

A bilateral acceleration comparison between CENAM and INMETRO

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Abstract

A bilateral key comparison was conducted in the area of vibration between the National Institute of Metrology, Standardization and Industrial Quality (INMETRO), Brazil and the Centro Nacional de Metrología (CENAM), in Mexico; with INMETRO acting as pilot laboratory. This comparison was registered in the BIPM key comparison database (Mutual Recognition Arrangement - Appendix B) as SIM.AUV.V-K1.1 and the measurements were carried out by the participating laboratories from October 2004 to March 2006. The aim of this exercise was to compare primary interferometric measurements of complex charge sensitivity of standard accelerometers under sinusoidal linear accelerations in the frequency range from 10 Hz to 10 kHz. In addition, it was intended to provide a link between INMETRO and the key comparison reference values (KCRVs) established in the CIPM key comparison CCAUV.V-K1. This link of the regional metrology organization (RMO) key-comparison SIM.AUV.V-K1.1 to the International Committee for Weights and Measures (CIPM) key-comparison CCAUV.V-K1 can be established because CENAM participated in both comparisons. Both participants used automated calibration systems based on homodyne quadrature laser interferometers to measure the sensitivity magnitude and the phase shift of two back-to-back standard accelerometers in compliance with the international standard ISO 16063-11:1999.

The results reported by the participating laboratories at 30 specified frequencies and the respective calculated degrees of equivalence are presented. These results show an agreement better than 0,3 % from 10 Hz to 5 kHz and than 1% from 6 kHz to 10 kHz in sensitivity magnitude and better than 0,6° in phase shift in the entire frequency range.

Keywords: Calibration, interlaboratory comparison, vibration, accelerometer, metrology.

1. Introduction

This paper presents an overview of the results of the bilateral key comparison in the area of vibration (quantity of acceleration), SIM.AUV.V-K1.1. This comparison was organized and conducted in accordance with the guidelines for CIPM comparisons [1]. The calibrations were performed from October 2004 to March 2006 in accordance with the international standard ISO 16063-11:1999 [2] and the Technical Protocol [3], which specifies in detail the aim and the task of the comparison, the conditions of measurement, the

reference standards used, measurement instructions, time schedule and other items. A brief survey is given in the following sections.

2. Task and purpose of the comparison

The main task of this comparison was to measure the magnitude and phase shift of the complex charge sensitivity of two back-to-back accelerometer standards in the frequency range from 10 Hz to 10 kHz.

The magnitude of the complex sensitivity of an accelerometer is determined as the ratio of the amplitude of the accelerometer output charge to the amplitude of the acceleration at its reference surface. The phase shift of the complex charge sensitivity is calculated as the difference between the initial phase angle of the output charge and the initial phase angle of the acceleration. According to ISO 16063-1:1998 [4] the acceleration vector is, for back-to-back accelerometers, considered positive when directed from its reference top surface into the accelerometer to be calibrated by comparison.

It was requested to the participants to use a calibrated charge amplifier to measure the output charge and phase shift of the accelerometer standards, applying appropriate electrical calibration methods.

The main purpose of this exercise was to provide an objective evidence of the current measurement capabilities of the participating laboratories. Since the key comparison CCAUV.V-K1 [5] was limited to measurements of sensitivity magnitude in the frequency range from 40 Hz to 5 kHz, it was necessary to obtain some other means to evaluate the conformity of measurements in a broader frequency range and for phase shift. The results of this bilateral comparison will serve to support CMC entries from both CENAM and INMETRO in this range of measurements not covered by the CIPM key comparison CCAUV.V-K1.

Another important purpose of the present exercise is the dissemination of the key comparison reference values (KCRVs), which were established in CCAUV.V-K1 to the countries of the Interamerican Metrology System (SIM). The results reported for sensitivity magnitude in the present bilateral regional key comparison can be used for the linkage of INMETRO to the key comparison reference values (KCRVs) computed for the CIPM key comparison CCAUV.V-K1. This linkage is possible because CENAM participated in both comparisons. The present paper will not cover this subject, which will be included in the final report of the comparison SIM.AUV.V-K1.1.

3. Conditions of measurement

The participating laboratories observed fully or to a large extent the conditions stated in the Technical Protocol [3], i.e.

- Methods: Calibrations carried out in accordance with ISO 16063-11:1999 [2], preferably method 3: sine-approximation method.

- Frequencies in hertz: 10; 12,5; 16; 20; 25; 31,5; 40; 50; 63; 80; 100; 125; 160; 200; 315; 400; 500; 630; 800; 1000; 1250; 1600; 2000; 3150; 4000; 5000; 6000; 6300; 7000; 8000; 9000; 10000 Hz (160 Hz is the reference frequency).
- Displacement measurements: It was recommended to take into account and to minimize disturbing effects such as rocking motion, motion distortion and harshness from the vibration exciter on the final results of the calibration.
- Acceleration amplitudes: The recommended range between 10 to 120 m/s² was complied with.
- Environmental conditions: Ambient and accelerometer temperature during the calibration: (23 ± 2) °C.
- Mounting procedure: Mounting torque of the accelerometer (2 ± 0,1) N m
- Reporting of results: Magnitude of the charge sensitivity in pico coulombs per metres per second squared (pC/(m/s²)), phase shift in degrees and associated expanded uncertainties of measurement evaluated for a coverage factor of k=2.
- Transportation of artifacts: The accelerometers were hand-carried by representatives of the participating NMIs, in order to assure their physical integrity

4. Reference standards

During the preparatory stage, the INMETRO thoroughly investigated the characteristics (long-term stability, linearity, etc.) of a series of reference standard accelerometers considered to be candidates for the reference standards to be used in the comparison. Later, CENAM requested the inclusion of a second accelerometer. Both accelerometers chosen (referred to as A and B) were back-to-back reference standards Brüel & Kjær model 8305 with a nominal charge sensitivity (magnitude) of 0,13 pC/(m/s²).

5. Calibration systems

In this bilateral comparison between INMETRO and CENAM the sine-approximation method specified in ISO 16063-11 (method 3) was applied. Both NMIs implemented and used for their measurements, versions of homodyne interferometers with two output signals in quadrature (i.e. phase-shifted by 90 degrees).

The motion was interferometrically sensed at equally spaced points on the polished top surface of the back-to-back accelerometers without use of any dummy mass. In order to minimize the effect of any non-rectilinear motion, the displacement was measured at least at two different points.

The charge sensitivity of the accelerometers was determined by using a calibrated charge amplifier. Although not being clearly established in the Technical Protocol [3], the participating laboratories carried out calibrations of their charge amplifiers shortly before the interferometric calibrations. For this purpose, a standard capacitor and a standard voltmeter, both traceable to national standards were used. While CENAM applied values of the electric quantities similar to those found in accelerometer calibration, INMETRO used fixed electric values (10 pC input signal) within the frequency range of the comparison. The phase shift of the amplifiers was determined by measurements of frequency response functions (FRF) with dual-channel

frequency analyzers and by the data acquisition devices used to implement the sine-approximation method.

The calibration system developed at the INMETRO is fully synchronized and employs a flexible sampling rate to acquire the interferometer and accelerometer output signals and high-pass moving average filtering as described in detail by Ripper et al. [6] [7]

6. Bilateral comparison reference value

The participants have reached consensus and considered the weighted mean as the most appropriate method for this particular comparison to compute the comparison reference values (RVs) and the degrees of equivalence. Detailed analysis and application of the method for use in comparisons in the field of vibration is documented in the CCAUV.V-K1 report [5].

Calculation of comparison reference values using the weighted mean method:

The data reported by each participating laboratory i for the accelerometers A & B are

- (1) $x_{i,f}$: the best estimate of sensitivity at frequency f , and
- (2) $u(x_{i,f})$: the associated standard uncertainty of sensitivity reported at frequency f .

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

$x_{R,f} = \frac{\sum_{i=1}^n x_{i,f}}{\sum_{i=1}^n \frac{1}{u^2(x_{i,f})}}$,	$u(x_{R,f}) = \sqrt{\frac{1}{\sum_{i=1}^n \frac{1}{u^2(x_{i,f})}}}$	(1)
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For simplicity purposes, the reference value $x_{R,f}$ and the associated standard uncertainty $u(x_{R,f})$ obtained by Eq. (1) can be denoted respectively by x_{WM} (or WN) and u_{WM} . The expanded uncertainty of measurement associated with the reference value is then

$$U_{WM} = k \cdot u_{WM} \quad (2)$$

The degree of equivalence of the participants relative to the reference value, can be determined for the magnitude as well as the phase shift measurements for both accelerometers using

$$D_{i-WM} = x_i - x_{WM} \quad , \quad U_{i-WM} = k \cdot \sqrt{u_i^2 - u_{WM}^2} \quad , \quad (3)$$

where U_{i-WM} is the expanded uncertainty of measurement associated with the calculated difference between a laboratory result and the reference value D_{i-WM} .

Calculation of the degree of equivalence between a pair of laboratories:

The degree of equivalence between the participating laboratories at frequency f , was determined using

$$D_{ij} = x_i - x_j \quad (4)$$

$$u(D_{ij}) = \sqrt{u_i^2 + u_j^2} \quad , \quad U_{ij} = k \cdot u(D_{ij}) \quad (5)$$

where D_{ij} represents the difference between the measurement results obtained by the laboratories i and j at each frequency point for the magnitude and phase shift and U_{ij} is the associated expanded uncertainty of measurement for a given coverage factor k .

7. Results

The results presented in tables 1a and 1b are the final measurement results submitted by the two participating laboratories for respectively sensitivity magnitude and phase shift of accelerometer A. The corresponding results reported for accelerometer B are presented in tables 2a and 2b. These final results were calculated as the arithmetic mean of repeated calibrations obtained on different days. For simplification purposes, these tables present only the frequencies for which both laboratories reported results. The complete set of data will be available in the final report of the comparison. Tables 1a, 1b, 2a and 2b include:

- the complex sensitivity measurement results per laboratory,
- the reference value calculated by the weighted mean method,
- the degrees of equivalences between the participating laboratories and the calculated weighted mean value D_i -WM,
- the degrees of equivalences between the participating laboratories D_{ij} , and the respective associated expanded uncertainties for $k = 2$.

Figure 1 presents graphs of the results of the measured complex sensitivity values reported by the participating laboratories for accelerometers A & B and the reference value calculated by the weighted mean method (WM).

Figure 2 presents graphs of the degrees of equivalence between the participating laboratories for accelerometers A & B.

8. Summary and/ or conclusions

A bilateral key comparison registered as SIM.AUV.V-K1.1 was conducted in the area of vibration between INMETRO and CENAM to evaluate the degree of equivalence between their primary interferometric measurement capabilities of complex charge sensitivity of accelerometers. Two standard reference accelerometers, of the back-to-back type, were calibrated under sinusoidal linear accelerations in the frequency range from 10 Hz to 10 kHz, by applying the sine-approximation method in accordance with the international standard ISO 16063-11:1999.

A very good agreement was demonstrated between the results reported by the participants.

At the reference frequency of 160 Hz, the participating laboratories reported relative expanded uncertainties ($k = 2$) much smaller than the limit of 0,5 % specified by the ISO standard. The degree of equivalence demonstrated between the laboratories and the reference value calculated at this frequency was lower than 0,05 % in sensitivity magnitude and $0,02^\circ$ in phase shift.

In the lower frequency range from 10 Hz to 1 kHz, the differences between the sensitivity magnitudes results were within $\pm 0,1$ % and between phase shift results were within $\pm 0,1^\circ$ from the reference values for both accelerometers.

In the frequency range from 40 Hz to 5 kHz covered by the key comparison CCAUV.V-K1, the differences between the corresponding CENAM and INMETRO results were smaller than 0,20 % and 0,28 % for the sensitivity magnitude and $0,22^\circ$ and $0,32^\circ$ for the phase shift measured respectively for accelerometers A and B (22 measurement points).

The results have shown an agreement within $\pm 0,3$ % from 10 Hz to 5 kHz and $\pm 1\%$ from 6 kHz to 10 kHz in sensitivity magnitude and within $\pm 0,6^\circ$ in phase shift for the whole frequency range of analysis.

In all cases, except one, the differences of the results between the laboratories were smaller than the respective uncertainties calculated for sensitivity magnitude and phase shift. This level of agreement is very satisfactory since a coverage factor $k=2$ was used.

In conclusion, the degrees of equivalence calculated from the data submitted by the two laboratories, support the uncertainties of measurement reported by them for the calibration of the complex sensitivities of accelerometers over the frequency range from 10 Hz to 10 kHz. Both laboratories demonstrated considerable improvements of the measurement capabilities currently stated in the CMCs, which are available at the BIPM key comparison data base. The results obtained in this comparison may serve to support future claims for CMC reviews, including new entries and reduction of uncertainties

9. References

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Table 1a: Accelerometer A; results of sensitivity magnitude reported by the laboratories and calculated degrees of equivalence. Uncertainties are reported for $k=2$.

Frequency (Hz)	INMETRO		CENAM		Weighted Mean			Degrees of equivalence (Magnitude)					
	Sensitivity Magnitude ($\mu\text{C}/(\text{m/s}^2)$)	U_c (%)	Sensitivity Magnitude ($\mu\text{C}/(\text{m/s}^2)$)	U_c (%)	WM ($\mu\text{C}/(\text{m/s}^2)$)	U_{WM} (%)	D_{INM-WN} (%)	U_{INM-WN} (%)	D_{CEN-WN} (%)	U_{CEN-WN} (%)	$D_{CEN-IMM}$ (%)	$U_{CEN-IMM}$ (%)	
10	0,13087	0,35	0,13070	0,25	0,13076	0,20	0,09	0,29	-0,04	0,15	-0,13	0,43	
16	0,13084	0,35	0,13072	0,25	0,13076	0,20	0,06	0,29	-0,03	0,15	-0,09	0,43	
25	0,13081	0,25	0,13071	0,20	0,13075	0,16	0,05	0,20	-0,03	0,12	-0,08	0,32	
40	0,13080	0,25	0,13088	0,20	0,13085	0,16	-0,04	0,20	0,02	0,13	0,06	0,32	
50	0,13079	0,25	0,13089	0,20	0,13085	0,16	-0,05	0,20	0,03	0,13	0,08	0,32	
63	0,13077	0,25	0,13093	0,20	0,13087	0,16	-0,07	0,19	0,05	0,13	0,12	0,32	
80	0,13076	0,25	0,13089	0,20	0,13084	0,16	-0,06	0,20	0,04	0,13	0,10	0,32	
100	0,13075	0,25	0,13088	0,20	0,13083	0,16	-0,06	0,20	0,04	0,13	0,10	0,32	
125	0,13074	0,25	0,13084	0,20	0,13080	0,16	-0,05	0,20	0,03	0,13	0,08	0,32	
160	0,13070	0,25	0,13080	0,20	0,13076	0,16	-0,05	0,20	0,03	0,13	0,08	0,32	
200	0,13068	0,25	0,13078	0,20	0,13074	0,16	-0,05	0,20	0,03	0,13	0,08	0,32	
250	0,13068	0,25	0,13073	0,20	0,13071	0,16	-0,02	0,20	0,02	0,12	0,04	0,32	
315	0,13067	0,25	0,13078	0,20	0,13074	0,16	-0,05	0,20	0,03	0,13	0,08	0,32	
400	0,13068	0,25	0,13080	0,20	0,13075	0,16	-0,06	0,20	0,04	0,13	0,09	0,32	
500	0,13067	0,25	0,13079	0,20	0,13074	0,16	-0,06	0,20	0,04	0,13	0,09	0,32	
630	0,13071	0,25	0,13068	0,20	0,13069	0,16	0,02	0,20	-0,01	0,12	-0,03	0,32	
800	0,13068	0,25	0,13080	0,20	0,13075	0,16	-0,06	0,20	0,04	0,13	0,10	0,32	
1000	0,13073	0,25	0,13077	0,20	0,13075	0,16	-0,02	0,20	0,01	0,12	0,03	0,32	
1250	0,13076	0,25	0,13096	0,20	0,13088	0,16	-0,09	0,19	0,06	0,13	0,15	0,32	
1600	0,13090	0,25	0,13103	0,20	0,13098	0,16	-0,06	0,20	0,04	0,13	0,10	0,32	
2000	0,13103	0,25	0,13100	0,20	0,13101	0,16	0,02	0,20	-0,01	0,12	-0,03	0,32	
2500	0,13132	0,25	0,13106	0,25	0,13119	0,18	0,10	0,18	-0,10	0,18	-0,20	0,35	
3150	0,13167	0,35	0,13178	0,25	0,13174	0,20	-0,05	0,28	0,03	0,15	0,08	0,43	
4000	0,13237	0,35	0,13217	0,25	0,13224	0,20	0,10	0,29	-0,05	0,15	-0,15	0,43	
5000	0,13334	0,60	0,13315	0,25	0,13318	0,23	0,12	0,55	-0,02	0,10	-0,14	0,65	
6000	0,13447	0,60	0,13409	0,40	0,13421	0,33	0,20	0,50	-0,09	0,22	-0,28	0,72	
7000	0,13579	0,80	0,13518	0,40	0,13530	0,36	0,36	0,72	-0,09	0,18	-0,45	0,90	
8000	0,13728	0,80	0,13609	0,40	0,13633	0,36	0,70	0,72	-0,17	0,18	-0,88	0,90	
9000	0,13873	0,80	0,13759	0,60	0,13800	0,48	0,53	0,65	-0,29	0,36	-0,83	1,00	
10000	0,14190	0,80	0,14045	0,60	0,14097	0,48	0,66	0,65	-0,37	0,36	-1,03	1,00	

Table 1b: Accelerometer A: results of phase shift reported by the laboratories and calculated degrees of equivalence. Uncertainties are reported for $k=2$.

Frequency (Hz)	INMETRO		CENAM		Weighed Mean		Degrees of equivalence (Phase shift)						
	Phase shift (°)	U_c (°)	Phase shift (°)	U_c (°)	WM (°)	U_{WM} (°)	D_{INM-WN} (°)	U_{INM-WN} (°)	D_{CEN-WN} (°)	U_{CEN-WN} (°)	$D_{CEN-IMI}$ (°)	$U_{CEN-IMI}$ (°)	
10	0.03	0.25	-0.02	0.15	-0.01	0.13	0.04	0.21	-0.01	0.08	-0.05	0.29	
16	0.02	0.25	0.04	0.15	0.04	0.13	-0.01	0.21	0.00	0.08	0.02	0.29	
25	0.00	0.25	0.01	0.15	0.01	0.13	-0.01	0.21	0.00	0.08	0.01	0.29	
40	-0.01	0.25	0.03	0.15	0.02	0.13	-0.03	0.21	0.01	0.08	0.04	0.29	
50	-0.02	0.25	-0.01	0.15	-0.01	0.13	-0.01	0.21	0.00	0.08	0.01	0.29	
63	-0.03	0.25	-0.04	0.15	-0.04	0.13	0.01	0.21	0.00	0.08	-0.01	0.29	
80	-0.03	0.25	-0.01	0.15	-0.01	0.13	-0.01	0.21	0.00	0.08	0.02	0.29	
100	-0.03	0.25	-0.01	0.15	-0.02	0.13	-0.01	0.21	0.01	0.08	0.02	0.29	
125	-0.03	0.25	-0.04	0.15	-0.04	0.13	0.01	0.21	0.00	0.08	-0.01	0.29	
160	-0.05	0.25	-0.02	0.15	-0.03	0.13	-0.02	0.21	0.01	0.08	0.03	0.29	
200	-0.04	0.25	-0.01	0.15	-0.02	0.13	-0.02	0.21	0.01	0.08	0.03	0.29	
250	-0.03	0.25	0.08	0.15	0.05	0.13	-0.08	0.21	0.03	0.08	0.11	0.29	
315	-0.03	0.25	0.04	0.15	0.02	0.13	-0.05	0.21	0.02	0.08	0.07	0.29	
400	0.01	0.25	0.00	0.15	0.00	0.13	0.00	0.21	0.00	0.08	-0.01	0.29	
500	-0.02	0.25	-0.01	0.15	-0.01	0.13	-0.01	0.21	0.00	0.08	0.01	0.29	
630	-0.02	0.25	-0.01	0.15	-0.01	0.13	0.00	0.21	0.00	0.08	0.01	0.29	
800	-0.02	0.25	0.05	0.15	0.03	0.13	-0.05	0.21	0.02	0.08	0.07	0.29	
1000	0.00	0.25	0.04	0.15	0.03	0.13	-0.03	0.21	0.01	0.08	0.04	0.29	
1250	0.01	0.25	0.08	0.20	0.05	0.16	-0.04	0.20	0.03	0.12	0.07	0.32	
1600	0.04	0.25	0.03	0.20	0.03	0.16	0.00	0.20	0.00	0.12	-0.01	0.32	
2000	0.04	0.25	0.10	0.20	0.08	0.16	-0.04	0.20	0.02	0.12	0.06	0.32	
2500	0.06	0.25	0.27	0.20	0.19	0.16	-0.13	0.20	0.08	0.12	0.21	0.32	
3150	0.05	0.50	0.12	0.20	0.11	0.19	-0.06	0.46	0.01	0.07	0.07	0.54	
4000	0.11	0.50	0.02	0.40	0.05	0.31	0.05	0.39	-0.03	0.25	-0.09	0.64	
5000	0.10	0.50	0.32	0.40	0.23	0.31	-0.13	0.39	0.09	0.25	0.22	0.64	
6000	0.25	1.0	0.27	0.40	0.27	0.37	-0.02	0.93	0.00	0.15	0.02	1.08	
7000	0.08	1.0	0.24	0.60	0.20	0.51	-0.12	0.86	0.04	0.31	0.16	1.17	
7500	-0.05	1.0	0.17	0.60	0.11	0.51	-0.17	0.86	0.06	0.31	0.22	1.17	
8500	0.11	1.0	0.39	0.60	0.31	0.51	-0.21	0.86	0.08	0.31	0.28	1.17	
9000	0.73	1.0	0.66	0.60	0.68	0.51	0.05	0.86	-0.02	0.31	-0.07	1.17	
10000	0.49	1.0	0.90	0.60	0.79	0.51	-0.30	0.86	0.11	0.31	0.41	1.17	

Table 2a: Accelerometer B; results of sensitivity magnitude reported by the laboratories and calculated degrees of equivalence. Uncertainties are reported for $k=2$.

Frequency (Hz)	INMETRO		CENAM		Weighted Mean			Degrees of equivalence (Magnitude)					
	Sensitivity Magnitude ($\mu\text{C}/(\text{m/s}^2)$)	U_c (%)	Sensitivity Magnitude ($\mu\text{C}/(\text{m/s}^2)$)	U_c (%)	WM ($\mu\text{C}/(\text{m/s}^2)$)	U_{WM} (%)	D_{INM-WN} (%)	U_{INM-WN} (%)	D_{CEN-WN} (%)	U_{CEN-WN} (%)	$D_{CEN-IMM}$ (%)	$U_{CEN-IMM}$ (%)	
10	0,12859	0,35	0,12845	0,25	0,12850	0,20	0,07	0,29	-0,04	0,15	-0,11	0,43	
16	0,12865	0,35	0,12862	0,25	0,12863	0,20	0,02	0,28	-0,01	0,15	-0,03	0,43	
25	0,12875	0,25	0,12868	0,20	0,12871	0,16	0,03	0,20	-0,02	0,12	-0,06	0,32	
40	0,12887	0,25	0,12870	0,20	0,12877	0,16	0,08	0,20	-0,05	0,12	-0,13	0,32	
50	0,12892	0,25	0,12886	0,20	0,12888	0,16	0,03	0,20	-0,02	0,12	-0,04	0,32	
63	0,12895	0,25	0,12895	0,20	0,12895	0,16	0,00	0,20	0,00	0,12	0,00	0,32	
80	0,12900	0,25	0,12901	0,20	0,12901	0,16	0,00	0,20	0,00	0,12	0,01	0,32	
100	0,12905	0,25	0,12908	0,20	0,12907	0,16	-0,01	0,20	0,01	0,12	0,02	0,32	
125	0,12910	0,25	0,12919	0,20	0,12915	0,16	-0,04	0,20	0,03	0,13	0,07	0,32	
160	0,12912	0,25	0,12915	0,20	0,12914	0,16	-0,01	0,20	0,01	0,12	0,02	0,32	
200	0,12915	0,25	0,12916	0,20	0,12916	0,16	-0,01	0,20	0,00	0,12	0,01	0,32	
250	0,12918	0,25	0,12942	0,20	0,12932	0,16	-0,11	0,19	0,07	0,13	0,19	0,32	
315	0,12922	0,25	0,12936	0,20	0,12930	0,16	-0,07	0,19	0,04	0,13	0,11	0,32	
400	0,12932	0,25	0,12931	0,20	0,12931	0,16	0,00	0,20	0,00	0,12	-0,01	0,32	
500	0,12925	0,25	0,12932	0,20	0,12929	0,16	-0,03	0,20	0,02	0,13	0,05	0,32	
630	0,12936	0,25	0,12940	0,20	0,12938	0,16	-0,02	0,20	0,01	0,12	0,03	0,32	
800	0,12936	0,25	0,12933	0,20	0,12934	0,16	0,01	0,20	-0,01	0,12	-0,02	0,32	
1000	0,12942	0,25	0,12934	0,20	0,12937	0,16	0,04	0,20	-0,02	0,12	-0,06	0,32	
1250	0,12949	0,25	0,12967	0,20	0,12960	0,16	-0,08	0,19	0,05	0,13	0,14	0,32	
1600	0,12965	0,25	0,12970	0,20	0,12968	0,16	-0,02	0,20	0,01	0,12	0,03	0,32	
2000	0,12980	0,25	0,12948	0,20	0,12960	0,16	0,15	0,20	-0,10	0,12	-0,24	0,32	
2500	0,13008	0,25	0,12972	0,25	0,12990	0,18	0,14	0,18	-0,14	0,18	-0,28	0,35	
3150	0,13046	0,35	0,13042	0,25	0,13043	0,20	0,02	0,28	-0,01	0,15	-0,03	0,43	
4000	0,13112	0,35	0,13115	0,25	0,13114	0,20	-0,02	0,28	0,01	0,15	0,02	0,43	
5000	0,13203	0,60	0,13177	0,25	0,13181	0,23	0,17	0,55	-0,03	0,10	-0,20	0,65	
6000	0,13327	0,60	0,13249	0,40	0,13273	0,33	0,41	0,50	-0,18	0,22	-0,59	0,72	
7000	0,13489	0,80	0,13381	0,40	0,13402	0,36	0,65	0,72	-0,16	0,18	-0,81	0,90	
8000	0,13650	0,80	0,13572	0,40	0,13587	0,36	0,46	0,72	-0,11	0,18	-0,57	0,90	
9000	0,13777	0,80	0,13812	0,60	0,13799	0,48	-0,16	0,64	0,09	0,36	0,25	1,00	
10000	0,14058	0,80	0,14098	0,60	0,14084	0,48	-0,18	0,64	0,10	0,36	0,28	1,00	

Table 2b: Accelerometer B, results of phase shift reported by the laboratories and calculated degrees of equivalence. Uncertainties are reported for $k=2$.

Frequency (Hz)	INMETRO		CENAM		Weighed Mean		Degrees of equivalence (Phase shift)					
	Phase shift (°)	U_c (°)	Phase shift (°)	U_c (°)	WM (°)	U_{WM} (°)	D_{INM-WN} (°)	U_{INM-WN} (°)	D_{CEN-WN} (°)	U_{CEN-WN} (°)	$D_{CEN-NMI}$ (°)	$U_{CEN-NMI}$ (°)
10	0.15	0.25	0.04	0.15	0.07	0.13	0.08	0.21	-0.03	0.08	-0.11	0.29
16	0.16	0.25	0.04	0.15	0.07	0.13	0.09	0.21	-0.03	0.08	-0.12	0.29
25	0.14	0.25	0.12	0.15	0.13	0.13	0.02	0.21	-0.01	0.08	-0.02	0.29
40	0.15	0.25	0.14	0.15	0.14	0.13	0.01	0.21	0.00	0.08	-0.01	0.29
50	0.14	0.25	0.15	0.15	0.15	0.13	-0.01	0.21	0.00	0.08	0.01	0.29
63	0.13	0.25	0.10	0.15	0.11	0.13	0.02	0.21	-0.01	0.08	-0.03	0.29
80	0.13	0.25	0.14	0.15	0.14	0.13	-0.01	0.21	0.00	0.08	0.01	0.29
100	0.12	0.25	0.13	0.15	0.13	0.13	-0.01	0.21	0.00	0.08	0.01	0.29
125	0.11	0.25	0.11	0.15	0.11	0.13	0.00	0.21	0.00	0.08	0.00	0.29
160	0.09	0.25	0.11	0.15	0.10	0.13	-0.02	0.21	0.01	0.08	0.02	0.29
200	0.10	0.25	0.13	0.15	0.12	0.13	-0.03	0.21	0.01	0.08	0.03	0.29
250	0.10	0.25	0.23	0.15	0.19	0.13	-0.10	0.21	0.04	0.08	0.13	0.29
315	0.10	0.25	0.11	0.15	0.11	0.13	-0.01	0.21	0.00	0.08	0.01	0.29
400	0.13	0.25	0.10	0.15	0.11	0.13	0.02	0.21	-0.01	0.08	-0.03	0.29
500	0.08	0.25	0.15	0.15	0.13	0.13	-0.05	0.21	0.02	0.08	0.07	0.29
630	0.09	0.25	0.12	0.15	0.11	0.13	-0.02	0.21	0.01	0.08	0.03	0.29
800	0.07	0.25	0.15	0.15	0.13	0.13	-0.06	0.21	0.02	0.08	0.08	0.29
1008	0.08	0.25	0.06	0.15	0.07	0.13	0.01	0.21	-0.01	0.08	-0.02	0.29
1250	0.09	0.25	0.13	0.20	0.12	0.16	-0.02	0.20	0.01	0.12	0.04	0.32
1600	0.11	0.25	0.24	0.20	0.19	0.16	-0.08	0.20	0.05	0.12	0.13	0.32
2000	0.10	0.25	0.27	0.20	0.20	0.16	-0.11	0.20	0.07	0.12	0.17	0.32
2500	0.10	0.25	0.27	0.20	0.20	0.16	-0.10	0.20	0.07	0.12	0.17	0.32
3150	0.13	0.50	0.29	0.20	0.27	0.19	-0.14	0.46	0.02	0.07	0.16	0.54
4000	0.16	0.50	0.48	0.40	0.36	0.31	-0.19	0.39	0.12	0.25	0.32	0.64
5000	0.18	0.50	0.47	0.40	0.36	0.31	-0.18	0.39	0.11	0.25	0.29	0.64
6000	0.29	1.0	0.57	0.40	0.53	0.37	-0.24	0.93	0.04	0.15	0.28	1.08
7000	0.19	1.0	0.76	0.60	0.61	0.51	-0.42	0.86	0.15	0.31	0.57	1.17
8000	0.33	1.0	0.85	0.60	0.71	0.51	-0.38	0.86	0.14	0.31	0.52	1.17
9000	0.30	1.0	0.64	0.60	0.55	0.51	-0.25	0.86	0.09	0.31	0.34	1.17
10000	0.21	1.0	0.77	0.60	0.62	0.51	-0.41	0.86	0.15	0.31	0.56	1.17

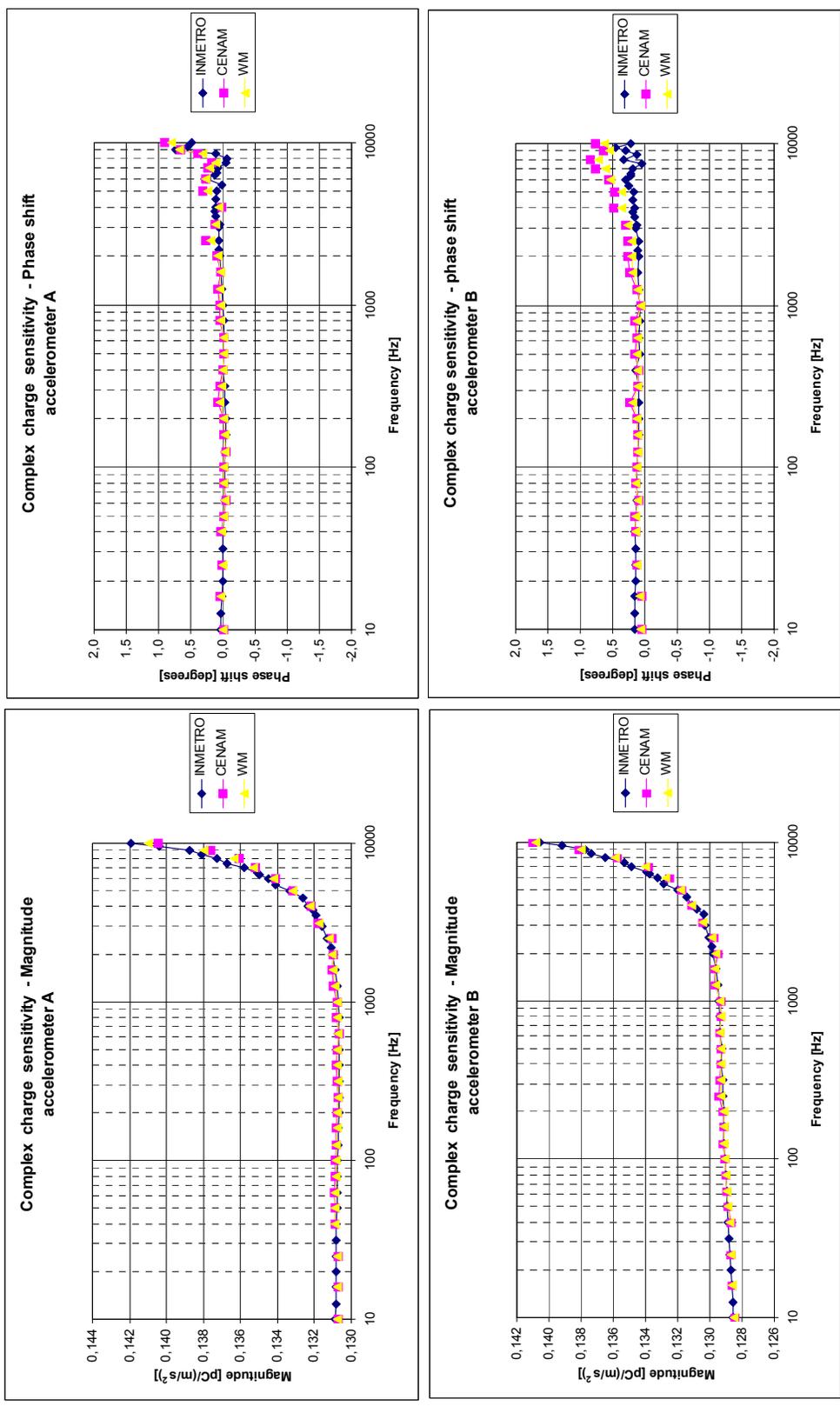
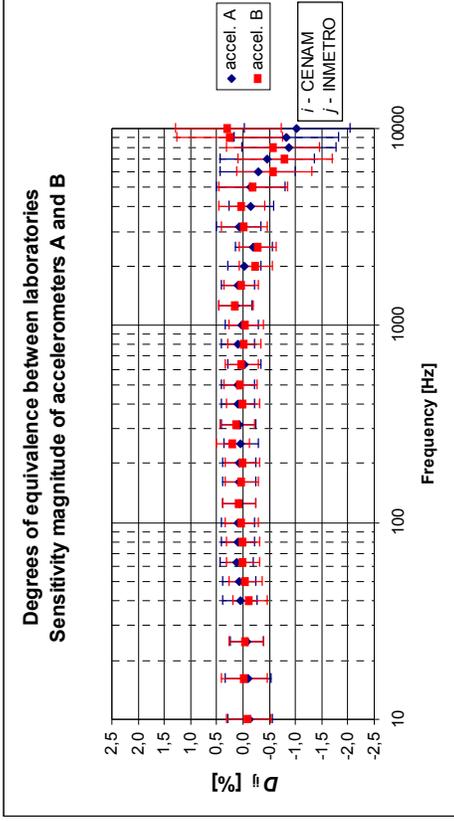
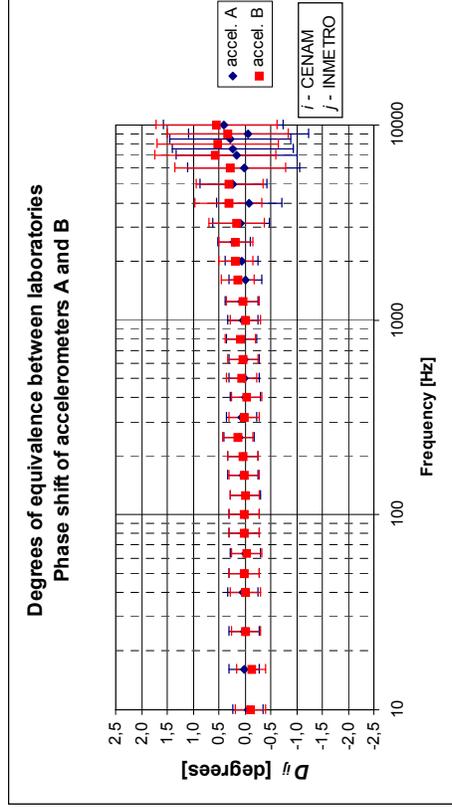


Figure 1: Results of the measured complex sensitivity values reported by the laboratories for accelerometers A & B and calculated weighted mean (WM) reference value



(a)



(b)

Figure 2: Degrees of equivalence D_{ij} and expanded uncertainties U_{ij} ($k=2$) calculated between the participating laboratories for accelerometers A & B:
(a) magnitude of the measured complex sensitivity, (b) phase shift