Final Report

CCEM-K5 Comparison of 50/60 Hz Power

Nile Oldham, Thomas Nelson
Electricity Division
Nien Fan Zhang, and Hung-kung Liu
Statistical Engineering Division

National Institute of Standards and Technology
Gaithersburg, MD 20899
USA
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Abstract
Electrical standards of low-frequency (50/60 Hz) power at 15 National Metrology Institutes (NMIs) were compared to establish the relationship between the electrical units at these laboratories. The results of this comparison are described. The differences between each laboratory's values and the reference values were within the measurement expanded uncertainties at a coverage factor k=2.

1. Introduction

To support mutual recognition agreements between nations, the Comité International des Poids et Mesures - Comité Consultatif d'Électricité et Magnétisme (CIPM-CCEM) sponsors international comparisons of electromagnetic units between national metrology institutes (NMIs) [1]. In 1995, the first CCEM- sponsored international comparison of 50/60 Hz electric power was organized. The National Institute of Standards and Technology (NIST) was selected as the *pilot laboratory*, which is responsible for providing the traveling standard, coordinating the schedule, collecting and analyzing the comparison data, and preparing the draft report. All of the CCEM member laboratories were invited to participate, and the comparison began in June 1996. Previous international comparisons of electric power have been conducted independently between three or four NMIs [2,3].

2. Participants

At the start, 15 NMIs from five metrology regions had agreed to participate. During the comparison, one NMI (KRISS in Korea) withdrew after submitting data, and another (NMI/VSL in the Netherlands) performed tests but never submitted data. In late 1998 two additional NMIs (CENAM in Mexico and INMETRO in Brazil) requested inclusion in the comparison, and the CCEM granted an extension. Of the 15 active participants at the end of the comparison, four requested bilateral retests, thus testing for the comparison eventually took nearly five years to complete. The final NMI results were received in May 2001.

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

Laboratory	Region	Measurement Date
NIST, National Institute of Standards and Technology, USA	SIM	Jun 1996 – Oct 2000
NRC, National Research Council, Canada	SIM	Jun 1996 and Sep 1998
PTB, Physikalische-Technische Bundesanstalt, Germany	EUROMET/ COOMET	Aug 1996 and May 1999
SP, Swedish National Research and Testing Institute, Sweden	EUROMET	Sep 1996 and Oct 2000
CSIRO-NML, Commonwealth Scientific and Industrial Research Organization - National Measurement Laboratory, Australia	APMP	Nov 1996
MSL, Measurement Standards Laboratory, New Zealand	APMP	Dec 1996 and Aug 2000
NPL, National Physical Laboratory, UK	EUROMET	Mar 1997
IEN, Istituto Elettrotecnico Nazionale, Italy	EUROMET	Apr 1997
INTI, Instituto Nazional de Technologia Industrial, Argentina	SIM	Aug 1997
NIM , National Institute of Metrology, China	APMP	Mar 1998 and Jun 2000
VNIIM, D.I. Mendeleyev Institute for Metrology, Russia	COOMET	Jun 1998
PSB, Productivity and Standards Board, Singapore	APMP	Dec 1998
CSIR-NML, Council for Scientific and Industrial Research – National Measurement Laboratory, South Africa	SADCMET	Feb 1999 and Sep 2000
INMETRO, Instituto Nacional de Metrologia, Normalização e Qualidade Industrial - Brazil	SIM	Jul 1999
CENAM, Centro Nacional de Metrología - Mexico	SIM	Aug 1999

While the CCEM comparison was being conducted, three other regional power comparisons were ongoing in NORAMET (NRC – pilot) and EUROMET (PTB – pilot) and APMP. To better link these comparisons, second measurements were performed at NRC in 1998 and at PTB in 1999. Measurements performed in 2000 were retests requested by the participating NMIs.

3. Traveling Standard

Previous international comparisons of electric power have utilized thermal wattmeters and power transducers based on time-division-multiplication. For this comparison however, serious consideration was given to a digitally synthesized power source as a traveling standard. However, most NMI power standards are intended to calibrate measuring instruments and not sources; therefore, the pilot laboratory decided to use a commercial power transducer, which is similar to the devices normally tested at most calibration laboratories.

The selected instrument was a Rotek MSB-001, based on a time-division-multiplication scheme developed by Miljanić, Stojanović and Bošnjaković [4]. It has separate (electrically isolated) voltage and current inputs on the front panel. There are two voltage ranges, 120 V and 240 V, and two current ranges, 1 A and 5 A. The internal dc reference voltages (nominally +7 V and –7 V) can be monitored at the front panel. The instrument is configured as an ac power-to-dc voltage transducer, with a nominal full-scale dc output of 10 V, which is also available on the front panel. Although it can be powered at any frequency between 50 Hz and 70 Hz with no measurable change in error, the nominal supply voltage is 115 V at 60 Hz.

The instrument used as the traveling standard for the comparison (serial number 87028) is the more stable of two instruments that had been regularly monitored for several years in the Power and Energy laboratory in the Electricity Division at NIST. Measurements of the standard between 20º C and 23º C indicated a negligible temperature coefficient in this range. Short-term changes in relative humidity between 30 % and 60 % produced no measurable effect. Voltage, current, and power factor coefficients were negligible within ±0.2 % of nominal values. With no voltage or current applied, there was a small dc offset at the output. Each NMI measured this offset and the dc reference voltages. *Although there were small drifts in these voltages, they were compensated for by the normalization procedure described below, thus the measured voltages were not used in the analysis.*

4. Test Points

After consultation with several other NMIs, the pilot lab decided to perform the comparison at 120 V, 5 A, 53 Hz, at 1.0, 0.5, and 0.0 power factors (pf). Instructions to the participants were as follows:

- Power the traveling standard at 120 V (between 50 Hz and 70 Hz) and energize it with test signals of 120 V, 5 A for at least 8 hours before testing.
- Perform tests at 53 Hz, 120 V, 5 A, at 1.0 PF, 0.5 PF (lead and lag), and 0.0 PF (lead and lag); set test parameters to within 0.1% of nominal; perform the tests within two weeks, de-energizing the standard at least once (for >2 hours) during the test.
- Measure the standard's output voltage using a high impedance voltmeter.
- Report the mean errors and uncertainties (k=1) in terms of apparent power μW/(VA).
- Record the mean dc ref voltages (+7 V and -7 V) during the test.
- Record the mean output offset voltage (with no test power applied), but do not correct for the offset.
- Record the average ambient temperature and humidity during the test.
- Comment on any significant behavior.

Ideally, each NMI would have tested and returned the traveling standard to the pilot lab; however, the large number of participants and the limited schedule mandated a more efficient approach. Therefore, the traveling standard was cycled through two NMIs before returning to NIST. Although the traveling standard began to drift early in the second year of the comparison, NIST measurements at two- to three-month intervals were deemed adequate to compensate for this drift.

5. Results

During the comparison, preliminary results were presented at the Conference on Precision Electromagnetic Measurements CPEM98 and CPEM2000 [5]. The final results submitted by each participant are given in Table 2.

Table 2. Errors and Standard Uncertainties (k=1) in µW/(VA)

$x_{i,j}$	**Results of measurements carried out by laboratory *i at power factor j***										
$u_i(j)$	**Combined standard uncertainty (*k*=1) of** $x_{i,j}$										
	1.0		***0.5Lead***		***0.5Lag***		***0.0Lead***		***0.0Lag***		
Lab$_i$	$x_{i,1.0}$	*u*	$x_{i,0.5Lead}$	*u*	$x_{i,0.5Lag}$	*u*	$x_{i,0.0Lag}$	*u*	$x_{i,0.0Lag}$	*u*	**Meas**
	µW/(VA)	µW/(VA)	µW/(VA)	µW/(VA)	µW/(VA)	µW/(VA)	µW/(VA)	µW/(VA)	µW/(VA)	µW/(VA)	**Date**
NRC	**29**	6	**26**	6	**-27**	6	**-7**	5	**-68**	5	Jun-96
NIST	**26**	7	**17**	7	**-24**	7	**-13**	6	**-59**	6	Jul-96
PTB*	**23**	7	**9**	7	**-18**	7	**-20**	6	**-53**	6	Aug-96
SP*	**-10**	15	**-5**	11	**-43**	11	**-18**	9	**-60**	9	Sep-96
NIST	**27**	7	**20**	7	**-22**	7	**-7**	6	**-63**	6	Oct-96
CSIRO-NML	**31**	7	**15**	8	**-20**	8	**-3**	7	**-62**	7	Nov-96
MSL*	**66**	34	**27**	24	**-4**	24	**-12**	18	**-73**	18	Dec-96
NIST	**22**	7	**17**	7	**-25**	7	**-14**	6	**-54**	6	Feb-97
NPL	**38**	16	**2**	13	**-4**	13	**-41**	14	**-44**	14	Mar-97
IEN	**23**	15	**4**	15	**-21**	15	**-27**	15	**-58**	16	Apr-97
NIST	**21**	7	**12**	7	**-20**	7	**-16**	6	**-52**	6	May-97
INTI	**42**	10	**20**	17	**-20**	17	**-9**	19	**-50**	19	Aug-97
NIST	**22**	7	**15**	7	**-21**	7	**-13**	6	**-53**	6	Sep-97
NIST	**20**	7	**12**	7	**-26**	7	**-13**	6	**-55**	6	Nov-97
NIM*	**37**	6	**-2**	4	**1**	4	**-40**	5	**-37**	4	Mar-98
NIST	**14**	7	**5**	7	**-27**	7	**-20**	6	**-55**	6	Apr-98
VNIIM	**30**	9	**-8**	14	**-53**	14	**-8**	12	**-70**	12	Jun-98
NRC	**14**	6	**11**	6	**-37**	6	**-15**	5	**-73**	5	Sep-98
NIST	**9**	7	**5**	7	**-30**	7	**-17**	6	**-57**	6	Nov-98
PSB	**38**	31	**3**	31	**-17**	31	**-36**	31	**-65**	31	Dec-98
CSIR-NML*	**-21**	30	**-6**	30	**-45**	30	**-32**	30	**-54**	30	Feb-99
NIST	**8**	7	**6**	7	**-32**	7	**-18**	6	**-58**	6	Mar-99
PTB	**15**	5	**-1**	5	**-18**	5	**-22**	5	**-56**	5	May-99
NIST	**8**	7	**8**	7	**-34**	7	**-18**	6	**-59**	6	Jun-99
INMETRO	**6**	30	**21**	30	**-56**	30	**-14**	30	**-77**	30	Aug-99
CENAM	**19**	17	**4**	17	**-28**	17	**-34**	27	**-55**	27	Aug-99
NIST	**10**	7	**4**	7	**-30**	7	**-23**	6	**-60**	6	Sep-99
NIST	**9**	7	**11**	7	**-28**	7	**-15**	6	**-54**	6	Jun-00
NIM	**20**	6	**23**	6	**-36**	6	**-14**	6	**-72**	6	Jul-00
MSL	**20**	14	**16**	15	**-37**	15	**-18**	16	**-69**	16	Aug-00
NIST	**17**	7	**12**	7	**-21**	7	**-12**	6	**-52**	6	Aug-00
CSIR-NML	**13**	40	**-1**	40	**-14**	40	**-43**	40	**-57**	40	Sep-00
SP	**27**	15	**6**	11	**-14**	11	**-25**	9	**-47**	9	Oct-00
NIST	**21**	7	**11**	7	**-22**	7	**-21**	6	**-57**	6	Nov-00

Values marked with an asterisk were not used in the final results. NIM discovered an error in their scaling transformers and requested a bilateral comparison. Subsequently SP, MSL, and CSIR-NML (all had problems with their ac voltage standards during their tests) requested bilateral comparisons. The first tests made by these four NMIs were not used in the final results.

As planned, PTB and NRC performed two tests during the comparison. The two NRC values were averaged for the final results. The second PTB test was performed using a newer, more accurate system. To provide a better link between the CCEM and EUROMET comparisons, PTB decided not to include the first measurement.

Data from Table II are also plotted for each power factor in figures 1 through 5, with trend lines (fit to the NIST values) to show how the traveling standard drifted during the comparison.

Figure 1. Reported Results
120 V, 5 A, PF 1.0 (k=1)

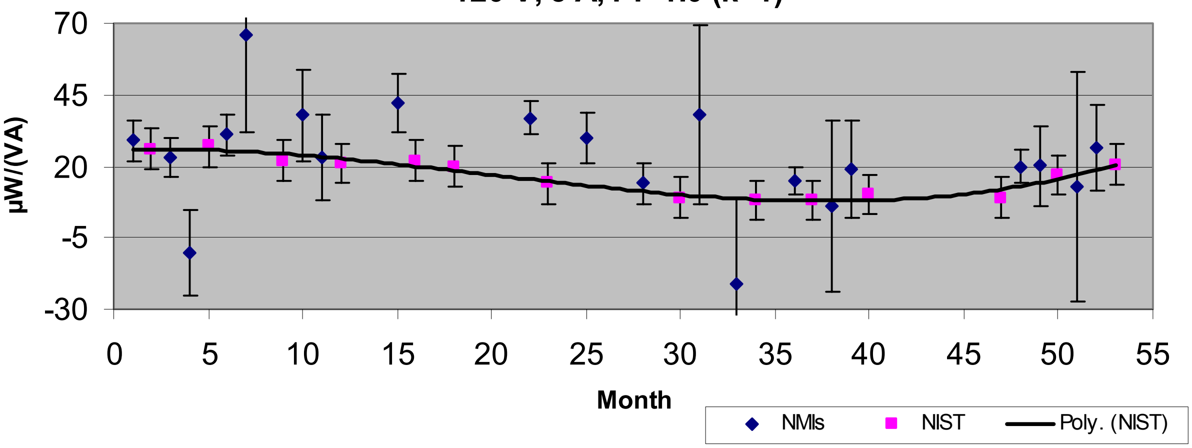


Figure 2. Reported Results
120 V, 5 A, PF 0.5 Lead (k=1)

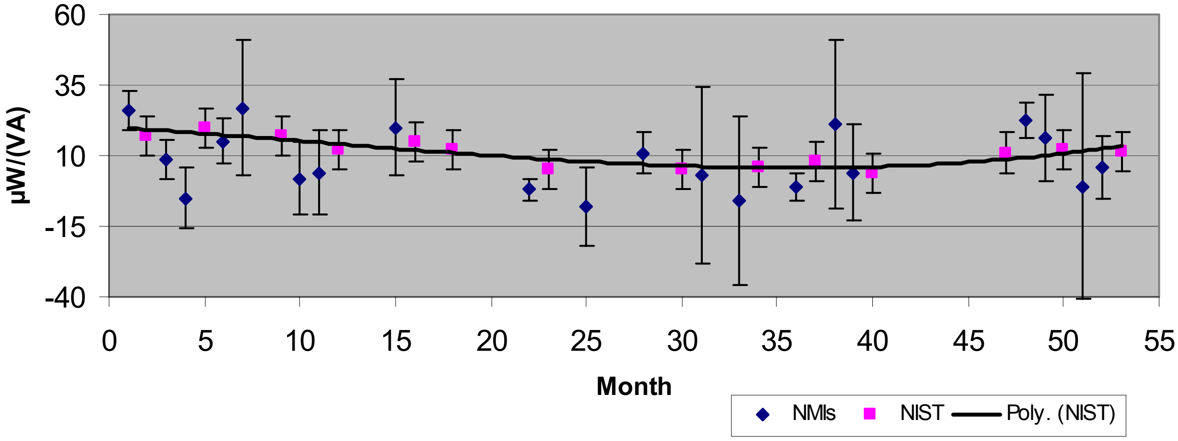


Figure 3. Reported Results
120 V, 5 A, PF 0.5 Lag (k=1)

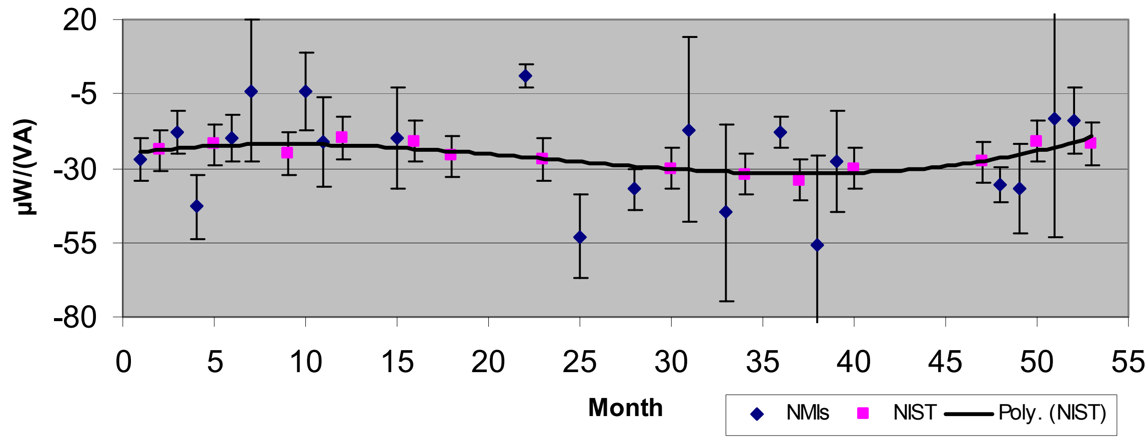


Figure 4. Reported Results
120 V, 5 A, PF 0.0 Lead (k=1)

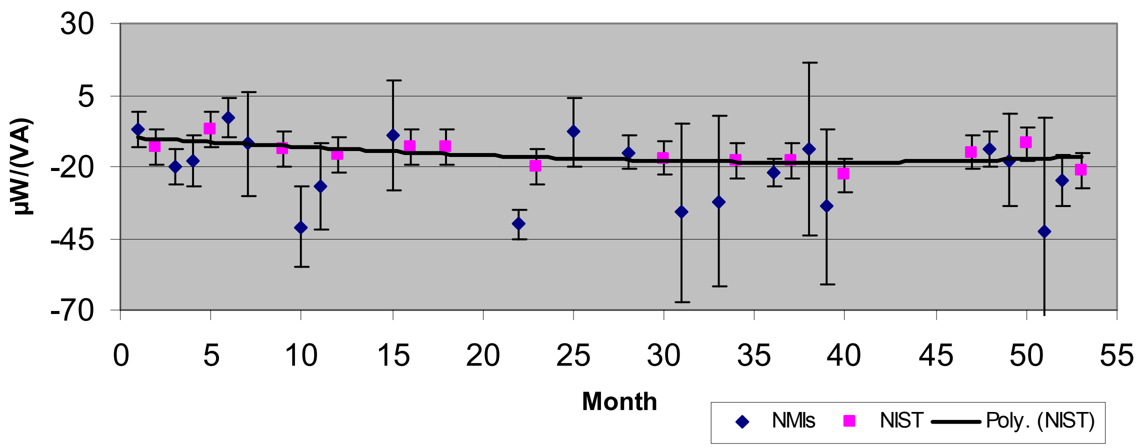
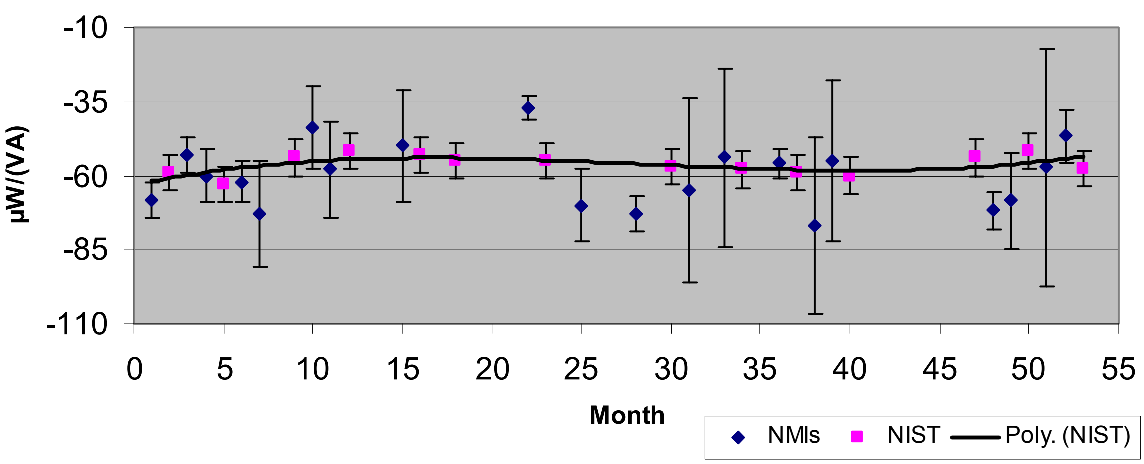


Figure 5. Reported Results
120 V, 5 A, PF 0.0 Lag (k=1)



<u>The Drift Effect</u>

To estimate drifts in the traveling standard, a polynomial regression was fitted to the fourteen NIST measurements for each power factor. A 3rd-order polynomial regression was selected to track the apparent sinusoidal behavior of the traveling standard. The regressions are as follows:

$$x_{NIST,1}(k) = 25.7534 + 0.1944 \times t_{NIST}(k) - 0.04761 \times t_{NIST}^2(k) + 0.0008 \times t_{NIST}^3(k) + \varepsilon_1(k)$$

$$x_{NIST,2}(k) = 20.1842 - 0.4406 \times t_{NIST}(k) - 0.0090 \times t_{NIST}^2(k) + 0.0003 \times t_{NIST}^3(k) + \varepsilon_2(k)$$

$$x_{NIST,3}(k) = -25.4289 + 0.8471 \times t_{NIST}(k) - 0.0590 \times t_{NIST}^2(k) + 0.0009 \times t_{NIST}^3(k) + \varepsilon_3(k)$$

$$x_{NIST,4}(k) = -9.6134 - 0.3658 \times t_{NIST}(k) + 0.0009 \times t_{NIST}^2(k) + 0.0001 \times t_{NIST}^3(k) + \varepsilon_4(k)$$

$$x_{NIST,5}(k) = -63.2616 + 1.2975 \times t_{NIST}(k) - 0.0552 \times t_{NIST}^2(k) + 0.0006 \times t_{NIST}^3(k) + \varepsilon_5(k)$$

where $x_{NIST,j}(k)$= the k^{th} measurements made by NIST for the j^{th} case ($j=1$ for 1.0, $j=2$ for 0.5 Lead , $j=3$ for 0.5 Lag, $j=4$ for 0.0 Lead, and $j=5$ for 0.0 Lag), and $t_{NIST}(k)$= the k^{th} time (in months) from the beginning of the comparison when NIST made the measurements, $k=1,2,...,14$, $\varepsilon_j(k)$=random error with zero mean and variance of $\sigma_r^2(j)$ due to the j^{th} regression.

The corresponding standard deviations of the residuals are:

$s_r(1)=1.816$, $s_r(2)=2.524$, $s_r(3)=2.185$, $s_r(4)=3.628$, and $s_r(5)=2.807$,

which are estimates of $\sigma_r(j)$ for j=1,2,3,4,5.

For the j^{th} case, the regression can be expressed in a matrix form:

$$\overrightarrow{X}_{NIST,j} = T_{NIST}\overrightarrow{\beta}(j)$$

where $\overrightarrow{X}_{NIST,j} = (x_{NIST,j}(1),...,x_{NIST,j}(14))'$ is a column vector, $\overrightarrow{\beta}(j)$ is the 4 by 1 column vector of the regression parameters, and T_{NIST} is a 14 by 4 matrix with the elements of the first column being 1's and other (k,n) elements (for $k=1,2...,14$ and $n=2,3,4$) being $t_{NIST}^{n-1}(k)$. For a matrix A or a vector, A' is the transpose of A.

For the total of 15 NMIs, the difference $D_i(j)(i=1,2,...,15)$ for the i^{th} NMI and the j^{th} case is defined as

$$D_i(j) = x_{i,j} - xp_{i,j}$$

where $x_{i,j}$ is the measurement made by the i^{th} NMI at time of t_i for the j^{th} case and $xp_{i,j}$ is the prediction of the measurement of the i^{th} NMI at t_i based on the j^{th} regression described in the above. When the i^{th} NMI is NIST, which is the pilot NMI, the corresponding difference $AVE[D_{NIST}(j)]$ for the j^{th} case is defined as the average of the differences at $t_{NIST}(k)$ for $k=1,2,...,14$. Namely,

$$AVE[D_{NIST}(j)] = \frac{\sum_{k=1}^{14}[x_{NIST,j}(k) - xp_{NIST,j}(k)]}{14}$$

where $xp_{NIST,j}(k)$ is the prediction from the j^{th} regression at $t_{NIST}(k)$. $AVE[D_{NIST}(j)]$ has zero mean and thus is usually estimated by zero. The uncertainty of $D_i(j)$ is given by

$$u^2_{D_i(j)} = u_i^2(j) + s_r^2(j)(1 + \vec{t}_i(T'_{NIST}T_{NIST})^{-1}\vec{t}_i')$$

where the row vector $\vec{t}_i = (1, t_i, t_i^2, t_i^3)$ and $u_i(j)$ is the uncertainty of the measurements made by the i^{th} NMI for the j^{th} case and $s_r^2(j)$ is the estimate of the residual variance of the j^{th} regression based on the measurements of the pilot NMI. When the i^{th} NMI is NIST, the corresponding uncertainty for $AVE[D_{NIST}(j)]$ is given by

$$u^2_{AVE[D_{NIST}(j)]} = u^2_{B,NIST}(j) + \frac{u^2_{A,NIST}(j)}{14}$$

where $u_{A,NIST}(j)$ and $u_{B,NIST}(j)$ are the uncertainties due to Type A and Type B evaluations from the uncertainty budget of NIST for the j^{th} case.

Reference Values

Key comparison reference values $X_{KCRV}(j)$ for each of the five test points were calculated as the weighted mean of $D_i(j)$ from the 15 NMIs including NIST as the first NMI. That is,

$$X_{KCRV}(j) = \sum_{i=1}^{15} w_i(j) \times D_i(j)$$

where the weights $w_i(j)$ are determined by the uncertainties of $D_i(j)$:

$$w_i(j) = \frac{\frac{1}{u^2_{D_i(j)}}}{\sum_{k=1}^{15}\frac{1}{u^2_{D_k(j)}}}$$

Note that $D_1(j) = AVE[D_{NIST}(j)]$ and $u_{D_1(j)} = U_{AVE[D_{NIST}(j)]}$ for NIST. Note also that while each NMI measurement is realized independently of the other NMI measurements, the predictions, which are based on the regression of the NIST measurements, are not statistically independent from each other. Therefore all $D_i(j)$ in the weighted mean are statistically correlated and thus the traditional formula for the weighted mean cannot be applied. The uncertainty of the reference value is given by

$$u_{KCRV}^2(j) = \frac{1}{\sum_{i=1}^{15} \frac{1}{u_{D_i(j)}^2}} + \frac{2s_r^2(j)}{(\sum_{i=1}^{15} \frac{1}{u_{D_i(j)}^2})^2} \times \sum_{i>k,i=2}^{15} \sum_{k=2}^{15} \frac{\vec{t}_i (T_{NIST}^{'} T_{NIST})^{-1} \vec{t}_k^{'}}{u_{D_i(j)}^2 \times u_{D_k(j)}^2}$$

The weighted mean can be influenced if one or more NMIs have differences $D_i(j)$ significantly larger than their corresponding $U_{D_i(j)}$. Four NMIs identified and corrected errors in their power standards after making measurements. These labs requested follow-up tests and it was decided to use the results of these follow-up tests (rather than their initial tests and uncertainties) to compute the reference value. The reference values and their uncertainties are given in Table 3.

Table 3. Reference Values and Uncertainties

Power Factor	X_{KCRV}	u_{KCRV}
1.0	7	5
0.5 Lead	-1	5
0.5 Lag	-1	5
0.0 Lead	0	5
0.0 Lag	-3	5

<u>Equivalence</u>

The differences between each of the NMI values and the predicted value (based on 14 independent measurements performed at the Pilot NMI) were adjusted by the reference values to generate $D_{i,KCRV}(j)$ the NMI- Reference differences:

$$D_{i,KCRV}(j) = D_i(j) - X_{KCRV}(j)$$

The corresponding uncertainty when the i^{th} NMI is not the pilot NMI is given by

$$u_{D_{i,KCRV}}^2(j) = [1 - 2w_i(j)] \times u_{D_i(j)}^2 + u_{KCRV}^2(j) - 2 \times s_r^2(j) \sum_{k \neq i,k=2}^{15} w_k(j) [\vec{t}_i (T_{NIST}^{'} T_{NIST})^{-1} \vec{t}_k^{'}]$$

For NIST, the difference is $D_{1,KCRV}(j)$, which is defined as

$$D_{NIST,KCRV}(j) = AVE[D_{NIST}(j)] - X_{KCRV}(j)$$

and its uncertainty is given by

$$u^2_{D_{NIST,KCRV}}(j) = [1 - 2w_1(j)] \times (u^2_{B,NIST}(j) + \frac{u^2_{A,NIST}(j)}{14}) + u^2_{KCRV}(j)$$

where w_1 is the corresponding weight for NIST. The differences and the expanded combined uncertainty (using a coverage factor of k=2) denoted by $U_{D_{i,KCRV}}$ are listed in Table 4 and plots of these data are shown in Figures 6 through 10.

The degree of equivalence between two NMIs ($i \neq k$) for the j^{th} case is defined as

$$D_{i,k}(j) = D_i(j) - D_k(j)$$

The uncertainty of $D_{i,k}(j)$ when neither is the pilot NMI is given by

$$u^2_{i,k} = u^2_i(j) + u^2_k(j) + s^2_r(j)[2 + \vec{t}_i (T'_{NIST} T_{NIST})^{-1} \vec{t}'_i + \vec{t}_k (T'_{NIST} T_{NIST})^{-1} \vec{t}'_k - 2 \times \vec{t}_i (T'_{NIST} T_{NIST})^{-1} \vec{t}'_k]$$

When one NMI is the pilot NMI, NIST, the degree of equivalence is

$$D_{1,k}(j) = D_{NIST,k}(j) = AVE[D_{NIST}(j) - D_k(j)]$$

The corresponding uncertainty is given by

$$u^2_{1,k}(j) = u^2_{NIST,k}(j) = u^2_{B,NIST}(j) + \frac{u^2_{A,NIST}(j)}{14} + u^2_k(j) + s^2_r(j)[1 + \vec{t}_k (T'_{NIST} T_{NIST})^{-1} \vec{t}'_k]$$

Matrices of Equivalence are listed in Tables 5-9. They show the difference between laboratory pairs and the expanded combined uncertainties (k=2) of those differences.

Table 4. Differences and Combined Standard Uncertainties in µW/(VA)

$D_{i,KCRV}$ **Differences**

$U_{D_{i,KCRV}}$ **Expanded combined standard uncertainties of** $D_{i,KCRV}$ (k=2)

i		**1.0 pf**		**0.5Lead**		**0.5Lag**		**0.0Lead**		**0.0Lag**	
	NMI	$D_{i,KCRV}$	$U_{D_{i,KCRV}}$	$D_{i,KCRV}$	$U_{D_{i,KCRV}}$	$D_{i,KCRV}$	$U_{D_{i,KCRV}}$	$D_{i,KCRV}$	$U_{D_{i,KCRV}}$	$D_{i,KCRV}$	$U_{D_{i,KCRV}}$
1	**NIST**	-7	12	1	12	1	12	0	9	3	9
2	**CSIRO-NML**	-1	14	-1	16	3	16	9	15	-2	15
3	**NPL**	8	32	-12	26	19	26	-28	29	14	28
4	**IEN**	-7	30	-10	30	2	30	-14	31	0	32
5	**INTI**	15	20	9	34	4	34	6	39	7	38
6	**VNIIM**	10	18	-15	28	-25	28	9	25	-11	24
7	**NRC**	-4	14	5	12	-3	12	7	12	-11	11
8	**PSB**	22	62	-3	62	13	62	-18	62	-4	62
9	**PTB**	0	10	-7	10	12	10	-4	12	7	11
10	**INMETRO**	-9	60	15	60	-26	60	4	60	-13	60
11	**CENAM**	4	34	-2	34	2	34	-16	54	9	54
12	**NIM**	-1	12	13	12	-14	12	3	13	-7	13
13	**MSL**	-2	28	5	30	-16	30	-1	33	-4	32
14	**CSIR-NML**	-12	80	-14	80	3	80	-26	80	7	80
15	**SP**	1	30	-8	22	1	22	-9	19	17	19

Figure 6. Deviation from Reference Value
120 V, 5 A, PF 1.0 (k=2)

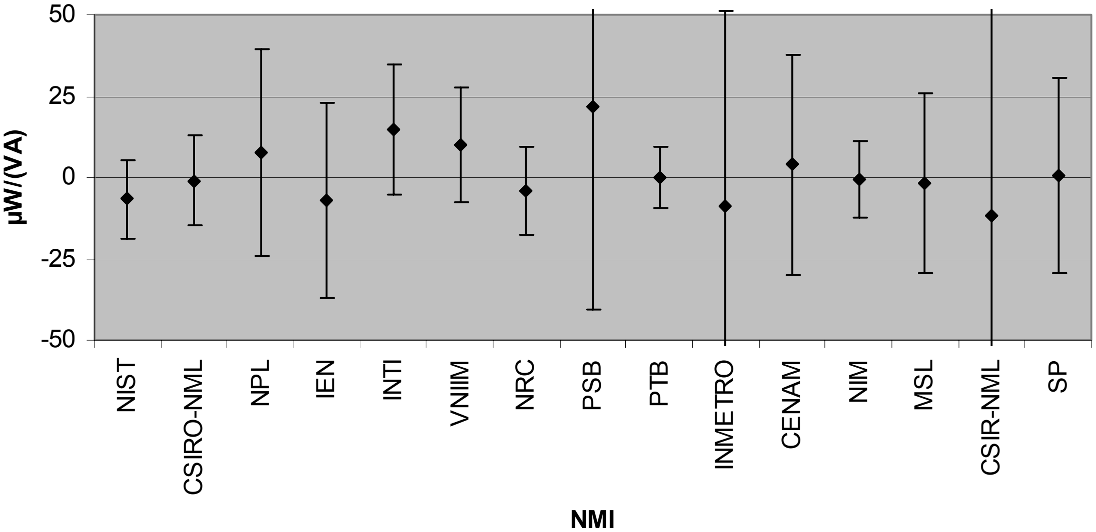


Figure 7. Deviation from Reference Value
120 V, 5 A, PF 0.5 Lead (k=2)

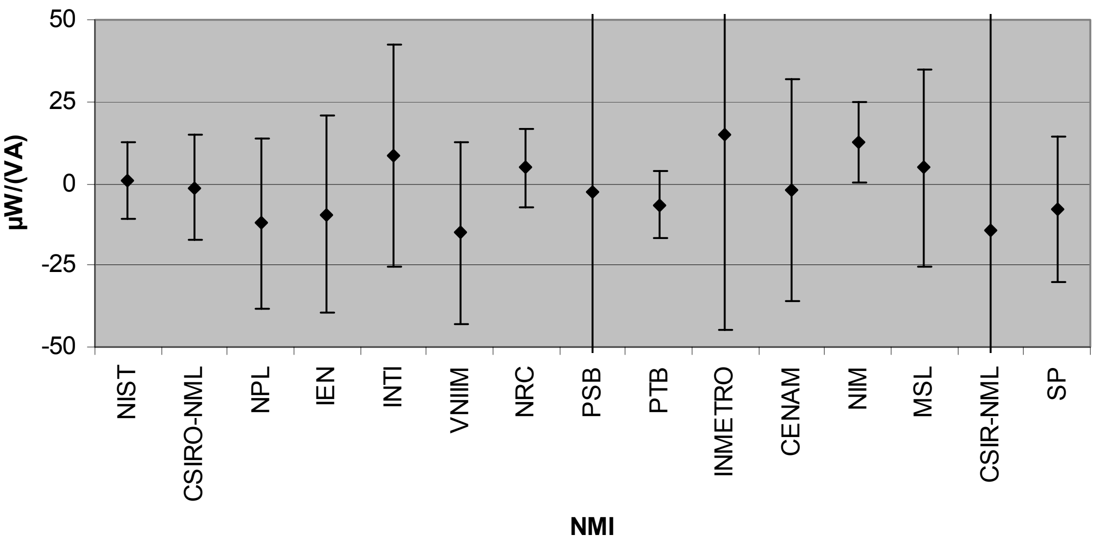


Figure 8. Deviation from Reference Value
120 V, 5 A, PF 0.5 Lag (k=2)

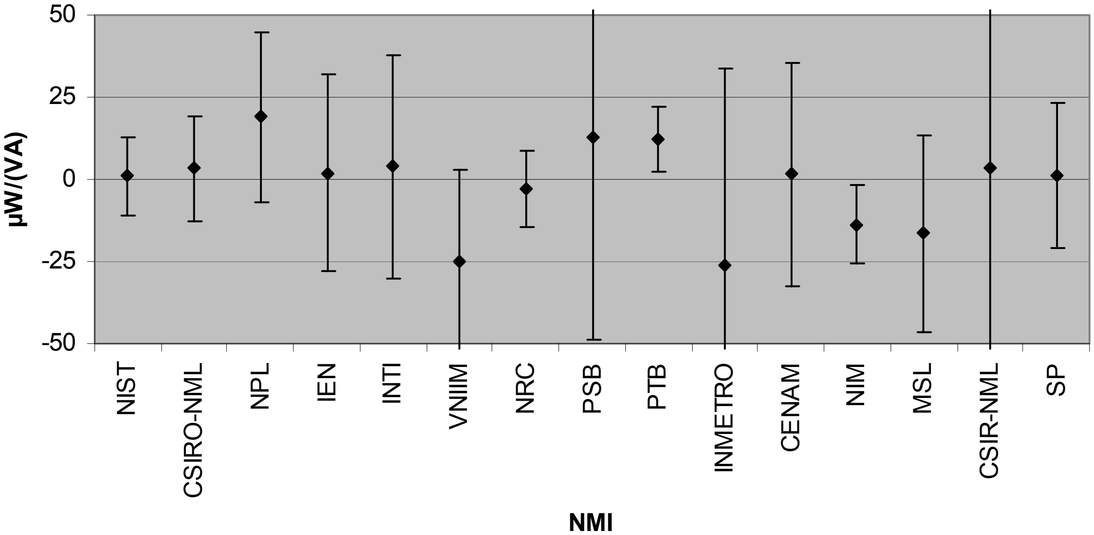
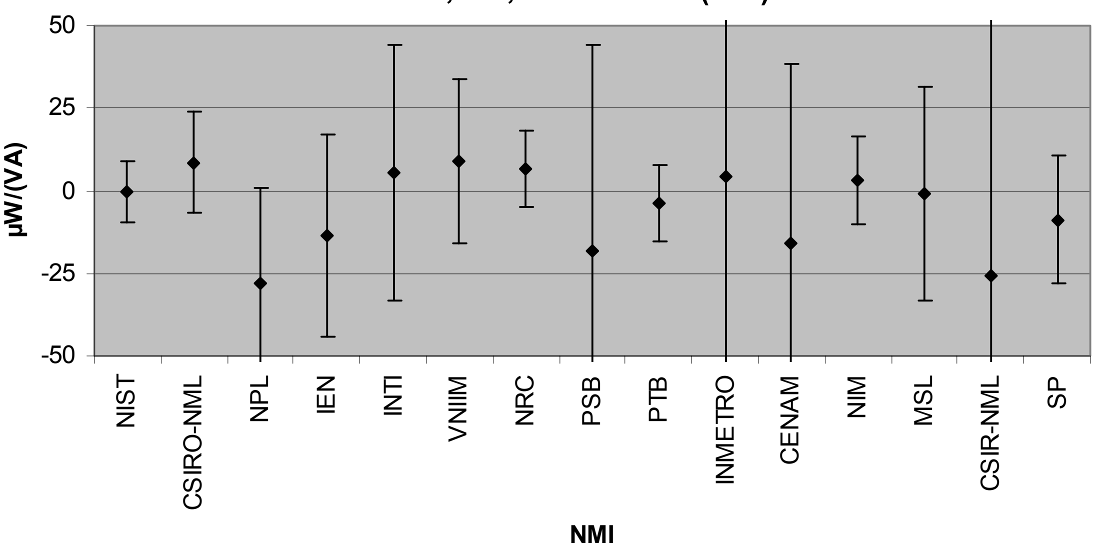


Figure 9. Deviation from Reference Value
120 V, 5 A, PF 0.0 Lead (k=2)



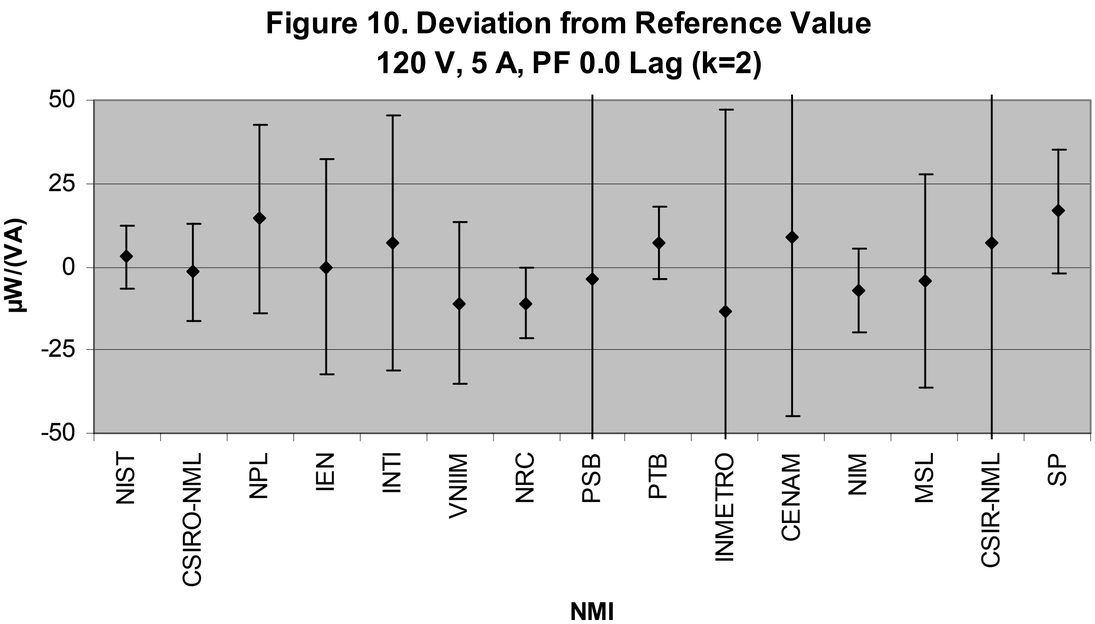


Figure 10. Deviation from Reference Value
120 V, 5 A, PF 0.0 Lag (k=2)
50
25
0
-25
-50
µW/(VA)
NIST
CSIRO-NML
NPL
IEN
INTI
VNIIM
NRC
PSB
PTB
INMETRO
CENAM
NIM
MSL
CSIR-NML
SP
NMI

Table 5. Equivalence at 1.0 Power Factor

	NIST	CSIRO - NML	NPL	IEN	INTI	VNIIM	NRC	PSB	PTB	INMETRO	CENAM	NIM	MSL	CSIR - NML	SP
NIST	-	-6±20	-14±35	0±33	-21±24	-17±22	-3±20	-28±64	-7±17	2±62	-11±37	-6±18	-5±31	5±81	-7±33
CSIRO – NML	6±20	-	-9±35	6±34	-16±25	-11±24	3±21	-22±64	-1±18	8±62	-5±37	0±19	1±32	11±81	-2±34
NPL	14±35	9±35	-	14±44	-7±38	-2±37	12±35	-14±70	8±34	17±68	4±47	8±35	9±43	19±86	7±44
IEN	0±33	-6±34	-14±44	-	-22±36	-17±35	-3±34	-28±69	-7±32	2±67	-11±46	-6±33	-5±41	5±86	-8±43
INTI	21±24	16±25	7±38	22±36	-	5±27	19±25	-7±65	15±23	24±64	11±40	15±24	16±35	26±83	14±36
VNIIM	17±22	11±24	2±37	17±35	-5±27	-	14±23	-12±65	10±21	19±63	6±39	10±22	12±34	22±82	9±36
NRC	3±20	-3±21	-12±35	3±34	-19±25	-14±23	-	-26±64	-4±18	5±62	-8±37	-4±19	-2±32	8±81	-5±34
PSB	28±64	22±64	14±70	28±69	7±65	12±65	26±64	-	22±63	30±86	18±71	22±63	23±68	33±101	21±69
PTB	7±17	1±18	-8±34	7±32	-15±23	-10±21	4±18	-22±63	-	9±61	-4±36	0±16	2±30	12±81	-1±32
INMETRO	-2±62	-8±62	-17±68	-2±67	-24±64	-19±63	-5±62	-30±86	-9±61	-	-13±69	-8±61	-7±66	3±100	-10±67
CENAM	11±37	5±37	-4±47	11±46	-11±40	-6±39	8±37	-18±71	4±36	13±69	-	4±36	6±44	16±87	3±46
NIM	6±18	0±19	-8±35	6±33	-15±24	-10±22	4±19	-22±63	0±16	8±61	-4±36	-	1±31	11±81	-1±33
MSL	5±31	-1±32	-9±43	5±41	-16±35	-12±34	2±32	-23±68	-2±30	7±66	-6±44	-1±31	-	10±85	-2±41
CSIR – NML	-5±81	-11±81	-19±86	-5±86	-26±83	-22±82	-8±81	-33±101	-12±81	-3±100	-16±87	-11±81	-10±85	-	-12±86
SP	7±33	2±34	-7±44	8±43	-14±36	-9±36	5±34	-21±69	1±32	10±67	-3±46	1±33	2±41	12±86	-

Table 6. Equivalence at 0.5 Lead (capacitive)

	NIST	CSIRO - NML	NPL	IEN	INTI	VNIIM	NRC	PSB	PTB	INMETRO	CENAM	NIM	MSL	CSIR - NML	SP
NIST	-	2±21	13±30	11±33	-7±37	16±31	-4±18	4±64	8±17	-14±62	3±37	-12±18	-4±33	15±81	9±26
CSIRO - NML	-2±21	-	11±31	8±35	-10±38	14±33	-6±22	2±64	5±20	-16±63	1±38	-14±22	-6±35	13±82	7±28
NPL	-13±30	-11±31	-	-2±40	-21±43	3±39	-17±30	-9±68	-6±29	-27±66	-10±44	-25±30	-17±40	2±84	-4±35
IEN	-11±33	-8±35	2±40	-	-18±46	6±42	-14±33	-7±69	-3±33	-25±68	-8±46	-22±33	-14±43	4±86	-2±38
INTI	7±37	10±38	21±43	18±46	-	24±45	4±37	11±71	15±36	-7±69	10±49	-4±37	4±46	22±87	17±41
VNIIM	-16±31	-14±33	-3±39	-6±42	-24±45	-	-20±31	-12±68	-9±31	-30±67	-13±45	-28±32	-20±42	-1±85	-7±37
NRC	4±18	6±22	17±30	14±33	-4±37	20±31	-	7±64	11±17	-10±62	7±37	-8±19	0±33	19±81	13±26
PSB	-4±64	-2±64	9±68	7±69	-11±71	12±68	-7±64	-	4±63	-18±87	-1±71	-15±64	-8±69	11±102	5±66
PTB	-8±17	-5±20	6±29	3±33	-15±36	9±31	-11±17	-4±63	-	-22±61	-4±36	-19±17	-11±33	7±81	2±26
INMETRO	14±62	16±63	27±66	25±68	7±69	30±67	10±62	18±87	22±61	-	17±69	3±62	10±68	29±100	23±64
CENAM	-3±37	-1±38	10±44	8±46	-10±49	13±45	-7±37	1±71	4±36	-17±69	-	-15±37	-7±46	12±87	6±41
NIM	12±18	14±22	25±30	22±33	4±37	28±32	8±19	15±64	19±17	-3±62	15±37	-	8±33	27±81	21±26
MSL	4±33	6±35	17±40	14±43	-4±46	20±42	0±33	8±69	11±33	-10±68	7±46	-8±33	-	19±86	13±38
CSIR - NML	-15±81	-13±82	-2±84	-4±86	-22±87	1±85	-19±81	-11±102	-7±81	-29±100	-12±87	-27±81	-19±86	-	-6±83
SP	-9±26	-7±28	4±35	2±38	-17±41	7±37	-13±26	-5±66	-2±26	-23±64	-6±41	-21±26	-13±38	6±83	-

Table 7. Equivalence at 0.5 Lag (inductive)

	NIST	CSIRO - NML	NPL	IEN	INTI	VNIIM	NRC	PSB	PTB	INMETRO	CENAM	NIM	MSL	CSIR - NML	SP
NIST	-	-2±21	-18±29	-1±33	-3±37	26±31	4±18	-12±64	-11±17	27±62	-1±37	15±18	17±33	-2±81	0±26
CSIRO - NML	2±21	-	-16±31	1±35	-1±38	28±33	6±21	-10±64	-9±20	29±62	2±38	17±21	20±35	0±82	2±28
NPL	18±29	16±31	-	17±40	15±43	44±39	22±29	6±68	7±29	45±66	17±43	33±30	35±40	16±84	18±35
IEN	1±33	-1±35	-17±40	-	-2±46	27±42	5±33	-11±69	-10±32	28±67	0±46	16±33	18±43	-1±86	1±38
INTI	3±37	1±38	-15±43	2±46	-	29±44	7±37	-9±71	-8±36	30±69	2±49	18±37	20±46	1±87	3±41
VNIIM	-26±31	-28±33	-44±39	-27±42	-29±44	-	-22±31	-38±68	-37±30	1±66	-27±44	-11±31	-9±42	-28±85	-26±36
NRC	-4±18	-6±21	-22±29	-5±33	-7±37	22±31	-	-16±64	-15±17	23±62	-4±37	11±18	14±33	-6±81	-4±26
PSB	12±64	10±64	-6±68	11±69	9±71	38±68	16±64	-	1±63	39±86	11±71	27±64	29±69	10±102	12±66
PTB	11±17	9±20	-7±29	10±32	8±36	37±30	15±17	-1±63	-	38±61	11±36	26±17	29±32	9±81	11±25
INMETRO	-27±62	-29±62	-45±66	-28±67	-30±69	-1±66	-23±62	-39±86	-38±61	-	-28±69	-12±62	-10±67	-29±100	-27±64
CENAM	1±37	-2±38	-17±43	0±46	-2±49	27±44	4±37	-11±71	-11±36	28±69	-	16±37	18±46	-2±87	0±41
NIM	-15±18	-17±21	-33±30	-16±33	-18±37	11±31	-11±18	-27±64	-26±17	12±62	-16±37	-	2±33	-17±81	-15±26
MSL	-17±33	-20±35	-35±40	-18±43	-20±46	9±42	-14±33	-29±69	-29±32	10±67	-18±46	-2±33	-	-20±86	-18±38
CSIR - NML	2±81	0±82	-16±84	1±86	-1±87	28±85	6±81	-10±102	-9±81	29±100	2±87	17±81	20±86	-	2±83
SP	0±26	-2±28	-18±35	-1±38	-3±41	26±36	4±26	-12±66	-11±25	27±64	0±41	15±26	18±38	-2±83	-

Table 8. Equivalence at 0.0 Lead (capacitive)

	NIST	CSIRO - NML	NPL	IEN	INTI	VNIIM	NRC	PSB	PTB	INMETRO	CENAM	NIM	MSL	CSIR - NML	SP
NIST	-	-9±0	28±0	14±33	-6±40	-9±27	-7±16	18±63	4±17	-4±62	16±56	-3±18	1±35	25±81	9±23
CSIRO – NML	9±19	-	37±33	22±35	3±42	0±30	2±21	27±65	12±21	4±63	24±57	5±22	10±37	34±82	17±26
NPL	-28±31	-37±33	-	-14±42	-34±48	-37±38	-34±32	-10±69	-24±32	-32±67	-12±62	-31±32	-27±44	-2±86	-19±35
IEN	-14±33	-22±35	14±42	-	-19±50	-23±40	-20±34	4±70	-10±34	-18±68	2±63	-17±34	-13±45	12±86	-5±37
INTI	6±40	-3±42	34±48	19±50	-	-3±46	-1±41	24±74	9±41	1±72	21±67	2±42	6±51	31±89	14±44
VNIIM	9±27	0±30	37±38	23±40	3±46	-	2±28	27±67	13±28	5±66	25±60	6±29	10±42	34±84	18±32
NRC	7±16	-2±21	34±32	20±34	1±41	-2±28	-	25±64	10±18	2±62	22±56	3±19	8±35	32±82	15±24
PSB	-18±63	-27±65	10±69	-4±70	-24±74	-27±67	-25±64	-	-14±64	-22±87	-2±83	-21±64	-17±71	7±102	-9±66
PTB	-4±17	-12±21	24±32	10±34	-9±41	-13±28	-10±18	14±64	-	-8±62	12±56	-7±19	-3±35	22±82	5±24
INMETRO	4±62	-4±63	32±67	18±68	-1±72	-5±66	-2±62	22±87	8±62	-	20±81	1±62	5±69	30±101	13±64
CENAM	-16±56	-24±57	12±62	-2±63	-21±67	-25±60	-22±56	2±83	-12±56	-20±81	-	-19±56	-15±64	10±97	-7±58
NIM	3±18	-5±22	31±32	17±34	-2±42	-6±29	-3±19	21±64	7±19	-1±62	19±56	-	4±36	29±82	12±24
MSL	-1±35	-10±37	27±44	13±45	-6±51	-10±42	-8±35	17±71	3±35	-5±69	15±64	-4±36	-	24±87	8±38
CSIR – NML	-25±81	-34±82	2±86	-12±86	-31±89	-34±84	-32±82	-7±102	-22±82	-30±101	-10±97	-29±82	-24±87	-	-17±83
SP	-9±23	-17±26	19±35	5±37	-14±44	-18±32	-15±24	9±66	-5±24	-13±64	7±58	-12±24	-8±38	17±83	-

Table 9. Equivalence at 0.0 Lag (inductive)

	NIST	CSIRO - NML	NPL	IEN	INTI	VNIIM	NRC	PSB	PTB	INMETRO	CENAM	NIM	MSL	CSIR - NML	SP
NIST	-	5±19	-11±30	3±34	-4±40	14±27	14±16	7±63	-4±16	16±61	-6±55	10±17	7±34	-4±81	-14±22
CSIRO - NML	-5±19	-	-16±32	-2±36	-9±41	9±29	9±19	2±64	-9±19	12±62	-11±56	6±20	3±36	-9±82	-18±25
NPL	11±30	16±32	-	14±43	7±48	25±38	25±31	18±69	7±31	28±67	5±62	21±32	19±43	7±85	-2±34
IEN	-3±34	2±36	-14±43	-	-7±50	11±41	11±35	4±70	-7±35	13±69	-9±63	7±35	4±46	-7±87	-17±38
INTI	4±40	9±41	-7±48	7±50	-	18±46	18±40	11±73	0±40	20±72	-2±67	14±41	12±50	0±89	-10±43
VNIIM	-14±27	-9±29	-25±38	-11±41	-18±46	-	0±27	-7±67	-18±27	2±65	-20±60	-4±28	-7±41	-18±84	-28±31
NRC	-14±16	-9±19	-25±31	-11±35	-18±40	0±27	-	-7±63	-18±16	2±61	-20±56	-4±18	-7±35	-18±81	-28±23
PSB	-7±63	-2±64	-18±69	-4±70	-11±73	7±67	7±63	-	-11±63	10±87	-13±83	3±64	1±70	-11±102	-20±65
PTB	4±16	9±19	-7±31	7±35	0±40	18±27	18±16	11±63	-	20±61	-2±56	14±18	12±35	0±81	-10±23
INMETRO	-16±61	-12±62	-28±67	-13±69	-20±72	-2±65	-2±61	-10±87	-20±61	-	-22±81	-6±62	-9±68	-20±100	-30±63
CENAM	6±55	11±56	-5±62	9±63	2±67	20±60	20±56	13±83	2±56	22±81	-	16±56	13±63	2±97	-8±58
NIM	-10±17	-6±20	-21±32	-7±35	-14±41	4±28	4±18	-3±64	-14±18	6±62	-16±56	-	-3±35	-14±81	-24±23
MSL	-7±34	-3±36	-19±43	-4±46	-12±50	7±41	7±35	-1±70	-12±35	9±68	-13±63	3±35	-	-11±86	-21±38
CSIR - NML	4±81	9±82	-7±85	7±87	0±89	18±84	18±81	11±102	0±81	20±100	-2±97	14±81	11±86	-	-10±82
SP	14±22	18±25	2±34	17±38	10±43	28±31	28±23	20±65	10±23	30±63	8±58	24±23	21±38	10±82	-

Uncertainty budgets for each participant are given in the Appendix.

6. Conclusions

The CCEM International Comparison of 50/60 Hz Power began in June 1996 and was completed in May 2001. Of the 17 NMIs that performed tests during the comparison, 15 asked to be included in the final report. Each NMI performed tests on the traveling standard (power-to-dc converter) at 120 V, 5 A, 53 Hz at 1.0, 0.5 lead, 0.5 lag, 0.0 lead, and 0.0 lag power factors. This resulted in the 75 data points reported in the appendices, only a few of which deviated from the reference values by more than the expanded standard uncertainties. In more general terms, most of the NMIs' measurements agreed with the reference values to within 20 μW/(VA), which is only about four times larger than the recognized state-of-the-art for sinusoidal power and about 50 times better than the best commercial measurements made for revenue purposes.

As an increasing number of nonlinear loads influence power quality, international standards have been developed to address the issue of non-sinusoidal power and energy, and many NMIs have developed systems capable of measuring distorted power. It is the opinion of the authors that future international power comparisons should test non-sinusoidal as well as sinusoidal power.

7. References

1. "Key comparisons and mutual recognition arrangement," Bureau International des Poids et Mesures website: http://www.bipm.fr/enus/8_Key_Comparisons/key_comparisons.html

2. E. So et al, "NRC-NIST Comparison of Power Meter Calibrations at 60 Hz and Ranges up to 600 V, 100 A," IEEE Trans. Instrum., pp. 353-355, April 2001.

3. W. Moore et al., "An international comparison of power meter calibrations conducted in 1987," IEEE Trans. Instrum. Meas. IM 48, no. 2, pp. 418-421, April 1989.

4. P. Miljanić et al., "The development of a high precision time-division power meter," in CPEM 84 Dig., Delft, the Netherlands, pp 67-68, 1984.

5. N. Oldham et al., "An international comparison of 50/60 Hz power (1996-1999)," IEEE Trans. Instrum. Meas. Vol. 50, no. 2, April 2001.

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Appendix – Uncertainty Budgets

1. NIST

Power Bridge standard uncertainties (x10^{-6})

Uncertainty Evaluation	Parameter	Power Factor				
		1.0	**0.5 lead**	**0.5 lag**	**0.0 lead**	**0.0 lag**
Type A (ν=13)	Std dev of mean of polynomial fit	0.5	0.7	0.5	1	0.8
Type B (ν>10)	ac voltage	5	3	3		
(ν>10)	ac resistance	2	2	2		
(ν>10)	dissipation factor		3	3	3	3
(ν>10)	current comparator	2	3	3	3	3
(ν>10)	scaling transformers	3	3	3	3	3
Combined (k=1)		6	6	6	5	5

2. NRC

Power Bridge standard uncertainties (x10^{-6})

Uncertainty Evaluation	Parameter	Power factor		
		1.0	**0.5**	**0.0**
Type A (ν =18)	Traveling standard tests	1	1	1
Type B (ν >10)	ac voltage	5	3	
(ν > 10)	ac resistance	2	2	
(ν > 10)	dissipation factor		3	3
(ν > 10)	Current comparator	2	2	2
(ν > 10)	Scaling transformers	3	3	3
Combined (k=1)		6	6	5

3. CSIRO-NML

Source of uncertainty	Value	Type	r %	u_s			ν
				1.0 PF	0.866 PF	0 PF	
Dc input voltage	2 ppm	B	10	1.2	1.2		50
Dc voltage across dc shunt	2 ppm	B	10	1.2	1.2		50
Dc resistance of dc shunt	5 ppm	B	20	2.9	2.9		12
Voltage transformer ratio	1.2 ppm	B	10	1.2	1.2		50
Voltage transformer phase	2 μrad	B	10	0	1.8		50
Current transformer ratio	3 ppm	B	10	3	3		5
Current transformer phase	3 μrad	B	10	0	5.2		5
Current transformer ratio stability	5 ppm	B	20	3	3		12
Current transformer phase stability	10 μrad	B	20	0	10		12
Power comparator phase angle	5 μrad	B	20	0	5		12
Ac/dc transfer error of power comparator	2 ppm	B	5	1.2	1.2		200
Rounding of IUT error	0.5 ppm	B	0	0.5	0.5		∞
Random component of calibration process	1, 2.5 ppm	A		1	2.5		4

Repeatability of IUT error over 4 days	2.7, 4.1 ppm	A		2.7	4.1		3
Zero power-factor random error	3.5 µrad	A				3.5	5
Zero power-factor repeatability over 4 days	5.5 µrad	A				5.5	3
Zero power-factor rounding	0.5 µrad	B	0			0.5	∞
Phase angle of thermal wattmeter	2.0 µrad	A				2.0	5
TOTAL u_s				6.3	14.5	6.8	
ν				50	45	6	

Expressing uncertainties in terms of µwatts/VA and rounding.

	Power factor		
	1.0	0.5	0.0
Uncertainty Degrees of freedom	7 50	8 45	7 6

4. NPL

Uncertainty Component	*Amplitude (uW/VA)*	*Phase (uW/VA)*
Sampling ADC Heads	10	3
IVD	1	1
CT	11	12
Resistor	4	2
Total NPL System	15	12

Power Factor	*NPL System (uW/VA)*	*DVM (uW/VA)*	*Type A (uW/VA)*	*Total (k=1) (uW/VA)*
UPF	15	4	2	**16**
0.5	13	4	2	**14**
ZPF	12	4	2	**14**

5. IEN

Uncertainty components	**Type**		**Amplitude** [10^{-6}]		**Phase** [µrad]
Voltage at 5 V	B	ru_{U5V}	6.7		-
Ratio 120 V- 5 V	B	ru_{rU}	2.1	$u_{\varphi rU}$	2.1
Ratio 5 V - 0.1 V	B	ru_{rI}	2.2	$u_{\varphi ri}$	2.2
AC resistor	B	ru_R	3		
Ratio of the current transformer	B	ru_{rappI}	5		
Current to voltage converter	B			$u_{\varphi rappI}$	15
Uncertainty of the power measurement (k=1)					
Power factor 1			14.9		
Power factor 0.5			15.2		
Power factor 0			15.3		

6. INTI

power factor = 1						
Uncertainty source	**Symbol**	c_i	u_i	n_i	$c_i^2 . u_i^2$	
Type A	u_A	1	3.0E-06	19	9.00E-12	
DC Voltage	U_{dc}	2	2.0E-06	30	1.60E-11	
Resistance	R	1	2.0E-06	30	4.00E-12	
thermal converter ac-dc difference	d_{TC}	1	4.0E-06	30	1.60E-11	
cross influencies	*o.i.*	1	3.0E-06	30	9.00E-12	
magnitude error of the voltage transformer	F_U	1	5.0E-06	30	2.50E-11	
magnitude error of the current transformer	F_i	1	5.0E-06	30	2.50E-11	
phase error of the voltage transformer	d_U	0	6.0E-06	30	0.00E+00	
phase error of the current transformer	d_i	0	6.0E-06	30	0.00E+00	
Combined Uncertainty (k=1)	u_c				**10**	µW/(VA)
power factor = 0.5						
Uncertainty source	**Symbol**	c_i	u_i	n_i	$c_i^2 . u_i^2$	
Type A	u_A	1	4.0E-06	19	1.60E-11	
DC Voltage	U_{dc}	2	3.0E-06	30	3.60E-11	
Resistance	R	1	4.0E-06	30	1.60E-11	
thermal converter ac-dc difference	d_{TC}	1	4.0E-06	30	1.60E-11	
cross influencies	*o.i.*	1	4.0E-06	30	1.60E-11	
magnitude error of the voltage transformer	F_U	0.5	5.0E-06	30	6.25E-12	
magnitude error of the current transformer	F_i	0.5	5.0E-06	30	6.25E-12	
phase error of the voltage transformer	d_U	0.866	6.0E-06	30	2.70E-11	
phase error of the current transformer	d_i	0.866	6.0E-06	30	2.70E-11	
Combined Uncertainty (k=1)	u_c				**13**	**mW/VA**
power factor = 0.0						
Uncertainty source	**Symbol**	c_i	u_i	n_i	$c_i^2 . u_i^2$	
Type A	u_A	1	5.0E-06	19	2.50E-11	
DC Voltage	U_{dc}	2	4.0E-06	30	6.40E-11	
Resistance	R	1	5.0E-06	30	2.50E-11	
thermal converter ac-dc difference	d_{TC}	1	4.0E-06	30	1.60E-11	
cross influencies	*o.i.*	1	6.0E-06	30	3.60E-11	

magnitude error of the voltage transformer	F_U	0	5.0E-06	30	0.00E+00	
magnitude error of the current transformer	F_i	0	5.0E-06	30	0.00E+00	
phase error of the voltage transformer	d_U	1	6.0E-06	30	3.60E-11	
phase error of the current transformer	d_i	1	6.0E-06	30	3.60E-11	
Combined Uncertainty (k=1)	u_c				**16**	**mW/VA**
c_i = sensitivity coefficient						
u_i = standard uncertainty						
n_i = degrees of freedom						

7. VNIIM

Uncertainty budget of measurements (μW/VA)

Type	Source of uncertainty	Power factor		
		1.0	0.5	0.0
A (ν = 50)	Standard deviation of reading	3.2	4.5	5.8
B (ν = 20)	DC Voltage (120V)	4.0	2.0	
B (ν = 20)	DC Voltage on Shunt	3.0	2.0	
B (ν = 20)	DC Ref. Resistor	2.0	1.0	
B (ν = 30)	AC/DC voltage divider error	3.0	2.0	
B (ν = 30)	Voltage divider phase error		6.3	6.3
B (ν = 30)	AC/DC Current Shunt error	2.0	2	
B (ν = 30)	Current Shunt phase error		4.8	4.8
B (ν = 10)	AC/DC Current Shunt self heating error		5.3	
B (ν = 40)	AC/DC Power Comparator error	5.0	3	
B (ν = 40)	Power Comparator phase error		6.8	6.8
	Combined (k = 1)	9	14	12

8. PSB

Uncertainty budget of the measurements (μW/VA)

Uncertainty	Parameter		Power	Factor
		1.0	0.5	0.0
Type A		4	5	3
Type B				
	Calibration uncertainty of standard	30	30	30
	Drift of standard	2	2	5

	Multimeter (Standard)	2	1	1
	Multimeter (UUT)	3	2	1
Combined	(k=1)	31	31	31

9. PTB

Uncertainty Evaluation	**Parameter**	**Uncertainty (k=1)**
Type A	Traveling std. observations	3.5×10^{-6} (ν = 10)
Type B	Voltage transformer	$\Delta\alpha_u$, $\Delta\beta_u = 0.5 \times 10^{-6}$ (ν >10)
	Current transformer	$\Delta\alpha_i$, $\Delta\beta_i = 0.5 \times 10^{-6}$ (ν>10)
	Ac Shunt	$\Delta\alpha_r$, $\Delta\beta_r = 0.5 \times 10^{-6}$ (ν>10)
	Sampling and DFT	ΔA, $\Delta B = \pm 0.4 \times 10^{-6}$ (upper and lower limits)
	RMS Voltmeter	$\Delta U_{DVM}/U_n = 1 \times 10^{-6}$ (ν >10)
Combined		$<5\times 10^{-6}$ (k = 1)

10. INMETRO

X_i	**Estimate** x_{ei}	Δx_i (*)	**Standard Uncertainty** $u(x_i)$	Sensitivity Coefficients c_{Pi}	**Uncertainty Contribution** $u_i(y)$ **(W)**	$u_i^2(y)$ **(W²)**
V	120 V	__	0,0012 V	$1{,}9998\cdot 10^{-3} n_R$ A	$2{,}39\cdot 10^{-6}\ n_R$	$5{,}76\cdot 10^{-12} n_R^2$
R	120006,6 Ω	__	0,7 Ω	$-1{,}0\cdot 10^{-6} n_R$ A^2	$-7{,}0\cdot 10^{-7} n_R$	$4{,}90\cdot 10^{-13} n_R^2$
D	$8{,}1\cdot 10^{-5}$	__	$2{,}5\cdot 10^{-5}$	$-0{,}111309 n_C$ W	$-2{,}8\cdot 10^{-6} n_C$	$7{,}84\cdot 10^{-12} n_C^2$
C	23215,6 pF	__	0,7 pF	$-388{,}42 n_C$ V^{2}Hz	$-2{,}72\cdot 10^{-10} n_C$	$7{,}39\cdot 10^{-20} n_C^2$
F	53 Hz	__	$1{,}1\cdot 10^{-4}$ Hz	$2{,}7\cdot 10^{-8} n_C$ V^{2}F	$-3{,}0\cdot 10^{-12} n_C$	$9{,}00\cdot 10^{-24} n_C^2$
A	0	$1\cdot 10^{-5}$	$5{,}8\cdot 10^{-6}$	$0{,}119993 n_R$ W	$6{,}95\cdot 10^{-7} n_R$	$4{,}84\cdot 10^{-13} n_R^2$
B	0	$1\cdot 10^{-5}$	$5{,}8\cdot 10^{-6}$	$0{,}111309 n_C$ W	$6{,}45\cdot 10^{-7} n_C$	$4{,}17\cdot 10^{-13} n_C^2$

* Error limits.

Combined Uncertainty	**1.0 PF**	**0.5 PF**	**0.0 PF**
Active Power (w_P)	30	30	30

11. CENAM

PARAMETERS	POWER FACTOR		
	1	0.5	0
Tipo A, std. dev. of ROTEK	1	1	1
Tipo B, AC Voltage	5	5	5
AC Resistance	12	12	
Dissipation factor		5	5
Current comparator + current transformers	10	10	26
Combined Uncertainty (k=1)	**16.4**	**17.2**	**27.0**

12. NIM

Type B evaluation in the test of 1998 (10^{-6})

Uncertainty Factor k=1	PF=1.0	Pf=0.5	PF=0.0
1. IVD and CT Ratio error□1□Angler error□1	SQR(1^2+1^2)=1.41	SQR($1^2+1^2+(1\times tg60°)^2+(1\times tg60°)^2$)/2 =1.41	SQR(1^2+1^2)=1.41
2. DC power 2.1. Dc voltage reference 0.5/3 2.2. DVM stability 2.3. DC resistor 0.6	1.31 0.33 SQR(0.5^2+1^2)=1.12 0.6	1.57/2=0.78 0.33 SQR(1^2+1^2)=1.41 0.6	0 0 0 0
3. compensation from emf 1	1	1	1
4. Synchronous with ac power stability	1.33	1.33	1.33
5. AC/DC transfer difference	1	1	1
6. DC voltage output measured by DVM	1	1	1
Combined	2.91 (3) (1)	2.71 (3) (1)	2.60 (3) (1)

(1): The final values are evaluated as 3.

Type B evaluation in the test of 2000 (10^{-6})

Uncertainty Factor k=1	PF=1.0	Pf=0.5	PF=0.0
1. Evaluation in 1998	3	3	3
2. Compensation for IVD and CT	4	4	4
Combined	5	5	5

Budget for the test of 2000 (10^{-6})

Power factor	Type A		Type B		u_C	v_{eff}	$t_{0.68}$□v_{eff}□	**U**$_C$ (2)
	St.dev	v	value	v				
1.0	0.6	17	5	8	5.04	8.3	1.07	5.4 (6)
0.5C	0.7	11	5	8	5.05	8.3	1.07	5.4 (6)
0.5L	0.6	12	5	8	5.04	8.3	1.07	5.4 (6)
0.0C	0.6	11	5	8	5.04	8.3	1.07	5.4 (6)
0.0L	0.5	10	5	8	5.02	8.1	1.07	5.4 (6)

(2): The calculation results are 5.4 and the final values are evaluated as 6.

13. MSL

		Power Factor					
		1		**0.5**		**0.0**	
Uncertainty	**Parameter**	standard uncertainty (mW/W)	degrees of freedom	standard uncertainty (mW/W)	degrees of freedom	standard uncertainty (mW/W)	degrees of freedom
Type A	standard deviation of readings	5.4	15.9	2.7	13.7	5.4	13.7
Type B	AC voltage	7.8	5.2	3.9	5.2		
	current shunt resistance	8.0	3.1	4.0	3.1		
	resistive voltage divider ratio	3.0	3.1	1.5	3.1		
	bridge components	6.0	6.9	3.0	6.9		
	phase reference standard (note 1)			11.7	5.1	13.5	5.1
	capacitor dissipation factor (note 2)			3.2	4.1	3.7	4.1
	current shunt phase (note 2)			5.2	3.1	6.0	3.1
	resistive divider phase (note 2)			2.8	4.1	3.2	4.1
	combined standard uncertainty and degrees of freedom	14.1	17.3	15.2	13.1	16.4	10.4
note 1: the capacitor dissipation factor, current shunt, and voltage divider phases were calibrated against the same phase reference standard.							
note 2: additional uncertainty arising from comparison with the phase reference standard.							

14. CSIR-NML

Quantity X_i	Standard uncertainty $u(x_i)$	Probability distribution method of evaluation(A,B)	Sensitivity coefficient c_i	Uncertainty contribution $u_i(R)$ µW/W	Degrees of freedom ν_i ν_i
Calibration of Internal Capacitance	20 µW/W	Normal	1	10	>200
Calibration of Internal Resistance	20 µW/W	Normal	1	10	>200
Calibration of 4920 AC Measuring Standard	50 µW/W	Normal	1	25	>200
Calibration of Voltage Divider	10 µW/W	Normal	1	5	>200

System Error	5 µW/W	Rectangular	1	2,9	>200
Calibration of Input Capacitor	10 µW/W	Normal	1	5	>200
Calibration of Output Capacitor	10 µW/W	Normal	1	5	>200
AC Source Short Term Stability	3 µW/W	Normal	1	1,5	>200
Calibration of Long Scale Digital Multi-Meter	10 µW/W	Normal	1	5	>200
Power Factor	1 µW/W	Rectangular	1	0,6	>200
Environment	5 µW/W	Rectangular	1	2,9	>200
Repeatability of Reference Voltage	2,3 µW/W	Normal	1	2,3	>200
Repeatability of Measurements	4 µW/W	Normal	1	4	5
				$u(R) =$ 31,5	$\nu_{\text{eff}} =$ 19115

15. SP:

Source of uncertainty at power factor = 1.0	Standard uncertainty (µW/W)	probability distribution	Sensitivity coefficient	Contribution to the std uncert (µW/W)
DSWM voltage, traceability & stability	10	normal	1	10
DSWM current, traceability & stability	10	normal	1	10
DSWM phase, traceability & stability	7	normal	0	0
Measurement setup	4	rectangular	1	4
Std uncert of measurement	2	normal	1	2
Standard uncertainty, k=1				14,9

Source of uncertainty at power factor = 0,5	Standard uncertainty (µW/W)	probability distribution	Sensitivity coefficient	Contribution to the std uncert (µW/W)
DSWM voltage traceability & stability	10	normal	0,5	5
DSWM current traceability & stability	10	normal	0,5	5
DSWM phase traceability & stability	7	normal	0,87	6
Measurement	4	rectangular	1	4
Std uncert of measurement	2	normal	1	2
Standard uncertainty, k=1				10,3

Source of uncertainty at power factor = 0	Standard uncertainty (µW/W)	probability distribution	Sensitivity coefficient	Contribution to the std uncert (µW/W)
DSWM voltage traceability & stability	10	Normal	0	0
DSWM current traceability & stability	10	Normal	0	0

DSWM phase traceability & stability	7	Normal	1	7
Measurement	4	rectangular	1	4
Std uncert of measurement	2	Normal	1	2
Standard uncertainty, k=1				8,3

The standard uncertainty at power factor 1 is 15 µW/W relative the apparent power
The standard uncertainty at power factor 0,5 is 11 µW/W relative the apparent power
The standard uncertainty at power factor 0 is 9 µW/W relative the apparent power