Pilot Study EURAMET.AUV.V-P1:
Bilateral comparison on magnitude of the complex charge sensitivity of accelerometers from 10 Hz to 10 kHz

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Contents

1. Foreword

Sponsored by the Trade Support System Project (TSP-2), a bilateral sinusoidal vibration comparison was carried out between the RCM-LIPI (Indonesia) and the LNE (France), for the magnitude sensitivity of back-to-back (BB) and single-ended (SE) accelerometers in the frequency range 10 Hz to 10 kHz, which was registered as EURAMET.AUV.V-S1. The technical protocol (c.f. App A) specifies in detail the aim and the task of the comparison, the conditions of measurements, the transfer standard used, measurement instructions and other items.

The results obtained by RCM-LIPI for the comparison EURAMET.AUV.V-S1 have shown discrepancies in high frequencies above 5 kHz and did not support mutual equivalence of the calibration results within declared uncertainties. From the discussion between RCM-LIPI and the pilot, it was agreed that RCM-LIPI should identify the problem, make an improvement on their measurement techniques and it was proposed to the CCAUV-KCWG that the comparison initially registered as a supplementary comparison would be turned into pilot project because the same transducers would be used for a second round of measurements. The proposal was agreed by CCAUV-KCWG and the comparison EURAMET.AUV.V-S1 was renamed as pilot project EURAMET.AUV.V-P1.

Improvements on the measurement techniques and recalibration of charge amplifier were performed by RCM-LIPI. The results from second round of measurements on the same accelerometer artifacts show that the improvement has successful. The sensitivities discrepancies problem in high frequencies was solved and the deviation of sensitivities between RCM-LIPI and LNE are within the declared uncertainties for both BB and SE accelerometers.

2. Task and purpose of the pilot study

RCM-LIPI LIPI has no CMCs in comparison calibration for the magnitude of the complex sensitivity of accelerometers for the moment. A CMC submission for frequency range 40 Hz to 5 kHz, which was supported by inter-laboratory comparison APMP.AUV.V-K1.2, was undergoing inter-RMO review by the time this comparison was conducted. The purpose of this comparison is to extend the frequency range and uncertainty claims of the RCM-LIPI for vibration calibration facilities from 10 Hz to 10 kHz in the future. As the results of the supplementary comparison EURAMET.AUV.V-S1 failed to prove the expected improvement, it was transferred into a pilot study which cannot support directly the intended extension of frequency range but it provide evidences of the final improvements achieved.

3. Description of the machines

The calibration system used by RCM-LIPI for this comparison included a Polytec Laser Dopler Vibrometer, a B&K 4809 vibration exciter, a PULSE Data Acquisition System and a B&K 3629 Vibration Transducer Calibration System as shown in Figure 1.

Figure 1. RCM-LIPI vibration calibration facilities

The LNE facilities included their medium and high frequency primary calibration bench, as shown in Figure 2. The stated expanded uncertainties (*k*=2) for sensitivity magnitude from 10 Hz to 10 kHz were:

0,30 % from 10 Hz to 5 000 Hz

0,60 % from 5 000 to 7 000 Hz

1,0 % from 7 000 Hz to 10 000 Hz.

LNE has already participated in the Vibration Key Comparison CCAUV.V-K2 using this same calibration system. For all frequencies, LNE results were considered to be within the subset of consistent values, presenting unilateral degrees of equivalence from the KCRV smaller than its expanded uncertainty.

Figure 2. LNE vibration medium and high frequencies facilities

4. Comparison Artifact

The comparison was carried out using two piezoelectric transducers. The transducers used are detailed in Table 1.

Table 1. Transducers used in the comparison

Identification	Manufacturer	Type	Serial Number	Nominal sens.
SE	Bruel & Kjaer	8305-001 SE	2481861	0.126 pC/(m/s²)
BB	Bruel & Kjaer	8305 BB	2679379	0.126 pC/(m/s²)

Transducers were delivered with the following accessories:

- Specific mechanical adaptor for SE configuration.
- Cable for connection between accelerometers and conditioner

The charge amplifier (CA) used for the calibration was not included in the set of artifacts. It should be provided by each participant. The accelerometers were to be calibrated for magnitude of the complex charge sensitivity according to those procedures and conditions implemented by the NMI in conformance with ISO 16063-11. The sensitivities reported should be for the accelerometers alone, excluding any effects from the charge amplifier.

5. Measurement Points

The frequency range of the measurements was agreed to be from 10 Hz to 10 kHz. Specifically the laboratories agreed to measure at the following frequencies (all values in Hz):

10, 12.5, 16, 20, 25, 31.5, 40, 63, 80, 100, 125, 160, 200, 250, 315, 400, 500, 630, 800, 1000, 1250, 1500, 1600, 2000, 2500, 3000, 3150, 3500, 4000, 4500, 5000, 5500, 6000, 6300, 6500, 7000, 7500, 8000, 8500, 9000, 9500, 10000.

The measurement condition should be kept according to the laboratory's standard conditions for calibration of customer accelerometers in order to claim their best measurement capability or CMC where applicable. This presumed that these conditions were in compliance with those defined by the applicable ISO documentary standards [3, 4, 5], simultaneously.

6. Comparison Results

Both accelerometers were circulated together. The pilot laboratory calibrated the transducers before sending the devices to the participant laboratory. After return, they were re-calibrated by the pilot. One complete measurement cycle (pilot – participant – pilot) is called a loop. The drift is evaluated by the difference between the two measurements made by the pilot at the beginning and at the end of the comparison. Reference value is defined as the mean of the two pilot measurements. Raw results obtained in the first loop are presented in the following Table 2 for both accelerometers and both participants. Uncertainties are expanded absolute ones.

Table 2. Comparison results obtained for the first loop of measurements

	8305 SE accelerometer					
	result obtained by LNE				result obtained by RCM-LIPI	
Frequency	1st meas	2nd meas	mean sensitivity	expanded uncertainty	sensitivity	expanded uncertainty
Hz	pC/(ms^2)				pC/(ms^2)	
10	0.12587	0.12537	0.12562	0.00038	0.12380	0.00110
12.5	0.12597	0.12544	0.12571	0.00038	0.12410	0.00110
16	0.12602	0.12547	0.12575	0.00038	0.12440	0.00110
20	0.12606	0.12552	0.12579	0.00038	0.12420	0.00110
25	0.12605	0.12554	0.12580	0.00038	0.12430	0.00110
31.5	0.12612	0.12559	0.12586	0.00038	0.12440	0.00110
40	0.12606	0.12558	0.12582	0.00038	0.12444	0.00087
63	0.12606	0.12549	0.12578	0.00038	0.12449	0.00087
80	0.12612	0.12566	0.12589	0.00038	0.12460	0.00087
100	0.12608	0.12562	0.12585	0.00038	0.12445	0.00087
125	0.12610	0.12562	0.12586	0.00038	0.12466	0.00087
160	0.12610	0.12564	0.12587	0.00038	0.12463	0.00087
200	0.12608	0.12564	0.12586	0.00038	0.12483	0.00087
250	0.12621	0.12570	0.12596	0.00038	0.12493	0.00087
315	0.12620	0.12572	0.12596	0.00038	0.12330	0.00086
400	0.12620	0.12575	0.12598	0.00038	0.12635	0.00088
500	0.12622	0.12577	0.12600	0.00038	0.12613	0.00088
630	0.12623	0.12579	0.12601	0.00038	0.12583	0.00088
800	0.12627	0.12582	0.12605	0.00038	0.12500	0.00088
1000	0.12632	0.12587	0.12610	0.00038	0.12554	0.00088
1250	0.12640	0.12595	0.12618	0.00038	0.12580	0.00088
1500	0.12650	0.12605	0.12628	0.00038	0.12566	0.00088
1600	0.12655	0.12609	0.12632	0.00038	0.12559	0.00088
2000	0.12665	0.12624	0.12645	0.00038	0.12601	0.00088
2500	0.12691	0.12654	0.12673	0.00038	0.12636	0.00088
3000	0.12725	0.12688	0.12707	0.00038	0.12666	0.00089
3150	0.12735	0.12696	0.12716	0.00038	0.12755	0.00089
3500	0.12759	0.12723	0.12741	0.00038	0.12799	0.00090
4000	0.12806	0.12767	0.12787	0.00038	0.12804	0.00090
4500	0.12860	0.12824	0.12842	0.00039	0.12845	0.00090
5000	0.12908	0.12879	0.12894	0.00077	0.12763	0.00089
5500	0.12981	0.12937	0.12959	0.00078	0.12920	0.00130
6000	0.13044	0.13012	0.13028	0.00078	0.12540	0.00130
6300	0.13123	0.13101	0.13112	0.00079	0.13580	0.00190
6500	0.13108	0.13085	0.13097	0.00079	0.13390	0.00190
7000	0.13215	0.13183	0.13199	0.00130	0.13410	0.00130
7500	0.13315	0.13266	0.13291	0.00130	0.13610	0.00140
8000	0.13361	0.13317	0.13339	0.00130	0.14280	0.00140
8500	0.13559	0.13527	0.13543	0.00140	0.13520	0.00160
9000	0.13651	0.13630	0.13641	0.00140	0.13780	0.00170
9500	0.13793	0.13768	0.13781	0.00140	0.13910	0.00170
10000	0.13915	0.13897	0.13906	0.00140	0.14050	0.00170

	8305 BB accelerometer					
	result obtained by LNE				result obtained by RCM-LIPI	
Frequency	1st meas	2nd meas	mean sensitivity	expanded uncertainty	sensitivity	expanded uncertainty
Hz	pC/(ms^2)				pC/(ms^2)	
10	0.12614	0.12621	0.12618	0.00038	0.12498	0.00100
12.5	0.12624	0.12629	0.12627	0.00038	0.12507	0.00100
16	0.12627	0.12632	0.12630	0.00038	0.12521	0.00100
20	0.12633	0.12629	0.12631	0.00038	0.12497	0.00100
25	0.12636	0.12613	0.12625	0.00038	0.12501	0.00100
31.5	0.12638	0.12624	0.12631	0.00038	0.12509	0.00100
40	0.12630	0.12626	0.12628	0.00038	0.12507	0.00088
63	0.12628	0.12619	0.12624	0.00038	0.12511	0.00088
80	0.12638	0.12630	0.12634	0.00038	0.12515	0.00088
100	0.12635	0.12627	0.12631	0.00038	0.12517	0.00088
125	0.12635	0.12626	0.12631	0.00038	0.12526	0.00088
160	0.12637	0.12627	0.12632	0.00038	0.12529	0.00088
200	0.12643	0.12637	0.12640	0.00038	0.12539	0.00088
250	0.12633	0.12623	0.12628	0.00038	0.12555	0.00088
315	0.12637	0.12630	0.12634	0.00038	0.12520	0.00150
400	0.12638	0.12632	0.12635	0.00038	0.12630	0.00150
500	0.12641	0.12631	0.12636	0.00038	0.12600	0.00150
630	0.12641	0.12633	0.12637	0.00038	0.12600	0.00100
800	0.12645	0.12636	0.12641	0.00038	0.12600	0.00100
1000	0.12649	0.12640	0.12645	0.00038	0.12610	0.00100
1250	0.12655	0.12647	0.12651	0.00038	0.12610	0.00100
1500	0.12664	0.12656	0.12660	0.00038	0.12610	0.00100
1600	0.12666	0.12658	0.12662	0.00038	0.12600	0.00100
2000	0.12679	0.12672	0.12676	0.00038	0.12640	0.00100
2500	0.12701	0.12694	0.12698	0.00038	0.12680	0.00100
3000	0.12727	0.12720	0.12724	0.00038	0.12720	0.00100
3150	0.12739	0.12729	0.12734	0.00038	0.12740	0.00100
3500	0.12763	0.12755	0.12759	0.00038	0.12770	0.00100
4000	0.12796	0.12786	0.12791	0.00038	0.12940	0.00120
4500	0.12831	0.12823	0.12827	0.00038	0.12900	0.00120
5000	0.12872	0.12856	0.12864	0.00077	0.12870	0.00120
5500	0.12927	0.12910	0.12919	0.00078	0.12990	0.00120
6000	0.12975	0.12975	0.12975	0.00078	0.13000	0.00120
6300	0.13039	0.13019	0.13029	0.00078	0.13320	0.00120
6500	0.13030	0.13002	0.13016	0.00078	0.13240	0.00120
7000	0.13105	0.13104	0.13105	0.00130	0.13280	0.00120
7500	0.13185	0.13175	0.13180	0.00130	0.13360	0.00120
8000	0.13250	0.13256	0.13253	0.00130	0.13490	0.00160
8500	0.13415	0.13376	0.13396	0.00130	0.13620	0.00160
9000	0.13406	0.13463	0.13435	0.00130	0.13670	0.00160
9500	0.13536	0.13599	0.13568	0.00140	0.13690	0.00160
10000	0.13815	0.13822	0.13819	0.00140	0.13810	0.00170

The sensitivity results are graphically represented with the expanded uncertainties bars on Figure 3 and Figure 4.

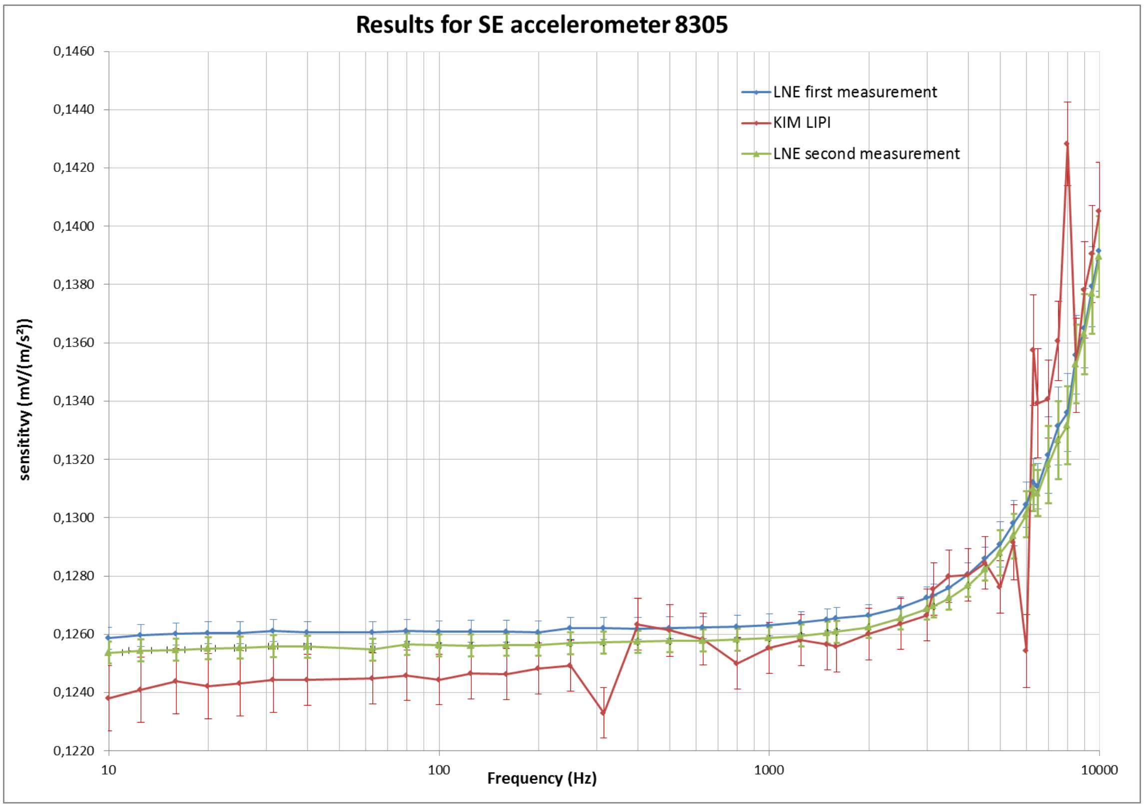

Figure 3. Comparison result chart for SE accelerometer (1st loop of measurements)

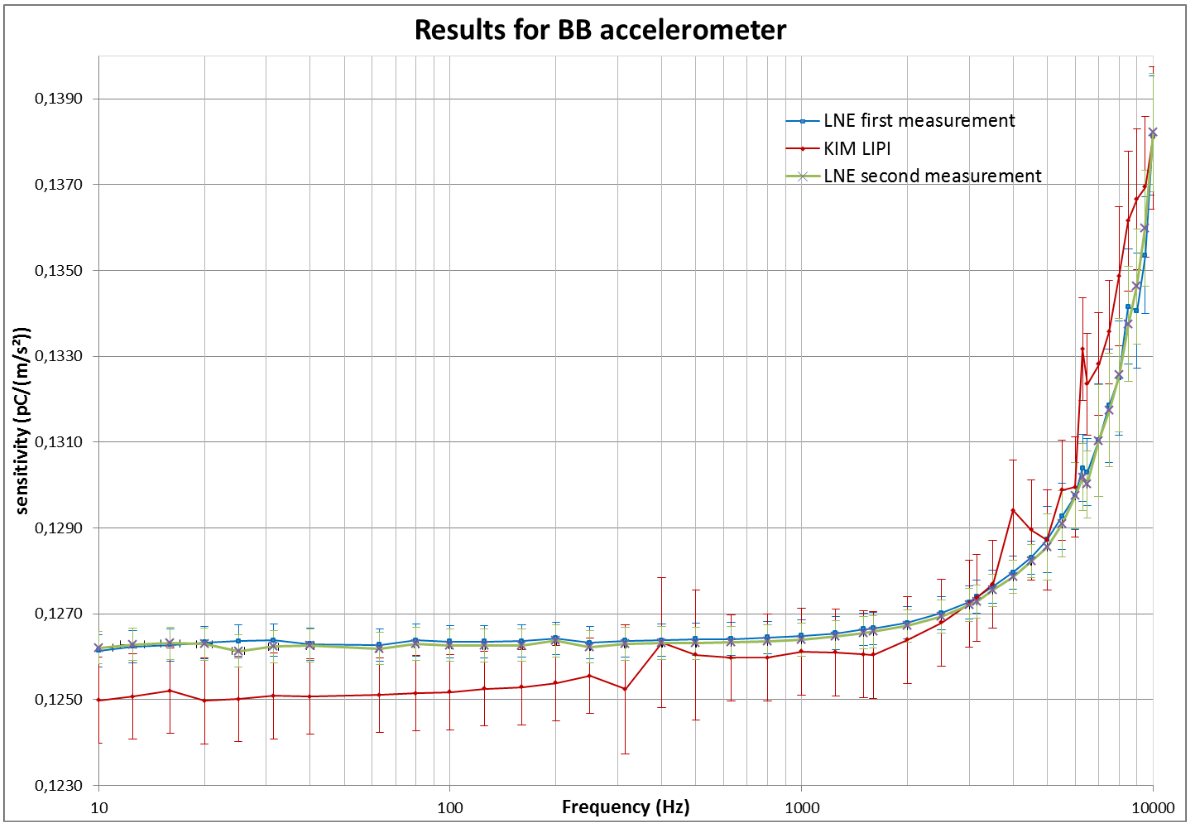

Figure 4. Comparison result chart for BB accelerometer (1st loop of measurements)

To evaluate consistency between results of the two participants, two parameters were estimated:

$$D_i = x_i(\text{RCM LIPI}) - x_i(\text{LNE})$$

$$u_i^2 = u_i^2(\text{RCM LIPI}) + u_i^2(\text{LNE})$$

with x_i : the sensitivity of the accelerometers at the frequency *I*,

D_i : the difference in unit between the results of the two laboratories,

u_i(LAB) : the standard uncertainty of the LAB

U_i : the standard uncertainty on the degree of equivalence.

Results with D_i,> $2.u_i$, where $2.u_i = U_i$, are marked by a yellow background and red police as shown in Table 3.

Table 3. Comparison analysis table (1st loop of measurements)

	8305 SE accelerometer			8305 BB accelerometer	
Frequency	D_i	U_i	Frequency	D_i	U_i
Hz	10^{-3} pC/(m/s²)		Hz	10^{-3} pC/(m/s²)	
10	**-1.82**	1.16	10	**-1.19**	1.07
12.5	**-1.61**	1.16	12.5	**-1.19**	1.07
16	**-1.34**	1.16	16	**-1.08**	1.07
20	**-1.59**	1.16	20	**-1.34**	1.07
25	**-1.49**	1.16	25	**-1.23**	1.07
31.5	**-1.45**	1.16	31.5	**-1.22**	1.07
40	**-1.38**	0.95	40	**-1.21**	0.96
63	**-1.28**	0.95	63	**-1.12**	0.96
80	**-1.29**	0.95	80	**-1.19**	0.96
100	**-1.40**	0.95	100	**-1.14**	0.96
125	**-1.20**	0.95	125	**-1.05**	0.96
160	**-1.24**	0.95	160	**-1.03**	0.96
200	**-1.03**	0.95	200	**-1.01**	0.96
250	**-1.03**	0.95	250	-0.73	0.96
315	**-2.66**	0.94	315	-1.14	1.55
400	0.38	0.96	400	-0.05	1.55
500	0.13	0.96	500	-0.36	1.55
630	-0.18	0.96	630	-0.37	1.07
800	**-1.04**	0.96	800	-0.40	1.07
1000	-0.55	0.96	1000	-0.34	1.07
1250	-0.38	0.96	1250	-0.41	1.07
1500	-0.62	0.96	1500	-0.50	1.07
1600	-0.73	0.96	1600	-0.62	1.07
2000	-0.44	0.96	2000	-0.35	1.07
2500	-0.37	0.96	2500	-0.18	1.07
3000	-0.41	0.97	3000	-0.03	1.07
3150	0.40	0.97	3150	0.06	1.07
3500	0.58	0.98	3500	0.11	1.07
4000	0.17	0.98	4000	**1.49**	1.26
4500	0.03	0.98	4500	0.73	1.26
5000	**-1.30**	1.18	5000	0.06	1.43
5500	-0.39	1.52	5500	0.72	1.43
6000	**-4.88**	1.52	6000	0.25	1.43
6300	**4.68**	2.06	6300	**2.91**	1.43
6500	**2.94**	2.06	6500	**2.24**	1.43
7000	**2.10**	1.84	7000	1.80	1.77
7500	**3.20**	1.91	7500	1.80	1.77
8000	**9.40**	1.91	8000	**2.40**	2.06
8500	-0.20	2.13	8500	**2.20**	2.06
9000	1.40	2.20	9000	**2.40**	2.06
9500	1.30	2.20	9500	1.20	2.13
10000	1.40	2.20	10000	-0.12	2.20

From the Table 3, it can be seen that accelerometer sensitivities present discrepancies in the entire frequency range. In low frequency range, results from RCM-LIPI show an unexpected bump at 315 Hz with an increase of the sensitivity of around 0.8% for both accelerometers before and after 315 Hz. This bump is not normal since it is well known that the sensitivity of accelerometer is very flat between 40 Hz to 1000Hz. In very high frequencies, while for the BB accelerometer, the sensitivity curve is quite smooth, it is not the case for the SE one, which is quite disrupted. Disturbances around 8 kHz to 9 kHz are probably due to the transverse sensitivity of the accelerometer. From the results obtained for the first loop of measurements it can be concluded that no mutual equivalence of the calibration results was obtained by the participating institutes within the declared uncertainties over the considered frequency range.

7. Improvements implemented by RCM-LIPI

In order to identify the problem in their calibration system, RCM-LIPI performed a system investigation. In the first step, the charge amplifier was checked. The identification of the charge amplifier installed on RCM-LIPI's system is as follows:

- Conditioning: B&K 2692
- Serial: 2578893
- Channel: 1
- Gain: 10
- Ref. Freq.: 160 Hz
- Freq. Range: 10 Hz to 12000 Hz

It was found after using the calibration software B&K 3629 that charge amplifier gain setup was not flat, as shown in Figure 5.

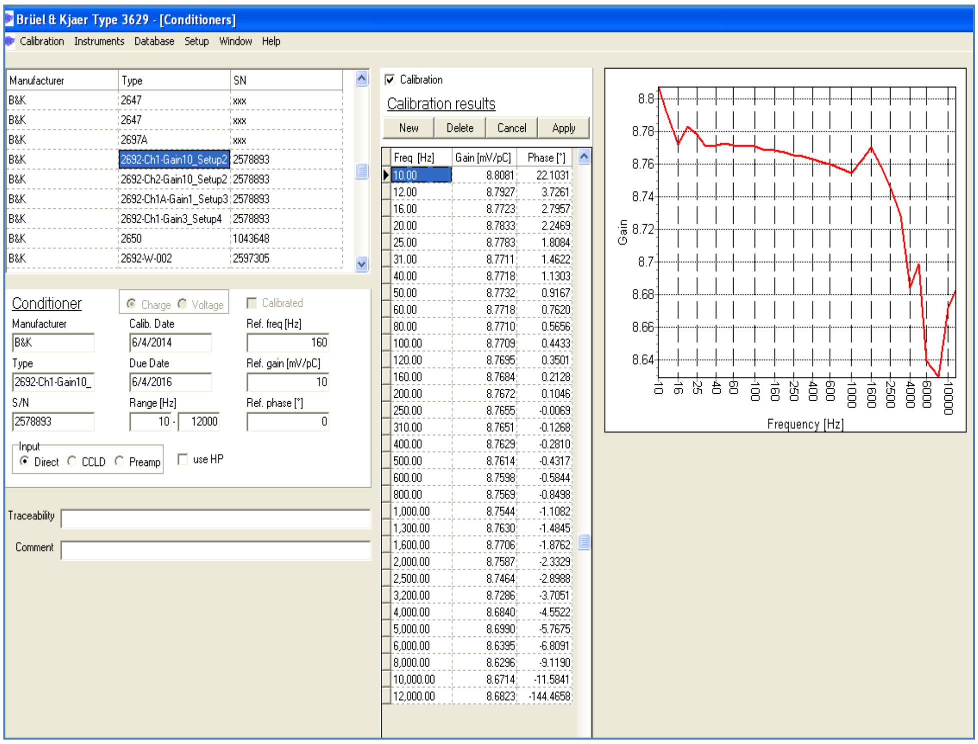

Figure 5. Conditioning amplifier S/N: 2578893 gain curve

The nominal gain of charge amplifier is 10 in the gain setup but the measurement results show a mean value around 8.7, which deviates around 13% from the nominal value. From this evidence, it was suspected that part of the problem came from the installed charge amplifier. This installed charge amplifier (S/N: 2578893) was replaced with another charge amplifier unit (S/N: 2597306). The gain of this charge amplifier was calibrated manually with a calibrated precision capacitor and a digital voltmeter as shown in Figure 6.

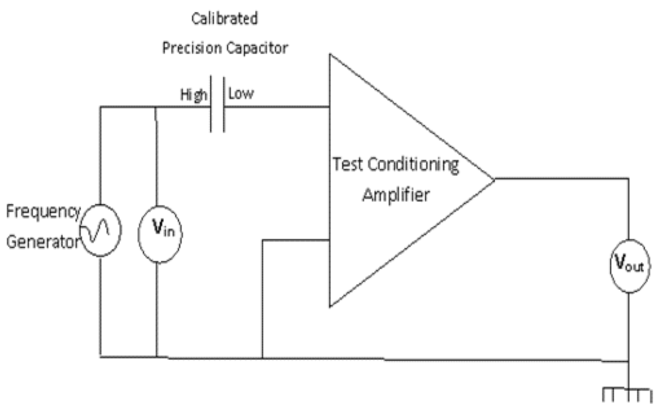

Figure 6. Manual vibration conditioning amplifier calibration setup

The gain obtained from manual calibration was entered on the conditioning amplifier gain setup within B&K 3629 software as seen on Figure 7.

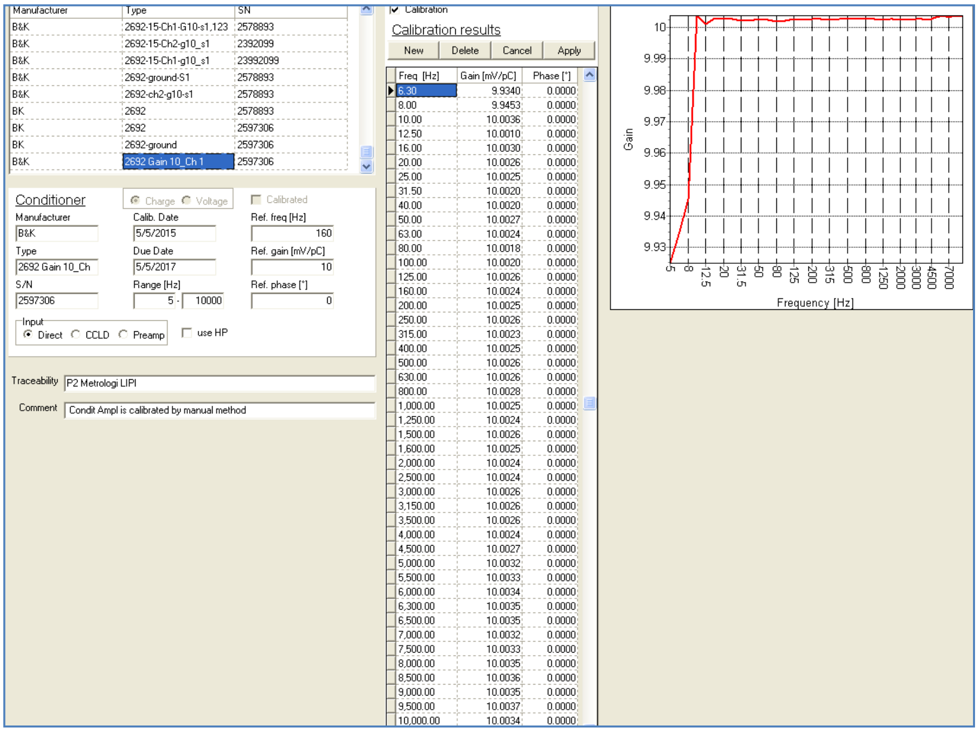

Figure 7. Result of charge amplifier gain calibration S/N: 2597306

Other improvement was made on the determination of measurement position. In the first measurement loop, the measurements of BB and SE accelerometers by RCM-LIPI were made on 3 points and the final accelerometer sensitivity was reported as average of these 3 measurement values. The distance between each measurement point was not equal as can be seen in Figure 8 and Figure 9 for BB and SE respectively.

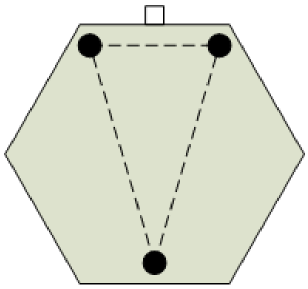

Figure 8. First loop measurement point of BB accelerometer by RCM-LIPI

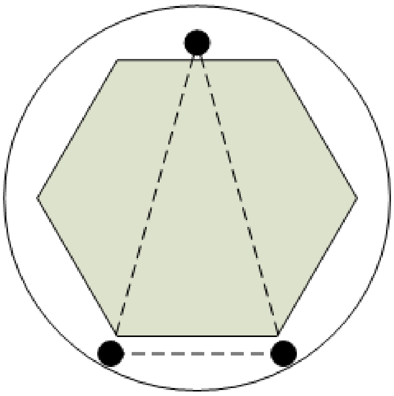

Figure 9. First loop measurement point of SE accelerometer by RCM-LIPI

The improvement was made by determining measurement point in symmetrical point as shown in Figure 10 and Figure 11 for BB and SE respectively.

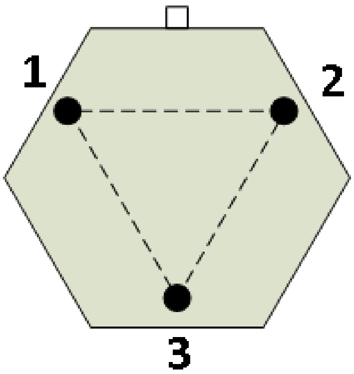

Figure 10. Improvement on BB accelerometer measurement points

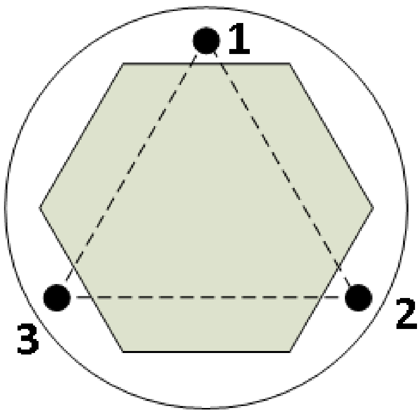

Figure 11. Improvement on SE accelerometer measurement points

After these improvements, the second measurement was performed by RCM-LIPI. The artifact of comparison is the same as in the first loop comparison, BB (SN: 2679379) and SE (2481861). The accelerometer sensitivity result obtained in the second measurement for BB and SE accelerometer can be seen on Table 4 and Figure 10 respectively.

8. Result after Improvements

Final sensitivity values obtained by RCM-LIPI for the SE and BB accelerometers are compared with the accelerometer sensitivities obtained by LNE in the first measurement loop as shown in Table 4. The results from LNE in tables 2 and 4 are the same.

Table 4. Comparison analysis table

	8305 SE accelerometer					
	result obtained by LNE				result obtained by P2M-LIPI	
Frequency	1st meas	2nd meas	mean sensitivity	expanded uncertainty	sensitivity	expanded uncertainty
Hz	pC/(ms^2)				pC/(ms^2)	
10	0.12587	0.12537	0.12562	0.00038	0.12643	0.00110
12.5	0.12597	0.12544	0.12571	0.00038	0.12636	0.00110
16	0.12602	0.12547	0.12575	0.00038	0.12630	0.00110
20	0.12606	0.12552	0.12579	0.00038	0.12619	0.00110
25	0.12605	0.12554	0.12580	0.00038	0.12625	0.00110
31.5	0.12612	0.12559	0.12586	0.00038	0.12624	0.00110
40	0.12606	0.12558	0.12582	0.00038	0.12625	0.00087
63	0.12606	0.12549	0.12578	0.00038	0.12627	0.00087
80	0.12612	0.12566	0.12589	0.00038	0.12623	0.00087
100	0.12608	0.12562	0.12585	0.00038	0.12621	0.00087
125	0.12610	0.12562	0.12586	0.00038	0.12626	0.00087
160	0.12610	0.12564	0.12587	0.00038	0.12623	0.00087
200	0.12608	0.12564	0.12586	0.00038	0.12617	0.00087
250	0.12621	0.12570	0.12596	0.00038	0.12641	0.00087
315	0.12620	0.12572	0.12596	0.00038	0.12645	0.00086
400	0.12620	0.12575	0.12598	0.00038	0.12654	0.00088
500	0.12622	0.12577	0.12600	0.00038	0.12645	0.00088
630	0.12623	0.12579	0.12601	0.00038	0.12649	0.00088
800	0.12627	0.12582	0.12605	0.00038	0.12666	0.00088
1000	0.12632	0.12587	0.12610	0.00038	0.12651	0.00088
1250	0.12640	0.12595	0.12618	0.00038	0.12662	0.00088
1500	0.12650	0.12605	0.12628	0.00038	0.12666	0.00088
1600	0.12655	0.12609	0.12632	0.00038	0.12671	0.00088
2000	0.12665	0.12624	0.12645	0.00038	0.12691	0.00088
2500	0.12691	0.12654	0.12673	0.00038	0.12718	0.00088
3000	0.12725	0.12688	0.12707	0.00038	0.12753	0.00089
3150	0.12735	0.12696	0.12716	0.00038	0.12668	0.00089
3500	0.12759	0.12723	0.12741	0.00038	0.12780	0.00090
4000	0.12806	0.12767	0.12787	0.00038	0.12841	0.00090
4500	0.12860	0.12824	0.12842	0.00039	0.12902	0.00090
5000	0.12908	0.12879	0.12894	0.00077	0.12936	0.00089
5500	0.12981	0.12937	0.12959	0.00078	0.13012	0.00130
6000	0.13044	0.13012	0.13028	0.00078	0.13061	0.00130
6300	0.13123	0.13101	0.13112	0.00079	0.13098	0.00190
6500	0.13108	0.13085	0.13097	0.00079	0.13122	0.00190
7000	0.13215	0.13813	0.13514	0.00130	0.13265	0.00130
7500	0.13315	0.13266	0.13291	0.00130	0.13400	0.00140
8000	0.13361	0.13317	0.13339	0.00130	0.13517	0.00140
8500	0.13559	0.13527	0.13543	0.00140	0.13747	0.00160
9000	0.13651	0.13630	0.13641	0.00140	0.13774	0.00170
9500	0.13793	0.13768	0.13781	0.00140	0.13936	0.00170
10000	0.13915	0.13897	0.13906	0.00140	0.13938	0.00170

	8305 BB accelerometer					
	result obtained by LNE				result obtained by P2M-LIPI	
Frequency	1st meas	2nd meas	mean sensitivity	expanded uncertainty	sensitivity	expanded uncertainty
Hz	pC/(ms^2)				pC/(ms^2)	
10	0.12614	0.12621	0.12618	0.00038	0.12611	0.00100
12.5	0.12624	0.12629	0.12627	0.00038	0.12648	0.00100
16	0.12627	0.12632	0.12630	0.00038	0.12648	0.00100
20	0.12633	0.12629	0.12631	0.00038	0.12666	0.00100
25	0.12636	0.12613	0.12625	0.00038	0.12672	0.00100
31.5	0.12638	0.12624	0.12631	0.00038	0.12682	0.00100
40	0.12630	0.12626	0.12628	0.00038	0.12685	0.00088
63	0.12628	0.12619	0.12624	0.00038	0.12691	0.00088
80	0.12638	0.12630	0.12634	0.00038	0.12694	0.00088
100	0.12635	0.12627	0.12631	0.00038	0.12695	0.00088
125	0.12635	0.12626	0.12631	0.00038	0.12692	0.00088
160	0.12637	0.12627	0.12632	0.00038	0.12691	0.00088
200	0.12643	0.12637	0.12640	0.00038	0.12693	0.00088
250	0.12633	0.12623	0.12628	0.00038	0.12685	0.00088
315	0.12637	0.12630	0.12634	0.00038	0.12668	0.00150
400	0.12638	0.12632	0.12635	0.00038	0.12726	0.00150
500	0.12641	0.12631	0.12636	0.00038	0.12716	0.00150
630	0.12641	0.12633	0.12637	0.00038	0.12698	0.00100
800	0.12645	0.12636	0.12641	0.00038	0.12701	0.00100
1000	0.12649	0.12640	0.12645	0.00038	0.12710	0.00100
1250	0.12655	0.12647	0.12651	0.00038	0.12719	0.00100
1500	0.12664	0.12656	0.12660	0.00038	0.12725	0.00100
1600	0.12666	0.12658	0.12662	0.00038	0.12728	0.00100
2000	0.12679	0.12672	0.12676	0.00038	0.12742	0.00100
2500	0.12701	0.12694	0.12698	0.00038	0.12755	0.00100
3000	0.12727	0.12720	0.12724	0.00038	0.12779	0.00100
3150	0.12739	0.12729	0.12734	0.00038	0.12787	0.00100
3500	0.12763	0.12755	0.12759	0.00038	0.12790	0.00100
4000	0.12796	0.12786	0.12791	0.00038	0.12817	0.00120
4500	0.12831	0.12823	0.12827	0.00038	0.12899	0.00120
5000	0.12872	0.12856	0.12864	0.00077	0.12912	0.00120
5500	0.12927	0.12910	0.12919	0.00078	0.12990	0.00120
6000	0.12975	0.12975	0.12975	0.00078	0.13016	0.00120
6300	0.13039	0.13019	0.13029	0.00078	0.13085	0.00120
6500	0.13030	0.13002	0.13016	0.00078	0.13132	0.00120
7000	0.13105	0.13104	0.13105	0.00130	0.13176	0.00120
7500	0.13185	0.13175	0.13180	0.00130	0.13220	0.00120
8000	0.13250	0.13256	0.13253	0.00130	0.13346	0.00160
8500	0.13415	0.13376	0.13396	0.00130	0.13535	0.00160
9000	0.13406	0.13463	0.13435	0.00130	0.13544	0.00160
9500	0.13536	0.13599	0.13568	0.00140	0.13634	0.00160
10000	0.13815	0.13822	0.13819	0.00140	0.13695	0.00170

The results after improvements by RCM-LIPI are graphically represented with the expanded uncertainty bars on Figure 12 and Figure 13.

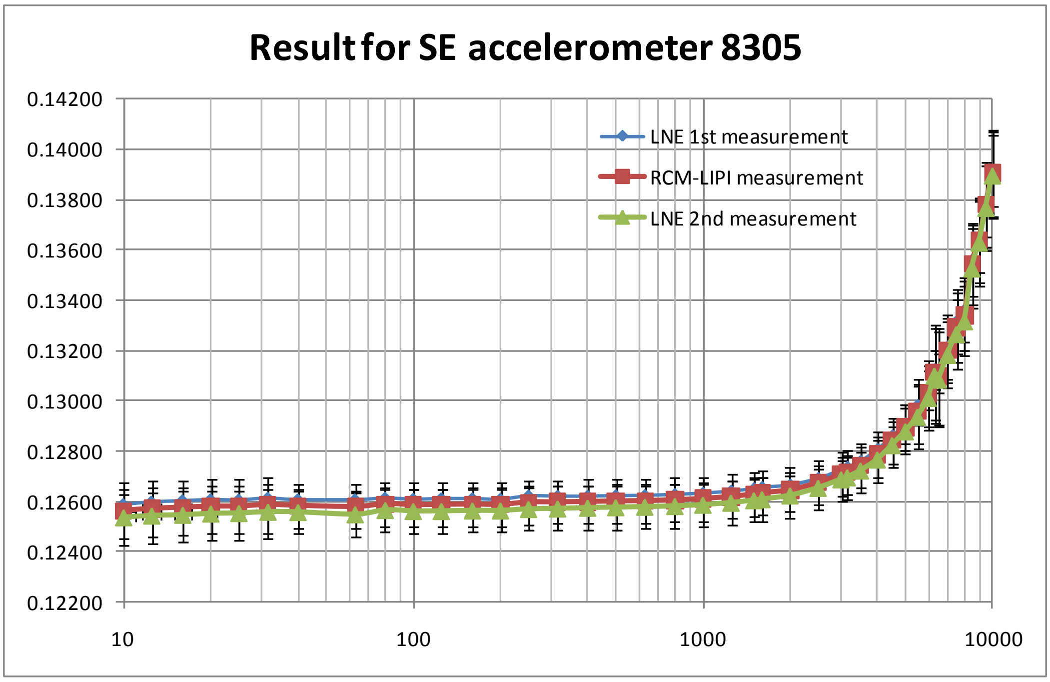

Figure 12. Results for SE accelerometer after RCM-LIPI improvements

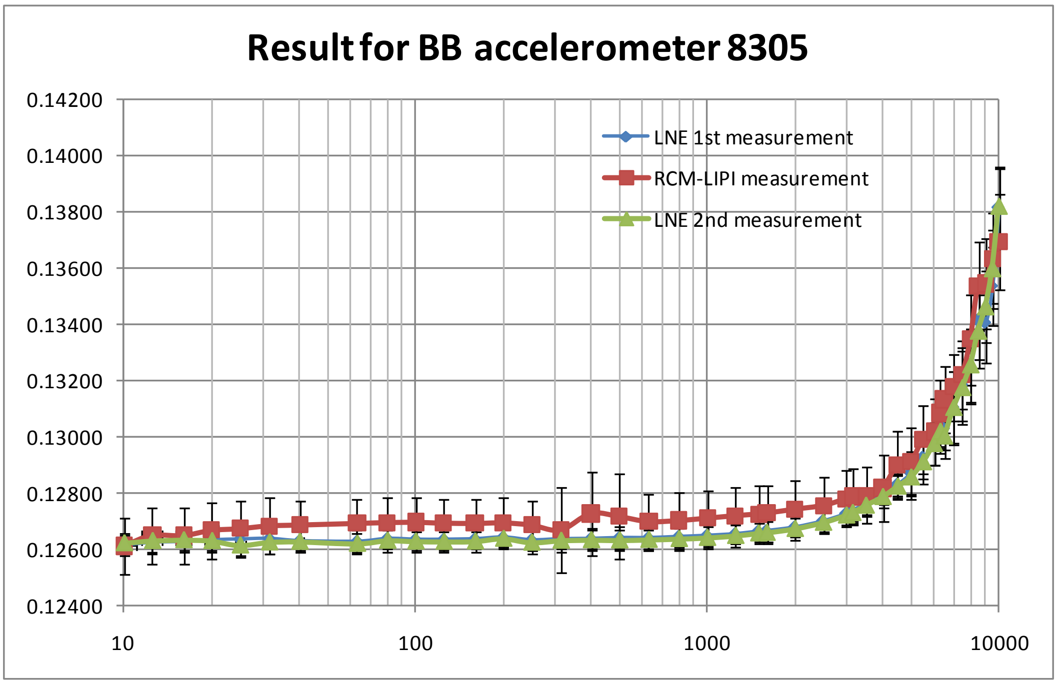

Figure 13. Results for BB accelerometer after RCM-LIPI improvements

Consistency of the results after the improvements were then re-evaluated by calculating the value of D_i and U_i between LNE result and RCM-LIPI. From the comparison analysis result on Table 5 can be seen that D_i < U_i for all frequencies of measurement.

Table 5. Analysis after improvements by RCM-LIPI

	8305 SE accelerometer			8305 BB accelerometer	
Frequency	D_i	U_i	Frequency	D_i	U_i
Hz	10^{-3} pC/(m/s^2)		Hz	10^{-3} pC/(m/s^2)	
10	-0.81	1.16	10	-0.06	1.07
12.5	-0.65	1.16	12.5	0.22	1.07
16	-0.56	1.16	16	0.19	1.07
20	-0.40	1.16	20	0.35	1.07
25	-0.46	1.16	25	0.48	1.07
31.5	-0.39	1.16	31.5	0.51	1.07
40	-0.43	0.95	40	0.57	0.96
63	-0.50	0.95	63	0.68	0.96
80	-0.34	0.95	80	0.60	0.96
100	-0.36	0.95	100	0.64	0.96
125	-0.40	0.95	125	0.61	0.96
160	-0.36	0.95	160	0.59	0.96
200	-0.31	0.95	200	0.53	0.96
250	-0.45	0.95	250	0.57	0.96
315	-0.49	0.94	315	0.34	1.55
400	-0.57	0.96	400	0.91	1.55
500	-0.45	0.96	500	0.80	1.55
630	-0.48	0.96	630	0.61	1.07
800	-0.62	0.96	800	0.61	1.07
1000	-0.42	0.96	1000	0.66	1.07
1250	-0.44	0.96	1250	0.68	1.07
1500	-0.38	0.96	1500	0.65	1.07
1600	-0.39	0.96	1600	0.66	1.07
2000	-0.46	0.96	2000	0.67	1.07
2500	-0.45	0.96	2500	0.57	1.07
3000	-0.46	0.97	3000	0.56	1.07
3150	0.47	0.97	3150	0.53	1.07
3500	-0.39	0.98	3500	0.31	1.07
4000	-0.54	0.98	4000	0.26	1.26
4500	-0.60	0.98	4500	0.72	1.26
5000	-0.43	1.18	5000	0.48	1.43
5500	-0.53	1.52	5500	0.72	1.43
6000	-0.33	1.52	6000	0.41	1.43
6300	0.14	2.06	6300	0.56	1.43
6500	-0.26	2.06	6500	1.16	1.43
7000	-0.65	1.84	7000	0.76	1.77
7500	-1.10	1.91	7500	0.40	1.77
8000	-1.77	1.91	8000	0.96	2.06
8500	-2.07	2.13	8500	1.35	2.06
9000	-1.34	2.20	9000	1.14	2.06
9500	-1.56	2.20	9500	0.64	2.13
10000	-0.28	2.20	10000	-1.27	2.20

9. Conclusions

The bilateral comparison of SE and BB accelerometers between RCM-LIPI and LNE has been conducted in 2 measurement loops. In the first measurement loop, comparison result obtained by RCM-LIPI showed discrepancies within all frequency range for both BB and SE accelerometers from LNE results.

System investigations conducted by RCM-LIPI concluded that the problem came from the charge amplifier and the determination of measurement point. RCM-LIPI calibrated a second charge amplifier manually by using a precision capacitor and reallocated the laser measurement points to more symmetrical positions. Second measurement loop was then performed and discrepancies problems were solved. Accelerometer sensitivities obtained by RCM-LIPI approximated close to LNE results, presenting a maximum deviation of 1 % for BB sensitivity at 9000 Hz and of 1.38% at 8500Hz for SE sensitivity.

According to the comparison analysis after improvement, mutual equivalence of the calibration result can be achieved by the participating institutes within the declared uncertainties over the considered frequency range from 10 Hz to 10 kHz.

In the future, it is planned to initiate accelerometer calibration bilateral comparison with another NMI to extend RCM-LIPI's measurement frequency range.

Appendix A: Technical protocol of the comparison

TECHNICAL PROTOCOL FOR BILATERAL COMPARISON
(Magnitude of the complex charge sensitivity of accelerometers)
EURAMET.AUV.V-P1

1. INTRODUCTION

The comparison is organized within the EU-Indonesia Trade Support Programme II, Sub-project Number APE12-06, “Improvement of traceability of Metrology and Calibration measurements of Puslit RCM-LIPI”. This technical protocol is based on the CIPM Key Comparison CCAUV.V-K2 and on the results and conclusions of this comparison.

The comparison will be accomplished in accordance with the EURAMET Guidelines on Conducting Comparisons and CCEM Guidelines for Planning, Organizing, Conducting and Reporting Key, Supplementary and Pilot Comparisons. It also follows the guidelines for measurement comparisons defined in the CIPM MRA document [1].

Two National Metrology Institutes will take part in this comparison: LNE (France) and RCM-LIPI (Indonesia).

LNE is acting as the pilot laboratory and in this function is responsible for providing the travelling standard, the evaluation of the measurement results and the final report.

2. TRAVELLING STANDARDS AND MEASURING CONDITIONS

A set of two piezoelectric accelerometers will be circulated among the participating laboratories. The individual transducers are a BK 8305-001 “single ended” (SE) type SN 2481861 and a BK 8305 “back to back” (BB) type SN 2679379, which belong to the pilot laboratory LNE.
It was demonstrated during CCAUV.V-K2 key comparison that there is a dependency between the accelerometer sensitivity and the material of the moving coil.
As the laboratories don’t have the same kind of exciters (moreover different materials for the moving coils) and in order to minimize their influences on the results, an adapter is also circulated with the SE accelerometer during the comparison.
This adapter is defined in [2] and is supplied by the pilot.

The accelerometers are to be calibrated for magnitude of the complex charge sensitivity according to those procedures and conditions implemented by the NMI in conformance with ISO 16063-11. The sensitivities reported shall be for the accelerometers alone, excluding any effects from the charge amplifier.

The frequency range of the measurements was agreed to be from 10 Hz to 10 kHz. Specifically the laboratories will measure at the following frequencies (all values in Hz):
10, 12.5, 16, 20, 25, 31.5, 40, 63, 80, 100, 125, 160, 200, 250, 315, 400, 500, 630, 800, 1000, 1250, 1500, 1600, 2000, 2500, 3000, 3150, 3500, 4000, 4500, 5000, 5500, 6000, 6300, 6500, 7000, 7500, 8000, 8500, 9000, 9500, 10000.

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

The participating laboratories should be able to provide magnitude results over the whole frequency range with their uncertainties for the majority of the specified frequencies.
The charge amplifier (CA) used for the calibration is not provided within the set of the artifacts; It must therefore be provided by the individual participant.
The measurement condition should be kept according to the laboratory's standard conditions for calibration of customer accelerometers in order to claim their best measurement capability or CMC where applicable. This presumes that these conditions comply with those defined by the applicable ISO documentary standards [3,4,5], simultaneously.
Specific conditions for the measurements are:

- Acceleration amplitudes: preferably 50 m/s² to 100 m/s².
  A range of 2 m/s² to 200 m/s² is admissible.
- Ambient temperature and accelerometer temperature during the calibration: (23 ± 2) ºC. The laboratory temperature should be measured and reported.
- Relative humidity: max. 75 %.
- Mounting torque of the accelerometer: 2.0 N·m.

3. CIRCULATION TYPE, SCHEDULE AND TRANSPORTATION

The pilot laboratory, LNE, will first calibrate the set of accelerometers. Then the participating laboratory, RCM-LIPI, will calibrate and return it to the pilot laboratory, LNE. The pilot will calibrate the set at the end to check the stability.

4. MEASUREMENT AND ANALYSIS INSTRUCTIONS

The participating laboratories have to observe the following instructions:

- The charge amplifier used for the measurement of the accelerometer's response has to be calibrated with equipment traceable to national measurement standards.
- The motion of the BB accelerometer shall be measured with the laser directly on the (polished) top surface of the transducer without any additional reflector or dummy mass.
- The motion of the SE accelerometer should be measured on the moving part of an adapter, close to the accelerometer's mounting surface, since the mounting (reference) surface is usually not directly accessible.
- The mounting surface of the accelerometer and the moving part of the exciter must be slightly lubricated before mounting.
- The cable between accelerometer and charge amplifier should be taken from the set of DUT delivered to the laboratory.
- In order to reduce the influence of non-rectilinear motion, the measurements should be performed for at least three different laser positions which are symmetrically distributed over the respective measurement surface.
- It is advised that the measurement results should be compiled from complete measurement series carried out at different days under nominally the same conditions, except that the accelerometer is remounted and the cable reattached. The standard deviation of the subsequent measurements should be included in the report.
- For acceleration signals $a(t)$ of the form

$$a(t) = \hat{a} \cdot \cos(\omega t + \varphi_a) \qquad (1)$$

and the respective charge output signal of the transducer is of the form

$$q(t) = \hat{q} \cdot \cos(\omega t + \varphi_q) \qquad (2)$$

5. COMMUNICATION OF THE RESULTS TO THE PILOT LABORATORY

The results have to be submitted to the pilot laboratory within six weeks after completion of the measurements.

Timetable:

Measurement at LNE:	week 18-20
Measurement at RCM-LIPI:	week 24-33
Measurement at LNE:	week 35-37

The laboratories will submit one printed and signed calibration report for each accelerometer to the pilot laboratory including the following:

- A description of the calibration systems used for the comparison and the mounting techniques for the accelerometer.
- A description of the calibration methods used.
- A documented record of the ambient conditions during measurements.
- The calibration results, including the relative expanded measurement uncertainty, 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]). This should include information on the type of uncertainty (A or B), assumed distribution function and repeatability component.
  Since it is generally agreed that the chosen accelerometers are not the optimal choice as “best device under test” (DUT) for the frequencies below 40 Hz, an additional uncertainty component, attributed to the DUT, if necessary, shall be added to the measurement uncertainties estimated by the participants. This component is supposed to cover the influence of the possible electrostrictive or tribo-electric effect of cable motion. In addition, the participating laboratories shall also to consider the effects of mounting in their uncertainty budget.

In addition, the participating laboratory will receive two electronic spreadsheets prepared by the pilot laboratory, where the calibration results have to be filled in following the structure given in the files. The use of the electronic spreadsheets 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.

6. REFERENCES

[1] Measurement comparisons in the CIPM MRA (CIPM MRA-D-05, Version 1.6)

[2] A study of the dispersion on primary calibration results of single-ended accelerometers at high frequencies, Gustavo P. Ripper, Giancarlo B. Micheli, and Ronaldo S. Dias, XX IMEKO World Congress, 2012

[3] ISO 16063-1:1998 “Methods for the calibration of vibration and shock transducers -- Part 1: Basic concepts.

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

[5] ISO/IEC 17025:2005 “General requirements for the competence of testing and calibration laboratories”.

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

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

7. CONTACT

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Appendix B: Measurement uncertainty budget

Measurement uncertainties applicable for the sine approximation method used in EURAMET.AUV.V-P1 from 10 Hz to 10 000 Hz.

RCM-LIPI / SE accelerometer

No.	Components	Type	Distribution	dof	Source	Relative Uncertainty in each frequency, in %									
						10	12,5	16	20	25	31,5	40	63	80	100
1	Acceleration Amplitude					0,20315	0,20315	0,18021	0,20167	0,20315	0,18021	0,08401	0,23313	0,23311	0,23540
1.1	Signal Generator Frequency	B	rect	30	B&K	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144
1.2	Interferometer Signal Filtering Effect on Phase Measurement Amplitude	B	rect	30	B&K	0,06455	0,06455	0,06455	0,06455	0,06455	0,06455	0,06455	0,06455	0,06455	0,06455
1.3	Laser Wavelength Stability	B	rect	30	B&K	0,00009	0,00009	0,00009	0,00009	0,00009	0,00009	0,00009	0,00009	0,00009	0,00009
1.4	Motion Disturbance Effect	A	Normal	5	experiment	0,19262	0,19262	0,16824	0,19105	0,19262	0,16824	0,05375	0,22401	0,22399	0,22637
2	Voltage Amplitude					0,08026	0,08026	0,08026	0,07204	0,07176	0,07167	0,06820	0,06903	0,06899	0,07106
2.1	Signal Generator Frequency	B	rect	30	B&K	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144
2.2	Voltage Measurement Error	B	rect	30	B&K	0,07159	0,07159	0,07159	0,07159	0,07159	0,07159	0,06813	0,06813	0,06813	0,06813
2.3	Transverse Motion Effect	A	Normal	4	experiment	0,03624	0,03624	0,03624	0,00792	0,00467	0,00299	0,00289	0,01101	0,01077	0,02016
3	Charge Amplifier					0,33260	0,33452	0,32642	0,32462	0,32621	0,32460	0,32857	0,21053	0,20726	0,20712
3.1	Standard Capacitor	B	rect	30	NMI	0,04776	0,04727	0,04786	0,04727	0,04786	0,04785	0,04730	0,00242	0,00242	0,00214
3.2	Input Voltage	B	rect	30	B&K	0,31754	0,31754	0,31754	0,31754	0,31754	0,31754	0,31754	0,20207	0,20207	0,20207
3.3	Output Voltage	B	rect	30	B&K	0,03175	0,03175	0,03175	0,03175	0,03175	0,03175	0,03175	0,02021	0,02021	0,02021
3.4	Type A of Charge Amplifier	A	Normal	4	experiment	0,08061	0,08846	0,04918	0,03606	0,04774	0,03511	0,06230	0,05544	0,04136	0,04067
						0,04870	0,03093	0,01486	0,01143	0,00891	0,00717	0,00761	0,01057	0,01006	0,01901
4,1	Repeatability	A	Normal	4	experiment	0,04870	0,03093	0,01486	0,01143	0,00891	0,00717	0,00761	0,01057	0,01006	0,01901
	Combined Uncertainty (Uc)					0,40088	0,40071	0,38169	0,38906	0,39104	0,37819	0,34602	0,32179	0,31962	0,32206
	k Factor					2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00
	Expanded Uncertainty (U95)					0,80176	0,80142	0,76338	0,77812	0,78207	0,75638	0,69203	0,64357	0,63924	0,64413
	U95 round up					0,90	0,90	0,80	0,80	0,80	0,80	0,70	0,70	0,70	0,70
	Stated Uncertainty (U95%)					**0,9**	**0,9**	**0,9**	**0,9**	**0,9**	**0,9**	**0,7**	**0,7**	**0,7**	**0,7**

No.	Components	Type	Distribution	dof	Source	Relative Uncertainty in each frequency, in %										
						125	160	200	250	315	400	500	630	800	1000	1250
1	Acceleration Amplitude					0,24525	0,23970	0,24238	0,25262	0,26535	0,25504	0,24806	0,22430	0,23061	0,24669	0,23104
1.1	Signal Generator Frequency	B	rect	30	B&K	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144
1.2	Interferometer Signal Filtering Effect on Phase Measurement Amplitude	B	rect	30	B&K	0,06455	0,06455	0,06455	0,06455	0,06455	0,06455	0,06455	0,06455	0,06455	0,06455	0,06455
1.3	Laser Wavelength Stability	B	rect	30	B&K	0,00009	0,00009	0,00009	0,00009	0,00009	0,00009	0,00009	0,00009	0,00009	0,00009	0,00009
1.4	Motion Disturbance Effect	A	Normal	5	experiment	0,23659	0,23084	0,23363	0,24423	0,25737	0,24674	0,23951	0,21480	0,22138	0,23809	0,22183
2	Voltage Amplitude					0,07232	0,07264	0,08494	0,08687	0,08372	0,08956	0,18692	0,17035	0,16898	0,14625	0,17286
2.1	Signal Generator Frequency	B	rect	30	B&K	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144
2.2	Voltage Measurement Error	B	rect	30	B&K	0,06813	0,06813	0,06813	0,06813	0,06813	0,06813	0,06813	0,04041	0,04041	0,04041	0,04041
2.3	Transverse Motion Effect	A	Normal	4	experiment	0,02423	0,02517	0,05072	0,05387	0,04864	0,05811	0,17406	0,16548	0,16407	0,14055	0,16806
3	Charge Amplifier					0,20516	0,20493	0,20510	0,20503	0,20477	0,20510	0,20468	0,20443	0,20494	0,20506	0,20506
3.1	Standard Capacitor	B	rect	30	NMI	0,00214	0,00214	0,00214	0,00214	0,00214	0,00214	0,00214	0,00214	0,00214	0,00214	0,00214
3.2	Input Voltage	B	rect	30	B&K	0,20207	0,20207	0,20207	0,20207	0,20207	0,20207	0,20207	0,20207	0,20207	0,20207	0,20207
3.3	Output Voltage	B	rect	30	B&K	0,02021	0,02021	0,02021	0,02021	0,02021	0,02021	0,02021	0,02021	0,02021	0,02021	0,02021
3.4	Type A of Charge Amplifier	A	Normal	4	experiment	0,02909	0,02737	0,02864	0,02816	0,02615	0,02864	0,02548	0,02334	0,02744	0,02832	0,02832
						0,01395	0,03370	0,03380	0,03266	0,15339	0,16647	0,01473	0,06165	0,12972	0,06073	0,05736
4,1	Repeatability	A	Normal	4	experiment	0,01395	0,03370	0,03380	0,03266	0,15339	0,16647	0,01473	0,06165	0,12972	0,06073	0,05736
	Combined Uncertainty (Uc)					0,32812	0,32537	0,33042	0,33833	0,37799	0,37795	0,37227	0,35344	0,37491	0,35774	0,35860
	k Factor					2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00
	Expanded Uncertainty (U95)					0,65624	0,65073	0,66083	0,67666	0,75598	0,75590	0,74454	0,70687	0,74982	0,71549	0,71721
	U95 round up					0,70	0,70	0,70	0,70	0,80	0,80	0,80	0,80	0,80	0,80	0,80
	Stated Uncertainty (U95%)					**0,7**	**0,7**	**0,7**	**0,7**	**0,7**	**0,7**	**0,7**	**0,7**	**0,7**	**0,7**	**0,7**

No.	Components	Type	Distribution	dof	Source	Relative Uncertainty in each frequency, in %										
						1500	1600	2000	2500	3000	3150	3500	4000	4500	5000	5500
1	Acceleration Amplitude					0,23104	0,21788	0,20676	0,25579	0,24388	0,24388	0,21031	0,21031	0,22967	0,22967	0,22967
1.1	Signal Generator Frequency	B	rect	30	B&K	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144
1.2	Interferometer Signal Filtering Effect on Phase Measurement Amplitude	B	rect	30	B&K	0,06455	0,06455	0,06455	0,06455	0,06455	0,06455	0,06455	0,06455	0,06455	0,06455	0,06455
1.3	Laser Wavelength Stability	B	rect	30	B&K	0,00009	0,00009	0,00009	0,00009	0,00009	0,00009	0,00009	0,00009	0,00009	0,00009	0,00009
1.4	Motion Disturbance Effect	A	Normal	5	experiment	0,22183	0,20809	0,19642	0,24750	0,23518	0,23518	0,20016	0,20016	0,22041	0,22041	0,22041
2	Voltage Amplitude					0,03813	0,16072	0,16018	0,16319	0,03813	0,15104	0,03813	0,15544	0,03813	0,20694	0,20694
2.1	Signal Generator Frequency	B	rect	30	B&K	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144
2.2	Voltage Measurement Error	B	rect	30	B&K	0,03811	0,03811	0,03811	0,03811	0,03811	0,03811	0,03811	0,03811	0,03811	0,03811	0,03811
2.3	Transverse Motion Effect	A	Normal	4	experiment	0,00000	0,15613	0,15558	0,15867	0,00000	0,14614	0,00000	0,15069	0,00000	0,20339	0,20339
3	Charge Amplifier					0,20496	0,20432	0,20404	0,20413	0,20413	0,20429	0,20429	0,20474	0,20417	0,20438	0,20429
3.1	Standard Capacitor	B	rect	30	NMI	0,00000	0,00214	0,00214	0,00214	0,00214	0,00214	0,00214	0,00214	0,00214	0,00214	0,00214
3.2	Input Voltage	B	rect	30	B&K	0,20207	0,20207	0,20207	0,20207	0,20207	0,20207	0,20207	0,20207	0,20207	0,20207	0,20207
3.3	Output Voltage	B	rect	30	B&K	0,02021	0,02021	0,02021	0,02021	0,02021	0,02021	0,02021	0,02021	0,02021	0,02021	0,02021
3.4	Type A of Charge Amplifier	A	Normal	4	experiment	0,02766	0,02236	0,01967	0,02060	0,02060	0,02213	0,02213	0,02595	0,02095	0,02291	0,02213
						0,04760	0,06723	0,04637	0,02727	0,01750	0,05532	0,15089	0,19955	0,11639	0,06960	0,21092
4,1	Repeatability	A	Normal	4	experiment	0,04760	0,06723	0,04637	0,02727	0,01750	0,05532	0,15089	0,19955	0,11639	0,06960	0,21092
	Combined Uncertainty (Uc)					0,31481	0,34578	0,33495	0,36671	0,32080	0,35649	0,33195	0,38747	0,33081	0,37708	0,42638
	k Factor					2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00
	Expanded Uncertainty (U95)					0,62962	0,69157	0,66990	0,73341	0,64159	0,71298	0,66390	0,77494	0,66162	0,75416	0,85275
	U95 round up					0,70	0,70	0,70	0,80	0,70	0,80	0,70	0,80	0,70	0,80	0,90
	Stated Uncertainty (U95%)					**0,7**	**0,7**	**0,7**	**0,7**	**0,7**	**0,7**	**0,7**	**0,7**	**0,7**	**0,7**	**1,0**

No.	Components	Type	Distribution	dof	Source	Relative Uncertainty in each frequency, in %									
						6000	6300	6500	7000	7500	8000	8500	9000	9500	10 000
1	Acceleration Amplitude					0,29784	0,29397	0,29784	0,29397	0,29397	0,29397		0,29397	0,29784	0,30144
1.1	Signal Generator Frequency	B	rect	30	B&K	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144
1.2	Interferometer Signal Filtering Effect on Phase Measurement Amplitude	B	rect	30	B&K	0,06455	0,06455	0,06455	0,06455	0,06455	0,06455	0,06455	0,06455	0,06455	0,06455
1.3	Laser Wavelength Stability	B	rect	30	B&K	0,00009	0,00009	0,00009	0,00009	0,00009	0,00009	0,00009	0,00009	0,00009	0,00009
1.4	Motion Disturbance Effect	A	Normal	5	experiment	0,29075	0,28679	0,29075	0,28679	0,28679	0,28679	0,28679	0,28679	0,29075	0,29444
2	Voltage Amplitude					0,20694	0,20694	0,20694	0,20694	0,20694	0,28309		0,28837	0,28837	0,28837
2.1	Signal Generator Frequency	B	rect	30	B&K	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144
2.2	Voltage Measurement Error	B	rect	30	B&K	0,03811	0,03811	0,03811	0,03811	0,03811	0,03811	0,03811	0,03811	0,03811	0,03811
2.3	Transverse Motion Effect	A	Normal	4	experiment	0,20339	0,20339	0,20339	0,20339	0,20339	0,28051	0,28051	0,28584	0,28584	0,28584
3	Charge Amplifier					0,20518	0,20429	0,20518	0,20518	0,20518	0,20518		0,20518	0,20518	0,20435
3.1	Standard Capacitor	B	rect	30	NMI	0,00214	0,00214	0,00214	0,00214	0,00214	0,00214	0,00214	0,00214	0,00214	0,00214
3.2	Input Voltage	B	rect	30	B&K	0,20207	0,20207	0,20207	0,20207	0,20207	0,20207	0,20207	0,20207	0,20207	0,20207
3.3	Output Voltage	B	rect	30	B&K	0,02021	0,02021	0,02021	0,02021	0,02021	0,02021	0,02021	0,02021	0,02021	0,02021
3.4	Type A of Charge Amplifier	A	Normal	4	experiment	0,02923	0,02213	0,02923	0,02923	0,02923	0,02923	0,02923	0,02923	0,02923	0,02269
						0,24867	0,46103	0,55352	0,14389	0,03141	0,14274	0,53705	0,18622	0,10116	0,09061
4,1	Repeatability	A	Normal	4	experiment	0,24867	0,46103	0,55352	0,14389	0,03141	0,14274	0,53705	0,18622	0,10116	0,09061
	Combined Uncertainty (Uc)					0,48525	0,61929	0,69283	0,43823	0,41512	0,47857	0,53705	0,49634	0,47350	0,47328
	k Factor					2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00
	Expanded Uncertainty (U95)					0,97050	1,23859	1,38567	0,87646	0,83025	0,95714	1,07409	0,99268	0,94700	0,94657
	U95 round up					1,00	1,30	1,40	0,90	0,90	1,00	1,10	1,00	1,00	1,00
	Stated Uncertainty (U95%)					**1,0**	**1,4**	**1,4**	**1,0**	**1,0**	**1,0**	**1,2**	**1,2**	**1,2**	**1,2**

RCM-LIPI / BB accelerometer

No.	Components	Type	Distribution	dof	Source	Relative Uncertainty in each frequency, in %									
						10	12,5	16	20	25	31,5	40	63	80	100
1	Acceleration Amplitude					0,20315	0,20315	0,18021	0,20167	0,20315	0,18021	0,08401	0,23313	0,23311	0,23540
1.1	Signal Generator Frequency	B	rect	30	B&K	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144
1.2	Interferometer Signal Filtering Effect on Phase Measurement Amplitude	B	rect	30	B&K	0,06455	0,06455	0,06455	0,06455	0,06455	0,06455	0,06455	0,06455	0,06455	0,06455
1.3	Laser Wavelength Stability	B	rect	30	B&K	0,00009	0,00009	0,00009	0,00009	0,00009	0,00009	0,00009	0,00009	0,00009	0,00009
1.4	Motion Disturbance Effect	A	Normal	5	experiment	0,19262	0,19262	0,16824	0,19105	0,19262	0,16824	0,05375	0,22401	0,22399	0,22637
2	Voltage Amplitude					0,08026	0,08026	0,08026	0,07204	0,07176	0,07167	0,06820	0,06903	0,06899	0,07106
2.1	Signal Generator Frequency	B	rect	30	B&K	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144
2.2	Voltage Measurement Error	B	rect	30	B&K	0,07159	0,07159	0,07159	0,07159	0,07159	0,07159	0,06813	0,06813	0,06813	0,06813
2.3	Transverse Motion Effect	A	Normal	4	experiment	0,03624	0,03624	0,03624	0,00792	0,00467	0,00299	0,00289	0,01101	0,01077	0,02016
3	Charge Amplifier					0,33260	0,33452	0,32642	0,32462	0,32621	0,32460	0,32857	0,21053	0,20726	0,20712
3.1	Standard Capacitor	B	rect	30	NMI	0,04776	0,04727	0,04786	0,04727	0,04786	0,04785	0,04730	0,00242	0,00242	0,00214
3.2	Input Voltage	B	rect	30	B&K	0,31754	0,31754	0,31754	0,31754	0,31754	0,31754	0,31754	0,20207	0,20207	0,20207
3.3	Output Voltage	B	rect	30	B&K	0,03175	0,03175	0,03175	0,03175	0,03175	0,03175	0,03175	0,02021	0,02021	0,02021
3.4	Type A of Charge Amplifier	A	Normal	4	experiment	0,08061	0,08846	0,04918	0,03606	0,04774	0,03511	0,06230	0,05544	0,04136	0,04067
						0,01403	0,01375	0,01156	0,01510	0,01351	0,01198	0,01233	0,01179	0,01474	0,03400
4,1	Repeatability	A	Normal	4	experiment	0,01403	0,01375	0,01156	0,01510	0,01351	0,01198	0,01233	0,01179	0,01474	0,03400
	Combined Uncertainty (Uc)					0,39816	0,39975	0,38158	0,38918	0,39117	0,37831	0,34615	0,32183	0,31980	0,32329
	k Factor					2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00
	Expanded Uncertainty (U95)					0,79631	0,79951	0,76315	0,77837	0,78234	0,75662	0,69231	0,64366	0,63961	0,64659
	U95 round up					0,80	0,80	0,80	0,80	0,80	0,80	0,70	0,70	0,70	0,70
	Stated Uncertainty (U95%)					**0,8**	**0,8**	**0,8**	**0,8**	**0,8**	**0,8**	**0,7**	**0,7**	**0,7**	**0,7**

No.	Components	Type	Distribution	dof	Source	Relative Uncertainty in each frequency, in %										
						125	160	200	250	315	400	500	630	800	1000	1250
1	Acceleration Amplitude					0,24525	0,23970	0,24238	0,25262	0,26535	0,25504	0,24806	0,22430	0,23061	0,24669	0,23104
1.1	Signal Generator Frequency	B	rect	30	B&K	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144
1.2	Interferometer Signal Filtering Effect on Phase Measurement Amplitude	B	rect	30	B&K	0,06455	0,06455	0,06455	0,06455	0,06455	0,06455	0,06455	0,06455	0,06455	0,06455	0,06455
1.3	Laser Wavelength Stability	B	rect	30	B&K	0,00009	0,00009	0,00009	0,00009	0,00009	0,00009	0,00009	0,00009	0,00009	0,00009	0,00009
1.4	Motion Disturbance Effect	A	Normal	5	experiment	0,23659	0,23084	0,23363	0,24423	0,25737	0,24674	0,23951	0,21480	0,22138	0,23809	0,22183
2	Voltage Amplitude					0,07232	0,07264	0,08494	0,08687	0,08372	0,08956	0,18692	0,17035	0,16898	0,14625	0,17286
2.1	Signal Generator Frequency	B	rect	30	B&K	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144
2.2	Voltage Measurement Error	B	rect	30	B&K	0,06813	0,06813	0,06813	0,06813	0,06813	0,06813	0,06813	0,04041	0,04041	0,04041	0,04041
2.3	Transverse Motion Effect	A	Normal	4	experiment	0,02423	0,02517	0,05072	0,05387	0,04864	0,05811	0,17406	0,16548	0,16407	0,14055	0,16806
3	Charge Amplifier					0,20516	0,20493	0,20510	0,20503	0,20477	0,20510	0,20468	0,20443	0,20494	0,20506	0,20506
3.1	Standard Capacitor	B	rect	30	NMI	0,00214	0,00214	0,00214	0,00214	0,00214	0,00214	0,00214	0,00214	0,00214	0,00214	0,00214
3.2	Input Voltage	B	rect	30	B&K	0,20207	0,20207	0,20207	0,20207	0,20207	0,20207	0,20207	0,20207	0,20207	0,20207	0,20207
3.3	Output Voltage	B	rect	30	B&K	0,02021	0,02021	0,02021	0,02021	0,02021	0,02021	0,02021	0,02021	0,02021	0,02021	0,02021
3.4	Type A of Charge Amplifier	A	Normal	4	experiment	0,02909	0,02737	0,02864	0,02816	0,02615	0,02864	0,02548	0,02334	0,02744	0,02832	0,02832
						0,01914	0,03936	0,03867	0,04049	0,41226	0,48549	0,25519	0,13176	0,07961	0,04873	0,09654
4,1	Repeatability	A	Normal	4	experiment	0,01914	0,03936	0,03867	0,04049	0,41226	0,48549	0,25519	0,13176	0,07961	0,04873	0,09654
	Combined Uncertainty (Uc)					0,32838	0,32600	0,33095	0,33918	0,53787	0,59231	0,45110	0,37213	0,36065	0,35590	0,36691
	k Factor					2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00
	Expanded Uncertainty (U95)					0,65676	0,65200	0,66190	0,67835	1,07574	1,18463	0,90220	0,74425	0,72130	0,71180	0,73383
	U95 round up					0,70	0,70	0,70	0,70	1,10	1,20	1,00	0,80	0,80	0,80	0,80
	Stated Uncertainty (U95%)					**0,7**	**0,7**	**0,7**	**0,7**	**1,2**	**1,2**	**1,2**	**0,8**	**0,8**	**0,8**	**0,8**

No.	Components	Type	Distribution	dof	Source	Relative Uncertainty in each frequency, in %										
						1500	1600	2000	2500	3000	3150	3500	4000	4500	5000	5500
1	Acceleration Amplitude					0,23104	0,21788	0,20676	0,25579	0,24388	0,24388	0,21031	0,21031	0,22967	0,22967	0,22967
1.1	Signal Generator Frequency	B	rect	30	B&K	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144
1.2	Interferometer Signal Filtering Effect on Phase Measurement Amplitude	B	rect	30	B&K	0,06455	0,06455	0,06455	0,06455	0,06455	0,06455	0,06455	0,06455	0,06455	0,06455	0,06455
1.3	Laser Wavelength Stability	B	rect	30	B&K	0,00009	0,00009	0,00009	0,00009	0,00009	0,00009	0,00009	0,00009	0,00009	0,00009	0,00009
1.4	Motion Disturbance Effect	A	Normal	5	experiment	0,22183	0,20809	0,19642	0,24750	0,23518	0,23518	0,20016	0,20016	0,22041	0,22041	0,22041
2	Voltage Amplitude					0,03813	0,16072	0,16018	0,16319	0,03813	0,15104	0,03813	0,15544	0,03813	0,20694	0,20694
2.1	Signal Generator Frequency	B	rect	30	B&K	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144
2.2	Voltage Measurement Error	B	rect	30	B&K	0,03811	0,03811	0,03811	0,03811	0,03811	0,03811	0,03811	0,03811	0,03811	0,03811	0,03811
2.3	Transverse Motion Effect	A	Normal	4	experiment	0,00000	0,15613	0,15558	0,15867	0,00000	0,14614	0,00000	0,15069	0,00000	0,20339	0,20339
3	Charge Amplifier					0,20496	0,20432	0,20404	0,20413	0,20413	0,20429	0,20429	0,20474	0,20417	0,20438	0,20429
3.1	Standard Capacitor	B	rect	30	NMI	0,00000	0,00214	0,00214	0,00214	0,00214	0,00214	0,00214	0,00214	0,00214	0,00214	0,00214
3.2	Input Voltage	B	rect	30	B&K	0,20207	0,20207	0,20207	0,20207	0,20207	0,20207	0,20207	0,20207	0,20207	0,20207	0,20207
3.3	Output Voltage	B	rect	30	B&K	0,02021	0,02021	0,02021	0,02021	0,02021	0,02021	0,02021	0,02021	0,02021	0,02021	0,02021
3.4	Type A of Charge Amplifier	A	Normal	4	experiment	0,02766	0,02236	0,01967	0,02060	0,02060	0,02213	0,02213	0,02595	0,02095	0,02291	0,02213
						0,06047	0,05918	0,06708	0,04632	0,05675	0,07277	0,03511	0,26072	0,13209	0,25152	0,03111
4,1	Repeatability	A	Normal	4	experiment	0,06047	0,05918	0,06708	0,04632	0,05675	0,07277	0,03511	0,26072	0,13209	0,25152	0,03111
	Combined Uncertainty (Uc)					0,31701	0,34431	0,33844	0,36861	0,32531	0,35961	0,29775	0,42224	0,33665	0,44789	0,37186
	k Factor					2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00
	Expanded Uncertainty (U95)					0,63402	0,68862	0,67688	0,73722	0,65061	0,71923	0,59550	0,84449	0,67331	0,89578	0,74371
	U95 round up					0,70	0,70	0,70	0,80	0,70	0,80	0,60	0,90	0,70	0,90	0,80
	Stated Uncertainty (U95%)					**0,8**	**0,8**	**0,8**	**0,8**	**0,8**	**0,8**	**0,8**	**0,9**	**0,9**	**0,9**	**0,9**

No.	Components	Type	Distribution	dof	Source	Relative Uncertainty in each frequency, in %										
						5500	6000	6300	6500	7000	7500	8000	8500	9000	9500	10 000
1	Acceleration Amplitude					0,22967	0,29784	0,29397	0,29784	0,29397	0,29397	0,29397		0,29397	0,29784	0,30144
1.1	Signal Generator Frequency	B	rect	30	B&K	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144
1.2	Interferometer Signal Filtering Effect on Phase Measurement Amplitude	B	rect	30	B&K	0,06455	0,06455	0,06455	0,06455	0,06455	0,06455	0,06455	0,06455	0,06455	0,06455	0,06455
1.3	Laser Wavelength Stability	B	rect	30	B&K	0,00009	0,00009	0,00009	0,00009	0,00009	0,00009	0,00009	0,00009	0,00009	0,00009	0,00009
1.4	Motion Disturbance Effect	A	Normal	5	experiment	0,22041	0,29075	0,28679	0,29075	0,28679	0,28679	0,28679	0,28679	0,28679	0,29075	0,29444
2	Voltage Amplitude					0,20694	0,20694	0,20694	0,20694	0,20694	0,20694	0,28309		0,28837	0,28837	0,28837
2.1	Signal Generator Frequency	B	rect	30	B&K	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144	0,00144
2.2	Voltage Measurement Error	B	rect	30	B&K	0,03811	0,03811	0,03811	0,03811	0,03811	0,03811	0,03811	0,03811	0,03811	0,03811	0,03811
2.3	Transverse Motion Effect	A	Normal	4	experiment	0,20339	0,20339	0,20339	0,20339	0,20339	0,20339	0,28051	0,28051	0,28584	0,28584	0,28584
3	Charge Amplifier					0,20429	0,20518	0,20429	0,20518	0,20518	0,20518	0,20518		0,20518	0,20518	0,20435
3.1	Standard Capacitor	B	rect	30	NMI	0,00214	0,00214	0,00214	0,00214	0,00214	0,00214	0,00214	0,00214	0,00214	0,00214	0,00214
3.2	Input Voltage	B	rect	30	B&K	0,20207	0,20207	0,20207	0,20207	0,20207	0,20207	0,20207	0,20207	0,20207	0,20207	0,20207
3.3	Output Voltage	B	rect	30	B&K	0,02021	0,02021	0,02021	0,02021	0,02021	0,02021	0,02021	0,02021	0,02021	0,02021	0,02021
3.4	Type A of Charge Amplifier	A	Normal	4	experiment	0,02213	0,02923	0,02213	0,02923	0,02923	0,02923	0,02923	0,02923	0,02923	0,02923	0,02269
						0,03111	0,04562	0,13527	0,10508	0,08019	0,17014	0,36572	0,45949	0,26940	0,21137	0,30092
4,1	Repeatability	A	Normal	4	experiment	0,03111	0,04562	0,13527	0,10508	0,08019	0,17014	0,36572	0,45949	0,26940	0,21137	0,30092
	Combined Uncertainty (Uc)					0,37186	0,41918	0,43506	0,42974	0,42163	0,44754	0,58515	0,45949	0,53315	0,50857	0,55348
	k Factor					2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00
	Expanded Uncertainty (U95)					0,74371	0,83836	0,87011	0,85947	0,84326	0,89507	1,17030	0,91898	1,06631	1,01714	1,10695
	U95 round up					0,80	0,90	0,90	0,90	0,90	0,90	1,20	1,00	1,10	1,10	1,20
	Stated Uncertainty (U95%)					**0,9**	**0,9**	**0,9**	**0,9**	**0,9**	**0,9**	**1,2**	**1,2**	**1,2**	**1,2**	**1,2**

LNE

SE and BB amplitude uncertainty

i		Description	type	Contribution Incertitude	10 Hz to 40 Hz	> 40 Hz to 2 kHz	> 2 kHz to 5 kHz	> 5 kHz to 7 kHz	> 7 kHz to 10 kHz
					%	%	%	%	%
uncertainty on the measurement of the output of the accelerometer signal									
1	u(ûV)	output voltage measurement	B	u1 (S)	0,054	0,052	0,053	0,053	0,053
1a	u(SA)	conditionner gain	B	u1a (SA)	0,104	0,104	0,104	0,104	0,104
2	u(ûF)	voltage filtering effects on the amplitude output	B	u2 (S)	0,006	0,006	0,006	0,006	0,006
3	u(ûD)	voltage perturbation on the measure of the ouput voltage	B	u3 (S)	0,006	0,006	0,006	0,006	0,006
4	u(ûT)	effect of transverse acceleration on the output voltage	B	u4 (S)	0,033	0,033	0,033	0,067	0,133
5	u(STE)	effect of temperature sensitivity of the accelerometer on the output voltage	B	u12 (S)	0,030	0,030	0,030	0,030	0,030
uncertainty on the measurement of the phase amplitude amplitude									
6	u(φ̂M,Q)	effects of the interferometric quadrature output signal disturbance on the phase amplitude measurement	B	u5 (S)	0,029	0,029	0,029	0,058	0,058
7	u(φ̂M,F)	Effect of the interferometric signal filtering on the phase amplitude measurement (limitation of the frequency band)		u6 (S)	included in i6				
8	u(φ̂M,VDφ̂	effect of voltage disturbance on the phase amplitude measurement		u7 (S)	included in i6				
9	u(φ̂M,MD)	effect of motion of the vibration disturbance on the phase amplitude measurement	B	u8 (S)	0,017	0,017	0,017	0,101	0,267
10	u(φ̂M,PD)	residual interferometrics effects on the phase amplitude measurement		u9 (S)	included in i6				
11	u(φ̂M,RE)	longitudinal and transverse motion of the insulated table of the laser	B	u10 (S)	0,041	0,041	0,041	0,041	0,041
11b	u(φ̂M,LD)	w avelenght of the laser effect	B	u10b (S)	0,001	0,001	0,001	0,001	0,001
12	u(fFG)	vibration frequency measurement	B	u11 (S)	0,002	0,002	0,002	0,002	0,002
13		repeatability on the 3 measurements (case of BB accelerometer)	A	u13(S)	0,019	0,013	0,019	0,062	0,097
		Relative standard uncertainty on accelerometer magnitude sensitivity (k=1)			**0,15**	**0,15**	**0,15**	**0,27**	**0,48**
		Relative expanded uncertainty on accelerometer magnitude sensitivity (k=2)			**0,30%**			**0,60%**	**1,0%**