acceleration peak value	0,1	%	Rectangular √3	2,00	1,73	0,058	1	%	0,058	100	infinite	e.g. random noise in the photoelectric measuring chain
$a_{peak,MD}$	Effect of motion disturbance on acceleration peak value	0,3	%	Rectangular √3	2,00	1,73	0,173	1	%	0,173	100	infinite	e.g. drift; relative motion between accelerometer reference surface and spot sensed by the interferometer
$a_{peak,PD}$	Effect of phase disturbance on acceleration peak value	0,1	%	Rectangular √3	2,00	1,73	0,058	1	%	0,058	100	infinite	e.g. phase noise in the interferometer signal
$a_{peak,DSP}$	Acceleration peak determination accuracy	0,4	%	Rectangular √3	2,00	1,73	0,231	1	%	0,231	100	infinite	Double differentiation and peak detection accuracy
$S_{sh,RE}$	Residuel effects on shock sensitivity measurement	0,3	%	Rectangular √3	2,00	1,73	0,173	1	%	0,173	100	infinite	e.g. effect of resonance excitation in the transducer or shock machine
	Resolution of Standard / Equipment (If applicable)										100		
	▼ Unit Under Test / Calibration (Uncorrelated) ▼					NOTE! ONLY CHANGE BLUE CELLS - All OTHER CELLS (WHITE) ARE PROTECTED							
$u_{peak,V}$	Accelerometer output voltage peak measurement	0,1	%	Triangular √6		1,73	0,058	1	%	0,058	100	infinite	NI PXI-5922 Specifications (0,5 % of input + 50 µV)
$u_{peak,V}$	Accelerometer output voltage peak fit	0,15	%	Normal k = 3		2,00	0,075	1	%	0,075	100	infinite	Closeness fot fit to measured pulse (e.g. r² value)
$u_{peak,V}$	Effect of filtering & residual charge on sensitivity measurement	0,4	%	Triangular √6		1,73	0,231	1	%	0,231	100	infinite	Filtering effect is small as the same filter is applied to both signals. (Ratio of accelerometer output voltage
$u_{peak,V}$	Effect of voltage disturbance on accelerometer output voltage peak measurement	0,05	%	Normal k = 2,576		1,00	0,050	1	%	0,050	100	infinite	Distortion in accelerometer output peak voltage and residuel charge effect correction
$u_{peak,V}$	Effect of transverse motion on accelerometer output voltage peak measurement	2	%			1,73	1,155	0,03	%	0,035	100	infinite	Transverse motion in the presence of transverse sensitivity. Taken 3 % transverse sensitivity.
$u_{amp\,G}$	Uncertainty in conditioning amplifier gain calibration	0,52	%			2,00	0,259	1	%	0,259	100	infinite	σ of gain values over selected frequency span (typically 10 Hz to 10 kHz)
	Resolution of UUT / Equipment (If applicable)										100		
	Data - Type "B" Evaluation Range of the results (Rectangular)										100		
	Data - Type "A" Evaluation Exp Std Dev of the Mean (ESDM)	0,15	%	Normal k = 1		1,73	0,087	1	%	0,087		9	No of Readings 10
About UBM	TOTAL COMBINED UNCERTAINTY									%			

Best Measurement Capability (Excluding UUT contribution)	Combined Uncertainty (Normal)	▼ Level of Confidence ▼		0,392	V_{eff}	infinite	Checked and Approved By:
	Expanded Uncertainty	95,45 %	K = 2	0,78	k =	2,00	
Uncertainty of Measurement (Including UUT contribution)	Combined Uncertainty (Normal)	▼ Level of Confidence ▼		0,542	V_{eff}	infinite	
	Expanded Uncertainty	95,45 %	K = 2	1,09	k =	2,00	

UNCERTAINTY BUDGET MATRIX (UBM)

Certificate No	AVVS-3618
Procedure No	AVVS-0019

Reference: Guide to the Expression of Uncertainty in Measurement, issued by BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML - ISO 1995 (ISBN 92-67-10188-9)

Description:	Shock sensitivity calibration (modulus) as per ISO 16063-13	Make & model:	Brüel & Kjær / Endevco / PCB	Range:	> 2 km/s² to 10 km/s² 0,1 ms to 1,0 ms
		Serial number:	0		
Metrologist	Ian Veldman				

Mathematical Model: $S = \frac{\hat{u}}{\hat{a}} = \frac{\hat{u}}{\hat{s}}$

Symbol	Input Quantity (Source of Uncertainty)	Estimated Uncertainty		Probability Distribution	k	Divisor factor	Standard Uncertainty	Sensitivity Coefficient		Standard Uncertainty Contribution $U_i(y)$	Reliability	Degrees of Freedom	Remarks
u	▼ Standards and Reference Equipment (Uncorrelated) ▼	(XI)	Unit	(N, R, T, U)	▼	▼	U(XI)	CI	Unit	%	%	v	
$a_{peak\,Q}$	Effect of interferometer quadrature output signal disturbance on acceleration peak value	0,1	%	Rectangular √3	2,00	1,73	0,058	1	%	0,058	100	infinite	e.g. offsets, voltage amplitude deviations, quadrature <> 90°
$a_{peak\,F}$	Effect of interferometer signal filtering effect on acceleration peak value	0,3	%	Rectangular √3	2,00	1,73	0,173	1	%	0,173	100	infinite	Frequency and band limitation
$a_{peak\,VD}$	Effect of voltage disturbance on acceleration peak value	0,1	%	Rectangular √3	2,00	1,73	0,058	1	%	0,058	100	infinite	e.g. random noise in the photoelectric measuring chain
$a_{peak\,MD}$	Effect of motion disturbance on acceleration peak value	0,4	%	Rectangular √3	2,00	1,73	0,231	1	%	0,231	100	infinite	e.g. drift; relative motion between accelerometer reference surface and spot sensed by the interferometer
$a_{peak\,PD}$	Effect of phase disturbance on acceleration peak value	0,1	%	Rectangular √3	2,00	1,73	0,058	1	%	0,058	100	infinite	e.g. phase noise in the interferometer signal
$a_{peak\,DSP}$	Acceleration peak determination accuracy	0,4	%	Rectangular √3	2,00	1,73	0,231	1	%	0,231	100	infinite	Double differentiation and peak detection accuracy
$S_{sh,RE}$	Residual effects on shock sensitivity measurement	0,3	%	Rectangular √3	2,00	1,73	0,173	1	%	0,173	100	infinite	e.g. effect of resonance excitation in the transducer or shock machine
	Resolution of Standard / Equipment (If applicable)										100		
	▼ Unit Under Test / Calibration (Uncorrelated) ▼												
	NOTE! ONLY CHANGE BLUE CELLS - All OTHER CELLS (WHITE) ARE PROTECTED												
$u_{peak\,V}$	Accelerometer output voltage peak measurement	0,1	%	Triangular √6		1,73	0,058	1	%	0,058	100	infinite	NI PXI-5922 Specifications (0,5 % of input + 50 µV)
$u_{peak\,Y}$	Accelerometer output voltage peak fit	0,15	%	Normal k = 3		2,00	0,075	1	%	0,075	100	infinite	Closeness fot fit to measured pulse (e.g. r² value)
$u_{peak\,V}$	Effect of filtering & residual charge on sensitivity measurement	0,4	%	Triangular √6		1,73	0,231	1	%	0,231	100	infinite	Filtering effect is small as the same filter is applied to both signals. (Ratio of accelerometer output voltage
$u_{peak\,V}$	Effect of voltage disturbance on accelerometer output voltage peak measurement	0,05	%	Normal k = 2,576		1,00	0,050	1	%	0,050	100	infinite	Distortion in accelerometer output peak voltage
$u_{peak\,V}$	Effect of transverse motion on accelerometer output voltage peak measurement	5	%			1,73	2,887	0,03	%	0,087	100	infinite	Transverse motion in the presence of transverse sensitivity. Taken 3 % transverse sensitivity.
$u_{amp\,G}$	Uncertainty in conditioning amplifier gain calibration	0,52	%			2,00	0,259	1	%	0,259	100	infinite	σ of gain values over selected frequency span (typically 10 Hz to 10 kHz)
	Resolution of UUT / Equipment (If applicable)										100		
	Data - Type "B" Evaluation Range of the results (Rectangular)										100		
	Data - Type "A" Evaluation Exp Std Dev of the Mean (ESDM)	0,25	%	Normal k = 1		1,73	0,144	1	%	0,144		9	No of Readings 10
About UBM	TOTAL COMBINED UNCERTAINTY									%			

Best Measurement Capability (Excluding UUT contribution)	Combined Uncertainty (Normal)	▼ Level of Confidence ▼	0,420	V_{eff}	infinite
	Expanded Uncertainty	95,45 % K = 2	0,84	k =	2,00
Uncertainty of Measurement (Including UUT contribution)	Combined Uncertainty (Normal)	▼ Level of Confidence ▼	0,580	V_{eff}	infinite
	Expanded Uncertainty	95,45 % K = 2	1,16	k =	2,00

Checked and Approved By:

7 –PTB

Voltage shock sensitivity

Uncertainty Budget for Shock Sensitivity of accelerometer measurement chain at PTB Schock NME 5 km/s²
Unit: mV/(m/s²)

i		Component	value	distribution		k	u	u²
1	$u\,(u_{peak,V})$	Voltage measurement, calibration uncertainty , long term drift	0,01%	rec	0,58	2	2,89E-05	8,33E-10
2	$u\,(u_{peak,D})$	Voltage measurement , noise,hum	0,02%	norm	1	2	1,00E-04	1,00E-08
3	$u\,(a_{peak,LDV})$	Dual channel LDV acceleration measurement	0,03%	norm	1	1	3,00E-04	9,00E-08
4	$u\,(S_{sh,F})$	Filter and peak fitting to peak sensitivity (acceleration,voltage jointly)	0,02%	rec	0,58	1	1,15E-04	1,33E-08
5	$u\,(u_{peak,T})$	effect of transverse, rocking and bending acceleration on accelerometer output voltage peak value (transverse sensitivity)	0,03%	norm	1	1	3,00E-04	9,00E-08
6	$u\,(a_{peak,MD})$	effect of transverse, rocking and bending acceleration and laser locations on LDV peak value	0,04%	rec	0,58	1	2,31E-04	5,33E-08
7	$u(S_{sh,Pu})$	effect of pulse shape variation on sensitivity (after 10kHz LP-filter)	0,10%	rec	0,58	1	5,77E-04	3,33E-07
8	$u(S_{sh,RE})$	residual effects on shock sensitivity measurement (e.g. effect of resonance excitation in the transducer or shock machine, random effect in repeated measurements; experimental standard deviation of arithmetic mean)	0,09%	norm	1	1	9,00E-04	8,10E-07

Relative Combined Uncertainty	0,12%
Relative Expanded Uncertainty (k=2)	0,24%
Stated Expanded Uncertainty (k=2)	0,25%

8 –NMIA

Voltage shock sensitivity

Source of Uncertainty	Symbol	U or semi-range (maximum) %	Probability distribution model	k factor	Sensitivity coefficient	Relative contribution, u_i %	DOF
Accelerometer output voltage peak value measurement	u_1	0.06	Rectangular	1.73	1	0.04	30
Voltage filter effect on accelerometer output voltage peak	u_2	0.11	Normal	2.00	1	0.06	30
Effect of residual non-linarites in determination of peak acceleration amplitude due to anvil and pulse characteristics.	u_3	0.10	Normal	2.00	1	0.05	10
Effect of voltage disturbance on accelerometer output voltage peak value	u_4	0.04	Normal	2.00	1	0.02	30
Effect of transverse, rocking, and bending acceleration on accelerometer output peak value	u_5	0.05	Rectangular	1.73	1	0.03	30
Effect of interferometer quadrature output signal disturbance on acceleration peak value	u_6	0.05	Normal	2.00	1	0.03	30
Stability of LDVs, and accuracy of laser wavelength	u_7	0.05	Normal	2.00	1	0.05	30
Effect of errors associated with baseline determination.	u_8	0.15	Normal	2.00	1	0.08	10
Interferometer signal filtering effect on acceleration peak value	u_9	0.19	Rectangular	1.73	1	0.11	30
Effect of voltage disturbance on acceleration peak value	u_{10}	0.10	Normal	2.00	1	0.05	30
Effect of motion disturbance on acceleration peak value	u_{11}	0.10	Normal	2.00	1	0.05	30
Effect of phase disturbance on acceleration peak value	u_{12}	0.01	Rectangular	1.73	1	0.01	30

Source of Uncertainty	Symbol	U or semi-range (maximum) %	Probability distribution model	k factor	Sensitivity coefficient	Relative contribution, u_i %	DOF
Residual interferometric effects on acceleration peak value	u_{I3}	0.01	Rectangular	1.73	1	0.01	30
Effect of resonance excited in accelerometer or SE-201	u_{I4}	0.01	Normal	2.00	1	0.01	30
Residual effects on shock sensitivity measurement including variation in repeated measurements	u_{I5}	0.10	Normal	2.00	1	0.05	30
Rounding error	u_{I6}	0.05	Rectangular	1.73	1	0.03	30
Combined uncertainty	u_c					0.19	
Effective degrees of freedom						131	
Coverage or k factor						2.0	
Expanded uncertainty of voltage sensitivity, U_c (round up of U_c)						0.4	
Stated expanded uncertainty in mV / (m·s⁻²) value.						**0.5**	

Charge shock sensitivity

Source of Uncertainty	Symbol	U or semi-range (maximum) %	Probability distribution model	k factor	Sensitivity coefficient	Relative contribution, u_i %	DOF
Accelerometer output voltage peak value measurement	u_1	0.06	Rectangular	1.73	1	0.04	30
Voltage filter effect on accelerometer output voltage peak	u_2	0.11	Normal	2.00	1	0.06	30
Effect of residual non-linarites in determination of peak acceleration amplitude due to anvil and pulse characteristics.	u_3	0.10	Normal	2.00	1	0.05	10
Effect of voltage disturbance on accelerometer output voltage peak value	u_4	0.04	Normal	2.00	1	0.02	30
Effect of transverse, rocking, and bending acceleration on accelerometer output peak value	u_5	0.05	Rectangular	1.73	1	0.03	30
Effect of interferometer quadrature output signal disturbance on acceleration peak value	u_6	0.05	Normal	2.00	1	0.03	30
Stability of LDVs, and accuracy of laser wavelength	u_7	0.05	Normal	2.00	1	0.05	30
Effect of errors associated with baseline determination.	u_8	0.15	Normal	2.00	1	0.08	10
Interferometer signal filtering effect on acceleration peak value	u_9	0.19	Rectangular	1.73	1	0.11	30
Effect of voltage disturbance on acceleration peak value	u_{10}	0.10	Normal	2.00	1	0.05	30
Effect of motion disturbance on acceleration peak value	u_{11}	0.10	Normal	2.00	1	0.05	30
Effect of phase disturbance on acceleration peak value	u_{12}	0.01	Rectangular	1.73	1	0.01	30
Residual interferometric effects on acceleration peak value	u_{13}	0.01	Rectangular	1.73	1	0.01	30

Source of Uncertainty	Symbol	U or semi-range (maximum) %	Probability distribution model	k factor	Sensitivity coefficient	Relative contribution, u_i %	DOF
Effect of resonance excited in accelerometer or SE-201	u_{14}	0.01	Normal	2.00	1	0.01	30
Residual effects on shock sensitivity measurement including variation in repeated measurements	u_{15}	0.10	Normal	2.00	1	0.05	30
Rounding error	u_{16}	0.05	Rectangular	1.73	1	0.03	30
Combined uncertainty	u_c					0.19	
Effective degrees of freedom						131	
Coverage or k factor						2.0	
Expanded uncertainty of voltage sensitivity, U_v (round up of U_c)						0.4	
Stated expanded uncertainty in mV / (m·s^{-2}) value.						**0.5**	
Uncertainty with calibration of charge amplifier, including effects of accelerometer cable on reference capacitance and broad-band characteristics of shock pulse.	u_{17}	0.14	Normal	2.00	1	0.07	30
Expanded uncertainty of charge sensitivity, U_c (round up of U_c)						0.5	
Stated expanded uncertainty in pC / (m·s^{-2}) value.						**0.6**	

9 –KRISS

Voltage shock sensitivity

	Uncertainty Component	Type (A or B)	Distribution
u_1	Voltage correction of digitizer	B	Normal
u_2	Zero voltage uncertainty	A	t
u_3	Quantization error of peak voltage	B	Rectangular
u_4	Influence of resonant vibration on anvil (for accelerometer)	B	Rectangular
u_5	Sampling time uncertainty of digitizer	B	Rectangular
u_6	Laser wavelength instability	B	Rectangular
u_7	Quantization error of phase displacement	B	Rectangular
u_8	Zero acceleration uncertainty	B	Rectangular
u_9	Influence of resonant vibration on anvil (for acceleration)	B	Rectangular
u_{10}	Transverse sensitivity effect	B	Rectangular
u_{11}	Relative motion between exciter and laser interferometer	B	Rectangular
u_{12}	Measurement repeatability	A	t
u_{13}	Subsequent measurement repeatability	B	Rectangular
u_{14}	Residual effects (long-term stability, reproducibility)	B	Rectangular
u_{15}	Calibration of charge amplifier and cable (only for SE type accelerometer)	B	Rectangular

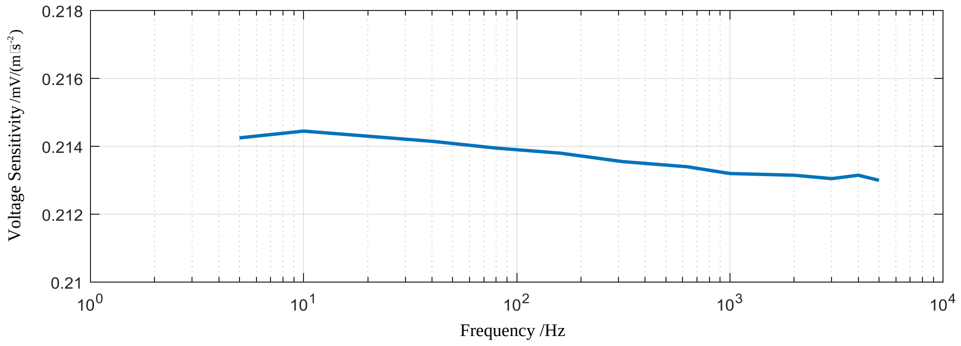
	Type	500 m/s²	1,000 m/s²	2,000 m/s²	3,000 m/s²	4,000 m/s²	5,000 m/s²	Probability distribution	Degree of freedom
u_1	B	6.0×10^{-3}	6.0×10^{-3}	6.0×10^{-3}	6.0×10^{-3}	6.0×10^{-3}	6.0×10^{-3}	Normal	infinite
u_2	A	5.0×10^{-2}	5.0×10^{-2}	5.0×10^{-2}	5.0×10^{-2}	5.0×10^{-2}	5.0×10^{-2}	t	infinite
u_3	B	4.3×10^{-3}	4.3×10^{-3}	4.3×10^{-3}	4.3×10^{-3}	4.3×10^{-3}	4.3×10^{-3}	Rectangular	infinite
u_4	B	2.0×10^{-1}	2.0×10^{-1}	2.0×10^{-1}	2.0×10^{-1}	2.0×10^{-1}	2.0×10^{-1}	Rectangular	infinite
u_5	B	1.5×10^{-11}	1.5×10^{-11}	1.5×10^{-11}	1.5×10^{-11}	1.5×10^{-11}	1.5×10^{-11}	Rectangular	infinite
u_6	B	1.5×10^{-4}	1.5×10^{-4}	1.5×10^{-4}	1.5×10^{-4}	1.5×10^{-4}	1.5×10^{-4}	Rectangular	infinite
u_7	B	1.0×10^{-1}	1.0×10^{-1}	1.0×10^{-1}	1.0×10^{-1}	1.0×10^{-1}	1.0×10^{-1}	Rectangular	infinite
u_8	B	1.0×10^{-1}	1.0×10^{-1}	1.0×10^{-1}	1.0×10^{-1}	1.0×10^{-1}	1.0×10^{-1}	Rectangular	infinite
u_9	B	2.0×10^{-1}	2.0×10^{-1}	2.0×10^{-1}	2.0×10^{-1}	2.0×10^{-1}	2.0×10^{-1}	Rectangular	infinite
u_{10}	B	4.2×10^{-2}	4.2×10^{-2}	4.2×10^{-2}	4.2×10^{-2}	4.2×10^{-2}	4.2×10^{-2}	Rectangular	infinite
u_{11}	B	1.0×10^{-2}	1.0×10^{-2}	1.0×10^{-2}	1.0×10^{-2}	1.0×10^{-2}	1.0×10^{-2}	Rectangular	infinite
u_{12}	A	4.1×10^{-4}	6.7×10^{-4}	2.8×10^{-4}	3.6×10^{-4}	2.4×10^{-4}	1.9×10^{-4}	t	16
u_{13}	B	1.5×10^{-4}	5.8×10^{-4}	2.0×10^{-4}	2.8×10^{-4}	1.6×10^{-4}	1.2×10^{-4}	Rectangular	infinite
u_{14}	B	4.5×10^{-1}	4.5×10^{-1}	4.5×10^{-1}	4.5×10^{-1}	4.5×10^{-1}	4.5×10^{-1}	Rectangular	infinite
Relative combined standard uncertainty		0.55	0.55	0.55	0.55	0.55	0.55		
Relative expanded uncertainty (k=2)		1.1	1.1	1.1	1.1	1.1	1.1		

Charge shock sensitivity

Acceleration m/s^2	Relative standard uncertainty, %														u_c, %	U, % (k=2)
	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}		
500	6.0×10^{-3}	5.0×10^{-2}	4.3×10^{-3}	2.0×10^{-1}	1.5×10^{-11}	1.5×10^{-4}	1.0×10^{-1}	1.0×10^{-1}	2.0×10^{-1}	4.2×10^{-2}	1.0×10^{-2}	4.1×10^{-4}	1.5×10^{-4}	4.5×10^{-1}	0.55	1.1
1,000	6.0×10^{-3}	5.0×10^{-2}	4.3×10^{-3}	2.0×10^{-1}	1.5×10^{-11}	1.5×10^{-11}	1.0×10^{-1}	1.0×10^{-1}	2.0×10^{-1}	4.2×10^{-2}	1.0×10^{-2}	6.7×10^{-4}	5.8×10^{-4}	4.5×10^{-1}	0.55	1.1
2,000	6.0×10^{-3}	5.0×10^{-2}	4.3×10^{-3}	2.0×10^{-1}	1.5×10^{-11}	1.5×10^{-11}	1.0×10^{-1}	1.0×10^{-1}	2.0×10^{-1}	4.2×10^{-2}	1.0×10^{-2}	2.8×10^{-4}	2.0×10^{-4}	4.5×10^{-1}	0.55	1.1
3,000	6.0×10^{-3}	5.0×10^{-2}	4.3×10^{-3}	2.0×10^{-1}	1.5×10^{-11}	1.5×10^{-11}	1.0×10^{-1}	1.0×10^{-1}	2.0×10^{-1}	4.2×10^{-2}	1.0×10^{-2}	3.6×10^{-4}	2.8×10^{-4}	4.5×10^{-1}	0.55	1.1
4,000	6.0×10^{-3}	5.0×10^{-2}	4.3×10^{-3}	2.0×10^{-1}	1.5×10^{-11}	1.5×10^{-11}	1.0×10^{-1}	1.0×10^{-1}	2.0×10^{-1}	4.2×10^{-2}	1.0×10^{-2}	2.4×10^{-4}	1.6×10^{-4}	4.5×10^{-1}	0.55	1.1
5,000	6.0×10^{-3}	5.0×10^{-2}	4.3×10^{-3}	2.0×10^{-1}	1.5×10^{-11}	1.5×10^{-11}	1.0×10^{-1}	1.0×10^{-1}	2.0×10^{-1}	4.2×10^{-2}	1.0×10^{-2}	1.9×10^{-4}	1.2×10^{-4}	4.5×10^{-1}	0.55	1.1

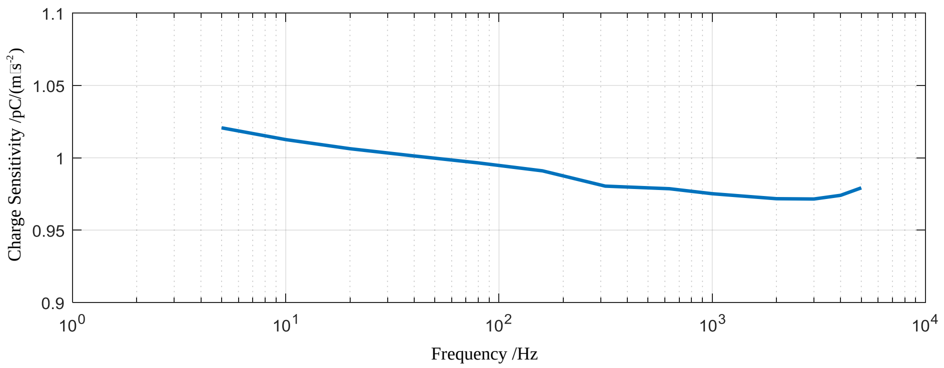
Annex D – Frequency response of comparison artefacts

Frequency response of accelerometer chain with a dummy mass of 20 g used in voltage shock sensitivity



Note: Uniformity in the frequency response of Accelerometer Chain with a dummy mass of 20 g (ENDEVCO 2270, S/N 14155 and Brüel & Kjær 2692, S/N 2752215) from 5 Hz to 5 kHz reveals insignificant influence of shock pulse width on voltage shock sensitivity measurement.

Frequency response of accelerometer used in charge shock sensitivity



Note: Non-uniformity in the frequency response of accelerometer PCB 357B03 (S/N LW50432) from 5 Hz to 5 kHz reveals significant influence of shock pulse width on charge shock sensitivity measurement.