Technical Protocol

Key Comparison SIM.EM.RF-K5b.CL
Scattering Coefficients by Broad-Band Methods
2 GHz - 18 GHz - Type N Connector

H. Silva and G. Monasterios
RF & Microwaves Metrology Laboratory
Instituto Nacional de Tecnología Industrial
Argentina

Version 1.0, September 21, 2012

Contents

1 Introduction

This key comparison is based on the responsibility of the Inter-american Metrology System (SIM) through the CIPM Mutual Recognition Agreement (MRA) to ensure the measurement capabilities of National Metrology Institutes (NMIs) in America.

Through a key comparison, the SIM provides metrology laboratories in the region the ability to demonstrate their achievements in high frequency measurements by linking their results to CCEM through a laboratory that has participated in both comparisons.

INTI proposes the realization and piloting of this first comparison on RF within the SIM, which consists in S-parameter measurements in the frequency range from 2 GHz to 18 GHz in an unbalanced coaxial system with Type N connector.

2 Traveling standards

2.1 Description of the standards

The traveling standards were chosen based on those used in the CCEM Key Comparison [3] in order to link both comparisons. These standards are commercially available devices covering some of the most important cases that arise in the measurement of S-parameters in a frequency range up to 18 GHz.

2.2 Details of traveling standards

The specifications of the standards are given below:

Description	Nominal Value	Model	Serial Number	Connector
Attenuator	3 dB	HP 8491B(opt.003)	MY39266530	Male/Female
Attenuator	20 dB	HP 8491B(opt.020)	MY39266597	Male/Female
Matched Load	50 Ω (VSWR=1.0)	HP 909F	55719	Male
Mismatched Load	VSWR=2.0	Maury 2562G	9006	Male

Table 1: *Traveling standards*

2.3   Photograph of traveling standards

Figure 1: *One-port devices*

Figure 2: *Two-port devices*

3   Quantities to be measured

Scattering parameters of Type N connector devices selected for this comparison will be measured from 2 GHz to 18 GHz (inclusive) in 1 GHz steps.

For one-port devices (matched and mismatched loads) the measurand is the complex-valued reflection coefficient S_{11}. The VSWR 1.0 (matched) load and VSWR 2.0 (mismatched) load were chosen to

perform reflection measurements with low and high magnitude values.

When measuring two-port devices (3 dB and 20 dB attenuators) the measurands are the four complex-valued S-parameters (S_{11}, S_{21}, S_{12} and S_{22}). The values of 3 dB and 20 dB were chosen to cover transmission measurements with high and low magnitude values.

The S-parameters must be informed in the form:

$$S_{ab} = x + jy \tag{1}$$

where x and y are the real and imaginary parts of the reported S-parameter, subindex a corresponds to reflected or transmitted wave port and subindex b corresponds to incident wave port. Both the real and imaginary parts are expressed in linear units, and $j = \sqrt{-1}$ is the imaginary unit.
The uncertainty of each measured S-parameter must be given in the form of combined standard uncertainty of the real part $u(x)$, imaginary part $u(y)$ and correlation coefficient between them, $u(x, y)$ (see section 7 for further details).

Note: For two-port devices, the male port will be referred to as port number 1 for the purposes of this protocol.

4 Evaluation of results

The analysis of the results will be done only for S_{11} (for one-port devices) and S_{21} (for two-port devices) in 2 GHz, 9 GHz and 18 GHz to reduce the amount of data to be analyzed for the comparison. This three frequencies were chosen to cover the low, medium and high frequency range.
In order to evaluate and compare the data reported by laboratories taking part in this comparison exercise, the following quantities will be calculated for each measurand in a way similar to [4], based on the guidelines in [1]:

4.1 Comparison reference value

The comparison reference value or CRV will be determined using an unweighted mean of the measurement results reported by the participants:

$$z_m = \frac{1}{N} \sum_{i=1}^{N} z_i \tag{2}$$

where z_m is the CRV and z_i is the value reported by laboratory i and N is the total number of participants in the comparison exercise.
Consistency test is not applied in this comparison and all reported values contribute the same amount to the computation of the CRV.

The CRV uncertainties are determined by a 2×2 covariance matrix of the form:

$$V_m = \begin{pmatrix} u^2(x_m) & u(x_m, y_m) \\ u(y_m, x_m) & u^2(y_m) \end{pmatrix} \tag{3}$$

where:

$$u^2(x_m) = \frac{1}{N(N-1)} \sum_{i=1}^{N} (x_i - x_m)^2 \qquad (4)$$

$$u^2(y_m) = \frac{1}{N(N-1)} \sum_{i=1}^{N} (y_i - y_m)^2 \qquad (5)$$

$$u(x_m, y_m) = \frac{1}{N(N-1)} \sum_{i=1}^{N} (x_i - y_m)(x_i - y_m) \qquad (6)$$

In (4), (5) and (6) x_m and y_m are the real and imaginary parts of the CRV. x_i and y_i are the real and imaginary parts of the individual reported values.

4.2 Degrees of equivalence

4.2.1 DoE with respect to the CRV

The degree of equivalence (or DoE) d_i for laboratory i with respect to the CRV is given by:

$$d_i = z_i - z_m \qquad (7)$$

The covariance matrix of this DoE for the unweighted mean CRV computation (as presented in section 4.1) is obtained by means of the expression:

$$V_{d_i} = V_m + (1 - \frac{2}{N})V_i \qquad (8)$$

where V_i is the covariance matrix resulting from measurement uncertainties reported by the participants (see section 7 for further details).

4.2.2 Bilateral DoE

The degree of equivalence d_{ij} between participants i and j, or bilateral DoE, is given by:

$$d_{ij} = z_i - z_j \qquad (9)$$

where z_i and z_j are the measurement values reported by lab i and lab j, respectively.
The covariance matrix of this bilateral DoE is simply obtained by:

$$V_{d_{ij}} = V_i + V_j \qquad (10)$$

where V_i and V_j are the covariance matrices resulting from measurement uncertainties reported by each laboratory.

4.2.3 Dimension reduction of DoE

The degrees of equivalence previously defined are complex-valued magnitudes. Proper evaluation of the degrees of equivalence requires a reduction in the number of dimensions of these parameters. This is accomplished by means of the expression detailed in [8]:

$$y = |d| \tag{11}$$

$$dy = |d|\sqrt{(d^T \ V_d^{-1}d)^{-1}k^2} \tag{12}$$

where d may be d_i for the degree of equivalence with respect to the CRV, or d_{ij} for the bilateral DoE.

The factor k is a suitable coverage factor chosen to give a 95% confidence level. Assuming that d follows a bivariate Gaussian distribution and the degrees of freedom are sufficiently high [11], then $k = 2.45$.

In (12), dy is the distance from y to the confidence boundary through the origin of the coordinate system and is referred to as a confidence indicator.

4.3 Proposal for linking to CCEM.RF-K5b.CL

In accordance with the linking methods detailed in [9] and [10], the following methodology for linking the results of this SIM comparison with those from the CCEM.RF-K5b.CL comparison [4] is proposed for discussion by all participants, introducing a correction factor c :

$$c = d_{L,ccem} - d_{L,sim} \tag{13}$$

where:
- L refers to a laboratory that has participated in both CCEM and SIM comparisons, acting as a link between them.
- $d_{L,sim}$ is the degree of equivalence with respect to the CRV from SIM comparison for linking lab L.
- $d_{L,ccem}$ is the degree of equivalence with respect to the KCRV from CCEM comparison for linking lab L.

The degree of equivalence $d_{i,ccem}$ with respect to the KCRV from the CCEM comparison for lab i in this SIM comparison can be calculated as follows:

$$d_{i,ccem} = d_i + c \tag{14}$$

where d_i is the degree of equivalence of lab i with respect to the CRV from this SIM comparison.

The following expression would be adequate to obtain the covariance matrix of $d_{i,ccem}$:

$$V_{d_{i,ccem}} = V_i + V_{KCRV} + V_d \tag{15}$$

where:
- V_i is the lab i covariance matrix.
- V_{KCRV} is the KCRV covariance matrix from CCEM.RF-K5b.CL comparison.

- V_d is a covariance matrix associated with the imperfect reproducibility of the results of the linking laboratory between CCEM and SIM comparison. This matrix should be supplied by the linking laboratory.

In addition, the expression (15) requires the absence of any correlation between the covariance matrices that appear in (15), and all the units must be the same.

As in section 4.2, transfer uncertainty due to drift or instabilities associated to traveling devices is not considered in this proposal for the computation of the degree of equivalence with respect to the KCRV from CCEM.RF-K5b.CL comparison (if any abnormal instability or drift is observed during the course of the comparison, equations (3) and (15) should both be modified to include this uncertainty contribution).

The degrees of equivalence $d_{i,ccem}$ requires a reduction in the number of dimensions. This is accomplished as explained in 4.2.3.

5 Organization

5.1 Pilot laboratory contacts

The pilot laboratory contacts are:

Hernando Silva (primary contact)
Email: metrologiarf@inti.gov.ar

Guillermo Monasterios (secondary contact)
Email: guillem@inti.gov.ar

Phone: +(5411)4724 6367
Fax: +(5411)4754 5194

INTI - Instituto Nacional de Tecnología Industrial
Av. General Paz 5445 - Edificio 42
B1650KNA - San Martín
Provincia de Buenos Aires
República Argentina

5.2 Participants

The following institutes (in alphabetical order by country) will take part in this key comparison:

Institute	Country	Name	Department	e-mail
INTI	Argentina	Hernando Silva	RF & Microwave Metrology Laboratory	hsilva@inti.gov.ar
NRC-INMS	Canada	Alain Michaud		Alain.michaud@nrc-cnrc.gc.ca
KRISS	Korea	Jin-Seob Kang	Center for Electromagnetic Wave	jinskang@kriss.re.kr
CENAM	Mexico	Susana Padilla	Scattering Parameters Laboratory	spadilla@cenam.mx
NIST	USA	Ronald Ginley	Radio Frequency Electronics Group (818.01)	rginley@boulder.nist.gov

Table 2: *List of participants*

5.3 Time schedule

The expected time required for a participant to take the measurements and ship the traveling standards to the next participant is 5 weeks.

The report with the results should be sent to the pilot laboratory within 1 month after taking the measurements.

The pilot laboratory will measure the devices at the beginning and end of the comparison.

If there are any difficulties in keeping the agreed schedule, the pilot laboratory should be contacted immediately by email to agree on how to proceed.

Institute	Country	Start date	Finish date	Comments
INTI	Argentina		October 22, 2012	Initial measurements
In transit	-			
CENAM	Mexico	November 5, 2012	Novembre 26, 2012	
In transit	-			
NIST	USA	December 10, 2012	January 14, 2013	Includes two extra weeks for christmas & new year holidays
In transit	-			
NRC-INMS	Canada	January 28, 2013	February 18, 2013	
In transit	-			
KRISS	Korea	March 4, 2013	March 25, 2013	
In transit	-			
INTI	Argentina	April 8, 2013		Final measurements

Table 3: *Proposed time schedule*

5.4 Transportation and financial aspects

Upon shipping the devices to the next laboratory, participants should notify the pilot laboratory and the next participant laboratory by email.
Similarly upon arrival, the previous laboratory and the pilot laboratory should be informed.

Each participant is responsible for arranging and paying the transportation and insurance (including customs clearance where necessary) of the devices since the arrival at their laboratory until arrival at the subsequent laboratory.
The value of insurance can be assumed to be USD 3200.

5.5 Unpacking, handling and packing

On arrival at each participating laboratory, the traveling standards and packaging will be carefully inspected for possible damage during shipment.
The pin depth of the center conductor should be checked on each element before starting with the measurements to prevent damage, and report the results in the confirmation of receipt according to Table 5 in Annex A.
If any damage is found, the pilot laboratory should be contacted immediately to agree on how to proceed.

Extreme care should be taken when handling the traveling standards in order to avoid damaging the center conductor pin and to maintain the stability of the devices in the course of the intercomparison.

Before the devices are shipped to the next laboratory the contents of the case should be checked against the enclosed packing list.

6 Measurement instructions

Every participant laboratory is responsible to apply their own technical procedures to successfully complete the measurements and to avoid damages of the traveling standards during the measurement process.

7 Uncertainty of measurement results

As stated in section 3, each S-parameter measured must be reported in the form of a real part x plus its combined standard uncertainty $u(x)$, and an imaginary part y plus its combined standard uncertainty $u(y)$. If it is assumed that $u(x) = u(y)$, then only a single value of uncertainty needs to be given.
Additionally, the covariance $u(x, y)$ between the real and imaginary parts of S_{ab} may also be given (or, alternatively, the correlation coefficient $r(x, y)$). This value will be assumed to be zero when not included in the results report.
The real and imaginary parts uncertainties $u(x)$ and $u(y)$ together with the correlation coefficient

$u(x, y)$ determine a 2×2 covariance matrix V_i for the uncertainty of a complex-valued measurand [11]:

$$V_i = \begin{pmatrix} u^2(x) & u(x, y) \\ u(y, x) & u^2(y) \end{pmatrix} \tag{16}$$

or, in terms of the correlation coefficient:

$$V_i = \begin{pmatrix} u^2(x) & r(x, y)u(x)u(y) \\ r(y, x)u(x)u(y) & u^2(y) \end{pmatrix} \tag{17}$$

In the above matrices, $u(x, y) = u(y, x)$ and $r(x, y) = r(y, x)$ so these matrices are symmetric.

The methods used to evaluate the measurement uncertainties are determined by each laboratory, which shall report a detailed uncertainty budget for each measured value (see section 8). The reference document [12] is a wide-spread guidance to deal with this task in the case of VNA measurements.

8 Report of results

The results of the measurement quantities (Annex A), a detailed evaluation of the uncertainties for each measurement (Annex B) and a short description of the method used for the measurements (Annex C) should be reported with the format given in the annexes. The tables for this purpose will be sent by email to all participants and will consist of two files, a Word format file for the descriptions and an Excel format file for the data.

Note: According to Section 4, the only necessary data required to be reported in Annex B (Uncertainty budget) corresponds to uncertainties of S_{11} in the case of one-port devices and S_{21} in the case of attenuators at three frequencies: 2 GHz, 9 GHz and 18 GHz. This gives a total of 12 complex measurands, that is, 4 devices at 3 frequencies per device for subsequent analysis.

Reports should be sent to the pilot laboratory via email as an attachment and as a signed paper version via conventional post.

9 Comparison report

Within 3 months after completion of the circulation, the pilot laboratory will prepare a first Draft A Report and send it to participants for comments.
This report will include:

- Measurement results of participating labs with their uncertainties.
- Computations of the CRV with their uncertainties.
- Computation of degrees of equivalence with respect to the CRV, Bilateral DoE, and degrees of equivalence with respect to the KCRV from CCEM comparison.
- Uncertainty budgets for each measurand as reported by participants.
- A summary of the measurement techniques employed by each participating laboratory.

If any anomalous results are observed for some participants, it will be informed before the emission of the Draft A Report to allow them to check their results.
Subsequently the procedure outlined in the CCEM guidelines [2] will be followed.

References

[1] Measurement comparisons in the context of the CIPM MRA. CIPM MRA-D-05, Version 1, October 2010.

[2] CCEM guidelines for planning, organizing, conducting and reporting key, supplementary and pilot comparisons, 2007, 30 pp.

[3] C.P.Eio; M.J.Maddock; N.M.Ridler; M.J.Salter, "CCEM.RF-K5b.CL Technical Protocol: Scattering Coefficients by Broad-Band Methods, 2-18 GHz - Type N Connector", Version 1, August 2003.

[4] C.P.Eio, "CCEM Key Comparison CCEM.RF-K5b.CL (GT-RF/92-3) Scattering Coefficients by Broad-Band Methods, 2-18 GHz - Type N Connector, Final Report of the Pilot Laboratory", May 2010.

[5] R.Judaschke, "CCEM.RF-K25.W Technical Protocol:RF power from 33 to 50 GHz in waveguide", May 2010.

[6] M.G.Cox, "The evaluation of key comparison data:An introduction", Metrologia, 2002, 39, pp 587-588.

[7] M.G.Cox, "The evaluation of key comparison data", Metrologia, 2002, 39, pp 589-595.

[8] M.Zeier, "On the analysis of multidimensional quantities in measurement comparison", CPEM 2006 Conference Digest, Torino, July 2006, pp 458-459.

[9] F.Delahaye; T.J.Witt, "Linking the results of 10 pF capacitance key comparisons CCEM-K4 and EUROMET 345", Precision Electromagnetic Measurements, 2002. Conference Digest 2002 Conference on , vol., no., pp. 526-527, 2002.

[10] B.Wood; A.Steele; R.Douglas, "Linking methodology with application to CCEM-K4 and EUROMET 345", CCEM/WGKC 01-17.

[11] N.M.Riddler; M.J.Salter, "An approach to the treatment of uncertainty in complex S-parameter measurements", Metrologia, 2002, 39, pp 295-302.

[12] "EA Guidelines on the Evaluation of Vector Network Analysers (VNA)". Euramet /cg-12/v 2.0, March 2011.

Annex A: Results

Laboratory: ....
Traveling standard: ....

Frequency GHz	Measurand $S_{a,b}$	$u(Re(S_{11}))$ combined 1-sigma	$u(Im(S_{11}))$ combined 1-sigma	r(x,y)
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				
12				
13				
14				
15				
16				
17				
18				

Table 4: *Table of results*

Device	Pin depth $[\mu m]$ Male port	Pin depth $[\mu m]$ Female port
Attenuator 3 dB		
Attenuator 20 dB		
Matched Load		-
Mismatched Load		-

Table 5: *Pin depth measurements*

Annex B: Uncertainty budget

Laboratory: ....
Traveling standard: ....
$S_{a,b}$ **@2 GHz**

Quantity	Standard Uncertainty $u(x_i)$	Probability distribution	Sensitivity coefficient c_i	Uncertainty contribution $c_i u(x_i)$
-	-	-	U_{total}	

Table 6:   *Uncertainty budget - 2 GHz*

$S_{a,b}$ **@9 GHz**

Quantity	Standard Uncertainty $u(x_i)$	Probability distribution	Sensitivity coefficient c_i	Uncertainty contribution $c_i u(x_i)$
-	-	-	U_{total}	

Table 7:   *Uncertainty budget - 9 GHz*

$S_{a,b}$ **@18 GHz**

Quantity	Standard Uncertainty $u(x_i)$	Probability distribution	Sensitivity coefficient c_i	Uncertainty contribution $c_i u(x_i)$
-	-	-	U_{total}	

Table 8:   *Uncertainty budget - 18 GHz*

Annex C: Description of the measurement method

Laboratory: ....

Please fill out the lines below including a description of the measurement method, traceability route and instruments used in the present comparison:

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This and any other relevant information provided by your laboratory will be included in the final report.