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INTERNATIONAL COMPARISON OF ACCELERATION STANDARDS - PRELIMINARY RESULTS OF SIM PROJECT AV-1

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Abstract. *This paper presents preliminary results obtained in an international intercomparison of the calibration of acceleration standards by participating laboratories of the Inter-American Metrology System (SIM). Participating laboratories were the National Metrology Institutes of five american countries, i.e., National Institute of Standards and Technology (NIST - U.S.A.), National Research Council (NRC - Canada), Centro Nacional de Metrología (CENAM - Mexico), Instituto Nacional de Metrologia, Normalização e Qualidade Industrial (INMETRO - Brazil) and Instituto Nacional de Tecnología Industrial (INTI - Argentina). Calibrations of three standard accelerometers by laser-interferometry and calibration of a signal conditioner were performed by each of the participating laboratories. A brief description of the experimental procedures and preliminary results for the calibration of the accelerometers are given in this paper.*

Keywords: Accelerometer, Calibration, Intercomparison, Interferometry.

1. INTRODUCTION

An intercomparison is a very important tool for National Metrology Institutes (NMI's) in evaluating their overall performance as well as in obtaining the mutual recognition of their measurement capabilities. As most of the national laboratories are at the highest hierarchical stage in the uncertainty pyramid, it is the usual procedure to verify results obtained from measurement processes for the evaluation of different physical quantities by means of international intercomparisons.

This intercomparison was officially carried out under the framework of SIM, joining two subregions: NORAMET (Canada, Mexico, USA) and SURAMET (Argentina, Brazil). It was conducted in a circular way (see Figure 1), that is, the measurements started and finished at the same laboratory, NIST - USA, called the pilot laboratory. The responsibility for the administrative organization was taken by CENAM - Mexico.

The process started in 1996. The measurements were carried out during 1998 and 1999. Each laboratory had 2 months for the measurements, and the measurement standards were hand carried to the next laboratory to ensure that the items would not suffer any abuse in transportation or at the customs of any country.

After conclusion of all measurements, the results were sent to NIST for analysis. Results presented here are preliminary, and conclusions or comments are based on the evaluation of the authors. Final conclusions must wait for statistical analysis to be finished and for the final meeting of the participants at CENAM.

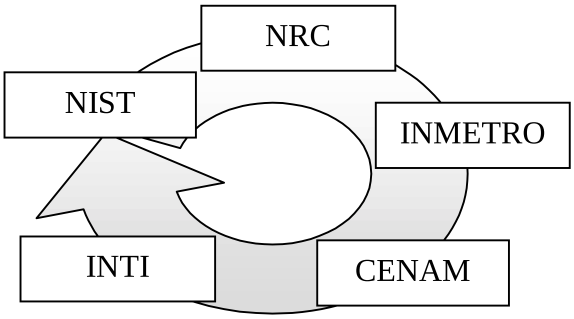


Figure 1

2. INSTRUMENTATION

One signal conditioner (charge amplifier) and three standard accelerometers from different manufactures were circulated, two transducers of the single-ended type and one of the “piggy-back” type (Table 1). Standard accelerometers are well known for their high temporal stability, an important factor when dealing with intercomparisons.

Table 1[1]

Equipment	Manufacturer	Model	Characteristics
Accelerometer	Brüel & Kjaer	8305	Double ended type
Accelerometer	Kistler	8002 K	Single ended type
Accelerometer	Endevco	2270 M8	Single ended type
Charge amplifier	Brüel & Kjaer	2626	

Note (1): Products used in this comparison does not imply recommendations of any manufacturer by the authors or their institutes.

3. CALIBRATION PROTOCOL

Each laboratory calibrated the received set, i.e., accelerometers and conditioner, according to an established protocol. This protocol was defined after agreement among the laboratories to choose measurement conditions achievable by all of the participants. Furthermore, several calibration services offered in the participating countries is in the frequency range of this comparison exercise.

3.1 Accelerometer Calibration

Regarding the mounting of the accelerometers, the recommended procedure was to use a mounting torque of 2 Nm and light-weight oil between the mounting surfaces. All laboratories were alerted to the fact that the Endevco 2270 M8 accelerometer base is insulated, and therefore it should be grounded by some means in case of the shaker table not being electrically grounded (the transducer case has small holes close to the connector for this purpose).

All accelerometer calibrations were performed using absolute laser interferometric methods according to standard ISO 5347-1/1993. The obtained charge sensitivity values and the values of the gain at the frequencies shown in Table 2 were reported. There were no restrictions imposed upon the data capture or analysis procedure. Either computer automated systems or manual methods were acceptable.

The displacement was measured near or on the sensing surface of the transducer, i.e., near the base of single-ended accelerometers and the top face of the double-ended accelerometers.

Table 2. Accelerometer calibration conditions

Frequency (Hz)	Acceleration (m/s^2 peak)	Calibration Method
50	20	Fringe counting
80	30	Fringe counting
100	30	Fringe counting
159.2	50	Fringe counting
250	50	Fringe counting
500	80	Fringe counting
800	100	Fringe counting
1000	100	Fringe counting
3500	60 / 93	Fringe disappearance / J1 null method
5000	122 / 190	Fringe disappearance / J1 null method

3.2 Charge amplifier calibration

The charge amplifier’s gain was obtained for the specified frequencies listed in Table 2 with the front panel controls set as shown in Table 3. The analysis of the amplifiers calibration data is still unfinished and will be present in a future work.

Table 3

Amplifier settings:	
Sensitivity:	1.00 pC/Unit
Range:	1-11pC/Unit
Volts/Unit Out:	0.01
Lower Freq. Limit 3dB:	0.3 Hz
Upper Freq. Limit 3dB:	Lin.

4. CALIBRATION METHODS

The calibration methods standardized in ISO 5347-1 that were used are the Fringe Counting Method and the J_1-null Method. Both are based on a Michelson interferometer. The first one, relies on the counting of the number of fringes when one of the arms of the interferometer is subjected to a sinusoidal displacement.

Figure 2 shows an interferometer where λ is the laser wavelength and l_1 and l_2 are the arm lengths between the beam-splitter and mirrors 1 and 2, respectively. $\xi(t) = \xi \cos(2\pi f t)$ is the harmonic displacement exerted on the moving mirror 2 with a displacement amplitude ξ and frequency *f*.

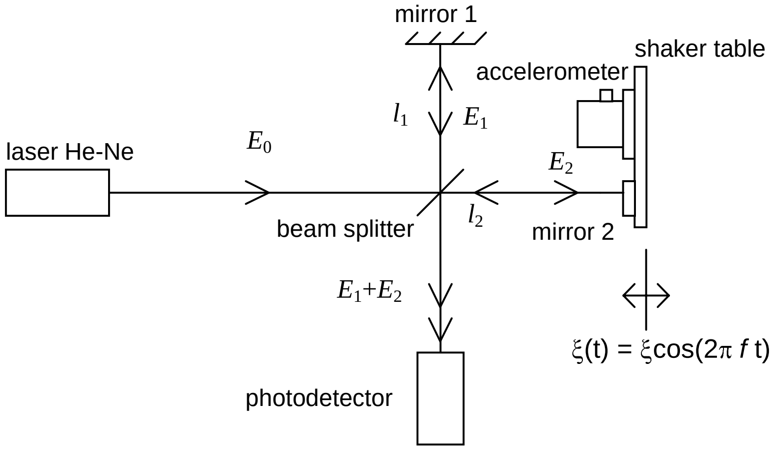


Figure 2 - Michelson interferometer

The luminous intensity *I(t)* at the photo-detector is given by Eq. (1), where E_1 and E_2 are the reflected laser beams from respectively the "fixed" mirror 1 and the "moving" mirror 2. *A* and *B* are constants of the system and $L = (l_1 - l_2)$.

$$I(t) = A + B\cos\left[\frac{4\pi}{\lambda}\left(L + \xi(t)\right)\right]. \tag{1}$$

Equation (1) can be expanded in Jacobi series, and rewritten as:

$$I(t) = A + B\cos\left(\frac{4\pi L}{\lambda}\right)\left[J_0\left(\frac{4\pi\xi}{\lambda}\right) - 2J_2\left(\frac{4\pi\xi}{\lambda}\right)\cos(2\omega t) + 2J_4\left(\frac{4\pi\xi}{\lambda}\right)\cos(4\omega t) - ...\right] -$$
$$- Bsin\left(\frac{4\pi L}{\lambda}\right)\left[2J_1\left(\frac{4\pi\xi}{\lambda}\right)\cos(\omega t) - 2J_3\left(\frac{4\pi\xi}{\lambda}\right)\cos(3\omega t) + ...\right], \tag{2}$$

where J_n are the Bessel functions of first kind and order n and $\omega = 2\pi f$ is the angular frequency of the displacement.

The light intensity varies, forming a pattern of dark and light fringes. It can be shown that for a period of vibration of mirror 2, the displacement amplitude is directly proportional to the number of light fringes, *N* (see Equation (3)).

$$\xi = N \times \frac{\lambda}{8} \tag{3}$$

At high frequencies, displacement amplitudes are relatively small and the number of fringes per vibration cycle decreases, increasing the measurement uncertainty. For frequencies above 800 Hz, the standardized method consists of filtering the photodetector signal with a bandpass filter centered at the vibration frequency. Referring to Equation (2), this filtering operation consists of rejecting all terms other than the one involving the Bessel function of first kind and first order J_1. The J_1-Null Method consists of searching for an amplitude corresponding to a zero crossing of the Bessel function as per Equation (4). Peak displacement amplitudes of the first five zero crossings of Bessel function J_1 for a red He-Ne laser (λ= 632.8 nm) are listed in Table 4.

$$J_1\left(\frac{4\pi\xi}{\lambda}\right)_n = 0 \tag{4}$$

Table 4

	Bessel function J_0		Bessel function J_1	
Zero point n	$\left(\frac{4\pi\xi}{\lambda}\right)_n$	Displacement ξ [nm]	$\left(\frac{4\pi\xi}{\lambda}\right)_n$	Displacement ξ [nm]
0	1	0.00	0.00000	0.00
1	2.40482	121.10	3.83170	192.95
2	5.52008	277.98	7.01559	353.28
3	8.65373	435.78	10.17346	512.30
4	11.79154	593.80	13.32369	670.94
5	14.93092	751.89	16.47063	829.41

Due to the fact that the above method is very time consuming and difficult to automate, NIST uses the Fringe Disappearance Method. It consists of finding the first zero crossing of the Bessel function of first kind of order zero $J_0(4\pi\xi/\lambda)$. At this displacement the phenomenon of fringe disappearance occurs, and a constant intensity illumination is observed on the photodetector. The implementation of this method is described by Robinson (1987) and Payne, which specific description of is beyond the scope of this paper.

4.1 Accelerometer sensitivity

Once determined the vibration displacement of the accelerometer reference surface, the acceleration a is calculated by Equation (5)

$$a = (2\pi f)^2 \xi, \tag{5}$$

and the voltage sensitivity S_s of the system, accelerometer plus signal conditioner, is given by

$$S_s = \frac{V}{a} = \frac{V_{rms}\sqrt{2}}{(2\pi f)^2 \xi}, \tag{6}$$

where V_{rms} is the rms voltage output of the system.

The determination of the charge sensitivity *Sq* of the accelerometer requires the knowledge of the signal conditioner gain *G:*

$$S_q = \frac{S_s}{G}\,. \tag{7}$$

4.2 Signal conditioner sensitivity

The gain of a charge amplifier is usually given in mV/pC, and obtained through a strictly electrical calibration procedure. With a standard capacitor *C*, a charge signal Q_{in} is fed into the amplifier and the output is measured, as shown in Figure 3,

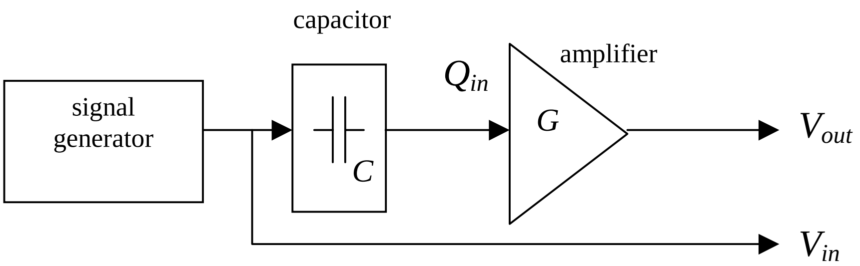


Figure 3 – Charge amplifier calibration

and *G* is computed by

$$G = \frac{V_{out}}{Q_{in}} = \frac{V_{out}}{V_{in}C}\,. \tag{8}$$

5. RESULTS

5.1 Accelerometer calibration results

The results of the comparison are shown in tables 5, 6, and 7 and in Figure 4. For each frequency, the mean value was calculated using the data from each participating laboratory. The data listed below are the deviations (%)from the mean for each laboratory.

Table 5 - deviation (%) from the mean for each laboratory

Accelerometer Endevco 2270M8

Freq	NIST	NRC	CENAM	INMETRO	INTI
50	0.16	-0.47	-0.06	0.01	0.36
80	-0.16	0.06	-0.16	0.03	0.22
100	-0.09	-0.07	-0.02	0.12	0.06
159.2	0.10	-0.24	-0.08	0.17	0.05
250	-0.04	-0.17	-0.03	0.13	0.12
500	-0.13	-0.34	-0.26	0.00	0.74
800	-0.02	-0.32	-0.31	0.02	0.63
1000	-0.39	-0.39	-0.07	0.02	0.84
3500	0.59	-0.90	0.08	0.35	
5000	0.84	-1.30	-0.37	0.67	

Table 6 - deviation (%) from the mean for each laboratory

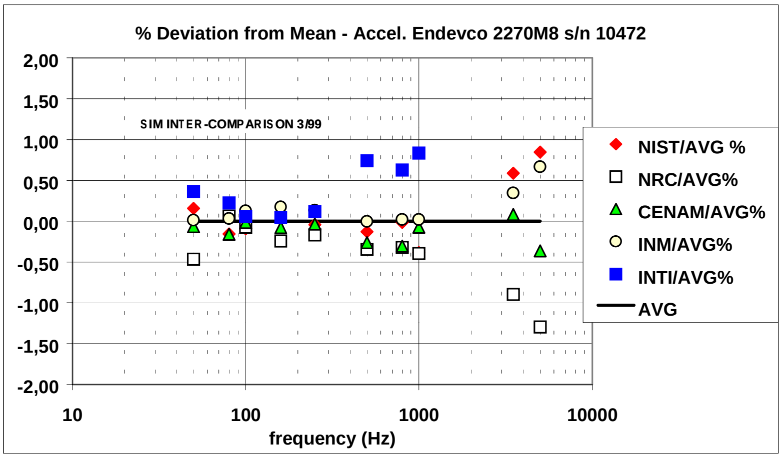
Accelerometer Brüel&Kjaer 8305

Freq	NIST	NRC	CENAM	INMETRO	INTI
50	0.12	-0.10	0.12	0.16	-0.43
80	0.12	0.31	0.12	0.07	-0.49
100	0.11	0.02	0.19	0.11	-0.34
159.2	0.06	0.04	0.14	0.07	-0.30
250	0.06	-0.02	-0.02	0.17	-0.14
500	-0.10	-0.17	0.06	0.08	0.07
800	-0.16	0.40	0.00	0.09	-0.25
1000	-0.34	0.95	-0.18	-0.03	-0.41
3500	0.83	-0.32	-0.46	0.34	-0.40
5000	0.65	-0.56	-0.56	0.71	-0.23

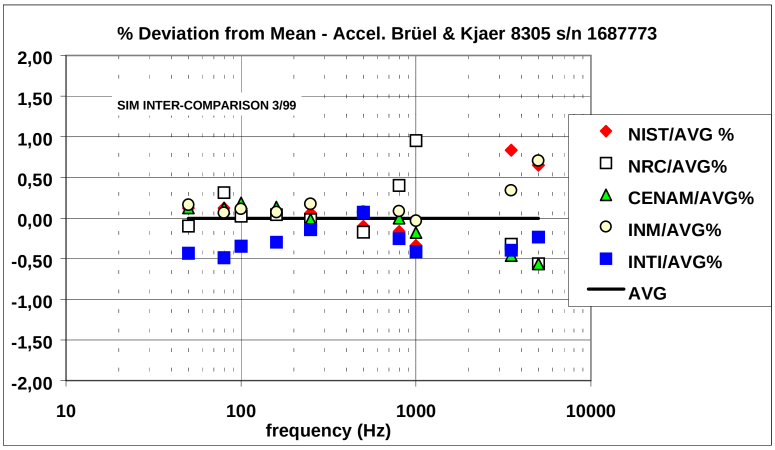
Table 7 - deviation (%) from the mean for each laboratory

Accelerometer Kistler 8002K

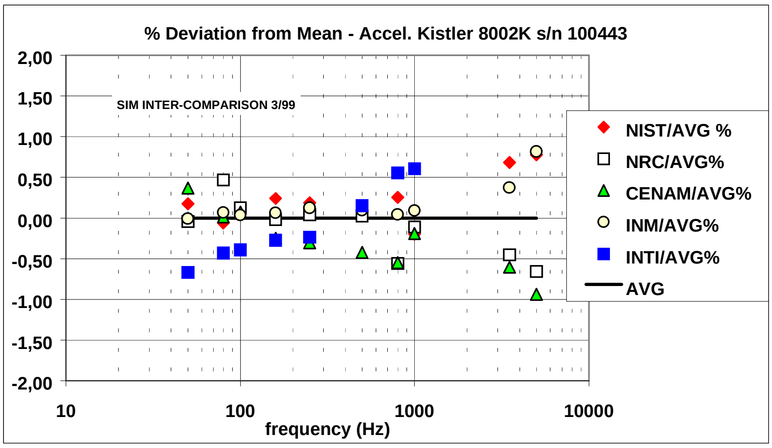
Freq	NIST	NRC	CENAM	INMETRO	INTI
50	0.18	-0.04	0.37	-0.01	-0.67
80	-0.06	0.47	0.01	0.07	-0.43
100	0.08	0.12	0.07	0.04	-0.39
159.2	0.24	-0.02	-0.25	0.06	-0.27
250	0.19	0.04	-0.31	0.13	-0.23
500	0.08	0.03	-0.42	0.09	0.15
800	0.25	-0.56	-0.55	0.04	0.56
1000	-0.20	-0.11	-0.19	0.09	0.60
3500	0.68	-0.45	-0.61	0.37	
5000	0.78	-0.66	-0.94	0.82	



(a)



(b)



(c)

Figure 4 –Deviation (%) of the reported results by each laboratory from the mean value of the charge sensitivity of accelerometers (a) Endevco, (b) Brüel & Kjaer and (c) Kistler.

Two calibration results were reported by NIST (pilot laboratory), one obtained at the start of the intercomparison, and one at the end. Negligible deviation was found in these two results, which suggests that no damage occurred to the transducers during the period of analysis. The average of this two results is taken as NIST AVG and is the value referenced to in the presented tables and plots. INTI did not report results for single-ended accelerometers for frequencies above 1 kHz.

The results show that most deviations lie between ± 0.5 % of the mean for frequencies up to 1 kHz and ± 1.0 % for 3.5 kHz and 5 kHz. For the reference frequency (159.2 Hz), the maximum deviation from mean found was of 0.30 %.

These deviations are in accordance with the applicable limits of relative uncertainty given in ISO 5347-1/1993, i.e., ± 0.5 % at the reference frequency, ± 1 % up to and including 1000 Hz and ± 2 % for frequencies above 1000 Hz.

Both the deviations from mean per accelerometer and the spread for different accelerometers were the smallest at about the standardized reference frequency. Obviously, all laboratories probably have more experience and knowledge of their systems in this frequency region, justifying the results. At higher frequencies, the calibration results for the B&K accelerometer presented the smallest deviations from the mean among the others. This fact can be explained by the relatively small distance between the laser-beam incidence point and the center of the accelerometer, as this is a double-ended type of transducer. This reduces the influence of cross motion of the shaker table. For single-ended accelerometers, the laser beam is usually pointed to a mirror or lapped surface close to the transducer. This condition magnifies errors.

6. CONCLUSIONS

The overall results obtained were highly satisfactory. They might have been even better if tighter rules had been established for the calibration protocol.

This project is undoubtedly increasing the technical exchange among the participating laboratories of the Inter-American Metrology System, and will proportion them a deeper knowledge of the limitations and future needs of their calibration systems.

We can say that this was the first successful Inter-American intercomparison on the calibration of vibration standards. Further work will be carried out to minimize some detected discrepancies. Future activities are to be decided soon in a meeting to be held at CENAM, Mexico, when a more formal statistical treatment of the data will be discussed.

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