



## Final Report

### SIM.EM-S5

# Voltage, Current and Resistance Comparison

June 2007 – October 2009

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*Abstract* — This is a report of the results of the second Interamerican Metrology System (SIM) comparison on calibration of digital multimeters, performed for strengthening the interaction among National Metrology Institutes (NMIs) and for establishing the degree of equivalence between those laboratories in accordance with the CIPM Mutual Recognition Agreement. From June 2007 to October 2009, four multimeters were used as traveling standards for measurements in eleven countries, with NIST-USA acting as pilot laboratory. Results for nine measurement points are presented as errors relative to a comparison reference value together with their uncertainty.

*Index Terms* — Comparison, multimeter, measurement error, measurement uncertainty.

## 1 Introduction

In order to strengthen the Interamerican Metrology System (SIM), interaction among its National Metrology Institutes (NMIs) is promoted. At the same time, in accordance with CIPM Mutual Recognition Agreement (MRA) objectives, NMIs establish the degree of equivalence between their national measurement standards by performing regional comparisons, among other activities.

The objective of this comparison, registered as SIM.EM-S5 (SIM 1.5) was to compare the measurement capabilities of NMIs in SIM and determine the degree of equivalence between laboratories in the areas of dc and ac voltage and current, and dc resistance.

This was an ongoing repetition of SIM.EM-S1.

## 2 Traveling standards

Four 8.5 digit DMMs (identified in the figures as H7, H8, K and W) were selected as traveling standards.

### 2.2 Traveling standard description

The following is the detail description of the traveling standards.

H7:

Description:	Digital multimeter
Manufacturer:	Hewlett Packard
Model:	3458A
Serial Number:	2823A15147

H8:

Description:	Digital multimeter
Manufacturer:	Hewlett Packard
Model:	3458A
Serial Number:	2823A15128

K:

Description:	Digital multimeter
Manufacturer:	Keithley
Model:	2002
Serial Number:	0626300

W:

Description:	Digital multimeter
Manufacturer:	Wavetek
Model:	4950 MTS
Serial Number:	28746

## 2.3 Quantities measured

**Table 1. Measurement points in DMM comparison**

Test No.	Test Voltage	Test frequency	DMM range	Comments
1	100 mV	dc	100 mV	
2	10 V	dc	10 V	
3	1 V	1 kHz	1 V	
4	10 V	100 kHz	10 V	
5	100 V	55 Hz	100 V	
6	10 mA	dc	10 mA	
7	1 A	55 Hz	1 A	20 min settling
8	10 $\Omega$		10 $\Omega$	1 min settling
9	100 k $\Omega$		100 k $\Omega$	

### Measurements conditions

It was recommended that environmental conditions of the laboratory were temperature ( $23 \pm 1$ ) °C and relative humidity ( $40 \pm 20$ ) %.

## 2.4 Method of computation of the CRV

2.4.1 Eleven NMIs of SIM participated in the comparison. In this comparison, four traveling standards or digital multimeters (DMM) were used. Each standard traveled only in one of the four loops. Each NMI, except NIST, which is the pilot lab, was only in one loop and made measurements only for one time period (except Argentina, which measured two times for the 4<sup>th</sup> standard in the 4<sup>th</sup> loop). Each NMI made measurements of nine functions at the same period.

2.4.2 The correction values E defined in 4.2 were treated as the measurements of the NMIs. For each function,  $X_i(j)$ ,  $i = 1, \dots, 11$  and  $j = 1, 2, 3, 4$  denotes the E values by the  $i$ th NMI for the  $j$ th standard in the  $j$ th loop. Without loss of generality, assign NIST as the first lab, i.e.,  $i = 1$  and Argentina as the 2<sup>nd</sup> lab, i.e.,  $i = 2$ . Assign Costa Rica as the last lab, i.e.,  $i = 11$ . For NIST, in each loop, the double measurements are denoted by  $X_{i,k}(j)$  for  $k = 1, 2$ . Similar notations were used for Argentina.

2.4.3 Based on the consideration on correlations between the measurements among some NMIs and calibration, for three standards (Keithley 2002, # 1, HP 3458A15128, # 2 and HP 3458A15147, # 3), a reference value was determined by a simple average of two E values from NIST. For the 4<sup>th</sup> standard (Wavetek 4950, # 4), a weighted mean for three labs (NIST, INTI, and INMETRO) was used. Specifically, there are four reference values corresponding to four standards in four loops. They are denoted by  $\bar{X}(j)$ ,  $j = 1, 2, 3, 4$ . In each loop combine NIST's E values first (by a simple average) to obtain the reference values for the first three standards. For the 4<sup>th</sup> standard, using a weighted mean combine the NIST's average with other two NMIs to get  $\bar{X}(j)$ . The same was done

for Argentina. Thus, the average for NIST is denoted by  $X_1(j) = (X_{1,1}(j) + X_{1,2}(j))/2$  for  $j = 1, 2, 3, 4$  and for Argentina  $X_2(4) = (X_{2,1}(4) + X_{2,2}(4))/2$ . Based on those, calculate  $\bar{X}(4)$  by a weighted average of  $X_1(4)$ ,  $X_2(4)$  and  $X_4(4)$ . The weights are based on the reciprocals of the variances (squares of the standard uncertainties). Namely,

$$\bar{X}(4) = \sum_{i=1,2,4} v_i X_i(4).$$

For example, for the second function or Test # 2, the weights are 0.26, 0.71, and 0.03 for these three labs.

2.4.4 In each loop (jth loop), for each NMI (ith NMI), a  $d$  value is calculated by

$$d_i(j) = X_i(j) - \bar{X}(j).$$

Note that for all NMIs except NIST, there is only one  $d$  value, i.e.,  $\{d_i(j) = d_i; i > 1\}$ .

However, for NIST there are four  $d$  values, i.e.,  $\{d_1(j); j = 1, 2, 3, 4\}$ . Note that for the first three of  $d_1(j)$ ,  $j = 1, 2, 3$ , they are zero. Only the 4<sup>th</sup> one is not zero. Then, combine the  $d$  values for  $d_1(j)$ ,  $j = 1, 2, 3, 4$  for NIST to obtain  $d_1$  by a simple average. Thus, we have  $\{d_i; i = 1, \dots, 11\}$ . The eleven  $d_i(j)$ 's can be put in five sets:

I = $\{d_1(1, 2, 3, 4)\}$	----- based on 4 loops leading to $d_1 = \sum_{j=1}^4 d_1(j) / 4$
	since $d_1(j) = 0, j = 1, 2, 3$ . Thus, $d_1 = d_1(4) / 4$ .
II = $\{d_3(1)\}$	----- based on 1 <sup>st</sup> loop
III = $\{d_5(2), d_8(2), d_{10}(2)\}$	----- based on 2 <sup>nd</sup> loop
IV = $\{d_9(3), d_{11}(3)\}$	----- based on 3 <sup>rd</sup> loop. Note in Test # 4, Lab 9 did not participate.
V = $\{d_2(4), d_4(4), d_6(4), d_7(4)\}$	----- based on 4 <sup>th</sup> loop

If we drop the loop index for the non-pilot labs, we have  $\{d_i; i = 1, \dots, 11\}$ .

Note that in the spread sheet of data, there were 19  $d$  values because there were eight E values from NIST and two E values from Argentina.

2.4.5 It was agreed in December 2012 that a comparison reference value (CRV) for each function would be based on the measurements from the three NMIs: NIST, INTI, and INMETRO, i.e.,  $\{d_i; i = 1, 2, 4\}$ . To calculate a CRV, we must have some assumptions. Firstly, we assume that for  $\{d_i, i = 1, 2, 4\}$ , there was no trend in time. Based on plots of  $\{d_i\}$ , we accept the assumption.

Secondly, to use a weighted mean to calculate the CRV of the  $\{d_i\}$ , we need to assume that  $\{d_i\}$  are independently Gaussian distributed with the same mean and possible different variances. By that, the weighted mean estimator has some optimal property. We can assume that the DMMs are equivalent. Thus, we accept the assumption of the same mean. We use a weighted mean to get a CRV. The weights are determined by the uncertainties of the three NMIs. The corresponding uncertainty of CRV will be calculated. Note that for NIST, from Point 2.4.4, the  $d$  value  $d_1$  depends on all four

reference values, thus,  $d_1$  is not necessarily independent with other  $\{d_i\}$ . In the four sets listed in the above, any  $d_i$  will be independent with the ones in other three sets. On the contrary, any  $d_i$  will be correlated with the ones in the same set for the other three sets. For example,  $d_3$  is independent with others.  $d_3$  is uncorrelated to  $d_1$  because  $d_1(1)=0$ .  $d_5$  is independent with  $d_3, d_9, d_{11}, d_2, d_4, d_6$ , and  $d_7$  except  $d_8$  and  $d_{10}$ .  $d_5$  is uncorrelated with  $d_1$  based on the same reason for  $d_3$ .

We used the weighted mean to calculate the CRV. Namely,

$$CRV = \sum_{i=1,2,4} w_i d_i,$$

where the weights  $\{w_i\}$  are based on the reciprocals of the variances (squares of the standard uncertainties) of  $\{d_i, i=1,2,4\}$ . See [2]. To calculate the standard uncertainty of the CRV,  $u_{CRV}$ , we may use two approaches:

- (1) Ignore the covariance for all the pairs of  $\{d_i\}$
- (2) Calculate the covariances for all the pairs. There are 55 covariances including some zeros as known.

Use the two approaches applied to the Test # 2 – 10v, dc as an example. For this function it turned out that the difference due to these two approaches is rather small. The calculations of the covariances can be provided upon request. Based on the agreements from SIM EM MWG meeting in Sept. 26, 2011, for simplicity, we ignore the covariance terms in the calculations.

2.4.6 Once for each function, a CRV is determined, we calculated the degrees of equivalence, which include two parts: (1) D.O.E of each NMI (in terms of  $d_i$ 's) w.r.t. the CRV; (2) D.O.E. of each pair of NMIs. The uncertainties of these values can be obtained too. Based on the agreements from SIM EM MWG meeting in Sept. 26, 2011, we will not calculate the pair-wise D.O.E. The D.O.E. of each NMI w.r.t. CRV is given by

$$d_{i,DOE} = d_i - CRV,$$

where  $d_i$  is the  $d$  value of Lab  $i$  ( $i=1, \dots, 11$ ). The uncertainties of D.O.E. are calculated correspondingly. For the corresponding standard uncertainties of  $d_{i,DOE}$ , for  $i=1, 2, 4$ , based on the assumption that all  $d_i$ 's are independent from each other, they are given by

$$u_{d_{i,DOE}}^2 = u_{d_i}^2 - u_{CRV}^2, \quad i=1, 2, 4.$$

See [3]. For  $i \neq 1, 2, 4$ , we assume that  $d_i$  and  $CRV$  are independent with each other.

2.4.7 Based on the information, we will not do any linkage to any CCEM comparison.

The results of  $d$  value of each lab w.r.t. to its reference value were calculated (listed in the 4<sup>th</sup> column) for all the 9 tests corresponding to the one in the spread sheet. The [.] in the first column

indicates which loop the NMI is in. The D.O.E. and the corresponding standard uncertainties are listed in Columns 6 and 7.

### 3 Organization

#### 3.1 Coordinator and members of the review committee

The original review committee members were:

Mark Parker, NIST, [mark.parker@nist.gov](mailto:mark.parker@nist.gov) (retired)

Harold Sánchez, ICE, [hsanchez@ice.co.cr](mailto:hsanchez@ice.co.cr)

Tom Nelson, NIST, [Thomas.nelson@nist.gov](mailto:Thomas.nelson@nist.gov)

The final review committee members were:

Gregory Kyriazis, INMETRO, [gakyriazis@inmetro.gov.br](mailto:gakyriazis@inmetro.gov.br)

Harold Sánchez, ICE, [hsanchez@ice.co.cr](mailto:hsanchez@ice.co.cr)

Rand Elmquist, NIST, [randolph.elmquist@nist.gov](mailto:randolph.elmquist@nist.gov)

#### 3.2 Participants

As the comparison was to be finished within a reasonable period of time, six weeks were proposed for each participant; this time included clearing customs, receiving, unpacking, preparing, making measurements, analyzing data, repeat testing if necessary, and shipping to the next laboratory. Unfortunately customs procedures delayed many of the participants.

The pilot laboratory was the National Institute of Standards and Technology (NIST). The traveling standards were tested at NIST and dispatched from NIST to pivot laboratories. Each standard was returned to NIST for retest after the regional comparison was completed.

Table 2. Participants, DMMs, dates, code.

Country	NMI	Digital multimeter				Code
		Keithley 2002	HP3458A 2823A15128	HP 3458A 2823A15147	Wavetek 4950 28746	
Costa Rica	ICE			2007-06-11		CR
United States	NIST				2008-04-07	US
United States	NIST	2008-04-18				US
Argentina	INTI				2008-05-15	AR
Trinidad-Tobago	TTBS	2008-06-20				TT
Brazil	INMETRO				2008-07-15	BR
United States	NIST		2008-07-18			US
Colombia	SIC		2008-09-26			CO
Uruguay	UTE				2008-11-15	UR
Chile	LCPNME				2009-01-15	CL
United States	NIST			2009-01-19		US
Perú	INECOPI		2009-03-13			PE
United States	NIST	2009-03-24				US
Panamá	CENAMEP			2009-04-03		PA
Argentina	INTI				2009-05-15	AR
Ecuador	CMEE		2009-07-20			EC
United States	NIST			2009-07-21		US
United States	NIST				2009-10-08	US
United States	NIST		2009-10-24			US

#### 3.3 Time schedule

Registration of this comparison in the BIPM database included a proposal for measurements during 2004 but, due to logistic complications, it was started in 2007 and finished in 2009.

### **3.4 Transportation**

It was proposed to use courier services. When possible, hand carrying was an option.

### **3.5 Shipping and Handling**

The traveling standards were shipped in properly padded containers.

### **3.6 Failure of the traveling standard**

No damages were reported on the traveling standards during the comparison.

### **3.7 Customs and financial aspects**

Each participating laboratory covered the costs of customs clearance, and shipment to the next laboratory.

Customs procedures in some countries in America are one of the most difficult problems for SIM comparisons.

## **4 Measurement instructions**

### **4.1 Tests before measurements**

It was recommended to inspect and report to the pilot laboratory and coordinator any abnormal condition of the standard, but fortunately there were no abnormal conditions reported.

### **4.2 Measurements**

It was recommended to perform at least 5 independent measurements at each test point and report the mean error of the DMM in parts in  $10^6$ .

The error E was defined by the following:  $A = R \cdot (1 - E \times 10^{-6})$ , where A is the true value of the quantity being measured and R is the DMM reading.

For these tests, measurements made on separate days were considered independent. Therefore, it was possible to complete the 5 sets of measurements in one week.

### **4.3 Method of measurement**

To avoid differences due to different configurations of the same traveling standards the following instructions were agreed upon.

#### **4.3.1 HP 3458A using a Fluke 5700A**

General instructions:

Energize the 3458A for at least 8 hours before the test  
Use only the front panel input terminals  
Disconnect all inputs and perform the 3458A ACAL ALL before starting each independent test  
Set the 3458A amplitude range for each test point  
Reset the 3458A before changing functions  
Wait 30 s, or make sure the readings have stabilized, before recording data

DCV

Connect the DMM to the calibrator as shown in Fig 4-1 A of the 5700A manual

3458A: DCV function

GUARD switch to OPEN

NPLC = 200

NDIG = 8

DCI

Connections as shown in Fig. 4-3 A of the 5700A manual

3458A: DCI function

GUARD switch to OPEN

NPLC = 200

ACV

Connections as shown in Fig. 4-1 A of the 5700A manual

3458A: ACV function

GUARD switch to OPEN

SETACV SYNCH

RES = 0.002

LFILTER ON (for frequencies less than 50 kHz)

ACI

Connections as shown in Fig. 4-3 A of the 5700A manual

3458A: ACI function

GUARD switch to OPEN

NPLC = 200

OHMF

Connections as shown in Fig. 4-4 A of the 5700A manual

5700A: comp on (less than or equal to 100 kW)

3458A: OHMF function

GUARD switch to OPEN

NPLC = 200

OCOMP ON

DELAY = 1

### **4.3.2 Keithley 2002 using a Fluke 5700A**

General instructions:

Energize the 2002 for at least 8 hours before the test

Use only the front panel input terminals

Set the 2002 amplitude range for each test point

Reset the 2002 before changing functions

Wait 30 s, or make sure the readings have stabilized, before recording data

DCV

Connect the DMM to the calibrator as shown in Fig 4-2 A of the 5700A manual (without guard)

2002: Configure, DCV

Speed, High Accuracy

Resolution, 8.5

Filter, Advanced, 10 Rdgs

Averaging Mode, Repeat

DCI

Connections as shown in Fig. 4-3 A of the 5700A manual

2202: Configure, DCI



Speed, High Accuracy  
Resolution, 8.5  
Filter, Advanced, 10 Rdgs  
Averaging Mode, Repeat  
ACV

Connections as shown in Fig. 4-1 A of the 5700A manual

2202: Configure, ACV

Speed, High Accuracy

Resolution, 8.5

Press Filter On switch

Filter, Advanced, 10 Rdgs

Units, Voltage

Coupling, AC

AC-Type, LF (#300Hz), RMS (>300 Hz)

Averaging Mode, Repeat

ACI

Connections as shown in Fig. 4-3 A of the 5700A manual

2202: Configure, DCI

Speed, High Accuracy

Resolution, 8.5

Filter, Advanced, 10 Rdgs

Averaging Mode, Repeat

OHM

Connections as shown in Fig. 4-4 A of the 5700A manual

2202: Configure, OHM4 #1 MW, Configure, OHM2 >1 MW

Speed, High Accuracy

Resolution, 8.5

Filter, Advanced, 10 Rdgs

Offset Comp, On #10 k W

### **4.3.3 Wavetek 4950 using a Fluke 5700A or a Wavetek 4808**

General instructions:

Energize the 4950 for at least 8 hours before the test

Perform zero function on all ranges to be tested

Set the 4950 amplitude and frequency range for each test point

Reset the 4950 before changing functions

Wait 30 s, or make sure the readings have stabilized, before recording data

Zeroing:

Place lead set in the shorting configuration and zero each DCV, and OHMS range to be tested using the zero key on front panel of 4950. When completed, place lead set in open configuration, and zero each DCI range to be tested.

DCV

Connect the DMM to the calibrator as shown in Fig 4-1 A of the 5700A manual

4950: DCV function

Select Range, 100%

Config, RemGu (remote guard, RemGu underlined)

DCI

Connect the DMM to the calibrator as shown in Fig 4-2 A of the 5700A manual

4950: DCI function

Select Range, 100%

Config, RemGu

ACV

Connect the DMM to the calibrator as shown in Fig 4-1 A of the 5700A manual

4950: ACV function

Select Range, 100%

Select Frequency

Config, RemGu

ACI

Connect the DMM to the calibrator as shown in Fig 4-3 A of the 5700A manual

4950: ACI function

Select Range, 100%

Select Frequency

Config, RemGu

OHMF

Connect the DMM to the calibrator as shown in Fig 4-4 A of the 5700A manual

4950: Ohms function

Select Range, 100%

Config, RemGu

## 5 Measurement Uncertainty

Participants were required to list the uncertainty contributions and the overall uncertainty budgets. The uncertainty was to be calculated following the ISO Guide to the Expression of Uncertainty in Measurements 1995 (GUM), including standard uncertainties, degrees of freedom, correlations, combined and expanded uncertainty. A spreadsheet format was provided for homogeneous reporting.

## 6 Measurement report

Participants were required to report:

- Description of the measuring method.
- Connection diagrams.
- The environmental conditions of the measurement: the temperature and the humidity with limits of variation.
- Date of measurements.
- The reference standard and its traceability to the SI.
- The results of the measurements.
- The associated standard uncertainties and the expanded uncertainties.
- Uncertainty budget, the uncertainty calculation complying with the requirements of the GUM.

## 7 Report of the comparison

The results of the SIM.EM-S5 regional supplemental comparison have been analyzed and reported and the analysis has been approved by all participants.

The results are presented in table form in Annex 1.

The graphs in Annex 2 plot  $d$  (corrected E)  $(\bar{d} \text{ for US}) X_i(j) - \bar{X}(j)$ , with expanded uncertainty of  $d$  ( $k=2$ ). Some outliers are not plotted for viewing convenience.

## References

- [1] H. Sanchez et al, "SIM Comparison of Electrical Units," Metrologia 2000, Sao Paulo, Brazil, Dec. 2000.
- [2] N. F. Zhang "The uncertainty associated with the weighted mean of measurement data." Metrologia 2006, 43, 195-204.
- [3] Cox, M. G. The evaluation of key comparison data, 2002, Metrologia, 39, 589-595.

### Annex 1

For Test # 1, 100 mV dc,

NMI, lab #	$\bar{X}$ or average in each loop (E)	Reference value $\bar{X}(j)$	$d$ (corrected E) ( $\bar{d}$ for US) $X_i(j) - \bar{X}(j)$	Expanded uncertainty of $d$ (k=2)	D.O.E.	$u_{i,DOE}$
US (loop1)	82.81	82.81			NIST	
US (loop 2)	0.14	0.14				
US (loop 3)	0.93	0.93				
US (loop 4)	-0.55	-0.4763	$\bar{d} = -0.02$	0.56	-0.004	0.060
Argentina (2) [4]	0.165	-0.4763	0.6	3.4	0.7	1.7
TT (3) [1]	-35	82.81	-117.8	15	-117.8	7.7
Brazil (4) [4]	-1	-0.4763	-0.5	3.6	-0.5	1.7
Colombia (5) [2]	-0.19	0.14	-0.3	12	-0.3	6.2
Uruguay (6) [4]	3.4	-0.4763	3.9	11	3.9	5.6
Chile (7) [4]	0.6	-0.4763	1.1	15	1.1	7.6
Peru (8) [2]	13.6	0.14	13.5	15	13.5	7.7
Panama (9) [3]	2.07	0.93	1.1	15	1.2	7.5
Ecuador (10) [2]	5.8	0.93	5.7	5.6	5.7	2.8
CR (11) [3]	8.6	0.93	7.7	12	7.7	6.0

CRV = -0.0143 and  $u_{CRV} = 0.27$ .

For Test # 2, 10V dc,

NMI, lab #	$\bar{X}$ or average in each loop (E)	Reference value $\bar{X}(j)$	$d$ (corrected E) or $\bar{d}$ for US $X_i(j) - \bar{X}(j)$	Expanded uncertainty of $d$ (k=2)	D.O.E.	$u_{i,DOE}$
US (loop1)	14.01	14.01			NIST	
US (loop 2)	5.54	5.54				
US (loop 3)	2.00	2.00				
US (loop 4)	1.94	1.6973	$\bar{d} = 0.06$	0.22	0.043	0.060
Argentina	1.62	1.6973	-0.08	0.32	-0.09	0.14

(2) [4]						
TT (3) [1]	2.00	14.01	-12.0	5.2	-12.0	2.6
Brazil (4) [4]	1.40	1.6973	-0.3	3.0	-0.3	1.5
Colombia (5) [2]	1.21	2.00	-0.8	4.2	-0.8	2.1
Uruguay (6) [4]	2.30	1.6973	0.60	1.8	0.59	0.89
Chile (7) [4]	2.00	1.6973	0.3	5.0	0.3	2.5
Peru (8) [2]	7.50	2.00	5.5	4.0	5.5	2.0
Panama (9) [3]	7.00	5.54	1.5	4.8	1.4	2.4
Ecuador (10) [2]	2.60	2.00	0.6	2.0	0.6	1.0
CR (11) [3]	4.50	2.00	-1.0	5.8	-1.1	2.9

CRV = 0.0174 and  $u_{CRV} = 0.09$ .

For Test # 3, 1V 1kHz ,

NMI, lab #	X or average in each loop (E)	Reference value $\bar{X}(j)$	$d$ (corrected E) or $\bar{d}$ for US $X_i(j) - \bar{X}(j)$	Expanded uncertainty of $d$ (k=2)	D.O.E.	$u_{i,DOE}$
US (loop1)	-66.54	-66.54			NIST	
US (loop 2)	36.33	36.33				
US (loop 3)	10.55	10.55				
US (loop 4)	14.14	16.3736	$\bar{d} = -0.6$	2.2	-0.36	0.44
Argentina (2) [4]	19.27	16.3736	2.9	5.2	3.1	2.4
TT (3) [1]	269	-66.54	335	116	335	58
Brazil (4) [4]	12	16.3736	-4.4	11	-4.2	5.3
Colombia (5) [2]	22.01	36.33	-14	56	-14	28
Uruguay (6) [4]	13	16.3736	-3.4	17	-3.2	8.5
Chile (7) [4]	14	16.3736	-2	26	-2	13
Peru (8) [2]	49.3	36.33	13	138	13	69
Panama (9) [3]	12.7	10.55	2	68	2	34
Ecuador (10) [2]	51.4	36.33	15	78	15	39
CR (11) [3]	26	10.55	15	54	16	27

CRV = -0.1976 and  $u_{CRV} = 0.96$ .

For Test # 4, 10 V 100 kHz , note that Panama did not participate in the comparison.

NMI, lab #	$X$ or average in each loop (E)	Reference value $\bar{X}(j)$	$d$ (corrected E) or $\bar{d}$ for US $X_i(j) - \bar{X}(j)$	Expanded uncertainty of $d$ (k=2)	D.O.E.	$u_{i,DOE}$
US (loop1)	-244.7	-244.7			NIST	
US (loop 2)	-219.81	-219.81				
US (loop 3)	44	44				
US (loop 4)	119.44	123.3954	$\bar{d} = -1.0$	4.2	-0.36	0.75
Argentina (2) [4]	125.6	123.3954	2.2	20	2.8	9.7
TT (3) [1]	-30592	-244.7	-30347	150	-30346	75
Brazil (4) [4]	125	123.3954	1.6	13	2.2	6.1
Colombia (5) [2]	-217.56	-219.81	2	124	3	62
Uruguay (6) [4]	112	123.3954	-11	26	-11	13
Chile (7) [4]	97	123.3954	-26	66	-26	32
Peru (8) [2]	-877.5	-219.81	-658	34	-657	17
Panama (9) [3]						
Ecuador (10) [2]	-16.7	-219.81	203	254	204	127
CR (11) [3]	-165	44	-209	122	-208	61

CRV = -0.6258 and  $u_{CRV} = 1.94$ .

For Test # 5, 100V 55 Hz ,

NMI, lab #	$X$ or average in each loop (E)	Reference value $\bar{X}(j)$	$d$ (corrected E) or $\bar{d}$ for US $X_i(j) - \bar{X}(j)$	Expanded uncertainty of $d$ (k=2)	D.O.E.	$u_{i,DOE}$
US (loop1)	-613.8	-613.8			NIST	
US (loop 2)	12.61	12.61				
US (loop 3)	16.68	16.68				
US (loop 4)	-23.47	-24.7229	$\bar{d} = 0.3$	3.8	0.11	0.75
Argentina (2) [4]	-23.83	-24.7229	0.9	11	0.7	5.5
TT (3) [1]	153	-613.8	767	80	767	40
Brazil (4) [4]	-27	-24.7229	-2.3	14	-2.5	6.8

Colombia (5) [2]	-18.15	12.61	-31	62	-31	31
Uruguay (6) [4]	-20	-24.7229	4.7	19	4.5	9.5
Chile (7) [4]	-32	-24.7229	-7	34	-7	17
Peru (8) [2]	258.2	12.61	246	184	245	92
Panama (9) [3]	5.2	16.68	-11	76	-1	38
Ecuador (10) [2]	-54.9	12.61	-68	212	-68	106
CR (11) [3]	5.8	16.68	-11	62	-11	31

CRV = 0.2065 and  $u_{CRV} = 1.76$ .

For Test # 6, 10 mA dc,

NMI, lab #	X or average in each loop (E)	Reference value $\bar{X}(j)$	$d$ (corrected E) or $\bar{d}$ for US $X_i(j) - \bar{X}(j)$	Expanded uncertainty of $d$ (k=2)	D.O.E.	$u_{i,DOE}$
US (loop1)	85.81	85.81			NIST	
US (loop 2)	12.95	12.95				
US (loop 3)	4.09	4.09				
US (loop 4)	17.38	16.6664	$\bar{d} = 0.18$	0.62	0.11	0.14
Argentina (2) [4]	16.26	16.6664	-0.41	1.2	-0.47	0.55
TT (3) [1]	-34	85.81	-120	50	-120	25
Brazil (4) [4]	18	16.6664	1.3	10	1.3	4.9
Colombia (5) [2]	7.37	12.95	-5.6	12	-5.6	6.2
Uruguay (6) [4]	22.9	16.6664	6.2	5.2	6.2	2.6
Chile (7) [4]	22	16.6664	5.3	15	5.3	7.6
Peru (8) [2]	34.5	12.95	22	82	21	41
Panama (9) [3]	2.5	4.09	-2	24	-2	12
Ecuador (10) [2]	-24.4	12.95	-37	36	-37	18
CR (11) [3]	10	4.09	6	40	6	20

CRV = 0.0646 and  $u_{CRV} = 0.28$ .

For Test # 7, 1A 55 Hz,

NMI, lab #	$X$ or average in each loop (E)	Reference value $\bar{X}(j)$	$d$ (corrected E) or $\bar{d}$ for US $X_i(j) - \bar{X}(j)$	Expanded uncertainty of $d$ (k=2)	D.O.E.	$u_{i,DOE}$
US (loop1)	-1099.3	-1099.3			NIST	
US (loop 2)	117.88	117.88				
US (loop 3)	2.49	2.49				
US (loop 4)	-43.53	-40.941	$\bar{d} = -0.6$	12	-1.4	4.9
Argentina (2) [4]	-37.58	-40.941	3.4	9.8	2.6	3.4
TT (3) [1]	1562	-1099.3	2661	348	2661	174
Brazil (4) [4]	-48	-40.941	-7	22	-8	10
Colombia (5) [2]	91.74	117.88	-26	300	-27	150
Uruguay (6) [4]	-59	-40.941	-18	32	-19	17
Chile (7) [4]	-11	-40.941	30	276	29	138
Peru (8) [2]	419	117.88	301	174	300	87
Panama (9) [3]	-8.1	2.49	-11	186	-11	93
Ecuador (10) [2]	10.8	117.88	-107	522	-108	261
CR (11) [3]	77	2.49	75	300	74	150

CRV = 0.7565 and  $u_{CRV} = 3.58$ .

For Test # 8, 10  $\Omega$ ,

NMI, lab #	$X$ or average in each loop (E)	Reference value $\bar{X}(j)$	$d$ (corrected E) or $\bar{d}$ for US $X_i(j) - \bar{X}(j)$	Expanded uncertainty of $d$ (k=2)	D.O.E.	$u_{i,DOE}$
US (loop1)	54.03	54.03			NIST	
US (loop 2)	-14.85	-14.85				
US (loop 3)	-8.14	-8.14				
US (loop 4)	-3.05	-1.6275	$\bar{d} = -0.36$	0.32	-0.050	0.020
Argentina (2) [4]	-2.995	-1.6275	-1.4	3.6	1.1	1.8
TT (3) [1]	-11097	54.03	-11151.0	8.2	-11150.7	4.1
Brazil (4) [4]	3.5	-1.6275	5.1	3.0	5.4	1.5

Colombia (5) [2]	-6.5	-14.85	8.4	8.2	8.7	4.1
Uruguay (6) [4]	-26	-1.6275	-24.4	6.2	-24.1	3.1
Chile (7) [4]	-3.5	-1.6275	-2	24	-2	12
Peru (8) [2]	5.2	-14.85	20	42	20	21
Panama (9) [3]	-6.2	-8.14	1.9	15	2.2	7.6
Ecuador (10) [2]	-3.4	-14.85	11.5	2.8	11.8	1.4
CR (11) [3]	-7.1	-8.14	1	24	1	12

CRV = -0.3059 and  $u_{CRV} = 0.15$ .

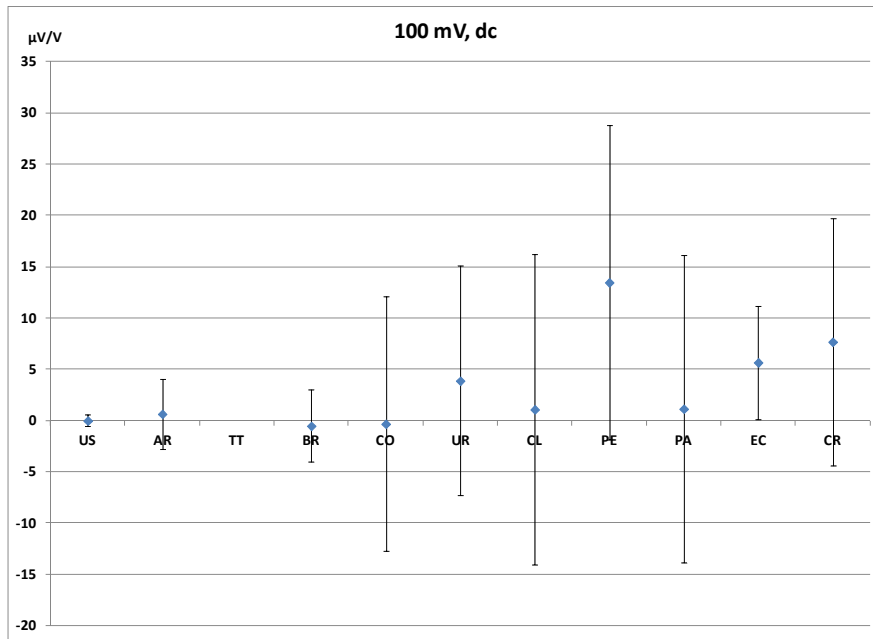
For Test # 9, 100 k $\Omega$ ,

NMI, lab #	$X$ or average in each loop (E)	Reference value $\bar{X}(j)$	$d$ (corrected E) or $\bar{d}$ for US $X_i(j) - \bar{X}(j)$	Expanded uncertainty of $d$ (k=2)	D.O.E.	$u_{i,DOE}$
US (loop1)	33.71	33.71			NIST	
US (loop 2)	-11.7	-11.7				
US (loop 3)	-9.36	-9.36				
US (loop 4)	0.41	0.6208	$\bar{d} = -0.05$	0.62	-0.02	0.12
Argentina (2) [4]	-0.725	0.6208	0.10	1.8	0.14	0.83
TT (3) [1]	-217	33.71	-251	76	-251	38
Brazil (4) [4]	0.7	0.6208	0.1	3.4	0.1	1.6
Colombia (5) [2]	-9.7	-11.7	2.0	8.6	2.0	4.3
Uruguay (6) [4]	-0.7	0.6208	-1.3	4.8	-1.3	2.4
Chile (7) [4]	-1.4	0.6208	-2.0	5.2	-2.0	2.7
Peru (8) [2]	9.1	-11.7	20.8	12	20.8	6.0
Panama (9) [3]	-8.7	-9.36	0.7	8.2	0.7	4.1
Ecuador (10) [2]	-5.4	-11.7	6.3	6.8	6.3	3.5
CR (11) [3]	-3.1	-9.36	6.3	11	6.3	5.7

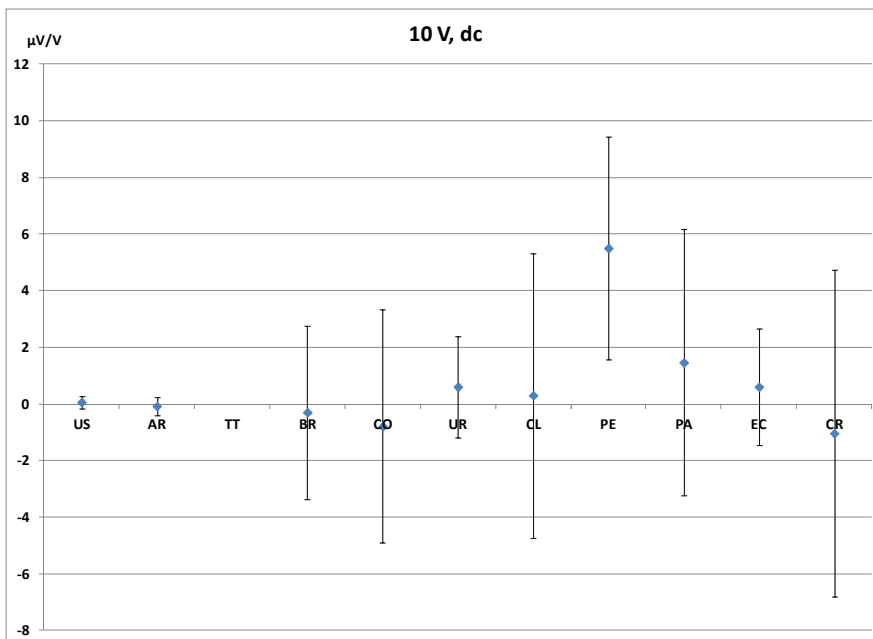
CRV = -0.0317 and  $u_{CRV} = 0.29$ .



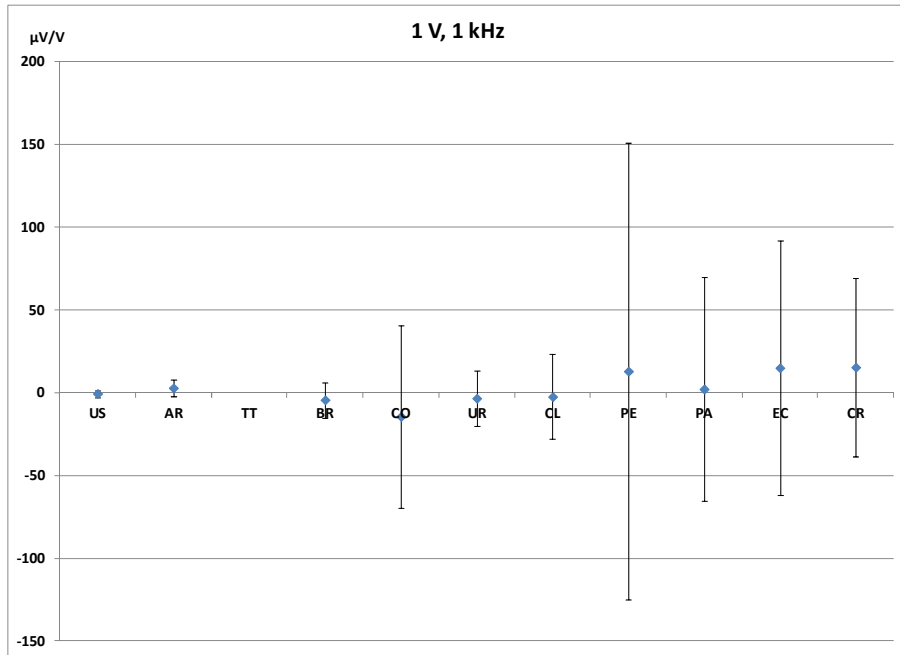
## Annex 2



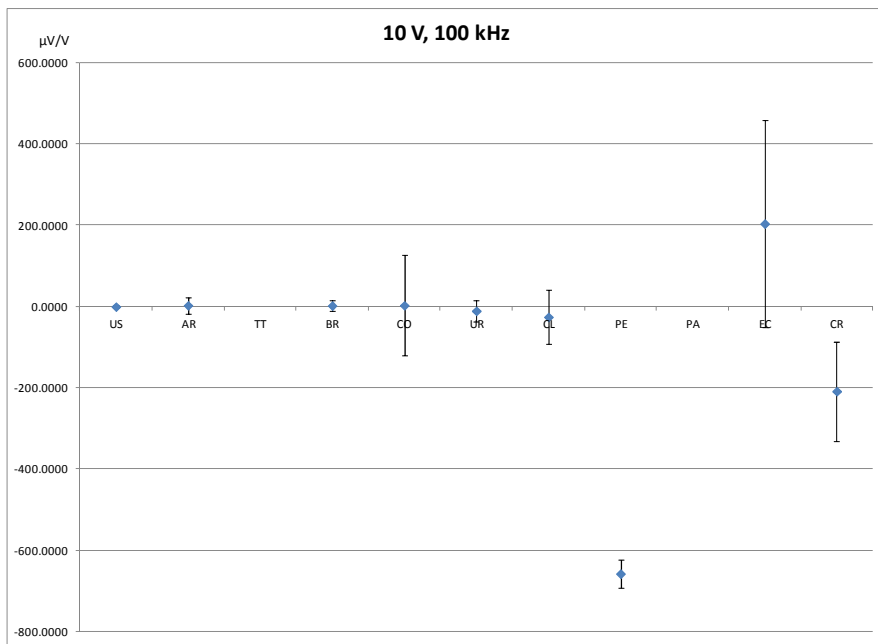
100 mV, dc.



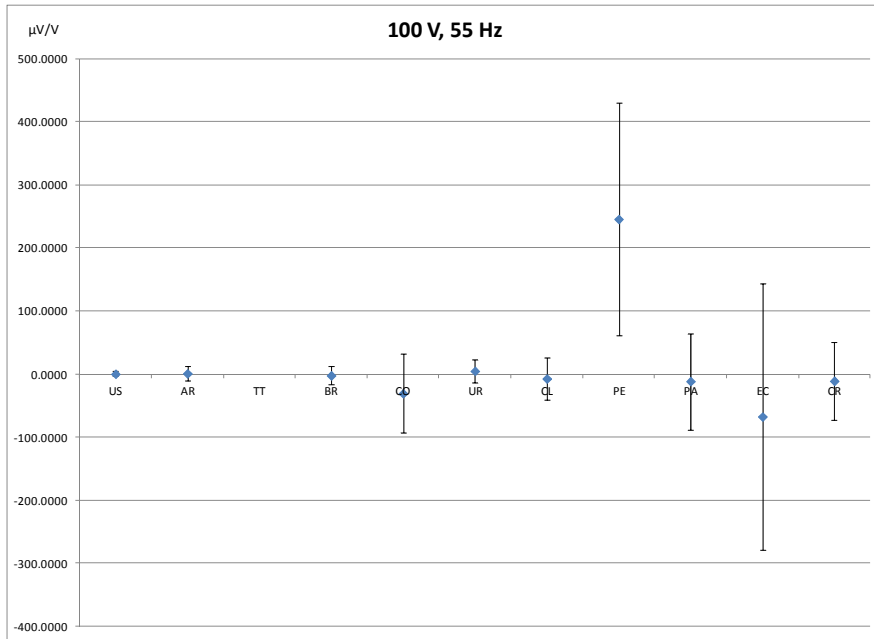
10 V, dc.



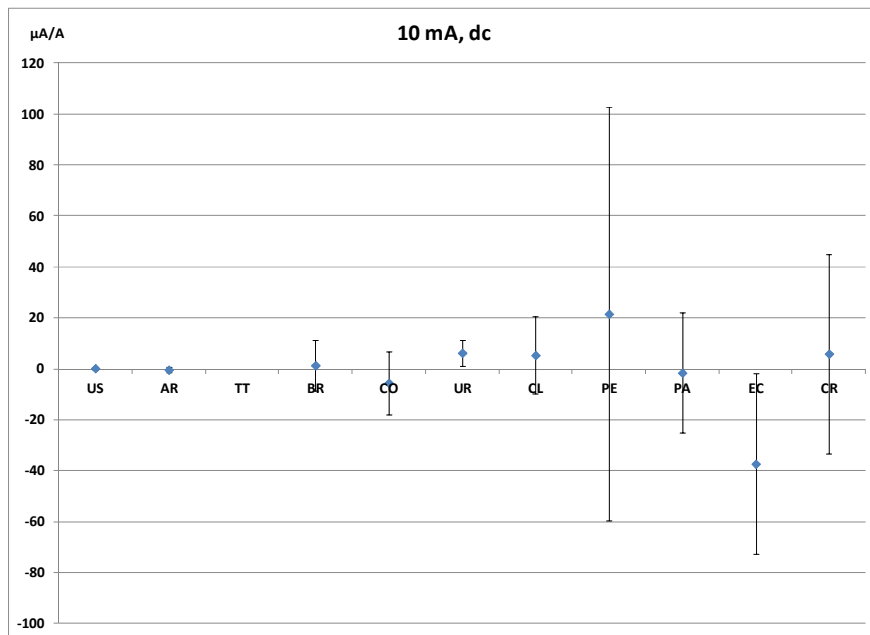
1 V, 1 kHz.



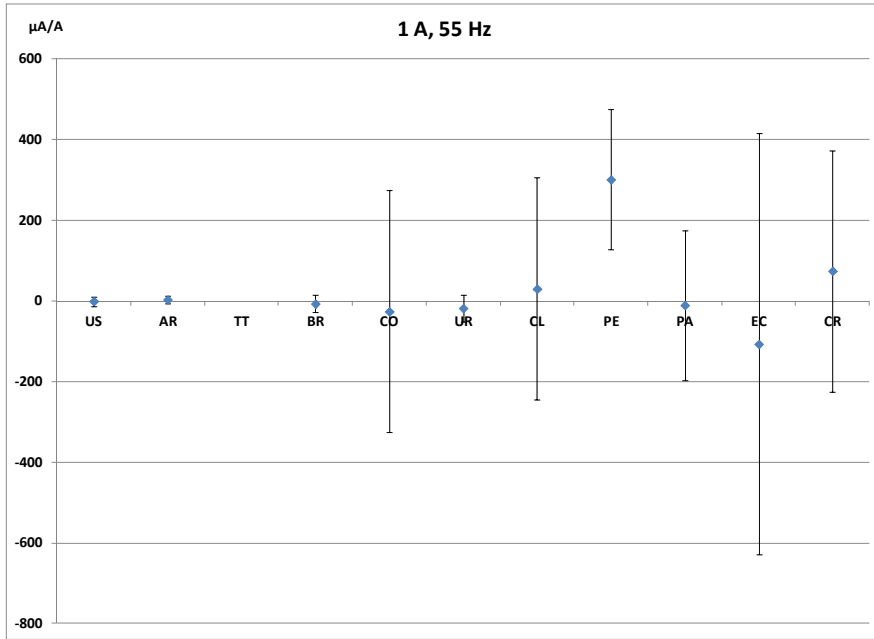
10 V, 100 kHz.



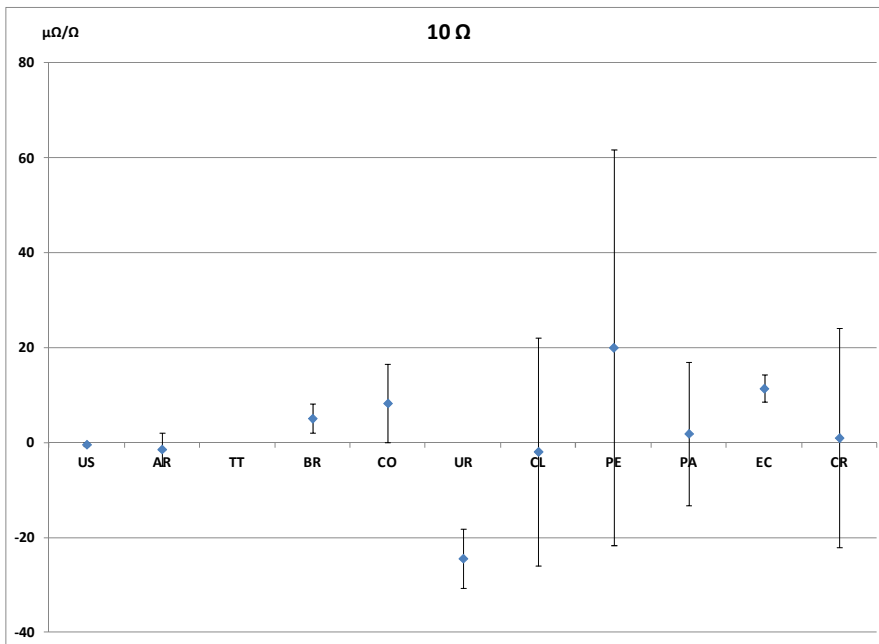
100 V, 55 Hz.



10 mA, dc.



1 A, 55 Hz.



10 Ω.

