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REPORT ON KEY COMPARISON AFRIMETS.AUV.V-K5 and LINKING to CCAUV.V-K5

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1 Introduction

This report presents the results of the key comparison, AFRIMETS.AUV.V-K5, in the area of primary vibration calibration (quantity of sinusoidal acceleration [1]) according to ISO 16063-11 standard [2]. It has the status of a Draft B report, to be submitted to the participants in this comparison for comments.

This comparison was a regional key comparison, following the CCAUV.V-K5 key comparison [3, 4], thereby providing regional support for the CIPM MRA in the field of vibration metrology. The Technical Protocol (see Appendix A) [5] specifies in detail the aim and the task of the comparison, the conditions of measurement, the transfer standards used, measurement instructions and other items. A brief excerpt is given in the following sections.

Following the resolutions of CCAUV [6] no bilateral DoE were calculated.

The monitoring data documenting the stability of the transducers are reported in Section 7.

2 Participants

Four National Metrology Institutes (NMIs) from three Regional Metrology Organizations (RMOs), AFRIMETS, APMP~~,~~ and SIM, participated in this key comparison, AFRIMETS.AUV.V-K5 (cf. Table 1).

Table 1: List of participating institutes and actual schedule of AFRIMETS.AUV.V-K5

Participating Metrology Institute	Acronym	Country	Metrology Region	Calibration Period
National Metrology Institute of South Africa	NMISA	South Africa	AFRIMETS	16 Aug 2021 to 7 Sep 2021
National Institute of Metrology (Thailand)	NIMT	Thailand	APMP	18 Apr 2022 to 6 May 2022
Instituto Nacional de Tecnología Industrial	INTI	Argentina	SIM	3 Oct 2022 to 21 Oct 2022
CSIR-National Physical Laboratory Acoustics and Vibration Standards	CSIR India	India	APMP	23 Jan 2023 to 10 Feb 2023

3 Task and Purpose of the Comparison

Through the CIPM, NMIs participate in key comparisons (KC) to evaluate and proof calibration system performance at the highest accuracy level, smallest uncertainty of measurement (UoM). However, in certain instances, participation in a CIPM might be impractical. For CSIR-NPL (India), NIMT (Thailand) and INTI (Argentina), to proof their calibration and measurement capabilities (CMCs), linked to the CIPM comparison, CCAUV.V-K5, this AFRIMETS key comparison was proposed.

In the fields of vibration and shock, the CIPM key comparison, CCAUV.V-K5 [3] was organized to compare measurements of sinusoidal linear accelerations in the frequency range from 10 Hz to 20 kHz. This regional key comparison, AFRIMETS.AUV.V-K5, was organized to establish a link between the CIPM KCRVs and participating laboratories from three different regions. The technical protocol for AFRIMETS.AUV.V-K5 [5] was drawn up with this goal in mind. The CIPM comparison coverage is extended based on the fact that a degree of equivalence derived from an RMO key comparison has the same status as one derived from a CIPM key comparison.

During the circulation period from August 2021 to February 2023, four NMIs from three RMOs calibrated two laboratory standard accelerometers of different types. The NMIs were tasked to calibrate the magnitude (S_{qa}) and phase shift (ϕ_{qa}) of the complex charge sensitivities (pC/(m/s^2)) [2, 5] of the two accelerometer standards at specified frequencies and different acceleration amplitudes as specified in Appendix A. The accelerometer standards were one double ended (BtoB) in design and the other single ended (SE) in design.

For the calibration of the two accelerometers, all participants applied primary means (laser interferometry) in accordance with ISO 16063-11 [2]. The charge sensitivities were calculated as the ratio of the amplitude of the accelerometer output charge to the amplitude of the measured acceleration level at the reference surface of the accelerometer. The reference surface was defined as the mounting surface of the SE accelerometer and the top surface for the BtoB accelerometer. For the participating laboratories, the charge sensitivity reported had to exclude effects from the applicable conditioning amplifier used. The participating laboratory provided the amplifier to be used and determined and corrected for the effect (gain and phase shift) of the amplifier on the calibration result. No conditioning amplifier accompanied the circulation of the accelerometer standards.

The magnitude and phase values reported by each participating laboratory (participating laboratory capability dependent) will be linked to the KCRVs over the frequency range 10 Hz to 20 kHz, as reported during CCAUV.V-K5. The values obtained from the NMISA primary vibration calibration system will serve as the link between the KCRV and the values reported by the participating laboratory.

NMISA scaled complex sensitivities and associated uncertainties [7], including the scaling mechanism used for the calculation of the unilateral DoE between each NMI and the CCAUV.V-K5 key comparison reference value (KCRV) are reported.

The calculated results of this key comparison could be used as support for the submission of CMCs in the framework of the CIPM MRA [4]. The comparison results may also be used to support voltage sensitivities of accelerometers / acceleration measuring chains, under the assumption that charge sensitivity depends on the calibration of voltage sensitivity of an acceleration measuring chain and the sensitivity of the charge amplifier used.

4. Conditions of measurement

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

- Frequencies (Hz):
  5, 6.3, 8, 10, 12.5, 16, 20, 25, 31.5, 40, 50, 63, 80, 100, 125, 160, 200, 250, 315, 400, 500, 630, 800, 1 000, 1 250, 1 500, 1 600, 2 000, 2 500, 3 000, 3 150, 3 500, 4 000, 4 500, 5 000, 5 500, 6 000, 6 300, 6 500, 7 000, 7 500, 8 000, 8 500, 9 000, 9 500, 10 000, 10 500, 11 000, 11 500, 12 000, 12 500, 13 000, 13 500, 14 000, 14 500, 15 000, 15 500, 16 000, 16 500, 17 000, 17 500, 18 000, 18 500, 19 000, 19 500, 20 000

  Calibration at frequencies < 10 Hz was optional and the results were not linked to the CIPM key comparison.

Specific conditions for the measurements of this key comparison were:

- acceleration amplitudes: preferably 10 m/s² to 100 m/s², frequency dependent.
- ambient temperature during the calibration:
  - (23 ± 2) ºC (actual values to be stated within tolerances of ± 0,3 ºC).
  - relative humidity: max. 75 %rh
- mounting torque of the accelerometer: (2,0 ± 0,2) N·m

The comparison was performed in compliance with the “Guidelines for CIPM key comparisons” [4] and “Guidance for carrying out key comparisons within the CCAUV (2015)” [7].

5 Transfer Standards

For the calibration task of this comparison, a set of two piezoelectric accelerometers were circulated among the participating laboratories.

The individual transducers were:

- One laboratory standard accelerometer, type Brüel & Kjær 8305-001 (SN: 2860147) “single ended” (SE) type,
  - the SE accelerometer/adaptor combination is referred to hereafter as the “SE Device”.

- An ENDEVCO 2270 (SN: 14317) “back to back” (BtoB) type.

Note: The SE type accelerometer was mounted on a mechanical adapter. The combination was handled as a single mechanical unit for mounting, following the guidelines in the technical protocol.

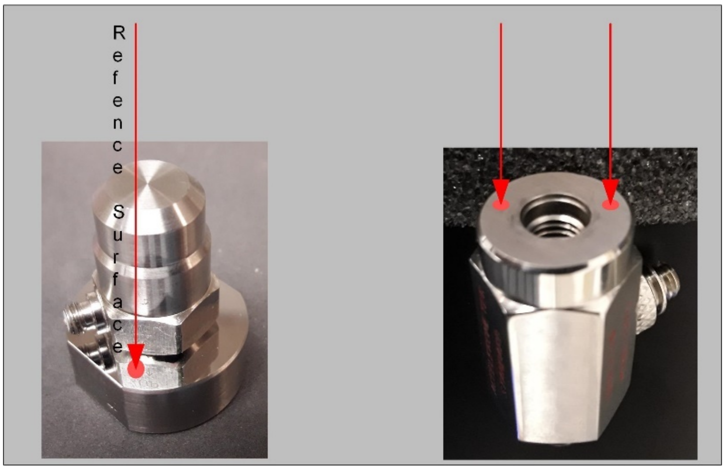

Figure 1: Reference surfaces indicated for the Brüel & Kjær 8305-001 accelerometer complete with adaptor and the ENDEVCO 2270

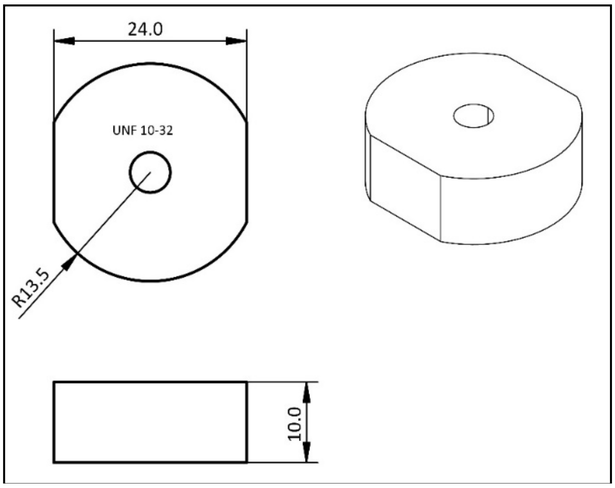

Figure 2: Drawing showing stainless steel adaptor dimensions. Drawing is not to scale.

6 Circulation Type and Transportation

A star type circulation was used for this comparison, i.e., after the measurements at each participating laboratory, the pilot laboratory checked the artifacts for stability and their general condition. The results of the stability measurements of the transfer standards are given in Section 7.

The accelerometers were packed in an aluminium case, supported with high density foam. This case was packed in a cardboard box, filled with foam chips, for shipment between participant and Pilot laboratory by courier. Each participating laboratory carried the shipping costs.

7. Results of Monitoring Measurements

The artifacts were monitored by the pilot laboratory over the period of the comparison. Due to the modified star-type circulation a monitoring measurement was performed in between the participant's measurements.

The different sensitivity frequency responses, including the uncertainties stated for the pilot laboratory, are presented in deviation plots in Figure 3 and Figure 4 below. The vertical axis gives the relative deviation from the mean of the monitoring measurements over the period monitored.

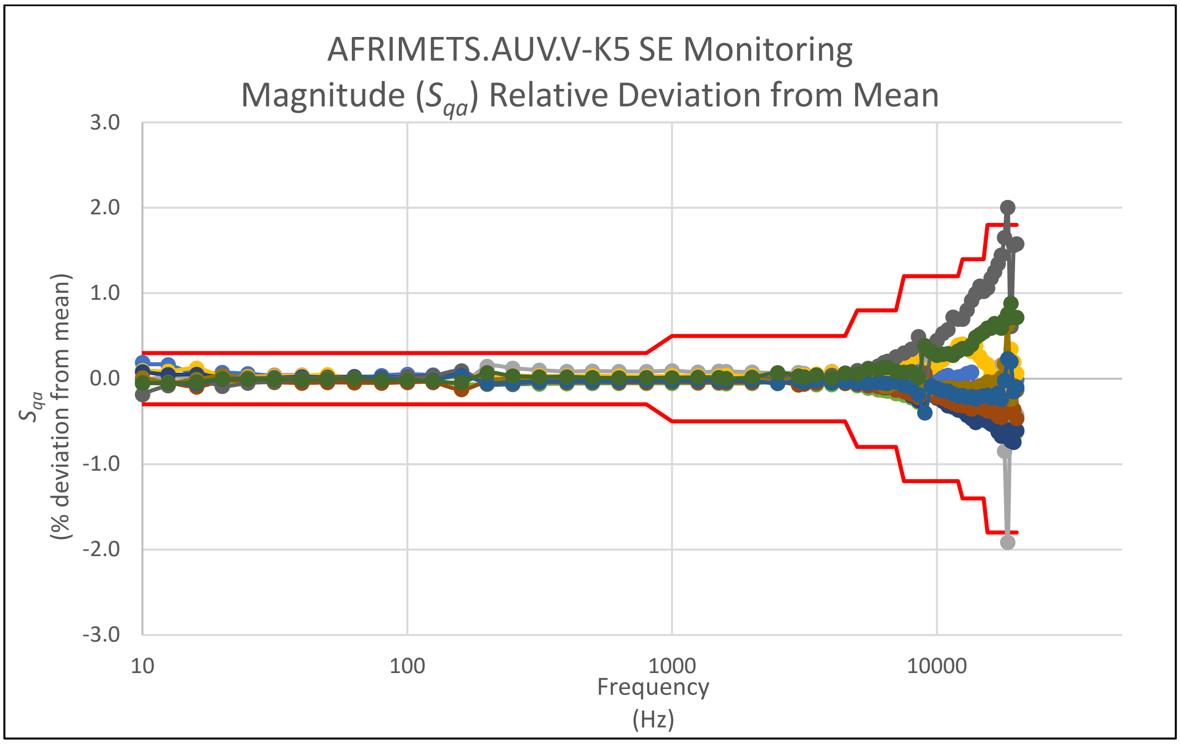

Figure 3: SE Magnitude (S_{qa}) monitoring relative deviation from mean, with Pilot Laboratory stated uncertainties.

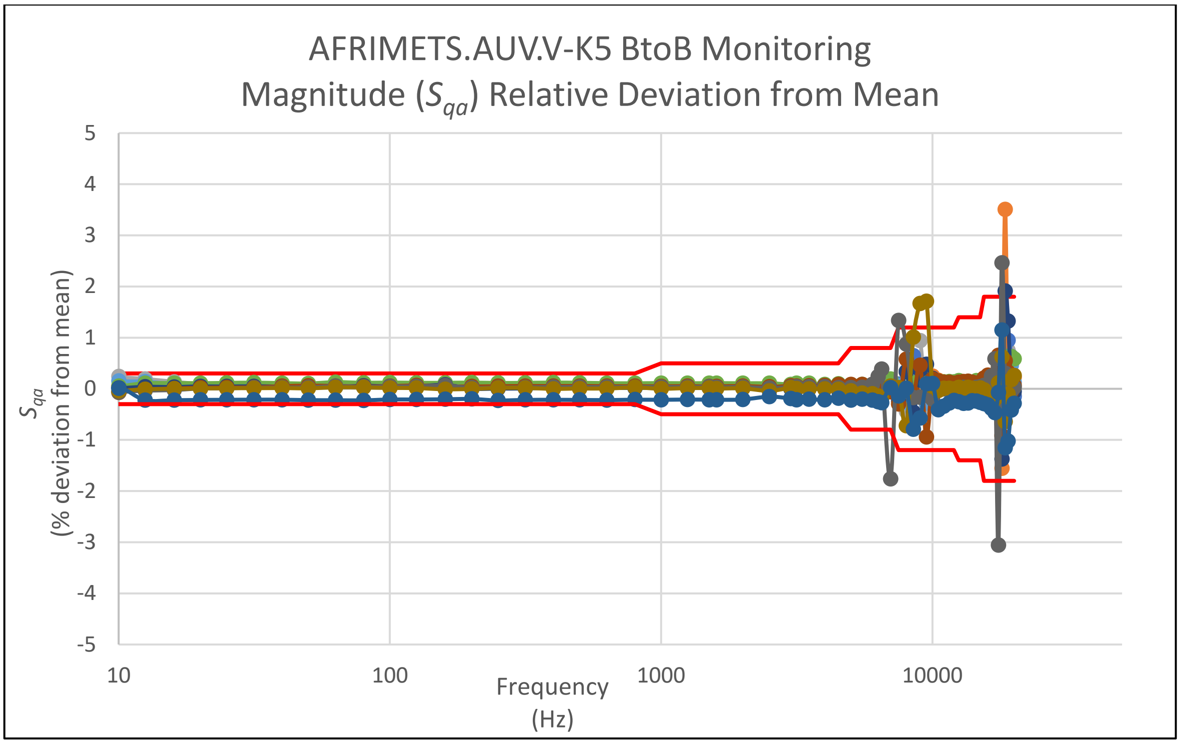

Figure 4: BtoB Magnitude (S_{qa}) monitoring relative deviation from mean, with Pilot Laboratory stated uncertainties.

The different phase shift frequency responses, including the uncertainties stated for the pilot laboratory, are presented on combined deviation plots in Figure 5 and Figure 6 below. The vertical axis gives the deviation from the mean of all monitoring phase shift measurements over the period monitored.

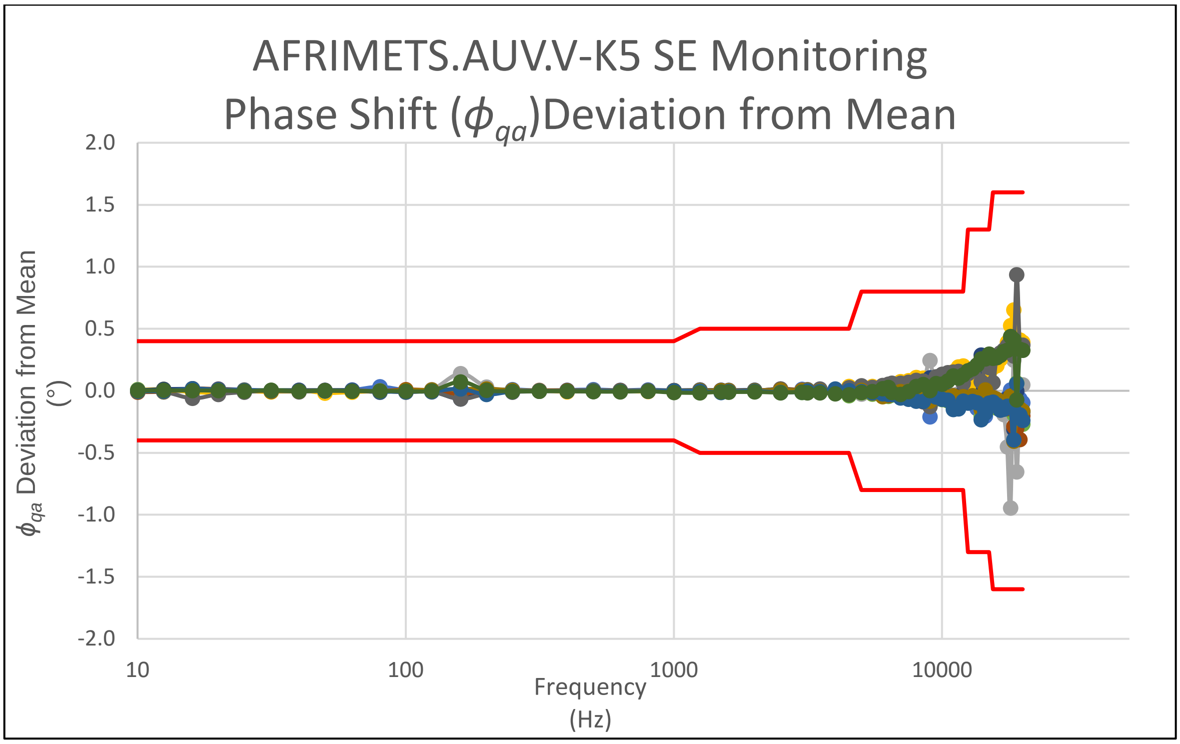

Figure 5: SE Phase shift (ϕ_{qa}) monitoring deviation from mean, with Pilot Laboratory stated uncertainties.

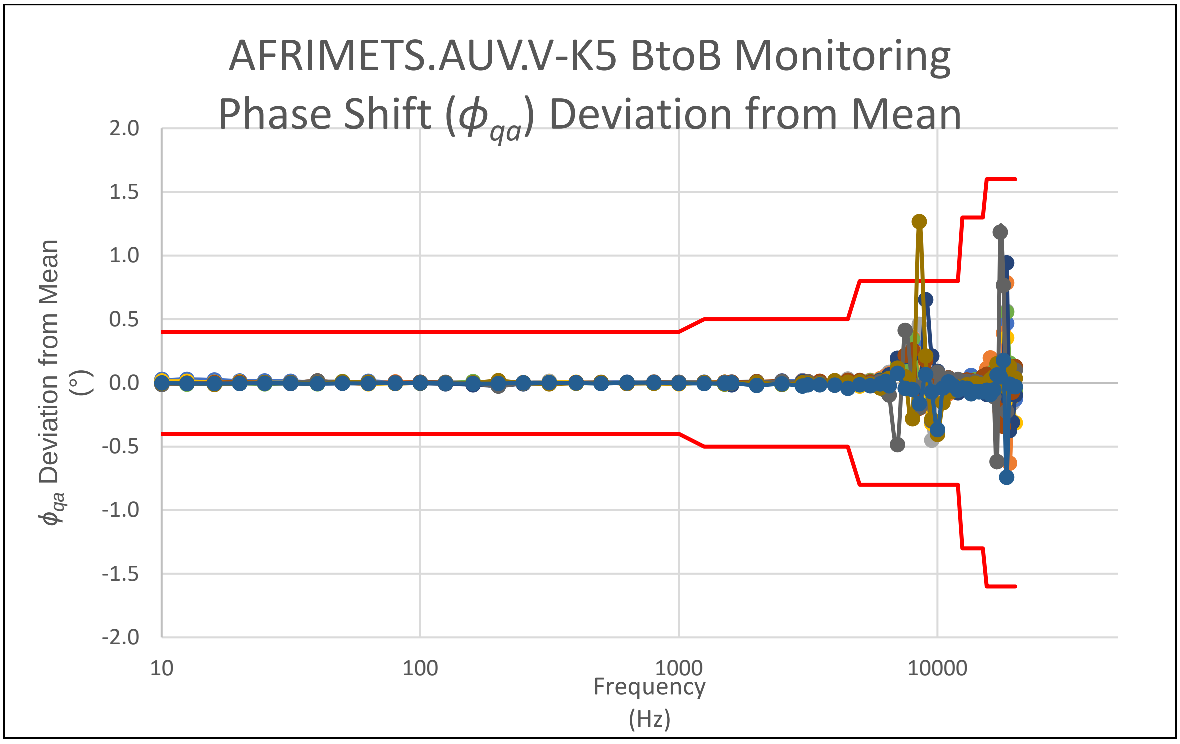

Figure 6: BtoB phase shift (ϕ_{qa}) monitoring deviation from mean, with Pilot Laboratory stated uncertainties.

The visual evaluation of the presented graphed results indicates that both accelerometers were acceptably stable within the measurement uncertainty of the pilot laboratory.

Between 7 kHz and 10 kHz the BtoB transducer exhibits some dispersion in the sensitivity results (Figure 4) which is attributed to accelerometer transverse sensitivity and the exciter cross-axis motion in that frequency range. For the SE transducer there are similar, but less pronounced effects (Figure 3).

The conclusion is that the transducers were stable during the intercomparison.

8 Results of the Participants

The following sections report the results submitted by the participants of the comparison to the pilot laboratory using the reporting spreadsheet provided to the participants by the pilot laboratory. It was part of the calibration protocol for results to be reported using a Microsoft Excel® Spreadsheet.

8.1 Participants System Descriptions

NMISA used method 3 as specified in ISO 16063-11, with a POLYTEC heterodyne interferometer, SPEKTRA SE-09 air-bearing vibration exciter with matching power amplifier and SPEKTRA CS-18 primary accelerometer calibration system. The interferometer is separated from the vibration platform using air bellows.

NIMT used a SPEKTRA CS18P STF based primary accelerometer calibration system, employing method 3 as specified in ISO 16063-11, with a POLYTEC CLV-1000KU interferometer. The system included a SPEKTRA SE-09 air-bearing vibration exciter with matching power amplifier. The interferometer is separated from the vibration platform using air bellows.

INTI used methods 1 & 2 as specified in ISO 16063-11, providing magnitude only calibration results. The system for the primary calibration is a homodyne Michelson interferometer with a single detector and an electrodynamic vibration exciter according to the guidelines given in ISO16063-11.

The following figures describes the systems for both methods implemented:

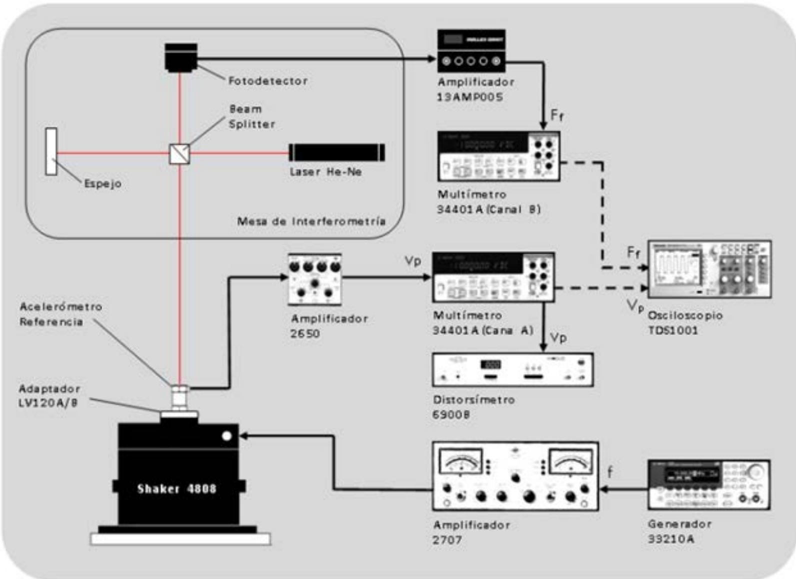

Figure 7: INTI fringe counting method arrangement

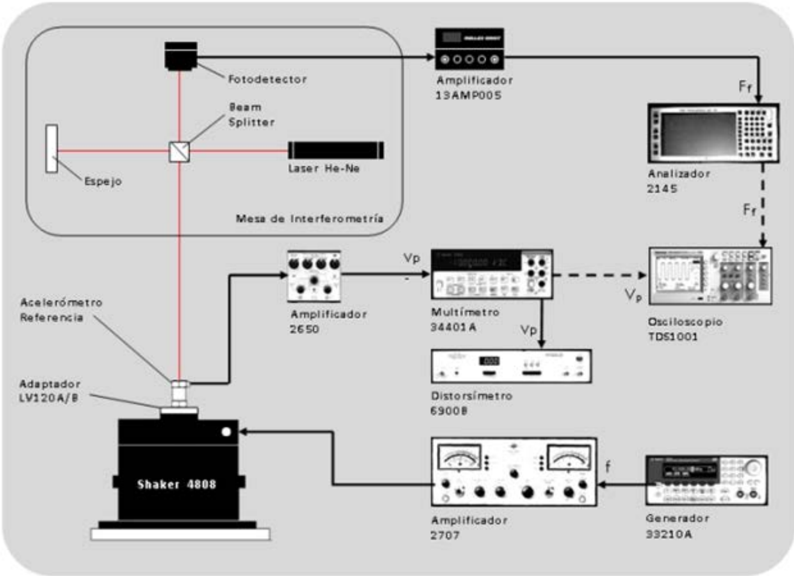

Figure 8: INTI minimum point method arrangement

INTI applied the following configuration w.r.t. the reference surfaces and measurement point positions. The measurements were taken at four points on the reference surface:

On the adaptor plate for the single-ended transducers:

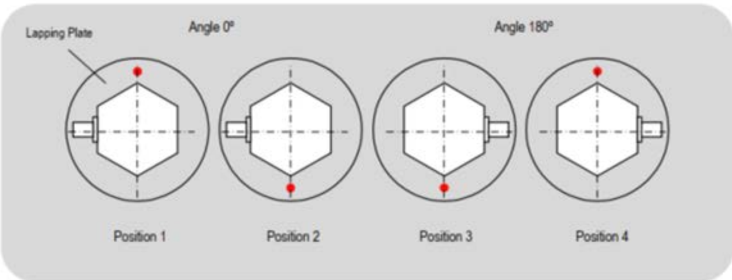

Figure 9: Reference surface and measurement positions for SE transducer

On top of the double-ended accelerometer:

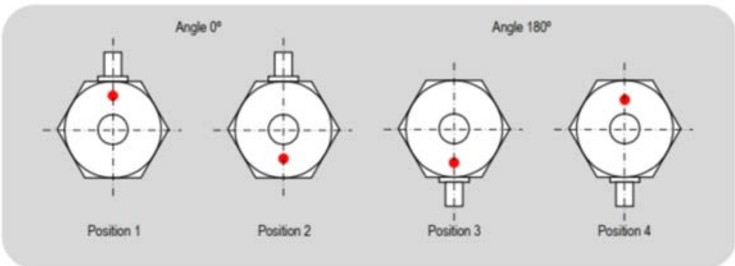

Figure 10: Reference surface and measurement positions for BtoB transducer

NPLI Measurement Methodology:

CSIR-National Physical Laboratory, India realizes the primary vibration standard in frequency range from 5 Hz to 10 kHz. The primary vibration calibration standard is based on the absolute calibration of vibration transducers as per ISO 16063-11 by laser interferometry technique using sine approximation method in range of 5 Hz to 10 kHz.

The primary vibration calibration system comprises of a TMS 9155D system that utilizes a Homodyne Renishaw, RLE 10 fibre optic laser encoder and a PCB 396C11 air bearing exciter with TMS Model 2100E21C power amplifier. The system used PCI 4461 and PCI 6251 data acquisition. A PCB 443B101 dual-mode charge amplifier is used for automated computer-controlled gain. The quadrature signals are online monitored using Renishaw software (RLE10-D_alignment.vi tool) and acquired through National Instruments, NI PCI 6251 card.

The laser beam is focused on the reference surface of the two piezoelectric accelerometers as mentioned in the protocol for determining the magnitude (S_{qa}) and phase (ϕ_{qa}) of their complex charge sensitivities. The homodyne interferometric signals: in-phase (I) and quadrature (Q) generated are analyzed to form a Lissajous figure which is a perfect circle. The lack of quadrature is corrected by least square ellipse fitting technique stipulated by Heydemann and digital band pass filtering is implemented to enhance the signal to noise ratio and circumvent any gain fluctuations and distortion, noise and hum in the measurements. The analogue quadrature signals corrected by Heydemann approach is demodulated using arc-tangent function with appropriate phase unwrapping and band pass filtering so as to obtain the accelerometer complex sensitivity (magnitude and phase). The total harmonic distortion (THD) is monitored while the calibration progresses at lower frequencies as it gives the signal integrity check in conjunction with signal to RMS ratio.

The conditioning amplifiers used (Dual mode charge amplifier, PCB 443B101) is calibrated using a 1 nF precision capacitor, which is traceable to the SI through the national capacitance standard.

8.2 Participants Reported Results

Table 2: Reported participant's results for the magnitude (S_{qa}) of the SE with relative expanded uncertainties (k = 2)

	NMISA		NIMT		NPLI		INTI	
f	X_i	U_{rel},X_i	X_i	U_{rel},X_i	X_i	U_{rel},X_i	X_i	U_{rel},X_i
Hz	pC/(m/s²)	%	pC/(m/s²)	%	pC/(m/s²)	%	pC/(m/s²)	%
5,0	0,12892	0,3	0,12903	0,3	0,12890	1,0		
6,3	0,12890	0,3	0,12898	0,3	0,12880	1,0		
8,0	0,12876	0,3	0,12888	0,3	0,12880	1,0		
10,0	0,12882	0,3	0,12883	0,3	0,12870	1,0	0,12917	1,2
12,5	0,12878	0,3	0,12890	0,2	0,12870	1,0	0,12905	1,2
16,0	0,12877	0,3	0,12888	0,3	0,12870	1,0	0,12887	1,2

	NMISA		NIMT		NPLI		INTI	
f	X_i	U_{rel},X_i	X_i	U_{rel},X_i	X_i	U_{rel},X_i	X_i	U_{rel},X_i
Hz	pC/(m/s²)	%	pC/(m/s²)	%	pC/(m/s²)	%	pC/(m/s²)	%
20,0	0,12870	0,3	0,12877	0,3	0,12870	1,0	0,12879	1,2
25,0	0,12870	0,3	0,12883	0,3	0,12870	1,0	0,12876	1,2
31,5	0,12869	0,3	0,12881	0,3	0,12860	1,0	0,12875	1,2
40,0	0,12869	0,3	0,12880	0,3	0,12860	1,0	0,12873	1,2
50,0	0,12869	0,3	0,12877	0,3	0,12860	1,0	0,12870	1,2
63,0	0,12869	0,3	0,12877	0,3	0,12860	1,0	0,12869	0,5
80,0	0,12870	0,3	0,12878	0,3	0,12860	1,0	0,12864	0,5
100	0,12871	0,3	0,12883	0,3	0,12860	1,0	0,12866	0,5
125	0,12876	0,3	0,12875	0,3	0,12850	1,0	0,12859	0,5
160	0,12888	0,3	0,12870	0,3	0,12850	1,0	0,12857	0,5
200	0,12853	0,3	0,12878	0,3	0,12850	1,0	0,12868	0,5
250	0,12856	0,3	0,12876	0,3	0,12850	1,0	0,12874	0,6
315	0,12858	0,3	0,12875	0,3	0,12850	1,0	0,12876	0,6
400	0,12861	0,3	0,12877	0,3	0,12850	1,0	0,12876	0,6
500	0,12863	0,3	0,12880	0,3	0,12850	1,0	0,12878	0,6
630	0,12866	0,3	0,12881	0,3	0,12860	1,0	0,12885	0,6
800	0,12869	0,3	0,12894	0,3	0,12870	1,0	0,12901	0,6
1 000	0,12873	0,5	0,12888	0,3	0,12880	1,0	0,12908	0,6
1 250	0,12884	0,5	0,12897	0,3	0,12850	1,0	0,12885	1,5
1 500	0,12891	0,5	0,12906	0,3	0,12850	1,0	0,12895	1,5
1 600	0,12899	0,5	0,12914	0,3	0,12850	1,0	0,12902	1,5
2 000	0,12919	0,5	0,12937	0,3	0,12860	1,0	0,12921	1,5
2 500	0,12948	0,5	0,12974	0,3	0,12870	1,0	0,12954	1,5
3 000	0,12991	0,5	0,13017	0,3	0,12890	1,0	0,12987	1,5
3 150	0,13010	0,5	0,13035	0,3	0,12900	1,0	0,13004	1,5
3 500	0,13047	0,5	0,13074	0,3	0,12920	1,0	0,13041	1,5
4 000	0,13115	0,5	0,13132	0,3	0,12940	1,0	0,13087	1,5
4 500	0,13182	0,5	0,13207	0,3	0,12950	1,0	0,13133	1,5
5 000	0,13250	0,8	0,13281	0,3	0,12960	1,0	0,13235	1,5
5 500	0,13334	0,8	0,13374	0,6	0,13000	1,5	0,13274	1,5
6 000	0,13421	0,8	0,13455	0,6	0,13010	1,5	0,13384	1,5
6 300	0,13476	0,8	0,13525	0,6	0,13030	1,5	0,13418	1,5
6 500	0,13518	0,8	0,13572	0,6	0,13080	1,5	0,13508	1,5
7 000	0,13634	0,8	0,13689	0,6	0,13080	1,5	0,13557	1,5
7 500	0,13760	1,2	0,13845	0,6	0,13090	1,5	0,13655	1,5
8 000	0,13892	1,2	0,13975	0,6	0,13090	1,5	0,13759	1,5
8 500	0,14048	1,2	0,14136	0,6	0,13160	1,5	0,13878	1,5
9 000	0,14076	1,2	0,14177	0,6	0,13180	1,5	0,14030	1,5
9 500	0,14313	1,2	0,14415	0,6	0,13260	1,5	0,14073	1,5
10 000	0,14502	1,2	0,14630	0,6	0,13330	1,5	0,14270	1,5
10 500	0,14698	1,2	0,14826	1,1				
11 000	0,14904	1,2	0,15048	1,1				
11 500	0,15110	1,2	0,15280	1,1				

	NMISA		NIMT		NPLI		INTI	
f	X_i	U_{rel},X_i	X_i	U_{rel},X_i	X_i	U_{rel},X_i	X_i	U_{rel},X_i
Hz	pC/(m/s²)	%	pC/(m/s²)	%	pC/(m/s²)	%	pC/(m/s²)	%
12 000	0,15342	1,2	0,15546	1,1				
12 500	0,15601	1,4	0,15821	1,1				
13 000	0,15874	1,4	0,16105	1,1				
13 500	0,16155	1,4	0,16410	1,1				
14 000	0,16463	1,4	0,16764	1,1				
14 500	0,16799	1,4	0,17136	1,1				
15 000	0,17164	1,4	0,17508	1,1				
15 500	0,17526	1,8	0,17905	1,4				
16 000	0,17945	1,8	0,18361	1,4				
16 500	0,18374	1,8	0,18855	1,4				
17 000	0,18853	1,8	0,19356	1,4				
17 500	0,19365	1,8	0,19889	1,4				
18 000	0,19928	1,8	0,20467	1,4				
18 500	0,20554	1,8	0,21090	1,4				
19 000	0,21229	1,8	0,21787	1,4				
19 500	0,22104	1,8	0,22557	1,4				
20 000	0,22761	1,8	0,23392	1,4				

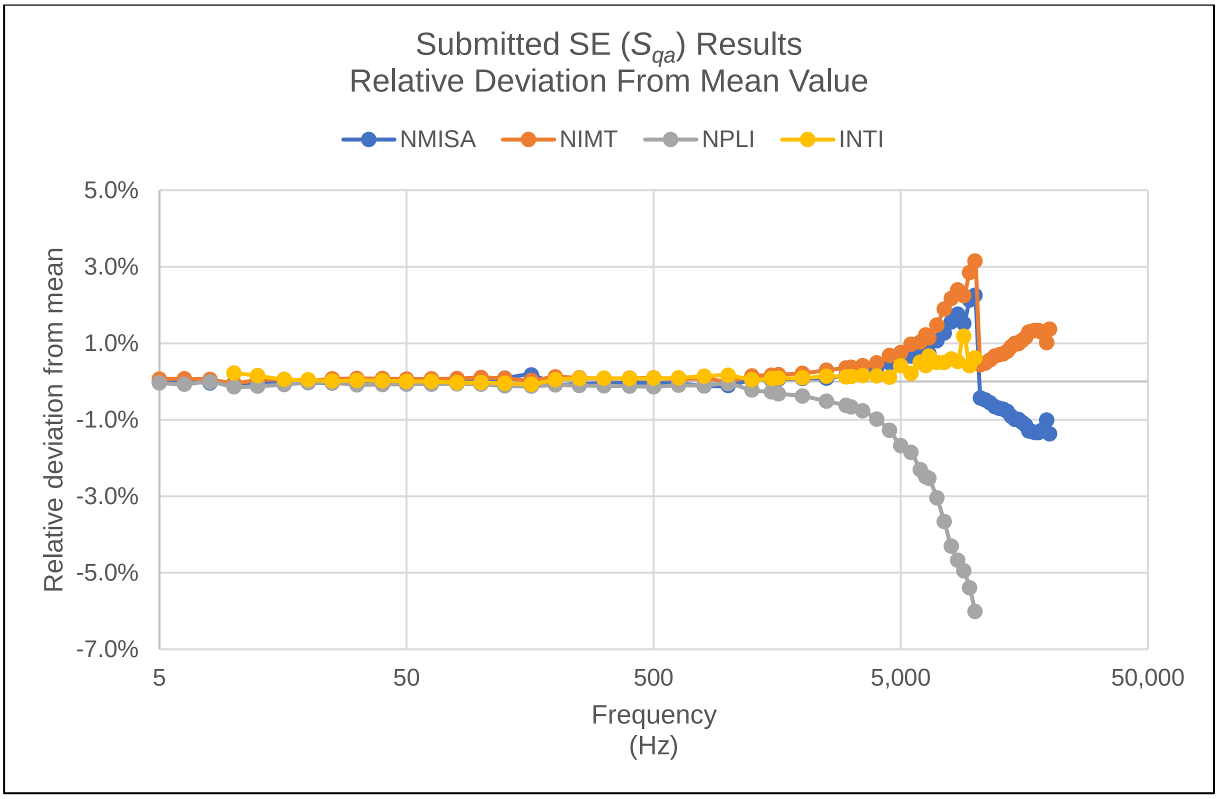

Figure 11: Submitted SE *(S_{qa})* magnitude results relative deviation from the mean value.

Table 3: Reported participant's results for the magnitude (S_{qa}) of the BtoB with relative expanded uncertainties (k = 2)

	NMISA		NIMT		NPLI		INTI	
f	X_i	U_{rel},X_i	X_i	U_{rel},X_i	X_i	U_{rel},X_i	X_i	U_{rel},X_i
Hz	**pC/(m/s²)**	**%**	**pC/(m/s²)**	**%**	**pC/(m/s²)**	**%**	**pC/(m/s²)**	**%**
5,0	0,18497	0,3	0,18476	0,3	0,18460	1,0		
6,3	0,18494	0,3	0,18485	0,3	0,18430	1,0		
8,0	0,18483	0,3	0,18483	0,3	0,18430	1,0		
10,0	0,18480	0,3	0,18479	0,3	0,18430	1,0	0,18456	1,2
12,5	0,18471	0,3	0,18474	0,2	0,18420	1,0	0,18440	1,2
16,0	0,18466	0,3	0,18467	0,3	0,18410	1,0	0,18420	1,2
20,0	0,18457	0,3	0,18461	0,3	0,18400	1,0	0,18408	1,2
25,0	0,18449	0,3	0,18454	0,3	0,18390	1,0	0,18402	1,2
31,5	0,18440	0,3	0,18446	0,3	0,18380	1,0	0,18398	1,2
40,0	0,18431	0,3	0,18440	0,3	0,18370	1,0	0,18389	1,2
50,0	0,18424	0,3	0,18430	0,3	0,18370	1,0	0,18385	1,2
63,0	0,18417	0,3	0,18421	0,3	0,18360	1,0	0,18383	0,5
80,0	0,18412	0,3	0,18414	0,3	0,18360	1,0	0,18376	0,5
100	0,18403	0,3	0,18417	0,3	0,18350	1,0	0,18366	0,5
125	0,18397	0,3	0,18406	0,3	0,18340	1,0	0,18365	0,5
160	0,18401	0,3	0,18400	0,3	0,18340	1,0	0,18363	0,5
200	0,18369	0,3	0,18390	0,3	0,18330	1,0	0,18363	0,5
250	0,18363	0,3	0,18380	0,3	0,18320	1,0	0,18366	0,6
315	0,18358	0,3	0,18372	0,3	0,18310	1,0	0,18364	0,6
400	0,18351	0,3	0,18364	0,3	0,18300	1,0	0,18368	0,6
500	0,18344	0,3	0,18358	0,3	0,18300	1,0	0,18381	0,6
630	0,18339	0,3	0,18353	0,3	0,18300	1,0	0,18397	0,6
800	0,18331	0,3	0,18343	0,3	0,18310	1,0	0,18432	0,6
1 000	0,18326	0,5	0,18337	0,3	0,18330	1,0	0,18410	0,6
1 250	0,18324	0,5	0,18335	0,3	0,18290	1,0	0,18336	1,5
1 500	0,18319	0,5	0,18331	0,3	0,18300	1,0	0,18347	1,5
1 600	0,18324	0,5	0,18334	0,3	0,18300	1,0	0,18342	1,5
2 000	0,18324	0,5	0,18335	0,3	0,18310	1,0	0,18348	1,5
2 500	0,18332	0,5	0,18348	0,3	0,18330	1,0	0,18360	1,5
3 000	0,18342	0,5	0,18357	0,3	0,18370	1,0	0,18382	1,5
3 150	0,18354	0,5	0,18366	0,3	0,18390	1,0	0,18388	1,5
3 500	0,18368	0,5	0,18380	0,3	0,18430	1,0	0,18402	1,5
4 000	0,18403	0,5	0,18401	0,3	0,18530	1,0	0,18422	1,5
4 500	0,18427	0,5	0,18428	0,3	0,18550	1,0	0,18454	1,5
5 000	0,18458	0,8	0,18464	0,3	0,18400	1,0	0,18504	1,5
5 500	0,18499	0,8	0,18502	0,6	0,18420	1,5	0,18559	1,5
6 000	0,18534	0,8	0,18541	0,6	0,18450	1,5	0,18633	1,5
6 300	0,18562	0,8	0,18562	0,6	0,18520	1,5	0,18722	1,5
6 500	0,18591	0,8	0,18582	0,6	0,18590	1,5	0,18592	1,5
7 000	0,18647	0,8	0,18622	0,6	0,18550	1,5	0,18677	1,5
7 500	0,18701	1,2	0,18677	0,6	0,18640	1,5	0,18742	1,5

	NMISA		NIMT		NPLI		INTI	
f	X_i	U_{rel},X_i	X_i	U_{rel},X_i	X_i	U_{rel},X_i	X_i	U_{rel},X_i
Hz	pC/(m/s²)	%	pC/(m/s²)	%	pC/(m/s²)	%	pC/(m/s²)	%
8 000	0,18511	1,2	0,18743	0,6	0,18740	1,5	0,18809	1,5
8 500	0,18905	1,2	0,18804	0,6	0,18850	1,5	0,18884	1,5
9 000	0,19178	1,2	0,18866	0,7	0,18860	1,5	0,18926	1,5
9 500	0,19078	1,2	0,18926	0,8	0,19040	1,5	0,19031	1,5
10 000	0,18979	1,2	0,18999	0,8	0,19160	1,5	0,19113	1,5
10 500	0,19104	1,2	0,19093	1,3				
11 000	0,19197	1,2	0,19188	1,2				
11 500	0,19274	1,2	0,19284	1,2				
12 000	0,19353	1,2	0,19373	1,2				
12 500	0,19463	1,4	0,19466	1,2				
13 000	0,19574	1,4	0,19569	1,3				
13 500	0,19649	1,4	0,19660	1,3				
14 000	0,19782	1,4	0,19759	1,3				
14 500	0,19900	1,4	0,19858	1,3				
15 000	0,20037	1,4	0,19983	1,4				
15 500	0,20181	1,8	0,20105	1,6				
16 000	0,20331	1,8	0,20244	1,5				
16 500	0,20502	1,8	0,20382	1,5				
17 000	0,20700	1,8	0,20549	1,5				
17 500	0,20966	1,8	0,20695	1,6				
18 000	0,20880	1,8	0,20807	1,6				
18 500	0,20642	1,8	0,20925	1,7				
19 000	0,21165	1,8	0,21213	1,7				
19 500	0,21311	1,8	0,21650	1,7				
20 000	0,21518	1,8	0,22118	1,6				

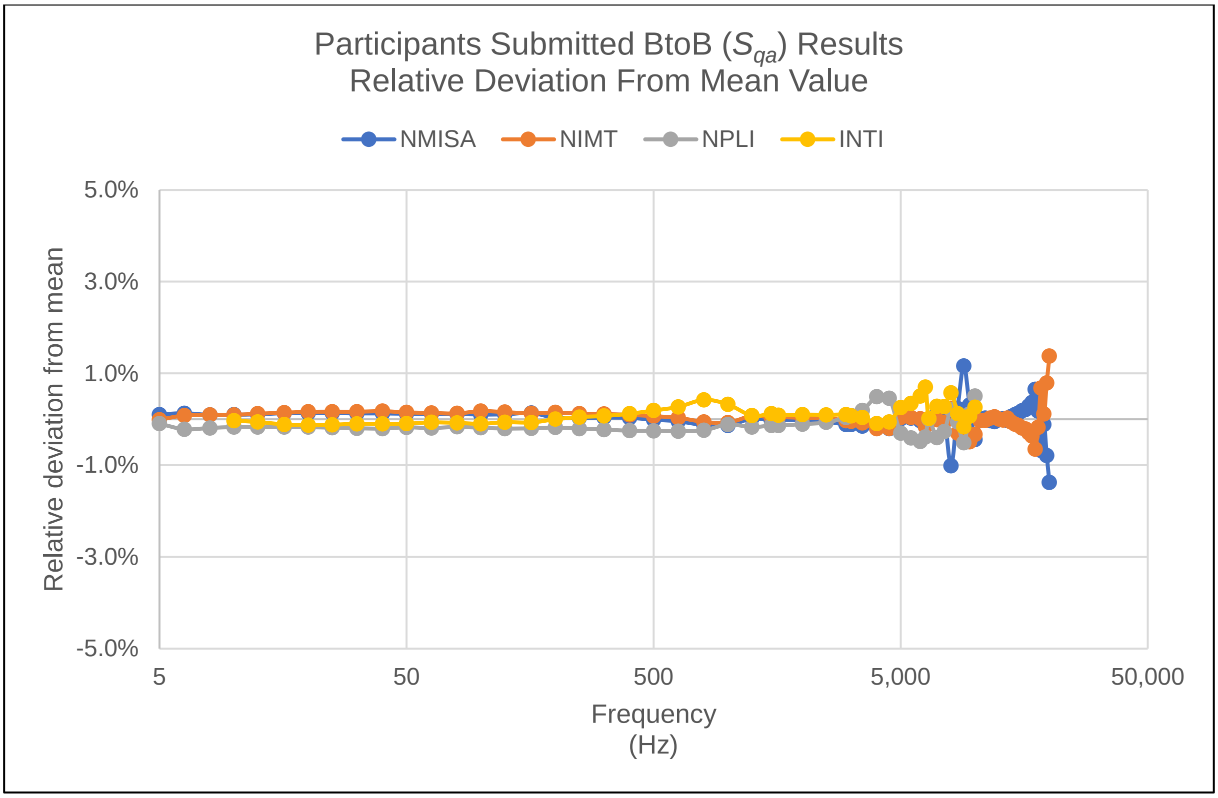

Figure 12: Submitted BtoB magnitude S_{qa} results relative deviation from the mean value.

Table 4: Reported participant's results for the phase shift (ϕ_{qa}) of the SE with expanded uncertainties (k = 2)

	NMISA		NIMT		NPLI		INTI	
f	ϕ_i	$U_{\phi i}$	ϕ_i	$U_{\phi i}$	ϕ_i	$U_{\phi i}$	ϕ_i	$U_{\phi i}$
Hz	°		°		°		°	
5,0	0,00	0,4	-0,22	0,3	0,26	1,5		
6,3	-0,02	0,4	-0,21	0,3	0,23	1,5		
8,0	-0,04	0,4	-0,21	0,3	0,23	1,5		
10,0	-0,01	0,4	-0,14	0,3	0,25	1,5		
12,5	-0,02	0,4	-0,10	0,3	0,21	1,5		
16,0	-0,03	0,4	-0,14	0,3	0,20	1,5		
20,0	-0,02	0,4	-0,13	0,3	0,19	1,5		
25,0	-0,01	0,4	-0,11	0,3	0,20	1,5		
31,5	-0,01	0,4	-0,12	0,3	0,19	1,5		
40,0	0,00	0,4	-0,12	0,3	0,13	1,5		
50,0	0,00	0,4	-0,12	0,3	0,06	1,5		
63,0	0,00	0,4	-0,11	0,3	0,05	1,5		
80,0	0,01	0,4	-0,10	0,3	0,09	1,5		
100	0,00	0,4	-0,10	0,3	0,14	1,5		
125	0,00	0,4	-0,08	0,3	0,08	1,5		
160	-0,22	0,4	-0,05	0,3	0,02	1,5		
200	-0,01	0,4	-0,05	0,3	-0,20	1,5		
250	0,01	0,4	-0,05	0,3	-0,16	1,5		
315	0,02	0,4	-0,04	0,3	-0,15	1,5		

	NMISA		NIMT		NPLI		INTI	
f	ϕ_i	$U_{\phi i}$	ϕ_i	$U_{\phi i}$	ϕ_i	$U_{\phi i}$	ϕ_i	$U_{\phi i}$
Hz	°		°		°		°	
400	0,03	0,4	-0,03	0,3	-0,18	1,5		
500	0,00	0,4	-0,03	0,3	-0,17	1,5		
630	0,00	0,4	-0,03	0,3	-0,20	1,5		
800	0,00	0,4	-0,02	0,3	-0,15	1,5		
1 000	0,01	0,4	-0,02	0,3	0,01	2,0		
1 250	-0,01	0,5	-0,03	0,3	-0,02	2,0		
1 500	-0,01	0,5	-0,04	0,3	-0,10	2,0		
1 600	-0,01	0,5	-0,03	0,3	-0,08	2,0		
2 000	-0,02	0,5	-0,05	0,3	-0,09	2,0		
2 500	0,00	0,5	-0,06	0,3	-0,09	2,0		
3 000	-0,04	0,5	-0,07	0,3	-0,12	2,0		
3 150	-0,02	0,5	-0,06	0,3	-0,10	2,0		
3 500	-0,05	0,5	-0,07	0,3	-0,16	2,0		
4 000	-0,06	0,5	-0,09	0,3	-0,21	2,0		
4 500	-0,04	0,5	-0,09	0,3	-0,27	2,0		
5 000	-0,09	0,8	-0,14	0,3	-0,29	2,0		
5 500	-0,12	0,8	-0,13	0,7	-0,33	2,0		
6 000	-0,14	0,8	-0,16	0,7	-0,35	2,0		
6 300	-0,14	0,8	-0,17	0,7	-0,39	2,0		
6 500	-0,12	0,8	-0,15	0,7	-0,38	2,0		
7 000	-0,10	0,8	-0,15	0,7	-0,43	2,0		
7 500	-0,14	0,8	-0,19	0,7	-0,45	2,0		
8 000	-0,19	0,8	-0,24	0,7	-0,47	2,0		
8 500	-0,23	0,8	-0,25	0,7	-0,48	2,0		
9 000	-0,23	0,8	-0,24	0,7	-0,51	2,0		
9 500	-0,16	0,8	-0,23	0,7	-0,38	2,0		
10 000	-0,21	0,8	-0,28	0,7	-0,40	2,0		
10 500	-0,25	0,8	-0,32	1,2				
11 000	-0,27	0,8	-0,36	1,2				
11 500	-0,25	0,8	-0,38	1,2				
12 000	-0,28	0,8	-0,36	1,2				
12 500	-0,31	1,3	-0,39	1,2				
13 000	-0,30	1,3	-0,41	1,2				
13 500	-0,34	1,3	-0,42	1,2				
14 000	-0,40	1,3	-0,46	1,2				
14 500	-0,39	1,3	-0,49	1,2				
15 000	-0,45	1,3	-0,58	1,2				
15 500	-0,44	1,6	-0,67	1,6				
16 000	-0,50	1,6	-0,72	1,6				
16 500	-0,52	1,6	-0,77	1,6				
17 000	-0,55	1,6	-0,86	1,6				
17 500	-0,58	1,6	-0,98	1,6				
18 000	-0,66	1,6	-0,98	1,6				

	NMISA		NIMT		NPLI		INTI	
f	ϕ_i	$U_{\phi i}$	ϕ_i	$U_{\phi i}$	ϕ_i	$U_{\phi i}$	ϕ_i	$U_{\phi i}$
Hz	°		°		°		°	
18 500	-0,81	1,6	-1,03	1,6				
19 000	0,97	1,6	-1,01	1,6				
19 500	-0,76	1,6	-1,02	1,6				
20 000	-0,89	1,6	-1,17	1,6				

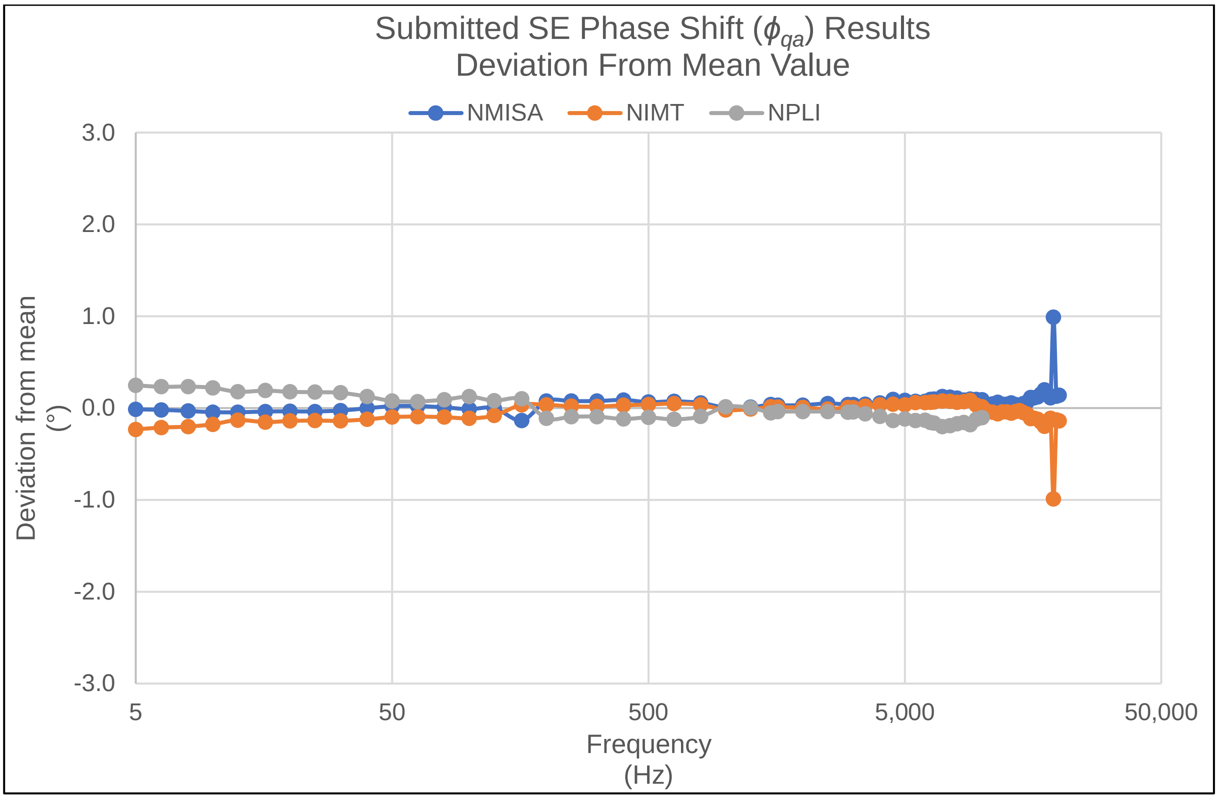

Figure 13: Submitted SE phase shift (ϕ_{qa}) results deviation from the mean value.

Table 5: Reported participant's results for the phase shift (ϕ_{qa}) of the BtoB with expanded uncertainties (k = 2)

	NMISA		NIMT		NPLI		INTI	
f	ϕ_i	$U_{\phi i}$	ϕ_i	$U_{\phi i}$	ϕ_i	$U_{\phi i}$	ϕ_i	$U_{\phi i}$
Hz	°		°		°		°	
5,0	180,21	0,4	0,11	0,3	-0,24	1,5		
6,3	180,15	0,4	0,03	0,3	-0,20	1,5		
8,0	180,08	0,4	-0,04	0,3	0,13	1,5		
10,0	180,04	0,4	-0,01	0,3	0,10	1,5		
12,5	180,01	0,4	-0,06	0,3	0,08	1,5		
16,0	179,97	0,4	-0,11	0,3	0,07	1,5		
20,0	179,95	0,4	-0,15	0,3	0,05	1,5		
25,0	179,93	0,4	-0,16	0,3	0,07	1,5		
31,5	179,91	0,4	-0,18	0,3	0,06	1,5		

	NMISA		NIMT		NPLI		INTI	
f	**ϕ_i**	**$U_{\phi i}$**	**ϕ_i**	**$U_{\phi i}$**	**ϕ_i**	**$U_{\phi i}$**	**ϕ_i**	**$U_{\phi i}$**
Hz	°		°		°		°	
40,0	179,90	0,4	-0,20	0,3	0,02	1,5		
50,0	179,90	0,4	-0,22	0,3	-0,05	1,5		
63,0	179,89	0,4	-0,22	0,3	-0,07	1,5		
80,0	179,89	0,4	-0,21	0,3	-0,04	1,5		
100	179,88	0,4	-0,21	0,3	-0,01	1,5		
125	179,87	0,4	-0,21	0,3	-0,05	1,5		
160	179,84	0,4	-0,20	0,3	-0,12	1,5		
200	179,84	0,4	-0,19	0,3	-0,21	1,5		
250	179,86	0,4	-0,19	0,3	-0,22	1,5		
315	179,87	0,4	-0,19	0,3	-0,23	1,5		
400	179,87	0,4	-0,19	0,3	-0,17	1,5		
500	179,84	0,4	-0,18	0,3	-0,19	1,5		
630	179,83	0,4	-0,22	0,3	-0,20	1,5		
800	179,83	0,4	-0,16	0,3	-0,18	1,5		
1 000	179,84	0,4	-0,19	0,3	-0,20	2,0		
1 250	179,82	0,5	-0,20	0,3	-0,25	2,0		
1 500	179,82	0,5	-0,20	0,3	-0,29	2,0		
1 600	179,81	0,5	-0,20	0,3	-0,30	2,0		
2 000	179,80	0,5	-0,20	0,3	-0,33	2,0		
2 500	179,81	0,5	-0,22	0,3	-0,37	2,0		
3 000	179,78	0,5	-0,23	0,3	-0,40	2,0		
3 150	179,80	0,5	-0,23	0,3	-0,43	2,0		
3 500	179,76	0,5	-0,24	0,3	-0,48	2,0		
4 000	179,76	0,5	-0,26	0,3	-0,55	2,0		
4 500	179,77	0,5	-0,27	0,3	-0,57	2,0		
5 000	179,74	0,8	-0,28	0,3	-0,65	2,0		
5 500	179,69	0,8	-0,29	0,7	-0,70	2,0		
6 000	179,70	0,8	-0,30	0,7	-0,81	2,0		
6 300	179,68	0,8	-0,32	0,7	-0,84	2,0		
6 500	179,69	0,8	-0,32	0,7	-0,87	2,0		
7 000	179,60	0,8	-0,33	0,7	-0,94	2,0		
7 500	179,47	0,8	-0,34	0,7	-1,00	2,0		
8 000	179,56	0,8	-0,36	0,7	-1,03	2,0		
8 500	180,25	0,8	-0,39	0,8	-1,13	2,0		
9 000	179,91	0,8	-0,41	0,7	-1,24	2,0		
9 500	179,21	0,8	-0,44	0,7	-1,39	2,0		
10 000	179,87	0,8	-0,47	0,7	-1,53	2,0		
10 500	179,67	0,8	-0,53	1,2				
11 000	179,62	0,8	-0,55	1,2				
11 500	179,57	0,8	-0,57	1,2				
12 000	179,51	0,8	-0,52	1,2				
12 500	179,48	1,3	-0,55	1,2				
13 000	179,50	1,3	-0,56	1,2				

	NMISA		NIMT		NPLI		INTI	
f	ϕ_i	$U_{\phi i}$	ϕ_i	$U_{\phi i}$	ϕ_i	$U_{\phi i}$	ϕ_i	$U_{\phi i}$
Hz	°		°		°		°	
13 500	179,45	1,3	-0,55	1,2				
14 000	179,38	1,3	-0,61	1,2				
14 500	179,38	1,3	-0,60	1,2				
15 000	179,35	1,3	-0,60	1,2				
15 500	179,32	1,6	-0,65	1,6				
16 000	179,27	1,6	-0,73	1,6				
16 500	179,20	1,6	-0,75	1,6				
17 000	179,07	1,6	-0,87	1,6				
17 500	178,73	1,6	-0,88	1,6				
18 000	177,39	1,6	-0,69	1,6				
18 500	179,35	1,6	-0,86	1,6				
19 000	179,21	1,6	-0,72	1,6				
19 500	179,20	1,6	-0,89	1,6				
20 000	179,18	1,6	-0,90	1,6				

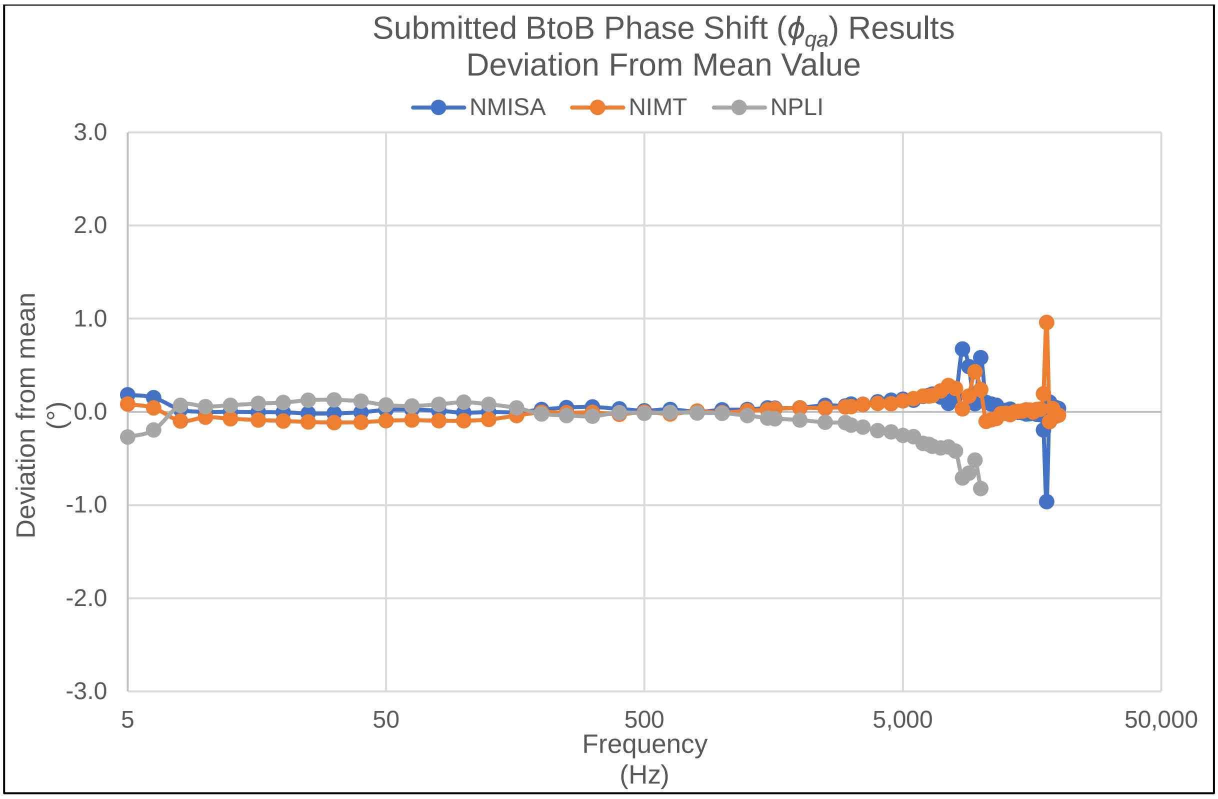

Figure 14: Submitted and corrected BtoB phase shift (ϕ_{qa}) results deviation from the mean value

8.2.1Corrected Acceleration Phase Direction

The phase shift data submitted by NIMT and NPLI did not conform to the acceleration phase direction specified in [1]. As a result, the pilot laboratory re-calculated the results submitted by the laboratories using (1). This correction did not have any effect on the UoM submitted for phase shift measurements by the two laboratories.

$$\dot{\emptyset}_i = 180 + \emptyset_i \qquad (1)$$

Following is the table documenting the phase shift data after the 180° correction was applied. The data in Table 8.5 was used to calculate the phase shift DoEs for the participants for the BtoB accelerometer.

Table 6: Reported participant's results for the phase shift of the BtoB with expanded uncertainties (*k* = 2), corrected for acceleration phase direction

	NMISA		NIMT		NPLI		INTI	
f	ϕ_i	$U_{\phi i}$	$\dot{\phi}_i$	$U_{\phi i}$	$\dot{\phi}_i$	$U_{\phi i}$	ϕ_i	$U_{\phi i}$
Hz	°		°		°		°	
5,0	180,21	0,4	180,11	0,3	179,76	1,5		
6,3	180,15	0,4	180,03	0,3	179,80	1,5		
8,0	180,08	0,4	179,96	0,3	180,13	1,5		
10,0	180,04	0,4	179,99	0,3	180,10	1,5		
12,5	180,01	0,4	179,94	0,3	180,08	1,5		
16,0	179,97	0,4	179,89	0,3	180,07	1,5		
20,0	179,95	0,4	179,85	0,3	180,05	1,5		
25,0	179,93	0,4	179,84	0,3	180,07	1,5		
31,5	179,91	0,4	179,82	0,3	180,06	1,5		
40,0	179,90	0,4	179,80	0,3	180,02	1,5		
50,0	179,90	0,4	179,78	0,3	179,95	1,5		
63,0	179,89	0,4	179,78	0,3	179,93	1,5		
80,0	179,89	0,4	179,79	0,3	179,96	1,5		
100	179,88	0,4	179,79	0,3	179,99	1,5		
125	179,87	0,4	179,79	0,3	179,95	1,5		
160	179,84	0,4	179,80	0,3	179,88	1,5		
200	179,84	0,4	179,81	0,3	179,79	1,5		
250	179,86	0,4	179,81	0,3	179,78	1,5		
315	179,87	0,4	179,81	0,3	179,77	1,5		
400	179,87	0,4	179,81	0,3	179,83	1,5		
500	179,84	0,4	179,82	0,3	179,81	1,5		
630	179,83	0,4	179,78	0,3	179,80	1,5		
800	179,83	0,4	179,84	0,3	179,82	1,5		
1 000	179,84	0,4	179,81	0,3	179,80	2,0		
1 250	179,82	0,5	179,80	0,3	179,75	2,0		
1 500	179,82	0,5	179,80	0,3	179,71	2,0		
1 600	179,81	0,5	179,80	0,3	179,70	2,0		
2 000	179,80	0,5	179,80	0,3	179,67	2,0		

	NMISA		NIMT		NPLI		INTI	
f	***ϕ**i*	***U**ϕi*	***ϕ̇**i*	***U**ϕi*	***ϕ̇**i*	***U**ϕi*	***ϕ**i*	***U**ϕi*
Hz	°		°		°		°	
2 500	179,81	0,5	179,78	0,3	179,63	2,0		
3 000	179,78	0,5	179,77	0,3	179,60	2,0		
3 150	179,80	0,5	179,77	0,3	179,57	2,0		
3 500	179,76	0,5	179,76	0,3	179,52	2,0		
4 000	179,76	0,5	179,74	0,3	179,45	2,0		
4 500	179,77	0,5	179,73	0,3	179,43	2,0		
5 000	179,74	0,8	179,72	0,3	179,35	2,0		
5 500	179,69	0,8	179,71	0,7	179,30	2,0		
6 000	179,70	0,8	179,70	0,7	179,19	2,0		
6 300	179,68	0,8	179,68	0,7	179,16	2,0		
6 500	179,69	0,8	179,68	0,7	179,13	2,0		
7 000	179,60	0,8	179,67	0,7	179,06	2,0		
7 500	179,47	0,8	179,66	0,7	179,00	2,0		
8 000	179,56	0,8	179,64	0,7	178,97	2,0		
8 500	180,25	0,8	179,61	0,8	178,87	2,0		
9 000	179,91	0,8	179,59	0,7	178,76	2,0		
9 500	179,21	0,8	179,56	0,7	178,61	2,0		
10 000	179,87	0,8	179,53	0,7	178,47	2,0		
10 500	179,67	0,8	179,47	1,2				
11 000	179,62	0,8	179,45	1,2				
11 500	179,57	0,8	179,43	1,2				
12 000	179,51	0,8	179,48	1,2				
12 500	179,48	1,3	179,45	1,2				
13 000	179,50	1,3	179,44	1,2				
13 500	179,45	1,3	179,45	1,2				
14 000	179,38	1,3	179,39	1,2				
14 500	179,38	1,3	179,40	1,2				
15 000	179,35	1,3	179,40	1,2				
15 500	179,32	1,6	179,35	1,6				
16 000	179,27	1,6	179,27	1,6				
16 500	179,20	1,6	179,25	1,6				
17 000	179,07	1,6	179,13	1,6				
17 500	178,73	1,6	179,12	1,6				
18 000	177,39	1,6	179,32	1,6				
18 500	179,35	1,6	179,14	1,6				
19 000	179,21	1,6	179,28	1,6				
19 500	179,20	1,6	179,11	1,6				
20 000	179,18	1,6	179,10	1,6				

9. Degree of Equivalence with Respect to the CIPM KCRVs

9.1. Linking Methodology

Introduction

A comparison within a regional metrology organization (RMO) can be approved as a regional key comparison within the framework of the CIPM MRA and included in the Key Comparison Data Base (KCDB) if the results are linked to the key comparison reference values (KCRVs) of the respective CIPM key comparison. It is therefore required to link the results of this AFRIMETS comparison to the CCAUV.V-K5 KCRVs.

The methodology used to link the results of the RMO key comparison, AFRIMETS.AUV.V-K5, 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 key comparison AFRIMETS.AUV.V-K5 is referred to as the RMO comparison.

Task of Linking

The participating laboratories of the RMO comparison submitted results for the calibration of a SE accelerometer and a BtoB accelerometer at specified frequencies in the frequency range from 10 Hz to 20 kHz, using laser interferometry in accordance with ISO 16063-11. The DoEs were calculated for the laboratories' results relative to the respective KCRV for the SE accelerometer as well as the BtoB accelerometer.

The linking task required the transformation of the RMO calibration results into quantities appropriate for the CIPM comparison enabling the transformed RMO results to be compared with the CIPM KCRVs. It includes the calculation of

a) The differences between the linking RMO results and the CIPM quantities for the NMI participating in both the CIPM and the RMO comparisons.
b) The differences between the transformed RMO results and the corresponding KCRVs for all participating laboratories.
c) The uncertainties associated with these differences.

9.2. Linking Procedure for Sensitivity Magnitude

The linking followed the method outlined in [8, 9, 10, 11, 12] which has been used in earlier accelerometer RMO comparisons. A summary mathematical deduction is shown.

Since the measurements were performed using primary methods and therefore none of the other participants are traceable to NMISA, no correlations were taken into account for uncertainty calculations of DoEs.

The measurand in the CIPM comparison is denoted by X. The values x_1, $u(x_1)$,..., 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, $u(y_1)$,..., y_M, $u(y_M)$ denote the best estimates and associated standard uncertainties of the laboratories.

Furthermore, $G = \{1,..., p\}$ ($p \leq \min(N, M)$) 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 laboratories. 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 with the associated uncertainty**.

Since no information about correlations was available, the estimators $x_1, ..., x_N, y_1, ..., y_M$ were treated as being uncorrelated.

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

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

$$y = \frac{\sum_{l \in G} \frac{x_l}{u^2(y_l)}}{\sum_{l \in G} \frac{1}{u^2(y_l)}} \qquad u^2(y) = \frac{1}{\sum_{l \in G} \frac{1}{u^2(y_l)}} \tag{3}$$

Note: In this RMO comparison, NMISA was the only linking laboratory. The measured values reported by NMISA with the associated uncertainties were used as the linking values, as was decided in the Calibration Protocol [5].

Then r is estimated according to

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

$z_l = ry_l$ denotes the corrected measurand in the regional comparison.

The uncertainty of DoE estimates on the difference

$$d_l = ry_l - x_l \tag{5}$$

is given by the following equations where

$$p_l = \frac{y_l}{y} \tag{6}$$

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 [11].

The calculations split up in two cases:

1) l is not a participant of the CIPM comparison. This means that *y* and *r* are independent of y_l.

By use of the law of error propagation we find

$$\begin{aligned} u^2(d_l) &= \left(\frac{\partial d_l}{\partial x}\right)^2 u^2(x) + \left(\frac{\partial d_l}{\partial y}\right)^2 u^2(y) + \left(\frac{\partial d_l}{\partial y_l}\right)^2 u^2(y_l) \\ &= (p_l - 1)^2 u^2(x) + r^2 (1 + p_l^2 \frac{u^2(y)}{u^2(y_l)}) u^2(y_l) \end{aligned} \tag{7}$$

2) l is a participant of the CIPM comparison. This means that *y* and *r* are dependent of y_l.

By use of the law of error propagation we find

$$\begin{aligned} u^2(d_l) &= \left(\frac{\partial d_l}{\partial x}\right)^2 u^2(x) + \left(\frac{\partial d_l}{\partial y_l}\right)^2 u^2(y_l) \\ &= (p_l - 1)^2 u^2(x) + r^2 (1 - p_l \frac{u^2(y)}{u^2(y_l)})^2 u^2(y_l) \end{aligned} \tag{8}$$

The degrees of equivalence are defined as the differences between the corrected results in the RMO comparison and the KCRV of the CIPM comparison, with the uncertainties on d_l with a confidence of 95 % or $k = 2$,

$$U_l = 2\sqrt{u^2(d_l)} \tag{9}$$

9.3. Linking Procedure for Phase Shift

For this comparison, a similar linking procedure for phase shift was followed as was reported in [11, 12].

The methodology is to remove the phase shift bias from the results of the single linking laboratory, NMISA, in AFRIMETS.AUV.V-K5 so to move it's phase results onto its linked results in CCAUV.V-K5. So doing compensate for the differences in phase of the devices used in the two comparisons. This shift, with the associated uncertainty, was then applied as an additive term to the participants (NIMT and NPLI) reported phase values in order to make their phase results comparable to those of CCAUV.V-K5.

Let $\delta(f)$ be the difference between the results of the linking laboratory in AFRIMETS.AUV.V-K5, $\varphi_l^{RMO}(f)$, and its results in CCAUV.V-K5, $\varphi_l^{CIPM}(f)$. For any single frequency, f,

$$\delta(f) = \varphi_l^{CIPM}(f) - \varphi_l^{RMO}(f) \tag{10}$$

The uncertainty of this difference is:

$$u_\delta^2 = (u_l^{CIPM})^2 + (u_l^{RMO})^2 \tag{11}$$

The covariance of the different results of the linking laboratory was considered to be negligible in the above equation.

The phase degree of equivalence of participant *i* of this AFRIMETS KC with respect to the CCAUV.V-K5 phase reference value (KCRV) is given by

$$d_i = \varphi_i^{RMO} + \delta - \varphi_l^{CIPM} \tag{12}$$

$$u_i^2 = (u_i^{RMO})^2 + u_\delta^2 - (u_l^{CIPM})^2 \tag{13}$$

provided that laboratory *i* is not the linking laboratory.

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 95 % or $k = 2$, i.e.

$$U_l = 2\sqrt{u^2(d_l)} \tag{14}$$

9.4 Laboratory Sensitivity Magnitude Degrees of Equivalence and Transformation Factors, *r*

In the subsequently presented tables results with $|D_i(f)| > U_{D_i}(f)$ where $U_{D_i}(f) = 2u_{D_i}(f)$ are marked by a yellow background.

9.4.1 The Double-Ended Accelerometer (SN 14317)

Table 7: Unilateral degrees of equivalence for the magnitude and Transformation Factors *r* of the BtoB

	NIMT		NPLI		INTI		CCAUV/ AFRIMETS	
f	d_i	$U(d_i)$	d_i	$U(d_i)$	d_i	$U(d_i)$	*r*	*u(r)*
Hz	fC/(m/s²)	fC/(m/s²)	fC/(m/s²)	fC/(m/s²)	fC/(m/s²)	fC/(m/s²)		
10	0,00	0,52	-0,34	1,33	-0,17	1,58	0,6927	0,0011
12,5	0,02	0,47	-0,36	1,33	-0,21	1,58	0,6931	0,0011
16	0,01	0,56	-0,39	1,33	-0,31	1,58	0,6933	0,0011
20	0,03	0,56	-0,39	1,33	-0,34	1,58	0,6935	0,0011
25	0,04	0,53	-0,41	1,33	-0,32	1,58	0,6939	0,0011
31,5	0,05	0,53	-0,42	1,33	-0,29	1,58	0,6943	0,0011
40	0,06	0,53	-0,42	1,33	-0,29	1,58	0,6945	0,0011
50	0,04	0,53	-0,38	1,33	-0,28	1,58	0,6947	0,0011
63	0,02	0,53	-0,40	1,33	-0,24	0,74	0,6950	0,0011
80	0,01	0,53	-0,36	1,33	-0,25	0,74	0,6951	0,0011
100	0,10	0,53	-0,37	1,33	-0,26	0,74	0,6954	0,0011
125	0,06	0,53	-0,40	1,33	-0,22	0,74	0,6955	0,0011
160	-0,01	0,53	-0,43	1,33	-0,26	0,74	0,6954	0,0011
200	0,15	0,53	-0,27	1,33	-0,04	0,75	0,6965	0,0011
250	0,12	0,53	-0,30	1,33	0,02	0,86	0,6968	0,0011
315	0,10	0,53	-0,33	1,33	0,05	0,86	0,6971	0,0011
400	0,08	0,53	-0,36	1,33	0,12	0,86	0,6974	0,0011
500	0,10	0,53	-0,31	1,33	0,26	0,86	0,6977	0,0011
630	0,10	0,53	-0,27	1,33	0,40	0,86	0,6981	0,0011
800	0,09	0,53	-0,15	1,34	0,71	0,86	0,6984	0,0011
1 000	0,08	0,74	0,03	1,43	0,59	1,00	0,6989	0,0018
1 250	0,08	0,74	-0,24	1,43	0,08	2,03	0,6992	0,0018
1 500	0,08	0,74	-0,13	1,43	0,20	2,03	0,6997	0,0018
1 600	0,07	0,74	-0,17	1,43	0,12	2,03	0,6998	0,0018
2 000	0,08	0,76	-0,10	1,43	0,17	2,03	0,7004	0,0018
2 500	0,11	0,76	-0,02	1,44	0,20	2,04	0,7012	0,0018
3 000	0,11	0,77	0,20	1,44	0,28	2,04	0,7023	0,0018
3 150	0,08	0,77	0,25	1,45	0,24	2,04	0,7028	0,0018
3 500	0,09	0,77	0,44	1,45	0,24	2,05	0,7033	0,0018
4 000	-0,02	0,77	0,89	1,46	0,13	2,05	0,7038	0,0018

	NIMT		NPLI		INTI		CCAUV/ AFRIMETS	
f	***d**$_i$*	***U** (**d**$_i$)*	***d**$_i$*	***U** (**d**$_i$)*	***d**$_i$*	***U** (**d**$_i$)*	***r***	***u(r)***
Hz	**fC/(m/s²)**	**fC/(m/s²)**	**fC/(m/s²)**	**fC/(m/s²)**	**fC/(m/s²)**	**fC/(m/s²)**		
4 500	0,01	0,77	0,87	1,47	0,19	2,06	0,7065	0,0019
5 000	0,04	1,13	-0,41	1,67	0,32	2,23	0,7076	0,0030
5 500	0,02	1,33	-0,56	2,22	0,42	2,24	0,7085	0,0030
6 000	0,05	1,34	-0,60	2,23	0,70	2,25	0,7104	0,0030
6 300	0,00	1,35	-0,30	2,25	1,14	2,27	0,7131	0,0031
6 500	-0,06	1,35	-0,01	2,25	0,00	2,25	0,7134	0,0031
7 000	-0,18	1,36	-0,69	2,26	0,22	2,27	0,7157	0,0031
7 500	-0,17	1,82	-0,44	2,58	0,30	2,59	0,7202	0,0046
8 000	1,69	1,85	1,67	2,62	2,17	2,63	0,7279	0,0046
8 500	-0,73	1,84	-0,40	2,60	-0,16	2,61	0,7186	0,0045
9 000	-2,22	1,87	-2,26	2,57	-1,79	2,58	0,7092	0,0046
9 500	-1,10	1,99	-0,27	2,64	-0,34	2,64	0,7217	0,0048
10 000	0,15	2,02	1,32	2,70	0,98	2,69	0,7323	0,0047
10 500	-0,08	2,43					0,7353	0,0049
11 000	-0,06	2,45					0,7409	0,0049
11 500	0,08	2,46					0,7469	0,0050
12 000	0,15	2,50					0,7520	0,0050
12 500	0,02	2,76					0,7570	0,0057
13 000	-0,04	2,80					0,7620	0,0058
13 500	0,08	2,87					0,7695	0,0058
14 000	-0,18	2,95					0,7757	0,0059
14 500	-0,33	3,00					0,7799	0,0060
15 000	-0,42	3,05					0,7848	0,0060
15 500	-0,60	3,78					0,7911	0,0077
16 000	-0,70	3,77					0,7988	0,0079
16 500	-0,97	3,82					0,8075	0,0080
17 000	-1,23	3,93					0,8148	0,0080
17 500	-2,22	4,13					0,8187	0,0081
18 000	-0,62	4,18					0,8389	0,0083
18 500	2,45	4,53					0,8667	0,0088
19 000	0,42	4,54					0,8635	0,0088
19 500	2,98	4,71					0,8791	0,0090
20 000	5,36	4,73					0,8931	0,0089

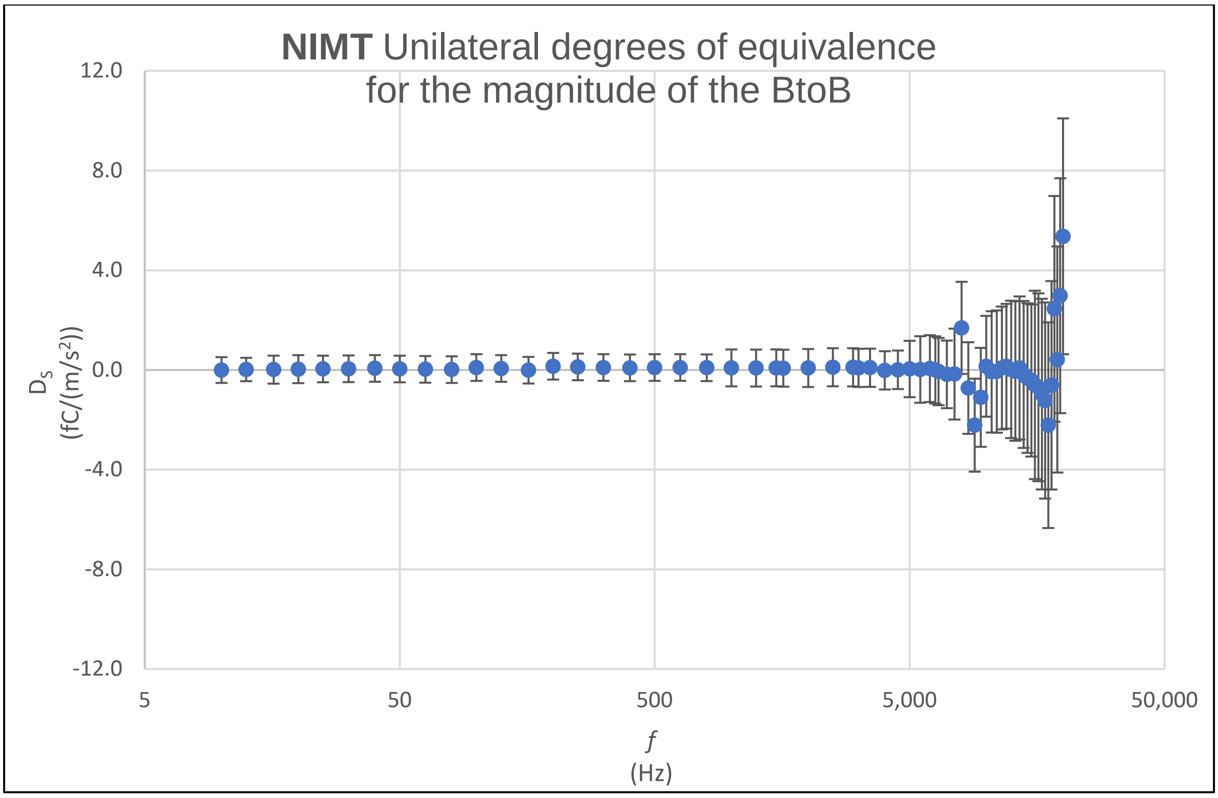

Figure 15: NIMT Magnitude unilateral degrees of equivalence of the BtoB

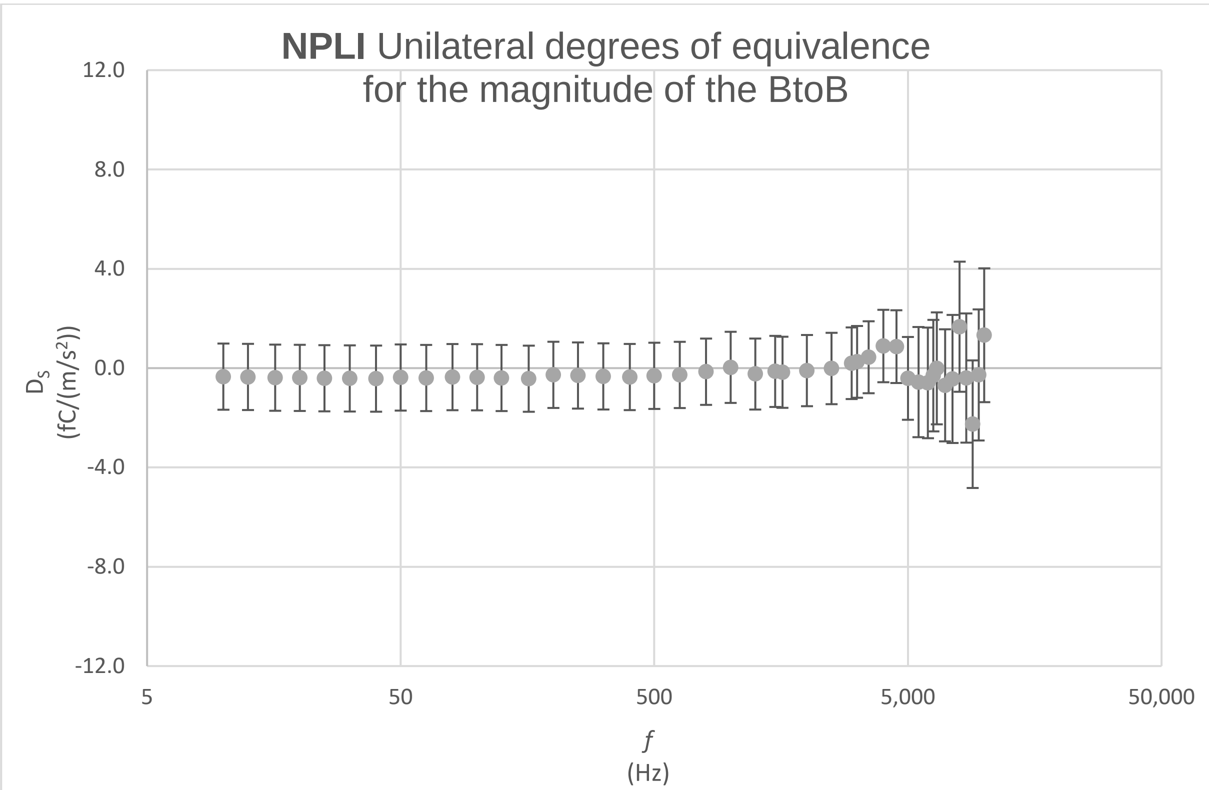

Figure 16: NPLI Magnitude unilateral degrees of equivalence of the BtoB

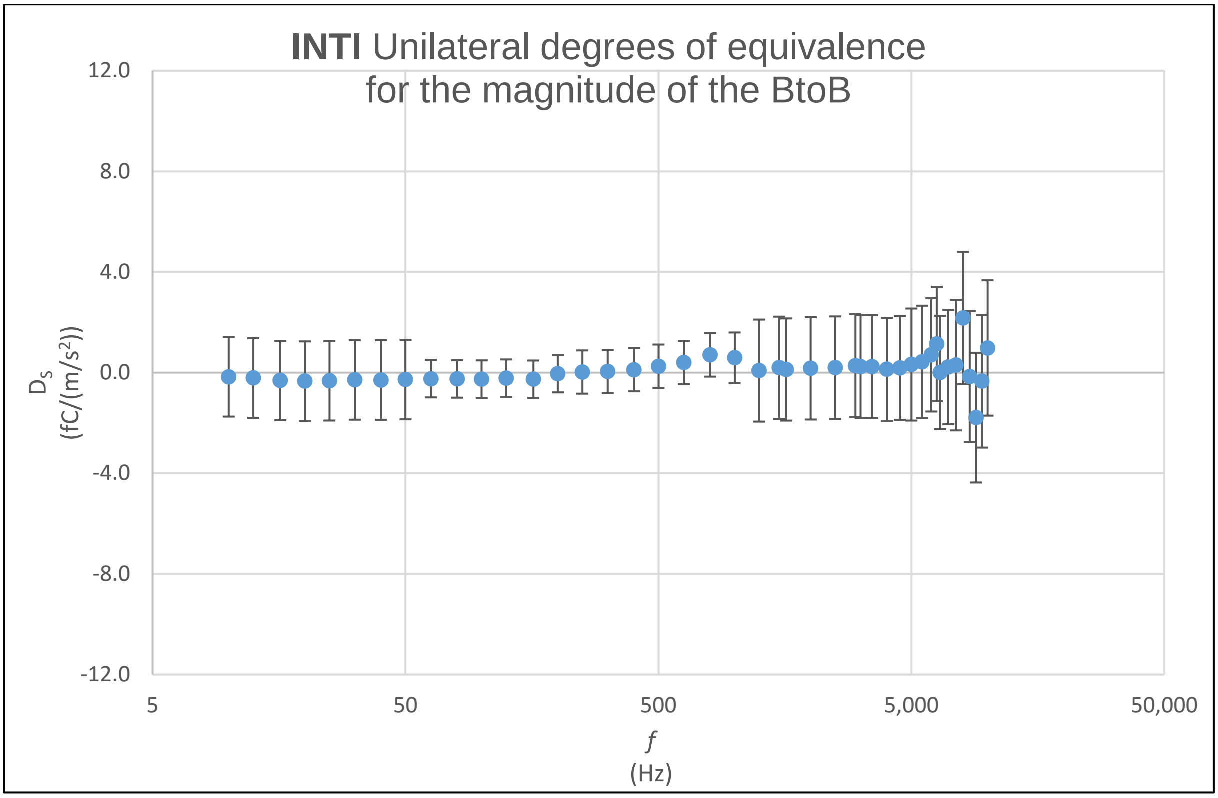

Figure 17: INTI Magnitude unilateral degrees of equivalence of the BtoB

9.4.2 The Single-Ended Accelerometer (SN 2860147)

Table 8: Unilateral degrees of equivalence for the magnitude and Transformation Factors *r* of the SE

	NIMT		NPLI		INTI		CCAUV/ AFRIMETS	
f	***d_i***	***U (d_i)***	***d_i***	***U (d_i)***	***d_i***	***U (d_i)***	***r***	***u(r)***
Hz	**fC/(m/s²)**	**fC/(m/s²)**	**fC/(m/s²)**	**fC/(m/s²)**	**fC/(m/s²)**	**fC/(m/s²)**		
10	0,01	0,53	-0,12	1,32	0,34	1,57	0,9826	0,0016
12,5	0,12	0,47	-0,08	1,32	0,26	1,57	0,9830	0,0016
16	0,10	0,56	-0,07	1,32	0,09	1,57	0,9830	0,0016
20	0,07	0,56	0,00	1,32	0,09	1,57	0,9835	0,0016
25	0,13	0,53	0,00	1,32	0,06	1,57	0,9835	0,0016
31,5	0,12	0,53	-0,09	1,32	0,06	1,57	0,9835	0,0016
40	0,11	0,53	-0,09	1,32	0,04	1,57	0,9835	0,0016
50	0,08	0,53	-0,09	1,32	0,01	1,57	0,9834	0,0016
63	0,08	0,53	-0,09	1,32	-0,01	0,74	0,9833	0,0016
80	0,08	0,53	-0,10	1,32	-0,06	0,74	0,9834	0,0016
100	0,12	0,53	-0,11	1,32	-0,05	0,74	0,9831	0,0016
125	0,00	0,53	-0,25	1,32	-0,16	0,74	0,9827	0,0016
160	-0,18	0,53	-0,37	1,32	-0,30	0,74	0,9818	0,0016
200	0,25	0,53	-0,02	1,32	0,15	0,74	0,9847	0,0016

	NIMT		NPLI		INTI		CCAUV/ AFRIMETS	
f	d_i	$U(d_i)$	d_i	$U(d_i)$	d_i	$U(d_i)$	*r*	*u(r)*
Hz	fC/(m/s²)	fC/(m/s²)	fC/(m/s²)	fC/(m/s²)	fC/(m/s²)	fC/(m/s²)		
250	0,20	0,53	-0,06	1,32	0,18	0,85	0,9845	0,0016
315	0,16	0,53	-0,08	1,32	0,17	0,85	0,9844	0,0016
400	0,15	0,53	-0,11	1,32	0,15	0,85	0,9842	0,0016
500	0,17	0,53	-0,13	1,32	0,15	0,85	0,9842	0,0016
630	0,15	0,53	-0,06	1,32	0,19	0,85	0,9841	0,0016
800	0,25	0,53	0,01	1,32	0,32	0,85	0,9841	0,0016
1 000	0,14	0,73	0,07	1,42	0,34	0,99	0,9842	0,0025
1 250	0,13	0,73	-0,33	1,41	0,01	2,00	0,9838	0,0026
1 500	0,15	0,73	-0,40	1,41	0,04	2,01	0,9842	0,0025
1 600	0,15	0,73	-0,48	1,41	0,03	2,01	0,9839	0,0025
2 000	0,18	0,76	-0,58	1,41	0,02	2,01	0,9838	0,0025
2 500	0,26	0,76	-0,77	1,42	0,06	2,02	0,9841	0,0026
3 000	0,26	0,76	-0,99	1,42	-0,04	2,02	0,9834	0,0026
3 150	0,24	0,76	-1,08	1,42	-0,06	2,02	0,9829	0,0026
3 500	0,26	0,76	-1,25	1,42	-0,06	2,03	0,9821	0,0026
4 000	0,17	0,76	-1,72	1,42	-0,28	2,03	0,9810	0,0026
4 500	0,24	0,77	-2,28	1,42	-0,49	2,04	0,9802	0,0025
5 000	0,30	1,12	-2,84	1,63	-0,14	2,21	0,9803	0,0040
5 500	0,39	1,33	-3,27	2,17	-0,59	2,21	0,9798	0,0042
6 000	0,33	1,34	-4,03	2,17	-0,36	2,23	0,9793	0,0042
6 300	0,48	1,35	-4,37	2,17	-0,57	2,23	0,9795	0,0042
6 500	0,53	1,35	-4,29	2,18	-0,09	2,25	0,9791	0,0042
7 000	0,54	1,36	-5,42	2,17	-0,75	2,25	0,9775	0,0042
7 500	0,84	1,84	-6,55	2,46	-1,02	2,57	0,9780	0,0060
8 000	0,81	1,85	-7,84	2,46	-1,30	2,58	0,9769	0,0060
8 500	0,85	1,86	-8,65	2,46	-1,66	2,59	0,9734	0,0060
9 000	0,99	1,89	-8,80	2,48	-0,45	2,64	0,9813	0,0061
9 500	0,99	1,90	-10,27	2,48	-2,34	2,63	0,9746	0,0061
10 000	1,24	1,93	-11,41	2,49	-2,26	2,67	0,9730	0,0061
10 500	1,25	2,37					0,9692	0,0063
11 000	1,40	2,40					0,9670	0,0063
11 500	1,64	2,44					0,9671	0,0063
12 000	1,96	2,47					0,9655	0,0064
12 500	2,12	2,75					0,9641	0,0073
13 000	2,23	2,80					0,9618	0,0072
13 500	2,45	2,83					0,9573	0,0073
14 000	2,88	2,89					0,9566	0,0074
14 500	3,22	2,96					0,9562	0,0074
15 000	3,27	3,00					0,9505	0,0073
15 500	3,60	3,86					0,9487	0,0093

	NIMT		NPLI		INTI		CCAUV/ AFRIMETS	
f	***dᵢ***	***U* (*dᵢ*)**	***dᵢ***	***U* (*dᵢ*)**	***dᵢ***	***U* (*dᵢ*)**	***r***	***u(r)***
Hz	**fC/(m/s²)**	**fC/(m/s²)**	**fC/(m/s²)**	**fC/(m/s²)**	**fC/(m/s²)**	**fC/(m/s²)**		
16 000	3,96	3,97					0,9500	0,0094
16 500	4,53	4,05					0,9426	0,0094
17 000	4,72	4,15					0,9404	0,0094
17 500	4,90	4,24					0,9357	0,0094
18 000	5,04	4,36					0,9345	0,0094
18 500	4,97	4,46					0,9278	0,0094
19 000	5,11	4,53					0,9144	0,0091
19 500	4,12	4,68					0,9096	0,0091
20 000	5,74	4,86					0,9087	0,0091

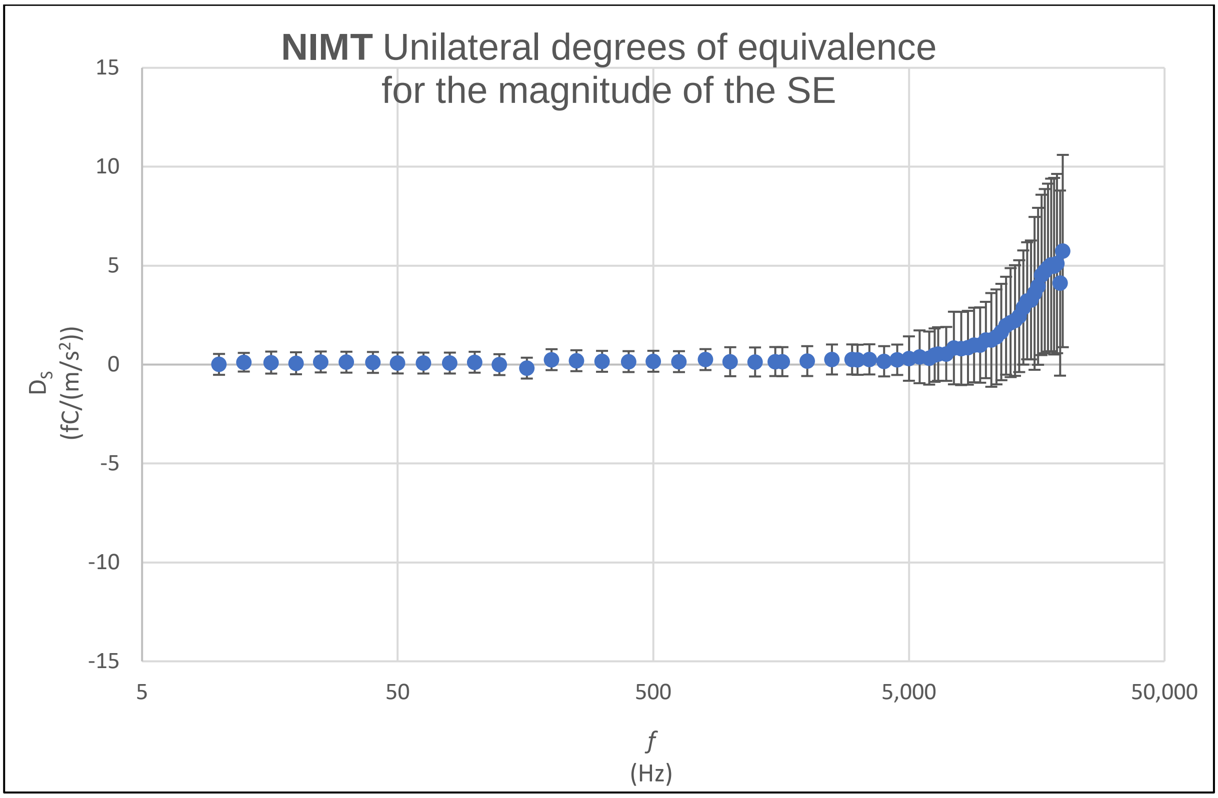

Figure 18: NIMT Magnitude unilateral degrees of equivalence of the SE

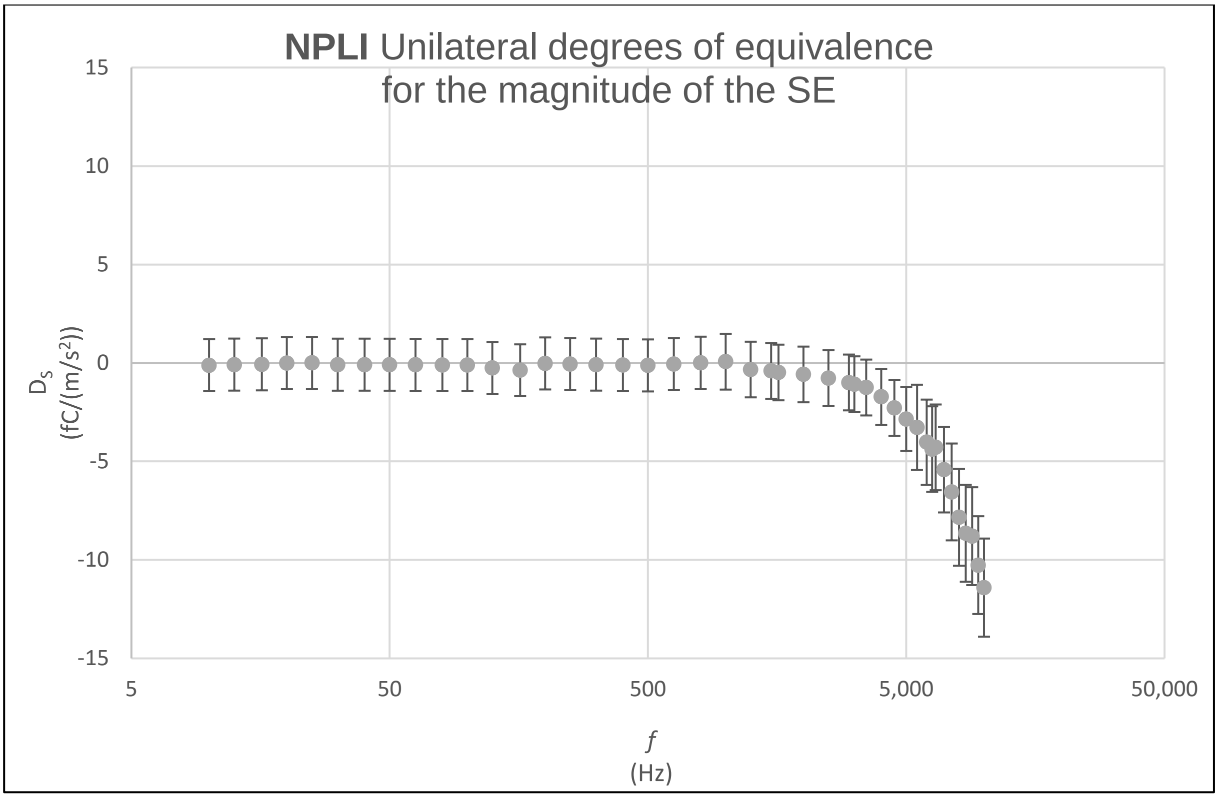

Figure 19: NPLI Magnitude unilateral degrees of equivalence of the SE

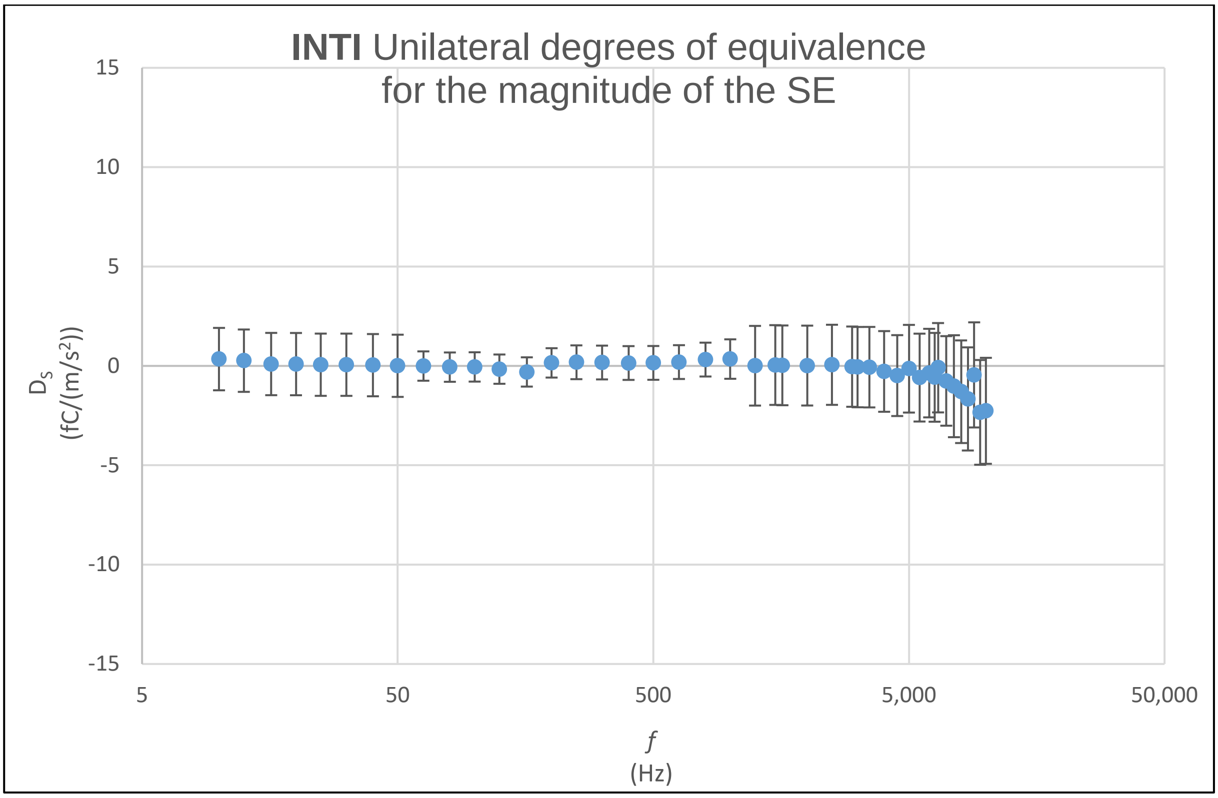

Figure 20: INTI Magnitude unilateral degrees of equivalence of the SE

9.5 Laboratory Phase Shift Degrees of Equivalence and Correction Values, *δ*

9.5.1 The Double-Ended Accelerometer (SN 14317)

Table 9: Unilateral degrees of equivalence for the phase and correction values *δ* of the BtoB

	NIMT		NPLI		CCAUV - AFRIMETS	
f	***d_i***	***U* (*d_i*)**	***d_i***	***U* (*d_i*)**	***δ***	***u(δ)***
Hz	**(°)**	**(°)**	**(°)**	**(°)**		
10	-0,06	0,5	0,06	1,6	-0,0563	0,22
12,5	-0,07	0,5	0,07	1,6	-0,0209	0,22
16	-0,08	0,5	0,09	1,6	0,0196	0,22
20	-0,09	0,5	0,10	1,6	0,0423	0,22
25	-0,09	0,5	0,14	1,6	0,0551	0,22
31,5	-0,10	0,5	0,15	1,6	0,0718	0,22
40	-0,11	0,5	0,12	1,6	0,0794	0,22
50	-0,12	0,5	0,05	1,6	0,0833	0,22
63	-0,11	0,5	0,04	1,6	0,0897	0,22
80	-0,11	0,5	0,07	1,6	0,0781	0,22
100	-0,09	0,5	0,11	1,6	0,1015	0,22
125	-0,08	0,5	0,08	1,6	0,1103	0,22
160	-0,04	0,5	0,05	1,6	0,1450	0,22
200	-0,03	0,5	-0,05	1,6	0,1585	0,22
250	-0,06	0,5	-0,09	1,6	0,1364	0,22
315	-0,06	0,5	-0,10	1,6	0,1212	0,22
400	-0,06	0,5	-0,04	1,6	0,1193	0,22
500	-0,01	0,5	-0,03	1,6	0,1422	0,22
630	-0,05	0,5	-0,03	1,6	0,1491	0,22
800	0,01	0,5	-0,01	1,6	0,1437	0,22
1 000	-0,03	0,5	-0,04	2,0	0,1404	0,22
1 250	-0,01	0,6	-0,07	2,1	0,1268	0,27
1 500	-0,02	0,6	-0,11	2,1	0,1102	0,27
1 600	-0,01	0,6	-0,11	2,1	0,1081	0,27
2 000	0,00	0,6	-0,13	2,1	0,1156	0,27
2 500	-0,03	0,6	-0,18	2,1	0,0928	0,27
3 000	-0,01	0,6	-0,18	2,1	0,1136	0,27
3 150	-0,03	0,6	-0,23	2,1	0,0721	0,28
3 500	0,00	0,6	-0,24	2,1	0,0822	0,28
4 000	-0,01	0,6	-0,31	2,1	0,0544	0,28
4 500	-0,04	0,6	-0,34	2,1	0,0082	0,28
5 000	-0,02	0,9	-0,39	2,2	-0,0002	0,42
5 500	0,02	1,0	-0,39	2,2	0,0363	0,45

	NIMT		NPLI		CCAUV - AFRIMETS	
f	***d_i***	***U* (*d_i*)**	***d_i***	***U* (*d_i*)**	***δ***	***u(δ)***
Hz	**(°)**	**(°)**	**(°)**	**(°)**		
6 000	0,00	1,1	-0,51	2,2	0,0300	0,45
6 300	-0,01	1,1	-0,52	2,2	0,0304	0,45
6 500	-0,01	1,1	-0,56	2,2	-0,0190	0,45
7 000	0,07	1,1	-0,54	2,2	0,0190	0,45
7 500	0,19	1,1	-0,47	2,2	0,0735	0,45
8 000	0,09	1,1	-0,59	2,2	0,0645	0,46
8 500	-0,64	1,1	-1,38	2,2	-0,6832	0,46
9 000	-0,32	1,1	-1,15	2,2	-0,4130	0,46
9 500	0,34	1,1	-0,60	2,2	0,6284	0,47
10 000	-0,34	1,0	-1,40	2,2	0,0005	0,47
10 500	-0,20	1,4			-0,2923	0,50
11 000	-0,17	1,4			0,0916	0,55
11 500	-0,14	1,4			0,1097	0,55
12 000	-0,04	1,4			0,1797	0,55
12 500	-0,03	1,8			0,2875	0,76
13 000	-0,06	1,8			0,1974	0,77
13 500	0,00	1,8			0,2270	0,77
14 000	0,01	1,8			0,2707	0,77
14 500	0,02	1,8			-0,2511	0,72
15 000	0,04	1,8			0,2822	0,77
15 500	0,04	2,2			-0,3785	0,87
16 000	-0,01	2,2			0,3818	0,94
16 500	0,05	2,2			0,4641	0,94
17 000	0,06	2,2			0,5961	0,94
17 500	0,39	2,2			0,9420	0,94
18 000	1,92	2,2			2,2494	0,94
18 500	-0,21	2,2			0,3015	0,94
19 000	0,07	2,2			0,4217	0,94
19 500	-0,09	2,2			0,5280	0,94
20 000	-0,07	2,2			0,4902	0,94

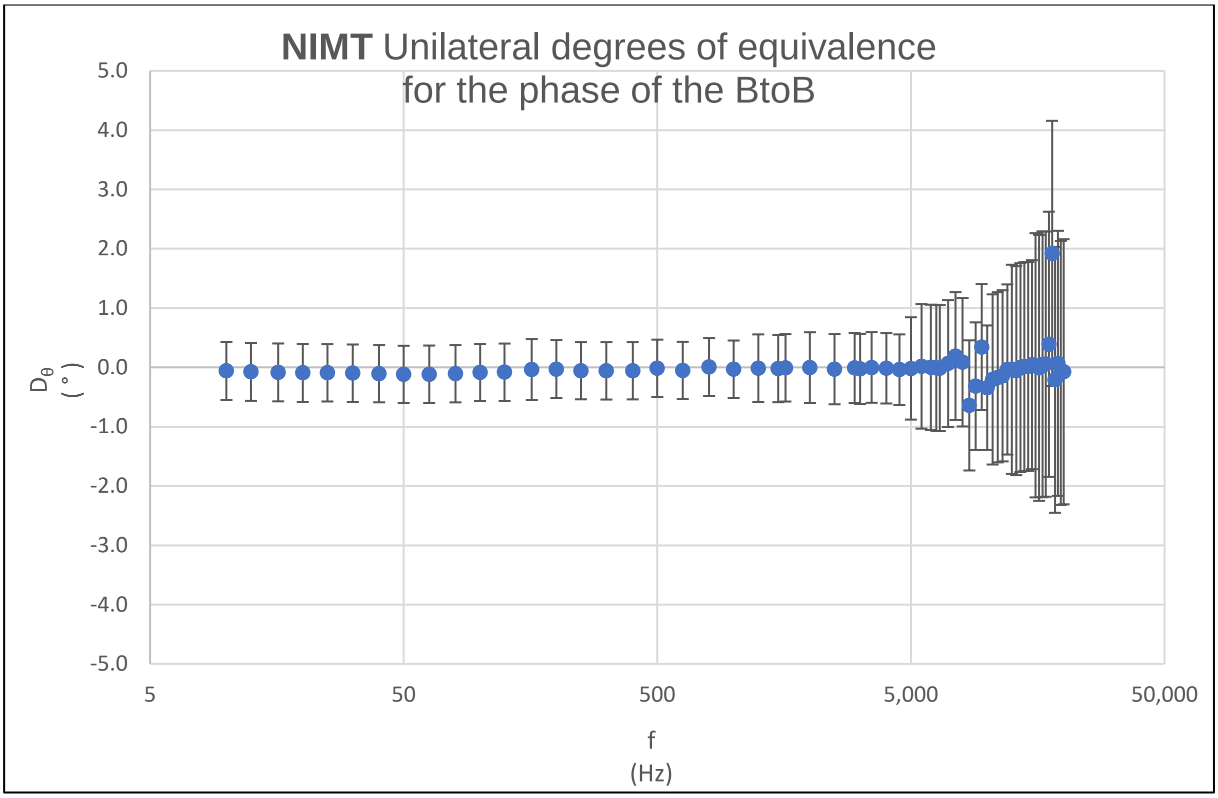

Figure 21: NIMT Phase unilateral degrees of equivalence of the BtoB

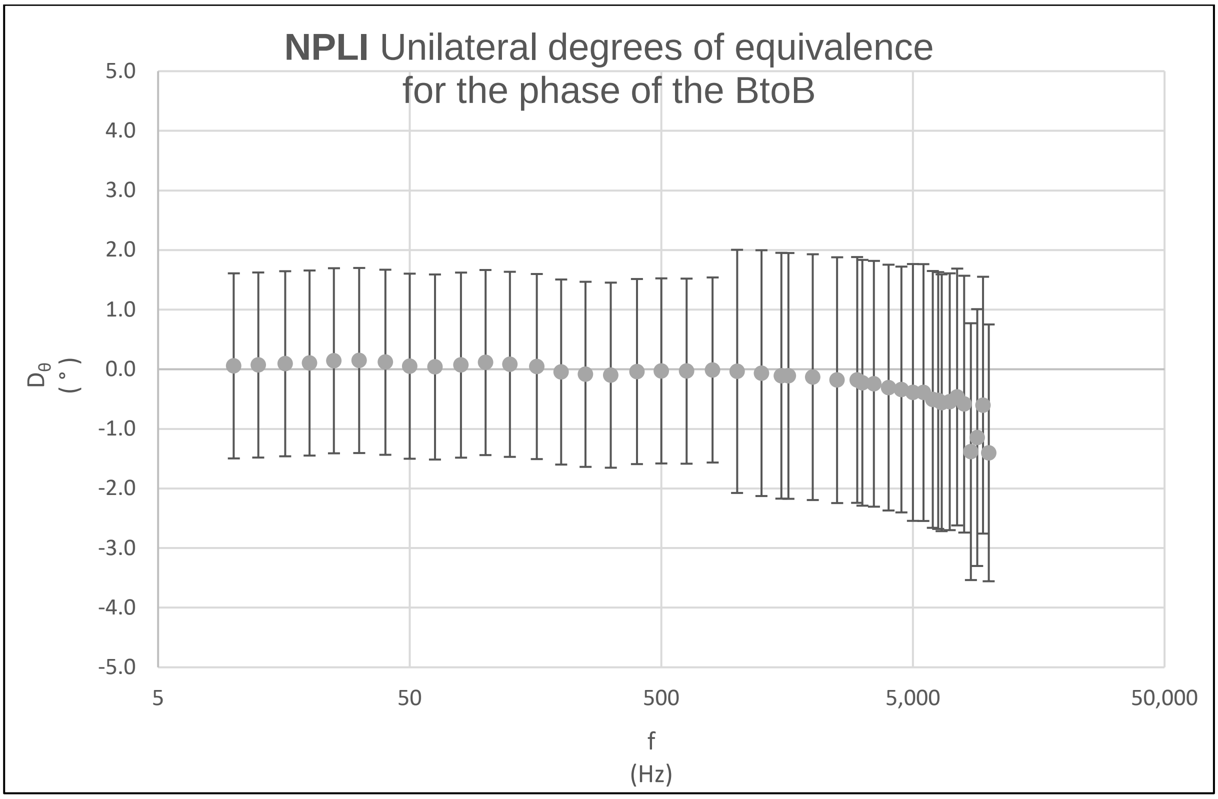

Figure 22: NPLI Phase unilateral degrees of equivalence of the BtoB

9.5.1 The Single-Ended Accelerometer (SN 2860147)

Table 10: Unilateral degrees of equivalence for the phase and correction values *δ* of the SE

	NIMT		NPLI		CCAUV - AFRIMETS	
f	d_i	$U(d_i)$	d_i	$U(d_i)$	δ	$U(\delta)$
Hz	**(°)**	**(°)**	**(°)**	**(°)**		
10	-0,06	0,5	0,06	1,6	-0,0563	0,22
12,5	-0,07	0,5	0,07	1,6	-0,0209	0,22
16	-0,08	0,5	0,09	1,6	0,0196	0,22
20	-0,09	0,5	0,10	1,6	0,0423	0,22
25	-0,09	0,5	0,14	1,6	0,0551	0,22
31,5	-0,10	0,5	0,15	1,6	0,0718	0,22
40	-0,11	0,5	0,12	1,6	0,0794	0,22
50	-0,12	0,5	0,05	1,6	0,0833	0,22
63	-0,11	0,5	0,04	1,6	0,0897	0,22
80	-0,11	0,5	0,07	1,6	0,0781	0,22
100	-0,09	0,5	0,11	1,6	0,1015	0,22
125	-0,08	0,5	0,08	1,6	0,1103	0,22
160	-0,04	0,5	0,05	1,6	0,1450	0,22
200	-0,03	0,5	-0,05	1,6	0,1585	0,22
250	-0,06	0,5	-0,09	1,6	0,1364	0,22
315	-0,06	0,5	-0,10	1,6	0,1212	0,22
400	-0,06	0,5	-0,04	1,6	0,1193	0,22
500	-0,01	0,5	-0,03	1,6	0,1422	0,22
630	-0,05	0,5	-0,03	1,6	0,1491	0,22
800	0,01	0,5	-0,01	1,6	0,1437	0,22
1 000	-0,03	0,5	-0,04	2,0	0,1404	0,22
1 250	-0,01	0,6	-0,07	2,1	0,1268	0,27
1 500	-0,02	0,6	-0,11	2,1	0,1102	0,27
1 600	-0,01	0,6	-0,11	2,1	0,1081	0,27
2 000	0,00	0,6	-0,13	2,1	0,1156	0,27
2 500	-0,03	0,6	-0,18	2,1	0,0928	0,27
3 000	-0,01	0,6	-0,18	2,1	0,1136	0,27
3 150	-0,03	0,6	-0,23	2,1	0,0721	0,28
3 500	0,00	0,6	-0,24	2,1	0,0822	0,28
4 000	-0,01	0,6	-0,31	2,1	0,0544	0,28
4 500	-0,04	0,6	-0,34	2,1	0,0082	0,28
5 000	-0,02	0,9	-0,39	2,2	-0,0002	0,42
5 500	0,02	1,0	-0,39	2,2	0,0363	0,45
6 000	0,00	1,1	-0,51	2,2	0,0300	0,45
6 300	-0,01	1,1	-0,52	2,2	0,0304	0,45
6 500	-0,01	1,1	-0,56	2,2	-0,0190	0,45
7 000	0,07	1,1	-0,54	2,2	0,0190	0,45

	NIMT		NPLI		CCAUV - AFRIMETS	
f	***d*** d_i	***U*** **(d_i)**	d_i	***U*** **(d_i)**	***δ***	***U (δ)***
Hz	**(°)**	**(°)**	**(°)**	**(°)**		
7 500	0,19	1,1	-0,47	2,2	0,0735	0,45
8 000	0,09	1,1	-0,59	2,2	0,0645	0,46
8 500	-0,64	1,1	-1,38	2,2	-0,6832	0,46
9 000	-0,32	1,1	-1,15	2,2	-0,4130	0,46
9 500	0,34	1,1	-0,60	2,2	0,6284	0,47
10 000	-0,34	1,0	-1,40	2,2	0,0005	0,47
10 500	-0,20	1,4			-0,2923	0,50
11 000	-0,17	1,4			0,0916	0,55
11 500	-0,14	1,4			0,1097	0,55
12 000	-0,04	1,4			0,1797	0,55
12 500	-0,03	1,8			0,2875	0,76
13 000	-0,06	1,8			0,1974	0,77
13 500	0,00	1,8			0,2270	0,77
14 000	0,01	1,8			0,2707	0,77
14 500	0,02	1,8			-0,2511	0,72
15 000	0,04	1,8			0,2822	0,77
15 500	0,04	2,2			-0,3785	0,87
16 000	-0,01	2,2			0,3818	0,94
16 500	0,05	2,2			0,4641	0,94
17 000	0,06	2,2			0,5961	0,94
17 500	0,39	2,2			0,9420	0,94
18 000	1,92	2,2			2,2494	0,94
18 500	-0,21	2,2			0,3015	0,94
19 000	0,07	2,2			0,4217	0,94
19 500	-0,09	2,2			0,5280	0,94
20 000	-0,07	2,2			0,4902	0,94

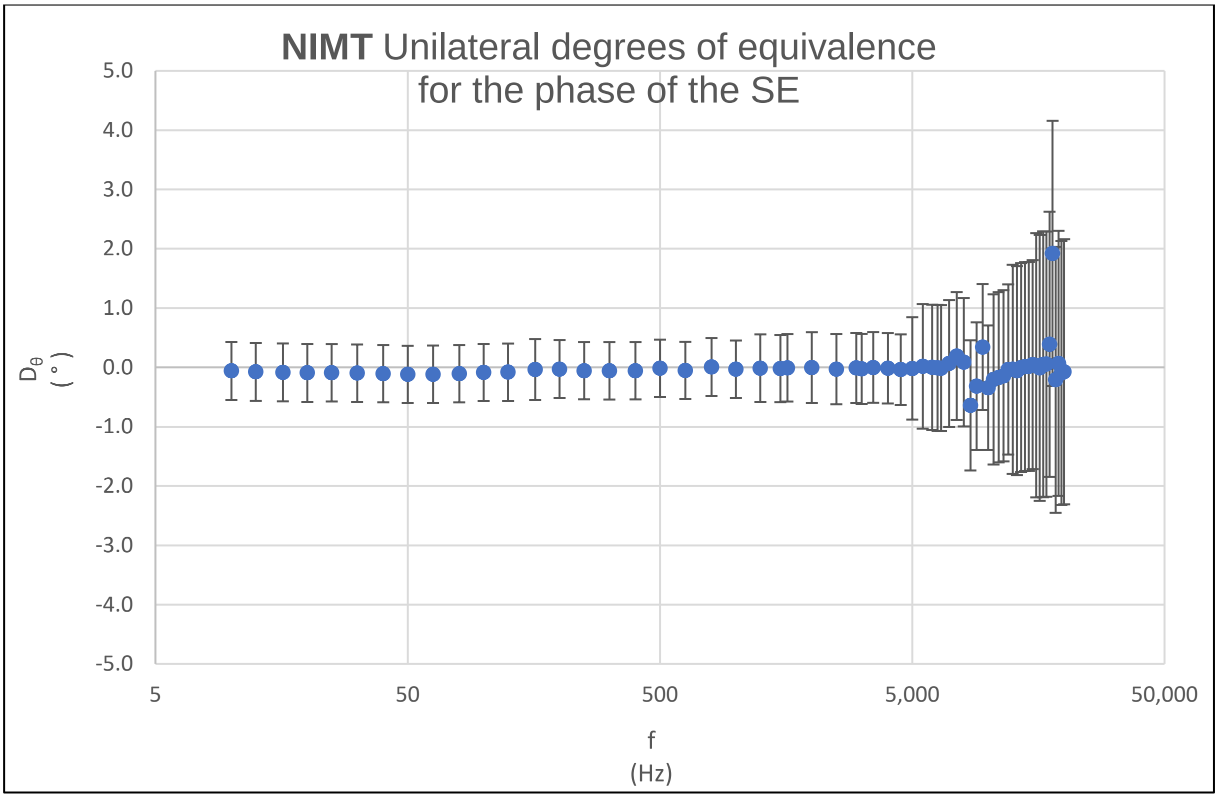

Figure 23: NIMT Phase unilateral degrees of equivalence of the SE

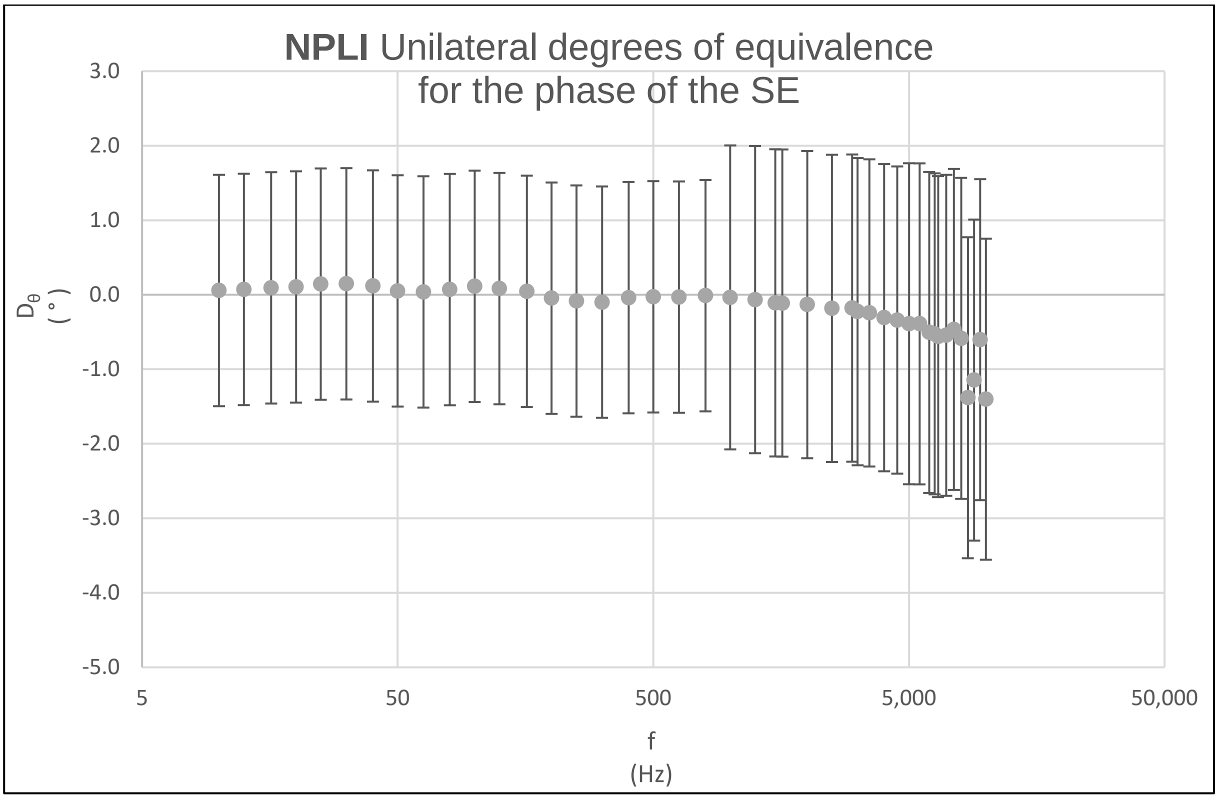

Figure 24: NPLI Phase unilateral degrees of equivalence of the SE

11 Conclusion

Participants in CIPM comparisons have the responsibility to disseminate the KCRV to their regions, as well as to NMIs from other regions, that cannot participate in the CIPM comparisons. In this role, NMISA piloted this AFRIMETS key comparison in the field of Vibration, providing three NMIs, from two metrology regions, with the opportunity to link their Calibration and Measurement Capabilities with the relevant KCRV.

This AFRIMETS Key comparison followed the CCAUV.V-K5 key comparison [3]. It's protocol, to a large extend, mirrored the protocol of CCAUV.V-K5. The two transfer standards used, the SE device from the same manufacturer with the same nominal sensitivity with the BtoB device from a different manufacturer with double the nominal sensitivity. Both devices posed the same challenges experienced during [3].

The participants applied laser interferometry in accordance with ISO 16063-11 [2] as specified in [5]. Between the four participants (linking laboratory included), three different methods specified in [2] were implemented. That was Method 1, Method 2 and Method 3. Participants implementing Method 3 made use of commercial interferometers, in contrast with the inhouse developed interferometers used for Methods 1 and Method 2 by one of the participants. All interferometers are sensitive to the reflective quality of the surface being focus on. The inhouse interferometers were more sensitive to the reflective quality of the measurement surface focused on. This necessitated INTI to the lap the BtoB accelerometer top surface. The stability monitoring measurements confirmed that this action did not affect the BtoB accelerometer sensitivity.

The circulation of the artifacts was problematic since the comparison was initiated during covid-19. Import and export restrictions at the time resulted in numerous delays, which resulted in the circulation period having to be amended. Fortunately, based on the stability measurements, the stability of the accelerometers was not negatively influenced by the delays. The data presented support that the devices were stable over the comparison period, within the pilot laboratory measurement of uncertainty.

Complex calibration values from a single linking laboratory, NMISA, were used for the linking of the AFRIMETS comparison complex calibration values with the complex KCRVs. Two different linking methods were used for the sensitivity magnitude results and the sensitivity phase results. For the sensitivity magnitude, a correction factor, *r*, with its associated uncertainty was determined. A correction value, δ, with its associated uncertainty was determined for linking the phase results.

For the three participants, unilateral DoE between the participant calibration results and the KCRVs were calculated. The DoE were evaluated for consistency using: $|D_i(f)| > U_{D_i}(f)$ where $U_{D_i}(f) = 2u_{D_i}(f)$. Out of the 63 measurements per accelerometer, per parameter (magnitude and phase), per participant, for the BtoB accelerometer one participating NMI had two measurement points failing the criteria. For the SE accelerometer, one NMI had nine measurement points failing the criteria. A second NMI had 14 measurement points failing the SE accelerometer criteria.

With the experience and lessons gained from the comparison CCAUV.V-K5 the AFRIMETS had decided to mount and fix the SE artifact onto a steel-adapter for the calibration measurements in order to ensure identical mounting conditions for all participants. The goal behind this was to provide all participants with the same measurement surface for the laser to be focussed on. The adapter circulated with the SE accelerometer was of a slightly different design than the one used in CCAUV.V-K5. It was expected that it would improve the level of comparability between results at high frequencies.

The problem of the position dependence was minimised largely by averaging of multiple positions as requested by the TP [5]. The larger spread of the SE results at high frequencies is evidence of systemic difficulties with the calibration of SE devices at frequencies above 10 kHz and requires further investigation.

The results indicate mainly difficulties with the magnitude results for the complex sensitivity. The phase results exhibited consistency between the participants over the reduced scope.

An additional task of the comparison was performing of the measurement chain with the participant's provided charge amplifier, calibrated by the participant. Due to this requirement, the consistency of the comparison results demonstrate the participants' capability of magnitude and/or phase of the complex transfer function calibration of charge amplifiers. This capability could be expected to be valid for other kinds of conditioning amplifiers.

Despite challenges the Key Comparison AFRIMETS.AUV.V-K5 can be considered successful for most participants. It established many new consistent unilateral degrees of equivalence.

12 Acknowledgements

As Pilot laboratory, NMISA commends INTI in this, INTI's first participation in a key comparison. As with all participating NMIs, a successful participation can only be achieved through a collaborative effort.

Federico Ariel Serrano acknowledges the contributions by Alexis Gastón Zapata and Ramiro Benevenia during this AFRIMETS key comparison.

13 References

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Annex A: Technical Protocol

NMISA
20 April 2021
C.S. Veldman

Technical protocol of the Bi-Lateral Comparison AFRIMETS.AUV.V-K5

Task and Purpose of the Comparison
Through the CIPM, NMIs participate in key comparisons (KC) to evaluate and proof calibration system performance at the highest accuracy level (smallest uncertainty of measurement). However, in certain instances, participation in a CIPM might be impractical. For CSIR-NPL, India, NIMT, Thailand and INTI, Argentina to proof their capabilities, linked to the CIPM comparison, CCAUV.V-K5, this AFRIMETS key comparison, AFRIMETS.AUV.V-K5, is proposed.

The task of this bi-lateral comparison is to measure the complex charge sensitivity (pC/(m/s^2)) [1, 2] of two accelerometer(s) of different types, at specified frequencies by primary means in accordance with ISO 16063-11 “Methods for the calibration of vibration and shock transducers -- Part 11: Primary vibration calibration by laser interferometry” [3]. For the participating laboratories, the charge sensitivity reported will exclude effects from the applicable conditioning amplifier used. The participating laboratory shall provide the amplifier to be used and determine and correct for the effect (gain) of the amplifier on the calibration result. **No conditioning amplifier will accompany the circulation of the transfer standards.**

The comparison reference values (CRVs) will be obtained from the NMISA primary vibration calibration system and the degrees of equivalence between the values of the participating laboratory and the CRVs determined. The reported sensitivities and associated uncertainties are then supposed to be used for the calculation of the DoE between the participating NMI and the CCAUV.V-K5 key comparison reference values (KCRVs).

The reported values (participating laboratory capability dependent), magnitude and phase, will be linked to the KCRV over the frequency range 10 Hz to 20 kHz as reported during CCAUV.V-K5. The values obtained from the NMISA primary vibration calibration system will serve as the link between the KCRV and the values reported by the participating laboratory.

Pilot Laboratory

Pilot laboratory for this comparison is:

National Metrology Laboratory of South Africa (NMISA)
Acoustics, Ultrasound and Vibration Section
CSIR Campus, Building 7
Meiring Naude Road
Brummeria
0184
South Africa

Contact Person:
C.S. Veldman
Phone: +27 12 841 4008
E-mail: CSVeldman@NMISA.org

***The address above is the delivery address for the set of artefacts*.**

The delivery address for reports is:

C.S. Veldman
NMISA, AUV
Private Bag X34
Lynnwood Ridge
0040
South Africa

Participants
The following laboratories have been registered as participants in the agreed comparison:

Contact details of participating laboratory representative(s):

1) NMISA / South Africa (Pilot & Reference Laboratory)
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Acoustics, Ultrasound and Vibration Laboratory
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Subgerencia Operativa Metrología Científica e Industrial

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E-mail: fserrano@inti.gob.ar

Terms of Participation

Following recommendations from the published document, "Recommendations from the Working Group on the Implementation and Operation of the CIPM MRA" [4], NMISA, as member of AFRIMETS, is piloting this key comparison as the linking laboratory between NPLI, NIMT, INTI (participating NMIs) and CCAUV.V-K5. Following this recommendation, this technical protocol is distributed to the chairman of the CCAUV Key Comparison Working Group (CCAUV KCWG) for review and approval on behalf of the CCAUV.

The participating NMIs wishes to demonstrate the degree of equivalence of their primary vibration calibration capability internationally. For this, these participating NMIs indicated their willingness to participate in this key comparison to support future CMC submissions.

The intent is to cover the scope of CCAUV.V-K5, within the current capability of the participating NMI, with a sufficiently low measurement uncertainty by the participants. The participating NMIs agree to participate in this key comparison voluntarily and to abide by the stipulations laid out in this protocol.

The participating NMI will carry all related cost for its leg of the comparison (courier- and customs fees, export from South Africa and re-import to South Africa). The artifacts will be circulated as follows:

Leg 1: From South Africa to India, back to South Africa from India.
Import/export: Temporary export.
NPLI is responsible for all courier arrangements and costs. This includes collection from NMISA, South Africa and delivery to NMISA, South Africa.
Leg 2: From South Africa to Thailand, back to South Africa from Thailand.
Import/export: Temporary export.
NIMT is responsible for all courier arrangements and costs. This includes collection from NMISA, South Africa and delivery to NMISA, South Africa.
Leg 3: From South Africa to Argentina, back to South Africa from Argentina.
Import/export: Temporary export.
INTI is responsible for all courier arrangements and costs. This includes collection from NMISA, South Africa and delivery to NMISA, South Africa.

The Pilot Laboratory, NMISA, will make the artefacts available for the duration of the comparison. NMISA will arrange the ATA Carnet and carry the cost for the carnet. NMISA will compile all documentation required for the temporarily export.

NMISA will submit its official comparison results to the CCAUV Secretariat at a date not later than the date on which the artefacts are shipped to the first participant, NPLI. These calibration results will be used to link the results of the participating NMIs to the KCRV for the frequency interval 10 Hz to 20 kHz and to calculate a CRV from 5 Hz to < 10 Hz.

Devices Under Test and Measurement Conditions
For the calibration task of this Comparison, a set of two piezoelectric accelerometers will be circulated among the participating laboratories.

The individual transducers being:

- a Brüel & Kjær 8305-001 (SN: 2860147) “single ended” (SE) type,
    - the SE accelerometer/adaptor combination is referred to hereafter as the “SE Device”
- an ENDEVCO 2270 (SN: 14317) “back to back” (BtoB) type.

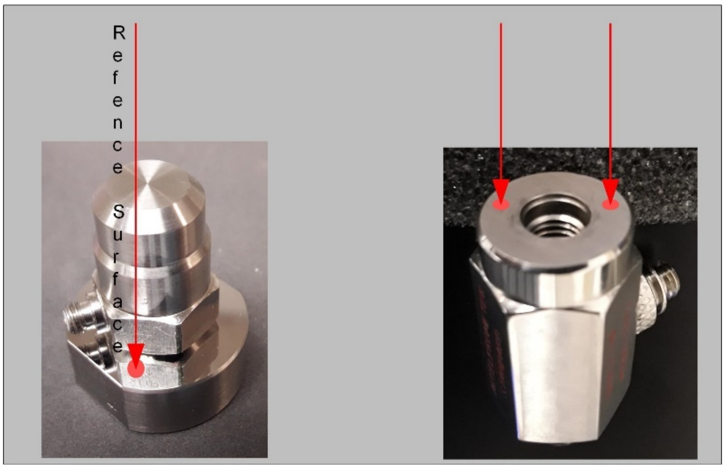

Figure 25: Reference surfaces indicated for the Brüel & Kjær 8305-001 accelerometer complete with adaptor and the ENDEVCO 2270

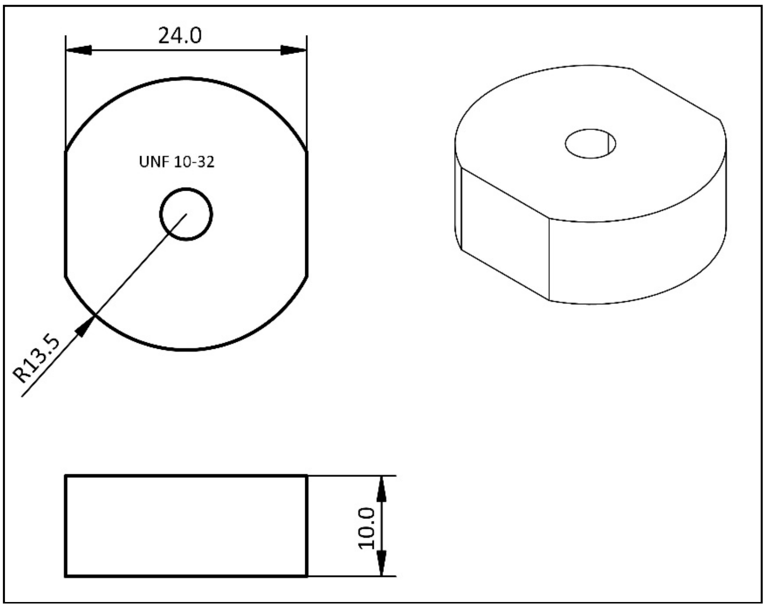

Figure 26: Drawing showing stainless steel adaptor dimensions. Drawing is not to scale.

The accelerometers are to be calibrated for magnitude (S_{qa}) and phase (θ_{qa}) of their complex charge sensitivity according to those procedures and conditions implemented by the NMI in conformance with ISO 16063-11 [3] which provide magnitude and phase information of the artefact. The sensitivities reported shall be for the accelerometer's alone, excluding any effects from the charge amplifier.

The frequency range of the measurements was agreed to be from 5 Hz to 20 kHz. **Laboratories whose current capability does not cover the complete frequency range of 5 Hz to 20 kHz, will submit calibration results over its capability current frequency range.**

Only the frequency subset of 10 Hz to 20 kHz will be linked to CCAUV.V-K5. The laboratories are supposed to measure at the following frequencies (all values are in Hz).

5, 6.3, 8, 10, 12.5, 16, 20, 25, 31.5, 40, 50, 63, 80, 100, 125, 160, 200, 250, 315, 400, 500, 630, 800, 1 000, 1 250, 1 500, 1 600, 2 000, 2 500, 3 000, 3 150, 3 500, 4 000, 4 500, 5 000, 5 500, 6 000, 6 300, 6 500, 7 000, 7 500, 8 000, 8 500, 9 000, 9 500, 10 000, 10 500, 11 000, 11 500, 12 000, 12 500, 13 000, 13 500, 14 000, 14 500, 15 000, 15 500, 16 000, 16 500, 17 000, 17 500, 18 000, 18 500, 19 000, 19 500, 20 000.

Note: this set does deviate from the standard frequencies of ISO 266 [5].

Participating laboratories will provide magnitude and phase results**,** over the specified frequency range. Laboratories are required to provide calibration results that fall within its system's calibration capabilities at the time of this comparison only.

The charge amplifier used for the calibration is not provided within the set of the artefacts, it must therefore be provided by the individual participants. **By this measure, the capability of the participating laboratory to calibrate charge amplifiers can be implicitly verified**.

The measurement condition should be kept according to the laboratory's standard conditions for calibration of customer accelerometers for claiming their best Calibration and Measurement Capability (CMC) where applicable. This presumes that these conditions comply with those defined by the applicable ISO documentary standards [2, 3, 6], simultaneously.

Specific conditions for the measurements of this key comparison are:

- acceleration amplitudes: preferably 10 m/s² to 100 m/s², frequency dependent. A range of 2 m/s² to 800 m/s² is admissible.
- ambient temperature during the calibration:
    - (23 ± 2) ºC (actual values to be stated within tolerances of ± 0,3 ºC).
    - relative humidity: max. 75 %RH
- mounting torque of the accelerometer: (2,0 ± 0,1) N·m

Circulation Type, Schedule, and Transportation

The transducers will be circulated in a circular and star like fashion with a measurement period of three weeks provided for each participant. The transducers are measured at the pilot laboratory before they are transported to participants, and after it is received back from participants to monitor the stability and identify any drift during the circulation period.

A total period of five weeks is allocated for each laboratory, covering both calibration and transportation. Three weeks for measurements and two weeks for transportation.

The pilot laboratory are sensitive to the possibility of delays in transport, customs clearing and quarantine requirements imposed to comply with Covid 19 protocols.

Planned circulation period**:** Six months

Preparatory stage:

Basic investigation, e.g. test of linearity and previous long-term stability analysis of transfer standards: April 2021 to August 2021. Envisaged circulation stability check on completion of device circulation: January 2022.

Comparison Reference Values: August 2021
Start of first circulation period: January 2022
End of first the circulation period: February 2022
Stability Check 1: March 2022
Start of the second circulation period: April 2022
End of the second circulation period: May 2022
Stability Check 2: May 2022
Completion of the circulation period: July 2022
Draft report: November 2022
***Final report*:** March 2023

The schedule is planned as follows:
See attached Excel file with schedule.

Participant	Country Code	Measurement		Transport of Artifacts		Monitoring	
		From	To	From	To	From	To
NMISA	ZA	Stability measurements				Apr 2021	Aug 2021
NMISA Reference Values	ZA	16 Aug 2021	3 Sept 2021	8 Sep 2021 SA to India	15 Sep 2021	-	-
NPLI	IN	20 Sep 2021	8 Oct 2021	13 Oct 2021 India to SA	20 Oct 2021	-	-
NMISA Monitoring	ZA			3 Nov 2021 SA to Thailand	10 Nov 2021	25 Oct 2021	29 Oct 2021
NIMT	TH	15 Nov 2021	3 Dec 2021	8 Dec 2021 Thailand to SA	15 Dec 2021		
NMISA Monitoring	ZA			12 Jan 2022 SA to Argentina	19 Jan 2022	3 Jan 2022	7 Jan 2022
INTI	AR	24 Jan 2022	11 Feb 2022	16 Feb 2022 Argentina to SA	23 Feb 2022		
NMISA Monitoring	ZA	-	-	-	-	28 Feb 2022	4 Apr 2022

Transportation and Financial Aspects
For transportation, the artefacts are packed in a protective aluminum box, which in turn is put into a card-board container.
The dimensions are: 39 cm x 27 cm x 19 cm

The approximated weight is: 2 kg.
The accelerometers must be sent by an international logistic service providing a tracking system. The transportation must include an insurance covering a total value of R 150 000 in case the set of accelerometers gets damaged or lost during transportation.
As an alternative the artefact may be hand carried by a member of the participating laboratory to the following laboratory, at the cost of the sending, not receiving, laboratory.
Each participating laboratory is responsible for its own costs for the measurements, transportation to following participant, and any customs charges as well as any damage that may occur within its country. The cost of transportation to the following (receiving) laboratory shall be covered by the participating (sending) laboratory.

Handling, Measurement and Analysis Instructions
All participating laboratories must observe the following instructions:

- The charge amplifier used for the measurement of the accelerometer's response must be calibrated with equipment traceable to national measurement standards.
- *The SE accelerometers shall be mounted together with the mounting adapter, that comes attached to it. The combined SE accelerometer with adapter (SE Device) should be handled as a single mechanical unit for mounting.*
    - *The mounting adapter must not be adjusted, loosened, or removed.*
    - *The mounting and dismounting torque between the adapter and the vibration exciter shall be applied via the mounting adapter.*
    - Do not apply mechanical force to the accelerometer itself when fastening or unfastening the SE device.
- The motion of the SE accelerometers shall be measured on the polished top surface of the mounting adapter that comes attached, close to the accelerometer's housing as indicated in Figure 1 on page 4.
- The motion of the BtoB accelerometer should be measured with the laser directly on the (polished) reference surface of the transducer **without any additional reflector, mirror, or dummy mass** (c.f. Figure 1 on page 4).
- The sensitivity at the reference surface of accelerometer shall be reported.
- The mounting surface of the accelerometers and the moving part of the vibration exciter must be slightly lubricated before mounting.
- To reduce the influence of non-rectilinear motion, the measurements should ideally be performed for at least three different laser positions which are symmetrically distributed over the respective measurement surfaces. *The number of positions will be calibration system dependent.*
- For each accelerometer, the calibrations are to be carried out in accordance with the usual procedure of the participating 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**.
- The contribution of the conditioning amplifier shall be included in the Uncertainty of Measurement (UoM).

Communication of the Results to the Pilot Laboratory

Each participating laboratory will submit one printed and one signed calibration report for each accelerometer configuration to the pilot laboratory including the following:

- A description of the calibration systems used for the comparison, including the mounting techniques for the accelerometer.
- A description of the calibration methods used.
- The calibration results, including the relative expanded uncertainty of measurement, 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, [6, 7, 8]). Including among others information on the type of uncertainty (A or B), assumed distribution function and repeatability component.

In addition, each participating laboratory will receive an electronic Excel spreadsheet prepared by the pilot laboratory, where the calibration results must be filled in following the structure given in the Excel file. The use of the electronic spreadsheet 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 laboratory. The data submitted in the electronic spreadsheet shall be deemed the official results submitted for the comparison.
The results must be submitted to the pilot laboratory within four weeks after the measurements were completed by the participating laboratory.
The pilot laboratory will submit its set of results to the executive secretary of CCAUV in advance to the first measurement of the first participating laboratory.

Remarks on the Post Processing

Presuming consistency of the results as evaluated in [9], the CRVs and the degrees of equivalence (DoE) will be determined by comparing the laboratory observed values with the reference values obtained from primary calibration as stated in clause **Devices Under Test and Measurement Conditions.**

Degrees of equivalence with respect to the Comparison Reference Values

The unilateral DoE is to be calculated for the participants will be referred to the CIPM KCRV (CCAUV.V-K5) after linking provided by NMISA. The equations shall include the uncertainty added by the linking process.
The unilateral degrees of equivalence with respect to the CRVs will be calculated according to:

$$d_{i,CRV}(a) = x_i(a) - x_{CRV}(a) \qquad (1)$$

$$u^2 = \begin{cases} u_i^2(a) - u_{CRV}^2(a) \text{ for results within the LCS} \\ u_i^2(a) + u_{CRV}^2(a) \text{ for results not within the LCS} \end{cases} \qquad (2)$$

$$u_{i,KCRV}^2(a) = \begin{cases} u_i^2(a) - u_{KCRV}^2(a) \text{ for results within the LCS} \\ u_i^2(a) + u_{KCRV}^2(a) \text{ for results not within the LCS} \end{cases} \qquad (3)$$

References

[1] ISO 2041 “Mechanical vibration, shock and condition monitoring – Vocabulary.”

[2] ISO 16063-1 “Methods for the calibration of vibration and shock transducers -- Part 1: Basic concepts.”

[3] ISO 16063-11 “Methods for the calibration of vibration and shock transducers -- Part 11: Primary vibration calibration by laser interferometry.”
[4] BIPM, “Recommendations from the Working Group on the Implementation and Operation of the CIPM MRA”, 23rd August 2016 http://www.bipm.org/utils/common/documents/CIPM-MRA-review/Recommendations-from-the-WG.pdf.
[5] ISO 266 “Acoustics — Preferred frequencies.”
[6] ISO/IEC 17025 “General requirements for the competence of testing and calibration laboratories.”
[7] ISO/IEC Guide 98-3 “Uncertainty of measurement -- Part 3: Guide to the expression of uncertainty in measurement (GUM:1995).
[8] ISO/IEC Guide 98-3/Suppl 1 “Propagation of distributions using a Monte Carlo method.”
[9] ISO 13528 “Statistical methods for use in proficiency testing by interlaboratory comparison.”

Appendix B: Measurement Uncertainty Budgets of Participants

B.1 NMISA

B.1.1 Magnitude

UNCERTAINTY BUDGET MATRIX (UBM)										Certificate No	AFRIMETS.AUV.V-K5 B TO B	
										Procedure No	AVVS-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: / Serial number:				Range:	0,1 Hz to 20 kHz				Metrologist: Ian Veldman	
Mathematical Model:		$S = \hat{u}/\hat{a} = \hat{u}/(2\pi f)^2 d$										
Symbol	Input Quantity (Source of Uncertainty)	Standard Uncertainty Contribution $U_i(y)$								Reliability	Degrees of Freedom	Remarks
		[redacted]		0,5 Hz to 1 kHz	> 1 kHz < 5 kHz	5 kHz to 7 kHz	> 7 kHz to 12 kHz	> 12 kHz to 15 kHz	>15 kHz to 20 kHz		infinite	
u	▼ Standards and Reference Equipment (Uncorrelated) ▼	%	%	%	%	%	%	%	%	%	v	
φ_U	Interferometer output signal disturbance on phase amplitude	0,006	0,006	0,006	0,058	0,058	0,058	0,173	0,289	100	infinite	e.g. offsets, voltage amplitude deviations, <= 90° Corrected with Heydemann procedure
φ_{VD}	Effect of voltage disturbance on phase amplitude measurement	0,000	0,000	0,000	0,000	0,001	0,001	0,001	0,002	100	infinite	Additive uncorrelated noise is reduced by 1/√n Where n=number of samples per vibration cycle. Worse case <10%/1000
φ_{MD}	Effect of motion disturbance on phase amplitude measurement	0,009	0,009	0,009	0,144	0,289	0,462	0,462	0,462	100	infinite	Relative motion between sensing spot, cutter and accelerometer. Worse case calculated for 16mm double-ended accelerometer
φ_{PD}	Effect of phase disturbance on phase amplitude measurement	0,006	0,006	0,006	0,029	0,058	0,058	0,115	0,289	100	infinite	Corrected for using Heydemann correction procedure
φ_{RE}	Residual interferometric effects on phase amplitude measurement	0,006	0,006	0,006	0,006	0,029	0,029	0,058	0,173	100	infinite	Not aware of any
f_{FG}	Vibration frequency measurement accuracy	0,029	0,029	0,029	0,040	0,058	0,115	0,289	0,260	100	infinite	ISO 16063-11 requirement: ≤ 0,05 % of reading
λ_U	Uncertainty on laser wavelength measurement	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	100	infinite	Uncertainty quoted on certificate
$\hat{u}_V$	Accelerometer output voltage measurement (ADC resolution/accuracy)	0,173	0,087	0,058	0,046	0,058	0,058	0,058	0,058	100	infinite	Manufacturer's specification worse case on 1 V range
S_F	Filtering effect on sensitivity measurement	0,115	0,087	0,058	0,058	0,144	0,173	0,173	0,115	100	infinite	$e=(f/f_{cg})^2$
G_{CA}	Charge amplifier gain accuracy	0,200	0,150	0,050	0,125	0,100	0,118	0,150	0,100	100	infinite	Conditiong amplifier uncertainty
	▼ Unit Under Test / Calibration (Uncorrelated) ▼											
$\hat{u}_D$	Effect of voltage disturbance on accelerometer output voltage measurement	0,025	0,005	0,003	0,025	0,025	0,025	0,050	0,050	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	0,025	0,025	0,025	0,030	0,050	0,050	0,150	0,175	100	infinite	Transeverse error for a transverse sensitivity of 1%
$\hat{u}_{RES}$	Residual effects on accelerometer output voltage measurement	0,150	0,050	0,025	0,035	0,050	0,150	0,175	0,150	100	infinite	Tribo-electric effect
$\hat{u}_s$	Standard deviation on accelerometer output voltage measurement	0,250	0,140	0,100	0,100	0,150	0,200	0,300	0,500		7	ESDM for sensitivity calulation using 4 points
About UBM	TOTAL COMBINED UNCERTAINTY											
Best Measurement Capability (Excluding UUT contribution)	Combined Uncertainty (Normal) ▼Confidence Level▼	0,29	0,196	0,101	0,219	0,358	0,531	0,632	0,710	V_{eff}	infinite	Checked and Approved By:
	Expanded Uncertainty k = 2 95,45 %	0,58	0,39	0,20	0,44	0,72	1,06	1,27	1,42	k =	2,00	
Uncertainty of Measurement (Including UUT contribution)	Combined Uncertainty (Normal) ▼Confidence Level▼	[redacted]		0,144	0,243	0,392	0,586	0,721	0,881	V_{eff}	infinite	
	Expanded Uncertainty k = 2 95,45 %			0,3	0,5	0,8	1,2	1,4	1,8	k =	2,00	

B.1.2 Phase

UNCERTAINTY BUDGET MATRIX (UBM)							Certificate No		AFRIMETS.AUV.V-K5
							Procedure No		AVVS-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:	Complex Sensitivity Calibration (Phase) as per ISO 16063-11 method 3	**Make & model:**	Brüel & Kjær Endevco	**Range:**	0.1 Hz to 20 kHz				**Metrologist**
		Serial number:							Ian Veldman
Mathematical Model:		$S_{phase} = UUT_{Phase} - Ref_{Phase} - Ref_{Delay} - AtoD_{Phase} - DSP_{Delay}$							
Symbol	**Input Quantity (Source of Uncertainty)**	**Standard Uncertainty Contribution Ui(y)**					**Reliability**	**Degrees of Freedom**	**Remarks**
		0,1 Hz to 1 kHz	**> 1 kHz < 5 kHz**	**5 kHz to 12 kHz**	**> 12 kHz to 15 kHz**	**> 15 kHz to 20 kHz**		infinite	
u	**▼ Standards and Reference Equipment (Uncorrelated) ▼**	(°)	(°)	(°)	(°)	(°)	%	*v*	
$\varphi_{x,O}$	Interferometer output signal disturbance on displacement phase measurement	0,058	0,075	0,115	0,289	0,202	100	infinite	e.g. offsets, voltage amplitude deviations, <= 90° Corrected with Heydemann procedure
$\varphi_{x,VD}$	Effect of voltage disturbance on displacement phase measurement	0,029	0,058	0,069	0,144	0,202	100	infinite	Additive uncorrelated noise is reduced by 1/√n Where n=number of samples per vibration cycle. Worse case +10%/1000
$\varphi_{x,MD}$	Effect of motion disturbance on displacement phase measurement	0,029	0,058	0,069	0,115	0,231	100	infinite	Relative motion between sensing spot, exiter and accelerometer. Worse case calculated for 16mm double ended accelerometer.
$\varphi_{x,PD}$	Effect of phase disturbance on displacement phase measurement	0,058	0,115	0,087	0,144	0,173	100	infinite	Corrected for using Heydemann correction procedure
$\varphi_{x,RE}$	Residual interferometric effects on displacement phase measurement	0,012	0,046	0,058	0,173	0,173	100	infinite	Not aware of any
$\Delta_{\varphi E}$	Environmental effects on phase shift measurement	0,017	0,029	0,058	0,115	0,087	100	infinite	ISO 16063-11 requirement: ≤ 0,05 % of reading
$\varphi_{u,V}$	Accelerometer output phase measurement (ADC resolution/accuracy)	0,075	0,100	0,150	0,200	0,175	100	infinite	SAM phase calculation accuracy
$\varphi_{u,F}$	Filtering effect on accelerometer output phase measurement	0,058	0,087	0,231	0,289	0,289	100	infinite	e=(f/fHp)2
$\varphi_{C,A}$	Charge amplifier phase accuracy	0,100	0,050	0,127	0,127	0,127	100	infinite	Certified value
	▼ Unit Under Test / Calibration (Uncorrelated) ▼								
φ_D	Effect of voltage disturbance on accelerometer output phase measurement	0,029	0,069	0,144	0,231	0,289	100	infinite	U_{THD} = ½(d/100)2; Maximum allowed by ISO 16063
φ_T	Effect of transverse motion on accelerometer output phase measurement	0,029	0,029	0,058	0,058	0,058	100	infinite	Transeverse error for a transverse sensitivity of 1%
φ_{RES}	Residual effects on accelerometer output voltage measurement	0,050	0,025	0,025	0,025	0,058	100	infinite	Tribo-electric effect
φ_{RES}	Standard deviation on accelerometer phase shift measurement	0,100	0,100	0,150	0,300	0,500	100	infinite	ESDM for sensitivity calulation using 5 cycles minimum
About UBM	**TOTAL COMBINED UNCERTAINTY**								
Best Measurement Capability (<u>Excluding</u> UUT contribution)	Combined Uncertainty (Normal) / ▼Confidence Level▼	0,17	0,22	0,36	0,57	0,58	V_{eff}	infinite	Checked and Approved By:
	Expanded Uncertainty / $k = 2$ 95,45 %	0,3	0,4	0,7	1,1	1,15	k =	2,00	[signature]
Uncertainty of Measurement (Including UUT contribution)	Combined Uncertainty (Normal) / ▼Confidence Level▼	0,20	0,24	0,39	0,64	0,77	V_{eff}	infinite	
	Expanded Uncertainty / $k = 2$ 95,45 %	0,4	0,5	0,8	1,3	1,6	k =	2,00	

B.2 NIMT

B.2.1 Magnitude

4. Uncertainty Budget

Type	Source of Uncertainty	Symbol	Probability Distribution	Divisor	Ci	u(xi)	ν_{eff}
B	Vibration velocity (uncertainty of tracing back)	U_1	normal	2	1	$\frac{U_1}{2}$	∞
B	Voltage U_x	U_2	normal	2	1	$\frac{U_2}{2}$	∞
B	Angular frequency of v signal	U_3	square	$\sqrt{3}$	1	$\frac{U_3}{\sqrt{3}}$	∞
B	Amplifier gain	U_4	normal	2	1	$\frac{U_4}{2}$	∞
B	Frequency response	U_5	normal	2	1	$\frac{U_5}{2}$	∞
B	Transverse motion	U_6	square	$\sqrt{3}$	1	$\frac{U_6}{\sqrt{3}}$	∞
B	Harmonics	U_7	square	$\sqrt{3}$	1	$\frac{U_7}{\sqrt{3}}$	∞
B	Hum	U_8	normal	2	1	$\frac{U_8}{2}$	∞
B	Noise	U_9	normal	2	1	$\frac{U_9}{2}$	∞
B	Effect of geometric location	U_{10}	square	$\sqrt{3}$	1	$\frac{U_{10}}{\sqrt{3}}$	∞
B	Sensor attachment	U_{11}	square	$\sqrt{3}$	1	$\frac{U_{11}}{\sqrt{3}}$	∞
B	Cable routing and fixing	U_{12}	square	$\sqrt{3}$	1	$\frac{U_{12}}{\sqrt{3}}$	∞
B	Relative motion	U_{13}	square	$\sqrt{3}$	1	$\frac{U_{13}}{\sqrt{3}}$	∞
B	Temperature change	U_{14}	square	$\sqrt{3}$	1	$\frac{U_{14}}{\sqrt{3}}$	∞
B	Linearity	U_{15}	square	$\sqrt{3}$	1	$\frac{U_{15}}{\sqrt{3}}$	∞
B	Temporal instability of v signal	U_{16}	square	$\sqrt{3}$	1	$\frac{U_{16}}{\sqrt{3}}$	∞
B	Residual effects	U_{17}	square	$\sqrt{3}$	1	$\frac{U_{17}}{\sqrt{3}}$	∞
	Combined Uncertainty	U_c	normal				
	Expanded Uncertainty	U_e	normal $(k=2)$				
	Approved Uncertainty	U					

Table 1: Sources of uncertainty for sensitivity calibration

Uncertainty (%) of magnitude						
Frequency (Hz)	5 Hz …< 10 Hz	10Hz .. 1.6 kHz	1.6 kHz …5kHz	5 kHz …10 kHz	10 kHz … 15 kHz	15 kHz … 20 kHz
U_1	0.050	0.100	0.100	0.100	0.100	0.100
U_2	0.015	0.015	0.015	0.015	0.026	0.026
U_3	0.000	0.000	0.000	0.000	0.000	0.000
U_4	0.010	0.010	0.010	0.010	0.010	0.010
U_5	0.025	0.025	0.025	0.020	0.020	0.020
U_6	0.004	0.008	0.040	0.144	0.404	0.404
U_7	0.000	0.000	0.000	0.000	0.000	0.000
U_8	0.005	0.005	0.005	0.005	0.005	0.005
U_9	0.0005	0.005	0.0005	0.0005	0.0005	0.0005
U_{10}	0.000	0.0866	0.0866	0.1155	0.2309	0.4619
U_{11}	0.000	0.0185	0.0577	0.1155	0.2252	0.2252
U_{12}	0.1212	0.0808	0.0404	0.0404	0.000	0.000
U_{13}	0.0058	0.0006	0.0006	0.0006	0.0006	0.0006
U_{14}	0.0009	0.0009	0.0009	0.0009	0.0009	0.0009
U_{15}	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006
U_{16}	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006
U_{17}	0.0289	0.0289	0.0289	0.0289	0.0289	0.0289

Table 2: Uncertainty budget for sensitivity calibration.

B.2.2 Phase

Type	Source of Uncertainty	Symbol	Probability Distribution	Divisor	Ci	u(xi)	Υ_{eff}
B	Vibration velocity (uncertainty of tracing back)	U_{p1}	normal	2	1	$\frac{U_{p1}}{2}$	∞
B	Voltage U_x	U_{p2}	normal	2	1	$\frac{U_{p2}}{2}$	∞
B	Angular frequency of v signal	U_{p3}	square	$\sqrt{3}$	1	$\frac{U_{p3}}{\sqrt{3}}$	∞
B	Amplifier gain	U_{p4}	normal	2	1	$\frac{U_{p4}}{2}$	∞
B	Frequency response	U_{p5}	normal	2	1	$\frac{U_{p5}}{2}$	∞
B	Transverse motion	U_{p6}	square	$\sqrt{3}$	1	$\frac{U_{p6}}{\sqrt{3}}$	∞
B	Harmonics	U_{p7}	square	$\sqrt{3}$	1	$\frac{U_{p7}}{\sqrt{3}}$	∞
B	Hum	U_{p8}	normal	2	1	$\frac{U_{p8}}{2}$	∞
B	Noise	U_{p9}	normal	2	1	$\frac{U_{p9}}{2}$	∞
B	Effect of geometric location	U_{p10}	square	$\sqrt{3}$	1	$\frac{U_{p10}}{\sqrt{3}}$	∞
B	Sensor attachment	U_{p11}	square	$\sqrt{3}$	1	$\frac{U_{p11}}{\sqrt{3}}$	∞
B	Cable routing and fixing	U_{p12}	square	$\sqrt{3}$	1	$\frac{U_{p12}}{\sqrt{3}}$	∞
B	Relative motion	U_{p13}	square	$\sqrt{3}$	1	$\frac{U_{p13}}{\sqrt{3}}$	∞
B	Temperature change	U_{p14}	square	$\sqrt{3}$	1	$\frac{U_{p14}}{\sqrt{3}}$	∞
B	Linearity	U_{p15}	square	$\sqrt{3}$	1	$\frac{U_{p15}}{\sqrt{3}}$	∞
B	Temporal instability of v signal	U_{p16}	square	$\sqrt{3}$	1	$\frac{U_{p16}}{\sqrt{3}}$	∞
B	Residual effects	U_{p17}	square	$\sqrt{3}$	1	$\frac{U_{p17}}{\sqrt{3}}$	∞
	Combined Uncertainty	U_{pc}	normal				
	Expanded Uncertainty	U_{pe}	normal ($k = 2$)				
	Approved Uncertainty	U_p					

Table 3: Sources of uncertainty for phase calibration.

Uncertainty (°) of phase						
Frequency (Hz)	5 Hz …< 10 Hz	10Hz .. 1.6 kHz	1.6 kHz …5kHz	5 kHz …10 kHz	10 kHz … 15 kHz	15 kHz … 20 kHz
U_1	0.025	0.025	0.025	0.025	0.050	0.050
U_2	0.050	0.050	0.050	0.050	0.050	0.050
U_3	0.000	0.000	0.000	0.000	0.000	0.000
U_4	0.050	0.050	0.050	0.100	0.100	0.100
U_5	0.050	0.050	0.050	0.100	0.100	0.100
U_6	0.000	0.029	0.040	0.144	0.404	0.404
U_7	0.000	0.000	0.000	0.000	0.000	0.000
U_8	0.005	0.005	0.005	0.005	0.005	0.005
U_9	0.0005	0.005	0.0005	0.0005	0.0005	0.0005
U_{10}	0.0058	0.0577	0.0577	0.1443	0.2887	0.5774
U_{11}	0.000	0.0404	0.0808	0.1617	0.1617	0.1617
U_{12}	0.0577	0.0289	0.0000	0.0000	0.000	0.000
U_{13}	0.0577	0.0289	0.0289	0.0289	0.0289	0.0289
U_{14}	0.0058	0.0058	0.0058	0.0058	0.0058	0.0058
U_{15}	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006
U_{16}	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006
U_{17}	0.0577	0.0577	0.0577	0.0577	0.0577	0.0577

Table 4: Uncertainty budget for phase calibration.

B.3 NPLI

B.3.1 Magnitude

Charge Sensitivity uncertainty budget (in %)						
i	Standard Uncertainty contribution $u(x_i)$	ISO -SAM- Urel(S)	Uncertainty contribution $u_i(y)$	5 ≤ f < 1000 Hz	1000 ≤ f < 5000 Hz	5500 ≤ f ≤ 10,000 Hz
1	$u(\hat{u}_V)$	accelerometer output voltage measurement(waveform recorder; e.g. ADC-resolution)	$u_1(S)$	0,231	0,231	0,289
2	$u(\hat{u}_F)$	voltage filtering effect on accelerometer output amplitude measurement(frequency band limitation)	$u_2(S)$	0,06	0,06	0,115
3	$u(\hat{u}_D)$	effect of voltage disturbance on accelerometer output voltage measurement (e.g. hum and noise)	$u_3(S)$	0,115	0,115	0,115
4	$u(\hat{u}_T)$	effect of transverse, rocking, and bending acceleration on accelerometer output voltage measurement (transverse sensitivity)	$u_4(S)$	0,115	0,115	0,115
5	$u(\hat{\varphi}_{M,Q})$	effect of interferometer quadrature output signal disturbance on phase amplitude measurement(e.g. offsets, voltage amplitude deviation, deviation from 90° nominal angle difference)	$u_5(S)$	0,06	0,09	0,09
6	$u(\hat{\varphi}_{M,F})$	interferometer signal filtering effect on phase amplitude measurement (frequency band limitation)	$u_6(S)$	0,06	0,06	0,09
7	$u(\hat{\varphi}_{M,VD})$	effect of voltage disturbance on phase amplitude measurement(e.g. random noise in the photoelectric measuring chains)	$u_7(S)$	0,06	0,06	0,231
8	$u(\hat{\varphi}_{M,MD})$	effect of motion disturbance on phase amplitude measurement(e.g. drift; relative motion between the accelerometer reference surface and the spot sensed by the interferometer)	$u_8(S)$	0,231	0,202	0,289
9	$u(\hat{\varphi}_{M,PD})$	effect of phase disturbance on phase amplitude measurement(e.g. phase noise of the interferometer signals)	$u_9(S)$	0,06	0,06	0,115
10	$u(\hat{\varphi}_{M,RE})$	residual interferometric effects on amplitude measurement(interferometer function); cosine error due to laser beam impinging the shining surface of transducer	$u_{10}(S)$	0,289	0,289	0,4616
11	$u(f_{FG})$	vibration frequency measurement (frequency generator and indicator)	$u_{11}(S)$	0,001	0,001	0,001
12	$u(S_{RE})$	residual effects on sensitivity measurement(e.g. random effect in repeat measurements; experimental standard devitation of arithmetic mean)	$u_{12}(S)$	0,11	0,13	0,21
		Combined Uncertainty (in %)		0,50	0,50	0,75
		Expanded Uncertainty (k =2) in %		1,00	1,00	1,50

B.3.2 Phase

Phase Shift uncertainty budget (in degrees)							
i	Standard Uncertainty contribution u(xi)	ISO -SAM - U(Δφ)	Uncertainty contribution ui(y)	5 ≤ *f* < 40 Hz	40 ≤ *f* < 1,000 Hz	1000 ≤ *f* < 5,000 Hz	5000 ≤ *f* ≤ 10,000 Hz
1	u(φ [illegible])	accelerometer output phase measurement(waveform recorder; e.g. ADC-resolution)	$u_1(\Delta\phi)$	0,231	0,231	0,4616	0,4616
2	u(φ [illegible])	voltage filtering effect on accelerometer output phase measurement(frequency band limitation)	$u_2(\Delta\phi)$	0,1731	0,231	0,289	0,289
3	u(φ [illegible])	effect of voltage disturbance on accelerometer output phase measurement (e.g. hum and noise)	$u_3(\Delta\phi)$	0,1731	0,1731	0,1731	0,1731
4	u(φ [illegible])	effect of transverse, rocking, and bending acceleration on accelerometer output phase measurement (transverse sensitivity)	$u_4(\Delta\phi)$	0,18	0,18	0,18	0,18
5	u(φ [illegible])	effect of interferometer quadrature output signal disturbance on displacement phase measurement(e.g. offsets, voltage amplitude deviation, deviation from 90° nominal angle difference)	$u_5(\Delta\phi)$	0,1731	0,1731	0,299	0,299
6	u(φ [illegible])	interferometer signal filtering effect on displacement phase amplitude measurement (frequency band limitation)	$u_6(\Delta\phi)$	0,1731	0,1731	0,1731	0,1731
7	u(φ [illegible])	effect of voltage disturbance on displacement phase amplitude measurement(e.g. random noise in the photoelectric measuring chains)	$u_7(\Delta\phi)$	0,1731	0,1731	0,289	0,289
8	u(φ [illegible])	effect of motion disturbance on displacement phase amplitude measurement(e.g. drift; relative motion between the accelerometer reference surface and the spot sensed by the interferometer)	$u_8(\Delta\phi)$	0,1731	0,1731	0,1731	0,1731
9	u(φ [illegible])	effect of phase disturbance on displacement phase amplitude measurement(e.g. phase noise of the interferometer signals)	$u_9(\Delta\phi)$	0,1731	0,1731	0,289	0,289
10	u(φ [illegible])	residual interferometric effects on displacement phase amplitude measurement(interferometer function), uncertainty due to effect of armature insert of vibration exciter, PCB 396C11 and Cosine error due to laser beam impinging the shining surface of transducer	$u_{10}(\Delta\phi)$	0,4616	0,4616	0,4616	0,4616
11	u(Δφ [illegible])	residual effects on phase shift measurement(e.g. random effect in repeat measurements; experimental standard devitation of arithmetic mean)	$u_{11}(\Delta\phi)$	0,17	0,14	0,23	0,25
		Combined Uncertainty (in °)		0.75°	0.75°	1.00°	1.00°
		Expanded Uncertainty (*k* =2) in °		1.50°	1.50°	2.00°	2.00°

B.4 INTI

B.4.1 Magnitude BtoB

PEMA12A: Piezoelectric accelerometers calibration by laser interferometry according to ISO 16063-11: Fringe Count. B&K 8305-001

Frecuency	10 Hz to 50 Hz

Fuente de incertidumbre Tipo B	Value	Interval		c_i [1]		Distribution[2]	Factor	n_i [3]	u_i	Contribution %	W-S	$(u_i \cdot c_i)^2$
Reference Standard Transducer Voltage Measurement (multimeter accuracy)		6,70E-02	mV	5,74E-03	pC/mV(m/s2)	R	1,7	12	3,87E-02	9,9%	1,87E-07	4,93E-08
Reference Standard Transducer Voltage Measurement (multimeter resolution)		5,00E-05	mV	5,74E-03	pC/mV(m/s2)	R	1,7	10000	2,89E-05	0,0%	6,94E-23	2,74E-14
Reference Standard Transducer Frequency Measurement Excitation (multimeter accuracy)		4,80E-02	Hz	-1,61E-02	pC/(m/s3)	R	1,7	12	2,77E-02	40,3%	4,92E-08	2,00E-07
Fringe Count Frequency Measurement (multimeter accuracy)		1,50E+02	Hz	-5,16E-06	pC/(m/s3)	R	1,7	12	8,67E+01	40,3%	4,70E+06	2,00E-07
Laser Wavelenght Uncertainty	6,3281E-07	1,50E-07	m	-4,08E-01	pC/(m2/s2)	N	2,0	10000	7,50E-08	0,0%	3,16E-33	9,37E-16
Charge Amplifier Calibration		1,58E-01	[mV/pC]	-2,62E-03	pC2/mV(m/s2	N	2,0	10000	7,89E-02	8,6%	3,87E-09	4,27E-08
Base Strain	0,003	3,00E-06	pC/(m/s2)	1,00E+00		N	2,0	10000	1,50E-06	0,0%	5,06E-28	2,25E-12
Reference Standard Transducer Temperature Influence		5,17E-05	pC/(m/s2)	1,00E+00		N	2,0	10001	2,58E-05	0,1%	4,45E-23	6,67E-10
Estimation of type B uncertainty, k =1	u_c					N (1σ)		5,17E-20				7,02E-04

Type A uncertainty source		c_i [1]			n_i [3]	u_i	Contribution %	W-S	$(u_i \cdot c_i)^2$
Reference Standard Transducer Voltage Repeatability	mV	5,74E-03	pC/mV(m/s^2)		1,20E+01	9,87E-03	0,6%	7,91E-10	3,21E-09
Reference Standard Transducer Excitation Frequency Repeatability	Hz	-1,61E-02	pC/(m/s^3)		1,20E+01	0,00E+00	0,0%	0,00E+00	0,00E+00
Fringe Count Frequency Repeatability	Hz	-5,16E-06	pC/(m/s^3)		1,20E+01	2,31E+00	0,0%	2,38E+00	1,42E-10
Repeatability sensitivity calculation	pC/(m/s2)	1,00E+00	-		1,20E+01	2,85E-05	0,0%	5,53E-20	8,14E-10
Estimation of type A uncertainty, k =1									6,45E-05
Contribution %							99,8%		
Sumation ci^2									4,97E-07
Incertidumbre combinada									7,05E-04

Expanded uncertainty		Distribution[2]	Factor	
	Type A, N(95%)	k	2,0	
	Type B, N(95%)	k	2,0	
Expanded uncertainty, k=2				1,41E-03

Final uncertainty	Unit		Value
Final uncertainty	[pC/(m/s^2)]		1,41E-03
	[%]		1,2

(1) Sensitivity coefficients

(2) N: normal; R:rectangular

(3) Degrees of freedom

PEMA12A: Piezoelectric accelerometers calibration by laser interferometry according to ISO 16063-11: Fringe Count. B&K 8305-001

Frecuency	>50 Hz to 200 Hz

Fuente de incertidumbre Tipo B	Value	Interval		c_i (1)		Distribution (2)	Factor	n_i (3)	u_i	Contribution %	W-S	$(u_i \cdot c_i)^2$
Reference Standard Transducer Voltage Measurement (multimeter accuracy)		1,39E-01	mV	1,41E-03	pC/mV(m/s2)	R	1,7	12	8,00E-02	16,2%	3,41E-06	1,28E-08
Reference Standard Transducer Voltage Measurement (multimeter resolution)		5,00E-07	mV	1,41E-03	pC/mV(m/s2)	R	1,7	10000	2,89E-07	0,0%	6,94E-31	1,67E-19
Reference Standard Transducer Frequency Measurement Excitation (multimeter accuracy)		2,00E-02	Hz	-1,28E-03	pC/(m/s3)	R	1,7	12	1,15E-02	0,3%	1,48E-09	2,18E-10
Fringe Count Frequency Measurement (multimeter accuracy)		1,61E+00	Hz	-1,59E-05	pC/(m/s3)	R	1,7	12	9,31E-01	0,3%	6,25E-02	2,18E-10
Laser Wavelenght Uncertainty	6,3281E-07	1,50E-07	m	-4,05E-01	pC/(m2/s2)	N	2,0	10000	7,50E-08	0,0%	3,16E-33	9,20E-16
Charge Amplifier Calibration		1,59E-01	[mV/pC]	-2,58E-03	pC2/mV(m/s2	N	2,0	10000	7,94E-02	52,9%	3,98E-09	4,19E-08
Base Strain	0,003	3,00E-06	pC/(m/s2)	1,00E+00		N	2,0	10000	1,50E-06	0,0%	5,06E-28	2,25E-12
Reference Standard Transducer Temperature Influence		5,15E-05	pC/(m/s2)	1,00E+00		N	2,0	10001	2,58E-05	0,8%	4,40E-23	6,63E-10
Estimation of type B uncertainty, k =1	u_c					N (1σ)		4,99E-14				2,36E-04

Type A uncertainty source		c_i (1)			n_i (3)	u_i	Contribution %	W-S	$(u_i \cdot c_i)^2$
Reference Standard Transducer Voltage Repeatability	mV	1,41E-03	pC/mV(m/s^2)		1,20E+01	9,83E-02	24,4%	7,80E-06	1,94E-08
Reference Standard Transducer Excitation Frequency Repeatability	Hz	-1,28E-03	pC/(m/s^3)		1,20E+01	0,00E+00	0,0%	0,00E+00	0,00E+00
Fringe Count Frequency Repeatability	Hz	-1,59E-05	pC/(m/s^3)		1,20E+01	1,62E+00	0,8%	5,75E-01	6,62E-10
Repeatability sensitivity calculation	pC/(m/s2)	1,00E+00	-		1,20E+01	5,79E-05	0,0%	9,36E-19	3,35E-09
Estimation of type A uncertainty, k =1									1,53E-04
Contribution %							95,8%		
Sumation ci^2									7,92E-08
Incertidumbre combinada									2,81E-04

Expanded uncertainty		Distribution (2)	Factor	
	Type A, N(95%)	k	2,0	
	Type B, N(95%)	k	2,0	
Expanded uncertainty, k=2				5,63E-04

Final uncertainty			
Final uncertainty	[pC/(m/s^2)]		5,63E-04
	[%]		0,5

(1) Sensitivity coefficients

(2) N: normal; R:rectangular

(3) Degrees of freedom

PEMA12A: Piezoelectric accelerometers calibration by laser interferometry according to ISO 16063-11: Fringe Count. B&K 8305-001

Frecuency	>200 Hz to 1 kHz

Fuente de incertidumbre Tipo B	Value	Interval		c_i (1)		Distribution (2)	Factor	n_i (3)	u_i	Contribution %	W-S	$(u_i \cdot c_i)^2$
Reference Standard Transducer Voltage Measurement (multimeter accuracy)		4,09E-01	mV	1,29E-03	pC/mV(m/s2)	R	1,7	12	2,36E-01	70,5%	2,59E-04	9,33E-08
Reference Standard Transducer Voltage Measurement (multimeter resolution)		5,00E-07	mV	1,29E-03	pC/mV(m/s2)	R	1,7	10000	2,89E-07	0,0%	6,94E-31	1,39E-19
Reference Standard Transducer Frequency Measurement Excitation (multimeter accuracy)		8,00E-02	Hz	-2,94E-04	pC/(m/s3)	R	1,7	12	4,62E-02	0,1%	3,79E-07	1,84E-10
Fringe Count Frequency Measurement (multimeter accuracy)		4,40E-01	Hz	-5,34E-05	pC/(m/s3)	R	1,7	12	2,54E-01	0,1%	3,48E-04	1,84E-10
Laser Wavelenght Uncertainty	6,3281E-07	1,50E-07	m	-3,72E-01	pC/(m2/s2)	N	2,0	10000	7,50E-08	0,0%	3,16E-33	7,77E-16
Charge Amplifier Calibration		1,59E-01	[mV/pC]	-2,37E-03	pC2/mV(m/s2	N	2,0	10000	7,95E-02	26,8%	4,00E-09	3,54E-08
Base Strain	0,003	3,00E-06	pC/(m/s2)	1,00E+00		N	2,0	10000	1,50E-06	0,0%	5,06E-28	2,25E-12
Reference Standard Transducer Temperature Influence		5,18E-05	pC/(m/s2)	1,00E+00		N	2,0	10001	2,59E-05	0,5%	4,48E-23	6,70E-10
Estimation of type B uncertainty, k =1	u_c					N (1σ)		2,77E-11				3,60E-04

Type A uncertainty source		c_i (1)			n_i (3)	u_i	Contribution %	W-S	$(u_i \cdot c_i)^2$
Reference Standard Transducer Voltage Repeatability	mV	1,29E-03	pC/mV(m/s²)		1,20E+01	1,07E-02	0,1%	1,10E-09	1,92E-10
Reference Standard Transducer Excitation Frequency Repeatability	Hz	-2,94E-04	pC/(m/s³)		1,20E+01	0,00E+00	0,0%	0,00E+00	0,00E+00
Fringe Count Frequency Repeatability	Hz	-5,34E-05	pC/(m/s³)		1,20E+01	7,61E-01	1,3%	2,80E-02	1,66E-09
Repeatability sensitivity calculation	pC/(m/s2)	1,00E+00	-		1,20E+01	2,68E-05	0,0%	4,28E-20	7,17E-10
Estimation of type A uncertainty, k =1									5,06E-05
Contribution %							99,5%		
Sumation ci^2									1,32E-07
Incertidumbre combinada									3,64E-04

Expanded uncertainty		Distribution (2)	Factor	
	Type A, N(95%)	k	2,0	
	Type B, N(95%)	k	2,0	
Expanded uncertainty, k=2				7,28E-04

Final uncertainty	[pC/(m/s²)]	7,28E-04
	[%]	0,6

(1) Sensitivity coefficients

(2) N: normal; R:rectangular

(3) Degrees of freedom

PEMA12A: Piezoelectric accelerometers calibration by laser interferometry according to ISO 16063-11: Zeros of Bessel Function. B&K 8305-001

Frecuency	1 kHz to 10 kHz

Fuente de incertidumbre Tipo B	Value	Interval		c_i (1)		Distribution (2)	Factor	n_i (3)	u_i	Contribution %	W-S	$(u_i \cdot c_i)^2$
Reference Standard Transducer Voltage Measurement (multimeter accuracy)		7,12E-01	mV	2,07E-04	pC/mV(m/s2)	R	1,7	12	4,11E-01	0,7%	2,38E-03	7,23E-09
Reference Standard Transducer Voltage Measurement (multimeter resolution		5,00E-07	mV	2,07E-04	pC/mV(m/s2)	R	1,7	10000	2,89E-07	0,0%	6,94E-31	3,56E-21
Reference Standard Transducer Frequency Measurement Excitation (multimeter accuracy)		9,50E-01	Hz	-1,50E-05	pC/(m/s3)	R	1,7	12	5,48E-01	0,0%	7,54E-03	6,72E-11
Zero Point (Bessel Function)	3,8317	0,00E+00		-3,71E-02	pC/(m/s2)	N	2,0	10000	0,00E+00	0,0%	0,00E+00	0,00E+00
Laser Wavelenght Uncertainty	6,3281E-07	1,50E-07	m	-2,24E-01	pC/(m2/s2)	N	2,0	10000	7,50E-08	0,0%	3,16E-33	2,83E-16
Charge Amplifier Calibration		1,59E-02	[mV/pC]	-1,43E-02	pC2/mV(m/s2	N	2,0	10000	7,96E-03	1,3%	4,01E-13	1,29E-08
Base Strain	0,003	3,00E-06	pC/(m/s2)	1,00E+00		N	2,0	10000	1,50E-06	0,0%	5,06E-28	2,25E-12
Reference Standard Transducer Temperature Influence		5,68E-05	pC/(m/s2)	1,00E+00		N	2,0	10000	2,84E-05	0,1%	6,51E-23	8,07E-10
Estimation of type B uncertainty, k =1	u_c					N (1σ)		4,45E-14				1,45E-04

Type A uncertainty source		c_i (1)			n_i (3)	u_i	Contribución %	W-S	$(u_i \cdot c_i)^2$
Reference Standard Transducer Voltage Repeatability	mV	2,07E-04	$pC/mV(m/s^2)$		1,20E+01	3,41E+00	49,0%	1,12E+01	4,96E-07
Reference Standard Transducer Excitation Frequency Repeatability	Hz	-1,50E-05	$pC/(m/s^3)$		1,20E+01	0,00E+00	0,0%	0,00E+00	0,00E+00
Repeatability sensitivity calculation	pC/(m/s2)	1,00E+00	-		1,20E+01	7,04E-04	0,0%	2,05E-14	4,96E-07
Estimation of type A uncertainty, k =1									9,96E-04
Contribution %							51,1%		
Sumation ci^2									1,01E-06
Incertidumbre combinada									1,01E-03

Expanded uncertainty		Distribution (2)	Factor	
	Type A, N(95%)	k	2,0	
	Type B, N(95%)	k	2,0	
Expanded uncertainty, k=2				2,01E-03

Final uncertainty			
Final uncertainty	$[pC/(m/s^2)]$		2,01E-03
	[%]		1,5

(1) Sensitivity coefficients

(2) N: normal; R:rectangular

(3) Degrees of freedom

B.4.2 Magnitude SE

PEMA12A: Piezoelectric accelerometers calibration by laser interferometry according to ISO 16063-11: Fringe Count. ENDEVCO 2270

Frecuency	10 Hz to 50 Hz

Fuente de incertidumbre Tipo B	Value	Interval		c_i [1]		Distribution[2]	Factor	n_i [3]	u_i	Contribution %	W-S	$(u_i \cdot c_i)^2$
Reference Standard Transducer Voltage Measurement (multimeter accuracy)		5,55E-02	mV	1,44E-02	pC/mV(m/s2)	R	1,7	12	3,20E-02	18,7%	8,77E-08	2,11E-07
Reference Standard Transducer Voltage Measurement (multimeter resolution)		5,00E-05	mV	1,44E-02	pC/mV(m/s2)	R	1,7	10000	2,89E-05	0,0%	6,94E-23	1,72E-13
Reference Standard Transducer Frequency Measurement Excitation (multimeter accuracy)		3,75E-02	Hz	-2,96E-02	pC/(m/s3)	R	1,7	12	2,17E-02	36,5%	1,83E-08	4,11E-07
Fringe Count Frequency Measurement (multimeter accuracy)		7,69E+01	Hz	-1,44E-05	pC/(m/s3)	R	1,7	12	4,44E+01	36,5%	3,23E+05	4,11E-07
Laser Wavelenght Uncertainty	6,3281E-07	1,50E-07	m	-5,85E-01	pC/(m2/s2)	N	2,0	10000	7,50E-08	0,0%	3,16E-33	1,93E-15
Charge Amplifier Calibration		1,58E-01	[mV/pC]	-3,76E-03	pC2/mV(m/s2	N	2,0	10000	7,88E-02	7,8%	3,85E-09	8,77E-08
Base Strain	0,003	3,00E-06	pC/(m/s2)	1,00E+00		N	2,0	10000	1,50E-06	0,0%	5,06E-28	2,25E-12
Reference Standard Transducer Temperature Influence		7,41E-05	pC/(m/s2)	1,00E+00		N	2,0	10001	3,70E-05	0,1%	1,88E-22	1,37E-09
Estimation of type B uncertainty, k =1	u_c					N (1σ)		3,90E-18				1,06E-03

Type A uncertainty source		c_i [1]			n_i [3]	u_i	Contribution %	W-S	$(u_i \cdot c_i)^2$
Reference Standard Transducer Voltage Repeatability	mV	1,44E-02	pC/mV(m/s²)		1,20E+01	4,17E-03	0,3%	2,53E-11	3,59E-09
Reference Standard Transducer Excitation Frequency Repeatability	Hz	-2,96E-02	pC/(m/s³)		1,20E+01	0,00E+00	0,0%	0,00E+00	0,00E+00
Fringe Count Frequency Repeatability	Hz	-1,44E-05	pC/(m/s³)		1,20E+01	1,16E+00	0,0%	1,50E-01	2,80E-10
Repeatability sensitivity calculation	pC/(m/s2)	1,00E+00	-		1,20E+01	2,77E-05	0,0%	4,89E-20	7,66E-10
Estimation of type A uncertainty, k =1									6,81E-05
Contribution %							99,9%		
Sumation ci²									1,13E-06
Incertidumbre combinada									1,06E-03

Expanded uncertainty		Distribution[2]	Factor	
	Type A, N(95%)	k	2,0	
	Type B, N(95%)	k	2,0	
Expanded uncertainty, k=2				2,12E-03

Final uncertainty			
	[pC/(m/s²)]		2,12E-03
	[%]		1,2

(1) Sensitivity coefficients

(2) N: normal; R:rectangular

(3) Degrees of freedom

PEMA12A: Piezoelectric accelerometers calibration by laser interferometry according to ISO 16063-11: Fringe Count. ENDEVCO 2270

Frecuency	>50 Hz to 200 Hz

Fuente de incertidumbre Tipo B	Value	Interval		c_i [1]		Distribution [2]	Factor	n_i [3]	u_i	Contribution %	W-S	$(u_i \cdot c_i)^2$
Reference Standard Transducer Voltage Measurement (multimeter accuracy)		4,55E-01	mV	1,42E-03	pC/mV(m/s2)	R	1,7	12	2,62E-01	59,7%	3,96E-04	1,39E-07
Reference Standard Transducer Voltage Measurement (multimeter resolution)		5,00E-07	mV	1,42E-03	pC/mV(m/s2)	R	1,7	10000	2,89E-07	0,0%	6,94E-31	1,68E-19
Reference Standard Transducer Frequency Measurement Excitation (multimeter accuracy)		1,60E-02	Hz	-2,29E-03	pC/(m/s3)	R	1,7	12	9,24E-03	0,2%	6,07E-10	4,46E-10
Fringe Count Frequency Measurement (multimeter accuracy)		2,01E+00	Hz	-1,82E-05	pC/(m/s3)	R	1,7	12	1,16E+00	0,2%	1,51E-01	4,46E-10
Laser Wavelenght Uncertainty	6,3281E-07	1,50E-07	m	-5,78E-01	pC/(m2/s2)	N	2,0	10000	7,50E-08	0,0%	3,16E-33	1,88E-15
Charge Amplifier Calibration		1,59E-01	[mV/pC]	-3,69E-03	pC2/mV(m/s2	N	2,0	10000	7,94E-02	36,9%	3,98E-09	8,56E-08
Base Strain	0,003	3,00E-06	pC/(m/s2)	1,00E+00		N	2,0	10000	1,50E-06	0,0%	5,06E-28	2,25E-12
Reference Standard Transducer Temperature Influence		7,34E-05	pC/(m/s2)	1,00E+00		N	2,0	10001	3,67E-05	0,6%	1,82E-22	1,35E-09
Estimation of type B uncertainty, k =1	u_c					N (1σ)		3,39E-13				4,76E-04

Type A uncertainty source		c_i [1]			n_i [3]	u_i	Contribution %	W-S	$(u_i \cdot c_i)^2$
Reference Standard Transducer Voltage Repeatability	mV	1,42E-03	pC/mV(m/s^2)		1,20E+01	3,68E-02	1,2%	1,53E-07	2,73E-09
Reference Standard Transducer Excitation Frequency Repeatability	Hz	-2,29E-03	pC/(m/s^3)		1,20E+01	0,00E+00	0,0%	0,00E+00	0,00E+00
Fringe Count Frequency Repeatability	Hz	-1,82E-05	pC/(m/s^3)		1,20E+01	1,80E+00	0,5%	8,79E-01	1,08E-09
Repeatability sensitivity calculation	pC/(m/s2)	1,00E+00	-		1,20E+01	4,26E-05	0,0%	2,74E-19	1,81E-09
Estimation of type A uncertainty, k =1									7,50E-05
Contribution %							99,2%		
Sumation ci^2									2,32E-07
Incertidumbre combinada									4,82E-04

Expanded uncertainty		Distribution [2]	Factor	
	Type A, N(95%)	k	2,0	
	Type B, N(95%)	k	2,0	
Expanded uncertainty, k=2				9,64E-04

Final uncertainty	[pC/(m/s^2)]	9,64E-04
	[%]	0,5

(1) Sensitivity coefficients

(2) N: normal; R:rectangular

(3) Degrees of freedom

PEMA12A: Piezoelectric accelerometers calibration by laser interferometry according to ISO 16063-11: Fringe Count. ENDEVCO 2270

Frecuency	>200 Hz to 1 kHz

Fuente de incertidumbre Tipo B	Value	Interval		c_i [1]		Distribution [2]	Factor	n_i [3]	u_i	Contribution %	W-S	$(u_i \cdot c_i)^2$
Reference Standard Transducer Voltage Measurement (multimeter accuracy)		4,55E-01	mV	1,41E-03	pC/mV(m/s2)	R	1,7	12	2,63E-01	51,5%	3,96E-04	1,37E-07
Reference Standard Transducer Voltage Measurement (multimeter resolution)		5,00E-07	mV	1,41E-03	pC/mV(m/s2)	R	1,7	10000	2,89E-07	0,0%	6,94E-31	1,66E-19
Reference Standard Transducer Frequency Measurement Excitation (multimeter accuracy)		2,50E-02	Hz	-1,46E-03	pC/(m/s3)	R	1,7	12	1,44E-02	0,2%	3,62E-09	4,41E-10
Fringe Count Frequency Measurement (multimeter accuracy)		1,29E+00	Hz	-2,81E-05	pC/(m/s3)	R	1,7	12	7,47E-01	0,2%	2,59E-02	4,41E-10
Laser Wavelenght Uncertainty	6,3281E-07	1,50E-07	m	-5,75E-01	pC/(m2/s2)	N	2,0	10000	7,50E-08	0,0%	3,16E-33	1,86E-15
Charge Amplifier Calibration		1,59E-01	[mV/pC]	-3,66E-03	pC2/mV(m/s2	N	2,0	10000	7,95E-02	31,8%	3,99E-09	8,47E-08
Base Strain	0,003	3,00E-06	pC/(m/s2)	1,00E+00		N	2,0	10000	1,50E-06	0,0%	5,06E-28	2,25E-12
Reference Standard Transducer Temperature Influence		7,35E-05	pC/(m/s2)	1,00E+00		N	2,0	10001	3,67E-05	0,5%	1,82E-22	1,35E-09
Estimation of type B uncertainty, k =1	u_c					N (1σ)		1,91E-12				4,73E-04

Type A uncertainty source		c_i [1]			n_i [3]	u_i	Contribution %	W-S	$(u_i \cdot c_i)^2$
Reference Standard Transducer Voltage Repeatability	mV	1,41E-03	$pC/mV(m/s^2)$		1,20E+01	1,22E-01	11,1%	1,84E-05	2,96E-08
Reference Standard Transducer Excitation Frequency Repeatability	Hz	-1,46E-03	$pC/(m/s^3)$		1,20E+01	0,00E+00	0,0%	0,00E+00	0,00E+00
Fringe Count Frequency Repeatability	Hz	-2,81E-05	$pC/(m/s^3)$		1,20E+01	3,86E+00	4,4%	1,85E+01	1,18E-08
Repeatability sensitivity calculation	pC/(m/s2)	1,00E+00	-		1,20E+01	3,18E-05	0,0%	8,56E-20	1,01E-09
Estimation of type A uncertainty, k =1									2,06E-04
Contribution %							99,6%		
Sumation ci^2									2,66E-07
Incertidumbre combinada									5,16E-04

Expanded uncertainty		Distribution [2]	Factor	
	Type A, N(95%)	k	2,0	
	Type B, N(95%)	k	2,0	
Expanded uncertainty, k=2				1,03E-03

Final uncertainty			
Final uncertainty	$[pC/(m/s^2)]$		1,03E-03
	[%]		0,6

(1) Sensitivity coefficients

(2) N: normal; R:rectangular

(3) Degrees of freedom

PEMA12A: Piezoelectric accelerometers calibration by laser interferometry according to ISO 16063-11: Zeros of Bessel Function. ENDEVCO 2270

Frecuency	1 kHz to 10 kHz

Fuente de incertidumbre Tipo B	Value	Interval		c_i [1]		Distribution [2]	Factor	n_i [3]	u_i	Contribution %	W-S	$(u_i \cdot c_i)^2$
Reference Standard Transducer Voltage Measurement (multimeter accuracy)		2,81E+00	mV	4,42E-05	pC/mV(m/s2)	R	1,7	12	1,62E+00	1,2%	5,81E-01	5,15E-09
Reference Standard Transducer Voltage Measurement (multimeter resolution		5,00E-07	mV	4,42E-05	pC/mV(m/s2)	R	1,7	10000	2,89E-07	0,0%	6,94E-31	1,62E-22
Reference Standard Transducer Frequency Measurement Excitation (multimeter accuracy)		6,50E-01	Hz	-2,85E-05	pC/(m/s3)	R	1,7	12	3,75E-01	0,0%	1,65E-03	1,14E-10
Zero Point (Bessel Function)	3,8317	0,00E+00		-4,83E-02	pC/(m/s2)	N	2,0	10000	0,00E+00	0,0%	0,00E+00	0,00E+00
Laser Wavelenght Uncertainty	6,3281E-07	1,50E-07	m	-2,92E-01	pC/(m2/s2)	N	2,0	10000	7,50E-08	0,0%	3,16E-33	4,81E-16
Charge Amplifier Calibration		1,59E-01	[mV/pC]	-1,86E-03	pC2/mV(m/s2	N	2,0	10000	7,96E-02	5,0%	4,02E-09	2,19E-08
Base Strain	0,003	3,00E-06	pC/(m/s2)	1,00E+00		N	2,0	10000	1,50E-06	0,0%	5,06E-28	2,25E-12
Reference Standard Transducer Temperature Influence		7,40E-05	pC/(m/s2)	1,00E+00		N	2,0	10000	3,70E-05	0,3%	1,88E-22	1,37E-09
Estimation of type B uncertainty, k =1	u_c					N (1σ)		1,40E-15				1,69E-04

Type A uncertainty source		c_i [1]			n_i [3]	u_i	Contribución %	W-S	$(u_i \cdot c_i)^2$
Reference Standard Transducer Voltage Repeatability	mV	4,42E-05	$pC/mV(m/s^2)$		1,20E+01	1,02E+01	25,6%	9,08E+02	2,03E-07
Reference Standard Transducer Excitation Frequency Repeatability	Hz	-2,85E-05	$pC/(m/s^3)$		1,20E+01	0,00E+00	0,0%	0,00E+00	0,00E+00
Repeatability sensitivity calculation	pC/(m/s2)	1,00E+00	-		1,20E+01	7,51E-04	0,1%	2,65E-14	5,64E-07
Estimation of type A uncertainty, k =1									8,76E-04
Contribution %							32,2%		
Sumation ci^2									7,96E-07
Incertidumbre combinada									8,92E-04

Expanded uncertainty		Distribution [2]	Factor	
	Type A, N(95%)	k	2,0	
	Type B, N(95%)	k	2,0	
Expanded uncertainty, k=2				1,78E-03

Final uncertainty			
Final uncertainty	$[pC/(m/s^2)]$		1,78E-03
	[%]		1,0

(1) Sensitivity coefficients

(2) N: normal; R:rectangular

(3) Degrees of freedom