SIM International Comparison of 50/60 Hz Energy (2002-2007)

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Abstract: Results of the Inter-american Metrology System (SIM) international energy comparison are presented. Participating countries were Argentina, Brazil, Canada, Costa Rica, El Salvador, Mexico, Panama, Paraguay, Peru, Uruguay, and the United States.

Keywords: SIM, International comparison, Energy, traveling standard

1. Introduction

The Inter-american Metrology System (SIM) sponsors periodic international comparisons of electrical units maintained at National Metrology Institutes (NMIs) in the Americas. The first SIM electrical comparison was conducted in the late 1990s and used digital multimeters as traveling standards within the five sub regions in SIM to measure ac and dc voltage and current and dc resistance [1]. At about the same time, NIST was piloting the Consultative Committee for Electricity and Magnetism CCEM-K5 comparison of 50/60 Hz electric power [2] that included NMIs in North and South America. As a follow-up to the K5 comparison, NIST was selected to pilot the SIM comparison of 50/60 Hz electric energy, described below. The plan is to link to CCEM-K5 so that more NMIs in the Americas will be tied to the key comparison database maintained by the International Committee of Weights and Measures, CIPM [3].

After consultation with other NMIs[1], NIST metrologists decided to perform the comparison at 50 and 60 hertz. Three points were selected to test the amplitude and phase measuring capabilities of the NMIs: 120 volts and 5 amperes at power factors 1.0, 0.5 lead (ld), 0.5 lag (lg), where lead (capacitive) indicates that the current leads the voltage and where lag (inductive) indicates that the current lags the voltage. A list of participating laboratories is given in Table 1.

Table 1. List of participants, NMIs, and measurement dates.

Laboratory	Measurement date
NIST, USA	August 2002 – May 2007
ICE, Costa Rica	July 2003
SENACYT, Panama	August 2003
CONACYT, El Salvador	November 2003
CENAM, Mexico	June 2006
NRC, Canada	May 2007
INMETRO, Brazil	February 2004
UTE, Uruguay	April 2004
INTN, Paraguay	August 2004
SNM, Peru	April 2005
INTI, Argentina	July 2006

Two traveling standards (Radian model RM-11)[2] were used to reduce the time required to complete the comparison. These instruments are ac-power-to-frequency or energy-to-pulse converters based on the *time-division-multiplier* operating principle. With 120 V and 5 A applied at 1.0 power factor, the nominal output frequency of the converters is 16666.67 Hz. Coefficients of voltage, current, and power factor for these standards are negligible (less than 5 parts in 10^6) over a range of ±0.2 % of these parameters. Participants were asked to maintain a ±0.1 % tolerance. Temperature coefficients are also negligible in the range of 23 °C ± 3 °C. Humidity influences are more difficult to measure. Participants were asked to record the ambient temperature and humidity.

[1] NMI is used in this document to denote the laboratory responsible for energy standards within each country participating in the comparison.

[2] Identification of commercial equipment is not intended to imply recommendation or endorsement by NIST, nor is it intended to imply that the equipment is necessarily the best available for the purpose.

Some laboratories reported results in percentage registration, with uncertainties in percent of reading. Others reported results as errors in ppm, µW/W, µWh/Wh, µJ/J (all equivalent to parts in 10^6), with uncertainties in the same units. Some reported values in terms of reading and others in terms of full scale (applied VA). All values were converted to errors and standard uncertainties in parts in 10^6 of reading. These normalized results are given in Table 2.

Table 2. Reported Errors $x_{i,k}$ and Standard Uncertainties $u_{i,k}$ (in parts in 10^6 of reading), where i denotes the NMI and k denotes the test point.

	Traveling standard 505228											
	60 Hz						50 Hz					
	1.0		0.5ld		0.5lg		1.0		0.5ld		0.5lg	
NMI_i	$x_{i,1}$	$u_{i,1}$	$x_{i,2}$	$u_{i,2}$	$x_{i,3}$	$u_{i,3}$	$x_{i,4}$	$u_{i,4}$	$x_{i,5}$	$u_{i,5}$	$x_{i,6}$	$u_{i,6}$
NIST	29	7	84	8	14	8	23	7	107	8	-19	8
ICE	-33	145	-26	146	-59	145						
SENACYT	58	67	209	114	-105	114						
CONACYT	-840	1020	-670	2760	-340	1860						
CENAM	17	20	60	23	-48	23	13	25	112	25	-73	25
NRC	45	5	90	6	38	6						
	Traveling standard 504967											
NIST	47	7	90	8	38	8	45	7	114	8	12	8
INMETRO	56	11	83	25	64	25	60	11	126	22	42	22
UTE							45	21	43	42	66	42
INTN							111	58	114	58	123	58
SNM	26	35	38	118	9	41						
INTI	89	21	-40	40	160	44	75	21	-58	40	172	40

2. Analysis

The traveling standards were measured at NIST before the comparison began, when the comparison was completed, and at several points during the comparison. Depending on the standard and the test frequency, NIST performed up to 100 independent measurements at each test point from 2002 to 2007. Since two traveling standards were used and measured at different NMIs, the comparison was treated as two independent loops with the pilot laboratory (NIST) as the common link. The single loop analysis and notation used in this comparison is based on that described by Zhang *et al*. in reference 4. In this case, for each test point in the j^{th} loop ($j = 1, 2$), we assume that a simple linear regression model[3] holds for measurements made by NIST,

$$X_{1k}(j) = \alpha_1(j) + \beta(j)t_{1k}(j) + \varepsilon_{1k}(j) \qquad (1)$$

for $k = 1, \ldots K_j$. The average of $\{t_{ik}(j), k = 1, \ldots, K_j\}$ is $t_1(j)$. The average of X_{1k} is X_1. We further assume that the random error, $\varepsilon_{1k}(j)$, has a zero mean and an uncertainty $u_1(j)$ for NIST. For the other laboratories ($i \neq 1$), measurements are taken at time $t_i(j)$ and the corresponding model is

$$X_i(j) = \alpha_i(j) + \beta(j)t_i(j) + \varepsilon_i(j) \qquad (2)$$
$$i = 2, \ldots, I_j,$$

where the random error has a zero mean and a standard uncertainty of $u_i(j)$ for $i = 2, \ldots I_j$ and I_j is the number of labs in the j^{th} loop.

Since the Type B uncertainties of the NIST measurements are the same for all time periods,

[3] The use of a linear model was questioned by CENAM but based on the distribution of NIST measurements, it was considered the best compromise.

as in reference 4, the regression parameters for the j^{th} artifact are estimated by:

$$\hat{\beta}(j) = \frac{\sum_{k=1}^{K_j}(t_{1k}(j) - t_1(j))(X_{ik}(j) - X_1(j))}{\sum_{k=1}^{K_j}(t_{1k}(j) - t_1(j))^2} \quad (3)$$

$$\hat{\alpha}_i(j) = X_i(j) - \hat{\beta}(j)t_i(j) \quad (4)$$
$$i = 1,\ldots,I_j .$$

The corresponding uncertainties and the covariance terms are obtained using eq.15 - 18 of reference 4.

The comparison reference value (CRV) at an optimal time $t^*(j)$ is, for the j^{th} loop:

$$CRV_{t^*(j)}(j) = \sum_{i=1}^{I_j} w_i(j)X_i(j) \quad (5)$$

where $t^*(j) = \sum_{i=1}^{I_j} w_i(j)t_i(j)$ and

$$w_i(j) = \frac{\frac{1}{u_i^2(j)}}{\sum_{k=1}^{I_j}\frac{1}{u_k^2(j)}} . \quad (6)$$

We use the simplified symbol *CRV(1)* to indicate the CRV for the 1st loop, using traveling standard 505228 and *CRV(2)* to represent the CRV for the 2nd loop, using traveling standard 504967. The regression components, *CRVs* and their uncertainties u_{CRV} are given in Table 3. Results from participants that obtain energy traceability from other NMIs or laboratories were not used in the CRV computation.

Table 3. Regression parameters, *CRV*, and u_{CRV} (in parts in 10^6).

Standard	60 Hz			50 Hz		
505228	1.0	0.5 lead	0.5 lag	1.0	0.5 lead	0.5 lag
α(1)	22	81	4	13	100	-31
β(1)	2	1	3	3	2	5
CRV(1)	39	87	26	22	108	-24
u_{CRV} *(1)*	4	5	5	7	8	8
504967						
α(2)	45	87	41	46	116	11
β(2)	1	2	-2	-1	-1	1
CRV(2)	52	85	44	51	107	23
u_{CRV} *(2)*	6	8	8	6	7	8

From reference 4, the degree of equivalence of the i^{th} laboratory , e.g., in the j^{th} loop ($j = 1, 2$) relative to the *CRV* in the corresponding loop is the difference

$$D_{i,CRV}(j) = \hat{\alpha}_i(j) + \hat{\beta}(j)t^*(j) - CRV(j) \quad (7)$$
$$j = 1, 2 .$$

The uncertainty of this difference is given in reference 4 (eqs. 31 and 33). The differences (D) and uncertainties (u_D) are given in Table 4.

Table 4. Degrees of equivalence and the corresponding uncertainties (in parts in 10^6).

	60 Hz						50 Hz					
	CRV(1) using traveling standard 505228											
	1.0		0.5ld		0.5lg		1.0		0.5ld		0.5lg	
NMI	D	u_D	D	u_D	D	u_D	D	u_D	D	u_D	D	u_D
NIST	-8	6	-2	7	-10	7	1	2	0	3	6	3
CENAM	-21	20	-26	23	-73	23	-12	24	2	24	-53	24
NRC	5	3	3	4	10	4						
	CRV(2) using traveling standard 504967											
NIST	-6	4	6	3	-6	3	-6	4	7	3	-11	4
INMETRO	5	9	-1	24	20	24	9	10	19	21	19	21
UTE							-6	20	-64	41	43	41
INTI	34	20	-128	39	121	43	25	20	-163	39	147	39

The degrees of equivalence between pairs of national measurement standards in the same loop, e.g., the j^{th} (j=1,2), is defined as the differences

$$\begin{aligned} & D_{i,k}(j,j) \\ & = D_{i,CRV}(j) - D_{k,CRV}(j) \\ & = \hat{\alpha}_i(j) + \hat{\beta}(j)t^*(j) - CRV(j) \qquad (8) \\ & -[\hat{\alpha}_k(j) + \hat{\beta}(j)t^*(j) - CRV(j)] \\ & = \hat{\alpha}_i(j) - \hat{\alpha}_k(j) \end{aligned}$$

when $i \neq k$. The corresponding uncertainty is given in reference 4 (eq.36). However, when the two non-pilot labs are in two different loops, e.g., the *ith* lab in the first loop and the *kth* lab in the second loop, measurements of the linking lab, NIST, are used. The degree of equivalence is calculated as follows:

$$\begin{aligned} & D_{i,k}(1,2) \\ & = D_{i,CRV}(1) - D_{1,CRV}(1) - [D_{k,CRV}(2) - D_{1,CRV}(2)] \\ & = D_{i,1}(1,1) - D_{k,1}(2,2) \end{aligned} \qquad (9)$$

where $D_{i,1}(1,1)$ and $D_{k,1}(2,2)$ are the pair-wise degrees of equivalence between the *ith* lab and NIST for the first loop and the *kth* lab and NIST for the second loop, respectively. The standard uncertainty of $D_{i,k}(1,2)$ is given by

$$u_{D_{i,k}(1,2)} = \sqrt{u^2_{D_{i,1}(1,1)} + u^2_{D_{k,1}(2,2)}} \qquad (10)$$

Pair-wise tables of equivalence are given, with uncertainties, in Appendix A, where a negative sign indicates that the NMI on the left of the table is lower than the NMI on the top of the table.

3. Conclusions

Results of the first SIM international comparison of 50/60 Hz energy have been presented. In several cases the degrees of equivalence exceed the estimated uncertainties. However, problems have been identified and these points will be rechecked via bilateral comparisons to resolve the differences.

The measurements took five years to complete, much longer than originally anticipated. Shipping, customs, and testing delays were the main problems. These must be addressed before the next comparison.

References

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Appendix A. Pair-Wise Tables of Equivalence

60 Hz, 1.0 power factor (in parts in 10^6)

Differences

	NIST	ICE	SENACYT	CONACYT	CENAM	NRC	INMETRO	UTE	INTN	SNM	INTI
NIST	0	57	-34	865	13	-14	-10			22	-40
ICE	-57	0	-91	808	-44	-71	-67			-35	-97
SENACYT	34	91	0	898	46	20	24			55	-6
CONACYT	-865	-808	-898	0	-852	-878	-874			-843	-905
CENAM	-13	44	-46	852	0	-26	-22			9	-52
NRC	14	71	-20	878	26	0	4			35	-26
INMETRO	10	67	-24	874	22	-4	0			31	-30
SNM	-22	35	-55	843	-9	-35	-31			0	-61
INTI	40	97	6	905	52	26	30			61	0

Standard uncertainties

	NIST	ICE	SENACYT	CONACYT	CENAM	NRC	INMETRO	UTE	INTN	SNM	INTI
NIST	0	145	67	1020	21	9	13			36	22
ICE	145	0	160	1030	146	145	146			150	147
SENACYT	67	160	0	1022	70	67	69			76	71
CONACYT	1020	1030	1022	0	1020	1020	1020			1021	1020
CENAM	21	146	70	1020	0	21	25			42	31
NRC	9	145	67	1020	21	0	16			37	24
INMETRO	13	146	69	1020	25	16	0			37	24
SNM	36	150	76	1021	42	37	37			0	41
INTI	22	147	71	1020	31	24	24			41	0

60 Hz, 0.5 lead (capacitive) power factor (in parts in 10^6)

Differences

	NIST	ICE	SENACYT	CONACYT	CENAM	NRC	INMETRO	UTE	INTN	SNM	INTI
NIST	0	108	-127	753	25	-5	7			54	134
ICE	-108	0	-235	644	-84	-113	-102			-55	26
SENACYT	127	235	0	879	151	122	133			180	261
CONACYT	-753	-644	-879	0	-728	-757	-746			-699	-619
CENAM	-25	84	-151	728	0	-29	-18			29	109
NRC	5	113	-122	757	29	0	11			58	139
INMETRO	-7	102	-133	746	18	-11	0			47	127
SNM	-54	55	-180	699	-29	-58	-47			0	80
INTI	-134	-26	-261	619	-109	-139	-127			-80	0

Standard uncertainties

	NIST	ICE	SENACYT	CONACYT	CENAM	NRC	INMETRO	UTE	INTN	SNM	INTI
NIST	0	146	114	2760	24	10	26			118	41
ICE	146	0	185	2764	148	146	149			188	152
SENACYT	114	185	0	2762	116	114	117			164	121
CONACYT	2760	2764	2762	0	2760	2760	2760			2763	2760
CENAM	24	148	116	2760	0	24	36			121	48
NRC	10	146	114	2760	24	0	28			119	42
INMETRO	26	149	117	2760	36	28	0			121	47
SNM	118	188	164	2763	121	119	121			0	125
INTI	41	152	121	2760	48	42	47			125	0

60 Hz, 0.5 lag (inductive) power factor (in parts in 10^6)

Differences

	NIST	ICE	SENACYT	CONACYT	CENAM	NRC	INMETRO	UTE	INTN	SNM	INTI
NIST	0	66	113	348	63	-20	-26			27	-127
ICE	-66	0	46	282	-3	-87	-92			-40	-193
SENACYT	-113	-46	0	236	-49	-133	-138			-86	-240
CONACYT	-348	-282	-236	0	-285	-369	-374			-321	-475
CENAM	-63	3	49	285	0	-84	-89			-36	-190
NRC	20	87	133	369	84	0	-6			47	-107
INMETRO	26	92	138	374	89	6	0			53	-101
SNM	-27	40	86	321	36	-47	-53			0	-154
INTI	127	193	240	475	190	107	101			154	0

Standard uncertainties

	NIST	ICE	SENACYT	CONACYT	CENAM	NRC	INMETRO	UTE	INTN	SNM	INTI
NIST	0	145	114	1860	24	10	26			42	45
ICE	145	0	184	1866	147	145	148			151	152
SENACYT	114	184	0	1863	116	114	117			122	123
CONACYT	1860	1866	1863	0	1860	1860	1860			1860	1861
CENAM	24	147	116	1860	0	24	36			48	51
NRC	10	145	114	1860	24	0	28			43	46
INMETRO	26	148	117	1860	36	28	0			48	51
SNM	42	151	122	1860	48	43	48			0	60
INTI	45	152	123	1861	51	46	51			60	0

50 Hz, 1.0 power factor (in parts in 10^6)

Differences

	NIST	CENAM	INMETRO	UTE	INTN	INTI
NIST	0	13	-15	0	-66	-31
CENAM	-13	0	-28	-13	-79	-44
INMETRO	15	28	0	15	-51	-16
UTE	0	13	-15	0	-66	-31
INTN	66	79	51	66	0	35
INTI	31	44	16	31	-35	0

Standard uncertainties

	NIST	CENAM	INMETRO	UTE	INTN	INTI
NIST	0	26	13	22	58	22
CENAM	26	0	29	34	64	34
INMETRO	13	29	0	24	59	24
UTE	22	34	24	0	62	30
INTN	58	64	59	62	0	62
INTI	22	34	24	30	62	0

50 Hz, 0.5 lead (capacitive) power factor (in parts in 10^6)

Differences

	NIST	CENAM	INMETRO	UTE	INTN	INTI
NIST	0	-3	-12	71	0	170
CENAM	3	0	-9	74	2	173
INMETRO	12	9	0	83	12	182
UTE	-71	-74	-83	0	-71	99
INTN	0	-2	-12	71	0	170
INTI	-170	-173	-182	-99	-170	0

Standard uncertainties

	NIST	CENAM	INMETRO	UTE	INTN	INTI
NIST	0	26	23	43	59	41
CENAM	26	0	35	50	64	49
INMETRO	23	35	0	47	62	46
UTE	43	50	47	0	72	58
INTN	59	64	62	72	0	70
INTI	41	49	46	58	70	0

50 Hz, 0.5 lag (inductive) power factor (in parts in 10^6)

Differences

	NIST	CENAM	INMETRO	UTE	INTN	INTI
NIST	0	59	-30	-54	-111	-159
CENAM	-59	0	-89	-113	-170	-217
INMETRO	30	89	0	-24	-81	-129
UTE	54	113	24	0	-57	-105
INTN	111	170	81	57	0	-48
INTI	159	217	129	105	48	0

Standard uncertainties

	NIST	CENAM	INMETRO	UTE	INTN	INTI
NIST	0	26	24	43	59	41
CENAM	26	0	35	50	64	49
INMETRO	24	35	0	47	62	46
UTE	43	50	47	0	72	58
INTN	59	64	62	72	0	71
INTI	41	49	46	58	71	0