Final Report on Pilot Comparison of Low Intensity Shock

APMP.AUV.V-P1

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1 Introduction

This report presents the results of the first Asia Pacific Metrology Programme (APMP) comparison in the area of low-intensity 'shock', which in this case means monopole and dipole shock acceleration.

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

The Technical Protocol of May 2013 [3] specifies in detail the aim and the task of the comparison, the conditions of measurement, the transfer standards used, measurement instructions, time schedule and other items. A brief survey is given in the following sections.

2 Participants

Three metrology institutes from APMP economies and one secondary laboratory accredited by DAKKs for primary shock calibration in Germany have participated in the comparison APMP.AUV.V-P1 (see table 2.1).

Table 2.1: List of participating institutes

Participant	Economy	Calibration period
NIM	P. R. China	April, 2014
SPEKTRA	Germany	May, 2014
NIMT	Thailand	July, 2014
CMS/ITRI	Chinese Taipei	August, 2014

3 Task and Purpose of the Comparison

In the field of shock acceleration, there is no formal comparison either at Consultative Committee (CC) level or Regional Metrology Organization Technical Committee (RMO TC) level. Therefore during the meeting of APMP TCAUV in 2011, the decision was taken to make preparations for a pilot comparison targeted at low intensity shock acceleration.

This regional pilot comparison is organized in order to mainly compare primary measurements of half-sine or half-sine squared (monopole) linear shock accelerations in the range from 500 m/s² to 5 000 m/s². It is the task of the comparison to measure shock sensitivity of an accelerometer measuring chain (a standard accelerometer of back-to-back type with a charge amplifier) (Accelerometer Chain) at different peak acceleration values with associated pulse durations as specified in section 3 of [3]. The results of this APMP pilot comparison may serve as indirect supporting evidence for the registration of ‘calibration and measurement capabilities’ (CMCs) in the framework of the CIPM MRA.

The shock voltage sensitivity is calculated as the ratio of the amplitude of the Accelerometer Chain output voltage to the shock peak value at its reference surface. The shock voltage sensitivity shall be given in millivolts per meter per second squared (mV/(m/s²)) for the different measurement conditions specified in section 4 of [3].

For the calibration of the Accelerometer Chain, laser interferometry in compliance with method of the international standard ISO 16063-13:2001 [4] has to be applied.

The reported sensitivities and associated uncertainties were used for the calculation of the pilot comparison reference value (PCRV).

4 Conditions and Instructions of Measurement

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

- acceleration amplitudes:

  A range from 500 m/s² to 5 000 m/s² was admissible, with the following specific acceleration levels (all values in m/s²).

  500, 1 000, 2 000, 3 000, 4 000, 5 000.
- duration of monopole shock pulse is within 0.3 to 3 ms. A series of 0.5 ms, 1 ms, 1.5 ms and 2 ms are recommended, with the reference of 2 ms at a peak acceleration of 1 000 m/s².
- duration of dipole shock pulse at 1 000 m/s² as option is within 0.03 to 0.2 ms. A series of 0.03 ms, 0.05 ms, 0.07 ms, 0.10 ms, 0.15 ms and 0.20 ms are recommended, with the reference of 0.1 ms at a peak acceleration of 1 000 m/s².
- ambient temperature and accelerometer temperature during the calibration:

  (23 ± 3) ℃ (actual values to be stated within tolerances of ± 0.3 ℃).
- relative humidity: max. 75 % RH

- mounting torque of the accelerometer: (2.0 ±0.1) N·m

The comparison was performed in compliance with the “Guidelines for CIPM key comparisons” [1].

5 Transfer Standard as Artefact

For the purpose of the comparison the pilot laboratory selected one Accelerometer Chain of which monitoring data for 6 months were available and of which data were not included in any published international cooperation work.

- an accelerometer ENDEVCO 2270 (SN: 10466), with a Brüel & Kjær charge amplifier 2692 (SN: 2752215)

The investigation of the long-term stability was also done at the end of the circulation period. Part of the results of the NIM stability measurements and other individual data of the transfer standard are given in Section 7.

6 Circulation of the Artefact

The Accelerometer Chain was circulated in a ring type fashion with a measurement period of two weeks provided for each participating laboratory. At the beginning and the end of the circulation, the Accelerometer Chain was measured by the pilot laboratory in order to determine reference values and to monitor the stability of the Accelerometer Chain (c.f. section 7). Due to the unexpected malfunction of data acquisition system of the primary shock calibration system at CMS in June 2014, the circulation sequence had to be rearranged to improve measurement efficiency of the remaining task. The originally planned measurement loop was from NIM to SPEKTRA, to CMS, to NIMT, and back to NIM. The actual measurement loop was from NIM to SPEKTRA, to NIMT, to CMS, and back to NIM.

7 Results of the Monitoring Measurements

Starting with calibration data in November 2013, the artefact were monitored during the preparatory period and the end of the comparison when it was back at the pilot laboratory. As a representative of the overall change, the measurements at reference condition (monopole shock pulse of 2 ms duration at a peak acceleration of 1 000 m/s^2) are given in the following table.

Table 7.1: Shock voltage sensitivities of the Accelerometer Chain at reference condition during the monitoring measurements

Month rel. to 11/2013	S_{va} in mV/(m/s²)	rel. exp. Uncertainty in %
0	0.1968	0.5
1	0.1969	0.5
2	0.1968	0.5
3	0.1969	0.5
4	0.1968	0.5
5	0.1968	0.5
10	0.1969	0.5

These monitoring measurements can in the simplest way be summarized by the following statistical properties which indicate that the stability of the artefact was good considering the uncertainty claimed by the pilot laboratory in Appendix B.

Table 7.2: Mean and standard deviation of the shock voltage sensitivity of the Accelerometer Chain

Artefact	long term mean in mV/(m/s²)	rel. std. deviation in %
Accelerometer Chain	0.19684	0.03

8 Results of the Participants

The results include voltage sensitivities of the Accelerometer Chain exposed to shock pulse of both monopole and dipole acceleration .

8.1 Results of shock sensitivities under monopole shock excitation

Table 8.1: Reported calibration results in mV/(m/s²) for shock voltage sensitivities under monopole shock excitation with expanded relative uncertainty (k = 2) in %

Acceleration	Pulse duration	NIM		CMS		SPEKTRA	
		S_{va}	U_c	S_{va}	U_c	S_{va}	U_c
in m/s²	in ms	in mV/(m/s²)	in %	in mV/(m/s²)	in %	in mV/(m/s²)	in %
500	3.0	**0.1967**	0.5	**0.1966**	1.0	**0.1973**	0.5
1000	2.0	**0.1968**	0.5	**0.1970**	1.0	**0.1975**	0.5
2000	1.5	**0.1970**	0.5	**0.1971**	1.0	**0.1975**	0.7
3000	1.0	**0.1973**	0.5	**0.1971**	1.0	**0.1976**	0.7
4000	1.0	**0.1973**	0.5	**0.1971**	1.0	**0.1974**	0.7
5000	0.8	**0.1973**	0.5	**0.1971**	1.0	**0.1973**	0.7

8.2 Results of shock sensitivities under dipole shock excitation

Table 8.2: Reported calibration results in mV/(m/s²) for shock voltage sensitivities under dipole shock excitation at 1000 m/s² with expanded relative uncertainty (k = 2) in %

Acceleration	Pulse duration	NIM		NIMT		SPEKTRA	
		S_{va}	U_c	S_{va}	U_c	S_{va}	U_c
in m/s²	in ms	in mV/(m/s²)	in %	in mV/(m/s²)	in %	in mV/(m/s²)	in %
1000	0.20	**0.1972**	0.5	**0.1976**	0.6	**0.1977**	0.5
1000	0.15	**0.1973**	0.5	**0.1977**	0.6	**0.1974**	0.5
1000	0.10	**0.1976**	1.0	**0.1976**	0.7	**0.1977**	0.5
1000	0.07	**0.1981**	1.0	**0.1976**	1.0	**0.1978**	0.8
1000	0.05	**0.1985**	1.5	**0.1977**	1.0	**0.1976**	0.8
1000	0.03	**0.1990**	1.5	**0.1985**	1.0	**0.1972**	0.8

9 Degree of Equivalence with Respect to the PCRV

The weighted mean was agreed upon by all laboratories to calculate the PCRVs for the APMP.AUV.V-P1 data. PCRVs were calculated separately at each acceleration or pulse duration point measured for Accelerometer Chain.

Calculation of PCRVs using the weighted mean method

Tables 8.1 and 8.2 contain the data for the Accelerometer Chain reported by the participating laboratories. For each laboratory i these data are (1) $x_{i,a,d}$: best estimate of sensitivity at acceleration a and pulse duration d, and (2) $u(x_{i,a,d})$: associated standard uncertainty of sensitivity reported at acceleration and pulse duration.

For the transfer standard and at each acceleration a and pulse duration d, a pilot comparison reference value x_{WM} has been determined as the weighted mean of the results of n laboratories (for this comparison, n = 3) according to

$$x_{\mathrm{WM}} = \frac{\sum_{i=1}^{n} \frac{x_{i,a,d}}{u^2(x_{i,a,d})}}{\sum_{i=1}^{n} \frac{1}{u^2(x_{i,a,d})}} \tag{1}$$

$$u^2(x_{\mathrm{WM}}) = \frac{1}{\sum_{i=1}^{n} \frac{1}{u^2(x_{i,a,d})}} \quad (2)$$

The degree of equivalence, $D_{\mathrm{lab-WM}}$, and $U_{\mathrm{lab-WM}}$, was determined for the measurements for the Accelerometer Chain using

$$D_{\mathrm{lab-WM}} = X_{\mathrm{lab}} - X_{\mathrm{WM}}, \quad U_{\mathrm{lab-WM}} = k \cdot \sqrt{u_{\mathrm{lab}}{}^2 - u_{\mathrm{WM}}{}^2} \quad (3)$$

where X_{lab} represents the measurement results obtained by the laboratory at each acceleration and pulse duration and X_{WM} represents the reference value (PCRV) calculated as the weighted mean using Eq. (1). $U_{\mathrm{lab-WM}}$ is the uncertainty of measurement associated with the calculated $D_{\mathrm{lab-WM}}$ for k = 2.

Application of the weighted mean is justified when the data including the stated uncertainties are consistent with one another. To check this, the following criterion of chi-squared test has been applied:

$$\min_{\zeta} \sum_{i=1}^{n} (x_{i,a} - \zeta)^2 / u^2(x_{i,a}) \le (n-1) + k\sqrt{2(n-1)} \quad (4)$$

where n denotes the number of laboratories concerned, cf., e.g., [2] and k = 3. All the measurement results passed the consistency test.

9.1 DoE for shock sensitivities under monopole shock excitation

Table 9.1: Unilateral degrees of equivalence for shock voltage sensitivities under monopole shock excitation

Acceleration	**Pulse duration**	**PCRV**		**NIM**		**CMS**		**SPEKTRA**	
		X_{WM}	U_{WM}	D_i	U_i	D_i	U_i	D_i	U_i
in m/s²	**in ms**	**in mV/(m/s²)**	**in mV/(m/s²) ·10⁻⁴**	**in mV/(m/s²) ·10⁻⁴**		**in mV/(m/s²) ·10⁻⁴**		**in mV/(m/s²) ·10⁻⁴**	
500	3.0	**0.19694**	6.6	**-2.4**	7.3	**-3.4**	18.5	**3.3**	7.4
1000	2.0	**0.19712**	6.6	**-3.2**	7.3	**-1.2**	18.6	**3.4**	7.4
2000	1.5	**0.19716**	7.4	**-1.6**	6.5	**-0.6**	18.3	**3.3**	11.7
3000	1.0	**0.19734**	7.4	**-0.4**	6.5	**-2.4**	18.3	**2.0**	11.7
4000	1.0	**0.19729**	7.4	**0.1**	6.5	**-1.9**	18.3	**0.6**	11.6
5000	0.8	**0.19728**	7.4	**0.2**	6.5	**-1.8**	18.3	**0.6**	11.6

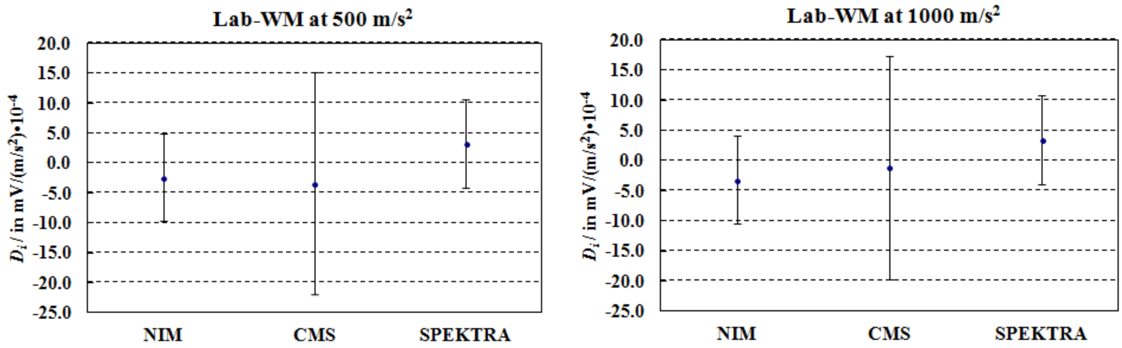


Figure 9.1: Degree of equivalence for voltage sensitivities under monopole shock excitation at 500 m/s^2, 3.0 ms and 1000 m/s^2, 2.0 ms

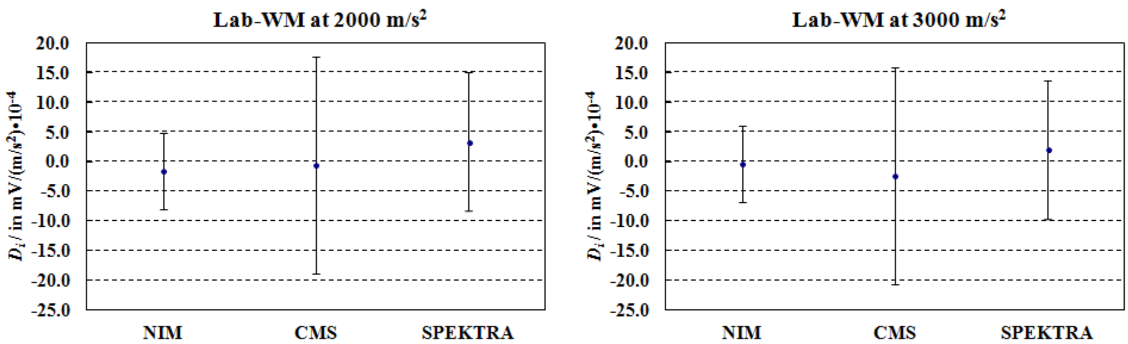


Figure 9.2: Degree of equivalence for voltage sensitivities under monopole shock excitation at 2000 m/s^2, 1.5 ms and 3000 m/s^2, 1.0 ms

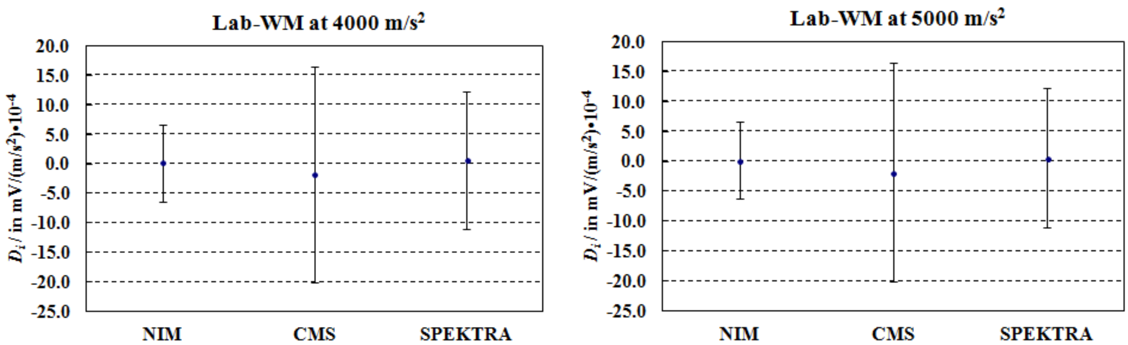
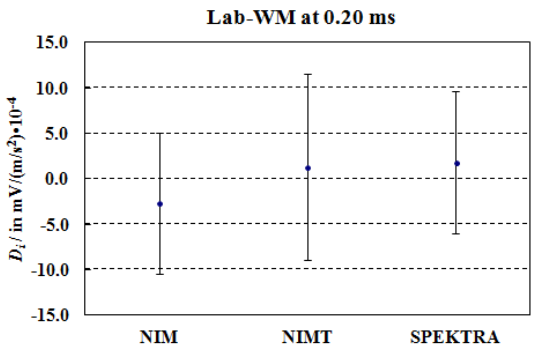


Figure 9.3: Degree of equivalence for voltage sensitivities under monopole shock excitation at 4000 m/s^2, 1.0 ms and 5000 m/s^2, 0.8 ms

9.2 DoE for shock sensitivities under dipole shock excitation

Table 9.2: Unilateral degrees of equivalence for shock voltage sensitivities under dipole shock excitation

Acceleration	Pulse duration	PCRV		NIM		NIMT		SPEKTRA	
		X_{WM}	U_{WM}	D_i	U_i	D_i	U_i	D_i	U_i
in m/s²	in ms	in mV/(m/s²)	in mV/(m/s²) ·10⁻⁴	in mV/(m/s²) ·10⁻⁴		in mV/(m/s²) ·10⁻⁴		in mV/(m/s²) ·10⁻⁴	
1000	0.20	**0.19747**	6.0	**-2.7**	7.8	**1.3**	10.2	**1.8**	7.8
1000	0.15	**0.19746**	6.0	**-1.6**	7.8	**2.4**	10.2	**-0.2**	7.8
1000	0.10	**0.19763**	7.4	**-0.3**	18.3	**-0.3**	11.7	**0.2**	6.5
1000	0.07	**0.19781**	10.5	**2.9**	16.8	**-2.1**	16.8	**-0.5**	11.9
1000	0.05	**0.19776**	11.4	**7.4**	27.5	**-0.6**	16.1	**-1.8**	10.9
1000	0.03	**0.19789**	11.4	**11.1**	27.6	**6.1**	16.2	**-7.1**	10.9



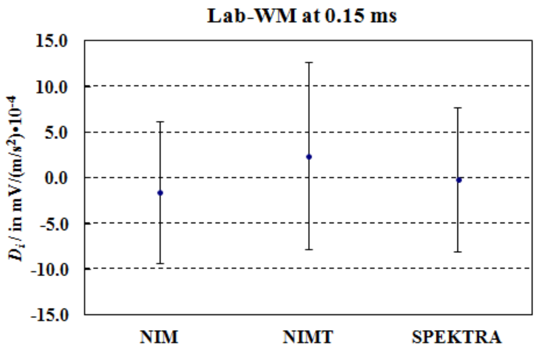
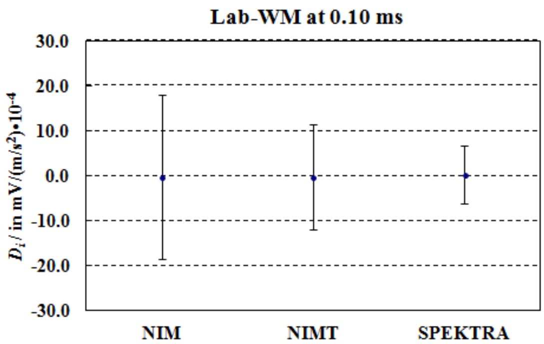


Figure 9.4: Degree of equivalence for voltage sensitivities under dipole shock excitation at 1000 m/s², 0.20 ms and 1000 m/s², 0.15 ms



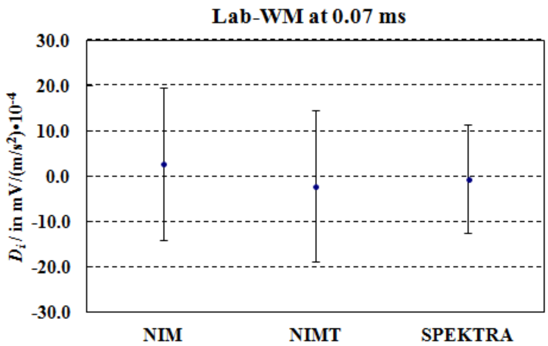


Figure 9.5: Degree of equivalence for voltage sensitivities under dipole shock excitation at 1000 m/s², 0.10 ms and 1000 m/s², 0.07 ms

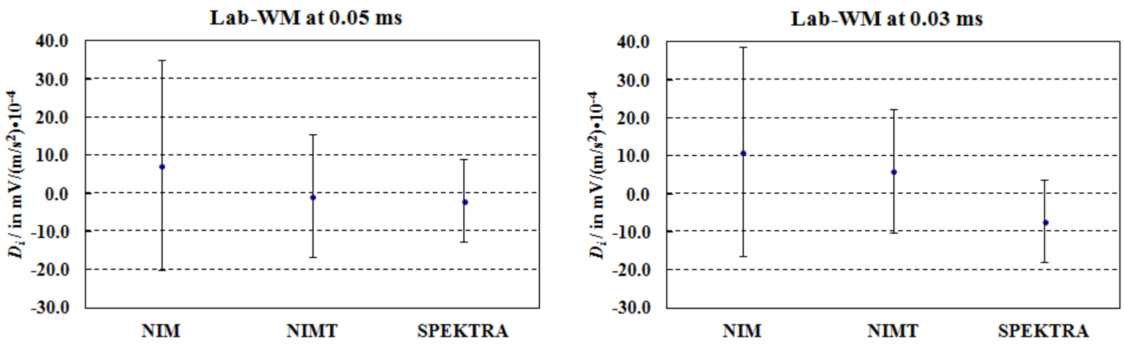


Figure 9.6: Degree of equivalence for voltage sensitivities under dipole shock excitation at 1000 m/s^2, 0.05 ms and 1000 m/s^2, 0.03 ms

10 Bilateral Degree of Equivalence between Participants

In order to compare the individual results of the participating laboratories of this comparison with one another, the Degree of Equivalence (DoE) of pairs of results with respect to a certain acceleration level and pulse duration can be calculated. These DoEs are each a pair of values of the difference D_{ij} between the respective participants i and j and the combined expanded uncertainty U_{ij} of this difference. These values shall be calculated for each measuring condition of acceleration level and pulse duration according to:

$$D_{ij} = x_i - x_j \tag{5}$$

$$U_{ij} = k \cdot \sqrt{u^2(x_i) + u^2(x_j)} \tag{6}$$

with a coverage factor of $k = 2$.

11 Conclusion

Four participant laboratories measured the shock voltage sensitivity of one Accelerometer Chain (a standard accelerometer of back-to-back type with a charge amplifier). Specifically, NIM, CMS and SPEKTRA measured its shock voltage sensitivity under monopole shock excitation in the acceleration range from 500 m/s^2 to 5 000 m/s^2; NIM, NIMT and SPEKTRA measured its shock voltage sensitivity under dipole shock excitation with the reference acceleration of 1000 m/s^2 and pulse duration from 0.03 ms to 2.0 ms. The results of the APMP.AUV.V-P1 are two sets of PCRVs, their uncertainties and unilateral degrees of equivalence illustrating the performance of the participant laboratories with respect to PCRVs.

The calibration results obtained for the Accelerometer Chain represent the current calibration capabilities of the participating laboratories for the shock voltage sensitivity of back-to-back accelerometers. At the reference acceleration of 1 000 m/s^2 and pulse duration of 2 ms (specified in ISO 16063-13:2001), the participating laboratories calibrated the Accelerometer Chain with their claimed relative expanded uncertainty (k = 2), the smallest of which equal to 0.5%, i.e. smaller than the limit specified by the ISO standard [4].

In conclusion, the degrees of equivalence calculated from the data submitted by the four laboratories, support the uncertainty of measurement reported by the four laboratories for the calibration of the shock sensitivities of accelerometer in the acceleration range from 500 m/s^2 to 5 000 m/s^2 under monopole shock excitation, with the only exception of NIMT which only reported measurement results of 1 000 m/s^2 under dipole shock excitation. The completion of APMP.AUV.V-P1 can serve as part of the basis for a planned key comparison targeted at low intensity shock range at CC level.

Bibliography

[1] 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.

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

[3] Technical Protocol of the APMP Pilot comparison APMP.AUV.V-P1 (Shock). NIM, Qiao SUN, May 2013.

[4] ISO 16063-13:1999 “Methods for the calibration of vibration and shock transducers - Part 11: Primary shock calibration using laser interferometry” .

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

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

Appendix A: Technical Protocol

National Institute of Metrology (NIM)

May, 2013 (participants revised)

Qiao SUN

Technical Protocol of the APMP Pilot Comparison

APMP.AUV.V-P1

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 is no formal comparison either at Consultative Committee (CC) level or Regional Metrology Organization Technical Committee (RMO TC) level. Therefore during the meeting of APMP TCAUV in 2011, the decision was taken to make preparations for a pilot comparison targeted at low shock (acceleration).

This regional pilot comparison is organized in order to compare primary measurements of 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 shock sensitivity of an accelerometer measuring chain (a standard accelerometer (of single-ended type) with a charge amplifier) (Accelerometer Chain) at different peak acceleration values with associated pulse durations as specified in section 3. The results of this APMP pilot comparison may serve as supporting evidence for the registration of ‘calibration and measurement capabilities’ (CMCs) in the framework of the CIPM MRA.

The shock voltage sensitivity is calculated as the ratio of the amplitude of the Accelerometer Chain output voltage to the shock peak value 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.

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

The reported sensitivities and associated uncertainties will be used for the calculation of mean values of the pilot comparison results and their associated uncertainties, as well as the deviations to the mean values with associated uncertainties.

2 Pilot Laboratory

Pilot laboratory for this regional pilot comparison is

Vibration and Gravity Section
Mechanics and Acoustics Metrology Division
National Institute of Metrology, P.R. China
BeiSanHuanDongLu 18, ChaoYang District, 100013 Beijing, P.R. China

This is the delivery address for the artefacts and the written and signed reports.

Contact Persons are

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3 Device under Test and Measurement Conditions

For the calibration task of this comparison one Accelerometer Chain will be circulated between the participating laboratories. The Accelerometer Chain is a ‘Back to Back’ (BB) type, namely an ENDEVCO 2270 (SN: 10466), with a charge amplifier, namely Brüel & Kjær 2692 (SN: 2752215).

The shock voltage sensitivity of the Accelerometer Chain is 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 sensitivities reported shall be for the Accelerometer chain, including all effects from the signal conditioner.

The peak acceleration range of the measurements was agreed to be from 500 m/s^2 to 5 000 m/s^2. Specifically, the laboratories are supposed to measure at the following acceleration levels (all values in m/s^2).

500, 1 000, 2 000, 3 000, 4 000, 5 000.

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

Specific conditions for the measurements of this comparison are:

- duration of monopole shock pulse is within 0.3 to 3 ms. A series of 0.5 ms, 1 ms, 1.5 ms and 2 ms are recommended, with the reference of 2 ms at a peak acceleration of 1 000 m/s^2.

- duration of dipole shock pulse at 1 000 m/s^2 as option is within 0.03 to 0.2 ms. A series of 0.03 ms, 0.05 ms, 0.07 ms, 0.10 ms, 0.15 ms and 0.20 ms are recommended, with the reference of 0.1 ms at a peak acceleration of 1 000 m/s^2.
- ambient temperature and accelerometer temperature during the calibration: (23 ± 3) ℃ (actual values to be stated within tolerances of ± 0.3 ℃).
- relative humidity: max. 75 % RH
- mounting torque of the accelerometer: (2.0 ±0.1) N·m

4 Circulation Type, Schedule and Transportation

The artefacts are circulated in a ring type fashion with a measurement period of two weeks provided for each participating laboratory and one week for the pilot laboratory. At the beginning and the end of the circulation as well as between certain subsequent measurements of participating laboratories, the Accelerometer Chain is measured at the pilot laboratory in order to monitor the stability of the accelerometer set.

The schedule is planned as follows:

Participant	Measurement (calendar week)	Transportation to next Participant (calendar week)
NIM	12-13/2014	14-15/2014
SPEKTRA	16-17/2014	18-19/2014
CMS	20-21/2014	22-23/2014
NIMT	24-25/2014	26-27/2014
NIM	28-29/2014	

The cost of transportation to the next laboratory shall be covered by the participating laboratory. The accelerometer set should be delivered by an international logistic service with on-line tracking system. The transportation has to include an insurance covering a value of USD 8 000 in case the accelerometer set gets damaged or lost during transportation. Hand-carry can be used as an option.

5 Measurement and Analysis Instructions

The participating laboratories have to observe the following instructions:

- The motion of the accelerometer should be measured at the center of the top surface of the dummy mass applied.
- 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 set delivered to the laboratory.
- 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 one printed and signed calibration report for accelerometer set to the pilot laboratory including the following:

- a description of the calibration system used for the comparison with a photo 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.

In addition, the use of the electronic spreadsheets for reporting is mandatory. The consistency between the results in electronic form and the printed and signed calibration report is the responsibility of the participating 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'

Appendix B: Uncertainty Budgets of the participants

Table B.1: NIM's uncertainty budget of shock voltage sensitivity under monopole shock excitation

No.	Source of influence	Source of uncertainty component	Distribution	Type	Uncertainty contribution
1	Electric quantity	Uncertainty of standard voltage generator	Normal	B	5.0×10^{-5}
2		Voltage correction coefficient uncertainty	Normal	A	5.0×10^{-4}
3	Accelerometer chain output	Zero voltage uncertainty	Normal	A	3.0×10^{-4}
4		Quantization error of peak voltage	Rectangular	B	5.0×10^{-5}
5		Influence of resonant vibration of anvil	Normal	B	1.0×10^{-3}
6	Reference acceleration	Sampling time interval of digitizer	Rectangular	B	1.0×10^{-6}
7		Instability of laser wave length	Normal	B	2.0×10^{-6}
8		Quantization error of phase displacement	Rectangular	B	1.0×10^{-3}
9		Zero acceleration uncertainty	Normal	B	1.0×10^{-3}
10		Influence of resonant motion of anvil	Normal	B	1.0×10^{-3}
11	Others	Transverse sensitivity effect	Normal	B	4.2×10^{-4}
12		Relative motion between exciter and laser interferometer	Normal	B	1.0×10^{-4}
13		Residual effects	Normal	A	1.5×10^{-4}
Relative combined standard uncertainty					2.1×10^{-3}
Relative expanded uncertainty （k=2）					4.3×10^{-3}

Table B.2: NIM’s uncertainty of shock voltage sensitivity under Dipole shock excitation

No.	Source of uncertainty component	Distribution	Type	Uncertainty contribution		
				Pulse duration		
				0.2 ms 0.15ms	0.1 ms 0.07ms	0.05 ms 0.03ms
1	Measurement of transfer standard’s peak voltage	Rectangular	A	0.0577	0.0577	0.173
2	Influence of signal filtering from DUT on transfer standard’s peak voltage	Rectangular	B	0.0577	0.289	0.289
3	Voltage disturbance on transfer standard’s peak voltage	Rectangular	B	0.0577	0.115	0.115
4	Influence of transverse motion on transfer standard’s peak voltage	Rectangular	B	0.0231	0.0231	0.0231
5	Influence of interferometric quadrature signals on transfer standard’s peak voltage	Rectangular	B	0	0	0
6	Influence of filtering of interferometric signals transfer standard’s peak voltage	Rectangular	B	0.0577	0.115	0.115
7	Influence of hum and noise	Rectangular	B	0.0577	0.0577	0.173
8	Influence of relative motion	Rectangular	B	0.0289	0.0289	0.0289
9	Influence of phase disturbance transfer standard’s peak voltage	Rectangular	B	0.0577	0.0577	0.0577
10	Residual effects	Normal	A	0.0103	0.0173	0.0173
11	Influence of amplifier tracking response	Rectangular	B	0.0577	0.115	0.289
12	Deviation of magnitude frequency response of transfer standard	Rectangular	A	0.0577	0.0577	0.115
13	Influence of magnitude linearity of transfer standard	Rectangular	B	0.0577	0.115	0.289
14	Stability of transfer standard	Normal	B	0.115	0.115	0.289
15	Environmental influence	Rectangular	B	0.0866	0.1	0.289
16	Influence from installation	Rectangular	B	0.0577	0.0866	0.0866
17	Other influences	Rectangular	B	0.0577	0.0577	0.115
Relative combined standard uncertainty				0.24	0.43	0.74
Relative expanded uncertainty （k=2）				0.47	0.86	1.47

Table B.3: CMS's uncertainty of shock voltage sensitivity under Monopole shock excitation

Uncertainty Source	Type A/B	Relative Expanded Uncertainty or Error Estimation %						Probability Distribution	Divisor	Sensitivity Coefficient	Degree of Freedom	Relative Uncertainty Component %					
		500 m/s^2	**1000 m/s^2**	**2000 m/s^2**	**3000 m/s^2**	**4000 m/s^2**	**5000 m/s^2**					**500 m/s^2**	**1000 m/s^2**	**2000 m/s^2**	**3000 m/s^2**	**4000 m/s^2**	**5000 m/s^2**
u_r : Repeating evaluation of system	A	0.0122	0.0862	0.0199	0.0161	0.0025	0.0130	t	1	1	9	0.0122	0.0862	0.0199	0.0161	0.0025	0.0130
$u_{\varepsilon 1}$: Sensitivity influence of voltage measurement owing to digital oscilloscope card	B	0.0305	0.0061	0.0030	0.0020	0.0015	0.0012	Rectangular	$\sqrt{3}$	1	200	0.0176	0.0035	0.0018	0.0012	0.0009	0.0176
$u_{\varepsilon 2}$: Sensitivity influence of voltage measurement owing to digital oscilloscope card	B	0.5	0.5	0.5	0.5	0.5	0.5	Normal	2	1	200	0.25	0.25	0.25	0.25	0.25	0.25
$u_{\varepsilon 3}$: Sensitivity influence of voltage measurement owing to digital oscilloscope card	B	0.002	0.002	0.002	0.002	0.002	0.002	Rectangular	$\sqrt{3}$	1	200	0.0011	0.0011	0.0011	0.0011	0.0011	0.0011
$u_{\varepsilon 4}$: Sensitivity influence of voltage measurement owing to digital filtering	B	0.0837	0.0837	0.0837	0.0837	0.0837	0.0837	Rectangular	$\sqrt{3}$	1	200	0.0483	0.0483	0.0483	0.0483	0.0483	0.0483
$u_{\varepsilon 5}$: Sensitivity influence of voltage measurement owing to hum and noise	A	0.0494	0.0494	0.0494	0.0494	0.0494	0.0494	t	1	1	9	0.0494	0.0494	0.0494	0.0494	0.0494	0.0494
$u_{\varepsilon 6}$: Influence of sensitivity measurement owing to charge stability for accelerometer	B	0.2	0.2	0.2	0.2	0.2	0.2	Rectangular	$\sqrt{3}$	1	200	0.1155	0.1155	0.1155	0.1155	0.1155	0.1155
$u_{\varepsilon 7}$: Sensitivity influence of voltage measurement owing to transverse swing	B	0.015	0.015	0.015	0.015	0.015	0.015	U	$\sqrt{2}$	1	200	0.0106	0.0106	0.0106	0.0106	0.0106	0.0106
$u_{\varepsilon 8}$: Influence of sensitivity measurement owing to accelerometer amplitude linearity	B	0.05	0.05	0.05	0.05	0.05	0.05	Rectangular	$\sqrt{3}$	1	200	0.0289	0.0289	0.0289	0.0289	0.0289	0.0289
$u_{\varepsilon 9}$: Sensitivity influence of voltage measurement owing to accelerometer amplitude	B	0.243	0.243	0.341	0.341	0.341	0.243	Rectangular	$\sqrt{3}$	1	200	0.1403	0.1403	0.1969	0.1969	0.1969	0.1403
$u_{\varepsilon 10}$: Sensitivity influence of voltage measurement owing to charge amplifier	B	0.1	0.1	0.1	0.1	0.1	0.1	Rectangular	$\sqrt{3}$	1	200	0.0577	0.0577	0.0577	0.0577	0.0577	0.0577
$u_{\varepsilon 11}$: Sensitivity influence of voltage measurement owing to charge amplifier	B	0.0126	0.0126	0.119	0.119	0.119	0.0126	Rectangular	$\sqrt{3}$	1	200	0.0073	0.0073	0.0687	0.0687	0.0687	0.0073
$u_{\varepsilon 12}$: Sensitivity influence of acceleration measurement owing to charge amplifier	B	0.012	0.012	0.0266	0.0266	0.0266	0.012	Rectangular	$\sqrt{3}$	1	200	0.0069	0.0069	0.015	0.015	0.015	0.0069
$u_{\varepsilon 13}$: Sensitivity influence of acceleration measurement owing to dual-channel	B	0.04	0.04	0.04	0.04	0.04	0.04	Rectangular	$\sqrt{3}$	1	200	0.0231	0.0231	0.0231	0.0231	0.0231	0.0231
$u_{\varepsilon 14}$: Sensitivity influence of acceleration measurement owing to digital filtering	B	0.0837	0.0837	0.0837	0.0837	0.0837	0.0837	Rectangular	$\sqrt{3}$	1	200	0.0483	0.0483	0.0483	0.0483	0.0483	0.0483
$u_{\varepsilon 15}$: Sensitivity influence of acceleration measurement owing to relative motion	B	0.4	0.4	0.4	0.4	0.4	0.4	Rectangular	$\sqrt{3}$	1	200	0.231	0.231	0.231	0.231	0.231	0.231
$u_{\varepsilon 16}$: Sensitivity influence of acceleration measurement owing to laser wavelength	B	0.0009	0.0009	0.0009	0.0009	0.0009	0.0009	Rectangular	$\sqrt{3}$	1	200	0.00053	0.00053	0.00053	0.00053	0.00053	0.00053
$u_{\varepsilon 17}$: Sensitivity influence of acceleration measurement owing to digital oscilloscope	B	0.013	0.013	0.013	0.013	0.013	0.013	Rectangular	$\sqrt{3}$	1	200	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075
Relative Assembly Standard Uncertainty u_c %												0.40	0.41	0.43	0.43	0.43	0.43
Effective Degree of Freedom v_{eff}												698	652	797	796	794	795
Coverage Factor k												2	2	2	2	2	2
Relative Expanded Uncertainty U_r %												0.80	0.82	0.86	0.86	0.86	0.86

Table B.4:NIMT's uncertainty budget of shock voltage sensitivity under bipole shock excitation

Pos.	Defining quantity / influence variable X j	MU-Term w (x j)	Distri-bution	Divisor	Numerical Value					
					acceleration 1,000 m/s²					
					0.03 ms	0.05 ms	0.07 ms	0.1 ms	0.15 ms	0.2 ms
1	Transfer coefficient of standard	w (S_S)	Normal	1	0.00125	0.00125	0.00125	0.00075	0.00075	0.00075
2	Voltage ratio *R*	*w* (*R*)	Normal	1	0.00100	0.00100	0.00100	0.00100	0.00100	0.00100
3	Amplifier gain G	*w* (*G*)	Normal	1	0.00010	0.00010	0.00010	0.00010	0.00010	0.00010
4	Frequency response of G	*w* (K_F)	Normal	1	0.00200	0.00200	0.00200	0.00050	0.00050	0.00050
5	Transverse motion	*w* (K_T)	Rectan	1.732	0.00025	0.00025	0.00025	0.00025	0.00025	0.00025
6	Base Strain	*w* (K_B)	Rectan	1.732	0.00020	0.00020	0.00020	0.00020	0.00020	0.00020
7	Geometric Measurement Site	*w* (K_{GL})	Rectan	1.732	0.00200	0.00200	0.00200	0.00100	0.00100	0.00100
8	Sensor mounting	*w* (K_{MT})	Rectan	1.732	0.00020	0.00020	0.00020	0.00020	0.00020	0.00020
9	Relative motion	*w* (K_{REL})	Rectan	1.732	0.00001	0.00001	0.00001	0.00100	0.00100	0.00100
10	Temperature change	*w* (K_{TK})	Rectan	1.732	0.00040	0.00040	0.00040	0.00040	0.00040	0.00040
11	Linearity	*w* (K_L)	Rectan	1.732	0.00060	0.00060	0.00060	0.00060	0.00060	0.00060
12	Long-term stability of S_S	w (K_I)	Rectan	1.732	0.00018	0.00018	0.00018	0.00018	0.00018	0.00018
13	Cable layout	*w* (K_{MC})	Rectan	1.732	0.00020	0.00020	0.00020	0.00020	0.00020	0.00020
14	Shock Peak Value	*w* (K_{MAX})	Rectan	1.732	0.00200	0.00200	0.00200	0.00100	0.00100	0.00100
15	Residual effects	*w* (K_{RES})	Rectan	1.732	0.00300	0.00300	0.00300	0.00200	0.00100	0.00100
16	Repeatibility	*w (Rep)*	Normal	1	0.00055	0.00024	0.00030	0.00012	0.00021	0.00012
17	Resolution of report	*w (Resol)*	Rectan	1.732	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003

	Relative measurement uncertainty			0.0050	0.0049	0.0049	0.0031	0.0026	0.0026
	Expanded measurement uncertainty			0.0099	0.0099	0.0099	0.0062	0.0052	0.0052
	Expanded meas. uncertainty	%		0.99	0.99	0.99	0.62	0.52	0.52

Table B.5: SPEKTRA’s uncertainty budget of shock voltage sensitivity under monopole shock excitation

Pos.	Defining quantity / influence variable X j	MU-Term w (x_j)	**Amplitude Range / Pulse Duration**					
			(0,2 - 2) km/s²		(2 - 20) km/s²		(20 - 100) km/s²	
			Contribution	Variance	Contribution	Variance	Contribution	Variance
1	Transfer coefficient of standard	w (S_S)	7.50E-04	5.63E-07	1.25E-03	1.56E-06	1.25E-03	1.56E-06
2	Voltage ratio *R*	w (R)	1.00E-03	1.00E-06	1.00E-03	1.00E-06	1.00E-03	1.00E-06
3	Amplifier gain G	w (G)	1.00E-04	1.00E-08	1.00E-04	1.00E-08	1.00E-04	1.00E-08
4	Frequency response of G	w (K_F)	5.00E-04	2.50E-07	1.00E-03	1.00E-06	1.00E-03	1.00E-06
5	Transverse motion	w (K_T)	2.00E-04	4.00E-08	5.00E-04	2.50E-07	5.00E-04	2.50E-07
6	Base Strain	w (K_B)	2.00E-04	4.00E-08	2.00E-04	4.00E-08	2.00E-04	4.00E-08
7	Geometric Measurement Site	w (K_{GL})	1.00E-03	1.00E-06	1.00E-03	1.00E-06	2.00E-03	4.00E-06
8	Sensor mounting	w (K_{MT})	2.00E-04	4.00E-08	2.00E-04	4.00E-08	2.00E-04	4.00E-08
9	Relative motion	w (K_{REL})	1.00E-03	1.00E-06	2.00E-03	4.00E-06	3.00E-03	9.00E-06
10	Temperature change	w (K_{TK})	4.00E-04	1.60E-07	4.00E-04	1.60E-07	4.00E-04	1.60E-07
11	Linearity	w (K_L)	6.00E-04	3.60E-07	6.00E-04	3.60E-07	6.00E-04	3.60E-07
12	Long-term stability of S_S	w (K_I)	1.80E-04	3.24E-08	1.80E-04	3.24E-08	1.80E-04	3.24E-08
13	Cable layout	w (K_{MC})	2.00E-04	4.00E-08	2.00E-04	4.00E-08	2.00E-04	4.00E-08
14	Shock Peak Value	w (K_{MAX})	1.00E-03	1.00E-06	1.00E-03	1.00E-06	2.00E-03	4.00E-06
15	Residual effects	w (K_{RES})	5.00E-04	2.50E-07	5.00E-04	2.50E-07	5.00E-04	2.50E-07

Relative measurement uncertainty		2.41E-03	3.28E-03	4.66E-03
Expanded measurement uncertainty		4.81E-03	6.56E-03	9.33E-03
Expanded meas. uncertainty	%	**0.48**	**0.66**	**0.93**

Table B.6: SPEKTRA's uncertainty budget of shock voltage sensitivity under bipole shock excitation

Pos.	Defining quantity / influence variable X j	MU-Term w (x_j)	**Amplitude Range / Pulse Duration**							
			(0,2 - 2,5) km/s² (200 - 150) µs		(0,2 - 5,5) km/s² (150 - 100) µs		(0,2 - 10) km/s² (100 - 30) µs		(10 - 50) km/s² (70 - 30) µs Multiburst	
			Contribution	Variance	Contribution	Variance	Contribution	Variance	Contribution	Variance
1	Transfer coefficient of standard	w (S_S)	7.50E-04	5.63E-07	7.50E-04	5.63E-07	1.25E-03	1.56E-06	1.25E-03	1.56E-06
2	Voltage ratio *R*	*w* (*R*)	1.00E-03	1.00E-06	1.00E-03	1.00E-06	1.00E-03	1.00E-06	1.00E-03	1.00E-06
3	Amplifier gain G	*w* (*G*)	1.00E-04	1.00E-08	1.00E-04	1.00E-08	1.00E-04	1.00E-08	1.00E-04	1.00E-08
4	Frequency response of G	w (K_F)	5.00E-04	2.50E-07	5.00E-04	2.50E-07	2.00E-03	4.00E-06	2.00E-03	4.00E-06
5	Transverse motion	w (K_T)	2.50E-04	6.25E-08	2.50E-04	6.25E-08	2.50E-04	6.25E-08	2.50E-04	6.25E-08
6	Base Strain	w (K_B)	2.00E-04	4.00E-08	2.00E-04	4.00E-08	2.00E-04	4.00E-08	2.00E-04	4.00E-08
7	Geometric Measurement Site	w (K_{GL})	1.00E-03	1.00E-06	1.00E-03	1.00E-06	2.00E-03	4.00E-06	2.00E-03	4.00E-06
8	Sensor mounting	w (K_{MT})	2.00E-04	4.00E-08	2.00E-04	4.00E-08	2.00E-04	4.00E-08	2.00E-04	4.00E-08
9	Relative motion	w (K_{REL})	1.00E-03	1.00E-06	1.00E-03	1.00E-06	1.00E-05	1.00E-10	0.00E+00	0.00E+00
10	Temperature change	w (K_{TK})	4.00E-04	1.60E-07	4.00E-04	1.60E-07	4.00E-04	1.60E-07	4.00E-04	1.60E-07
11	Linearity	w (K_L)	6.00E-04	3.60E-07	6.00E-04	3.60E-07	6.00E-04	3.60E-07	6.00E-04	3.60E-07
12	Long-term stability of S_S	w (K_I)	1.80E-04	3.24E-08	1.80E-04	3.24E-08	1.80E-04	3.24E-08	1.80E-04	3.24E-08
13	Cable layout	w (K_{MC})	2.00E-04	4.00E-08	2.00E-04	4.00E-08	2.00E-04	4.00E-08	2.00E-04	4.00E-08
14	Shock Peak Value	w (K_{MAX})	1.00E-03	1.00E-06	1.00E-03	1.00E-06	2.00E-03	4.00E-06	3.00E-03	9.00E-06

15	Residual effects	w (K_{RES})	5.00E-04	2.50E-07	5.00E-04	2.50E-07	5.00E-04	2.50E-07	5.00E-04	2.50E-07
	Relative measurement uncertainty			2.41E-03		2.41E-03		3.94E-03		4.53E-03
	Expanded measurement uncertainty			4.82E-03		4.82E-03		7.89E-03		9.07E-03
	Expanded meas. uncertainty	%		**0.48**		**0.48**		**0.79**		**0.91**