CCEM KEY COMPARISON CCEM.RF-K1d.W (GT-RF/97-3)

Measurement Techniques and Results of an Intercomparison

for RF Power in R 900

at frequencies of 75 and 94 GHz.

Draft B Report of the Pilot Laboratory

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ABSTRACT

A measurement comparison of effective efficiency has been carried out between four national metrology laboratories in waveguide R 900 at 75 and 94 GHz. The original indentification of the intercomparison was GT-RF/97/3 but was subsequently renumbered as CCEM.RF-K1d.W. One waveguide thermistor mount has been measured. The following four national laboratories of metrology participated NPL (United Kingdom), BNM-LCIE (France), NIST (United States of America), PTB (Germany). The National Physical Laboratory (United Kingdom) acted as the pilot laboratory for the comparison. Good agreement between the values provided has been observed. It can be noted from tables 2 to 5 of Appendix A that the degrees of equivalence for all the values reported, with respect to the reference value and between pairs of laboratories, are less than their associated uncertainty, at a level of confidence of 95%.

1. INTRODUCTION

During the BIPM meeting in France on 23 June 1998 an interest was shown in undertaking an international comparison in Waveguide Size R900. The comparison, detailed in Table IV of the Working Group Report [1], suggested a measurement of the Effective Efficiency of a Bolometer Mount at 94 GHz with 75 GHz and 110 GHz as optional frequencies. The intercomparison was given the identification GT-RF/97/3 but was subsequently renumbered as CCEM.RF-K1d.W. All participants reported results for effective efficiency at 94 GHz and three participants reported results at 75 GHz. Three of the four participants also report measurements of the Voltage Reflection Coefficient (Magnitude) of the Bolometer Mount. All the reported results are included in this report.

2. TRAVELLING STANDARD AND EFFECTIVE EFFICIENCY

The travelling standard provided by the pilot laboratory was a Hughes Thermistor Mount Model 45776H-1100 fitted with a short section of waveguide having a standard R900 flange. Bolometer mounts are used in national standards laboratories for the absolute determination of RF power. The thermistor element of the mount is connected as one of four resistors in a self-balancing bridge. When the resistance of the thermistor element changes with temperature the bridge is supplied with a DC bias current to keep the resistance of the thermistor element constant.

The RF performance of the bolometer mount is described by its effective efficiency, η and is given by:

$$\eta = \frac{P_{DC}}{P_{RF}} \qquad (1)$$

where P_{DC} is the DC substituted power and P_{RF} is the microwave power dissipated in the mount.

Participating laboratories were asked to provide a measure of effective efficiency of the travelling standard and if possible to measure the voltage reflection coefficient.

3. THE COMPARISON PROTOCOL AND SCHEDULE

The travelling standard was circulated to the participating laboratories and they were asked to provide a measure of the effective efficiency of the travelling standard at frequencies of 75 GHz and 94 GHz. Measurement of the voltage reflection coefficient of the travelling standard was optional. In three of the four laboratories the measurements were made with the section of waveguide connected to the Thermistor Mount but in the case of BNM-LCIE the measurements were made with the section of waveguide removed and then the results were corrected for the loss in this section, this was necessary for the travelling standard to fit in the BNM-LCIE microcalorimeter.

The table below gives the date of measurement at each of the participating laboratories and the measurements that were made on the travelling standard, the dates of measurement are consistent with the proposed schedule.

Laboratory	Date of Measurement	Measurements made at 75 GHz		Measurements made at 94 GHz	
		Effective Efficiency	Reflection Coefficient	Effective Efficiency	Reflection Coefficient
BNM-LCIE (France)	September 1998			✓	✓
PTB (Germany)	January 1999	✓		✓	
NPL (UK)	March 1999	✓	✓	✓	✓
NIST (USA)	April 1999	✓	✓	✓	✓
NPL (UK)	December 1999	✓	✓	✓	✓

4. METHODS OF MEASUREMENT

NPL (1) & NPL (2)

The measurement system used was a WG27 (R 900) multistate reflectometer (MSR) in combination with WG27 (R 900) standards, which have been established by previous measurements in a waterbath microcalorimeter [2]. In operation the MSR is first of all calibrated with a series of spacers, short circuits and matched loads to establish the correction factors for the reflectometer. The standard thermistor mount is placed at the measurement plane and is used to calibrate the MSR as a power transfer system. The device under test is attached to the MSR port and the effective efficiency and voltage reflection coefficient are measured using the previously obtained calibration data. The travelling standard was measured four times with disconnection and 180° rotation of the waveguide flange between each measurement. Measurements were performed at (23 ± 1) °C. The nominal power dissipated in the travelling standard mount was between 3 mW and 6 mW.

BNM-LCIE

The measurements of the effective efficiency of the device under test were performed, without the waveguide section, on the BNM-LCIE waterbath symmetrical microcalorimeter

[3]. A diode source with a source locking microwave counter was used. The thermistor mount was measured 5 times with 14 cycles of with RF/without RF. The RF power dissipated in the thermistor mount was 5mW.

The effective efficiency of the travelling standard, including the waveguide section, has been obtained using the following correction:

$$\eta \approx \left|S_{21}\right|^2 \frac{\left(1-\Gamma_1^2\right)}{\left(1-\Gamma^2\right)} \eta_1 \tag{2}$$

where η_1 is the effective efficiency of the mount without the waveguide, Γ_1 and Γ are respectively the magnitude of the reflection coefficient of the mount without and with the waveguide. $|S_{21}|$ is the attenuation of the waveguide. The magnitudes of the reflection coefficients were measured with 3 connecting/disconnecting owing to the tuned reflectometer method. The measurements were performed under ambient environmental conditions of (23 ± 1) °C and less than 60% relative humidity.

NIST

The efficiency of the device under test was measured on the NIST WR-10 dual six port measurement system [4,5]. The dual six-port was calibrated for reflection coefficient measurements using precision waveguide transmission lines and the thru-reflect-line (TRL) calibration technique. The WR-10 dual six port was calibrated for effective efficiency measurements using a WR-10 power standard whose effective efficiency had been determined from measurements in the NIST microcalorimeter [6]. The device under test was measured on each port of the dual six port 4 times with disconnect and 180 ° rotation of the device between each connect. The dual six port measurement system was calibrated for reflection coefficient and power measurement twice.

PTB

The device under test was connected to one of the R 900 feeding lines of the symmetrical twin-type PTB R 900 microcalorimeter, which is similar to the waveguide microcalorimeter described in [7]. The reference mount used for the symmetrical PTB microcalorimeter was a similar R 900 bolometer mount. By measuring the heating of the mount in the microcalorimeter during DC substitution measurements the effective efficiency of the device under test was determined [7]. The effective efficiency was measured 6 times for each frequency always disconnecting and reconnecting the mount again after each measurement. As a bolometer bridge an NBS Type II bolometer bridge was used.

5. MEASUREMENT RESULTS AND REFERENCE VALUES

The measurement results were presented to the pilot laboratory in the format of the mean of the effective efficiency and the mean of the magnitude of the reflection coefficient. Participants were asked to provide estimates of Type A and Type B uncertainties and the combined uncertainty for both measured quantities, at one standard deviation. The measurement results and associated uncertainties together with the reference values and associated uncertainties are shown in Figures 1a and 1b for 75 GHz and 2a and 2b for 94 GHz.

The complete set of measurements for each participant is presented in Appendix A, together with the associated uncertainties and degrees of equivalence with respect to the reference value and between laboratories.

Subsequent to the measurements, and in keeping with current guidelines on the presentation of results, the participants were asked for more details concerning the contributions to measurement uncertainty, for the primary measured quantity only (effective efficiency). The uncertainty budgets for each laboratory are given in Appendix B.

The uncertainties quoted by each of the participants were at the one standard uncertainty level. The expanded uncertainty was obtained by multiplying the standard uncertainty by a coverage factor of 2.0, which was sufficient to provide a level of confidence for the expanded uncertainty of approximately 95% for all the participants.

The reference value for each parameter and at each frequency was obtained from the unweighted mean of all the reported results, where the NPL result was obtained from the mean of the two NPL measurements. The unweighted mean was selected for the reference value because all four laboratories gave similar uncertainties and there were no results that could be considered as outliers. The uncertainty in the reference value was obtained from the root sum of squares of the individual uncertainties divided by the number of results, however, the NPL uncertainty was only counted once, see Appendix A page 11. This method is valid for uncorrelated measurements.

The results show good agreement between all the participants. This is demonstrated by the criteria that none of the degrees of equivalence, D, given in tables 2 to 5 of Appendix A exceed the expanded uncertainty, $U(D)$. It can be noted that the measurements of all the participants are based on the use of microcalorimeters, either directly or via transfer standards. It would be of great interest to compare results from measurements based on some different technique if and when one was developed at national standards level.

Measurement Results

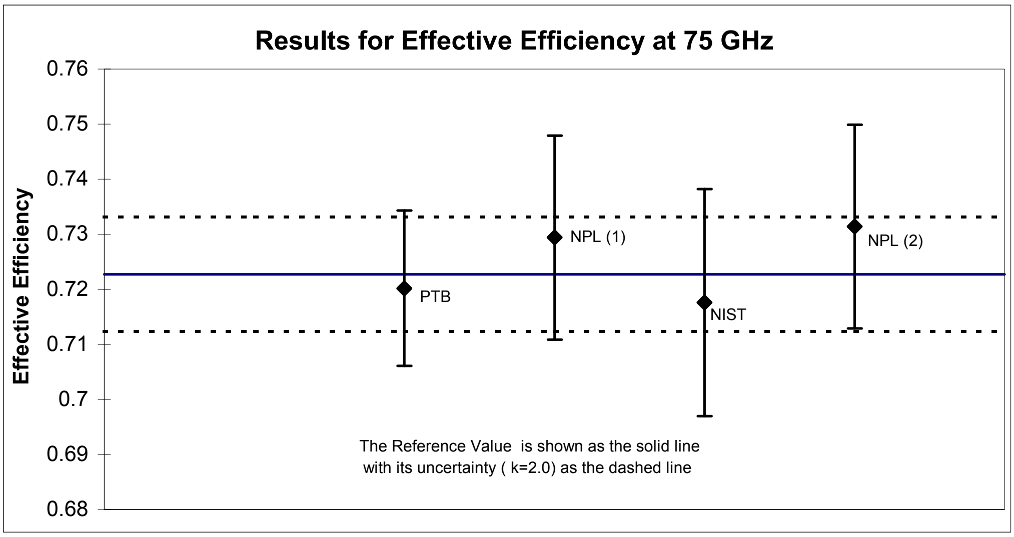

Figure 1a: The effective efficiency at 75 GHz and its associated expanded uncertainty (*k* =2.0) given by each of the participating laboratories together with the reference value and its associated uncertainty (*k* = 2.0).

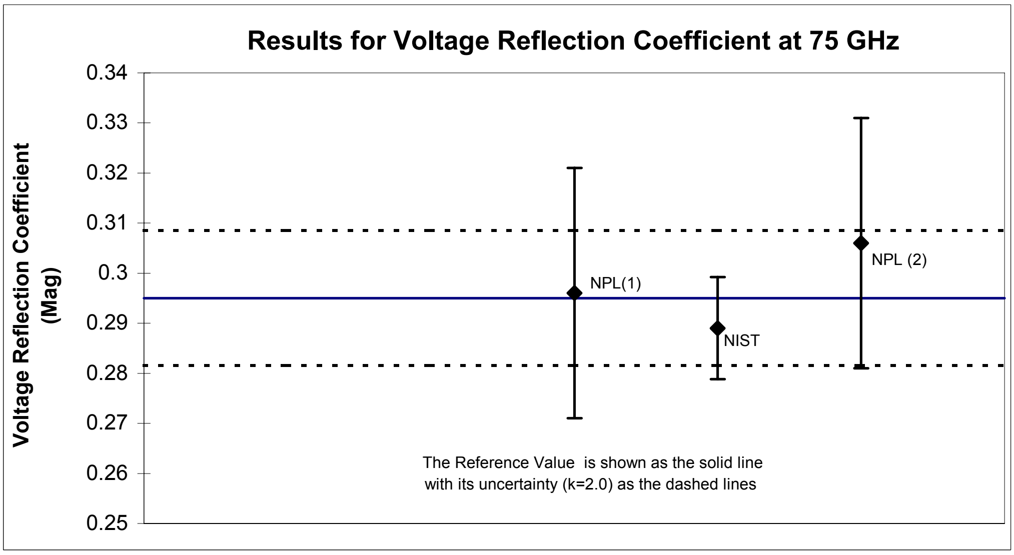

Figure 1b: The voltage reflection coefficient magnitude 75 GHz and its associated expanded uncertainty (*k* =2.0) given by each of the participating laboratories together with the reference value and its associated uncertainty (*k* = 2.0).

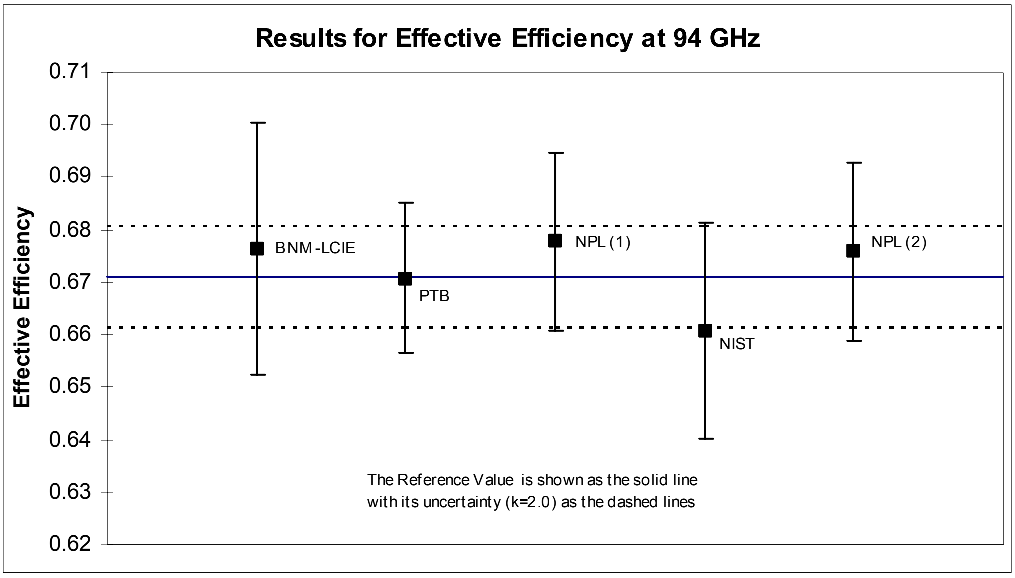

Figure 2a: The effective efficiency at 94 GHz and its associated expanded uncertainty (k =2.0) given by each of the participating laboratories together with the reference value and its associated uncertainty (k = 2.0).

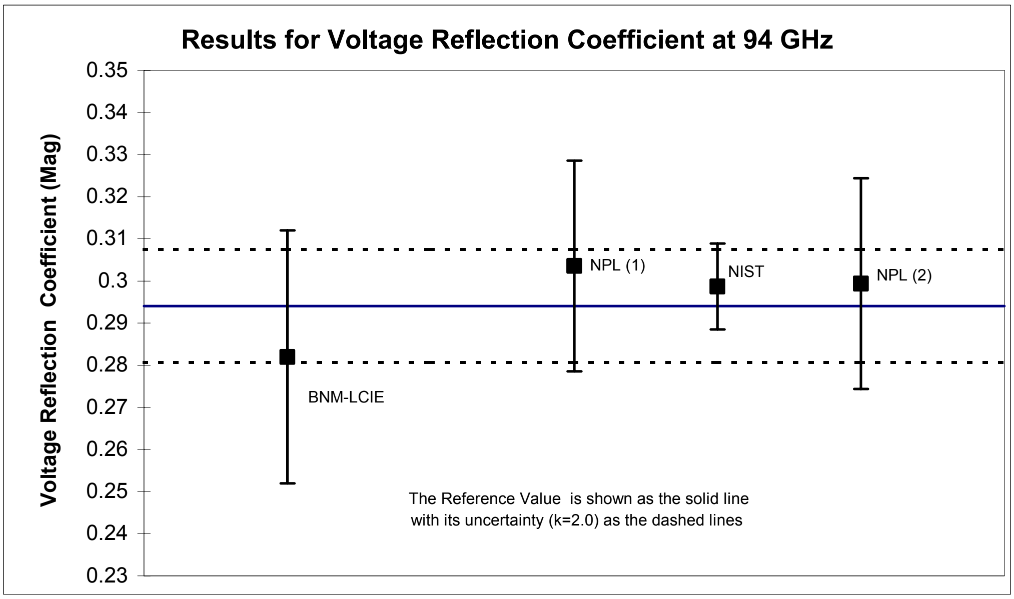

Figure 2b: The voltage reflection coefficient magnitude at 94 GHz and its associated expanded uncertainty (k =2.0) given by each of the participating laboratories together with the reference value and its associated uncertainty (k = 2.0).

6. REFERENCES

[1] Report of the Working Group on Radiofrequency Quantities of 23rd June 1997 at BIPM Sèvres, France. Table IV *New comparisons*

[2] A Fantom, Radio frequency and Microwave Power Measurements. Peter Peregrinus Ltd. Publishers, IEE Electrical Measurement Series 7, 1990.

[3] B. Torralba, J Achkar, "Development of new microcalorimeters in the frequency range 40-75 GHz", in Proc. CPEM 96, 1996, pp 452-453.

[4] C. A. Hoer, "Performance of a dual six-port automatic network analyzer", IEEE Trans. on MTT, Vol MTT-27, Dec 1979, pp 993-998.

[5] M. P. Weidman., "A semiautomated six-port for measuring millimeter-wave power and complex reflection coefficient", IEEE Trans. on MTT., vol MTT-12, Dec 1977, pp 1083-1085.

[6] J. W. Allen., F. R. Clague, N. T. Larsen and M. P. Weidman., "NIST microwave power standards in waveguide", NIST Tech. Note 1511, U. S. Dept. of Commerce, February, 1999.

[7] N. S. Chung, J. Shin, H. Bayer and R. Honigbaum, "Coaxial and waveguide microcalorimeters for RF and microwave power standards", IEEE Trans. Instrumentation Meas., Vol. 38, No.2 Apr 1989, pp. 460-464.

APPENDIX A

Key comparison **CCEM.RF-K1d.W**

MEASUREANDS: Effective Efficiency and Voltage Reflection Coefficient (Magnitude)

Pilot laboratory: NPL(UK)

η_i result of measurement of effective efficiency carried out by laboratory *i*

$U(\eta_i)$ expanded uncertainty (k = 2.0) of η_i , reported by laboratory *i*

Γ_i result of measurement of voltage reflection coefficient (magnitude) carried out by laboratory *i*

$U(\Gamma_i)$ expanded uncertainty (k = 2.0) of Γ_i , reported by laboratory *i*

Lab *i*	Results and Expanded Uncertainty (k = 2.0) at 75 GHz				Results and Expanded Uncertainty (k = 2.0) at 94 GHz				Date of Measurements
	η_i	$U(\eta_i)$	Γ_i	$U(\Gamma_i)$	η_i	$U(\eta_i)$	Γ_i	$U(\Gamma_i)$	
BNM-LCIE	-	-	-	-	0.6764	0.0231	0.282	0.0300	Sept 1998
PTB	0.7202	0.0141	-	-	0.6708	0.0143	-	-	Jan 1999
NPL(1)	0.7294	0.0185	0.296	0.025	0.6779	0.0172	0.304	0.025	March 1999
NIST	0.7176	0.0206	0.2890	0.0102	0.6609	0.0207	0.2987	0.0102	April 1999
NPL(2)	0.7314	0.0185	0.306	0.025	0.6760	0.0172	0.300	0.025	December 1999
Mean (Ref)	0.7227	0.0104	0.2950	0.0135	0.6713	0.0096	0.2942	0.0135	

Key comparison **CCEM.RF-K1d.W**

MEASUREANDS: Effective Efficiency and Voltage Reflection Coefficient (Magnitude)

The key comparison reference values of this comparison are obtained from the mean of the results of the participants, as follows:

$$\eta_R = \frac{\eta_{BNM-LCIE} + \overline{\eta_{NPL}} + \eta_{PTB} + \eta_{NIST}}{4} \qquad \text{where:} \qquad \overline{\eta_{NPL}} = \frac{\eta_{NPL(1)} + \eta_{NPL(2)}}{2}$$

and

$$\Gamma_R = \frac{\Gamma_{BNM-LCIE} + \overline{\Gamma_{NPL}} + \Gamma_{NIST}}{3} \qquad \text{where:} \qquad \overline{\Gamma_{NPL}} = \frac{\Gamma_{NPL(1)} + \Gamma_{NPL(2)}}{2}$$

The degrees of equivalence of each laboratory with respect to the reference value is given by a pair of terms:

$D_{\eta_i} = (\eta_i - \eta_R)$ and its expanded uncertainty $U(D_{\eta_i}) = 2.0\sqrt{u^2(\eta_i) + u^2(\eta_R) - 2\,\mathrm{cov}(\eta_i\,, \eta_R)}$

where:

$$u(\eta_R) = \frac{\sqrt{u^2(\eta_{BNM-LCIE}) + u^2(\eta_{PTB}) + u^2(\eta_{NPL}) + u^2(\eta_{NIST})}}{4}$$

equivalent expressions were used to obtain D_{Γ_i}, $u(\Gamma_R)$ and $U(D_{\Gamma_R})$

Table 2 Degrees of Equivalence for Effective Efficiency at 75 GHz

Lab j ⇒

Lab i ⇓	Reference		BNM-LCIE		PTB		NPL		NIST	
	D_{η_i}	$U(D_{\eta_i})$	$D_{\eta_{ij}}$	$U(D_{\eta_{ij}})$	$D_{\eta_{ij}}$	$U(D_{\eta_{ij}})$	$D_{\eta_{ij}}$	$U(D_{\eta_{ij}})$	$D_{\eta_{ij}}$	$U(D_{\eta_{ij}})$
BNM-LCIE										
PTB	-0.0025	0.0132					-0.0102	0.0233	0.0026	0.0250
NPL	0.0077	0.0149			0.0102	0.0233			0.0128	0.0277
NIST	-0.0051	0.0158			-0.0026	0.0250	-0.0128	0.0277		

Table 3 Degrees of Equivalence for Effective Efficiency at 94 GHz

Lab j ⇒

Lab i ⇓	Reference		BNM-LCIE		PTB		NPL		NIST	
	D_{η_i}	$U(D_{\eta_i})$	$D_{\eta_{ij}}$	$U(D_{\eta_{ij}})$	$D_{\eta_{ij}}$	$U(D_{\eta_{ij}})$	$D_{\eta_{ij}}$	$U(D_{\eta_{ij}})$	$D_{\eta_{ij}}$	$U(D_{\eta_{ij}})$
BNM-LCIE	0.0051	0.0189			0.0056	0.0272	-0.0006	0.0288	0.0155	0.0310
PTB	-0.0005	0.0139	-0.0056	0.0272			-0.0062	0.0224	0.0099	0.0252
NPL	0.0057	0.0146	0.0006	0.0288	0.0062	0.0224			0.0161	0.0269
NIST	-0.0104	0.0175	-0.0155	0.0310	-0.0099	0.0252	-0.0161	0.0269		

Table 4 Degrees of Equivalence for Voltage Reflection Coefficient at 75 GHz

Lab j $\Rightarrow$

Lab i $\Downarrow$	Reference		BNM-LCIE		PTB		NPL		NIST	
	D_{Γ_i}	$U(D_{\Gamma_i})$	$D_{\Gamma_{ij}}$	$U(D_{\Gamma_{ij}})$	$D_{\Gamma_{ij}}$	$U(D_{\Gamma_{ij}})$	$D_{\Gamma_{ij}}$	$U(D_{\Gamma_{ij}})$	$D_{\Gamma_{ij}}$	$U(D_{\Gamma_{ij}})$
BNM-LCIE										
PTB										
NPL	0.0060	0.0135							0.0120	0.0270
NIST	-0.0060	0.0135					-0.0120	0.0270		

Table 5 Degrees of Equivalence for Voltage Reflection coefficient at 94 GHz

Lab j $\Rightarrow$

Lab i $\Downarrow$	Reference		BNM-LCIE		PTB		NPL		NIST	
	D_{Γ_i}	$U(D_{\Gamma_i})$	$D_{\Gamma_{ij}}$	$U(D_{\Gamma_{ij}})$	$D_{\Gamma_{ij}}$	$U(D_{\Gamma_{ij}})$	$D_{\Gamma_{ij}}$	$U(D_{\Gamma_{ij}})$	$D_{\Gamma_{ij}}$	$U(D_{\Gamma_{ij}})$
BNM-LCIE	-0.0122	0.0219					-0.0200	0.0391	-0.0167	0.0317
PTB										
NPL	0.0078	0.0197	0.0200	0.0391					0.0033	0.0270
NIST	0.0045	0.0147	0.0167	0.0317			-0.0033	0.0270		

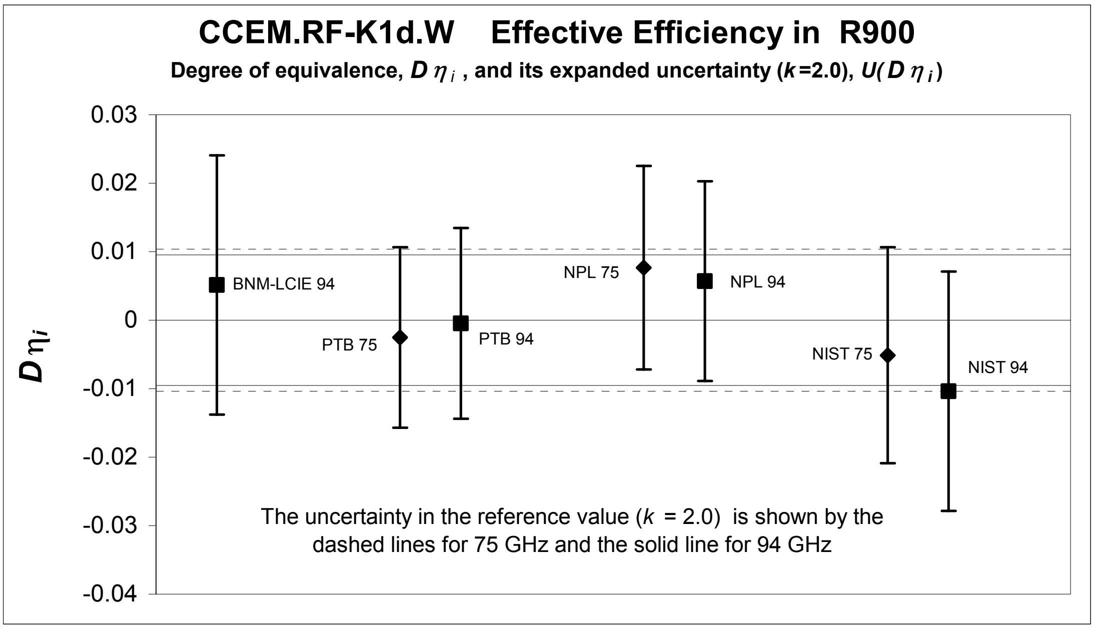

Figure 3a: Degrees of Equivalence with respect to the reference value for Effective Efficiency and the associated expanded uncertainties ($k = 2.0$)

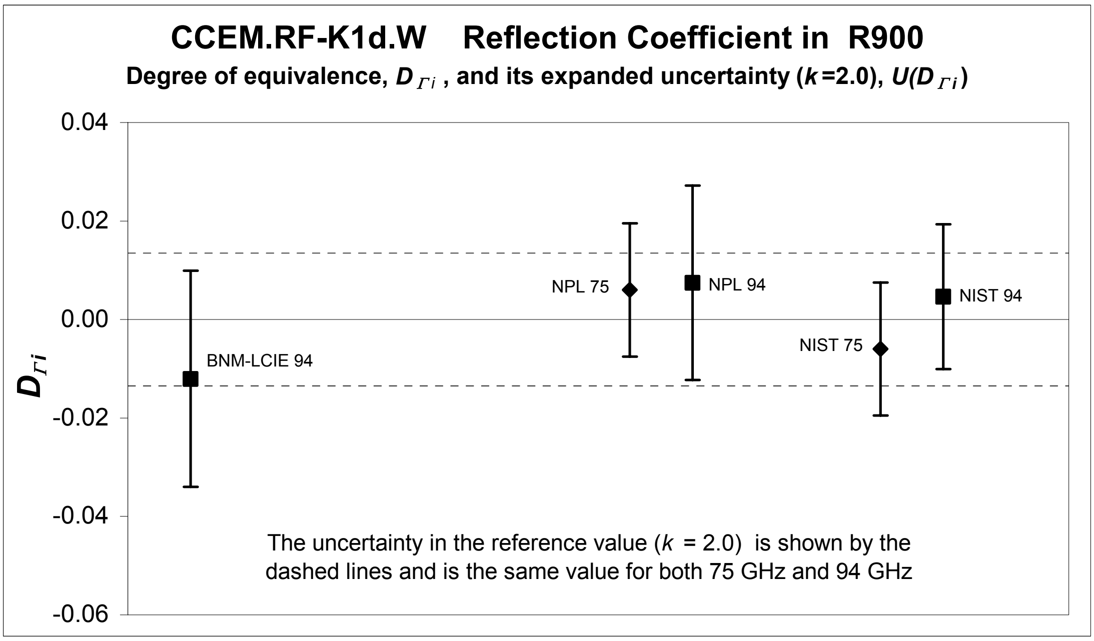

Figure 3b: Degrees of Equivalence with respect to the reference value for Voltage Reflection Coefficient (Magnitude) and the associated expanded uncertainties ($k = 2.0$).

APPENDIX B

The tables below give details of the uncertainty contributions appropriate to the measurement of Effective Efficiency for each of the participants.

Table 7 BNM-LCIE at 94 GHz

Source of uncertainty	**method of evaluation**	**probability distribution**	**effective degrees of freedom**	**contribution to standard uncertainty**
Standard deviation of measurement	Type A	Gaussian	11	0.002
Measurement of DC voltages	Type B	Rectangular	50	0.0015
Reproducibility, mismatch…	Type B	Gaussian	50	0.0054
Thin wall waveguide correction	Type B	Gaussian	50	0.0013
Adapter correction	Type B	Gaussian	50	0.0098
Standard uncertainty		Gaussian	100	0.0115
Expanded Uncertainty (k = 2.0)		Gaussian	100	0.0231

Table 8 NPL(1) & (2) at 75 GHz

Source of uncertainty	**method of evaluation**	**probability distribution**	**effective degrees of freedom**	**contribution to standard uncertainty**
Calibration of Standard Thermistor Mount in Micrcalorimeter	Type B	Gaussian	50	0.0088
Measurement of DC ratios	Type B	Gaussian	50	0.0004
Mismatch Correction	Type B	Gaussian	50	0.0022
Flange connection repeatability	Type A	Rectangular	3	0.002
Standard uncertainty		Gaussian	60	0.00925
Expanded Uncertainty (k = 2.0)		Gaussian	60	0.0185

Table 9 NPL (1) & (2) at 94 GHz

Source of uncertainty	method of evaluation	probability distribution	effective degrees of freedom	contribution to standard uncertainty
Calibration of Standard Thermistor Mount in Micrcalorimeter	Type B	Gaussian	50	0.0081
Measurement of DC ratios	Type B	Gaussian	50	0.0004
Mismatch Correction	Type B	Gaussian	50	0.0020
Flange connection repeatability	Type A	Rectangular	3	0.002
Standard uncertainty		Gaussian	60	0.00860
Expanded Uncertainty (k = 2.0)		Gaussian	60	0.0172

Table 10 PTB at 75 GHz

Source of uncertainty	method of evaluation	probability distribution	effective degrees of freedom	contribution to standard uncertainty
Bolometer DC Voltage ratio	Type A	Gaussian	5	0.0004
Correction for DC ratio	Type B	Rectangular	50	0.0007
Microcalorimeter thermal voltage ratio	Type A	Gaussian	5	0.0011
Correction of thermal voltage ratio	Type B	Rectangular	50	0.0021
Microcalorimeter equivalence correction factor	Type B	Rectangular	50	0.0066
Standard uncertainty		Gaussian	69	0.00705
Expanded Uncertainty (k = 2.0)		Gaussian	69	0.0141

Table 11 PTB at 94 GHz

Source of uncertainty	method of evaluation	probability distribution	effective degrees of freedom	contribution to standard uncertainty
Bolometer DC Voltage ratio	Type A	Gaussian	5	0.0010
Correction for DC ratio	Type B	Rectangular	50	0.0009
Microcalorimeter thermal voltage ratio	Type A	Gaussian	5	0.0016
Correction of thermal voltage ratio	Type B	Rectangular	50	0.0021
Microcalorimeter equivalence correction factor	Type B	Rectangular	50	0.0065
Standard uncertainty		Gaussian	69	0.00716
Expanded Uncertainty (k = 2.0)		Gaussian	69	0.0143

Table 12 NIST at 75 GHz

Source of uncertainty	method of evaluation	probability distribution	effective degrees of freedom	contribution to standard uncertainty
Calibration of Standard in Microcalorimeter	Type B	Gaussian	50	0.0090
Six-port Transfer System	Type A	Gaussian	5	0.0050
Flange Connection Repeatability	Type A	Gaussian	12	0.0006
Standard uncertainty		Gaussian	44	0.0103
Expanded Uncertainty (k = 2.0)		Gaussian	44	0.0206

Table 13 NIST at 94 GHz

Source of uncertainty	method of evaluation	probability distribution	effective degrees of freedom	contribution to standard uncertainty
Calibration of Standard in Microcalorimeter	Type B	Gaussian	50	0.0090
Six-port Transfer System	Type A	Gaussian	5	0.0050
Flange Connection Repeatability	Type A	Gaussian	12	0.0012
Standard uncertainty		Gaussian	44	0.0104
Expanded Uncertainty (k = 2.0)		Gaussian	44	0.0207