CIPM MRA
Comparison reports

SIM.AUV.V-S1

Secondary calibration of accelerometer sensitivity magnitude following ISO 16063-21:2003

SUPPLEMENTARY COMPARISON

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Report on the SIM supplementary comparison SIM.AUV.V-S1

Final Report

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ABSTRACT

The results of the SIM supplementary comparison in the secondary vibration calibration of the complex charge sensitivity (magnitude) concerning steady-state sinusoidal vibration are presented. This regional supplementary comparison followed the global CCAUV.V-K5 comparison over the frequency range from 10 Hz to 10 kHz. Measurement results reported by the two participants for magnitude of the complex charge sensitivity of back-to-back and single ended accelerometers were compared. A link to the CCAUV.V-K5 with the respective Degrees of Equivalence are reported.

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1 Introduction

This report presents the results of the regional supplementary comparison, SIM.AUV.V-S1, in primary vibration calibration (sinusoidal acceleration) according to ISO 16063-11 standard [2] for the pilot laboratory (PTB) without the use of a dummy mass. Secondary vibration calibration according to ISO 16063-21 standard [7] for the other participants. This comparison was a regional supplementary comparison following the CCAUV.V-K5 key comparison [5], thereby providing regional support for the CIPM MRA in the field of vibration metrology.

The Technical Protocol (see Appendix A) specifies in detail the aim and the task of the comparison, the measurement conditions, the transfer standards used, measurement instructions and other items. A brief excerpt is given in the following sections.

2 Participants

Two National Metrology Institutes participated in this comparison, one representative of SIM (the Regional Metrology Organization of the Americas) and one representative of EURAMET (the Regional Metrology Organization of Europe); they are listed in Table 2.1.

Table 7.1 List of participants of SIM.AUV.V-S1 and measurement schedule.

Laboratory Name	Acronym	Country	Country Code	RMO	Calibration week
Physikalisch-Technische Bundesanstalt	PTB	Germany	DE	EURAMET	44 (2023)
Centro Nacional de Metrología	CENAM	Mexico	MX	SIM	03 (2024)

Note: It is important to highlight that the technical protocol includes the participation of INACAL. However, INACAL withdrew from the comparison.

3 Task and Purpose of the Comparison

Centro Nacional de Metrología (CENAM, Mexico) was motivated to participate in the regional comparison SIM.AUV.V-S1 to confirm technical competence and to obtain evidence to support CENAM's CMCs for secondary calibration of vibration transducers.

Physikalisch-Technische Bundesanstalt (PTB) was the pilot and linking laboratory, as it participated in the last global key comparison, CCAUV.V-K5.

The task of the comparison was to measure the magnitude of the complex charge sensitivity of two standard accelerometers (one of single-ended design and one of back-to-back design) at different frequencies specified in the technical protocol (TP) (c.f. Appendix A). The magnitude of the complex charge sensitivity was calculated as the ratio of the amplitude

of the accelerometer output charge to the amplitude of the acceleration at its reference surface. The reference surface was defined as the top surface of the back-to-back accelerometer (BB) and the top surface of the mounting adapter (mounting surface) of the single-ended accelerometer (SE).

For measurements by secondary means, a single ended standard accelerometer (SE) calibrated by primary means was used for the calibration of the back-to-back accelerometer (BB). For the calibration of the SE accelerometer a BB accelerometer calibrated by primary means was used.

The magnitude of the complex charge sensitivity was given in units of pico-coulombs per meter per second squared: $pC/(m/s^2)$. Each participant used its own calibrated charge amplifier to measure the output charge of the accelerometer standards.

The specific task of this supplementary comparison was to measure the complex charge sensitivity of two different accelerometers at specified frequencies with primary (magnitude) and secondary means (magnitude), according to ISO 16063-11 “Methods for the calibration of vibration and shock transducers – Part 11: Primary vibration calibration by laser interferometry” and ISO 16063-21 “Methods for the calibration of vibration and shock transducers – Part 21: Vibration calibration by comparison to a reference transducer” respectively.

The reported measurement results were used to calculate the Degrees of Equivalence (DoE) between CENAM and the CCAUV.V-K5 KCRVs, through the pilot laboratory, to link CENAM to the CIPM KCRV. The results of the comparison will be used to provide additional support for the revised CENAM CMCs.

4 Transfer Standards as Artifacts

For the comparison, a set of two piezoelectric accelerometers were circulated among the participating laboratories:

- One transfer standard accelerometer, “single ended”, manufacturer: Brüel & Kjær, type 8305-001 (SN: 2825607), identified as SE subsequently.
- One reference standard accelerometer, “back-to-back”, manufacturer: Brüel & Kjær, type 8305 (SN: 895042), identified as BB subsequently.

5 Circulation of the Artifacts

The transfer standard accelerometers were delivered by CENAM personnel to PTB vibration primary laboratory, where the initial measurements were performed. The accelerometers were subsequently returned to CENAM for calibration.

6 Results of monitoring measurements

The artifacts were measured by PTB in January 2023, and a verification measurement (less frequency steps) was performed in November 2023, to see whether the artefacts had drifted over the course of 10 months. A deviation of less than 0.05% up to 8 kHz, and less than 0.2% to 17 kHz were found.

7 Results of the Participants

The following sections present both CENAM and PTB results using the agreed upon reporting spreadsheet. The results presented are given as

Quantity	Component	Variable	Unit
Magnitude of the complex charge sensitivity	Value	X_i	pC/(m/s^2)
	exp. rel. uncertainty	$U_{rel,Xi}$	%

where *i* is the index for frequency.

7.1 Results for the Complex Charge Sensitivity (Magnitude)

7.1.1 The Single-Ended Accelerometer (SN 2825607)

Table 7.1.1. Reported participant's results for the complex charge sensitivity (magnitude) of the SE with relative expanded uncertainties (*k* = 2)

Frequency	PTB		CENAM	
	X_i	$U_{rel,Xi}$	X_i	$U_{rel,Xi}$
Hz	pC/(m/s^2)	%	pC/(m/s^2)	%
10	0.12991	0.2	0.12990	0.6
12.5	0.12984	0.1	0.12991	0.6
16	0.12986	0.1	0.12988	0.6
20	0.12985	0.1	0.12985	0.6
25	0.12985	0.1	0.12983	0.6
31.5	0.12982	0.1	0.12983	0.6
40	0.12980	0.1	0.12983	0.6
63	0.12978	0.1	0.12983	0.6
80	0.12976	0.1	0.12986	0.6
100	0.12975	0.1	0.12989	0.6
125	0.12975	0.1	0.12993	0.6
160	0.12974	0.1	0.12992	0.6
200	0.12973	0.1	0.12993	0.6
250	0.12972	0.1	0.12992	0.6
315	0.12972	0.1	0.12989	0.6
400	0.12973	0.1	0.12985	0.6
500	0.12973	0.1	0.12989	0.6
630	0.12973	0.1	0.12992	0.6
800	0.12980	0.1	0.12994	0.6
1 000	0.12982	0.1	0.12998	0.6
1 250	0.12988	0.1	0.13004	0.6
1 600	0.12999	0.1	0.13023	0.6
2 000	0.13020	0.1	0.13052	0.6
2 500	0.13051	0.1	0.13096	0.8
3 150	0.13101	0.1	0.13155	0.8
4 000	0.13180	0.1	0.13258	0.8
5 000	0.13312	0.1	0.13389	1.0
6 300	0.13523	0.3	0.13617	1.0
8 000	0.13881	0.3	0.13905	1.5
10 000	0.14437	0.3	0.14300	1.5

7.1.2 The Back-to-Back Accelerometer (SN 895042)

Table 7.1.2. Reported participant's results for complex charge sensitivity (magnitude) of the BB with relative expanded uncertainties (k = 2)

Frequency	PTB		CENAM	
	X_i	$U_{rel,Xi}$	X_i	$U_{rel,Xi}$
Hz	pC/(m/s^2)	%	pC/(m/s^2)	%
10	0.12852	0.2	0.12862	0.6
12.5	0.12861	0.1	0.12869	0.6
16	0.12869	0.1	0.12876	0.6
20	0.12876	0.1	0.12882	0.6
25	0.12889	0.1	0.12887	0.6
31.5	0.12894	0.1	0.12891	0.6
40	0.12895	0.1	0.12895	0.6
63	0.12898	0.1	0.12902	0.6
80	0.12902	0.1	0.12904	0.6
100	0.12907	0.1	0.12907	0.6
125	0.12910	0.1	0.12907	0.6
160	0.12913	0.1	0.12910	0.6
200	0.12915	0.1	0.12912	0.6
250	0.12919	0.1	0.12915	0.6
315	0.12922	0.1	0.12917	0.6
400	0.12925	0.1	0.12923	0.6
500	0.12928	0.1	0.12926	0.6
630	0.12931	0.1	0.12931	0.6
800	0.12937	0.1	0.12935	0.6
1 000	0.12942	0.1	0.12942	0.6
1 250	0.12948	0.1	0.12946	0.6
1 600	0.12959	0.1	0.12954	0.6
2 000	0.12977	0.1	0.12969	0.6
2 500	0.13002	0.1	0.13005	0.8
3 150	0.13042	0.1	0.13042	0.8
4 000	0.13106	0.1	0.13121	0.8
5 000	0.13206	0.1	0.13212	1.0
6 300	0.13367	0.3	0.13375	1.0
8 000	0.13668	0.5	0.13675	1.5
10 000	0.14033	0.3	0.13983	1.5

8 Degree of Equivalence with Respect to the CIPM KC Reference Value

8.1 Linking

Introduction

A comparison within a regional metrology organization (RMO) can be approved as a regional supplementary comparison (SC) within the framework of the CIPM MRA and included in the Key comparison database (KCDB). SC usually are not linked to the CC KC, however, for this comparison the calculations were done as follows.

The methodology used to link the results of the RMO supplementary comparison, SIM.AUV.V-S1 to those of the CIPM key comparison CCAUV.V-K5 is described below. In the following, the CIPM key comparison CCAUV.V-K5 is referred to as the CIPM comparison and the RMO supplementary comparison SIM.AUV.V-S1 is referred to as the RMO comparison.

Task of Linking

The participating laboratory of the RMO comparison submitted results for the calibration of a SE accelerometer and a BB accelerometer at specified frequencies in the frequency range from 10 Hz to 10 kHz, using secondary means in accordance with ISO 16063-21. The Degrees of Equivalence (DoEs) were calculated for the laboratory results relative to the respective KCRV for the SE accelerometer as well as the BB accelerometer.

The linking task required the transformation of the RMO calibration results into quantities appropriate for the CIPM comparison in order to be compared with the CIPM KCRV. It includes the calculation of:

a) the differences between the combined RMO results and the CIPM quantities for the NMIs participating in both the CIPM and the RMO comparisons and
b) the differences between the transformed RMO results and the corresponding KCRV for the laboratories.
c) the uncertainties associated with these differences.

8.2 Linking procedure for magnitude

The linking followed the method outlined in [3] which has been used in earlier accelerometer RMO comparisons. Mathematical deduction is shown to avoid any confusion. The only assumption made is that there is no correlation between the measurements made by a laboratory on one accelerometer for the CIPM comparison and the measurements made on another accelerometer for the RMO comparison by the same laboratory.

The measurand in the CIPM comparison is denoted by X. The values $x_1, u(x_1), \dots, x_N, u(x_N)$ denote the best estimates and associated standard uncertainties of the laboratories.

The measurand in the RMO comparison is denoted by Y. The values $y_1, u(y_1), \dots, y_M, u(y_M)$ denote the best estimates and associated standard uncertainties of the laboratories.

Furthermore, $G = \{1, \dots, p\}$ $(p \leq \min(N, M)$ is the index set of the linking laboratories which participate in both the CIPM and RMO comparison. The laboratories are labelled 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 make the link between the two comparisons. The transformation factor is estimated using the KCRV of the CIPM comparison and the combined results in the RMO comparison of the linking laboratory. The estimated transformation factor is then applied to the results of the RMO comparison. For reference, the r values are listed as the last column in the DOE tables.

Since no information about correlations is available, the estimators $x_1, \dots, x_N, y_1, \dots, y_M$ are treated as being uncorrelated. Let x denote the KCRV of the CIPM comparison and y the weighted value of the linking laboratory in the RMO comparison.

$$x = \frac{\sum_{l=1}^{N} \frac{x_l}{u^2(x_l)}}{\sum_{l=1}^{N} \frac{1}{u^2(x_l)}} \qquad u^2(x) = \frac{1}{\sum_{l=1}^{N} \frac{1}{u^2(x_l)}}$$

$$y = \frac{\sum_{l \epsilon G} \frac{y_l}{u^2(y_l)}}{\sum_{l \epsilon G} \frac{1}{u^2(y_l)}} \qquad u^2(y) = \frac{1}{\sum_{l \epsilon G} \frac{1}{u^2(y_l)}}$$

Note: In this RMO comparison, PTB was the only linking laboratory. The measured values reported by PTB with the associated uncertainties were used as the linking values.

Then r is estimated according to

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

$z_l = r y_l$ denotes the corrected measurand in the regional comparison.

The uncertainty in the difference

$$d_l = r y_l - x = x \left(\frac{y_l}{y} - 1 \right)$$

is given by the following equations where

$$p_l = \frac{y_l}{y}$$

To calculate the uncertainties on d_l the proper mathematical tool is the law of error propagation. This requires partial differentiation of the formulas with proper respect to dependencies.

The calculations split up in two cases:

1) l is not a participant of the CIPM comparison. This means that x, y, and y_l are independent.
   By use of the law of error propagation we find

$$u^2(d_l) = \left(\frac{\partial d_l}{\partial x}\right)^2 u^2(x) + \left(\frac{\partial d_l}{\partial y}\right)^2 u^2(y) + \left(\frac{\partial d_l}{\partial y_l}\right)^2 u^2(y_l)$$

$$= (p_l - 1)^2 u^2(x) + r^2 \left(1 + p_l^2 \frac{u^2(y)}{u^2(y_l)}\right) u^2(y_l)$$

2) l is a participant of the CIPM comparison. This means that y and y_l are no longer independent.
   By use of the law of error propagation, and by noting that $u(y, y_l) = u^2(y)$, we find

$$u^2(d_l) = \left(\frac{\partial d_l}{\partial x}\right)^2 u^2(x) + \left(\frac{\partial d_l}{\partial y}\right)^2 u^2(y) + \left(\frac{\partial d_l}{\partial y_l}\right)^2 u^2(y_l) + 2\frac{\partial d_l}{\partial y}\frac{\partial d_l}{\partial y_l} u(y, y_l)$$

$$= (p_l - 1)^2 u^2(x) + r^2 \left(1 + p_l(p_l - 2)\frac{u^2(y)}{u^2(y_l)}\right) u^2(y_l)$$

The degrees of equivalence are defined as the differences between the corrected results in the RMO comparison and the KCRV of the CIPM comparison compared to the uncertainties on d_l with a confidence of approximately 95% or *k* = 2, i.e.

$$U_l = 2\sqrt{u^2(d_l)}$$

8.3 Analysis

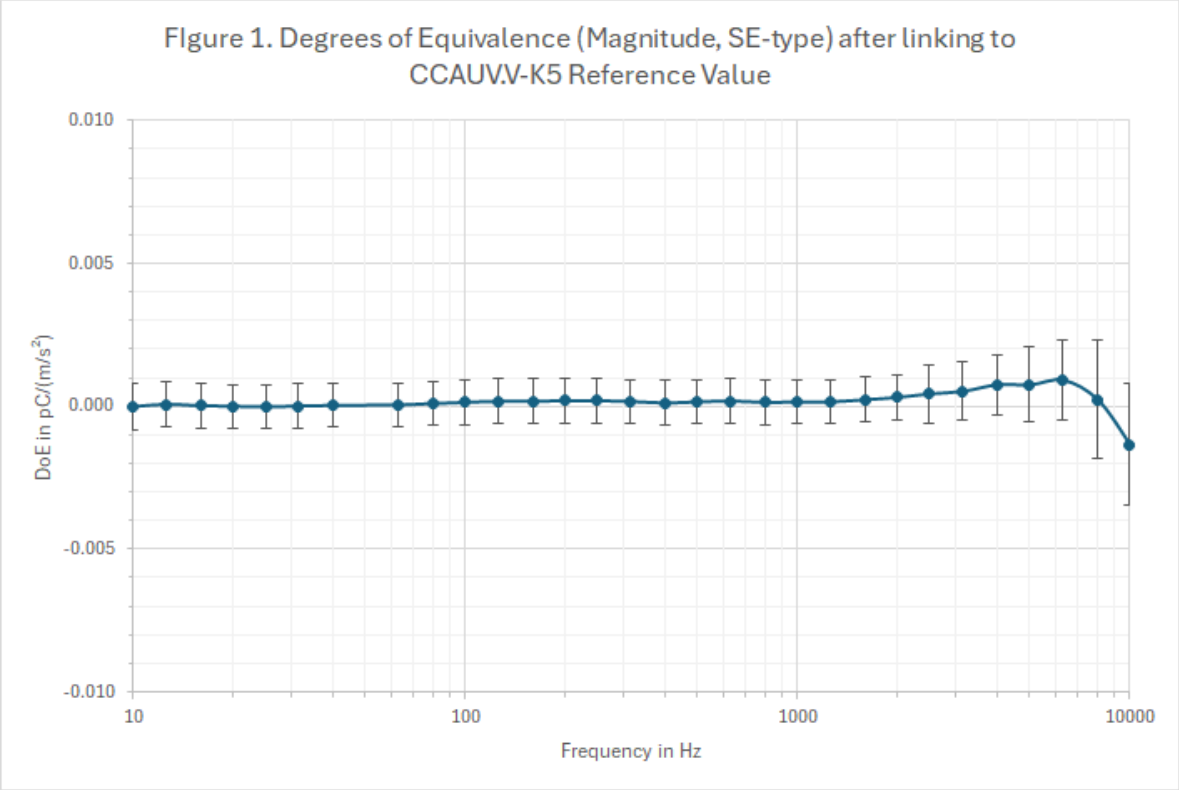
The measurement results were reported by the participants using the mandatory report spreadsheet (Excel file). To comply with the resolution implied by the measurement uncertainty and to generate a consistent picture in this report, all input data were rounded before further calculation in the following way:

Quantity	Unit	Representation
Complex Charge sensitivity (magnitude)	pC/(m/s^2)	0.xxxxx
Relative uncertainty	%	x.xx

8.4 Magnitude of the Complex Charge Sensitivity (Magnitude) of the SE

Table 8.4.1. Degrees of equivalence to the CCAUV.V-K5 KCRV for the complex charge sensitivity (magnitude) of the SE

Frequency	CENAM		CCAUV / SIM	
	d_l	$U(d_l)$	r	$u(r)$
Hz	pC/(m/s^2)	pC/(m/s^2)	Abs	(%)
10	-0.00001	0.00080	0.9743	0.0079
12.5	0.00007	0.00077	0.9750	0.0046
16	0.00002	0.00077	0.9748	0.0045
20	0.00000	0.00077	0.9748	0.0045
25	-0.00002	0.00077	0.9747	0.0045
31.5	0.00001	0.00077	0.9749	0.0045
40	0.00003	0.00077	0.9750	0.0045
63	0.00005	0.00077	0.9751	0.0045
80	0.00010	0.00077	0.9754	0.0045
100	0.00014	0.00077	0.9752	0.0045
125	0.00018	0.00077	0.9752	0.0045
160	0.00018	0.00077	0.9753	0.0045
200	0.00020	0.00077	0.9755	0.0045
250	0.00020	0.00077	0.9757	0.0045
315	0.00017	0.00077	0.9758	0.0045
400	0.00012	0.00077	0.9758	0.0045
500	0.00016	0.00077	0.9759	0.0045
630	0.00019	0.00077	0.9760	0.0045
800	0.00014	0.00077	0.9756	0.0045
1 000	0.00016	0.00077	0.9759	0.0045
1 250	0.00016	0.00077	0.9759	0.0046
1 600	0.00023	0.00077	0.9764	0.0046
2 000	0.00031	0.00078	0.9762	0.0046
2 500	0.00044	0.00103	0.9763	0.0046
3 150	0.00053	0.00104	0.9760	0.0046
4 000	0.00076	0.00104	0.9762	0.0046
5 000	0.00075	0.00131	0.9757	0.0046
6 300	0.00092	0.00139	0.9761	0.0120
8 000	0.00023	0.00208	0.9777	0.0119
10 000	-0.00134	0.00214	0.9774	0.0117



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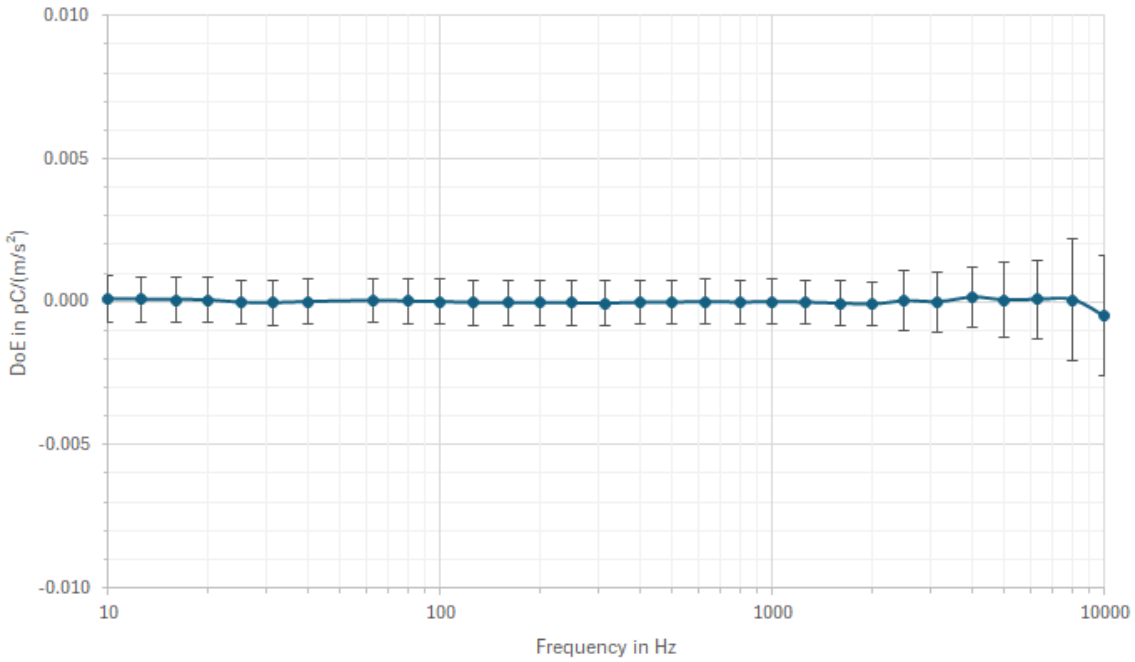
8.5 Magnitude of the Complex Charge Sensitivity (magnitude) of the BB

Table 8.5.1. Degrees of equivalence to the CCAUV.V-K5 KCRV for the complex charge sensitivity (magnitude) of the BB

Frequency	CENAM		CCAUV / SIM	
	d_l	$U(d_l)$	r	$u(r)$
Hz	pC/(m/s^2)	pC/(m/s^2)	Abs.	(%)
10	0.00010	0.00081	0.9960	0.0082
12.5	0.00008	0.00078	0.9954	0.0047
16	0.00007	0.00078	0.9947	0.0046
20	0.00006	0.00078	0.9940	0.0046
25	-0.00002	0.00078	0.9932	0.0046
31.5	-0.00003	0.00078	0.9929	0.0046
40	0.00000	0.00078	0.9927	0.0046
63	0.00004	0.00078	0.9924	0.0046
80	0.00002	0.00078	0.9919	0.0046
100	0.00000	0.00078	0.9915	0.0046
125	-0.00003	0.00078	0.9911	0.0046
160	-0.00003	0.00078	0.9909	0.0046
200	-0.00003	0.00078	0.9907	0.0046
250	-0.00004	0.00078	0.9904	0.0046
315	-0.00005	0.00078	0.9904	0.0046
400	-0.00002	0.00078	0.9902	0.0046
500	-0.00002	0.00078	0.9900	0.0046
630	0.00000	0.00078	0.9901	0.0046
800	-0.00002	0.00078	0.9896	0.0046
1 000	0.00000	0.00078	0.9896	0.0046
1 250	-0.00002	0.00078	0.9895	0.0046
1 600	-0.00005	0.00078	0.9895	0.0046
2 000	-0.00008	0.00078	0.9890	0.0046
2 500	0.00003	0.00104	0.9887	0.0047
3 150	0.00000	0.00104	0.9891	0.0047
4 000	0.00015	0.00105	0.9882	0.0047
5 000	0.00006	0.00131	0.9891	0.0061
6 300	0.00008	0.00138	0.9903	0.0126
8 000	0.00007	0.00213	0.9858	0.0193
10 000	-0.00050	0.00212	0.9904	0.0134

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Figure 2. Degrees of Equivalence (Magnitude, BB-type) after linking to CCAUV.V-K5 Reference Value



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9 Conclusion

This regional supplementary comparison was organized to confirm technical competence and support the improvement of calibration and measurement capabilities (CMCs) of CENAM for secondary calibration of accelerometers. The procedure was very similar to that of the CCAUV.V-K5. Two piezoelectric accelerometers, one BB type and one SE type, were calibrated in the frequency range of 10 Hz to 10 kHz. For primary results, in the case of the SE accelerometer, a mounting fixture like the one used in APMP.AUV.V-K5 [6] was used.

Despite the challenges involved, this regional comparison is considered successful since the results reported by the participants are consistent over the whole frequency range in magnitude, thus establishing new and consistent degrees of equivalence.

10 Acknowledgements

CENAM greatly appreciates all the support provided by the working group 1.71 “Realization of acceleration” from PTB, without which this supplementary regional comparison would not have been possible.

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

Appendix A: Technical Protocol

Technical Protocol for SIM.AUV.V-K5 & SIM.AUV.V-S1

2023-05-03

Task and Purpose of the Comparison

The Centro Nacional de Metrología (CENAM, Mexico) is motivated to participate in the bilateral comparison SIM.AUV.V-K5 to confirm technical competence and get evidence to support CENAM's CMCs for primary calibration of vibration transducers.
CENAM and the Instituto Nacional de Calidad (INACAL, Peru) are motivated to participate in the trilateral comparison SIM.AUV.V-S1 to confirm their technical competence and provide evidence to establish CMCs in secondary calibration.
Physikalisch-Technische Bundesanstalt (PTB) will be acting as pilot and linking laboratory, as it has taken part in the global CCAUV.V-K5.
The reported sensitivities and associated uncertainties are then to be used for the calculation of the Degrees of Equivalence (DoE) between CENAM, INACAL and the CCAUV.V-K5 KCRVs. CENAM and INACAL will be linked to the KCRV of this former comparison via the pilot laboratory. The results of the comparison will be used to provide additional support to the revised CMCs to get compatibility with the results of the CCAUV.V-K5. These results are expected to serve as evidence to be the foundation for the registration of the CMCs of CENAM and INACAL considering primary and secondary calibration of vibration transducers, as applicable.
Although separated in two distinct RMO-comparisons the measurements will be performed with a single set of artifacts, which is the reason to combine the technical protocols into a single document.

SIM.AUV.V-K5

The specific task of this bilateral comparison is to measure magnitude and phase of the complex charge sensitivity of two different accelerometers at specified frequencies with primary means i.e., according to ISO 16063-11 "Methods for the calibration of vibration and shock transducers – Part 11: Primary vibration calibration by laser interferometry".

SIM.AUV.V-S1

The specific task is the measurement of the magnitude of the charge sensitivity of the same set of accelerometers at specified frequencies with secondary means i.e., according to ISO 16063-21 "Methods for the calibration of vibration and shock transducers – Part 21: Vibration calibration by comparison to a reference transducer".

Note 1: Pilot laboratory will measure only by primary means.
Note 2: SIM.AUV.V-K5 will be linked to the CCAUV.V-K5.

Participants

SIM.AUV.V-K5:

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SIM.AUV.V-S1

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Devices under Test

For the calibration tasks of both comparisons, a set of two piezoelectric accelerometers will be circulated among the participating laboratories. The individual transducers are:

- a Brüel & Kjær 8305-001 (SN: 2825607) “single ended” (SE) type
- a Brüel & Kjær 8305 S (SN: 895042) “back-to-back” (BB) type.



Figure 1. Devices under test

Conditions of measurement

SIM.AUV.V-K5 Primary means (ISO 16063-11)

The accelerometers are to be calibrated for magnitude and phase of their complex charge sensitivity according to those procedures and conditions implemented by the NMI in conformance with ISO 16063-11, which provide magnitude and phase information of the artefact. The sensitivities reported shall be for an accelerometer alone, excluding any effects from the charge amplifier used for signal conditioning.
The frequency range of the measurements was agreed to be from 10 Hz to 20 kHz. Specifically, the laboratories are supposed to measure at the following frequencies (all values in Hz):

10, 12.5, 16, 20, 25, 31.5, 40, 50, 63, 80, 100, 125, 160, 200, 250, 315, 400, 500, 630, 800, 1000, 1250, 1600, 2000, 2500, 3150, 4000, 5000, 6300, 8000, 10 000, 11 000, 12 000, 13 000, 14 000, 15 000, 16 000, 17 000, 18 000, 19 000, 20 000.

The charge amplifier used for the calibration is not provided within the set of the artifacts, it must therefore be provided by the individual participant and calibrated properly. As a guideline for calibration the document “Calibration of conditioning amplifiers for dynamic application: Guideline DKD-R 3-2” shall be used (https://doi.org/10.7795/550.20190425EN). The simplified Method presented in section 3.2.1 shall be used by both participants using a 100 pF standard capacitor.

The calibrations shall be carried out in accordance with the usual procedure of the laboratory for the calibration of customer accelerometers, except as otherwise indicated in this protocol.

The SE type accelerometer is mounted on a mechanical adapter, which was designed and manufactured according to the drawing below:

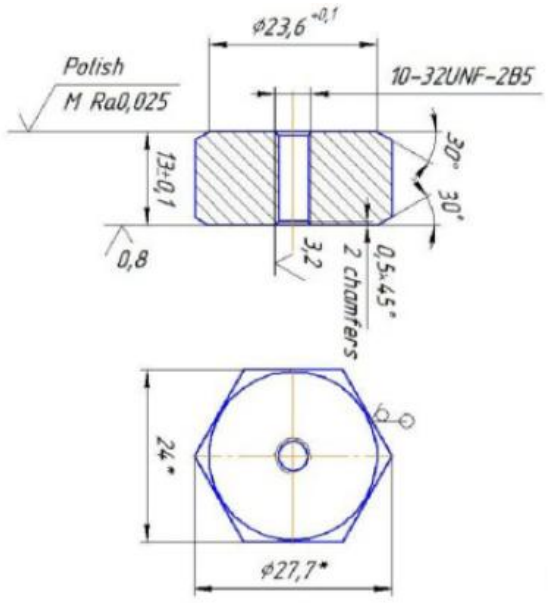


Figure 2. Mechanical adapter for SE type accelerometer (all dimensions in mm)

SIM.AUV.V-S1 Secondary means (ISO 16063-21)

The accelerometers are to be calibrated for magnitude of their complex charge sensitivity according to those procedures and conditions implemented by the NMI in conformance with ISO 16063-21, which provide magnitude information of the artefact. The sensitivities reported shall be for an accelerometer alone, excluding any effects from the charge amplifier.

The frequency range of the measurements was agreed to be from 10 Hz to 10 kHz. Specifically, the laboratories are supposed to measure at the following frequencies (all values in Hz):
10, 12.5, 16, 20, 25, 31.5, 40, 50, 63, 80, 100, 125, 160, 200, 250, 315, 400, 500, 630, 800, 1000, 1250, 1600, 2000, 2500, 3150, 4000, 5000, 6300, 8000, 10 000.

The charge amplifier used for the calibration is not provided within the set of the artifacts, it must therefore be provided by the individual participant and calibrated properly. As a guideline for calibration the document “Calibration of conditioning amplifiers for dynamic application: Guideline DKD-R 3-2” shall be used (https://doi.org/10.7795/550.20190425EN). The simplified Method presented in section 3.2.1 shall be used by the secondary laboratory of CENAM using a 100 pF standard capacitor.

The calibrations shall be carried out in accordance with the usual procedure of the laboratory for the calibration of customer accelerometers.

For comparison calibration, the mechanical adapter should not be used. The measurements for comparison method shall be carried out after the conclusion of the primary calibrations by laser interferometry.

PTB takes part in SIM.AUV.V-S1 as linking laboratory using the calibration results from the primary calibration by laser interferometry acquired in SIM.AUV.V-K5 (c.f. previous section)

General Specifications:
Specific conditions for the measurements are:

- Acceleration amplitudes: preferably 50 m/s² to 100 m/s² but a range of 2 m/s² to 200 m/s² is admissible for both, primary and secondary means.
- 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 %.
- Mounting torque of the accelerometer: (2.0 ± 0.1) N m.

Measurement instructions

SIM.AUV.V-K5 Primary means (ISO 16063-11)

- The measurand is the magnitude and phase of the complex charge sensitivity.
- The motion of the SE accelerometer shall be measured on the polished top surface of the mechanical adapter, close to the accelerometer's mounting surface since the mounting (reference) surface is usually not directly accessible.
- The motion of the BB accelerometer mounted in the normal position shall be measured with the laser directly on the (polished) top surface of the transducer without any additional reflector or dummy mass.
- The mounting surfaces of the accelerometer and the moving part of the exciter shall be slightly lubricated before mounting.
- The cable between the accelerometer and charge amplifier will be provided by the pilot laboratory (PTB).
- To reduce the influence of non-rectilinear motion, the measurements shall be performed for at least four different laser positions, which are equally spaced over the respective measurements surface.
- It is advised that the measurement results shall be compiled from complete measurement series carried out on different days, under nominally the same conditions, except that the accelerometer is remounted, and the cable reattached. The standard deviation of the subsequent measurements should be included in the report.
- The charge amplifier used for the measurement of the accelerometer's response shall be calibrated with the equipment traceable to national measurements standards and the method used shall be reported.

SIM.AUV.V-S1 Secondary means (ISO 16063-21)

- The measurand is the magnitude of the complex charge sensitivity.
- No mechanical adapters shall be used for the accelerometer calibrations.
- The SE type accelerometer shall be calibrated against a reference accelerometer previously calibrated by primary means.

- The BB type accelerometer shall be calibrated with a SE accelerometer previously calibrated by primary means.
- The mounting surfaces of the accelerometers and the moving part of the exciter shall slightly be lubricated before mounting.
- The cable between the accelerometer and charge amplifier will be provided by the pilot laboratory (PTB).
- It is advised that the measurement results shall be compiled from complete measurement series carried out on different days, under nominally the same conditions, except that the accelerometer is remounted, and the cable reattached. The standard deviation of the subsequent measurements should be included in the report.
- The charge amplifier used for the measurement of the accelerometer's response shall be calibrated with the equipment traceable to national measurements standards.

Communication of the results

The pilot laboratory will provide a spreadsheet template to all participants in which the reported results will be transferred to the pilot.
In addition, the participants will provide a PDF of their result spread sheet in order to avoid or detect any transmission errors, a tabulated uncertainty budget covering all calibration done within the scope of the relevant comparison, a description of the used calibration equipment.

These documents must be submitted to the pilot laboratory within six weeks after the measurements.

Circulation type

The set of artifacts is at PTB since June 2022. PTB will start the loop of the comparison measurements within SIM.AUV.V-K5. Then the artifacts be primary calibrated at CENAM followed by the secondary calibration at CENAM for SIM.AUV.V-S1. Finally, INACAL will receive the same set of artifacts for their calibration in the scope of SIM.AUV.V-S1

The cost of transportation between PTB and CENAM will be covered by CENAM. As an alternative, the artifacts may be hand carried by a member of the participating laboratory.

From CENAM to INACAL and back: The cost of transportation will be covered by INACAL. As an alternative, the artifacts may be hand carried by a member of the participating laboratory.

Time schedule

The measurement period is 4 weeks for both devices for primary means and 4 weeks for secondary means (both devices). The schedule is planned as follows

Participant	Measurement (Calendar week)
PTB	44-47 / 2023
Transportation	48 / 2023
CENAM (primary)	49-50 / 2023 and 01-02 / 2024
CENAM (secondary)	03-06 / 2024
Transportation	07 / 2024
INACAL (secondary)	08-11 / 2024

Appendix B: Measurement Uncertainty Budgets of the participants

CENAM

i	Description	Probability distribution model	Factor	Frequency (Hz)				
				1Hz to 16Hz	>16Hz to 2kHz	>2kHz to 5kHz	>5kHz to 6.3kHz	>6.3kHz to 10kHz
1	Calibration of reference transducer	normal (k=2)	0.5	0.15	0.15	0.25	0.30	0.40
2	Calibration of conditioning amplifier (reference channel)	normal (k=2)	0.5	0.025	0.025	0.025	0.025	0.025
3	Calibration of conditioning amplifier (device under test)	normal (k=2)	0.5	0.025	0.025	0.025	0.025	0.025
4	Acquisition card (reference channel)	normal (k=2)	1	0.050	0.050	0.050	0.050	0.050
5	Acquisition card (device under test)	normal (k=2)	1	0.050	0.050	0.050	0.050	0.050
6	Drift for 3 years, manufacturer specification < 0,05 % per year	rectangular	0.58	0.087	0.087	0.087	0.087	0.087
7	Influence of temperature variation. Reference transducer sensitivity, (23 ± 3) °C, < 0,02 % per °C Transducer to be calibrated, (23 ± 3) °C, < 0,1 % per °C	rectangular	0.58	0.069	0.069	0.069	0.069	0.069
8	Maximum allowed difference between the reference level before and after the measurement	rectangular	0.58	0.058	0.058	0.058	0.058	0.058
9	Influence of mounting parameters (torque)	rectangular	0.58	0.058	0.058	0.058	0.058	0.058
10	Influence of mounting parameters (cable)	rectangular	0.58	0.058	0.058	0.058	0.058	0.058
11	Acceleration distortion	rectangular	0.58	0.058	0.058	0.058	0.058	0.058
12	Transverse acceleration - Transverse vibration a_T for vibrator max 10 % - Transverse sens (reference) max. 2% - Transverse sens (DUT) max. 5 %	Special	0.24	0.127	0.127	0.127	0.127	0.127
13	Influence of base strain. Estimated to be less than	rectangular	0.58	0.029	0.029	0.029	0.029	0.029
14	Influence of relative motion. Estimated to be less than	rectangular	0.58	0.029	0.029	0.029	0.029	0.029
15	Influence of non-linearity of transducers. Estimated to be less than	rectangular	0.58	0.029	0.029	0.029	0.029	0.029
16	Influence of non-linearity of amplifiers. Estimated to be less than	rectangular	0.58	0.029	0.029	0.029	0.029	0.029
17	Influence of magnetic field from exciter. Estimated to be less than	rectangular	0.58	0.017	0.017	0.017	0.017	0.017
18	Influence of other environmental effects. Estimated to be less than	rectangular	0.58	0.017	0.017	0.017	0.017	0.017
19	Influence of residual effects (e.g. random effect in repeated measurements). Estimated to be less than	rectangular	0.58	0.058	0.058	0.058	0.058	0.058
Uncertainty for accelerometer sensitivity S_2		**% (*k* = 1)**		**0.28**	**0.28**	**0.34**	**0.38**	**0.46**
		% (*k* = 2)		**0.56**	**0.56**	**0.69**	**0.76**	**0.93**

PTB

Measurement uncertainty for magnitude

DUT	B&K 8305 or 8305-001	+ B&K 2650						
acceleration:	100 m/s²							
Voltage	typic. 1V							
Sample rate	10 MS/s	@ 12 Bit						
					combined frequency ranges			
Disturbing Component	**comment**	**95% value**	**distribution**	**factor**	**10 Hz to 5 kHz**	**to 10 kHz**	**to 15 kHz**	**to 20 kHz**
frequency of SAM	deviation of sample clock from generator clock		rectangular	1,73205081	5,77E-05	5,77E-05	5,77E-05	5,77E-05
Accelerometer Voltage	sampling of NI PXI-5922 or HP3458A	5,00E-04	rectangular	1,73205081	2,89E-04	2,89E-04	2,89E-04	2,89E-04
Velocity amplitude	wave length, optical adjustment, deviation between the two beams	1,16E-05	normal	2	5,80E-06	5,80E-06	5,80E-06	5,80E-06
harmon. Distortion	mainly 1st harmonic		Steiner	1	7,84E-06	7,84E-06	7,84E-06	7,84E-06
Humm on Voltage	typical 1mV	5,00E-07	Steiner	1,00	5,00E-07	5,00E-07	5,00E-07	5,00E-07
Noise on Voltage	MC on influence to SAM duration 20ms, Un=1,0mV		normal	1	3,30E-06	3,30E-06	3,30E-06	3,30E-06
Transverse Motion	S(transv) = 0,7% a(transv) < 4%		u-type	1,41421356	1,98E-04	1,98E-04	1,98E-04	1,98E-04
Base strain sensitivity	S = 0,005m/s² / µ€ € < 0,1 µm/m	0,000005	rectangular	1,73	2,89E-06	2,89E-06	2,89E-06	2,89E-06
mounting	S = 6e-4/Nm; dM = 0,2 Nm	0,00012	rectangular	1,73205081	6,93E-05	6,93E-05	6,93E-05	6,93E-05
Temperature	S=2,5e-4 /K dT = 0,3 K	0,000075	rectangular	1,73	4,33E-05	4,33E-05	4,33E-05	4,33E-05
Magnetic field	S=1/a *(m/s²)/T B < 0,03mT	0,0000003	rectangular	1,73	1,73E-07	1,73E-07	1,73E-07	1,73E-07
Airborne acoustics	S=0,008 m/s² at 154 dB max sound level 88 dB	8,00E-08	rectangular	1,73	4,62E-08	4,62E-08	4,62E-08	4,62E-08
Noise on Interferom.	noise level equiv. of 2 nm after demodulation, Monte Carlo		normal	1	1,10E-04	3,00E-04	6,20E-04	1,10E-03
a-synchronous Measurement	voltage/acceleration/voltage	1,00E-04	rectangular	1,73	5,77E-05	5,77E-05	5,77E-05	5,77E-05
charge ampl. calibration					2,12E-04	2,12E-04	2,12E-04	2,12E-04
resid. influences		1,00E-04	normal	1,41421356	7,07E-05	7,07E-05	7,07E-05	7,07E-05
exp. std. dev					2,30E-04	1,60E-04	4,40E-04	6,60E-04
rel. std. uncertainty	**in %**				**0,0501**	**0,0549**	**0,0874**	**0,1353**
rel. comb. exp. Uncertainty (k=2)	**in %**				**0,1002**	**0,1098**	**0,1748**	**0,2707**
stated rel. comb. exp. Uncertainty	**in %**				**0,1000**	**0,3000**	**0,5000**	**1,0000**