Ian Veldman, Dr. Gustavo Ripper

FINAL REPORT ON KEY COMPARISON AFRIMETS.AUV.V-K3 (AFRIMETS.AUV.V-S2)

NMISA-18-00147
Pretoria, Wednesday, 28 December 2018

List of tables

List of figures

1 Introduction

This report presents the results of a key comparison in the area of “vibration” (quantity of acceleration), AFRIMETS.AUV.V-K3. At the time, this bi-lateral comparison was registered as the supplementary comparison, AFRIMETS.AUV.V-S2. The CIPM comparison, CCAUV.V-K3, took place some time thereafter. This allowed for AFRIMETS.AUV.V-S2 to be renumbered to AFRIMETS.AUV.V-K3, and the comparison results linked to CCAUV.V-K3. The report has the status of a Final report.

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. Detailed analysis and application of the method for use 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 of September 2010 [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 overview is given in the following sections.

2 Participants

Two National Metrology Institutes (NMIs) from two Regional Metrology Organizations (RMOs), AFRIMETS and SIM, participated in this key comparison AFRIMETS.AUV.V-K3 (cf. Table 1).

Table 1: List of participating institutes

Participating Metrology Institute	Acronym	Country	Metrology Region	Calibration Period
National Metrology Institute of South Africa	NMISA	South Africa	AFRIMETS	October 2010 and April to May 2011
National Institute of Metrology, Quality and Technology	INMETRO	Brazil	SIM	November 2010 to February 2011

3 Task and purpose of the comparison

In the field of vibration and shock, this key comparison (AFRIMETS.AUV.V-K3) was organized in order to compare measurements of sinusoidal linear accelerations in the frequency range from 0,4 Hz to 50 Hz. The calibration and measurement capabilities (CMCs) of the participating NMIs for accelerometer calibration were to be examined and compared.

During the circulation period from October 2010 to May 2011, two NMIs from two RMOs calibrated an accelerometer, complete with power supply unit (PSU), as the transfer standard.

The NMIs were tasked to measure the magnitude of the voltage sensitivity of an accelerometer standard (double ended in design) at different frequencies and acceleration amplitudes as specified in clause 3 of [3]. The voltage sensitivity was calculated as the ratio of the amplitude of the accelerometer output voltage to the amplitude of the acceleration at the reference surface of the accelerometer. The reference surface was defined as the mounting surface of the accelerometer.

The magnitude of the voltage sensitivity was given in milli-volt per metre per second squared (mV/(m/s²)) for the different measurement conditions specified in clause 3 of [3]. A matching PSU was used to supply the accelerometer with the required bias in order to measure the output voltage of the accelerometer standard.

For the calibration of the accelerometer, NMISA applied laser interferometry in compliance with method 3 of the international standard ISO 16063-11:1999 [4], in order to cover the entire frequency range chosen, within a specified range of the acceleration amplitude with specified uncertainties.

For the calibration of the accelerometer, INMETRO applied laser interferometry in compliance with method 1 of the international standard ISO 16063-11:1999 [4], in order to cover the entire frequency range chosen, within a specified range of the acceleration amplitude with specified uncertainties.

4 Conditions of measurement

The participating laboratories observed fully the conditions stated in the Technical Protocol, i.e.

- frequencies:
  0.4 Hz, 0.5 Hz, 0.63 Hz, 0.8 Hz, 1.0 Hz, 1.25 Hz, 1.6 Hz, 2.0 Hz, 2.5 Hz, 3.15 Hz, 4.0 Hz, 5.0 Hz, 6.3 Hz, 8.0 Hz, 10 Hz, 12.5 Hz, 16 Hz, 20 Hz, 25 Hz, 31.5 Hz, 40 Hz, 50 Hz

  (16 Hz is reference frequency)
- amplitudes:
  A range of 0,1 m/s² to 50 m/s² was allowed, considering the displacement and acceleration limitations of the low frequency (LF) vibration exciter.
- ambient temperature and accelerometer temperature during the calibration: (23 ± 3) °C (actual values were stated within tolerances of ± 0,3 K).
- relative humidity: max. 75 %
- mounting torque of the accelerometer: (2 ± 0,1) N·m

The comparison was performed in compliance with the “Guidelines for CIPM key comparisons” [2].

5 Transfer standard

During the preparatory stage, NMISA investigated the characteristics (long-term stability, linearity, etc.) of the reference standard accelerometer (property of NMISA) considered to be a suitable artefact for the transfer standard to be used in the supplementary comparison. The following accelerometer was selected:

- A transfer standard accelerometer; PCB model 301M26
  - serial number: 1969
  - nominal voltage sensitivity: 50 mV/(m/s^2)

- Power supply unit (PSU); PCB model 482A21
  - serial number: 1778

6 Circulation type and transportation

- The comparison was a bi-lateral comparison. Measurements were first performed by NMISA, then by IMMETRO, followed by NMISA again.
- The transfer standard was transported in a closed box hand-carried by a representative of NMISA for delivery to a representative of INMETRO.
- After measurements were completed by INMETRO, the transfer standard was returned to NMISA by international courier service.

7 Measurement instructions

In accordance with the Technical Protocol [3], the participating laboratories observed the following instructions:

- The accelerometer, complete with PSU shall be calibrated as a unit.
- The motion of the accelerometer should be measured with the laser directly on the top surface of the transducer with or without any additional reflector.
- At low frequencies it is acceptable to use a retro-reflector in order to facilitate optical alignment of the interferometer during measurement of the displacement.
- The mounting surface of the accelerometer and the moving part of the exciter must be slightly lubricated before mounting.
- The cable between accelerometer and amplifier should be taken from the set delivered to the laboratory.
- In order to reduce the influence of non-rectilinear motion, the measurements should be distributed over the respective measurement surface.
- 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.

8 Communication of the results to the co-ordinating laboratory

INMETRO submitted the calibration report to NMISA including descriptions of:

- the calibration equipment
- the calibration methods used
- the ambient conditions
- the mounting technique
- the calibration results
- the uncertainty of measurement (k = 2) for each measurement result

In each case, the uncertainties were evaluated in accordance with the Guide to the expression of uncertainty in measurement (GUM), which had been adapted to the calibration of vibration and shock transducers as stated in ISO 16063-1:1998, Annex A.

9 Results of the measurements

In the bi-lateral comparison between INMETRO and NMISA of calibrations of the magnitude sensitivity of a reference accelerometer, the ratio-counting method specified in ISO 16063-11 (method 1) as well as the sine-approximation method specified in ISO 16063-11 (method 3) were applied.

NMISA used method 3 as specified in ISO 16063-11, with a modified Michelson interferometer as depicted in Fig. 3 and Fig. 4 of that international standard, as a sub-system of the calibration equipment. The special techniques and procedures developed at NMISA (standard measuring equipment with vibration exciter, interferometer, data acquisition and signal processing system etc.) are described in detail in [5].

INMETRO used method 1 as specified in ISO 16063-11, with a modified Michelson interferometer as depicted in Fig. 1 of that international standard, as a sub-system of the calibration equipment. The special techniques and procedures developed at INMETRO (standard measuring equipment with vibration exciter, interferometer, data acquisition and signal processing system etc.) are described in detail in [6], [7].

A number of tables and figures are given in the following sections to present the measurement results. The data is presented in table as well as in graphical formats, subdivided into:

- Sensitivity measurement results per laboratory
- Calculated Key Comparison Reference Values (KCRVs)
- Calculated degrees of equivalence

9.1 Key comparison reference value

The weighted mean was agreed upon by both laboratories to calculate the KCRVs for the AFRIMETS.AUV.V-K3 data. KCRVs are calculated separately at each frequency point measured (22 points in total).

Calculation of KCRVs using the weighted mean method

Tables 2 to 5 contain the data for the accelerometer reported by the participating laboratories. For each laboratory *i* these data are (1) $x_{i,f}$: best estimate of sensitivity at frequency *f*, and (2) $u(x_{i,f})$: associated standard uncertainty of sensitivity reported at frequency *f*.

For the transfer standard and at each frequency *f*, a key comparison reference value $x_{R,f}$ has been determined as the weighted mean of the results of n laboratories (for this comparison, n = 2) according to

$$x_{R,f} = \frac{\sum_{i=1}^{n} \frac{x_{i,f}}{u^2(x_{i,f})}}{\sum_{i=1}^{n} \frac{1}{u^2(x_{i,f})}} \tag{1}$$

$$u^2(x_{R,f}) = \frac{1}{\sum_{i=1}^{n} \frac{1}{u^2(x_{i,f})}} \tag{2}$$

The degree of equivalence, $D_{\text{NMI-WM}}$, and $U_{\text{NMI-WM}}$, was determined for the magnitude measurements for the accelerometer using

$$D_{\text{NMI-WM}} = x_{\text{NMI}} - x_{\text{WM}} , \qquad U_{\text{NMI-WM}} = \sqrt{U_{\text{NMI}}^2 + U_{\text{WM}}^2} \tag{3}$$

where x_{NMI} represents the measurement results obtained by the laboratory at each frequency point for the magnitude and x_{WM} represents the reference value (KCRV) calculated as the weighted mean using Eq. (1). $U_{\text{NMI-WM}}$ is the uncertainty of measurement associated with the calculated $D_{\text{NMI-WM}}$ for k = 2.

9.2 Results - Part 1: Laboratory individual measurements (stated results for standard frequency series)

The stated results given in Tables 2 and 3 are in all cases the final measurement results submitted by the two participating laboratories for the accelerometer.

NMISA submitted the arithmetic mean values for measurements obtained using two measurement results obtained for the calibration of the accelerometer. The first measurement result was obtained prior to sending the accelerometer to INMETRO while the second measurement result was obtained after the accelerometer was returned to NMISA by INMETRO.

NMISA submitted measurement results obtained using method 3 of [4]. Five measurements were performed, one per day for five days, for the accelerometer, prior to the accelerometer being delivered to INMETRO. Five measurements were performed, one per day for five days, for the accelerometer, after the accelerometer was returned to NMISA by INMETRO. The arithmetic mean of the two measurement sets was submitted as the comparison result.

INMETRO submitted measurement results obtained using method 1 of [4]. Five measurements were performed, one per day for five days, for each accelerometer. The arithmetic mean of the five measurements was submitted as the comparison result.

Table 2: Magnitude results of the sensitivity reported by NMISA

Frequency (Hz)	**Sensitivity magnitude (mV/(m/s^2))**	U_c		***Acceleration Level***
		(%)	**(mV/(m/s^2))**	**(m/s^2)**
0.4	47.396	0.3	0.14	0.5
0.5	47.475	0.3	0.14	0.5
0.63	47.555	0.3	0.14	0.5
0.8	47.640	0.3	0.14	0.5
1.0	47.730	0.3	0.14	1.0
1.25	47.801	0.3	0.14	1.0
1.6	47.873	0.3	0.14	1.0
2.0	47.941	0.3	0.14	2.0
2.5	47.992	0.3	0.14	2.0
3.15	48.048	0.3	0.14	2.0
4.0	48.099	0.3	0.14	2.0
5.0	48.147	0.3	0.14	2.0
6.3	48.182	0.3	0.14	2.0
8.0	48.229	0.3	0.14	2.0
10.0	48.262	0.3	0.14	5.0
12.5	48.294	0.3	0.14	5.0
16	48.327	0.3	0.14	5.0
20	48.364	0.3	0.15	5.0
25	48.388	0.3	0.15	5.0
31.5	48.435	0.3	0.15	5.0
40	48.483	0.3	0.15	5.0
50	48.499	0.3	0.15	5.0

Table 3: Magnitude results of the sensitivity reported by INMETRO

Frequency (Hz)	Sensitivity magnitude (mV/(m/s^2))	U_c		***Acceleration Level***
		(%)	(mV/(m/s^2))	(m/s^2)
0.4	47.454	0.3	0.14	0.1
0.5	47.501	0.3	0.14	0.2
0.63	47.605	0.3	0.14	0.2
0.8	47.677	0.3	0.14	0.5
1.0	47.739	0.3	0.14	1.0
1.25	47.822	0.3	0.14	1.0
1.6	47.903	0.3	0.14	1.0
2.0	47.960	0.3	0.14	1.0
2.5	48.020	0.3	0.14	2.0
3.15	48.069	0.3	0.14	2.0
4.0	48.115	0.3	0.14	2.0
5.0	48.159	0.3	0.14	2.0
6.3	48.188	0.3	0.14	4.0
8.0	48.219	0.3	0.14	4.0
10.0	48.247	0.3	0.14	4.0
12.5	48.277	0.3	0.14	4.0
16	48.307	0.3	0.14	4.0
20	48.331	0.3	0.14	4.0
25	48.357	0.3	0.15	4.0
31.5	48.374	0.3	0.15	4.0
40	48.397	0.3	0.15	4.0
50	48.412	0.3	0.15	4.0

Table 4: INMETRO, NMISA relative difference

Frequency (Hz)	$D_{\text{INMETRO-NMISA}}$ (%)	$U_{\text{INMETRO-NMISA}}$ (%)
0.4	0.12	0.42
0.5	0.05	0.42
0.63	0.11	0.42
0.8	0.08	0.42
1	0.02	0.42
1.25	0.04	0.42
1.6	0.06	0.42
2	0.04	0.42
2.5	0.06	0.42
3.15	0.04	0.42
4	0.03	0.42
5	0.02	0.42
6.3	0.01	0.42
8	-0.02	0.42
10	-0.03	0.42
12.5	-0.04	0.42
16	-0.04	0.42
20	-0.07	0.42
25	-0.06	0.42
31.5	-0.13	0.42
40	-0.18	0.42
50	-0.18	0.42

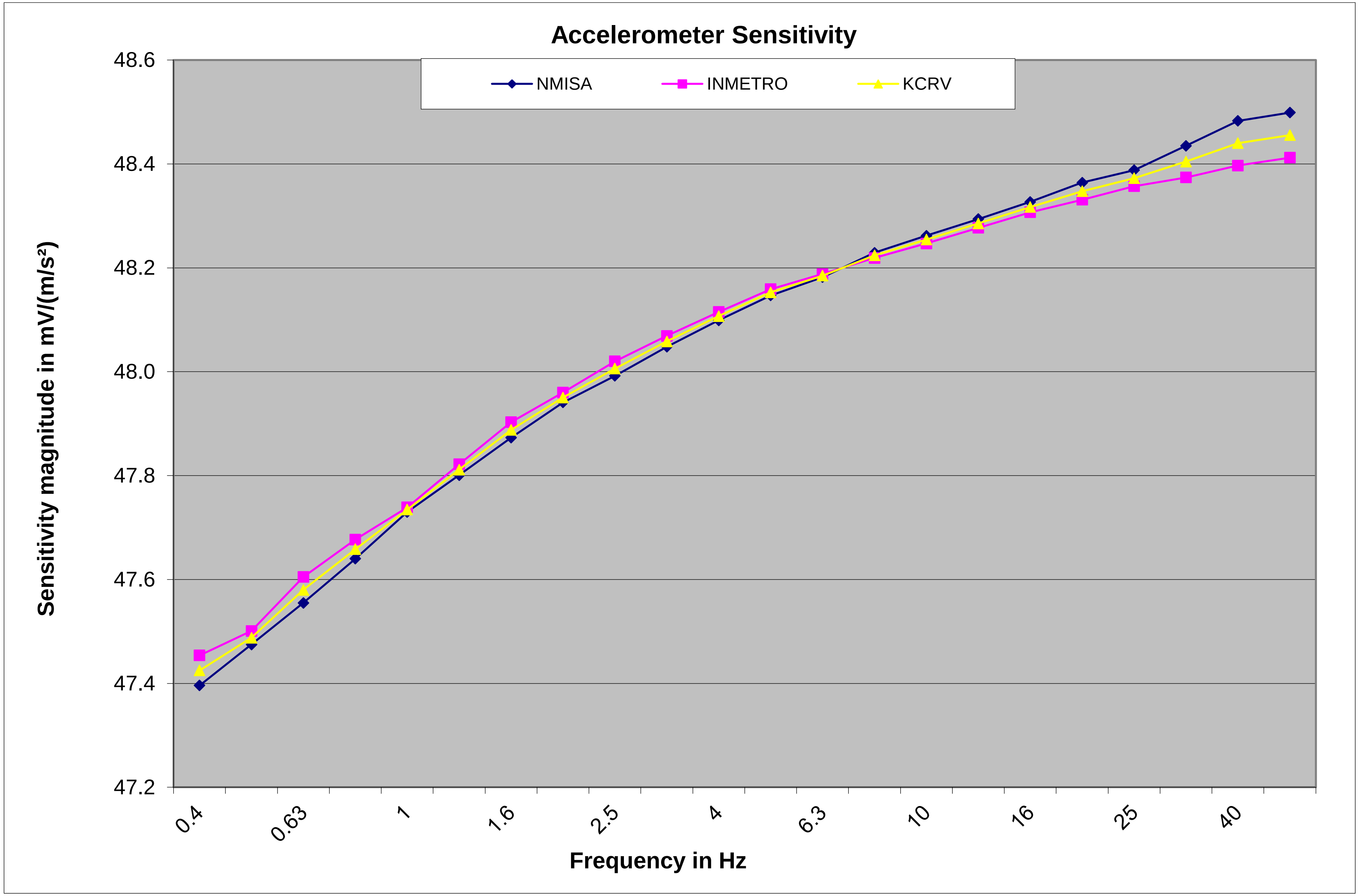

Figure 1: Sensitivity magnitude frequency response of the accelerometer standard as reported in tables 2 and 3

Table 5: Weighted mean and degrees of equivalence for the sensitivity magnitude measurements

Frequency (Hz)	Weighted Mean		Degrees of equivalence					
	WM (mV/(m/s^2))	U_{WM} (%)	$D_{NMISA-WM}$ (mV/(m/s^2))	$U_{NMISA-WM}$ (%)	$D_{INMETRO-WM}$ (mV/(m/s^2))	$U_{INMETRO-WM}$ (%)	$D_{INMETRO-NMISA}$ (%)	$U_{INMETRO-NMISA}$ (%)
0.4	47.425	0.21	-0.029	0.21	0.029	0.21	0.12	0.42
0.5	47.488	0.21	-0.013	0.21	0.013	0.21	0.05	0.42
0.63	47.580	0.21	-0.025	0.21	0.025	0.21	0.11	0.42
0.8	47.659	0.21	-0.019	0.21	0.018	0.21	0.08	0.42
1.0	47.735	0.21	-0.005	0.21	0.004	0.21	0.02	0.42
1.25	47.812	0.21	-0.011	0.21	0.010	0.21	0.04	0.42
1.6	47.888	0.21	-0.015	0.21	0.015	0.21	0.06	0.42
2.0	47.951	0.21	-0.009	0.21	0.010	0.21	0.04	0.42
2.5	48.006	0.21	-0.014	0.21	0.014	0.21	0.06	0.42
3.15	48.059	0.21	-0.011	0.21	0.011	0.21	0.04	0.42
4.0	48.107	0.21	-0.008	0.21	0.008	0.21	0.03	0.42
5.0	48.153	0.21	-0.006	0.21	0.006	0.21	0.02	0.42
6.3	48.185	0.21	-0.003	0.21	0.003	0.21	0.01	0.42
8.0	48.224	0.21	0.005	0.21	-0.005	0.21	-0.02	0.42
10.0	48.255	0.21	0.007	0.21	-0.008	0.21	-0.03	0.42
12.5	48.286	0.21	0.008	0.21	-0.009	0.21	-0.04	0.42
16	48.317	0.21	0.010	0.21	-0.010	0.21	-0.04	0.42
20	48.348	0.21	0.016	0.21	-0.017	0.21	-0.07	0.42
25	48.373	0.21	0.016	0.21	-0.015	0.21	-0.06	0.42
31.5	48.405	0.21	0.031	0.21	-0.030	0.21	-0.13	0.42
40	48.440	0.21	0.043	0.21	-0.043	0.21	-0.18	0.42
50	48.456	0.21	0.043	0.21	-0.044	0.21	-0.18	0.42

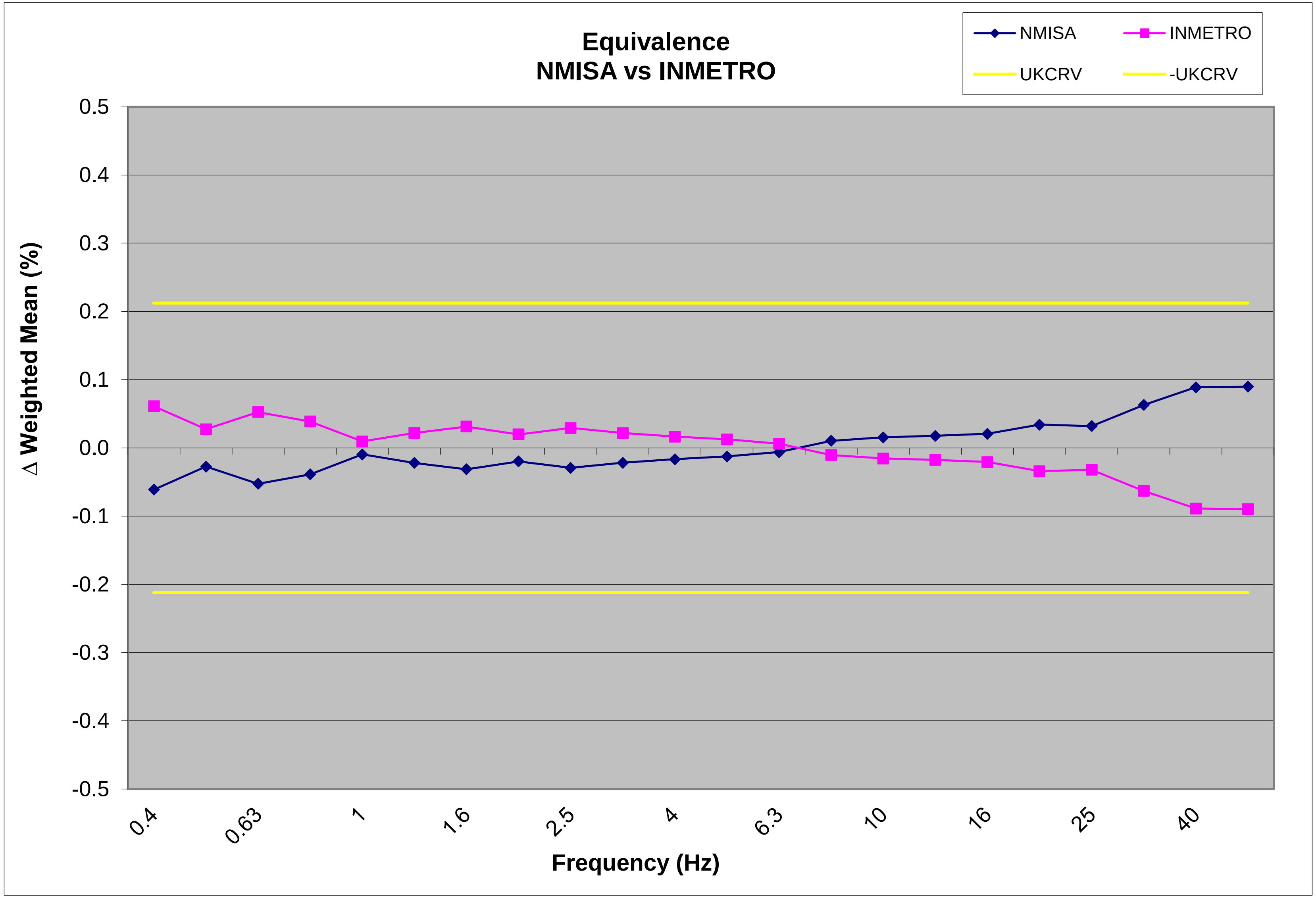

Figure 2: Degrees of equivalence for the sensitivity magnitude

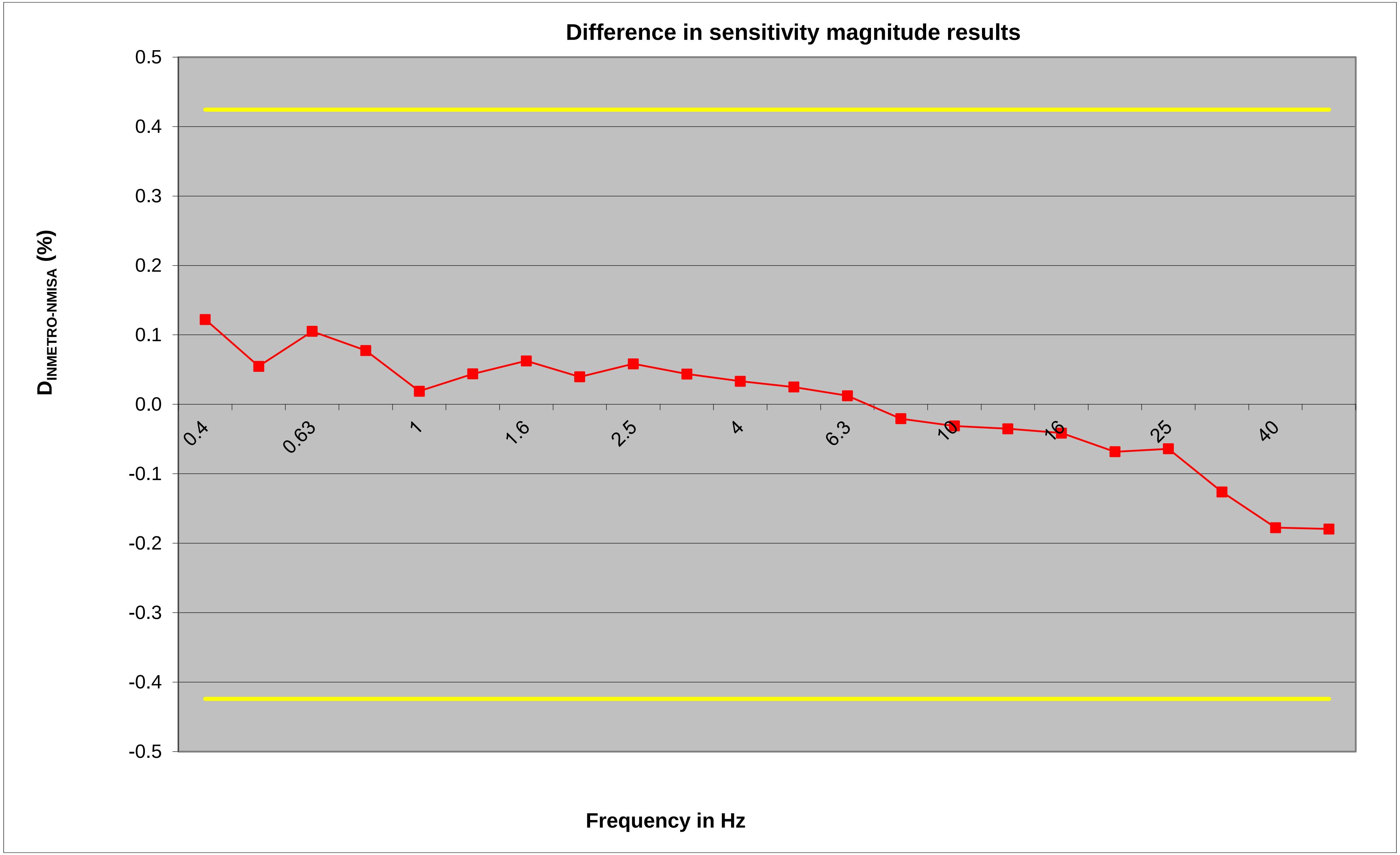

Figure 3: **Difference of sensitivity magnitude between INMETRO and NMISA in percent**

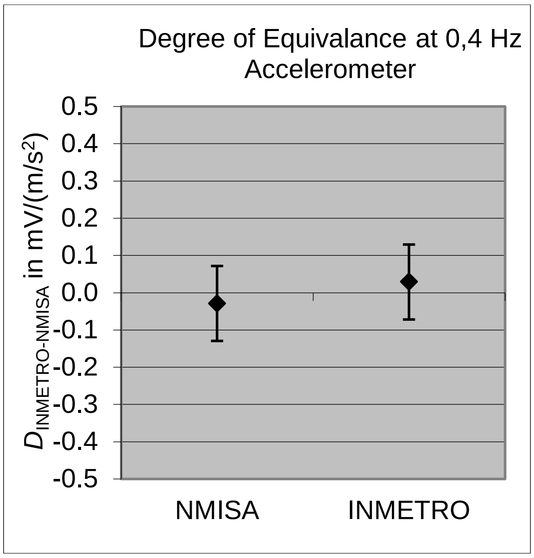

Figure 4: Degree of equivalence at 0.4 Hz

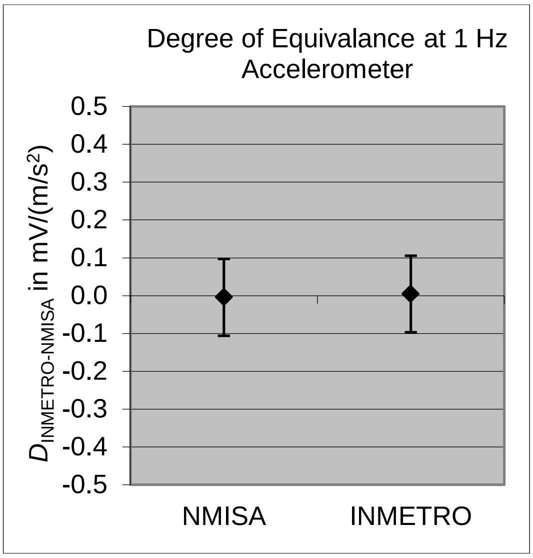

Figure 5: Degree of equivalence at 1 Hz

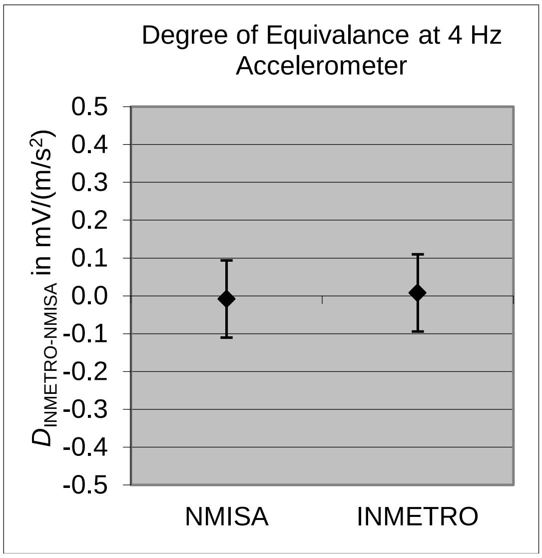

Figure 6: Degree of equivalence at 4 Hz

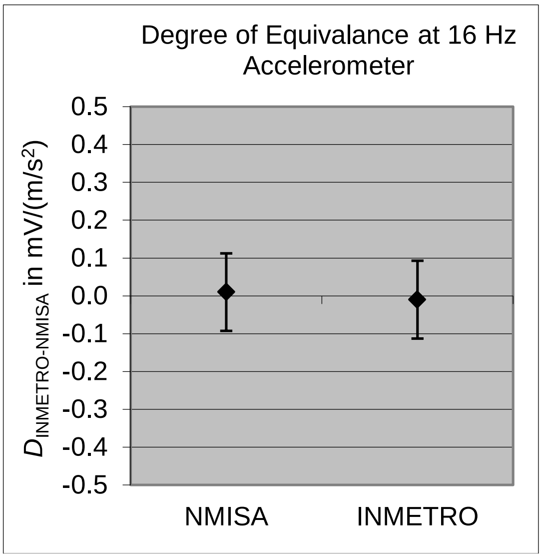

Figure 7: Degree of equivalence at 16 Hz

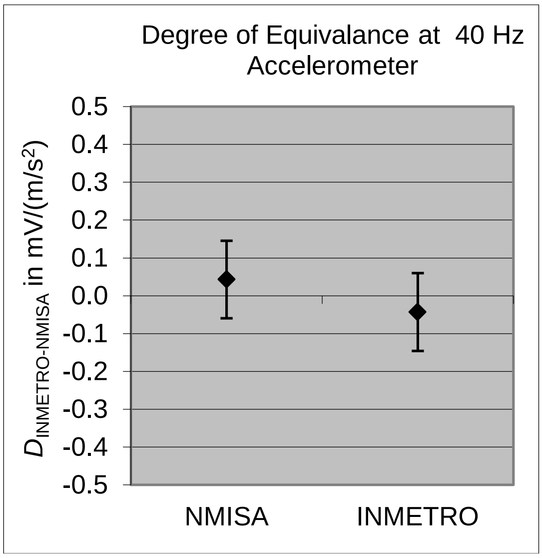

Figure 8: Degree of equivalence at 40 Hz

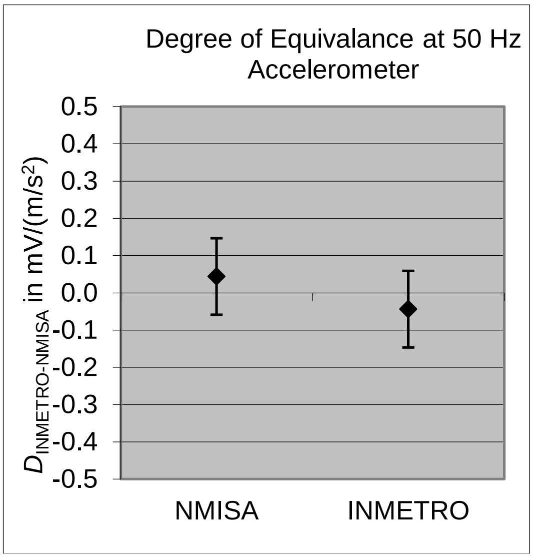

Figure 9: Degree of equivalence at 50 Hz

9.3 Results - Part 2: Comparison reference values and Laboratory degrees of equivalence

The key comparison reference values (KCRVs) for the sensitivity for the accelerometer are listed in table 5.

Table 5 lists the calculated magnitude KCRVs for the accelerometer. The table also lists the deviation of the reported sensitivities from the KCRVs by each individual laboratory ($D_{\text{NMI-WM}}$). The calculated associated uncertainty for the sensitivity results, ($U_{\text{NMI-WM}}$), for (k = 2) are reported in table 5.

Table 4 lists the difference in sensitivity magnitude values obtained between the two laboratories ($D_{\text{INMETRO-NMISA}}$). The calculated associated uncertainty for the difference in sensitivity results, ($U_{\text{INMETRO-NMISA}}$), for (k = 2) are reported with the difference values listed in table 4.

10 Discussion of the measurement results

An appropriate method to compute KCRVs and degrees of equivalence is discussed in section 9.1.

Though the participants applied laser interferometry in accordance with ISO 16063-11 as required [4], this international standard also specifies that three different interferometric methods are applicable in various versions and techniques.

Although two different methods were applied by the laboratories for AFRIMETS.AUV.V-K3 (i.e. ISO 16063-11 method 1 and method 3), the systems implemented were similar with respect to the vibration exciters and hardware used. The systems implemented were different with respect to vibration isolation systems, laser interferometers, signal processing configurations and measurement procedures. This explains the following observations.

Stability of the reference transducer:

- The Pilot laboratory measured the sensitivity of the reference transducer before and after the participating laboratory. The difference in sensitivity values obtained by the pilot laboratory for the reference transducer were smaller than 0.2 % over the frequency range of 0.4 Hz to 40 Hz.

Similarities between the declared uncertainties:

- The uncertainties declared by the laboratories for the same frequency and for the same accelerometer were the same;
    - Magnitude – 0.3 %

Frequency dependence of uncertainty:

- The declared uncertainties were not frequency-dependent over the frequency range of the comparison

Acceleration measurement capability:

- A comparison of the acceleration measurements is described by the calibration results for the accelerometer, assuming that there was no relative motion between the laser light spot sensing the motion and its reference surface. Both laboratories in this case demonstrated very good measurement capabilities, i.e. the relative deviations from the reference sensitivity values were clearly below 0.2 % for the accelerometer.

Credibility of uncertainty statements:

- ISO Standard 16063-11:1999 [4] provides well-established uncertainty budgets which were included as a formal part in the Technical Protocol. Accordingly, both laboratories submitted uncertainty budgets in compliance with the GUM.

11 Conclusions

Two NMIs measured the voltage sensitivity of a transfer standard (double-ended accelerometer) at 22 frequencies from 0.4 Hz to 50 Hz. The results of the AFRIMETS.AUV.V-K3 are a set of KCRVs, their uncertainties and degrees of equivalence illustrating the performance of the participant laboratories with respect to one another. From this complete set of results, six matrices of equivalence for accelerometer were selected and illustrated by means of graphs (figures 4 to 9).

In the calibration of the double-ended accelerometer, the reference surface (mounting surface) is accessible to the laser light beam. The calibration results obtained for the accelerometer represent the current calibration capabilities of the participating laboratories for the voltage sensitivity of double-ended accelerometers.

At the reference frequency of 16 Hz (specified in ISO 16063-11:1999), the participating laboratories calibrated the transfer standard with a relative expanded uncertainty (k = 2) equal to 0.3 %, i.e. smaller than the limit specified by the ISO standard [2], cf. also Technical Protocol [3].

For the frequency range 0.4 Hz to 50 Hz, the deviations between NMISA and INMETRO results were smaller than 0.2 % for the voltage sensitivity measurements (22 measurement points) for the accelerometer. This difference in measurement results include level non-linearity of the accelerometer as the two laboratories did not perform the calibrations at the same acceleration levels, as indicated in table 2 and table 3.

In conclusion, the degrees of equivalence calculated from the data submitted by the two laboratories, support the uncertainty of measurement reported by the two laboratories for the calibration of the modulus of the complex sensitivities of accelerometer over the frequency range 0.4 Hz to 50 Hz.

12 Acknowledgements

The authors would like to acknowledge the management of NMISA and INMETRO for their continued support for scientific research in metrology in the field of vibration.

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 Supplementary comparison AFRIMETS.AUV.V-S2 (Vibration). NMISA, C.S. Veldman, September 2010.

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

[5] Veldman C.S., “A novel implementation of an ISO standard for primary vibration calibration by laser interferometer”, *Metrologia* **40** (2003), pp. 1-8.

[6] Ripper, G.P., Ferreira C.D., Teixeira, D.B., Dias, R.S., Micheli G.B.; “A new system for primary calibration of vibration transducers at low frequencies”; In: Proc. IMEKO 2010 TC3, TC5 and TC22 Conferences, November 22-25, 2010, Pattaya, Chonburi, Thailand.

[7] Ripper, G.P., Ferreira C.D., Teixeira, D.B., Micheli G.B., Dias, R.S.; “Dynamic calibration of accelerometers in low frequencies at INMETRO”; In:Proc. VI SBEIN 2010, Rio de Janeiro, Brazil, October 20-22, 2010 (In Portuguese: Calibração dinâmica de acelerômetros em baixas frequências no INMETRO).

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

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

Appendix A: Uncertainty Budget

UNCERTAINTY BUDGET MATRIX (UBM)

Certificate No	AV\VS-2778
Procedure No	AV\VS-0001

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:	Sensitivty calibration (modulus) as per ISO 16063-11 method 3	Make & model:	PCB 301M19 / PCB 301M28	Range:	0,4 Hz to 50 Hz	Metrologist
		Serial number:				Ian Veldman

Mathematical Model: $S=\hat{u}/\hat{a}=\hat{u}/(2\pi f)^2 d$

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) ▼	(X_i)	Unit	(N, R, T, U)	▼	▼	$U(X_i)$	C_i	Unit	%	%	v	
φ_{IO}	Interferometer output signal disturbance on phase amplitude	0.01	%	Rectangular √3	2.00	1.73	5.77E-03	1	%	0.006	100	Infinite	e.g. offsets, voltage amplitude deviations, <> 90° Corrected with Heydemann procedure
φ_{VD}	Effect of voltage disturbance on phase amplitude measurement	0.01	%	Rectangular √3	2.00	1.73	5.77E-03	0.01	%	0.000	100	Infinite	Additive uncorrelated noise is reduced by 1/√n. Where n=number of samples per vibration cycle. Worse case
φ_{MD}	Effect of motion disturbance on phase amplitude measurement	0.015	%	Rectangular √3	2.00	1.73	8.66E-03	1	%	0.009	100	Infinite	accelerometer.
φ_{PD}	Effect of phase disturbance on phase amplitude measurement	0.01	%	Rectangular √3	2.00	1.73	5.77E-03	1	%	0.006	100	Infinite	Corrected for using Heydemann correction procedure
φ_{RE}	Residual interferometric effects on phase amplitude measurement	0.01	%	Rectangular √3	2.00	1.73	5.77E-03	1	%	0.006	100	Infinite	Not aware of any
f_{FG}	Vibration frequency measurement accuracy	0.05	%	Rectangular √3	2.00	1.73	2.89E-02	1	%	0.029	100	Infinite	ISO 16063-11 requirement: ≤ 0,05 % of reading
λ_U	Uncertainty on laser wavelength measurement	2.50E-11	nm	Normal k = 2	2.00	2.00	1.25E-11	100	%	0.000	100	Infinite	Uncertainty quoted on certificate
$\hat{u}_V$	Accelerometer output voltage measurement (ADC resolution/accuracy)	0.15	%	Rectangular √3	2.00	1.73	8.66E-02	1	%	0.087	100	Infinite	Manufacturer's specification worse case on 1 V range
S_F	Filtering effect on sensitivity measurement	0.11	%	Rectangular √3	2.00	1.73	6.35E-02	1	%	0.064	100	Infinite	$e=(f/f_{rp})^2$
G_{CA}	Conditioning amplifier gain accuracy	0.00	%	Normal k = 2	2.00	2.00	0.00E+00	1	%	0.000	100	Infinite	N/A Calibrated as a unit
	Resolution of Standard / Equipment (If applicable)										100		
	▼ Unit Under Test / Calibration (Uncorrelated) ▼					NOTE! ONLY CHANGE BLUE CELLS - All OTHER CELLS (WHITE) ARE PROTECTED							
$\hat{u}_D$	Effect of voltage disturbance on accelerometer output voltage measurement	0.005	%	Triangular √6		1.73	2.887E-03	1	%	0.003	100	Infinite	U_{THD} = ½(d/100)²; Maximum allowed by ISO 16063
$\hat{u}_T$	Effect of transverse motion on accelerometer output voltage measurement	0.1	%	Triangular √6		1.73	5.774E-02	1	%	0.058	100	Infinite	Transeverse error for a transverse sensitivity of 1%
$\hat{u}_{RES}$	Residual effects on accelerometer output voltage measurement	0.1	%	Normal k = 3		2.00	5.000E-02	1	%	0.050	100	Infinite	Tribo-electric effect
$\hat{u}_{\sigma}$	Standard deviation on accelerometer output voltage measurement	0.2	%	Normal k = 3		2.00	1.000E-01	1	%	0.100	100	Infinite	ESDM for sensitivity calulation using 5 cycles minimum
	Resolution of UUT / Equipment (If applicable)										100		
	Data - Type "B" Evaluation Range of the results (Rectangular)										100		
	#REF!			Normal k = 1								4	No of Readings 5
About UBM	TOTAL COMBINED UNCERTAINTY									%			

Best Measurement Capability (Excluding UUT contribution)	Combined Uncertainty (Normal)	▼ Level of Confidence ▼	0.112	V_{eff}	Infinite	Checked and Approved By:
	Expanded Uncertainty	95,45 % K = 2	0.224	k =	2.00	
Uncertainty of Measurement (Including UUT contribution)	Combined Uncertainty (Normal)	▼ Level of Confidence ▼	0.168	V_{eff}	Infinite	
	Expanded Uncertainty	95,45 % K = 2	0.3	k =	2.00	

UBM V5.03 - NMISA - Vibration Laboratory (Designed by BvO) VS-0001 ISO 16063-11 method 3 (modulus) - LF Complete with power unit.xls 0,4 Hz to 50 Hz

Uncertainty budget - Low-frequency interferometric calibration of a standard acceleration measuring chain
ISO 16063-11:1999 - Tables A.1 and A.5

$$S_{aa}(f_1) = \frac{\hat{u}}{(2\pi f_1)^2 \hat{s}} = \frac{8\sqrt{2}\, u_{rms}}{(2\pi f_1)^2 R_f \lambda}$$

						Relative expanded uncertainty or bounds of estimated error components (%)																					
						frequency (Hz)																					
i	Standard uncertainty component $u(x_i)$	Source of uncertainty	description	Probability distribution model	Factor k_i	0.4	0.5	0.63	0.8	1	1.25	1.6	2	2.5	3.15	4	5	6.3	8	10	12.5	16	20	25	31.5	40	50
1	$u(\hat{u}_V)$	accelerometer output voltage measurement (voltmeter)	calibration, stability and error of DAQ	retangular	0.58	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
2	$u(\hat{u}_D)$	effect of total distortion on accelerometer output voltage measurement	Considered negligeable with FFT measurement. Estimated to be less than	retangular	0.58	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
3	$u(\hat{u}_T)$	effect of transverse, rocking and bending acceleration on accelerometer output voltage measurement (transverse sensitivity)	measured transverse vibration limits, ST max 3% (residual effect after the average of 2 mountings)	special	0.2357022	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
4	$u(\hat{s}_Q)$	effect of displacement quantization on displacement measurement	Estimated to be less than	retangular	0.58	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	$u(\hat{s}_H)$	effect of trigger hysteresis on displacement measurement	Estimated to be less than	retangular	0.58	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.02
6	$u(\hat{s}_F)$	filtering effect on displacement measurement (frequency band limitation)	Low-pass and band-pass filtering applied	retangular	0.58	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
7	$u(\hat{s}_{VD})$	effect of voltage disturbance on displacement measurement (e.g. random noise in the photoelectric measuring chain)	Estimated to be less than	retangular	0.58	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
8	$u(\hat{s}_{MD})$	effect of motion disturbance on displacement measurement (e.g. total distortion; relative motion between the accelerometer reference surface and the spot sensed by the interferometer)	Estimated to be less than	retangular	0.58	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
9	$u(\hat{s}_{PD})$	effect of the phase disturbance on displacement measurement (e.g. phase noise of the interferometer signal)	Estimated to be less than	retangular	0.58	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
10	$u(\hat{s}_{RE})$	residual interferometric effects on displacement measurement (interferometer function)	Estimated to be less than	retangular	0.58	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
11	$u(f_{FG})$	vibration frequency measurement (frequency generator and indicator)	Estimated to be less than	retangular	0.58	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
12	$u(S_{RE})$	residual effects on sensitivity measurement (e.g. random effect in repeat measurements; experimental standard deviation of arithmetic mean)	Estimated to be less than (for N=20, avg of 10 measurements at 2 mounting positions)	retangular	0.58	0.12	0.12	0.12	0.12	0.12	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
13	$u(\lambda$ cal$)$	laser wavelength calibration	recommendation of CCL for non-stabilized He-Ne lasers	retangular	0.58	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	$u(\lambda$ env$)$	environmental effects on laser wavelength	Estimated to be less than (dT =+/- 2 °C, dP = +/- 70 hPa, dU = +/- 20 %)	retangular	0.58	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	$u(S_{RP})$	reproducibility	Estimated to be less than	retangular	0.58	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
16	$u(e_{T,A})$	reference amplifier tracking (deviations in gain for different amplification settings)	not apliable, only calibrated gains are used	retangular	0.58	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17	$u(e_{L,f,A})$	deviation from constant amplitude - frequency characteristic of reference amplifier	not apliable, only calibrated gains are used	retangular	0.58	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
18	$u(e_{L,f,R})$	deviation from constant amplitude - frequency characteristic of reference accelerometer	not apliable	retangular	0.58	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
19	$u(e_{L,a,A})$	amplitude effect on gain of reference amplifier	Estimated to be less than	retangular	0.58	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
20	$u(e_{L,a,R})$	amplitude effect on sensitivity (magnitude) of reference accelerometer	Estimated to be less than	retangular	0.58	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
21	$u(e_{I,A})$	instability of reference amplifier gain, and effect of source impedance on gain	Estimated to be less than	retangular	0.58	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
22	$u(e_{I,R})$	instability of sensitivity (magnitude) of reference accelerometer	Estimated to be less than	retangular	0.58	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
23	$u(e_{E,A})$	environmental effects on gain of reference amplifier	Estimated to be less than (Temp range from 22 to 25 degrees)	retangular	0.58	0.10	0.10	0.09	0.09	0.07	0.07	0.07	0.06	0.06	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
24	$u(e_{E,R})$	environmental effects on sensitivity (magnitude) of reference accelerometer	Estimated to be less than (Temp range from 22 to 25 degrees)	retangular	0.58	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06

	0.4	0.5	0.63	0.8	1	1.25	1.6	2	2.5	3.15	4	5	6.3	8	10	12.5	16	20	25	31.5	40	50
$u_{rel}(S_2)$ Estimated Uncertainty for accelerometer sensitivity (k=1)	0.15	0.15	0.15	0.15	0.14	0.14	0.14	0.14	0.14	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13
$u_{rel}(S_2)$ Estimated Uncertainty for accelerometer sensitivity (k=2)	0.30	0.30	0.29	0.29	0.29	0.28	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27

	frequency (Hz)																					
	0.4	0.5	0.63	0.8	1	1.25	1.6	2	2.5	3.15	4	5	6.3	8	10	12.5	16	20	25	31.5	40	50
Reported Uncertainty for accelerometer sensitivity (k=2)	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3

Appendix B: Linking the Sensitivity Results of AFRIMETS.AUV.V-K3 (AFRIMETS.AUV.V-S2)to CCAUV.V-K3

B1 Linking procedure for accelerometer voltage sensitivities

For the consistency of the procedure and therefore the comparability between the different key comparisons in the field of vibration performed so far, the linking of the accelerometer voltage sensitivity results (AVS) of the RMO comparison, AFRIMETS.AUV.V-K3, (formerly registered as supplementary regional comparison AFRIMETS.AUV.V-S2) to AVS of CCAUV.V-K3 were calculated according to the same scheme used for the linking of EUROMET.AUV.V-K1 [1] and applied for APMP.AUV.V-K3 and EURAMET.AUV.V-K3.

The linking transforms the results (y_i, $u(y_i)$) of the participants of AFRIMETS.AUV.V-K3 to scaled values z_i and their respective uncertainties $u(z_i)$, which are directly comparable to the results of CCAUV.V-K3.

The scaling was done with the linking factor R, which was calculated from the results of the linking laboratories (NMISA and INMETRO) in the RMO comparison and the KCRV of the CIPM comparison, CCAUV.V-K3.

The measurand in the CIPM comparison is denoted by X. The values, $\{(x_1, u(x_1)), \ldots, (x_N, u(x_N))\}$ denote the best estimates and associated standard uncertainties of the laboratories that have participated in the CIPM comparison. The measurand in the RMO comparison is denoted by Y. The values $\{(y_1, u(y_1)), \ldots, (y_N, u(y_M))\}$ denote the best estimates and associated standard uncertainties of the laboratories that have participated in the RMO comparison.

Furthermore, $G = \{1,..., p\}$ ($p \leq \min(N, M)$) is the index set of the linking laboratories which participated in both the CIPM and RMO comparisons. The laboratories were labeled such that any number within G denotes the same laboratory in both comparisons.

The value, $R = X/Y$ denotes the transformation factor between the two measurands to establish the link between the two comparisons. The transformation factor was estimated using the KCRV of the CIPM comparison and the combined results (weighted mean) in the RMO comparison of the linking laboratories. The estimated transformation factor was then applied to the results of the RMO comparison.

The estimators X_1, ..., X_N, Y_1, ..., Y_M were treated as being uncorrelated as no information about correlations of other participants were available.

Let x denote the KCRV of the CIPM comparison and y the weighted mean of the linking laboratories in the RMO comparison.

$$x = \frac{\sum_{i=1}^{N} \frac{x_i}{u^2(x_i)}}{\sum_{i}^{N} \frac{1}{u^2(x_i)}} \qquad u^2(x) = \frac{1}{\sum_{i=1}^{N} \frac{1}{u^2(x_i)}} \tag{1}$$

$$y = \frac{\sum_{i=1}^{G} \frac{y_i}{u^2(y_i)}}{\sum_{i}^{G} \frac{1}{u^2(y_i)}} \qquad u^2(y) = \frac{1}{\sum_{i=1}^{G} \frac{1}{u^2(y_i)}} \tag{2}$$

Then *R* is estimated according to

$$r = \frac{x}{y} \qquad u^2(r) = \frac{u^2(x)}{y^2} + \frac{x^2}{y^4} u^2(y) \tag{3}$$

Z = *RY* denotes the corrected measurand in the regional comparison and

$$z_I = r y_I \qquad u^2(z_I) = {y_I}^2 u^2(r) + r^2 u^2(y_I) + 2 r y_I u(r, y_I), \qquad I = 1..M$$

$$u(r, y_I) = \begin{cases} -\frac{x}{y^2} u^2(y), \ I \in G \\ 0, \ \text{otherwise} \end{cases} \tag{4}$$

are the corresponding estimates including the associated uncertainties.

The degrees of equivalence are defined as the differences between the corrected results in the RMO comparison and the KCRV of the CIPM comparison:

$$d_i = z_i - x, \quad i = 1, \ldots, M \tag{5}$$

And the standard uncertainties associated with these differences are:

$$u^2(d_i) = u^2(z_i) + \left[1 - 2\frac{z_i}{x}\right] u^2(x), \quad i = 1, .., M \tag{6}$$

B2 Degrees of Equivalence to the CCAUV Reference Value for Accelerometer Voltage Sensitivities

The linking laboratories for AVS were NMISA and INMETRO for all available measurement results at the different frequencies.

Table 1: Degrees of equivalence of the participants with respect to the KCRV of CCAUV.V-K3 for AVS reported in AFRIMETS.AUV.V-K3

Frequency →	0.4 Hz		0.5 Hz		0.63 Hz	
	D_i	U_i	D_i	U_i	D_i	U_i
Lab *i* ↓	in mV/(m/s^2)		in mV/(m/s^2)		in mV/(m/s^2)	
NMISA	**-0.08**	0.29	**-0.04**	0.29	**-0.07**	0.29
INMETRO	**0.08**	0.29	**0.04**	0.29	**0.07**	0.29

Frequency →	0.8 Hz	1.0 Hz	1.25 Hz

	D_i	U_i	D_i	U_i	D_i	U_i
Lab i ↓	in mV/(m/s^2)		in mV/(m/s^2)		in mV/(m/s^2)	
NMISA	**-0.05**	0.29	**-0.01**	0.29	**-0.03**	0.29
INMETRO	**0.05**	0.29	**0.01**	0.29	**0.03**	0.29

Frequency →	1.6 Hz		2.0 Hz		2.5 Hz	
	D_i	U_i	D_i	U_i	D_i	U_i
Lab i ↓	in mV/(m/s^2)		in mV/(m/s^2)		in mV/(m/s^2)	
NMISA	**-0.04**	0.29	**-0.03**	0.29	**-0.04**	0.29
INMETRO	**-0.06**	0.29	**-0.06**	0.29	**-0.02**	0.29

Frequency →	3.15 Hz		4 Hz		5 Hz	
	D_i	U_i	D_i	U_i	D_i	U_i
Lab i ↓	in mV/(m/s^2)		in mV/(m/s^2)		in mV/(m/s^2)	
NMISA	**-0.03**	0.29	**-0.02**	0.29	**-0.02**	0.29
INMETRO	**0.03**	0.29	**0.02**	0.29	**0.02**	0.29

Frequency →	6.3 Hz		8 Hz		10 Hz	
	D_i	D_i	D_i	U_i	D_i	U_i
Lab i ↓	in mV/(m/s^2)		in mV/(m/s^2)		in mV/(m/s^2)	
NMISA	**-0.01**	0.29	**0.01**	0.29	**0.02**	0.29
INMETRO	**0.01**	0.29	**-0.01**	0.29	**-0.02**	0.29

Frequency →	12.5 Hz		16 Hz		20 Hz	
	D_i	D_i	D_i	U_i	D_i	U_i
Lab i ↓	in mV/(m/s^2)		in mV/(m/s^2)		in mV/(m/s^2)	
NMISA	**0.02**	0.29	**0.03**	0.29	**0.05**	0.29
INMETRO	**-0.02**	0.29	**-0.03**	0.29	**-0.05**	0.29

Frequency	25 Hz	31.5 Hz	40 Hz

→						
	D_i	D_i	D_i	U_i	D_i	U_i
Lab *i* ↓	in mV/(m/s^2)		in mV/(m/s^2)		in mV/(m/s^2)	
NMISA	**0.04**	0.29	**0.09**	0.29	**0.12**	0.29
INMETRO	**-0.04**	0.29	**-0.09**	0.29	**-0.12**	0.29

Reference:

[1] Final Report of EUROMET.AUV.V-K1, Appendix A - Linking the results of the regional key comparison EUROMET.AUV.V-K1 to those of the CIPM key comparison CCAUV.V-K1, https://www.bipm.org/utils/common/pdf/final_reports/AUV/V-K1/EUROMET.AUV.V-K1.pdf

---------------------END OF REPORT---------------------