CIPM Key Comparison CCEM.RF-K28.W

RF power from 18 GHz to 26.5 GHz in rectangular waveguide

Final Report

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Abstract

This report summarizes the results of the measurements performed as a CIPM Key Comparison (CCEM.RF-K28.W) on high frequency power in waveguide among NIM, LNE, NPL, PTB, UME, CMI, SCL, NMC, KRISS and NIST. The comparison measurements have been performed between November 2022 and December 2024. In this comparison, the effective efficiency and calibration factor of two WR-42 (WG20 or R220) waveguide thermistor mounts were measured in the frequency range 18 GHz to 26.5 GHz.

Contents

1 Introduction

To support the metrological equivalence of national measurement standards in the framework of Mutual Recognition Arrangement (MRA), a CIPM key comparison CCEM.RF-K28.W in "RF power from 18 GHz to 26.5 GHz in rectangular waveguide" was approved and agreed among the NMIs in 2022 [1].

The main motivation for this comparison was to demonstrate accurate measurement capabilities and validation of the equivalence of WR-42 (WG20 or R220) waveguide power sensor calibration at 10 National Metrology Institutes (NMIs). The comparison is very significant for the participants to test their existing calibration systems and reference standards, especially over the entire waveguide band which becomes important for industry applications.

The pilot laboratory of this comparison is the National Institute of Metrology, China (NIM), and the supporting group consists of Physikalisch-Technische Bundesanstalt (PTB) and National Physical Laboratory (NPL). Details of the measurement task are described in [1].

2 Travelling Standards

Two travelling standards were provided by NIM. Both were commercial temperature-compensated thermistor power sensors (Type K486A) to be operated with a Hewlett Packard power meter, Model 432 (or compatible). The travelling standards are operated at a nominal resistance of 200 Ω. The specific devices were chosen with respect to stability and repeatability prior to the start of the comparison. They are denoted as NIM-1 (Serial No. 1606) and NIM-2 (Serial No. 05616).

Table 1: Travelling standards.

Standard No.	Serial No.	Acronym
1	1606	NIM-1
2	05616	NIM-2

Figure 1. NIM-1 and NIM-2 travelling standards

Table 2. The specifications of the Travelling Standards

Operating Frequency	18 GHz ~ 26.5 GHz
Connector Type	Input: WR-42(R220), UG-597/U interface Output: HP standard 6-pin connector as shown in Figure 2.
Temperature Coefficient	Negative Temperature Coefficient
Dimensions	Diameter 32.7mm Length 72.25 mm
Operating resistance	200 Ω
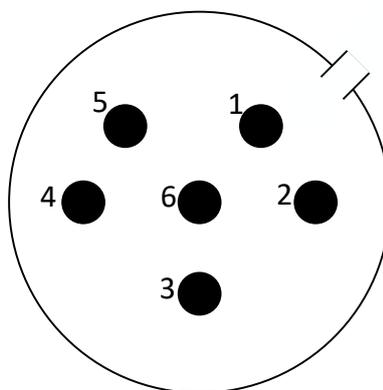
Figure 2. Pin assignment of HP standard 6-pin connector

The RF thermistor resistance is connected with power meter by pin 1 and pin 2. Compensating resistance is connected by pin 3 and pin 4, as shown in the Figure 3.
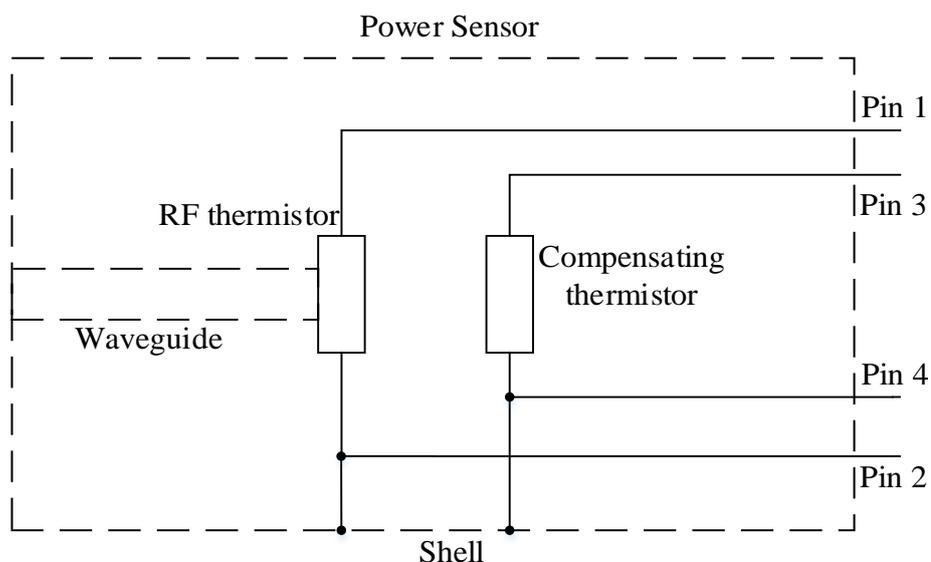
Figure 3. Sketch of pins in the travelling standard (power sensor)

The travelling standards should only be used with a Negative Temperature Coefficient (NTC) Type IV power meter referenced to 200 Ω or a HP/Keysight 432 power meter.

3   Participants and organization of the comparison

3.1   List of participants

Table 3. List of participants

	Institute	Acronym	Address	Contact Persons
China	National Institute of Metrology, China	NIM	No. 18, Bei San Huan Dong Lu Road, Chaoyang Dist., Beijing, China 100029	Dr. Xiaohai Cui cuixh@nim.ac.cn Tel: +86 10 64525201
France	Laboratoire national de métrologie et d'essais	LNE	29 avenue Roger Hennequin 78197 Trappes Cedex FRANCE	Mr. Djamel Allal Djamel.Allal@lne.fr
U.K.	National Physical Laboratory	NPL	Hampton Road Teddington Middlesex TW11 0LW United Kingdom	Mr. Murat Celep murat.celep@npl.co.uk and Mr. Daniel Stokes daniel.stokes@npl.co.uk
Germany	Physikalisch-Technische Bundesanstalt	PTB	Bundesallee 100 38116 Braunschweig Germany	Mr. Karsten Kuhlmann, Karsten.Kuhlmann@ptb.de, +49 531 592 2220 and Mr. Jürgen Rühaak, juergen.ruehaak@ptb.de +49 531 592 2223
Türkiye	National Metrology Institute of Türkiye	TÜBİTAK UME	TÜBİTAK Ulusal Metroloji Enstitüsü (UME) TÜBİTAK Gebze Yerleşkesi Barış Mah. Dr. Zeki Acar Cad. No:1 41470 Gebze-Kocaeli, TÜRKİYE	Dr. Erkan Danaci erkan.danaci@tubitak.gov.tr handan.sakarya@tubitak.gov.tr +90 262 679 50 00 / Ext.4500
Czech Republic	Czech Metrology Institute	CMI	Radiova 1136/3, Prague 10200, Czech Republic	Karel Dražil (kdrazil@cmi.cz) Tel: +420 266 020 173 and Jan Grajciar (jgrajciar@cmi.cz)
Hong Kong, China	Standards and Calibration Laboratory	SCL	4/F, North Tower, Tseung Kwan O Government Offices,	Dr. Terry LAI Terry.lai@itc.gov.hk

			30 Tong Yin Street, Tseung Kwan O, Sai Kung, New Territories, Hong Kong, China	
Singapore	National Metrology Centre, Agency for Science, Technology and Research	NMC, A*STAR	8 CleanTech Loop, #01-20, Singapore 637145	Dr. Yusong Meng meng_yusong@a-star.edu.sg
Korea	Korea Research Institute of Standards and Science	KRISS	267 Gajeong-ro, Yuseong-gu, Daejeon 34113, Rep. of Korea	Dr. Jae-Yong Kwon jykwon@kriss.re.kr and Dr. Tae-Weon Kang twkang@kriss.re.kr
United States of America	National Institute of Standards and Technology	NIST	325 Broadway Mail Stop 672.01 Boulder, CO, USA	Dr. Christian J. Long christian.long@nist.gov Tel: +1-303-497-6559

3.2 Comparison schedule

Table 4. Dates of Measurements

Institute	Country	Date of Measurement
NIM	China(pilot)	November 2022- December 2022
LNE	France	January 2022-February 2023
NPL	United Kingdom	March 2023-April 2023
UME	Türkiye	May 2023-June 2023
CMI	Czech Republic	July 2023-September 2023
PTB	Germany	October 2023-November 2023
NIM	China(pilot)	December 2023-January 2024
SCL	Hong Kong，China	January 2024-February 2024
NMC	Singapore	March 2024-June 2024
KRISS	Korea	July 2024-September 2024
NIST	U.S.A.	October 2024-November 2024
NIM	China(pilot)	December 2024

A schematic diagram of the comparison route is shown in Figure 4.
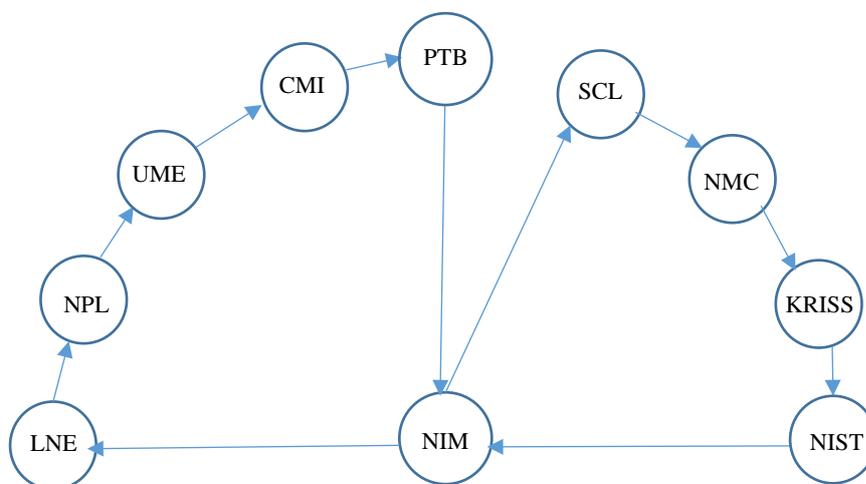
Figure 4. Schematic diagram of the comparison route

3.3 Organization of the comparison

The comparison was organized and controlled by the pilot laboratory (NIM). The devices under test were circulated among the participants in two loops, the first loop mainly involves European NMIs, whereas the second loop mainly involves NMIs around the Pacific. An interim measurement was carried out between the two loops by the pilot laboratory in December 2023.

3.4 Unexpected incidents

The comparison was generally well-organized, although some unexpected incidents occurred.

During the first loop, the planned measurement sequence (PTB → CMI → UME) was changed to UME → CMI → PTB due to construction delays at PTB. This adjustment led to a missing page in the ATA carnet for Germany, which caused delays in customs clearance.

In the second loop, NMC experienced delays because of ongoing system modifications and an internal peer review.

At KRISS, the plastic foam inside the thermistor mount was slightly displaced when connecting the NIM-1 mount to the VNA. After carefully repositioning the filler and repeating the measurements, the input reflection coefficient showed no significant variation compared to previous results.

NPL identified an error in their originally submitted data during the support group's review. Consequently, the original dataset was excluded from the KCRV calculation to ensure the integrity of the reference value. The revised data from NPL is provided in the appendix E for reference.

4 Measurement quantities and method of measurement

4.1 Effective efficiency and calibration factor

The effective efficiency, η_{eff}, of the travelling standards, as the ratio of the substituted DC power, $P_{\text{DC, sub}}$, with respect to the total absorbed RF power, $P_{\text{RF, abs}}$

$$\eta_{\text{eff}} = \frac{P_{\text{DC,sub}}}{P_{\text{RF, abs}}} \tag{1}$$

was measured as a primary measuring quantity at 18 GHz, 21 GHz, 24 GHz and 26.5 GHz.

Participants operating a direct comparison setup measured the calibration factor K_c. To enable a comparison between all participants, the corresponding calibration factor was calculated by those participants having measured the effective efficiency in a microcalorimeter setup from

$$K_c = (1 - |\Gamma|^2)\eta_{\text{eff}} \tag{2}$$

The input reflection coefficient, Γ, of the travelling standards was measured as a complex quantity stated as magnitude and phase at the measuring frequencies. The reflection coefficient was to be measured under balanced bridge condition, i.e. with a thermistor DC-resistance of 200 Ω. Since the reflection coefficient is regarded as an auxiliary quantity in this comparison, a comparison reference value has not been determined.

4.2 Method of measurement

a) Power level:
The incident power level to determine the calibration factor/effective efficiency was recorded and ideally approximately 3 mW.

b) Frequency points:
18 GHz, 21 GHz, 24 GHz and 26.5 GHz

c) Ambient conditions:
The reference ambient conditions for the measurements were:
Ambient temperature 23°C±1°C
Relative humidity 50%±10%

Table 5 gives a brief summary of the individual measurement methods employed by each participant. A detailed description, as provided by the participants, is given in Appendix B.

Table 5. Summary of the measurement techniques used by each participant

NMI	Method	Reference standard calibration method	Source of traceability
NIM	Microcalorimeter	/	/
LNE	Microcalorimeter	/	/
NPL	Microcalorimeter	/	/
UME	Microcalorimeter	/	/
CMI	Direct comparison	Standard thermistor mount	PTB
PTB	Microcalorimeter	/	/
SCL	Direct comparison	Microcalorimeter	SCL
NMC	Direct comparison	Standard thermistor mount	KRISS, NPL
KRISS	Microcalorimeter	/	/
NIST	Direct comparison	Microcalorimeter	NIST

5 Measurement results

5.1 Repeated measurements of the pilot institute

The measurements were undertaken at the pilot institute in November 2022 (initial), December 2023 (intermediate) and December 2024 (final), which is shown in Table 6.

Table 6. Dates of measurements at the pilot laboratory.

Date of Measurement.	Acronym
November 2022	NIM1
December 2023	NIM2
December 2024	NIM3
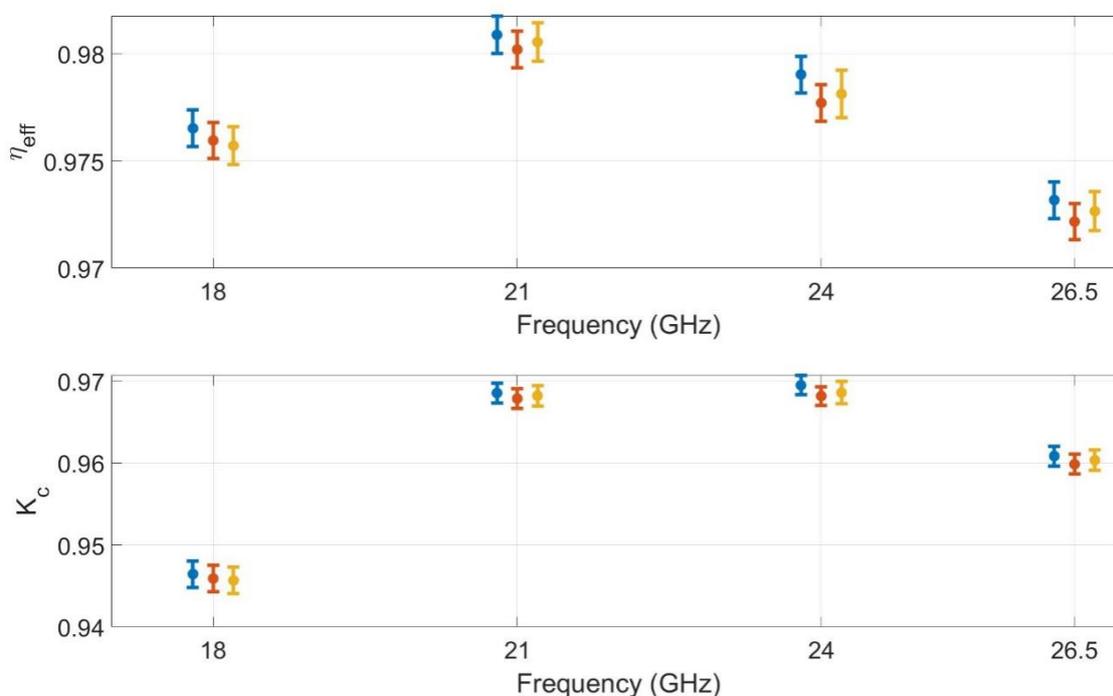
Figure 5. Pilot laboratory measurement of effective efficiency and calibration factor of travelling standard NIM-1 (SN 1606): Measurement NIM1 (——), NIM2 (——), NIM3 (——)

As shown in Figure 5, the effective efficiency and calibration factor of travelling standard NIM-1 show good stability (experimental standard deviations of all pilot laboratory measurements are less than 0.00073). For that reason, only the intermediate measurement result NIM2 has been taken into account in the calculation of the KCRV of travelling standard NIM-1.
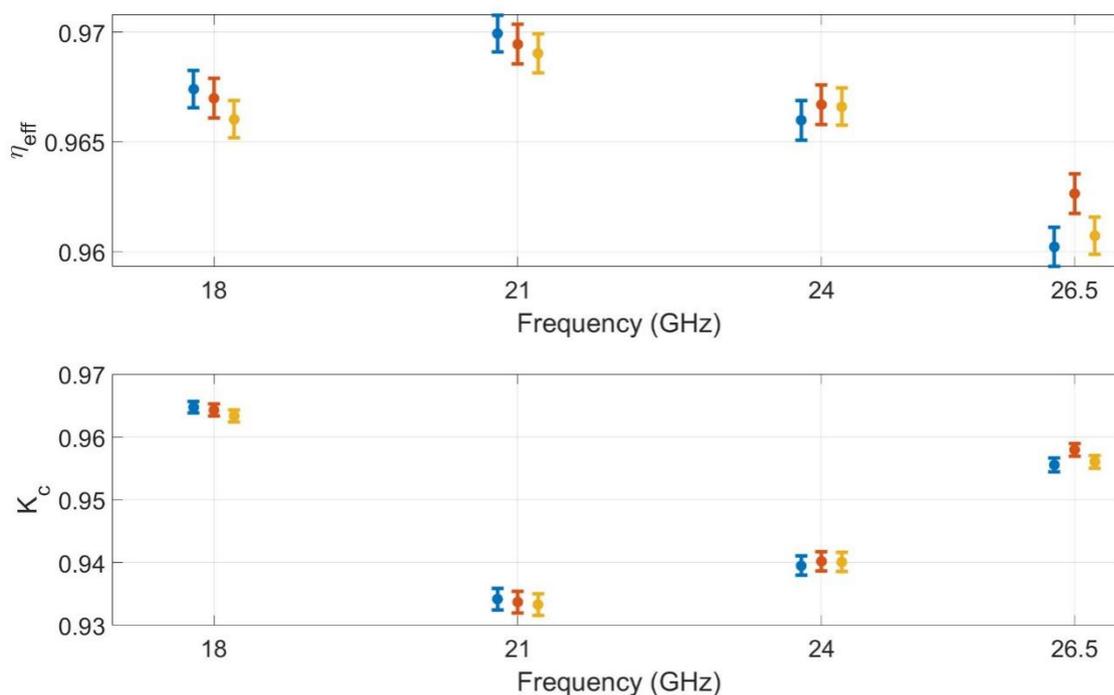
Figure 6. Pilot laboratory measurement of effective efficiency and calibration factor of travelling standard NIM-2 (SN 05616): Measurement NIM1 (——), NIM2 (——), NIM3 (——)

As shown in Figure 6, the effective efficiency and calibration factor of travelling standard NIM-2 show good stability (experimental standard deviations of all pilot laboratory measurements are less than 0.00074), except that it shows a slight instability at 26.5 GHz (experimental standard deviation is 0.00152). Overall, NIM-2 can be regarded as stable enough. For that reason, only the intermediate measurement result NIM2 has been taken into account in the calculation of the KCRV of travelling standard NIM-2.

5.2 Results of the participating institutes

The measured effective efficiency and the calibration factor, as defined in eqs. (1) and (2), along with the complex reflection coefficient of the two travelling standards were reported by the participating laboratories.

The results at the frequency points 18 GHz, 21 GHz, 24 GHz and 26.5 GHz were measured and reported by all participants. The overall measurement data are listed in Appendix C.

Due to different types of measurement systems used by participants, there is a significant variation in the reported uncertainties from each participant. Therefore, the weighted Key Comparison Reference Value (KCRV) algorithm was ultimately adopted.

Outliers can be identified using the Median Absolute Deviation (MAD) method. With seven independent participating laboratories (NPL was excluded since an error was identified in their original submitted data,

CMI and NMC were excluded since they were traceable to other NMIs), the multiplier k_1 is set to 1.686 as described in Appendix A [2].

The measurement results and their associated uncertainties ($k=1$) along with the key comparison reference values (KCRV) and associated uncertainties of two travelling standards at the frequency points 18 GHz, 21 GHz, 24 GHz and 26.5 GHz can be found in Tables 7 – 14. Each table is followed by a graphical illustration of the reported results and the corresponding KCRV. Furthermore, the statistical outlier boundary lines are plotted as dashed black lines.

Appendix A describes the methods applied to determine the KCRV and its associated uncertainty, along with the degrees of equivalence with respect to the KCRV. Only the degree of equivalence with respect to the KCRV, but not between the participants has been determined.

Participants were also asked to provide estimates of the Type A and Type B uncertainties and the combined standard uncertainty of the aforementioned measurands at each required frequency point. All uncertainty budgets provided by the participants can be found in Appendix D.

After the Draft A report was reviewed by the support group, NPL identified an error in their originally submitted results and consequently provided a revised dataset. These revised values from NPL were not used in calculating the Key Comparison Reference Values (Tables 7-14) or the Degrees of Equivalence (Tables 15-22). The KCRVs recalculated using the revised NPL data are provided in Appendix E for reference.

After the Draft A report had been circulated, NMC submitted a clarification regarding the 18 GHz result. The NMC reference power standard with a 3.5 mm connector used in this key comparison was traceable to two distinct microcalorimeters over the frequency ranges of 50 MHz–18 GHz for a coaxial microcalorimeter and 18 GHz–26.5 GHz for a waveguide one. The result at 18 GHz reported here is based on traceability to the coaxial microcalorimeter. NMC notes that if the calibration result from the waveguide microcalorimeter—against which the same standard was also calibrated—were used, the result at 18 GHz relative to the KCRV of this key comparison would be significantly improved. NMC intends to apply the corrected result for future CMC claims.

Results of travelling standard NIM-1 (SN: 1606)

Table 7. Measurements and standard uncertainties (k=1) of NIM-1 (SN 1606) at **18** GHz

Laboratory	Measurements used to calculate the KCRV				
	η_{eff}	$u(\eta_{\text{eff}})$ (k=1)	K_C	$u(K_C)$ (k=1)	
NIM	0.9760	0.0009	0.9459	0.0016	
LNE	0.9770	0.0030	0.9490	0.0030	
PTB	0.9756	0.0013	0.9463	0.0013	
UME	0.9773	0.0014	0.9491	0.0025	
KRISS	0.9763	0.0011	0.9475	0.0012	
NIST	0.9756	0.0023	0.9468	0.0022	
SCL			0.9420	0.0210	
KCRV	0.9762	0.0005	0.9470	0.0007	

Laboratory	Measurements not used to calculate the KCRV				
	η_{eff}	$u(\eta_{\text{eff}})$ (k=1)	K_C	$u(K_C)$ (k=1)	Reason for exclusion
NPL	0.9777	0.0030	0.9484	0.0029	Error identified by participant
SCL	0.9710	0.0220			Statistical outlier
CMI	0.9730	0.0046	0.9439	0.0043	Traceable to other participant
NMC	1.0000	0.0162	0.9684	0.0155	Traceable to other participant

Figure 7. Effective efficiency and calibration factor of travelling standard NIM-1 at 18 GHz. KCRV (—), u(KCRV) (----), outlier boundary (----).

Table 8. Measurements and standard uncertainties (k=1) of NIM-1 (SN 1606) at **21** GHz

Laboratory	Measurements used to calculate the KCRV				
	η_{eff}	$u(\eta_{\text{eff}})$ (k=1)	K_{C}	$u(K_{\text{C}})$ (k=1)	
NIM	0.9802	0.0008	0.9678	0.0012	
LNE	0.9800	0.0030	0.9680	0.0030	
PTB	0.9799	0.0015	0.9678	0.0016	
UME	0.9814	0.0015			
KRISS	0.9806	0.0012	0.9681	0.0012	
NIST	0.9814	0.0016			
SCL	0.9810	0.0230	0.9680	0.0220	
KCRV	0.9805	0.0005	0.9679	0.0007	

Laboratory	Measurements not used to calculate the KCRV				
	η_{eff}	$u(\eta_{\text{eff}})$ (k=1)	K_{C}	$u(K_{\text{C}})$ (k=1)	Reason for exclusion
NPL	0.9827	0.0015	0.9707	0.0015	Error identified by participant
UME			0.9694	0.0020	Statistical outlier
NIST			0.9690	0.0016	Statistical outlier
CMI	0.9743	0.0054	0.9626	0.0053	Traceable to other participant
NMC	0.9840	0.0199	0.9720	0.0197	Traceable to other participant

Figure 8. Effective efficiency and calibration factor of travelling standard NIM-1 at 21 GHz. KCRV (—), u(KCRV) (----), outlier boundary (----).

Table 9. Measurements and combined standard uncertainties (k=1) of NIM-1 (SN 1606) at **24** GHz

Laboratory	Measurements used to calculate the KCRV				
	η_{eff}	$u(\eta_{eff})$ (k=1)	K_C	$u(K_C)$ (k=1)	
NIM	0.9777	0.0008	0.9681	0.0011	
LNE	0.9770	0.0030	0.9670	0.0030	
PTB	0.9779	0.0012	0.9704	0.0013	
UME	0.9795	0.0015	0.9707	0.0018	
KRISS	0.9785	0.0012	0.9686	0.0012	
NIST	0.9787	0.0019	0.9689	0.0019	
SCL	0.9750	0.0220	0.9650	0.0220	
KCRV	0.9782	0.0005	0.9691	0.0006	

Laboratory	Measurements not used to calculate the KCRV				
	η_{eff}	$u(\eta_{eff})$ (k=1)	K_C	$u(K_C)$ (k=1)	Reason for exclusion
NPL	0.9849	0.0017	0.9758	0.0017	Error identified by participant
CMI	0.9739	0.0054	0.9647	0.0053	Traceable to other participant
NMC	0.9811	0.0221	0.9719	0.0219	Traceable to other participant
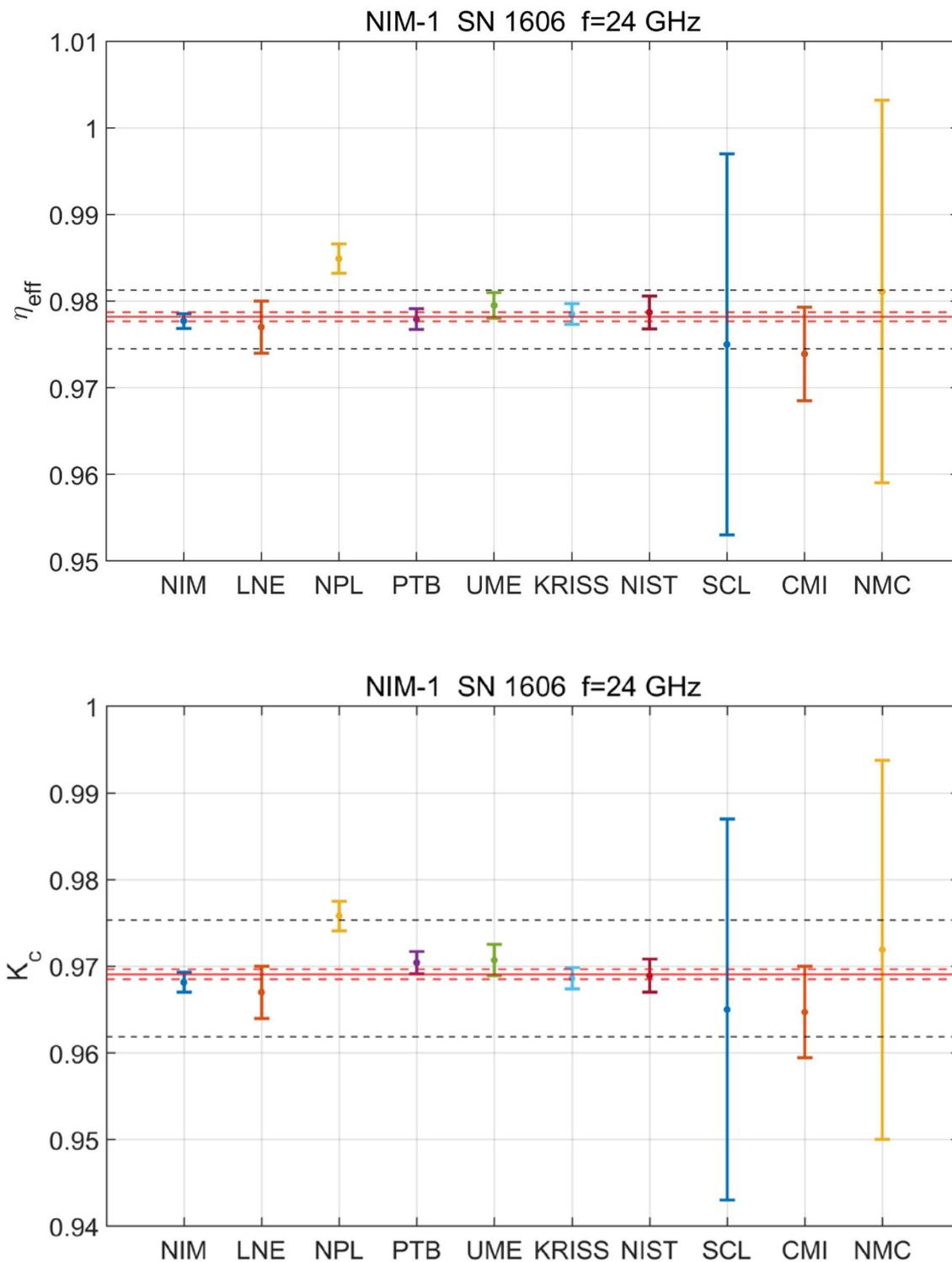
Figure 9. Effective efficiency and calibration factor of travelling standard NIM-1 at 24 GHz. KCRV (—), u(KCRV) (----), outlier boundary (----).

Table 10. Measurements and combined standard uncertainties (*k*=1) of NIM-1 (SN 1606) at **26.5** GHz

| Laboratory | Measurements used to calculate the KCRV | | | | |
	η_{eff}	$u(\eta_{eff})$ (*k*=1)	K_C	$u(K_C)$ (*k*=1)	
NIM	0.9722	0.0009	0.9598	0.0012	
LNE	0.9730	0.0030	0.9610	0.0030	
PTB	0.9722	0.0014	0.9602	0.0015	
UME	0.9737	0.0015	0.9603	0.0020	
KRISS	0.9727	0.0012	0.9586	0.0013	
NIST	0.9729	0.0019	0.9593	0.0019	
KCRV	0.9726	0.0005	0.9596	0.0007	

| Laboratory | Measurements not used to calculate the KCRV | | | | |
	η_{eff}	$u(\eta_{eff})$ (*k*=1)	K_C	$u(K_C)$ (*k*=1)	Reason for exclusion
NPL	0.9785	0.0014	0.9662	0.0014	Error identified by participant
SCL	0.9670	0.0280	0.9540	0.0270	Statistical outlier
CMI	0.9683	0.0054	0.9560	0.0053	Traceable to other participant
NMC	0.9713	0.0242	0.9586	0.0238	Traceable to other participant
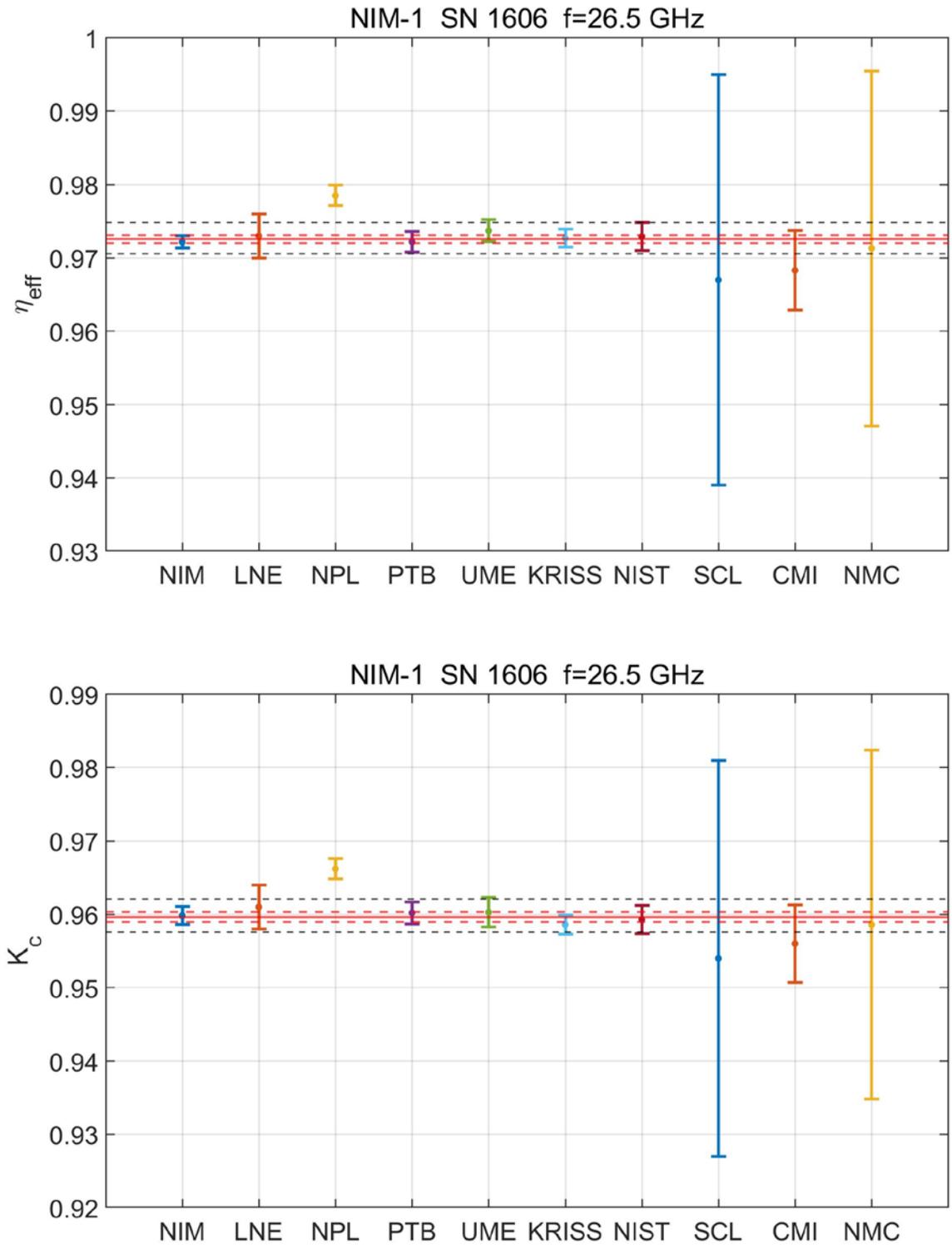
Figure 10. Effective efficiency and calibration factor of travelling standard NIM-1 at 26.5 GHz. KCRV (—), u(KCRV) (----), outlier boundary (----).

5.2.1 Results of travelling standard NIM-2 (SN: 05616)

Table 11. Measurements and combined standard uncertainties (k=1) of NIM-2 (SN 05616) at **18** GHz

Laboratory	Measurements used to calculate the KCRV				
	η_{eff}	$u(\eta_{\text{eff}})$ (k=1)	K_C	$u(K_C)$ (k=1)	
NIM	0.9670	0.0009	0.9643	0.0010	
LNE	0.9680	0.0030	0.9650	0.0030	
PTB	0.9658	0.0011	0.9631	0.0011	
UME	0.9679	0.0014	0.9652	0.0016	
KRISS	0.9679	0.0013	0.9656	0.0013	
NIST	0.9669	0.0017	0.9646	0.0017	
KCRV	0.9670	0.0005	0.9644	0.0005	

Laboratory	Measurements not used to calculate the KCRV				
	η_{eff}	$u(\eta_{\text{eff}})$ (k=1)	K_C	$u(K_C)$ (k=1)	Reason for exclusion
NPL	0.9719	0.0023	0.9691	0.0023	Error identified by participant
SCL	0.9620	0.0140	0.9590	0.0140	Statistical outlier
CMI	0.9629	0.0045	0.9602	0.0045	Traceable to other participant
NMC	0.9878	0.0160	0.9849	0.0158	Traceable to other participant

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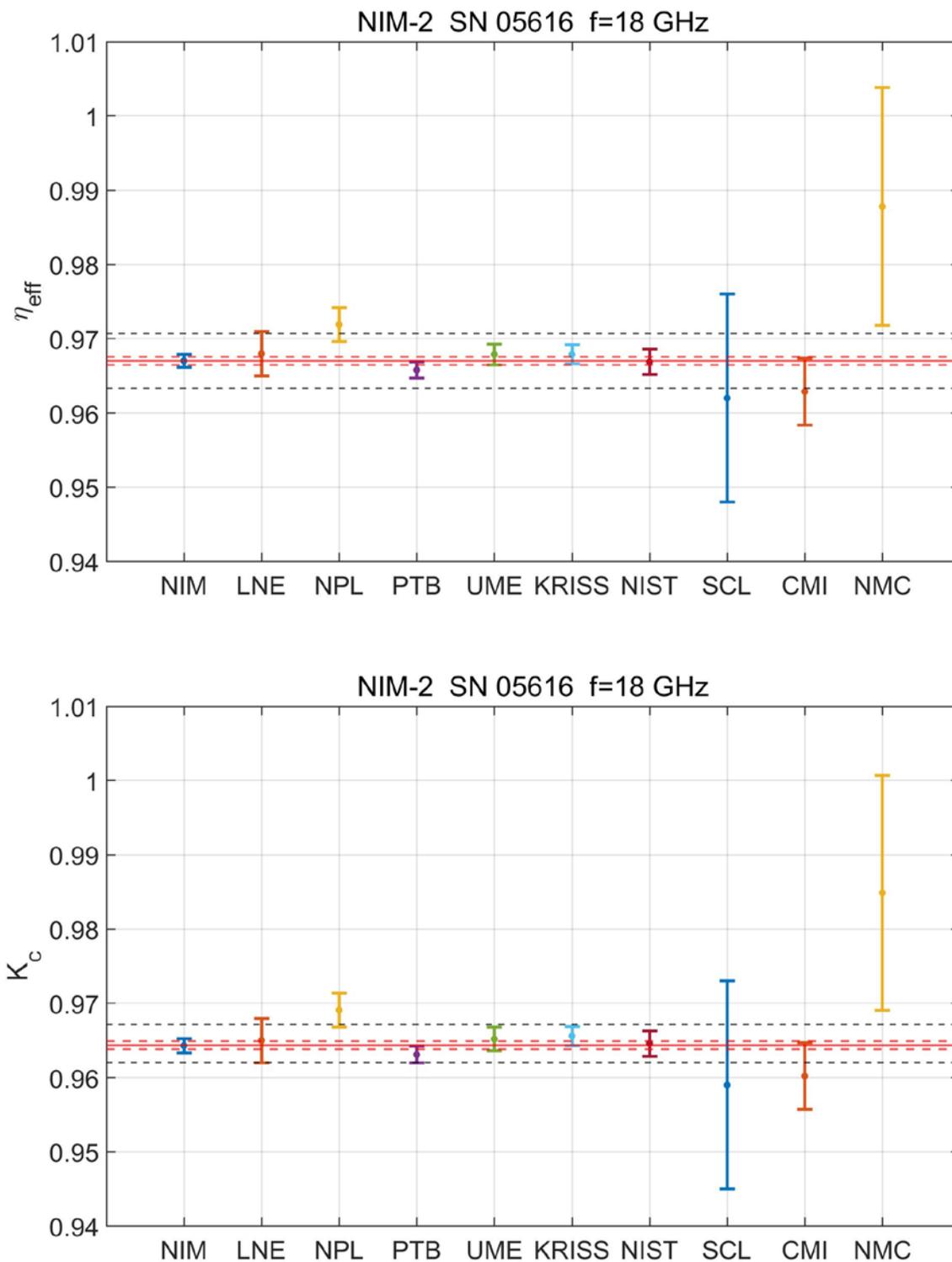
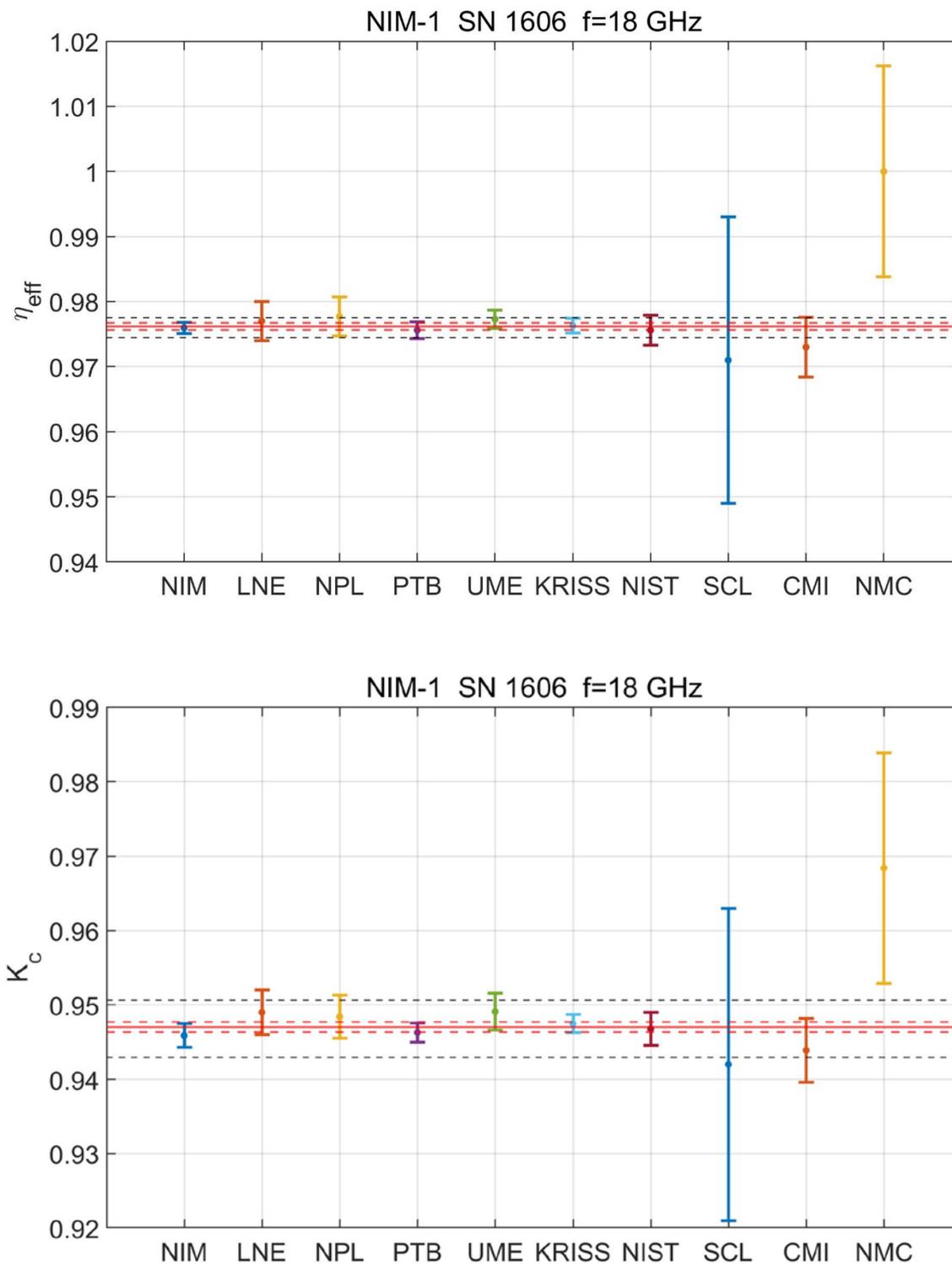

Figure 11. Effective efficiency and calibration factor of travelling standard NIM-2 at 18 GHz. KCRV (—), u(KCRV) (----), outlier boundary (----).

Table 12. Measurements and combined standard uncertainties (k=1) of NIM-2 (SN 05616) at **21** GHz

Laboratory	Measurements used to calculate the KCRV				
	η_{eff}	$u(\eta_{\text{eff}})$ (k=1)	K_{C}	$u(K_{\text{C}})$ (k=1)	
NIM	0.9694	0.0009	0.9337	0.0017	
LNE	0.9690	0.0030	0.9340	0.0030	
PTB	0.9671	0.0012	0.9302	0.0013	
UME	0.9711	0.0015	0.9352	0.0028	
KRISS	0.9690	0.0012	0.9318	0.0014	
NIST	0.9679	0.0014	0.9312	0.0013	
SCL	0.9710	0.0190	0.9340	0.0170	
KCRV	0.9689	0.0005	0.9318	0.0007	

Laboratory	Measurements not used to calculate the KCRV				
	η_{eff}	$u(\eta_{\text{eff}})$ (k=1)	K_{C}	$u(K_{\text{C}})$ (k=1)	Reason for exclusion
NPL	0.9727	0.0016	0.9365	0.0016	Error identified by participant
CMI	0.9621	0.0055	0.9263	0.0052	Traceable to other participant
NMC	0.9665	0.0198	0.9301	0.0189	Traceable to other participant
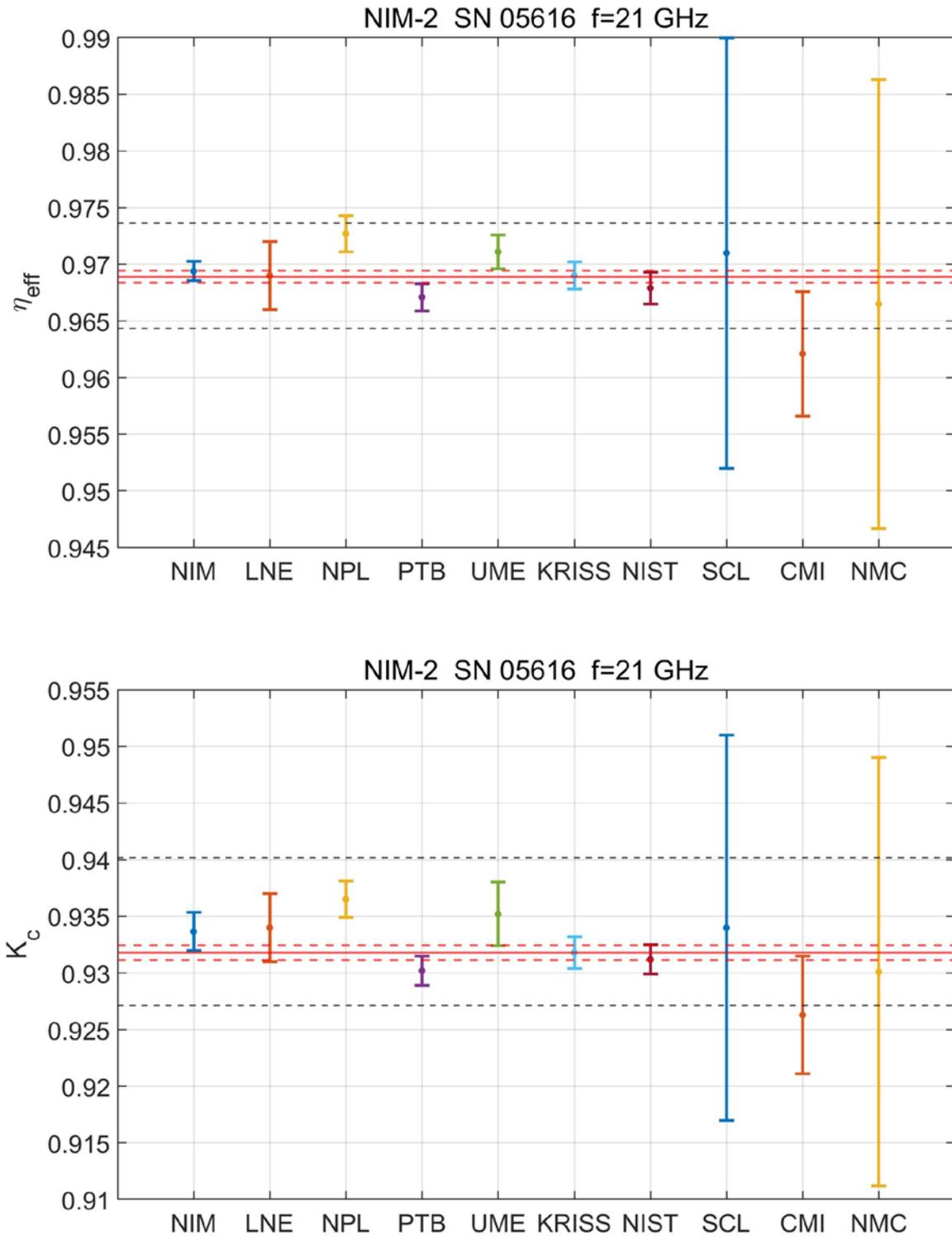
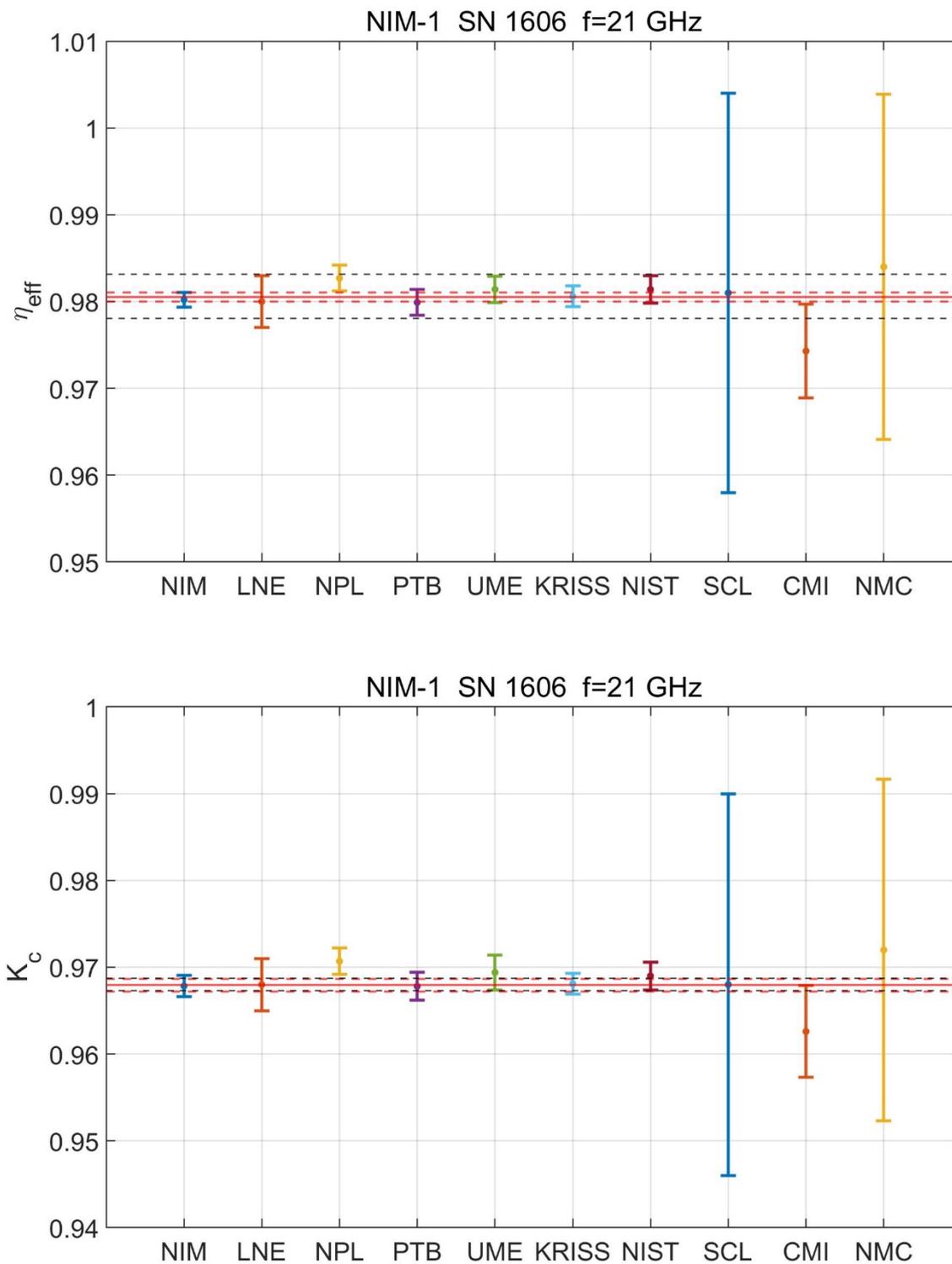Figure 12. Effective efficiency and calibration factor of travelling standard NIM-2 at 21 GHz. KCRV (—), u(KCRV) (----), outlier boundary (----).

Table 13. Measurements and expanded uncertainties (k=1) of NIM-2 (SN 05616) at **24** GHz

Laboratory	Measurements used to calculate the KCRV				
	η_{eff}	$u(\eta_{eff})$ (k=1)	K_C	$u(K_C)$ (k=1)	
NIM	0.9667	0.0009	0.9402	0.0015	
LNE	0.9680	0.0030	0.9410	0.0030	
PTB	0.9658	0.0011	0.9410	0.0012	
UME	0.9704	0.0015	0.9435	0.0025	
KRISS	0.9679	0.0015	0.9403	0.0016	
NIST	0.9648	0.0020	0.9376	0.0020	
KCRV	0.9670	0.0005	0.9402	0.0007	

Laboratory	Measurements not used to calculate the KCRV				
	η_{eff}	$u(\eta_{eff})$ (k=1)	K_C	$u(K_C)$ (k=1)	Reason for exclusion
NPL	0.9738	0.0015	0.9461	0.0015	Error identified by participant
SCL	0.9540	0.0170	0.9260	0.0160	Statistical outlier
CMI	0.9613	0.0053	0.9337	0.0051	Traceable to other participant
NMC	0.9679	0.0227	0.9404	0.0219	Traceable to other participant

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Figure 13. Effective efficiency and calibration factor of travelling standard NIM-2 at 24 GHz. KCRV (—), u(KCRV) (----), outlier boundary (----).

CCEM.RF-K28.W— RF power from 18 GHz to 26.5 GHz in rectangular waveguide

Table 14. Measurements and expanded uncertainties (*k*=1) of NIM-2 (SN 05616) at **26.5** GHz

Laboratory	Measurements used to calculate the KCRV				
	η_{eff}	$u(\eta_{\text{eff}})$ (*k*=1)	K_{C}	$u(K_{\text{C}})$ (*k*=1)	
NIM	0.9626	0.0009	0.9580	0.0010	
LNE	0.9650	0.0030	0.9600	0.0030	
PTB	0.9609	0.0015	0.9558	0.0015	
UME	0.9655	0.0015	0.9598	0.0017	
KRISS	0.9639	0.0013	0.9578	0.0013	
NIST	0.9599	0.0013	0.9543	0.0014	
SCL	0.9630	0.0250	0.9580	0.0250	
KCRV	0.9626	0.0005	0.9573	0.0006	

Laboratory	Measurements not used to calculate the KCRV				
	η_{eff}	$u(\eta_{\text{eff}})$ (*k*=1)	K_{C}	$u(K_{\text{C}})$ (*k*=1)	Reason for exclusion
NPL	0.9692	0.0016	0.9639	0.0016	Error identified by participant
CMI	0.9570	0.0053	0.9519	0.0053	Traceable to other participant
NMC	0.9591	0.0236	0.9535	0.0234	Traceable to other participant

*CCEM.RF-K28.W— RF power from 18 GHz to 26.5 GHz in rectangular waveguide*
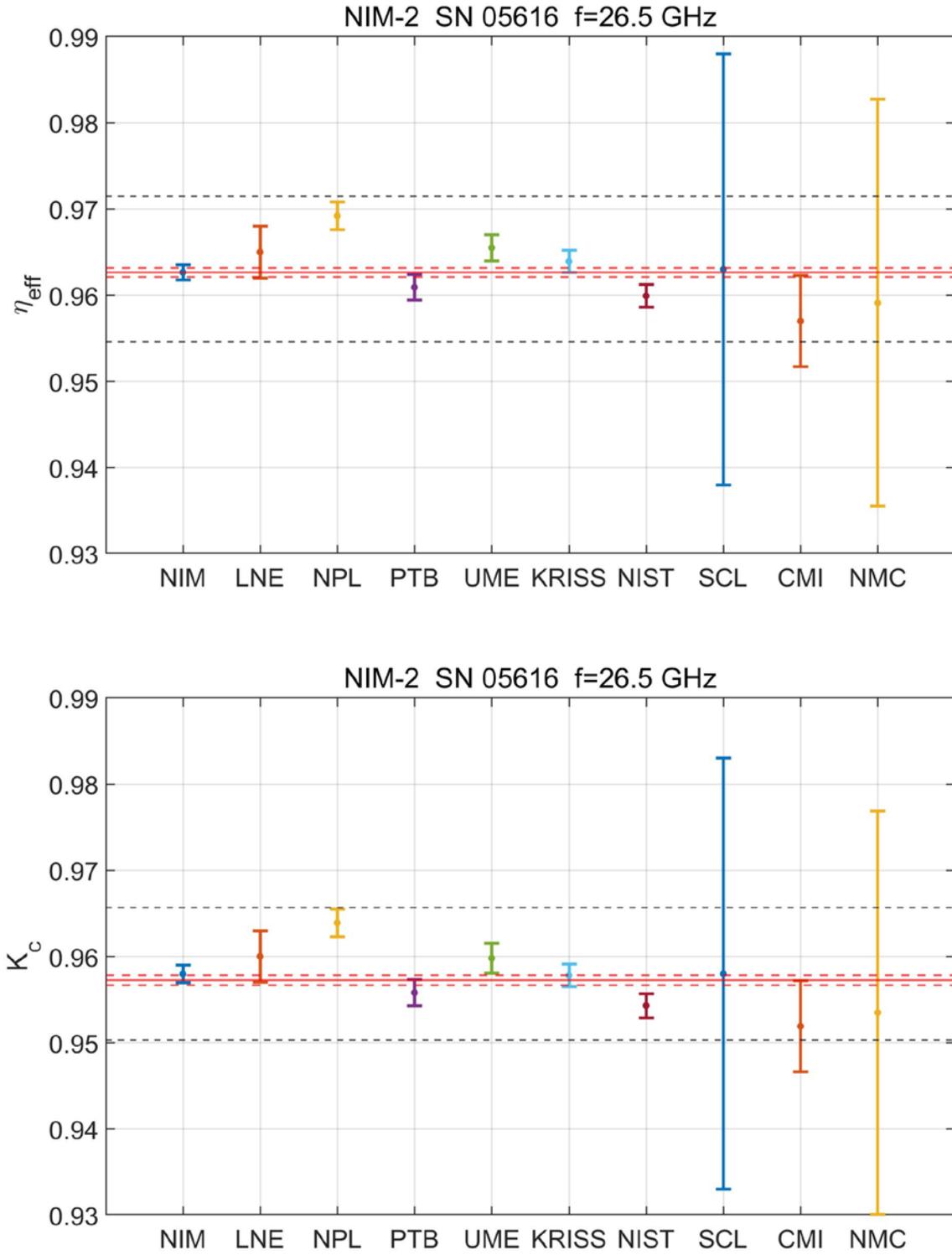
Figure 14. Effective efficiency and calibration factor of travelling standard NIM-2 at 26.5 GHz. KCRV (—), u(KCRV) (----), outlier boundary (----).

5.3 Degrees of equivalence of the participating institutes

The degrees of equivalence (DoE) of both effective efficiency and calibration factor were calculated with respect to the corresponding KCRV, as described in Appendix A. They are listed in Tables 15 to 22.

Table 15. Degrees of equivalence for NIM-1 (SN 1606) at **18** GHz

Laboratory	DoE with respect to the KCRV			
	$\Delta_{\eta_{\text{eff}}}$	$U(\Delta_{\eta_{\text{eff}}})$ $(k=2)$	$\Delta_{K_{\text{C}}}$	$U(\Delta_{K_{\text{C}}})$ $(k=2)$
NIM	-0.0002	0.0013	-0.0011	0.0029
LNE	0.0008	0.0059	0.0020	0.0058
NPL	0.0015	0.0061	0.0014	0.0060
PTB	-0.0006	0.0024	-0.0007	0.0022
UME	0.0011	0.0026	0.0021	0.0048
KRISS	0.0001	0.0019	0.0005	0.0020
NIST	-0.0006	0.0045	-0.0002	0.0042
SCL	-0.0052	0.0440	-0.0050	0.0420
CMI	-0.0032	0.0093	-0.0031	0.0087
NMC	0.0238	0.0324	0.0214	0.0310

Table 16. Degrees of equivalence for NIM-1 (SN 1606) at **21** GHz

Laboratory	DoE with respect to the KCRV			
	$\Delta_{\eta_{\text{eff}}}$	$U(\Delta_{\eta_{\text{eff}}})$ $(k=2)$	$\Delta_{K_{\text{C}}}$	$U(\Delta_{K_{\text{C}}})$ $(k=2)$
NIM	-0.0003	0.0013	-0.0001	0.0019
LNE	-0.0005	0.0059	0.0001	0.0058
NPL	0.0022	0.0032	0.0028	0.0033
PTB	-0.0006	0.0028	-0.0001	0.0028
UME	0.0009	0.0028	0.0015	0.0043
KRISS	0.0001	0.0021	0.0002	0.0019
NIST	0.0009	0.0030	0.0011	0.0028
SCL	0.0005	0.0460	0.0001	0.0440
CMI	-0.0062	0.0109	-0.0053	0.0107
NMC	0.0035	0.0398	0.0041	0.0394

Table 17. Degrees of equivalence for NIM-1 (SN 1606) at **24** GHz

Laboratory	DoE with respect to the KCRV			
	$\Delta_{\eta_{\text{eff}}}$	$U(\Delta_{\eta_{\text{eff}}})$ $(k=2)$	$\Delta_{K_{\text{C}}}$	$U(\Delta_{K_{\text{C}}})$ $(k=2)$
NIM	-0.0005	0.0013	-0.0009	0.0019
LNE	-0.0012	0.0059	-0.0021	0.0059
NPL	0.0067	0.0036	0.0067	0.0036
PTB	-0.0003	0.0022	0.0013	0.0023
UME	0.0013	0.0028	0.0016	0.0034
KRISS	0.0003	0.0022	-0.0005	0.0021
NIST	0.0005	0.0037	-0.0002	0.0036
SCL	-0.0032	0.0440	-0.0041	0.0440
CMI	-0.0043	0.0109	-0.0044	0.0107
NMC	0.0029	0.0442	0.0028	0.0438

Table 18. Degrees of equivalence for NIM-1 (SN 1606) at **26.5** GHz

Laboratory	DoE with respect to the KCRV			
	$\Delta_{\eta_{\text{eff}}}$	$U(\Delta_{\eta_{\text{eff}}})$ $(k=2)$	$\Delta_{K_{\text{C}}}$	$U(\Delta_{K_{\text{C}}})$ $(k=2)$
NIM	-0.0004	0.0013	0.0002	0.0020
LNE	0.0004	0.0059	0.0014	0.0059
NPL	0.0059	0.0030	0.0066	0.0031
PTB	-0.0004	0.0026	0.0006	0.0027
UME	0.0011	0.0028	0.0007	0.0038
KRISS	0.0001	0.0021	-0.0010	0.0022
NIST	0.0003	0.0036	-0.0003	0.0036
SCL	-0.0056	0.0560	-0.0056	0.0540
CMI	-0.0043	0.0109	-0.0036	0.0107
NMC	-0.0013	0.0484	-0.0010	0.0476

CCEM.RF-K28.W— RF power from 18 GHz to 26.5 GHz in rectangular waveguide

Table 19. Degrees of equivalence for NIM-2 (SN 05616) at **18** GHz

Laboratory	DoE with respect to the KCRV			
	$\Delta_{\eta_{\text{eff}}}$	$U(\Delta_{\eta_{\text{eff}}})$ $(k=2)$	$\Delta_{K_{\text{C}}}$	$U(\Delta_{K_{\text{C}}})$ $(k=2)$
NIM	0.0000	0.0014	-0.0001	0.0016
LNE	0.0010	0.0059	0.0006	0.0059
NPL	0.0049	0.0047	0.0047	0.0047
PTB	-0.0012	0.0019	-0.0013	0.0019
UME	0.0009	0.0026	0.0008	0.0030
KRISS	0.0009	0.0024	0.0012	0.0024
NIST	-0.0001	0.0032	0.0002	0.0032
SCL	-0.0050	0.0280	-0.0054	0.0280
CMI	-0.0041	0.0091	-0.0042	0.0091
NMC	0.0208	0.0320	0.0205	0.0316

Table 20. Degrees of equivalence for NIM-2 (SN 05616) at **21** GHz

Laboratory	DoE with respect to the KCRV			
	$\Delta_{\eta_{\text{eff}}}$	$U(\Delta_{\eta_{\text{eff}}})$ $(k=2)$	$\Delta_{K_{\text{C}}}$	$U(\Delta_{K_{\text{C}}})$ $(k=2)$
NIM	0.0005	0.0014	0.0018	0.0031
LNE	0.0001	0.0059	0.0022	0.0059
NPL	0.0038	0.0034	0.0047	0.0035
PTB	-0.0018	0.0022	-0.0016	0.0022
UME	0.0022	0.0028	0.0034	0.0054
KRISS	0.0001	0.0022	0.0000	0.0025
NIST	-0.0010	0.0026	-0.0006	0.0022
SCL	0.0021	0.0380	0.0022	0.0340
CMI	-0.0068	0.0110	-0.0055	0.0105
NMC	-0.0024	0.0396	-0.0017	0.0378

Table 21. Degrees of equivalence for NIM-2 (SN 05616) at **24** GHz

Laboratory	DoE with respect to the KCRV			
	$\Delta_{\eta_{\text{eff}}}$	$U(\Delta_{\eta_{\text{eff}}})$ $(k=2)$	$\Delta_{K_{\text{C}}}$	$U(\Delta_{K_{\text{C}}})$ $(k=2)$
NIM	-0.0003	0.0013	0.0000	0.0027
LNE	0.0010	0.0059	0.0008	0.0058
NPL	0.0068	0.0032	0.0059	0.0033
PTB	-0.0012	0.0019	0.0008	0.0019
UME	0.0034	0.0028	0.0033	0.0048
KRISS	0.0009	0.0028	0.0001	0.0028
NIST	-0.0022	0.0039	-0.0026	0.0037
SCL	-0.0130	0.0340	-0.0142	0.0320
CMI	-0.0057	0.0107	-0.0065	0.0103
NMC	0.0009	0.0454	0.0002	0.0438

Table 22. Degrees of equivalence for NIM-2 (SN 05616) at **26.5** GHz

Laboratory	DoE with respect to the KCRV			
	$\Delta_{\eta_{\text{eff}}}$	$U(\Delta_{\eta_{\text{eff}}})$ $(k=2)$	$\Delta_{K_{\text{C}}}$	$U(\Delta_{K_{\text{C}}})$ $(k=2)$
NIM	0.0000	0.0014	0.0007	0.0017
LNE	0.0024	0.0059	0.0027	0.0059
NPL	0.0066	0.0034	0.0066	0.0034
PTB	-0.0017	0.0028	-0.0015	0.0028
UME	0.0029	0.0028	0.0025	0.0032
KRISS	0.0013	0.0024	0.0005	0.0023
NIST	-0.0027	0.0024	-0.0030	0.0025
SCL	0.0004	0.0500	0.0007	0.0500
CMI	-0.0056	0.0107	-0.0054	0.0107
NMC	-0.0035	0.0472	-0.0038	0.0468

6   Conclusion

In this comparison, effective efficiency and calibration factor of two waveguide thermistor power sensors were determined by ten National Metrology Institutions (NMIs) between November 2022 and December 2024. Six institutes directly determined the effective efficiency by microcalorimeter measurements. And four participants applied second-order calibration methods (e.g. direct comparison), two of them using their own microcalorimeter-calibrated transfer standards and the other two using reference standards traceable to other NMIs.

The two travelling standards (NIM-1, SN 1606 & NIM-2, SN 05616) generally kept stable over the entire comparison.

The results were evaluated at four frequency points by determining the KCRV for both effective efficiency and calibration factor of the two travelling standards (NIM-1, SN 1606 & NIM-2, SN 05616). The reported results were related to the KCRV by calculating the Degrees of Equivalence and their expanded uncertainties.

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A   Treatment of the Results

Key comparison **CCEM.RF-K28.W**

Measurands: Effective efficiency, calibration factor.

Pilot Laboratory: NIM

Supporting laboratories: PTB and NPL

The following quantity symbols are used:

$\eta_{\text{eff, i}}$	Result of effective efficiency measured by laboratory i. If only the calibration factor has been determined, the effective efficiency has been calculated using eq. (2).
$u(\eta_{\text{eff, i}})$	Combined standard uncertainty of $\eta_{\text{eff, i}}$ reported by laboratory i.
$K_{\text{c, i}}$	Result of calibration factor measured by laboratory i.
$u(K_{\text{c, i}})$	Combined standard uncertainty of $K_{\text{c, i}}$ reported by laboratory i.

Outlying results were excluded in calculating the key comparison reference value (KCRV). Outliers were identified using the Median of Absolute Deviations (MAD) [2], defined by

$$\sigma \approx S(MAD) \equiv k_1 median\{|\eta_{\text{i}} - \eta_{\text{med}}|\} \tag{3}$$

where k_1 is a multiplier determined by simulation and η_{med} is the median of the set of measurement data $\{\eta\}$.

According to [2], the value of k_1 for 7 participants (NPL was excluded as an error was identified in its originally submitted data. CMI and NMC were excluded since they are traceable to other participants) is 1.686. A value of η_{i}, which differs from the median by more than 2.5·S (MAD), is considered as outlier, and this criterion is used to test each measurement result:

$$|\eta_{\text{i}} - \eta_{\text{med}}| > 2.5 \cdot S(MAD) \tag{4}$$

If the condition (4) is fulfilled for any result η_{i}, this value is identified as an outlier.

According to section 8 of the technical protocol [1], the KCRVs for this comparison are calculated using the weighted mean from the results as follows:

$$KCRV_{\text{weighted}} = \frac{\sum_{i=1}^{n}\left(\dfrac{x_i}{u_i^2}\right)}{\sum_{i=1}^{n}\left(\dfrac{1}{u_i^2}\right)} \tag{5}$$

where x_i is the measured value (of laboratory i), and u_i is the combined standard uncertainty (of laboratory

i), after inconsistent data have been identified and discarded.

The combined standard uncertainty associated with the KCRV is obtained using

$$u_{\text{KCRV}} = \sqrt{\frac{1}{\sum_{i=1}^{n}\left(\frac{1}{u_i^2}\right)}} \tag{6}$$

The degrees of equivalence of each laboratory with respect to the reference value are given by

$$\Delta x_i = x_i - \text{KCRV}_{\text{weighted}} \tag{7}$$

If x_i is not taken into account in the calculation of the KCRV, then the expanded standard uncertainty (k=2) in

Δx_i is given by

$$U_{\Delta x_i} = 2\sqrt{u_i^2 + u_{\text{KCRV}}^2} \tag{8}$$

If x_i is not an outlier, then the expanded standard uncertainty (k=2) in Δx_i is given by

$$U_{\Delta x_i} = 2\sqrt{u_i^2 - u_{\text{KCRV}}^2} \tag{9}$$

accounting for the existence of correlation between the KCRV and the measured value x_i.

The degrees of equivalence with respect to the KCRV of travelling standards are listed in Tables 15 to 22.

B   Technical Reports from the participating laboratories

B.1   NIM Measurements

To determine the effective efficiency, measurements were performed in the NIM WR-42 twin-load microcalorimeter. The measurement system is shown as Figure B.1.1. A type IV power meter was used as a bolometer bridge and a leveling output which was fed into the "AM in" connector of the source [3].
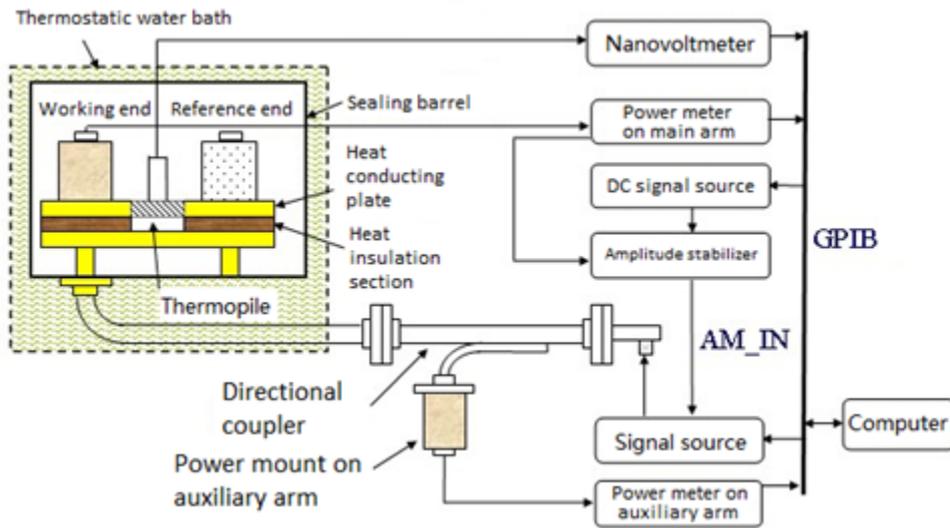
Figure B.1.1. Measurement system of NIM

The DC bias voltages of the type-IV power meter when the RF power is switched off and on were measured and denoted as V1 and V2, respectively. The thermopile voltages when the RF power is switched off and on, respectively, were also measured and denoted as e1 and e2. All these voltages were measured using an Agilent 34420A.

The effective efficiency was determined according to the following equation:

$$\eta_{\text{eff}} = g\eta_{\text{uncor}} = g\,\frac{1-\left(\dfrac{V_2}{V_1}\right)^2}{\dfrac{e_2}{e_1}-\left(\dfrac{V_2}{V_1}\right)^2} \tag{10}$$

Where g is the correction factor.

The calibration factor was determined by:

$$K_{\text{c}} = (1 - |\Gamma|^2)\eta_{\text{eff}} \tag{11}$$

The reflection coefficient (Γ) of the power sensors was measured by a calibrated vector network analyzer (VNA).

B.2   LNE Measurements

The microcalorimeter involved in the CCEM-RF-K28.W CIPM key comparison is a twin type microcalorimeter. The measurements were performed from 18 GHz to 26.5 GHz. Considering the very long time constant of our microcalorimeters, measurements were carried out only at the selected frequencies 18 GHz, 21 GHz, 24 GHz and 26.5 GHz for the evaluation of the Key Comparison Reference Value.

For the whole frequency bandwidth, we used as thermal insulation thin-wall waveguides that were available in the laboratory. In this regard, the travelling standards were calibrated directly in their WR42 reference plane.

The associated instruments were a homemade automatic Wheatstone bridge, an Agilent E8254A microwave signal generator, two Agilent 34420A nanovoltmeters for thermopile voltage measurements and for DC substituted voltage measurements. For each frequency, we carry out 7 RF ON/RF OFF cycles. The effective efficiency is calculated from:

$$\eta_{eff} = \frac{1}{1+\left(\left(\dfrac{E_2 - E_1}{E_1}\right)\times\left(\dfrac{V_1^2}{V_1^2 - V_2^2}\right)\right)} \tag{12}$$

where V1 and V2 are the DC substituted voltages without and with RF power respectively, E1 and E2 are the thermopile output voltages for the cycles without and with RF power respectively. Taking into account the thin-wall waveguides, the following correction is applied:

$$\eta_{effC} = \eta_{eff}\,\frac{e^{A.\log(10)/10}-1}{A.\log(10)/10} \tag{13}$$

Where A represents the thermal insulation waveguide attenuation.

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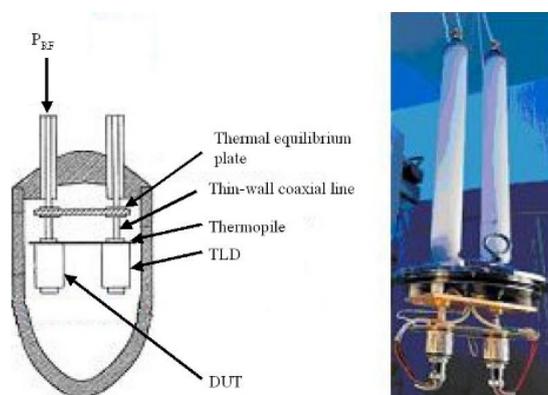
Figure B.2.1. Diagram and picture of the type of microcalorimeter used for the measurements

B.3   NPL Measurements

For the CCEM.RF-K28.W key comparison, NPL used a WR-42 single line microcalorimeter to characterise the two provided travelling standards, referred to from here on as the devices under test (DUT), NIM-1 and NIM-2. The characterisation of these travelling standards covered measurements of the Effective Efficiency (η_{eff}), the Calibration Factor (CF) and the voltage reflection coefficients (Linear magnitude ($|\Gamma|$), and phase). The traceability to the SI units for Effective Efficiency is established through DC quantities.

A diagram of the general structure of a microcalorimeter system is given in Figure B.3.1 and a description of the different elements is given below.

An Agilent E8257D signal generator was used as the source and provided a signal to the DUT at 18, 21, 24, and 26.5 GHz. The signal path consisted of a directional coupler, used to couple a portion of the source power into a reference sensor and the remainder passed through to a waveguide transmission line and thermal isolation section (TIS), before being terminated by the DUT.

An HP 432A power meter was used as a self-balancing bridge. This was connected to the RF thermistor of the DUT and an external compensating thermistor, so as to remove the additional heating effect. This meter was used to supply the DC bias voltages on the DUT when the RF power was switched on and off. The DC bias voltages are denoted as $V0$ (RF input off) and $V1$ (RF input on) and are used to calculate the DC substituted power [4]. These DC voltages were measured using a calibrated HP 34970A data acquisition unit.

These different DC bias conditions produce a temperature change in the DUT. These temperature changes were monitored by a radial thermopile with the different DUT temperatures producing different thermopile output voltages, e_0 and $e1$, when RF power is off and on respectively. These voltages were measured using a calibrated Keysight 34420A nanovoltmeter. The thermopile is also sensitive to and detects small thermal imbalances in the microcalorimeter system as well as larger temperature changes caused by the small amount of power that is dissipated in the TIS. Therefore, the thermopile output voltage is not just a function of the dissipated power in the DUT, but also includes an additional unbalance term and the heating effect from the TIS. The output voltage caused by the TIS heating effect (e_{TIS}) is characterised using a short foil method. This method is discussed in [5]. The thermal imbalance

voltage (e_u) in the microcalorimeter is characterised by monitoring the thermopile when no DC or RF power is applied to the system.

To dampen the effects of short-term ambient temperature changes, the TIS, Thermopile and DUT are housed inside the microcalorimeter head, an airtight, large metallic thermal mass. This can be seen in Error! Reference source not found. Figure B.3.1. These temperature effects are further mitigated by locating this within a close control air bath. The temperature inside of which, during measurements was (23.0000 ± 0.0010) °C with 50% humidity.

At minimum, six measurements were made of each DUT, three in each of the waveguide flange orientations. The nominal incident power applied to the DUT for all measurements was 3 mW, as outlined in the technical protocol. After setup and before measurements were taken, the microcalorimeter system was left for 24 hours to reach a thermal equilibrium.

The effective efficiency was calculated using the following equation:

$$\eta_{eff} = \frac{(1 - \frac{V_1^2}{V_0^2})}{\frac{e_1 - e_{TIS} - e_u}{e_0 - e_u} - \frac{V_1^2}{V_0^2}} \tag{14}$$

The Calibration Factor was calculated using:

$$C.F. = \eta_{eff}(1 - |\Gamma|^2) \tag{15}$$
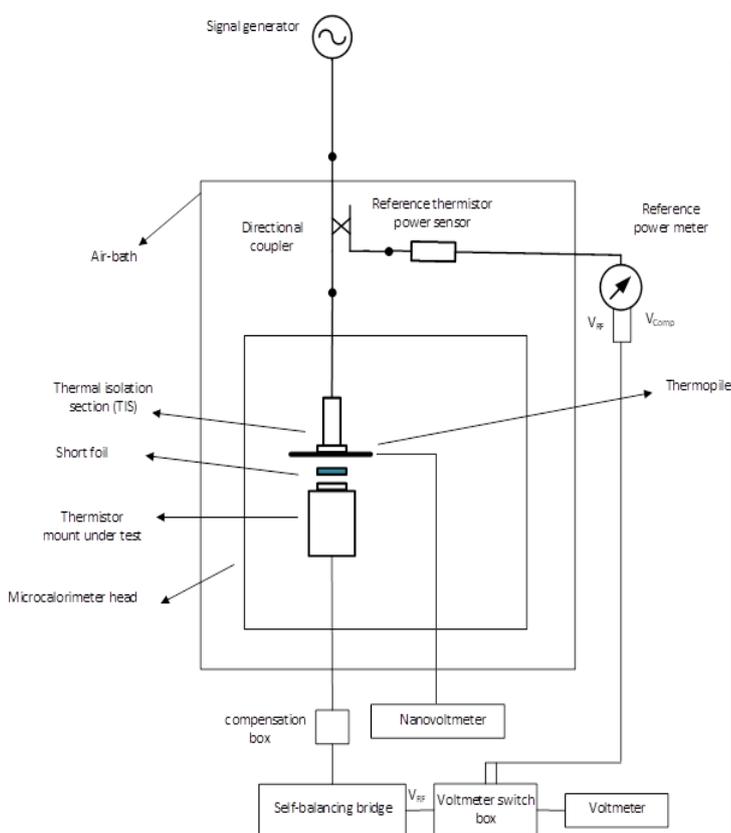
Figure B.3.1. General Structure of Waveguide Microcalorimeter Setup

Measurements of the Voltage Reflection Coefficients of the two travelling standards were made using NPLs primary impedance measurement system (PIMMS). PIMMS uses a Vector Network Analyser configured with an external TRL (Thru-Reflect-Line) type calibration algorithm, implemented by NPL, using calibration items traceable to SI units via their mechanical properties. The calibration was verified using traceably calibrated audit standards.

B.4   PTB Measurements

To determine η_{eff}, the bolometer sensor was placed in a waveguide microcalorimeter with the same flange type. The bolometer element was d.c.-connected to an automatically balancing bridge to determine the d.c. substitution power PS, that corresponds to the high frequency power absorbed by the bolometer element. The high frequency power incident to the sensor input was stabilized by means of a special regulating circuit. Inside the microcalorimeter there was a thermal connection between the flange of the device under test and the measurement plane in which the thermopile for the calorimetric determination of the high frequency power absorbed in the sensor was located. The effective efficiency was determined according to the following equation:

$$\eta_{\text{eff}} = \frac{1-\left(\dfrac{U_2}{U_1}\right)^2}{\dfrac{e_2}{e_1}-\left(\dfrac{U_2}{U_1}\right)^2}\cdot\left(1+\sum_i \Delta k_i\right) \tag{16}$$

with

U_1	bolometer bridge voltage with the RF power switched off,
U_2	bolometer bridge voltage with the RF power switched on,
e_1	value of the thermopile output voltage with the RF power switched off,
e_2	value of the thermopile output voltage with the RF power switched on,

$\left(1+\sum_i \Delta k_i\right)$ correction factor to eliminate various error influences.

To determine the calibration factor η_{cal} under operating conditions at nominal resistance, the input

reflection coefficient $|\Gamma|$ of the sensor was determined. From η_{eff} and $|\Gamma|$ the calibration factor is given:

$$\eta_{\text{cal}} = \eta_{\text{eff}} \cdot \left(1-|\Gamma|^2\right) \tag{17}$$

At the input of the interface, the high frequency power (PHF) supplied to the sensor is

$$P_{\text{HF}} = \frac{P_s}{\eta_{\text{cal}}} \tag{18}$$

B.5   UME Measurements

A twin micro-calorimeter is used for the measurements at TÜBİTAK UME. Two identical thermistor mounts are required to do effective efficiency measurements using the twin micro-calorimeter system. One of them is the equipment (DUT) whose effective efficiency (η) value is going to be measured; and the other one is used as the temperature reference point. There are two identical measurement lines at micro- calorimeter system. Both of the lines can be used at the measurements. However, during the measurement only one of lines is electrically connected. On that line, a microwave cable is used to establish proper high frequency connection and to transfer the microwave signals to the system, a temperature equivalence block (heat stabilizer, heat-sink) is used to ensure equal temperature distribution on both of the lines. Once the temperature equivalence on these two lines is achieved, microwave signal reaches to the thermistor mount with the help of the thin line, which transfers the heat to the device under test with the least possible ratio. Thin line is known electrically good conductor but thermally poor one.

Effective efficiency (η) is the ratio of a substituted DC power to a real microwave power. The Effective efficiency is calculated by using (19) at TÜBİTAK UME.

TÜBİTAK UME's micro-calorimeter system illustration is given in Figure B.5.1.

$$\eta = \frac{1}{1 + \dfrac{V_1^2}{V_1^2 - V_2^2} \dfrac{e_2 - e_1 L_n}{e_1 L_n}} \tag{19}$$

Where

    V_1 Wheatstone bridge output while RF off

    V_2 Wheatstone bridge output while RF on

    e_1 Thermopile output voltage while RF off

    e_2 Thermopile output voltage while RF on

Thermopile linearity

$$L_T = 1 + \frac{\Delta k}{k_1} \tag{20}$$

Where

    Δk Thermopile nonlinearity coefficient

    k_1 Thermopile conversion coefficient
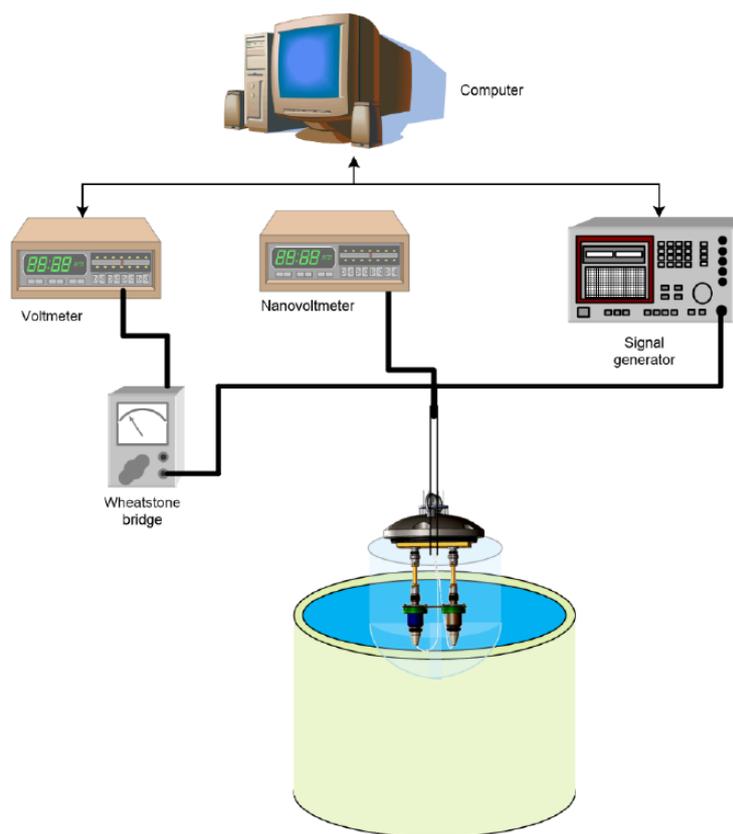
Figure B.5.1. TÜBİTAK UME's micro-calorimeter function block diagram

Measurement and effective efficiency calculation are performed by developed software. Software was updated in 2015. In order to calculation of Effective Efficiency, every voltage is measured 50 times while RF on and RF off.

Calibration factor is the ratio of the equivalent DC power read on display to the power applied to the input of the sensor as indicated in (21). Calibration factor covers mismatch losses as well as the losses inside the sensor.

Since calibration factor covers the losses included in effective efficiency, calibration factor can be expressed in terms of effective efficiency by:

$$CF = \eta(1 - \rho^2) \tag{21}$$

Where ρ is reflection coefficient of the sensor.

B.6   KRISS Measurements

A K-band waveguide microcalorimeter shown Figure B.6.1 [6] is used to measure the effective efficiency of the travelling standards, two waveguide thermistor mounts (TMs) with the R220 flange with RF off/on cycles.
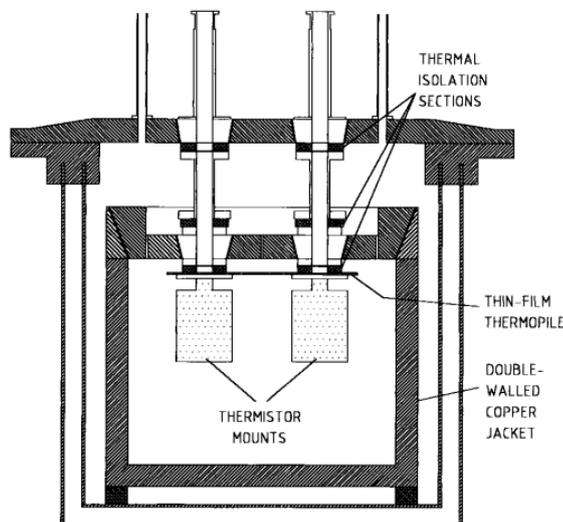
Figure B.6.1. Cross section of the K-band waveguide microcalorimeter.

A measurement system including peripheral instruments is shown in Figure B.6.2. As shown in Figure B.6.2, the effective efficiency of a TM is obtained using V1 and V2, the DC substituted voltages of the TM under test, and e1 and e2, the output voltages of a thermopile with RF power off and on. For the effective efficiency at a frequency, V1 and e1 is measured with RF power off. Next, RF power turns on and wait about 70 min until the output voltage of the thermopile is stabilized and e2 is measured. Meanwhile, just after RF power turns on, V2 is measured. From the measured values of DC substituted voltages and thermopile output voltages, an uncorrected effective efficiency η_e' is calculated [6]. By applying a frequency-dependent correction factor to η_e', the corrected effective efficiency η_e' is obtained. It is noted that the blue gridded space in Figure B.6.2. has been empty because the lab temperature is satisfactorily stable. Four independent measurements were made at Port 1 and Port 2 of the twin-type waveguide microcalorimeter under two distinctive connecting directions of the TM flange. Therefore, the pooled experimental standard deviation described in the GUM was obtained for Type A uncertainty evaluation of repeated measurements.
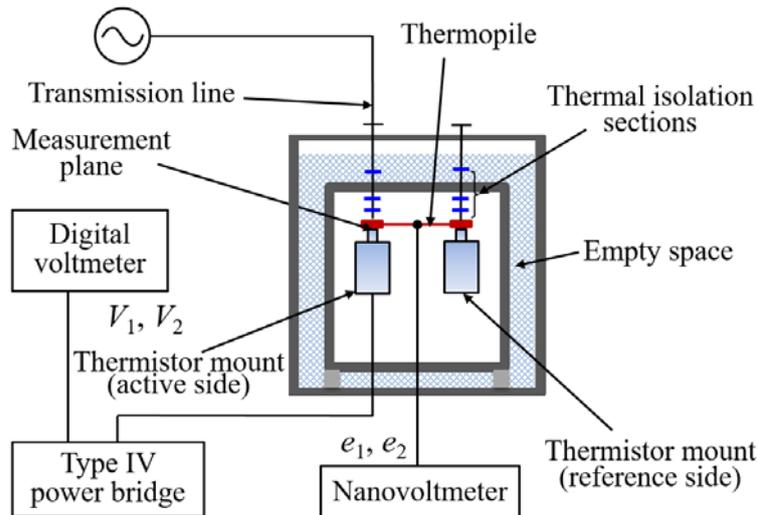
Figure B.6.2. The measurement system including peripheral instruments.

The reflection coefficient of a TM under test is measured using a vector network analyzer (VNA). The thru-reflect-line (TRL) technique is used to calibrate the VNA. Subsequently, the calibration factor K is obtained from η_e and the magnitude of the reflection coefficient $|\Gamma|$ of the TM at each frequency.

B.7 NIST Measurements

NIST measured the travelling standards NIM-1 and NIM-2 in a direct-comparison system, using the approach described in [7]. This procedure involves a power splitter and three power sensors. These sensors are referred to as the monitor (M), the calibration standard (S), and the unknown (U). During a measurement, we supply RF power to port 1 of the power splitter and attach a monitor to port 3 of the splitter. Then we perform measurements in two different configurations. First, we attach the calibration standard to port 2. At each frequency of interest, we supply RF power to the splitter, and record the power measured by the standard (P_S) and the monitor (P_{MS}). In the second configuration, we attach the unknown sensor to port 2, and repeat the same series of measurements, recording the power measured by the unknown sensor (P_U), and the monitor (P_{MU}). From these, we estimate the effective efficiency of the travelling standard (η_U) by:

$$\eta_U = \eta_S \frac{P_{MS}}{P_{MU}} \frac{P_U}{P_S} \frac{(1-|\Gamma_S|^2)}{(1-|\Gamma_U|^2)} \frac{|1-\Gamma_G\Gamma_U|^2}{|1-\Gamma_G\Gamma_S|^2} \tag{22}$$

Here, η_S is the effective efficiency of the calibration standard, Γ_S and Γ_U are the reflection coefficients of the calibration standard and the travelling standard, and Γ_G is the equivalent source mismatch.

In the measurements reported here, all three sensors (monitor, calibration standard, and unknown) are WR-42 thermistor mounts and the splitter is a WR-42 3 dB coupler. We measure RF power using the dc-substitution approach. During a dc-substitution measurement, the thermistor is maintained at a constant resistance of 200 Ω by a Type IV power meter [8]. NIST currently has two power sensors in WR-42 that serve as calibration standards. Both of these sensors are modified thermistor mounts [9]. The effective efficiency of these primary power sensor standards was measured in a microcalorimeter, also described in [9].

The operational limits of our laboratory environmental conditions are 23 °C ± 2 °C and 40 % ± 20 % relative humidity. The average humidity we recorded during the measurements we report here was 42 %, with standard deviation of 5 %. During the direct comparison measurements, the RF power incident on the power sensor was approximately 3 mW. We performed a total of 5 direct comparison measurements of both of the travelling standards. In each measurement, measurements were performed on both ports of the splitter in two connect cycles. Thus, there were a total of 20 connect cycles represented in these measurements. In each measurement, NIST used both calibration standards and averaged the estimates of η_U derived from Equation (22).

B.8   CMI Measurements

The waveguide thermistor mount K486A (with the power meter 432A + 2 multimeters) fitted with type WR-42 waveguide flange has been used as measurement standard, comparing its reading with that of the sensor under test (with the power meter 432A + 2 multimeters) and the third power sensor ECP-E26A with the power meter N1911A is used at the output of a characterized direction coupler in order to assure that the incident power in both measurements is similar. The technique is known as the direct calibration method. Mismatch vector correction has been applied, based on the complex knowledge of all reflection coefficients there involved, and the uncertainty associated to this correction has been incorporated into the expanded measurement uncertainty.

Calibration factor
Model function

$$CF_{DUT} = CF_{STD} \cdot \frac{P_{DUT}}{P_{STD}} \cdot \delta P \cdot C_{vector} \cdot \delta CF_{DUT} \tag{23}$$

CF_{STD} (1)   calibration factor of the standard sensor

P_{DUT} (W)   power indicated by the sensor under test with the power meter

P_{STD} (W)   power indicated by the standard sensor with the power meter

δP (1)   power ratio of the third (leveling) sensor

$$\delta P = \frac{P_{3STD}}{P_{3DUT}} \tag{24}$$

P_{3STD} (W)   power indicated by the third (leveling) sensor with the power meter, when sensor under test is connected

P_{3DUT} (W)   power indicated by the third (leveling) sensor with the power meter, when standard sensor is connected

C_{vector} (1)   mismatch vector correction

$$C_{vector} = \left| \frac{1 - \Gamma_{DUT} \Gamma_{EQSM}}{1 - \Gamma_{STD} \Gamma_{EQSM}} \right|^2 \tag{25}$$

Γ_{DUT} (1)   reflection coefficient of the sensor under test

Γ_{STD} (1)   reflection coefficient of the standard sensor

Γ_{EQSM} (1)   equivalent source match of the power splitter

δCF_{DUT} (1)   factor taking into account deviations in DUT measurements caused by random effects (connection of connectors,...)

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Effective Efficiency

Model function

$$\eta_{eff.} = \frac{CF_{DUT}}{(1 - \Gamma^2_{DUT})} \cdot \delta_{\eta_{eff.}} \tag{26}$$

CF_{DUT} (1)   calibration factor of the sensor under test

Γ_{DUT} (1)   reflection coefficient of the sensor under test

$\delta_{\eta_{eff.}}$ (1)   factor taking into account deviations in DUT measurements caused by random effects

B.9 SCL Measurements

The direct comparison method was applied to measure the absolute calibration factors and effective efficiencies of the two travelling standards NIM-1 and NIM-2 at 18 GHz, 21 GHz, 24 GHz and 26.5 GHz.

The absolute calibration factor of the UUT was compared directly with the laboratory 2.4 mm coaxial reference power sensor R&S NRP-Z56, which was connected with laboratory's power meter R&S NRX. A sinusoidal signal of approximately 9 dBm power level was applied from the laboratory's signal generator Keysight E8257D to the input port of laboratory's two-resistor power splitter such that there was a nominal 2 mW (3dBm) power level at the output ports (Port 2 and Port 3) of the power splitter. A laboratory power sensor was connected to Port 2 of the power splitter as a monitoring sensor on the power meters were recorded. Four measurements were taken with the reference power sensor and the UUT rotated 90° for each measurement. The schematic diagram is shown in Figure B.9.1. (Note: Prior to measurement of absolute calibration factor, zeroing of the reference power sensor and monitoring power sensor were performed.)
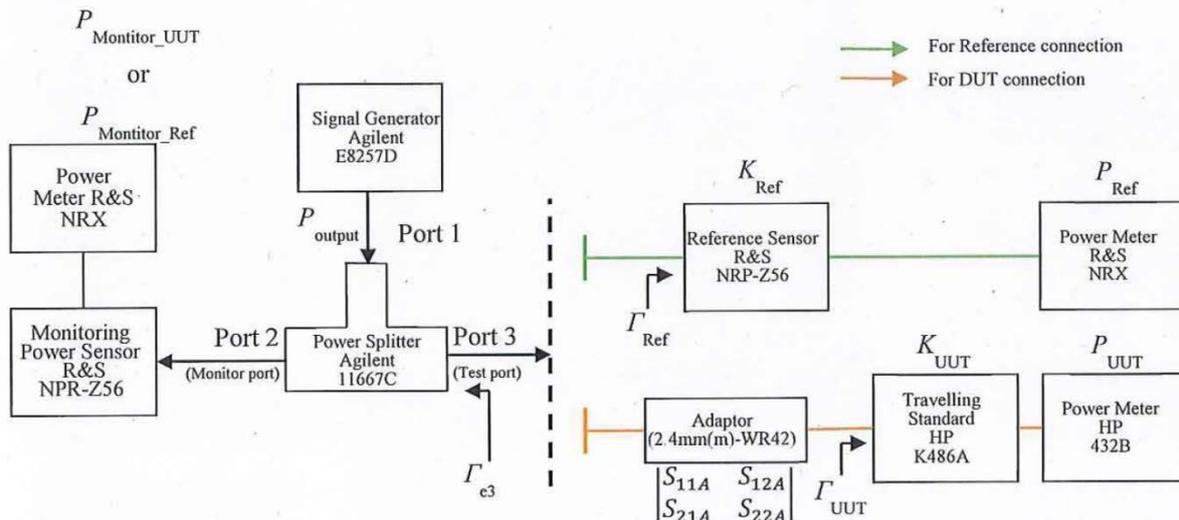
Figure B.9.1. Calibration setup for the measurement

The measurement model to measure the calibration factor of the UUT, Kuut, is shown below:

$$K_{UUT} = K_{Ref}\left(\frac{P_{UUT}}{P_{Monitor\_UUT}}\right)\left(\frac{P_{Monitor\_Ref}}{P_{Ref}}\right) \mid \frac{1 - \Gamma_{UUT}S_{22A} - \Gamma_{e3}(S_{11A} + \Gamma_{UUT}S_{21A}S_{12A} - \Gamma_{UUT}S_{22A}S_{11A})^2}{S_{21A}(1 - \Gamma_{Ref}\Gamma_{e3})} \mid^2 \quad (27)$$

Where

K_{Ref} : Calibration factor of Reference power sensor

P_{UUT} :   : Power measured at port 3 using the UUT

$P_{Monitor\_UUT}$: Power measured at port 2 using monitoring power sensor with UUT connected

$P_{\text{Monitor\_Ref}}$: Power measured at port 2 using monitoring power sensor with Reference power sensor connected

P_{ref} : Power measured at port 3 using the Reference power sensor

Γ_{UUT} : VRC of UUT

S_{11A} : S_{11} of Adaptor

S_{12A} : S_{12} of Adaptor

S_{21A} : S_{21} of Adaptor

S_{22A} : S_{22} of Adaptor

Γ_{e3} : VRC of Port 3 of Power splitter

Γ_{Ref} : VRC of with Reference power sensor

The effective efficiencies of the UUT, η_{UUT}, were calculated form the calibration factors and the voltage reflection coefficients by the following equation:

$$\eta_{\text{UUT.}} = \frac{K_{\text{UUT}}}{1 - |\Gamma_{\text{UUT}}|^2} \tag{28}$$

B.10 NMC Measurements

The calibration factors of the two thermistor mounts (travelling standards, DUT) were measured using the direct comparison measurement technique, which transfers the calibration factor of a reference power standard to an unknown thermistor mount (DUT).

The method is based on alternate connections between a reference standard and unknown thermistor mount (DUT) to one of the output ports of a passive power splitter. The other output port of the power splitter is used for correcting the power variation during the measurement.   A RF source is connected to the input port of the power splitter.

A waveguide to 3.5 mm (male) adaptor is used to connect the travelling standards to the output port of the power splitter. The loss factor, KA, of this adaptor is measured by taking a pair of closely matched adapters, connecting them back-to-back and measure its scattering parameter S21 using a vector network analyser.

To reduce mismatch error, the complex reflection coefficients of the reference power standard, unknown thermistor mounts (DUT) when connecting to the adaptor and power splitter were considered when computing the calibration factors of the two thermistor mounts (DUT).

The direct comparison system comprises one reference thermistor mount, a NBS Type IV power meter, a digital multimeter, a signal generator, a power splitter (3.5 mm) and a monitoring power meter and power sensor.

A vector network analyser was used to measure the reflection coefficients of the reference standards, travelling standards, adapter and the equivalent reflection coefficient of the power splitter.
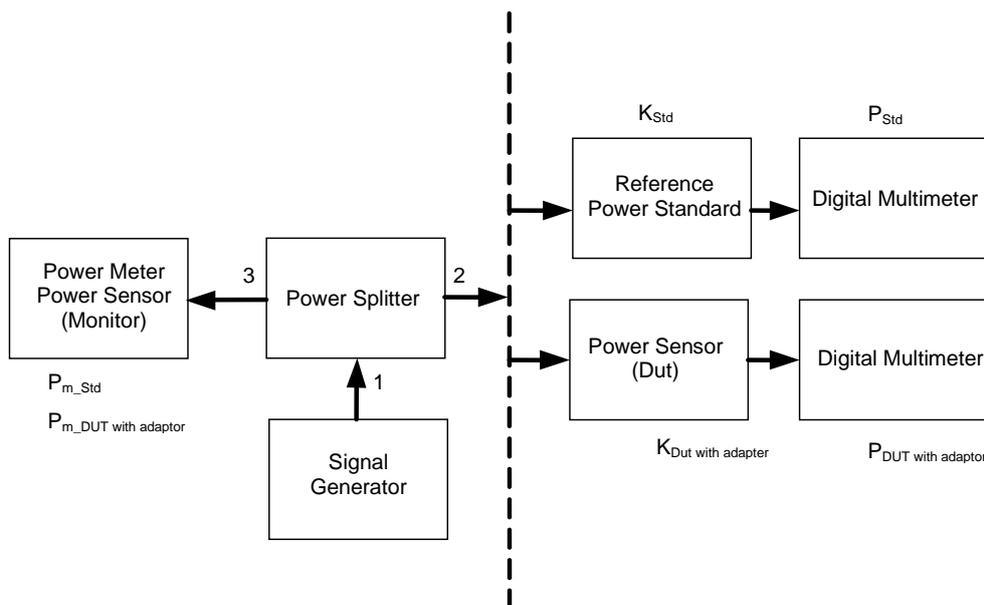
Figure B.10.1. Direct Comparison System Setup

The calibration factors of the travelling standards from 18 GHz to 26.5 GHz are traceable to a temperature stabilized thermistor mount reference power standard. It is traceable to the standard maintained at KRISS (Republic of Korea).

The reflection coefficients of the travelling standards are measured using a vector network analyser, which is traceable through impedance standards to NPL (UK).

All other working standards are traceable to the national reference standards maintained at the NMC (Singapore).

The mathematical model for the calibration factor of the thermistor mount (DUT) is as follows:

$$K_{DUT} = \frac{K_{Std}}{K_A} \times \frac{P_{DUT\,with\,adaptor}}{P_{Std}} \frac{P_{\mathrm{m}\_Std}}{P_{\mathrm{m}\_DUT\,with\,adaptor}} \times \frac{\left|1 - \Gamma_{DUT\,with\,adaptor}\Gamma_{EG}\right|^2}{\left|1 - \Gamma_{Std}\Gamma_{EG}\right|^2} \tag{29}$$

$$K_A = |S_{21A}|^2 \tag{30}$$

where K_{DUT} is the calibration factor of the travelling standard (DUT)

K_{Std} is the calibration factor of the reference standard

K_A is the loss factor of the waveguide to 3.5 mm (m) adaptor

S_{21A} is the scattering parameter of the pair of the matched adapters connecting back-to-back

P_{DUT} with adapter is the DC substitution power of the travelling standard when connecting to the adaptor

P_{Std} is the DC substitution power of the reference standard

P_{m_Std} is the power indication of monitor power meter for reference standard

P_{m_DUT} with adaptor is the power indication of monitor power meter for travelling standard when connecting to the adaptor

Γ_{Std} is the reflection coefficient of the reference standard

Γ_{DUT} with adaptor is the reflection coefficient of the travelling standard when connecting to the adaptor

Γ_{EG} is the equivalent source reflection coefficient of power splitter that is connected to   reference standard or travelling standard with adaptor

C   Reported results

C.1   NIM measurement data

Table C.1.1. Reported results of NIM

Laboratory	NIM							
Standard	NIM-1, SN1606							
Frequency (GHZ)	η_{eff}	$u(\eta_{eff})$ (k=1)	K_C	$u(K_C)$ (k=1)	$|\Gamma|$	$u(|\Gamma|)$ (k=1)	$\arg(\Gamma)$ (°)	$u(\arg(\Gamma))$ (°, k=1)
18	0.9760	0.0009	0.9459	0.0016	0.1707	0.0040	-128.0	0.6
21	0.9802	0.0008	0.9678	0.0012	0.1100	0.0040	46.5	0.6
24	0.9777	0.0008	0.9681	0.0011	0.0964	0.0040	58.9	0.6
26.5	0.9722	0.0009	0.9598	0.0012	0.1127	0.0040	15.2	0.6

Table C.1.2. Reported results of NIM

Laboratory	NIM							
Standard	NIM-2, SN05616							
Frequency (GHZ)	η_{eff}	$u(\eta_{eff})$ (k=1)	K_C	$u(K_C)$ (k=1)	$|\Gamma|$	$u(|\Gamma|)$ (k=1)	$\arg(\Gamma)$ (°)	$u(\arg(\Gamma))$ (°, k=1)
18	0.9670	0.0009	0.9643	0.0010	0.0526	0.0040	-106.9	0.6
21	0.9694	0.0009	0.9337	0.0017	0.1920	0.0040	37.3	0.6
24	0.9667	0.0009	0.9402	0.0015	0.1656	0.0040	64.8	0.6
26.5	0.9626	0.0009	0.9580	0.0010	0.0698	0.0040	52.4	0.6

C.2 LNE measurement data

Table C.2.1. Reported results of LNE

Laboratory	LNE							
Standard	NIM-1, SN1606							
Frequency (GHZ)	η_{eff}	$u(\eta_{eff})$ (k=1)	K_C	$u(K_C)$ (k=1)	$\|\Gamma\|$	$u(\|\Gamma\|)$ (k=1)	$\arg(\Gamma)$ (°)	$u(\arg(\Gamma))$ (°, k=1)
18	0.977	0.003	0.949	0.003	0.171	0.004	51.53	0.024
21	0.980	0.003	0.968	0.003	0.110	0.004	45.95	0.037
24	0.977	0.003	0.967	0.003	0.098	0.004	59.63	0.042
26.5	0.973	0.003	0.961	0.003	0.113	0.004	14.43	0.037

Table C.2.2. Reported results of LNE

Laboratory	LNE							
Standard	NIM-2, SN05616							
Frequency (GHZ)	η_{eff}	$u(\eta_{eff})$ (k=1)	K_C	$u(K_C)$ (k=1)	$\|\Gamma\|$	$u(\|\Gamma\|)$ (k=1)	$\arg(\Gamma)$ (°)	$u(\arg(\Gamma))$ (°, k=1)
18	0.968	0.003	0.965	0.003	0.053	0.004	70.18	0.077
21	0.969	0.003	0.934	0.003	0.191	0.004	37.18	0.021
24	0.968	0.003	0.941	0.003	0.168	0.004	64.95	0.024
26.5	0.965	0.003	0.960	0.003	0.074	0.004	51.22	0.056

C.3   NPL measurement data

Table C.3.1. Reported results of NPL

Laboratory	NPL							
Standard	NIM-1, SN1606							
Frequency (GHZ)	η_{eff}	$u(\eta_{\text{eff}})$ (k=1)	K_C	$u(K_C)$ (k=1)	$\|\Gamma\|$	$u(\|\Gamma\|)$ (k=1)	$\arg(\Gamma)$ (°)	$u(\arg(\Gamma))$ (°, k=1)
18	0.9777	0.0030	0.9484	0.0029	0.1731	0.0011	-127.6	0.4
21	0.9827	0.0015	0.9707	0.0015	0.1104	0.0015	46.6	0.8
24	0.9849	0.0017	0.9758	0.0017	0.0963	0.0016	59.1	0.9
26.5	0.9785	0.0014	0.9662	0.0014	0.1121	0.0018	14.7	0.9

Table C.3.2. Reported results of NPL

Laboratory	NPL							
Standard	NIM-2, SN05616							
Frequency (GHZ)	η_{eff}	$u(\eta_{\text{eff}})$ (k=1)	K_C	$u(K_C)$ (k=1)	$\|\Gamma\|$	$u(\|\Gamma\|)$ (k=1)	$\arg(\Gamma)$ (°)	$u(\arg(\Gamma))$ (°, k=1)
18	0.9719	0.0023	0.9691	0.0023	0.0528	0.0012	-110.9	1.2
21	0.9727	0.0016	0.9365	0.0016	0.1928	0.0011	37.6	0.3
24	0.9738	0.0015	0.9461	0.0015	0.1687	0.0010	65.4	0.4
26.5	0.9692	0.0016	0.9639	0.0016	0.0739	0.0012	51.2	0.9

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C.4 PTB measurement data

Table C.4.1 Reported results of PTB

Laboratory	PTB							
Standard	NIM-1, SN1606							
Frequency (GHZ)	η_{eff}	$u(\eta_{\text{eff}})$ (k=1)	K_C	$u(K_C)$ (k=1)	$|\varGamma|$	$u(|\varGamma|)$ (k=1)	arg($\varGamma$) (°)	$u(\text{arg}(\varGamma))$ (°, k=1)
18	0.9756	0.0013	0.9463	0.0013	0.1732	0.0015	-127.8	0.5
21	0.9799	0.0015	0.9678	0.0016	0.1114	0.0015	43.1	0.8
24	0.9779	0.0012	0.9704	0.0013	0.0874	0.0015	59.7	1.0
26.5	0.9722	0.0014	0.9602	0.0015	0.1113	0.0015	16.2	0.8

Table C.4.2 Reported results of PTB

Laboratory	PTB							
Standard	NIM-2, SN05616							
Frequency (GHZ)	η_{eff}	$u(\eta_{\text{eff}})$ (k=1)	K_C	$u(K_C)$ (k=1)	$|\varGamma|$	$u(|\varGamma|)$ (k=1)	arg($\varGamma$) (°)	$u(\text{arg}(\varGamma))$ (°, k=1)
18	0.9658	0.0011	0.9631	0.0011	0.0528	0.0015	-108.5	1.6
21	0.9671	0.0012	0.9302	0.0013	0.1954	0.0015	34.4	0.5
24	0.9658	0.0011	0.9410	0.0012	0.1603	0.0015	64.7	0.6
26.5	0.9609	0.0015	0.9558	0.0015	0.0734	0.0015	54.1	1.2

C.5   UME measurement data

Table C.5.1 Reported results of UME

Laboratory	UME							
Standard	NIM-1, SN1606							
Frequency (GHZ)	η_{eff}	$u(\eta_{\text{eff}})$ (k=1)	K_C	$u(K_C)$ (k=1)	$\lvert\Gamma\rvert$	$u(\lvert\Gamma\rvert)$ (k=1)	arg(Γ) (°)	$u(\text{arg}(\Gamma))$ (°, k=1)
18	0.9773	0.0014	0.9491	0.0025	0.1699	0.0063	-126.4	1.0
21	0.9814	0.0015	0.9694	0.0020	0.1105	0.0061	44.4	1.6
24	0.9795	0.0015	0.9707	0.0018	0.0948	0.0061	57.1	1.8
26.5	0.9737	0.0015	0.9603	0.0020	0.1173	0.0061	15.9	1.6

Table C.5.2 Reported results of UME

Laboratory	UME							
Standard	NIM-2, SN05616							
Frequency (GHZ)	η_{eff}	$u(\eta_{\text{eff}})$ (k=1)	K_C	$u(K_C)$ (k=1)	$\lvert\Gamma\rvert$	$u(\lvert\Gamma\rvert)$ (k=1)	arg(Γ) (°)	$u(\text{arg}(\Gamma))$ (°, k=1)
18	0.9679	0.0014	0.9652	0.0016	0.0527	0.0060	-107.4	6.5
21	0.9711	0.0015	0.9352	0.0028	0.1924	0.0065	36.1	3.8
24	0.9704	0.0015	0.9435	0.0025	0.1664	0.0063	63.8	1.9
26.5	0.9655	0.0015	0.9598	0.0017	0.0768	0.0061	50.2	2.2

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C.6   KRISS measurement data

Table C.6.1 Reported results of KRISS

Laboratory	KRISS							
Standard	NIM-1, SN1606							
Frequency (GHZ)	η_{eff}	$u(\eta_{\text{eff}})$ (k=1)	K_C	$u(K_C)$ (k=1)	$|\Gamma|$	$u(|\Gamma|)$ (k=1)	$\arg(\Gamma)$ (°)	$u(\arg(\Gamma))$ (°, k=1)
18	0.9763	0.0011	0.9475	0.0012	0.1717	0.0019	-127.0	0.6
21	0.9806	0.0012	0.9681	0.0012	0.1130	0.0019	47.2	1.0
24	0.9785	0.0012	0.9686	0.0012	0.1008	0.0019	58.5	1.1
26.5	0.9727	0.0012	0.9586	0.0013	0.1204	0.0018	16.7	1.0

Table C.6.2 Reported results of KRISS

Laboratory	KRISS							
Standard	NIM-2, SN05616							
Frequency (GHZ)	η_{eff}	$u(\eta_{\text{eff}})$ (k=1)	K_C	$u(K_C)$ (k=1)	$|\Gamma|$	$u(|\Gamma|)$ (k=1)	$\arg(\Gamma)$ (°)	$u(\arg(\Gamma))$ (°, k=1)
18	0.9679	0.0013	0.9656	0.0013	0.0484	0.0019	-102.7	2.2
21	0.9690	0.0012	0.9318	0.0014	0.1959	0.0018	35.4	0.6
24	0.9679	0.0015	0.9403	0.0016	0.1688	0.0019	62.9	0.6
26.5	0.9639	0.0013	0.9578	0.0013	0.0793	0.0019	51.8	1.4

C.7 NIST measurement data

Table C.7.1 Reported results of NIST

Laboratory	NIST							
Standard	NIM-1, SN1606							
Frequency (GHZ)	η_{eff}	$u(\eta_{eff})$ (k=1)	K_C	$u(K_C)$ (k=1)	$\|\Gamma\|$	$u(\|\Gamma\|)$ (k=1)	$\arg(\Gamma)$ (°)	$u(\arg(\Gamma))$ (°, k=1)
18	0.9756	0.0023	0.9468	0.0022	0.1720	0.0013	-127.74	0.68
21	0.9814	0.0016	0.9690	0.0016	0.1123	0.0009	47.02	0.67
24	0.9787	0.0019	0.9689	0.0019	0.0997	0.0011	57.83	1.25
26.5	0.9729	0.0019	0.9593	0.0019	0.1182	0.0014	15.61	0.73

Table C.7.2 Reported results of NIST

Laboratory	NIST							
Standard	NIM-2, SN05616							
Frequency (GHZ)	η_{eff}	$u(\eta_{eff})$ (k=1)	K_C	$u(K_C)$ (k=1)	$\|\Gamma\|$	$u(\|\Gamma\|)$ (k=1)	$\arg(\Gamma)$ (°)	$u(\arg(\Gamma))$ (°, k=1)
18	0.9669	0.0017	0.9646	0.0017	0.0492	0.0010	-105.96	1.40
21	0.9679	0.0014	0.9312	0.0013	0.1948	0.0010	35.43	0.58
24	0.9648	0.0020	0.9376	0.0020	0.1678	0.0013	62.73	0.82
26.5	0.9599	0.0013	0.9543	0.0014	0.0762	0.0018	51.45	1.10

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C.8 CMI measurement data

Table C.8.1 Reported results of CMI

Laboratory	CMI							
Standard	NIM-1, SN1606							
Frequency (GHZ)	η_{eff}	$u(\eta_{\text{eff}})$ (k=1)	K_{C}	$u(K_{\text{C}})$ (k=1)	$\lvert \Gamma \rvert$	$u(\lvert \Gamma \rvert)$ (k=1)	$\arg(\Gamma)$ (°)	$u(\arg(\Gamma))$ (°, k=1)
18	0.9730	0.0046	0.9439	0.0043	0.1729	0.0025	-127.3	1.2
21	0.9743	0.0054	0.9626	0.0053	0.1095	0.0025	46.7	1.7
24	0.9739	0.0054	0.9647	0.0053	0.0972	0.0025	60.0	360
26.5	0.9683	0.0054	0.9560	0.0053	0.1130	0.0025	16.5	1.7

Table C.8.2 Reported results of CMI

Laboratory	CMI							
Standard	NIM-2, SN05616							
Frequency (GHZ)	η_{eff}	$u(\eta_{\text{eff}})$ (k=1)	K_{C}	$u(K_{\text{C}})$ (k=1)	$\lvert \Gamma \rvert$	$u(\lvert \Gamma \rvert)$ (k=1)	$\arg(\Gamma)$ (°)	$u(\arg(\Gamma))$ (°, k=1)
18	0.9629	0.0045	0.9602	0.0045	0.0533	0.0025	-109.0	360
21	0.9621	0.0055	0.9263	0.0052	0.1930	0.0025	37.1	1.1
24	0.9613	0.0053	0.9337	0.0051	0.1696	0.0025	65.4	1.3
26.5	0.9570	0.0053	0.9519	0.0053	0.0731	0.0025	53.0	360

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C.9 SCL measurement data

Table C.9.1 Reported results of SCL

Laboratory	SCL							
Standard	NIM-1, SN1606							
Frequency (GHZ)	η_{eff}	$u(\eta_{eff})$ $(k=1)$	K_C	$u(K_C)$ $(k=1)$	$|\Gamma|$	$u(|\Gamma|)$ $(k=1)$	$\arg(\Gamma)$ $(°)$	$u(\arg(\Gamma))$ $(°, k=1)$
18	0.971	0.022	0.942	0.021	0.172	0.018	-126.3	3.8
21	0.981	0.023	0.968	0.022	0.114	0.018	48.0	3.9
24	0.975	0.022	0.965	0.022	0.100	0.018	60.0	3.9
26.5	0.967	0.028	0.954	0.027	0.116	0.018	16.1	3.9

Table C.8.2 Reported results of SCL

Laboratory	SCL							
Standard	NIM-2, SN05616							
Frequency (GHZ)	η_{eff}	$u(\eta_{eff})$ $(k=1)$	K_C	$u(K_C)$ $(k=1)$	$|\Gamma|$	$u(|\Gamma|)$ $(k=1)$	$\arg(\Gamma)$ $(°)$	$u(\arg(\Gamma))$ $(°, k=1)$
18	0.962	0.014	0.959	0.014	0.052	0.018	-107.0	4.5
21	0.971	0.019	0.934	0.017	0.196	0.018	37.7	3.9
24	0.954	0.017	0.926	0.016	0.170	0.018	65.1	3.9
26.5	0.963	0.025	0.958	0.025	0.075	0.018	51.5	4.2

C.10 NMC measurement data

Table C.10.1 Reported results of NMC

Laboratory	NMC							
Standard	NIM-1, SN1606							
Frequency (GHZ)	η_{eff}	$u(\eta_{eff})$ (k=1)	K_C	$u(K_C)$ (k=1)	$\|\Gamma\|$	$u(\|\Gamma\|)$ (k=1)	$\arg(\Gamma)$ (°)	$u(\arg(\Gamma))$ (°, k=1)
18	1.0000	0.0162	0.9684	0.0155	0.1778	0.0060	-127.33	2.46
21	0.9840	0.0199	0.9720	0.0197	0.1102	0.0058	46.58	3.88
24	0.9811	0.0221	0.9719	0.0219	0.0971	0.0058	60.25	3.98
26.5	0.9713	0.0242	0.9586	0.0238	0.1144	0.0058	13.77	3.98

Table C.10.2 Reported results of NMC

Laboratory	NMC							
Standard	NIM-2, SN05616							
Frequency (GHZ)	η_{eff}	$u(\eta_{eff})$ (k=1)	K_C	$u(K_C)$ (k=1)	$\|\Gamma\|$	$u(\|\Gamma\|)$ (k=1)	$\arg(\Gamma)$ (°)	$u(\arg(\Gamma))$ (°, k=1)
18	0.9878	0.0160	0.9849	0.0158	0.0535	0.0058	-107.72	6.72
21	0.9665	0.0198	0.9301	0.0189	0.1940	0.0060	36.36	2.69
24	0.9679	0.0227	0.9404	0.0219	0.1684	0.0060	64.58	2.84
26.5	0.9591	0.0236	0.9535	0.0234	0.0762	0.0058	48.79	4.66

D   Uncertainty Budgets

D.1   NIM uncertainty budgets

Table D.1.1 Measuring frequency: 18 GHz, Travelling standard: NIM-1, SN 1606

Quantity	Estimate	Standard uncertainty	Probability distribution / method of evaluation(A.B)	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
1. Effective efficiency, η_{eff} (= $\eta_{uncor} \times$ g)	0.9760	0.0009	Normal	0.9692	0.0008	16
1.1 Uncorrected effective efficiency, η_{uncor}	0.9721	0.0006	Normal	1.0040	0.0006	5
1.2 Correction factor, g	1.0040	0.0006	Normal / B	0.9721	0.0006	50
2. The magnitude of the reflection coefficient, $|\Gamma|$	0.1755	0.0040	Normal / B	-0.3426	0.0014	50
Result	0.9459	0.0016	-	-	-	66

Table D.1.2 Measuring frequency: 21 GHz, Travelling standard: NIM-1, SN 1606

Quantity	Estimate	Standard uncertainty	Probability distribution / method of evaluation(A.B)	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
1. Effective efficiency, η_{eff} (= $\eta_{uncor} \times$ g)	0.9802	0.0008	Normal	0.9874	0.0008	16
1.1 Uncorrected effective efficiency, η_{uncor}	0.9758	0.0006	Normal	1.0045	0.0006	5
1.2 Correction factor, g	1.0045	0.0006	Normal / B	0.9758	0.0006	50
2. The magnitude of the reflection coefficient, $|\Gamma|$	0.1123	0.0040	Normal / B	-0.2202	0.0009	50
Result	0.9678	0.0012	-	-	-	53

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Table D.1.3 Measuring frequency: 24 GHz, Travelling standard: NIM-1, SN 1606

Quantity	Estimate	Standard uncertainty	Probability distribution / method of evaluation(A.B)	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
1. Effective efficiency, η_{eff} (= $\eta_{uncor} \times g$)	0.9777	0.0008	Normal	0.9902	0.0008	16
1.1 Uncorrected effective efficiency, η_{uncor}	0.9742	0.0006	Normal	1.0036	0.0006	5
1.2 Correction factor, g	1.0036	0.0006	Normal / B	0.9742	0.0006	50
2. The magnitude of the reflection coefficient, |Γ|	0.0989	0.0040	Normal / B	-0.1935	0.0008	50
Result	0.9681	0.0011	-	-	-	46

Table D.1.4 Measuring frequency: 26.5 GHz, Travelling standard: NIM-1, SN 1606

Quantity	Estimate	Standard uncertainty	Probability distribution / method of evaluation(A.B)	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
1. Effective efficiency, η_{eff} (= $\eta_{uncor} \times g$)	0.9722	0.0009	Normal	0.9873	0.0008	16
1.1 Uncorrected effective efficiency, η_{uncor}	0.9682	0.0006	Normal	1.0041	0.0006	5
1.2 Correction factor, g	1.0041	0.0006	Normal / B	0.9682	0.0006	50
2. The magnitude of the reflection coefficient, |Γ|	0.1127	0.0040	Normal / B	-0.2190	0.0009	50
Result	0.9598	0.0012	-	-	-	51

Table D.1.5 Measuring frequency: 18 GHz, Travelling standard: NIM-2, SN 05616

Quantity	Estimate	Standard uncertainty	Probability distribution / method of evaluation(A.B)	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
1. Effective efficiency, η_{eff} (= $\eta_{uncor} \times$ g)	0.9670	0.0009	Normal	0.9972	0.0009	22
1.1 Uncorrected effective efficiency, η_{uncor}	0.9633	0.0007	Normal	1.0038	0.0007	8
1.2 Correction factor, g	1.0038	0.0006	Normal / B	0.9633	0.0006	50
2. The magnitude of the reflection coefficient, $|\Gamma|$	0.053	0.0040	Normal / B	-0.1018	0.0004	50
Result	0.9643	0.0010	-	-	-	33

Table D.1.6 Measuring frequency: 21 GHz, Travelling standard: NIM-2, SN 05616

Quantity	Estimate	Standard uncertainty	Probability distribution / method of evaluation(A.B)	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
1. Effective efficiency, η_{eff} (= $\eta_{uncor} \times$ g)	0.9694	0.0009	Normal	0.9631	0.0008	23
1.1 Uncorrected effective efficiency, η_{uncor}	0.9649	0.0006	Normal	1.0047	0.0006	8
1.2 Correction factor, g	1.0047	0.0006	Normal / B	0.9649	0.0006	50
2. The magnitude of the reflection coefficient, $|\Gamma|$	0.1920	0.0040	Normal / B	-0.3723	0.0015	50
Result	0.9337	0.0017	-	-	-	71

Table D.1.7 Measuring frequency: 24 GHz, Travelling standard: NIM-2, SN 05616

Quantity	Estimate	Standard uncertainty	Probability distribution / method of evaluation(A.B)	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
1. Effective efficiency, η_{eff} (= $\eta_{uncor} \times$ g)	0.9667	0.0009	Normal	0.9726	0.0008	23
1.1 Uncorrected effective efficiency, η_{uncor}	0.9631	0.0007	Normal	1.0037	0.0007	8
1.2 Correction factor, g	1.0037	0.0006	Normal / B	0.9631	0.0006	50
2. The magnitude of the reflection coefficient, |Γ|	0.1656	0.0040	Normal / B	-0.3203	0.0013	50
Result	0.9402	0.0015	-	-	-	73

Table D.1.8 Measuring frequency: 26.5 GHz, Travelling standard: NIM-2, SN 05616

Quantity	Estimate	Standard uncertainty	Probability distribution / method of evaluation(A.B)	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
1. Effective efficiency, η_{eff} (= $\eta_{uncor} \times$ g)	0.9626	0.0009	Normal	0.9951	0.0009	22
1.1 Uncorrected effective efficiency, η_{uncor}	0.9588	0.0007	Normal	1.0040	0.0007	8
1.2 Correction factor, g	1.0040	0.0006	Normal / B	0.9588	0.0006	50
2. The magnitude of the reflection coefficient, |Γ|	0.0698	0.0040	Normal / B	-0.1343	0.0005	50
Result	0.9580	0.0010	-	-	-	39

D.2   LNE uncertainty budgets

Measuring frequency: 18 GHz   Travelling standard: NIM-1

Quantity	Estimate	Standard uncertainty	Probability distribution / method of evaluation(A,B)	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
Voltmeter (DC) / V	0,76948	0,00000	Gaussian/ A, B	0,2564	0,0000	3988144
Voltmeter (RF) / V	0,66278	0,00000	Gaussian/ A, B	-0,2977	0,0000	12093
Nanovoltmeter (DC) / V	0,00011	5,14E-08	Gaussian/ A, B	31745,53	0,0016	119898649
Nanovoltmeter (RF) / V	0,00012	5,14E-08	Gaussian/ A, B	-31446,02	-0,0016	105447695
Insulating line / dB	0,113	0,021	Gaussian/ A, B	0,111	0,0023	8513
Reflection coefficient	0,171	0,004	Gaussian/ A, B	-0,334	-0,0014	11027721

Measuring frequency: 21 GHz   Travelling standard: NIM-1

Quantity	Estimate	Standard uncertainty	Probability distribution / method of evaluation(A,B)	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
Voltmeter (DC) / V	0,76904	0,00000	Gaussian/ A, B	0,2261	0,0000	3988144
Voltmeter (RF) / V	0,66359	0,00000	Gaussian/ A, B	-0,2620	0,0000	12093
Nanovoltmeter (DC) / V	0,00011	5,14E-08	Gaussian/ A, B	32407,76	0,0017	119898649
Nanovoltmeter (RF) / V	0,00012	5,14E-08	Gaussian/ A, B	-32147,05	-0,0017	105447695
Insulating line / dB	0,097	0,021	Gaussian/ A, B	0,111	0,0023	8513
Reflection coefficient	0,110	0,004	Gaussian/ A, B	-0,216	-0,0009	11027721

Measuring frequency: 24 GHz   Travelling standard: NIM-1

Quantity	Estimate	Standard uncertainty	Probability distribution / method of evaluation(A,B)	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
Voltmeter (DC) / V	0,76840	0,00000	Gaussian/ A, B	0,2445	0,0000	3988144
Voltmeter (RF) / V	0,66147	0,00001	Gaussian/ A, B	-0,2840	0,0000	12093
Nanovoltmeter (DC) / V	0,00011	1,03E-06	Gaussian/ A, B	33735,92	0,0348	119898649
Nanovoltmeter (RF) / V	0,00011	8,95E-07	Gaussian/ A, B	-33431,47	-0,0299	105447695
Insulating line / dB	0,095	0,021	Gaussian/ A, B	0,111	0,0023	8513
Reflection coefficient	0,098	0,004	Gaussian/ A, B	-0,191	-0,0008	11027721

Measuring frequency: 26,5 GHz   Travelling standard: NIM-1

Quantity	Estimate	Standard uncertainty	Probability distribution / method of evaluation(A,B)	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
Voltmeter (DC) / V	0,76913	0,00000	Gaussian/ A, B	0,2741	0,0000	3988144
Voltmeter (RF) / V	0,66422	0,00000	Gaussian/ A, B	-0,3174	0,0000	12093
Nanovoltmeter (DC) / V	0,00011	5,14E-08	Gaussian/ A, B	32129,80	0,0017	119898649
Nanovoltmeter (RF) / V	0,00012	5,14E-08	Gaussian/ A, B	-31816,26	-0,0016	105447695
Insulating line / dB	0,095	0,021	Gaussian/ A, B	0,111	0,0023	8513
Reflection coefficient	0,113	0,004	Gaussian/ A, B	-0,220	-0,0009	11027721

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Measuring frequency: 18 GHz   Travelling standard: NIM-2

Quantity	Estimate	Standard uncertainty	Probability distribution / method of evaluation(A,B)	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
Voltmeter (DC) / V	0,85201	0,00000	Gaussian/ A, B	0,3809	0,0000	122042
Voltmeter (RF) / V	0,75767	0,00000	Gaussian/ A, B	-0,4283	0,0000	12535
Nanovoltmeter (DC) / V	0,00012	5,14E-08	Gaussian/ A, B	35552,33	0,0018	91514964
Nanovoltmeter (RF) / V	0,00013	5,14E-08	Gaussian/ A, B	-35205,84	-0,0018	207057725
Insulating line / dB	0,113	0,021	Gaussian/ A, B	0,110	0,0023	8513
Reflection coefficient	0,053	0,004	Gaussian/ A, B	-0,103	-0,0004	377969

Measuring frequency: 21 GHz   Travelling standard: NIM-2

Quantity	Estimate	Standard uncertainty	Probability distribution / method of evaluation(A,B)	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
Voltmeter (DC) / V	0,85185	0,00000	Gaussian/ A, B	0,3502	0,0000	122042
Voltmeter (RF) / V	0,75696	0,00000	Gaussian/ A, B	-0,3941	0,0000	12535
Nanovoltmeter (DC) / V	0,00012	5,14E-08	Gaussian/ A, B	35546,52	0,0018	91514964
Nanovoltmeter (RF) / V	0,00013	5,14E-08	Gaussian/ A, B	-35226,00	-0,0018	207057725
Insulating line / dB	0,097	0,021	Gaussian/ A, B	0,110	0,0023	8513
Reflection coefficient	0,191	0,004	Gaussian/ A, B	-0,371	-0,0015	377969

Measuring frequency: 24 GHz   Travelling standard: NIM-2

Quantity	Estimate	Standard uncertainty	Probability distribution / method of evaluation(A,B)	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
Voltmeter (DC) / V	0,85186	0,00000	Gaussian/ A, B	0,3639	0,0000	122042
Voltmeter (RF) / V	0,75819	0,00000	Gaussian/ A, B	-0,4089	0,0000	12535
Nanovoltmeter (DC) / V	0,00012	1,03E-06	Gaussian/ A, B	36835,60	0,0380	91514964
Nanovoltmeter (RF) / V	0,00012	8,95E-07	Gaussian/ A, B	-36499,14	-0,0327	207057725
Insulating line / dB	0,095	0,021	Gaussian/ A, B	0,110	0,0023	8513
Reflection coefficient	0,168	0,004	Gaussian/ A, B	-0,326	-0,0013	377969

Measuring frequency: 26,5 GHz   Travelling standard: NIM-2

Quantity	Estimate	Standard uncertainty	Probability distribution / method of evaluation(A,B)	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
Voltmeter (DC) / V	0,85165	0,00000	Gaussian/ A, B	0,3838	0,0000	122042
Voltmeter (RF) / V	0,75687	0,00000	Gaussian/ A, B	-0,4318	0,0000	12535
Nanovoltmeter (DC) / V	0,00012	5,16E-08	Gaussian/ A, B	36556,17	0,0019	91514964
Nanovoltmeter (RF) / V	0,00012	5,14E-08	Gaussian/ A, B	-36193,00	-0,0019	207057725
Insulating line / dB	0,095	0,021	Gaussian/ A, B	0,110	0,0023	8513
Reflection coefficient	0,074	0,004	Gaussian/ A, B	-0,142	-0,0006	377969

D.3 NPL uncertainty budgets

Table D.3.1. Effective Efficiency Budget, Frequency: 18 GHz, NIM-1, SN 1606

Quantity	Estimate		Standard Uncertainty		Probability Distribution/ Method of Evaluation	Sensitivity Coefficient		Uncertainty Contribution	Degrees of Freedom
	Value	Unit	Value	Unit		Value	Unit		
V_1	2.719167	V	2.2E-04	V	Normal Distribution (k=1), Type A	-6.0E-02	$\frac{1}{V}$	1.7E-10	4499
			8.4E-05	V	Normal Distribution (k=1), Type B			2.5E-11	∞
V_o	3.073854	V	2.0E-05	V	Normal Distribution (k=1), Type A	5.3E-02	$\frac{1}{V}$	1.1E-12	4499
			9.1E-05	V	Normal Distribution (k=1), Type B			2.3E-11	∞
e_1	1.33829E-04	V	2.0E-08	V	Normal Distribution (k=1), Type A	-3.3E+04	$\frac{1}{V}$	4.5E-07	4499
			1.5E-08	V	Normal Distribution (k=1), Type B			2.6E-07	∞
e_o	1.32868E-04	V	4.5E-08	V	Normal Distribution (k=1), Type A	3.3E+04	$\frac{1}{V}$	2.3E-06	4499
			1.5E-08	V	Normal Distribution (k=1), Type B			2.6E-07	∞
e_u	1.638E-07	V	8.0E-09	V	Normal Distribution (k=1), Type A	-1.7E+02	$\frac{1}{V}$	1.8E-12	999
			1.2E-08	V	Normal Distribution (k=1), Type B			3.8E-12	∞
e_{TIS}	2.81E-07	V	2.4E-08	V	Normal Distribution (k=1), Type B	3.3E+04	$\frac{1}{V}$	6.6E-07	∞
					Combined Standard Uncertainty (k=1)			0.0020	> 1000

Table D.3.2. Calibration Factor Budget, Frequency: 18 GHz, NIM-1, SN 1606

Quantity	Estimate	Standard Uncertainty	Probability Distribution/Method of Evaluation	Sensitivity Coefficient	Uncertainty Contribution	Degrees of Freedom
Effective Efficiency (η_{eff})	0.9777	0.0030	Normal Distribution (k=1)	0.97	8.3E-06	>100
Reflection Coefficient ($|\Gamma|$)	0.1731	0.0011	Normal Distribution (k=1)	-0.34	1.5E-07	>100
			Combined Standard Uncertainty (k=1)		0.0029	>100

Table D.3.3. Effective Efficiency Budget, Frequency: 21 GHz, NIM-1, SN 1606

Quantity	Estimate		Standard Uncertainty		Probability Distribution/ Method of Evaluation	Sensitivity Coefficient		Uncertainty Contribution	Degrees of Freedom
	Value	Unit	Value	Unit		Value	Unit		
V_1	2.556755	V	1.5E-04	V	Normal Distribution (k=1), Type A	-3.1E-02	$\dfrac{1}{V}$	2.1E-11	4499
			8.1E-05	V	Normal Distribution (k=1), Type B			6.2E-12	∞
V_o	3.074001	V	3.0E-05	V	Normal Distribution (k=1), Type A	2.6E-02	$\dfrac{1}{V}$	6.2E-13	4499
			9.1E-05	V	Normal Distribution (k=1), Type B			5.5E-12	∞
e_1	1.34035E-04	V	2.2E-08	V	Normal Distribution (k=1), Type A	-2.4E+04	$\dfrac{1}{V}$	2.6E-07	4499
			1.5E-08	V	Normal Distribution (k=1), Type B			1.3E-07	∞
e_o	1.32966E-04	V	2.3E-08	V	Normal Distribution (k=1), Type A	2.4E+04	$\dfrac{1}{V}$	3.0E-07	4499
			1.5E-08	V	Normal Distribution (k=1), Type B			1.3E-07	∞
e_u	1.638E-07	V	8.0E-09	V	Normal Distribution (k=1), Type A	-1.3E+02	$\dfrac{1}{V}$	1.1E-12	999
			1.2E-08	V	Normal Distribution (k=1), Type B			2.4E-12	∞
e_{TIS}	3.19E-07	V	3.5E-08	V	Normal Distribution (k=1), Type B	2.4E+04	$\dfrac{1}{V}$	6.9E-07	∞
					Combined Standard Uncertainty (k=1)			0.0012	> 1000

Table D.3.4. Calibration Factor Budget, Frequency: 21 GHz, NIM-1, SN 1606

Quantity	Estimate	Standard Uncertainty	Probability Distribution/Method of Evaluation	Sensitivity Coefficient	Uncertainty Contribution	Degrees of Freedom
Effective Efficiency (η_{eff})	0.9827	0.0015	Normal Distribution (k=1)	0.99	2.1E-06	>100
Reflection Coefficient ($|\Gamma|$)	0.1104	0.0015	Normal Distribution (k=1)	-0.22	1.0E-07	>100
			Combined Standard Uncertainty (k=1)		0.0015	>100

Table D.3.5. Effective Efficiency Budget, Frequency: 24 GHz, NIM-1, SN 1606

Quantity	Estimate		Standard Uncertainty		Probability Distribution/ Method of Evaluation	Sensitivity Coefficient		Uncertainty Contribution	Degrees of Freedom
	Value	Unit	Value	Unit		Value	Unit		
V_1	2.512283	V	1.8E-04	V	Normal Distribution (k=1), Type A	-2.4E-02	$\frac{1}{V}$	2.0E-11	4499
			8.0E-05	V	Normal Distribution (k=1), Type B			3.7E-12	∞
V_o	3.074148	V	3.8E-05	V	Normal Distribution (k=1), Type A	2.0E-02	$\frac{1}{V}$	5.6E-13	4499
			9.1E-05	V	Normal Distribution (k=1), Type B			3.2E-12	∞
e_1	1.34171E-04	V	5.0E-08	V	Normal Distribution (k=1), Type A	-2.2E+04	$\frac{1}{V}$	1.2E-06	4499
			1.5E-08	V	Normal Distribution (k=1), Type B			1.1E-07	∞
e_o	1.32992E-04	V	3.4E-08	V	Normal Distribution (k=1), Type A	2.2E+04	$\frac{1}{V}$	5.6E-07	4499
			1.5E-08	V	Normal Distribution (k=1), Type B			1.2E-07	∞
e_u	1.638E-07	V	8.0E-09	V	Normal Distribution (k=1), Type A	-1.1E+02	$\frac{1}{V}$	8.2E-13	999
			1.2E-08	V	Normal Distribution (k=1), Type B			1.7E-12	∞
e_{TIS}	4.94E-07	V	2.0E-08	V	Normal Distribution (k=1), Type B	2.2E+04	$\frac{1}{V}$	1.9E-07	∞
					Combined Standard Uncertainty (k=1)			0.0015	> 1000

Table D.3.6. Calibration Factor Budget, Frequency: 24 GHz, NIM-1, SN 1606

Quantity	Estimate	Standard Uncertainty	Probability Distribution/Method of Evaluation	Sensitivity Coefficient	Uncertainty Contribution	Degrees of Freedom
Effective Efficiency (η_{eff})	0.9849	0.0017	Normal Distribution (k=1)	0.99	2.7E-06	>100
Reflection Coefficient ($|\Gamma|$)	0.0963	0.0016	Normal Distribution (k=1)	-0.19	8.8E-08	>100
			Combined Standard Uncertainty (k=1)		0.0015	>100

Table D.3.7. Effective Efficiency Budget, Frequency: 26.5 GHz, NIM-1, SN 1606

Quantity	Estimate		Standard Uncertainty		Probability Distribution/ Method of Evaluation	Sensitivity Coefficient		Uncertainty Contribution	Degrees of Freedom
	Value	Unit	Value	Unit		Value	Unit		
V_1	2.559593E+00	V	1.3E-04	V	Normal Distribution (k=1), Type A	-3.7E-02	$\frac{1}{V}$	2.3E-11	4499
			8.1E-05	V	Normal Distribution (k=1), Type B			9.1E-12	∞
V_o	3.074414E+00	V	3.2E-05	V	Normal Distribution (k=1), Type A	3.1E-02	$\frac{1}{V}$	9.9E-13	4499
			9.1E-05	V	Normal Distribution (k=1), Type B			8.0E-12	∞
e_1	1.34369E-04	V	2.0E-08	V	Normal Distribution (k=1), Type A	-2.3E+04	$\frac{1}{V}$	2.3E-07	4499
			1.5E-08	V	Normal Distribution (k=1), Type B			1.3E-07	∞
e_o	1.33016E-04	V	3.4E-08	V	Normal Distribution (k=1), Type A	2.4E+04	$\frac{1}{V}$	6.3E-07	4499
			1.5E-08	V	Normal Distribution (k=1), Type B			1.3E-07	∞
e_u	1.638E-07	V	8.0E-09	V	Normal Distribution (k=1), Type A	-1.6E+02	$\frac{1}{V}$	1.6E-12	999
			1.2E-08	V	Normal Distribution (k=1), Type B			3.4E-12	∞
e_{TIS}	4.52E-07	V	2.5E-08	V	Normal Distribution (k=1), Type B	2.3E+04	$\frac{1}{V}$	3.6E-07	∞
					Combined Standard Uncertainty (k=1)			0.0012	> 1000

Table D.3.8. Calibration Factor Budget, Frequency: 26.5 GHz, NIM-1, SN 1606

Quantity	Estimate	Standard Uncertainty	Probability Distribution/Method of Evaluation	Sensitivity Coefficient	Uncertainty Contribution	Degrees of Freedom
Effective Efficiency (η_{eff})	0.9785	0.0014	Normal Distribution (k=1)	0.99	1.9E-06	>100
Reflection Coefficient ($|\Gamma|$)	0.1121	0.0018	Normal Distribution (k=1)	-0.22	1.5E-07	>100
			Combined Standard Uncertainty (k=1)		0.0014	>100

Table D.3.9. Effective Efficiency Budget, Frequency: 18 GHz, NIM-2, SN 05616

Quantity	Estimate		Standard Uncertainty		Probability Distribution/ Method of Evaluation	Sensitivity Coefficient		Uncertainty Contribution	Degrees of Freedom
	Value	Unit	Value	Unit		Value	Unit		
V_1	3.060315E+00	V	2.0E-04	V	Normal Distribution (k=1), Type A	-7.6E-02	$\frac{1}{V}$	2.4E-10	4499
			9.1E-05	V	Normal Distribution (k=1), Type B			4.7E-11	∞
V_0	3.3944953E+00	V	1.5E-06	V	Normal Distribution (k=1), Type A	6.8E-02	$\frac{1}{V}$	1.1E-14	4499
			9.7E-05	V	Normal Distribution (k=1), Type B			4.4E-11	∞
e_1	1.60483E-04	V	3.7E-08	V	Normal Distribution (k=1), Type A	-3.2E+04	$\frac{1}{V}$	1.4E-06	4499
			1.6E-08	V	Normal Distribution (k=1), Type B			2.6E-07	∞
e_0	1.59353E-04	V	4.2E-08	V	Normal Distribution (k=1), Type A	3.2E+04	$\frac{1}{V}$	1.8E-06	4499
			1.6E-08	V	Normal Distribution (k=1), Type B			2.7E-07	∞
e_u	1.638E-07	V	8.0E-09	V	Normal Distribution (k=1), Type A	-1.7E+02	$\frac{1}{V}$	1.8E-12	999
			1.2E-08	V	Normal Distribution (k=1), Type B			3.8E-12	∞
e_{TIS}	2.87E-07	V	2.5E-08	V	Normal Distribution (k=1), Type B	3.2E+04	$\frac{1}{V}$	6.3E-07	∞
					Combined Standard Uncertainty (k=1)			0.0021	> 1000

Table D.3.10. Calibration Factor Budget, Frequency: 18 GHz, NIM-2, SN 05616

Quantity	Estimate	Standard Uncertainty	Probability Distribution/Method of Evaluation	Sensitivity Coefficient	Uncertainty Contribution	Degrees of Freedom
Effective Efficiency (η_{eff})	0.9719	0.0023	Normal Distribution (k=1)	1.00	5.2E-06	>100
Reflection Coefficient ($|\Gamma|$)	0.0528	0.0012	Normal Distribution (k=1)	-0.10	1.4E-08	>100
			Combined Standard Uncertainty (k=1)		0.0023	>100

Table D.3.11. Effective Efficiency Budget, Frequency: 21 GHz, NIM-2, SN 05616

Quantity	Estimate		Standard Uncertainty		Probability Distribution/ Method of Evaluation	Sensitivity Coefficient		Uncertainty Contribution	Degrees of Freedom
	Value	Unit	Value	Unit		Value	Unit		
V_1	2.933417E+00	V	1.3E-04	V	Normal Distribution (k=1), Type A	-5.3E-02	$\frac{1}{V}$	5.0E-11	4499
			8.8E-05	V	Normal Distribution (k=1), Type B			2.2E-11	∞
V_0	3.3945103E+00	V	2.1E-06	V	Normal Distribution (k=1), Type A	4.6E-02	$\frac{1}{V}$	9.0E-15	4499
			9.7E-05	V	Normal Distribution (k=1), Type B			2.0E-11	∞
e_1	1.60866E-04	V	2.7E-08	V	Normal Distribution (k=1), Type A	-2.3E+04	$\frac{1}{V}$	4.2E-07	4499
			1.6E-08	V	Normal Distribution (k=1), Type B			1.4E-07	∞
e_0	1.59400E-04	V	3.1E-08	V	Normal Distribution (k=1), Type A	2.4E+04	$\frac{1}{V}$	5.2E-07	4499
			1.6E-08	V	Normal Distribution (k=1), Type B			1.5E-07	∞
e_u	1.638E-07	V	8.0E-09	V	Normal Distribution (k=1), Type A	-1.7E+02	$\frac{1}{V}$	1.8E-12	999
			1.2E-08	V	Normal Distribution (k=1), Type B			3.7E-12	∞
e_{TIS}	3.42E-07	V	3.8E-08	V	Normal Distribution (k=1), Type B	2.3E+04	$\frac{1}{V}$	7.9E-07	∞
					Combined Standard Uncertainty (k=1)			0.0014	> 1000

Table D.3.12. Calibration Factor Budget, Frequency: 21 GHz, NIM-2, SN 05616

Quantity	Estimate	Standard Uncertainty	Probability Distribution/Method of Evaluation	Sensitivity Coefficient	Uncertainty Contribution	Degrees of Freedom
Effective Efficiency (η_{eff})	0.9727	0.0016	Normal Distribution (k=1)	0.96	2.5E-06	>100
Reflection Coefficient ($|\Gamma|$)	0.1928	0.0011	Normal Distribution (k=1)	-0.38	1.7E-07	>100
			Combined Standard Uncertainty (k=1)		0.0016	>100

Table D.3.13. Effective Efficiency Budget, Frequency: 24 GHz, NIM-2, SN 05616

Quantity	Estimate		Standard Uncertainty		Probability Distribution/ Method of Evaluation	Sensitivity Coefficient		Uncertainty Contribution	Degrees of Freedom
	Value	Unit	Value	Unit		Value	Unit		
V_1	2.917063E+00	V	1.3E-04	V	Normal Distribution (k=1), Type A	-4.8E-02	$\frac{1}{V}$	4.2E-11	4499
			8.8E-05	V	Normal Distribution (k=1), Type B			1.8E-11	∞
V_0	3.3945303E+00	V	2.4E-06	V	Normal Distribution (k=1), Type A	4.1E-02	$\frac{1}{V}$	9.7E-15	4499
			9.7E-05	V	Normal Distribution (k=1), Type B			1.6E-11	∞
e_1	1.61017E-04	V	2.7E-08	V	Normal Distribution (k=1), Type A	-2.3E+04	$\frac{1}{V}$	3.7E-07	4499
			1.6E-08	V	Normal Distribution (k=1), Type B			1.4E-07	∞
e_0	1.59429E-04	V	2.1E-08	V	Normal Distribution (k=1), Type A	2.3E+04	$\frac{1}{V}$	2.2E-07	4499
			1.6E-08	V	Normal Distribution (k=1), Type B			1.4E-07	∞
e_u	1.638E-07	V	8.0E-09	V	Normal Distribution (k=1), Type A	-1.6E+02	$\frac{1}{V}$	1.6E-12	999
			1.2E-08	V	Normal Distribution (k=1), Type B			3.3E-12	∞
e_{TIS}	4.96E-07	V	2.0E-08	V	Normal Distribution (k=1), Type B	2.3E+04	$\frac{1}{V}$	2.0E-07	∞
					Combined Standard Uncertainty (k=1)			0.0010	> 1000

Table D.3.14. Calibration Factor Budget, Frequency: 24 GHz, NIM-2, SN 05616

Quantity	Estimate	Standard Uncertainty	Probability Distribution/Method of Evaluation	Sensitivity Coefficient	Uncertainty Contribution	Degrees of Freedom
Effective Efficiency (η_{eff})	0.9738	0.0015	Normal Distribution (k=1)	0.97	2.0E-06	>100
Reflection Coefficient ($|\Gamma|$)	0.1687	0.0010	Normal Distribution (k=1)	-0.33	1.2E-07	>100
			Combined Standard Uncertainty (k=1)		0.0015	>100

Table D.3.15. Effective Efficiency Budget, Frequency: 26.5 GHz, NIM-2, SN 05616

Quantity	Estimate		Standard Uncertainty		Probability Distribution/ Method of Evaluation	Sensitivity Coefficient		Uncertainty Contribution	Degrees of Freedom
	Value	Unit	Value	Unit		Value	Unit		
V_1	2.942936E+00	V	1.3E-04	V	Normal Distribution (k=1), Type A	-6.1E-02	$\frac{1}{V}$	6.0E-11	4499
			8.8E-05	V	Normal Distribution (k=1), Type B			2.9E-11	∞
V_o	3.3945580E+00	V	7.5E-06	V	Normal Distribution (k=1), Type A	5.3E-02	$\frac{1}{V}$	1.6E-13	4499
			9.7E-05	V	Normal Distribution (k=1), Type B			2.6E-11	∞
e_1	1.61109E-04	V	3.3E-08	V	Normal Distribution (k=1), Type A	-2.4E+04	$\frac{1}{V}$	6.2E-07	4499
			1.6E-08	V	Normal Distribution (k=1), Type B			1.5E-07	∞
e_o	1.59421E-04	V	1.4E-08	V	Normal Distribution (k=1), Type A	2.4E+04	$\frac{1}{V}$	1.1E-07	4499
			1.6E-08	V	Normal Distribution (k=1), Type B			1.5E-07	∞
e_u	1.638E-07	V	8.0E-09	V	Normal Distribution (k=1), Type A	-1.9E+02	$\frac{1}{V}$	2.2E-12	999
			1.2E-08	V	Normal Distribution (k=1), Type B			4.6E-12	∞
e_{TIS}	4.41E-07	V	2.5E-08	V	Normal Distribution (k=1), Type B	2.4E+04	$\frac{1}{V}$	3.5E-07	∞
					Combined Standard Uncertainty (k=1)			0.0012	> 1000

Table D.3.16. Calibration Factor Budget, Frequency: 26.5 GHz, NIM-2, SN 05616

Quantity	Estimate	Standard Uncertainty	Probability Distribution/Method of Evaluation	Sensitivity Coefficient	Uncertainty Contribution	Degrees of Freedom
Effective Efficiency (η_{eff})	0.9692	0.0016	Normal Distribution (k=1)	0.99	2.4E-06	>100
Reflection Coefficient ($|\Gamma|$)	0.0739	0.0012	Normal Distribution (k=1)	-0.14	2.8E-08	>100
			Combined Standard Uncertainty (k=1)		0.0016	>100

D.4 PTB uncertainty budgets

Table D.4.1. Effective Efficiency Budget, Frequency: 18 GHz, NIM-1, SN 1606

Quantity	Estimate	Standard uncertainty	Probability distribution / method of evaluation(A, B)	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
Effective efficiency without correction	0.974109	$148 \cdot 10^{-6}$	A, normal	1.0	$150 \cdot 10^{-6}$	10
Correction factor	1.0015	$1.10 \cdot 10^{-3}$	B, normal	0.97	$1.1 \cdot 10^{-3}$	100
Voltage measurement	1	$577 \cdot 10^{-6}$	B, rectangular	0.98	$560 \cdot 10^{-6}$	100
Result	0.97557	0.00122				170

Table D.4.1. Calibration Factor Budget, Frequency: 18 GHz, NIM-1, SN 1606

Quantity	Estimate	Standard uncertainty	Probability distribution / method of evaluation(A, B)	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
Effective efficiency without correction	0.974109	$148 \cdot 10^{-6}$	A, normal	0.97	$140 \cdot 10^{-6}$	10
Correction factor	1.0015	$1.10 \cdot 10^{-3}$	B, normal	0.94	$1.0 \cdot 10^{-3}$	100
Voltage measurement	1	$577 \cdot 10^{-6}$	B, rectangular	0.95	$550 \cdot 10^{-6}$	100
Reflection coefficient	0.17321	$1.50 \cdot 10^{-3}$	B, normal	-0.34	$-510 \cdot 10^{-6}$	100
Result	0.94630	0.00129				220

Table D.4.3. Effective Efficiency Budget, Frequency: 21 GHz, NIM-1, SN 1606

Quantity	Estimate	Standard uncertainty	Probability distribution / method of evaluation(A, B)	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
Effective efficiency without correction	0.978475	$266 \cdot 10^{-6}$	A, normal	1.0	$270 \cdot 10^{-6}$	10
Correction factor	1.0015	$1.38 \cdot 10^{-3}$	B, normal	0.98	$1.4 \cdot 10^{-3}$	100
Voltage measurement	1	$577 \cdot 10^{-6}$	B, rectangular	0.98	$570 \cdot 10^{-6}$	100
Result	0.97994	0.00149				150

Table D.4.4. Calibration Factor Budget, Frequency: 21 GHz, NIM-1, SN 1606

Quantity	Estimate	Standard uncertainty	Probability distribution / method of evaluation(A, B)	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
Effective efficiency without correction	0.978475	$266 \cdot 10^{-6}$	A, normal	0.99	$260 \cdot 10^{-6}$	10
Correction factor	1.0015	$1.38 \cdot 10^{-3}$	B, normal	0.97	$1.3 \cdot 10^{-3}$	100
Voltage measurement	1	$577 \cdot 10^{-6}$	B, rectangular	0.97	$560 \cdot 10^{-6}$	100
Reflection coefficient	0.11139	$1.5 \cdot 10^{-3}$	B, normal	-0.22	$-330 \cdot 10^{-6}$	100
Result	0.96778	0.00151				160

Table D.4.5. Effective Efficiency Budget, Frequency: 24 GHz, NIM-1, SN 1606

Quantity	Estimate	Standard uncertainty	Probability distribution / method of evaluation(A, B)	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
Effective efficiency without correction	0.976425	$135 \cdot 10^{-6}$	A, normal	1.0	$140 \cdot 10^{-6}$	10
Correction factor	1.0015	$1.06 \cdot 10^{-3}$	B, normal	0.98	$1.0 \cdot 10^{-3}$	100
Voltage measurement	1	$577 \cdot 10^{-6}$	B, rectangular	0.98	$560 \cdot 10^{-6}$	100
Result	0.97789	0.00119				170

Table D.4.6. Calibration Factor Budget, Frequency: 24 GHz, NIM-1, SN 1606

Quantity	Estimate	Standard uncertainty	Probability distribution / method of evaluation(A, B)	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
Effective efficiency without correction	0.976425	$135 \cdot 10^{-6}$	A, normal	0.99	$130 \cdot 10^{-6}$	10
Correction factor	1.0015	$1.06 \cdot 10^{-3}$	B, normal	0.97	$1.0 \cdot 10^{-3}$	100
Voltage measurement	1	$577 \cdot 10^{-6}$	B, rectangular	0.97	$560 \cdot 10^{-6}$	100
Reflection coefficient	0.0874	$1.5 \cdot 10^{-3}$	B, normal	-0.17	$-260 \cdot 10^{-6}$	100
Result	0.97042	0.00121				190

Table D.4.7. Effective Efficiency Budget, Frequency: 26.5 GHz, NIM-1, SN 1606

Quantity	Estimate	Standard uncertainty	Probability distribution / method of evaluation(A, B)	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
Effective efficiency without correction	0.970775	$222 \cdot 10^{-6}$	A, normal	1.0	$220 \cdot 10^{-6}$	10
Correction factor	1.0015	$1.29 \cdot 10^{-3}$	B, normal	0.97	$1.3 \cdot 10^{-3}$	100
Voltage measurement	1	$577 \cdot 10^{-6}$	B, rectangular	0.97	$560 \cdot 10^{-6}$	100
Result	0.97223	0.00139				150

Table D.4.8. Calibration Factor Budget, Frequency: 26.5 GHz, NIM-1, SN 1606

Quantity	Estimate	Standard uncertainty	Probability distribution / method of evaluation(A, B)	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
Effective efficiency without correction	0.970775	$222 \cdot 10^{-6}$	A, normal	0.99	$220 \cdot 10^{-6}$	10
Correction factor	1.0015	$1.29 \cdot 10^{-3}$	B, normal	0.96	$1.2 \cdot 10^{-3}$	100
Voltage measurement	1	$577 \cdot 10^{-6}$	B, rectangular	0.96	$550 \cdot 10^{-6}$	100
Reflection coefficient	0.11131	$1.5 \cdot 10^{-3}$	B, normal	-0.22	$-320 \cdot 10^{-6}$	100
Result	0.96019	0.00141				170

Table D.4.9. Effective Efficiency Budget, Frequency: 18 GHz, NIM-2, SN 05616

Quantity	Estimate	Standard uncertainty	Probability distribution / method of evaluation(A, B)	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
Effective efficiency without correction	0.964303	$100\cdot10^{-6}$	A, normal	1.0	$100\cdot10^{-6}$	9
Correction factor	1.0015	$975\cdot10^{-6}$	B, normal	0.96	$940\cdot10^{-6}$	100
Voltage measurement	1	$577\cdot10^{-6}$	B, rectangular	0.97	$560\cdot10^{-6}$	100
Result	0.96575	0.00110				190

Table D.4.10. Calibration Factor Budget, Frequency: 18 GHz, NIM-2, SN 05616

Quantity	Estimate	Standard uncertainty	Probability distribution / method of evaluation(A, B)	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
Effective efficiency without correction	0.964303	$100\cdot10^{-6}$	A, normal	1.0	$100\cdot10^{-6}$	9
Correction factor	1.0015	$975\cdot10^{-6}$	B, normal	0.96	$940\cdot10^{-6}$	100
Voltage measurement	1	$577\cdot10^{-6}$	B, rectangular	0.96	$560\cdot10^{-6}$	100
Reflection coefficient	0.05276	$1.5\cdot10^{-3}$	B, normal	-0.10	$-150\cdot10^{-6}$	100
Result	0.96306	0.00110				190

Table D.4.11. Effective Efficiency Budget, Frequency: 21 GHz, NIM-2, SN 05616

Quantity	Estimate	Standard uncertainty	Probability distribution / method of evaluation(A, B)	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
Effective efficiency without correction	0.965643	$131 \cdot 10^{-6}$	A, normal	1.0	$130 \cdot 10^{-6}$	11
Correction factor	1.0015	$1.08 \cdot 10^{-3}$	B, normal	0.97	$1.0 \cdot 10^{-3}$	100
Voltage measurement	1	$577 \cdot 10^{-6}$	B, rectangular	0.97	$560 \cdot 10^{-6}$	100
Result	0.96709	0.00119				170

Table D.4.12. Calibration Factor Budget, Frequency: 21 GHz, NIM-2, SN 05616

Quantity	Estimate	Standard uncertainty	Probability distribution / method of evaluation(A, B)	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
Effective efficiency without correction	0.965643	$131 \cdot 10^{-6}$	A, normal	0.96	$130 \cdot 10^{-6}$	11
Correction factor	1.0015	$1.08 \cdot 10^{-3}$	B, normal	0.93	$1.0 \cdot 10^{-3}$	100
Voltage measurement	1	$577 \cdot 10^{-6}$	B, rectangular	0.93	$540 \cdot 10^{-6}$	100
Reflection coefficient	0.19536	$1.5 \cdot 10^{-3}$	B, normal	-0.38	$-570 \cdot 10^{-6}$	100
Result	0.93018	0.00128				240

Table D.4.13. Effective Efficiency Budget, Frequency: 24 GHz, NIM-2, SN 05616

Quantity	Estimate	Standard uncertainty	Probability distribution / method of evaluation(A, B)	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
Effective efficiency without correction	0.964365	$94.6 \cdot 10^{-6}$	A, normal	1.0	$95 \cdot 10^{-6}$	9
Correction factor	1.0015	$959 \cdot 10^{-6}$	B, normal	0.96	$930 \cdot 10^{-6}$	100
Voltage measurement	1	$577 \cdot 10^{-6}$	B, rectangular	0.97	$560 \cdot 10^{-6}$	100
Result	0.96581	0.00108				190

Table D.4.14. Calibration Factor Budget, Frequency: 24 GHz, NIM-2, SN 05616

Quantity	Estimate	Standard uncertainty	Probability distribution / method of evaluation(A, B)	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
Effective efficiency without correction	0.964365	$94.6 \cdot 10^{-6}$	A, normal	0.98	$92 \cdot 10^{-6}$	9
Correction factor	1.0015	$959 \cdot 10^{-6}$	B, normal	0.94	$900 \cdot 10^{-6}$	100
Voltage measurement	1	$577 \cdot 10^{-6}$	B, rectangular	0.94	$540 \cdot 10^{-6}$	100
Reflection coefficient	0.16026	$1.5 \cdot 10^{-3}$	B, normal	-0.31	$-460 \cdot 10^{-6}$	100
Result	0.94101	0.00115				250

Table D.4.15. Effective Efficiency Budget, Frequency: 26.5 GHz, NIM-2, SN 05616

Quantity	Estimate	Standard uncertainty	Probability distribution / method of evaluation(A, B)	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
Effective efficiency without correction	0.959498	$259 \cdot 10^{-6}$	A, normal	1.0	$260 \cdot 10^{-6}$	9
Correction factor	1.0015	$1.37 \cdot 10^{-3}$	B, normal	0.96	$1.3 \cdot 10^{-3}$	100
Voltage measurement	1	$577 \cdot 10^{-6}$	B, rectangular	0.96	$550 \cdot 10^{-6}$	100
Result	0.96094	0.00145				150

Table D.4.16. Calibration Factor Budget, Frequency: 26.5 GHz, NIM-2, SN 05616

Quantity	Estimate	Standard uncertainty	Probability distribution / method of evaluation(A, B)	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
Effective efficiency without correction	0.959498	$259 \cdot 10^{-6}$	A, normal	1.0	$260 \cdot 10^{-6}$	9
Correction factor	1.015	$1.37 \cdot 10^{-3}$	B, normal	0.95	$1.3 \cdot 10^{-3}$	100
Voltage measurement	1	$577 \cdot 10^{-6}$	B, rectangular	0.96	$550 \cdot 10^{-6}$	100
Reflection coefficient	0.07342	$1.5 \cdot 10^{-3}$	B, normal	-0.14	$-210 \cdot 10^{-6}$	100
Result	0.95576	0.00146				150

D.5   UME uncertainty budgets

Table D.5.1. Frequency: 18 GHz, NIM-1, SN 1606

Quantity	Estimate	Standard uncertainty	Probability distribution / method of evaluation (A,B)	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
Effective Efficiency	0.9773	0.0014	Normal	0.97114940	0.00000193	2
Reflection Coefficient	0.1699	0.0063	Normal	-0.33198754	0.00000432	8
CF	0.9491	u_{CF} (k=1)	0.0025	U_{CF} (k=2)	0.0050	

Table D.5.2. Frequency: 21 GHz, NIM-1, SN 1606

Quantity	Estimate	Standard uncertainty	Probability distribution / method of evaluation (A,B)	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
Effective Efficiency	0.9814	0.0015	Normal	0.98779204	0.00000211	2
Reflection Coefficient	0.1105	0.0061	Normal	-0.21686366	0.00000173	8
CF	0.9694	u_{CF} (k=1)	0.0020	U_{CF} (k=2)	0.0039	

Table D.5.3. Frequency: 24 GHz, NIM-1, SN 1606

Quantity	Estimate	Standard uncertainty	Probability distribution / method of evaluation (A,B)	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
Effective Efficiency	0.9795	0.0015	Normal	0.99101075	0.00000212	2
Reflection Coefficient	0.0948	0.0015	Normal	-0.18574103	0.00000128	8
CF	0.9707	u_{CF} (k=1)	0.0018	U_{CF} (k=2)	0.0037	

Table D.5.4. Frequency: 26.5 GHz, NIM-1, SN 1606

Quantity	Estimate	Standard uncertainty	Probability distribution / method of evaluation (A,B)	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
Effective Efficiency	0.9795	0.0015	Normal	0.99101075	0.00000212	2
Reflection Coefficient	0.0948	0.0015	Normal	-0.18574103	0.00000128	8
CF	0.9707	u_{CF} (k=1)	0.0018	U_{CF} (k=2)	0.0037	

Table D.5.5. Frequency: 18 GHz, NIM-2, SN 05616

Quantity	Estimate	Standard uncertainty	Probability distribution / method of evaluation (A,B)	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
Effective Efficiency	0.9679	0.0014	Normal	0.99722124	0.00000202	2
Reflection Coefficient	0.0527	0.0060	Normal	-0.10203952	0.00000038	8
CF	0.9652	u_{CF} (k=1)	0.0016	U_{CF} (k=2)	0.0031	

Table D.5.6. Frequency: 21 GHz, NIM-2, SN 05616

Quantity	Estimate	Standard uncertainty	Probability distribution / method of evaluation (A,B)	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
Effective Efficiency	0.9711	0.0015	Normal	0.96297755	0.00000200	2
Reflection Coefficient	0.1924	0.0065	Normal	-0.37371718	0.00000590	8
CF	0.9352	u_{CF} (k=1)	0.0028	U_{CF} (k=2)	0.0056	

Table D.5.7. Frequency: 24 GHz, NIM-2, SN 05616

Quantity	Estimate	Standard uncertainty	Probability distribution / method of evaluation (A,B)	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
Effective Efficiency	0.9704	0.0015	Normal	0.97229552	0.00000203	2
Reflection Coefficient	0.1664	0.0015	Normal	-0.32304779	0.00000416	8
CF	0.9435	u_{CF} (k=1)	0.0025	U_{CF} (k=2)	0.0050	

Table D.5.8. Frequency: 26.5 GHz, NIM-2, SN 05616

Quantity	Estimate	Standard uncertainty	Probability distribution / method of evaluation (A,B)	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
Effective Efficiency	0.9655	0.0015	Normal	0.99410164	0.00000224	2
Reflection Coefficient	0.0768	0.0061	Normal	-0.14829710	0.00000081	8
CF	0.9598	u_{CF} (k=1)	0.0017	U_{CF} (k=2)	0.0035	

D.6 KRISS uncertainty budgets

Table D.6.1. Frequency: 18 GHz, NIM-1, SN 1606

Quantity, X_i	Estimate, x_i	Standard uncertainty, $u(x_i)$	Probability distribution	Sensitivity coefficient, c_i	Uncertainty contribution, $|c_i| \cdot u(x_i)$	Degree of freedom, v_i
η_e, effective efficiency	0.9763	0.0011	normal	0.9705	0.0011	72556
L, rf loss in the thermal isolation sections	1.0032	0.0009	rectangular/ B	0.9731	0.0009	∞
A, wall loss of the thermistor mount	1.0003	0.0002	rectangular/ B	0.9760	0.0001	50
Q, nonlinear thermopile response	0.9994	0.0004	rectangular/ B	0.9769	0.0004	∞
η_e', uncorrected effective efficiency	0.9735	0.0005	normal	1.0029	0.0005	5269
V_2/V_1, dc substituted voltages of the thermistor mount	0.8637	8.58E-07	rectangular/ B	-0.3335	0.0000	∞
e_2/e_1, voltages of the thermopile	1.0069	6.37E-05	rectangular/ B	-7.3173	0.0005	∞
repeated measurement	0.9735	0.0001	t-dist/A	1	0.0001	19
$|\Gamma|$, magnitude of the reflection coefficient	0.1717	0.0019	normal	-0.3354	0.0006	1948
K, calibration factor (k=1)	0.9475	0.0012	normal			23268

Table D.6.2. Frequency: 21 GHz, NIM-1, SN 1606

Quantity, X_i	Estimate, x_i	Standard uncertainty, $u(x_i)$	Probability distribution	Sensitivity coefficient, c_i	Uncertainty contribution, $|c_i| \cdot u(x_i)$	Degree of freedom, v_i
η_e, effective efficiency	0.9806	0.0012	normal	0.9872	0.0011	42040
L, rf loss in the thermal isolation sections	1.0033	0.0009	rectangular/ B	0.9775	0.0009	∞
A, wall loss of the thermistor mount	1.0002	0.0001	rectangular/ B	0.9804	0.0001	50
Q, nonlinear thermopile response	0.9994	0.0003	rectangular/ B	0.9812	0.0003	∞
η_e', uncorrected effective efficiency	0.9778	0.0006	normal	1.0029	0.0006	3761
V_2/V_1, dc substituted voltages of the thermistor mount	0.8640	8.58E-07	rectangular/ B	-0.2841	0.0000	∞
e_2/e_1, voltages of the thermopile	1.0058	7.94E-05	rectangular/ B	-7.4207	0.0006	∞
repeated measurement	0.9778	0.0002	t-dist/A	1	0.0002	19

Quantity, X_i	Estimate, x_i	Standard uncertainty, $u(x_i)$	Probability distribution	Sensitivity coefficient, c_i	Uncertainty contribution, $|c_i|\cdot u(x_i)$	Degree of freedom, v_i
$|\Gamma|$, magnitude of the reflection coefficient	0.1130	0.0019	normal	-0.2217	0.0004	3384
K, calibration factor (k=1)	0.9681	0.0012	normal			44225

Table D.6.3. Frequency: 24 GHz, NIM-1, SN 1606

Quantity, X_i	Estimate, x_i	Standard uncertainty, $u(x_i)$	Probability distribution	Sensitivity coefficient, c_i	Uncertainty contribution, $|c_i|\cdot u(x_i)$	Degree of freedom, v_i
η_e, effective efficiency	0.9785	0.0012	normal	0.9898	0.0012	69571
L, rf loss in the thermal isolation sections	1.0033	0.0009	rectangular/ B	0.9753	0.0009	∞
A, wall loss of the thermistor mount	1.0002	0.0001	rectangular/ B	0.9782	0.0001	50
Q, nonlinear thermopile response	0.9994	0.0003	rectangular/ B	0.9790	0.0003	∞
η_e', uncorrected effective efficiency	0.9756	0.0006	normal	1.0029	0.0006	7635
V_2/V_1, dc substituted voltages of the thermistor mount	0.8635	8.58E-07	rectangular/ B	-0.3091	0.0000	∞
e_2/e_1, voltages of the thermopile	1.0064	8.20E-05	rectangular/ B	-7.3489	0.0006	∞
repeated measurement	0.9756	0.0001	t-dist/A	1	0.0001	19
$|\Gamma|$, magnitude of the reflection coefficient	0.1008	0.0019	normal	-0.1973	0.0004	1510
K, calibration factor (k=1)	0.9686	0.0012	normal			55991

Table D.6.4. Frequency: 26.5 GHz, NIM-1, SN 1606

Quantity, X_i	Estimate, x_i	Standard uncertainty, $u(x_i)$	Probability distribution	Sensitivity coefficient, c_i	Uncertainty contribution, $|c_i|\cdot u(x_i)$	Degree of freedom, v_i
η_e, effective efficiency	0.9727	0.0012	normal	0.9855	0.0012	36926
L, rf loss in the thermal isolation sections	1.0032	0.0009	rectangular/ B	0.9696	0.0009	∞
A, wall loss of the thermistor mount	1.0003	0.0002	rectangular/ B	0.9724	0.0002	50
Q, nonlinear thermopile response	0.9993	0.0004	rectangular/ B	0.9734	0.0004	∞
η_e', uncorrected effective efficiency	0.9700	0.0007	normal	1.0028	0.0007	4799
V_2/V_1, dc substituted voltages of the thermistor mount	0.8634	8.58E-07	rectangular/ B	-0.3740	0.0000	∞

e_2/e_1, voltages of the thermopile	1.0079	9.04E-05	rectangular/B	-7.2315	0.0007	∞
repeated measurement	0.9700	0.0002	t-dist/A	1	0.0002	19
$|\Gamma|$, magnitude of the reflection coefficient	0.1204	0.0018	normal	-0.2343	0.0004	43145
K, calibration factor (k=1)	0.9586	0.0013	normal			46447

Table D.6.5. Frequency: 18 GHz, NIM-2, SN 05616

Quantity, X_i	Estimate, x_i	Standard uncertainty, $u(x_i)$	Probability distribution	Sensitivity coefficient, c_i	Uncertainty contribution, $|c_i| \cdot u(x_i)$	Degree of freedom, v_i
η_e, effective efficiency	0.9679	0.0013	normal	0.9977	0.0013	49175
L, rf loss in the thermal isolation sections	1.0034	0.0010	rectangular/B	0.9647	0.0009	∞
A, wall loss of the thermistor mount	1.0003	0.0002	rectangular/B	0.9676	0.0002	50
Q, nonlinear thermopile response	0.9990	0.0006	rectangular/B	0.9689	0.0006	∞
η_e', uncorrected effective efficiency	0.9653	0.0006	normal	1.0027	0.0006	6159
V_2/V_1, dc substituted voltages of the thermistor mount	0.8898	8.58E-07	rectangular/B	-0.5357	0.0000	∞
e_2/e_1, voltages of the thermopile	1.0075	6.98E-05	rectangular/B	-8.7098	0.0006	∞
repeated measurement	0.9653	0.0001	t-dist/A	1	0.0001	18
$|\Gamma|$, magnitude of the reflection coefficient	0.0484	0.0019	normal	-0.0936	0.0002	3150
K, calibration factor (k=1)	0.9656	0.0013	normal			50792

Table D.6.6. Frequency: 21 GHz, NIM-2, SN 05616

Quantity, X_i	Estimate, x_i	Standard uncertainty, $u(x_i)$	Probability distribution	Sensitivity coefficient, c_i	Uncertainty contribution, $|c_i| \cdot u(x_i)$	Degree of freedom, v_i
η_e, effective efficiency	0.9690	0.0012	normal	0.9616	0.0012	55911
L, rf loss in the thermal isolation sections	1.0033	0.0010	rectangular/B	0.9658	0.0009	∞
A, wall loss of the thermistor mount	1.0003	0.0002	rectangular/B	0.9687	0.0002	50
Q, nonlinear thermopile response	0.9990	0.0006	rectangular/B	0.9700	0.0005	∞

η_e', uncorrected effective efficiency	0.9664	0.0005	normal	1.0027	0.0005	5760
V_2/V_1, dc substituted voltages of the thermistor mount	0.8901	8.58E-07	rectangular/ B	-0.5228	0.0000	∞
e_2/e_1, voltages of the thermopile	1.0072	5.92E-05	rectangular/ B	-8.7582	0.0005	∞
repeated measurement	0.9664	0.0001	t-dist/A	1	0.0001	19
$|\Gamma|$, magnitude of the reflection coefficient	0.1959	0.0018	normal	-0.3796	0.0007	101661
K, calibration factor (k=1)	0.9318	0.0014	normal			96398

Table D.6.7. Frequency: 24 GHz, NIM-2, SN 05616

Quantity, X_i	Estimate, x_i	Standard uncertainty, $u(x_i)$	Probability distribution	Sensitivity coefficient, c_i	Uncertainty contribution, $|c_i|\cdot u(x_i)$	Degree of freedom, v_i
η_e, effective efficiency	0.9679	0.0015	normal	0.9715	0.0015	59614
L, rf loss in the thermal isolation sections	1.0034	0.0010	rectangular/ B	0.9648	0.0009	∞
A, wall loss of the thermistor mount	1.0003	0.0002	rectangular/ B	0.9677	0.0002	50
Q, nonlinear thermopile response	0.9990	0.0006	rectangular/ B	0.9690	0.0006	∞
η_e', uncorrected effective efficiency	0.9654	0.0010	normal	1.0027	0.0010	18716
V_2/V_1, dc substituted voltages of the thermistor mount	0.8899	8.58E-07	rectangular/ B	-0.5352	0.0000	∞
e_2/e_1, voltages of the thermopile	1.0075	1.16E-04	rectangular/ B	-8.7206	0.0010	∞
repeated measurement	0.9654	0.0002	t-dist/A	1	0.0002	19
$|\Gamma|$, magnitude of the reflection coefficient	0.1688	0.0019	normal	-0.3267	0.0006	15638
K, calibration factor (k=1)	0.9403	0.0016	normal			73538

Table D.6.8. Frequency: 26.5 GHz, NIM-2, SN 05616

Quantity, X_i	Estimate, x_i	Standard uncertainty, $u(x_i)$	Probability distribution	Sensitivity coefficient, c_i	Uncertainty contribution, $|c_i|\cdot u(x_i)$	Degree of freedom, v_i
η_e, effective efficiency	0.9639	0.0013	normal	0.9937	0.0013	43905
L, rf loss in the thermal isolation sections	1.0033	0.0010	rectangular /B	0.9606	0.0009	∞
A, wall loss of the thermistor mount	1.0004	0.0002	rectangular	0.9634	0.0002	50

			/B			
Q, nonlinear thermopile response	0.9989	0.0006	rectangular /B	0.9649	0.0006	∞
$\eta_e{'}$, uncorrected effective efficiency	0.9613	0.0006	normal	1.0026	0.0006	6695
V_2/V_1, dc substituted voltages of the thermistor mount	0.8901	8.58E-07	rectangular /B	-0.5933	0.0000	∞
e_2/e_1, voltages of the thermopile	1.0084	6.26E-05	rectangular /B	-8.6361	0.0005	∞
repeated measurement	0.9613	0.0001	t-dist/A	1	0.0001	19
$|\Gamma|$, magnitude of the reflection coefficient	0.0793	0.0019	normal	-0.1529	0.0003	14103
K, calibration factor ($k=1$)	0.9578	0.0013	normal			48131

D.7   NIST uncertainty budgets

Table D.7.1. Uncertainty budget (k=1) for the effective efficiency of NIM-1 at 18 GHz

Quantity/category	Estimate	Method of evaluation (A or B)	Standard uncertainty	Degrees of freedom
Effective efficiency	0.9756	N/A	2.31E-03	139.19
S-Parameter SOL standard models	N/A	A	1.36E-03	N/A
Direct comparison repeatability	N/A	A	1.32E-03	N/A
Microcalorimeter repeatability	N/A	A	8.79E-04	N/A
Γ_G repeatability	N/A	A	7.77E-04	N/A
Microcalorimeter g_c	N/A	B	5.53E-04	N/A
Γ_S and Γ_U repeatability	N/A	A	1.53E-04	N/A
S-Parameter MTRL standard models	N/A	B	6.06E-05	N/A
Voltmeter systematic uncertainty	N/A	B	1.54E-06	N/A

Table D.7.2. Uncertainty budget (k=1) for the effective efficiency of NIM-1 at 21 GHz

Quantity/category	Estimate	Method of evaluation (A or B)	Standard uncertainty	Degrees of freedom
Effective efficiency	0.9814	N/A	1.63E-03	56.68
Direct comparison repeatability	N/A	A	1.21E-03	N/A
Microcalorimeter repeatability	N/A	A	8.26E-04	N/A
Microcalorimeter g_c	N/A	B	4.98E-04	N/A
S-Parameter SOL standard models	N/A	A	4.39E-04	N/A
Γ_S and Γ_U repeatability	N/A	A	2.86E-04	N/A
Γ_G repeatability	N/A	A	9.56E-05	N/A
S-Parameter MTRL standard models	N/A	B	2.02E-05	N/A
Voltmeter systematic uncertainty	N/A	B	1.70E-06	N/A

Table D.7.3. Uncertainty budget (k=1) for the effective efficiency of NIM-1 at 24 GHz

Quantity/category	Estimate	Method of evaluation (A or B)	Standard uncertainty	Degrees of freedom
Effective efficiency	0.9787	N/A	1.93E-03	125.70
S-Parameter SOL standard models	N/A	A	1.21E-03	N/A
Direct comparison repeatability	N/A	A	1.07E-03	N/A
Microcalorimeter repeatability	N/A	A	8.69E-04	N/A
Microcalorimeter g_c	N/A	B	4.63E-04	N/A
Γ_G repeatability	N/A	A	3.15E-04	N/A
Γ_S and Γ_U repeatability	N/A	A	2.41E-04	N/A
S-Parameter MTRL standard models	N/A	B	2.38E-05	N/A

Voltmeter systematic uncertainty	N/A	B	1.82E-06	N/A

Table D.7.4. Uncertainty budget (*k*=1) for the effective efficiency of NIM-1 at 26.5 GHz

Quantity/category	Estimate	Method of evaluation (A or B)	Standard uncertainty	Degrees of freedom
Effective efficiency	0.9729	N/A	1.86E-03	38.55
Direct comparison repeatability	N/A	A	1.55E-03	N/A
Microcalorimeter repeatability	N/A	A	8.22E-04	N/A
Microcalorimeter g_c	N/A	B	4.33E-04	N/A
S-Parameter SOL standard models	N/A	A	3.78E-04	N/A
Γ_S and Γ_U repeatability	N/A	A	1.94E-04	N/A
Γ_G repeatability	N/A	A	8.66E-05	N/A
S-Parameter MTRL standard models	N/A	B	8.14E-06	N/A
Voltmeter systematic uncertainty	N/A	B	2.11E-06	N/A

Table D.7.5. Uncertainty budget (*k*=1) for the calibration factor of NIM-1 at 18 GHz

Quantity/category	Estimate	Method of evaluation (A or B)	Standard uncertainty	Degrees of freedom
Calibration factor	0.9468	N/A	2.24E-03	140.14
S-Parameter SOL standard models	N/A	A	1.29E-03	N/A
Direct comparison repeatability	N/A	A	1.28E-03	N/A
Microcalorimeter repeatability	N/A	A	8.53E-04	N/A
Γ_G repeatability	N/A	A	7.54E-04	N/A
Microcalorimeter g_c	N/A	B	5.37E-04	N/A
Γ_S and Γ_U repeatability	N/A	A	3.15E-04	N/A
S-Parameter MTRL standard models	N/A	B	1.65E-04	N/A
Voltmeter systematic uncertainty	N/A	B	1.49E-06	N/A

Table D.7.6. Uncertainty budget (*k*=1) for the calibration factor of NIM-1 at 21 GHz

Quantity/category	Estimate	Method of evaluation (A or B)	Standard uncertainty	Degrees of freedom
Calibration factor	0.9690	N/A	1.61E-03	56.49
Direct comparison repeatability	N/A	A	1.19E-03	N/A
Microcalorimeter repeatability	N/A	A	8.16E-04	N/A
Microcalorimeter g_c	N/A	B	4.91E-04	N/A
S-Parameter SOL standard models	N/A	A	4.10E-04	N/A
Γ_S and Γ_U repeatability	N/A	A	2.95E-04	N/A
S-Parameter MTRL standard models	N/A	B	1.15E-04	N/A
Γ_G repeatability	N/A	A	9.44E-05	N/A

Voltmeter systematic uncertainty	N/A	B	1.68E-06	N/A

Table D.7.7. Uncertainty budget (*k*=1) for the calibration factor of NIM-1 at 24 GHz

Quantity/category	Estimate	Method of evaluation (A or B)	Standard uncertainty	Degrees of freedom
Calibration factor	0.9689	N/A	1.94E-03	124.60
S-Parameter SOL standard models	N/A	A	1.23E-03	N/A
Direct comparison repeatability	N/A	A	1.06E-03	N/A
Microcalorimeter repeatability	N/A	A	8.61E-04	N/A
Microcalorimeter g_c	N/A	B	4.58E-04	N/A
Γ_G repeatability	N/A	A	3.12E-04	N/A
Γ_S and Γ_U repeatability	N/A	A	2.60E-04	N/A
S-Parameter MTRL standard models	N/A	B	7.64E-05	N/A
Voltmeter systematic uncertainty	N/A	B	1.81E-06	N/A

Table D.7.8. Uncertainty budget (*k*=1) for the calibration factor of NIM-1 at 26.5 GHz

Quantity/category	Estimate	Method of evaluation (A or B)	Standard uncertainty	Degrees of freedom
Calibration factor	0.9593	N/A	1.87E-03	41.28
Direct comparison repeatability	N/A	A	1.53E-03	N/A
Microcalorimeter repeatability	N/A	A	8.11E-04	N/A
S-Parameter SOL standard models	N/A	A	4.54E-04	N/A
Microcalorimeter g_c	N/A	B	4.27E-04	N/A
Γ_S and Γ_U repeatability	N/A	A	2.48E-04	N/A
S-Parameter MTRL standard models	N/A	B	1.63E-04	N/A
Γ_G repeatability	N/A	A	8.54E-05	N/A
Voltmeter systematic uncertainty	N/A	B	2.08E-06	N/A

Table D.7.9. Uncertainty budget (*k*=1) for the effective efficiency of NIM-2 at 18 GHz

Quantity/category	Estimate	Method of evaluation (A or B)	Standard uncertainty	Degrees of freedom
Effective efficiency	0.9669	N/A	1.74E-03	447.83
S-Parameter SOL standard models	N/A	A	1.23E-03	N/A
Microcalorimeter repeatability	N/A	A	8.71E-04	N/A
Microcalorimeter g_c	N/A	B	5.48E-04	N/A
Direct comparison repeatability	N/A	A	5.06E-04	N/A
Γ_G repeatability	N/A	A	3.98E-04	N/A
Γ_S and Γ_U repeatability	N/A	A	1.70E-04	N/A
S-Parameter MTRL standard models	N/A	B	5.98E-05	N/A
Voltmeter systematic uncertainty	N/A	B	5.78E-06	N/A

Table D.7.10. Uncertainty budget (*k*=1) for the effective efficiency of NIM-2 at 21 GHz

Quantity/category	Estimate	Method of evaluation (A or B)	Standard uncertainty	Degrees of freedom
Effective efficiency	0.9679	N/A	1.39E-03	141.73
Microcalorimeter repeatability	N/A	A	8.15E-04	N/A
S-Parameter SOL standard models	N/A	A	7.83E-04	N/A
Direct comparison repeatability	N/A	A	5.20E-04	N/A
Microcalorimeter g_c	N/A	B	4.91E-04	N/A
Γ_S and Γ_U repeatability	N/A	A	3.41E-04	N/A
Γ_G repeatability	N/A	A	1.65E-04	N/A
S-Parameter MTRL standard models	N/A	B	3.33E-05	N/A
Voltmeter systematic uncertainty	N/A	B	5.82E-06	N/A

Table D.7.11. Uncertainty budget (*k*=1) for the effective efficiency of NIM-2 at 24 GHz

Quantity/category	Estimate	Method of evaluation (A or B)	Standard uncertainty	Degrees of freedom
Effective efficiency	0.9648	N/A	2.03E-03	140.26
S-Parameter SOL standard models	N/A	A	1.50E-03	N/A
Microcalorimeter repeatability	N/A	A	8.57E-04	N/A
Direct comparison repeatability	N/A	A	7.19E-04	N/A
Γ_S and Γ_U repeatability	N/A	A	4.79E-04	N/A
Microcalorimeter g_c	N/A	B	4.56E-04	N/A
Γ_G repeatability	N/A	A	4.19E-04	N/A
S-Parameter MTRL standard models	N/A	B	2.90E-05	N/A
Voltmeter systematic uncertainty	N/A	B	5.83E-06	N/A

Table D.7.12. Uncertainty budget (*k*=1) for the effective efficiency of NIM-2 at 26.5 GHz

Quantity/category	Estimate	Method of evaluation (A or B)	Standard uncertainty	Degrees of freedom
Effective efficiency	0.9599	N/A	1.34E-03	69.92
Direct comparison repeatability	N/A	A	9.28E-04	N/A
Microcalorimeter repeatability	N/A	A	8.11E-04	N/A
Microcalorimeter g_c	N/A	B	4.27E-04	N/A
Γ_S and Γ_U repeatability	N/A	A	2.30E-04	N/A
S-Parameter SOL standard models	N/A	A	1.80E-04	N/A
Γ_G repeatability	N/A	A	1.15E-05	N/A
Voltmeter systematic uncertainty	N/A	B	5.92E-06	N/A
S-Parameter MTRL standard models	N/A	B	1.44E-06	N/A

Table D.7.13. Uncertainty budget (*k*=1) for the calibration factor of NIM-2 at 18 GHz

Quantity/category	Estimate	Method of evaluation (A or B)	Standard uncertainty	Degrees of freedom
Calibration factor	0.9646	N/A	1.73E-03	449.40
S-Parameter SOL standard models	N/A	A	1.22E-03	N/A
Microcalorimeter repeatability	N/A	A	8.69E-04	N/A
Microcalorimeter g_c	N/A	B	5.47E-04	N/A
Direct comparison repeatability	N/A	A	5.05E-04	N/A
Γ_G repeatability	N/A	A	3.97E-04	N/A
Γ_S and Γ_U repeatability	N/A	A	1.86E-04	N/A
S-Parameter MTRL standard models	N/A	B	6.07E-05	N/A
Voltmeter systematic uncertainty	N/A	B	5.77E-06	N/A

Table D.7.14. Uncertainty budget (*k*=1) for the calibration factor of NIM-2 at 21 GHz

Quantity/category	Estimate	Method of evaluation (A or B)	Standard uncertainty	Degrees of freedom
Calibration factor	0.9312	N/A	1.30E-03	138.24
Microcalorimeter repeatability	N/A	A	7.84E-04	N/A
S-Parameter SOL standard models	N/A	A	6.32E-04	N/A
Direct comparison repeatability	N/A	A	5.00E-04	N/A
Microcalorimeter g_c	N/A	B	4.72E-04	N/A
Γ_S and Γ_U repeatability	N/A	A	3.51E-04	N/A
S-Parameter MTRL standard models	N/A	B	2.25E-04	N/A
Γ_G repeatability	N/A	A	1.58E-04	N/A
Voltmeter systematic uncertainty	N/A	B	5.60E-06	N/A

CCEM.RF-K28.W— RF power from 18 GHz to 26.5 GHz in rectangular waveguide

Table D.7.15. Uncertainty budget (*k*=1) for the calibration factor of NIM-2 at 24 GHz

Quantity/category	Estimate	Method of evaluation (A or B)	Standard uncertainty	Degrees of freedom
Calibration factor	0.9376	N/A	2.05E-03	133.49
S-Parameter SOL standard models	N/A	A	1.53E-03	N/A
Microcalorimeter repeatability	N/A	A	8.33E-04	N/A
Direct comparison repeatability	N/A	A	6.99E-04	N/A
Γ_S and Γ_U repeatability	N/A	A	5.58E-04	N/A
Microcalorimeter g_c	N/A	B	4.43E-04	N/A
Γ_G repeatability	N/A	A	4.07E-04	N/A
S-Parameter MTRL standard models	N/A	B	1.07E-04	N/A
Voltmeter systematic uncertainty	N/A	B	5.67E-06	N/A

Table D.7.16. Uncertainty budget (*k*=1) for the calibration factor of NIM-2 at 26.5 GHz

Quantity/category	Estimate	Method of evaluation (A or B)	Standard uncertainty	Degrees of freedom
Calibration factor	0.9543	N/A	1.36E-03	75.43
Direct comparison repeatability	N/A	A	9.22E-04	N/A
Microcalorimeter repeatability	N/A	A	8.07E-04	N/A
Microcalorimeter g_c	N/A	B	4.25E-04	N/A
Γ_S and Γ_U repeatability	N/A	A	3.13E-04	N/A
S-Parameter SOL standard models	N/A	A	2.54E-04	N/A
S-Parameter MTRL standard models	N/A	B	6.85E-05	N/A
Γ_G repeatability	N/A	A	1.15E-05	N/A
Voltmeter systematic uncertainty	N/A	B	5.88E-06	N/A

D.8   CMI uncertainty budgets

Model function

$$CF_{DUT} = CF_{STD} \cdot \frac{P_{DUT}}{P_{STD}} \cdot \delta P \cdot C_{vector} \cdot \delta CF_{DUT}$$

Table D.8.1. Uncertainty budget (k=1) for the calibration factor of NIM-1 at 18 GHz

Definition of contribution	Expected Value	Standard Uncertainty	Distribution Function / Method of Evaluation	Sensitivity Coefficient	Uncertainty contribution	Degree of Freedom
	xi	u(xi)		ci	u(yi)	vi
CF_{STD}	0.965 0	0.004 1	normal / B	9.78E-01	0.004 0	∞
$P_{DC,DUT}$	0.002 871 53	0.000 000 44	normal / B	3.29E+02	0.000 14	∞
$P_{DC,STD}$	0.005 813 77	0.000 000 44	normal / B	-1.62E+02	0.000 071	∞
δP	1.981 2	0.002 6	normal / B	4.76E-01	0.001 3	∞
C_{vector}	0.999 55	0.000 67	normal / B	9.44E-01	0.000 63	∞
δCF_{DUT}	1.000 00	0.000 23	normal / A	9.44E-01	0.000 21	12
Measured Value	**0.943 9**	**Combined Uncertainty**			**0.004 3**	**veff > 1 000**

Table D.8.2. Uncertainty budget (k=1) for the calibration factor of NIM-1 at 21 GHz

Definition of contribution	Expected Value	Standard Uncertainty	Distribution Function / Method of Evaluation	Sensitivity Coefficient	Uncertainty contribution	Degree of Freedom
	xi	u(xi)		ci	u(yi)	vi
CF_{STD}	0.961 8	0.004 4	normal / B	1.00E+00	0.004 4	∞
$P_{DC,DUT}$	0.002 919 35	0.000 000 44	normal / B	3.30E+02	0.000 14	∞
$P_{DC,STD}$	0.005 789 94	0.000 000 44	normal / B	-1.66E+02	0.000 073	∞
δP	1.984 3	0.005 2	normal / B	4.85E-01	0.002 5	∞
C_{vector}	1.000 33	0.000 26	normal / B	9.62E-01	0.000 25	∞
δCF_{DUT}	1.000 00	0.000 15	normal / A	9.63E-01	0.000 14	12
Measured Value	**0.962 6**	**Combined Uncertainty**			**0.005 3**	**veff > 1 000**

Table D.8.3. Uncertainty budget (k=1) for the calibration factor of NIM-1 at 24 GHz

Definition of contribution	Expected Value	Standard Uncertainty	Distribution Function / Method of Evaluation	Sensitivity Coefficient	Uncertainty contribution	Degree of Freedom
	xi	u(xi)		ci	u(yi)	vi
CF_{STD}	0.961 7	0.004 3	normal / B	1.00E+00	0.004 3	∞
$P_{DC,DUT}$	0.002 929 46	0.000 000 44	normal / B	3.29E+02	0.000 14	∞
$P_{DC,STD}$	0.005 830 29	0.000 000 44	normal / B	-1.65E+02	0.000 072	∞
δP	1.996 5	0.005 3	normal / B	4.83E-01	0.002 5	∞
C_{vector}	0.999 98	0.000 81	normal / B	9.65E-01	0.000 8	∞
δCF_{DUT}	1.000 00	0.000 16	normal / A	9.65E-01	0.000 16	12
Measured Value	**0.964 7**	**Combined Uncertainty**			**0.005 3**	**veff > 1 000**

Table D.8.4. Uncertainty budget (*k*=1) for the calibration factor of NIM-1 at 26.5 GHz

Definition of contribution	Expected Value	Standard Uncertainty	Distribution Function / Method of Evaluation	Sensitivity Coefficient	Uncertainty contribution	Degree of Freedom
	xi	u(xi)		ci	u(yi)	vi
CF_{STD}	0.966 8	0.004 4	normal / B	9.89E-01	0.004 3	∞
$P_{DC,DUT}$	0.001 578 44	0.000 000 44	normal / B	6.06E+02	0.000 26	∞
$P_{DC,STD}$	0.003 185 85	0.000 000 44	normal / B	-3.00E+02	0.000 13	∞
δP	1.996 0	0.005 3	normal / B	4.79E-01	0.002 5	∞
C_{vector}	0.999 88	0.000 74	normal / B	9.56E-01	0.000 70	∞
δCF_{DUT}	1.000 00	0.000 12	normal / A	9.56E-01	0.000 12	12
Measured Value	**0.956 0**	**Combined Uncertainty**			**0.005 3**	**veff > 1 000**

Table D.8.5. Uncertainty budget (*k*=1) for the calibration factor of NIM-2 at 18 GHz

Definition of contribution	Expected Value	Standard Uncertainty	Distribution Function / Method of Evaluation	Sensitivity Coefficient	Uncertainty contribution	Degree of Freedom
	xi	u(xi)		ci	u(yi)	vi
CF_{STD}	0.965 0	0.004 1	normal / B	9.95E-01	0.004 1	∞
$P_{DC,DUT}$	0.002 917 98	0.000 000 44	normal / B	3.29E+02	0.000 14	∞
$P_{DC,STD}$	0.005 820 85	0.000 000 44	normal / B	-1.65E+02	0.000 072	∞
δP	1.984 7	0.002 6	normal / B	4.84E-01	0.001 3	∞
C_{vector}	1.000 1	0.001 2	normal / B	9.60E-01	0.001 1	∞
δCF_{DUT}	1.000 00	0.000 15	normal / A	9.60E-01	0.000 15	12
Measured Value	**0.960 2**	**Combined Uncertainty**			**0.004 5**	**veff > 1 000**

Table D.8.6. Uncertainty budget (*k*=1) for the calibration factor of NIM-2 at 21 GHz

Definition of contribution	Expected Value	Standard Uncertainty	Distribution Function / Method of Evaluation	Sensitivity Coefficient	Uncertainty contribution	Degree of Freedom
	xi	u(xi)		ci	u(yi)	vi
CF_{STD}	0.961 8	0.0044	normal / B	9.63E-01	0.004 2	∞
$P_{DC,DUT}$	0.002 800 07	0.000 000 44	normal / B	3.31E+02	0.000 14	∞
$P_{DC,STD}$	0.005 793 04	0.000 000 44	normal / B	-1.60E+02	0.000 070	∞
δP	1.992 6	0.005 3	normal / B	4.65E-01	0.002 4	∞
C_{vector}	1.000 0	0.001 1	normal / B	9.26E-01	0.001 0	∞
δCF_{DUT}	1.000 00	0.000 31	normal / A	9.26E-01	0.000 29	12
Measured Value	**0.926 3**	**Combined Uncertainty**			**0.005 2**	**veff > 1 000**

Table D.8.7. Uncertainty budget (*k*=1) for the calibration factor of NIM-2 at 24 GHz

Definition of contribution	Expected Value	Standard Uncertainty	Distribution Function / Method of Evaluation	Sensitivity Coefficient	Uncertainty contribution	Degree of Freedom
	xi	u(xi)		ci	u(yi)	vi
CF_{STD}	0.961 7	0.004 3	normal / B	9.71E-01	0.004 1	∞
$P_{DC,DUT}$	0.002 855 05	0.000 000 44	normal / B	3.27E+02	0.000 14	∞
$P_{DC,STD}$	0.005 838 15	0.000 000 44	normal / B	-1.60E+02	0.000 070	∞
δP	1.985 0	0.005 2	normal / B	4.70E-01	0.002 5	∞
C_{vector}	1.000 18	0.000 24	normal / B	9.34E-01	0.000 23	∞
δCF_{DUT}	1.000 00	0.000 29	normal / A	9.34E-01	0.000 27	12
Measured Value	**0.933 7**	**Combined Uncertainty**			**0.005 1**	**veff > 1 000**

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Table D.8.8. Uncertainty budget (k=1) for the calibration factor of NIM-2 at 26.5 GHz

Definition of contribution	Expected Value	Standard Uncertainty	Distribution Function / Method of Evaluation	Sensitivity Coefficient	Uncertainty contribution	Degree of Freedom
	x_i	$u(x_i)$		c_i	$u(y_i)$	v_i
CF_{STD}	0.966 8	0.004 4	normal / B	9.85E-01	0.004 3	∞
$P_{DC,DUT}$	0.001 578 66	0.000 000 44	normal / B	6.03E+02	0.000 26	∞
$P_{DC,STD}$	0.003 190 23	0.000 000 44	normal / B	-2.98E+02	0.000 13	∞
δP	1.9894	0.0053	normal / B	4.78E-01	0.002 5	∞
C_{vector}	1.0001	0.0010	normal / B	9.52E-01	0.001 0	∞
δCF_{DUT}	1.00000	0.00022	normal / A	9.52E-01	0.000 21	12
Measured Value	**0.951 9**	**Combined Uncertainty**			**0.005 3**	**$v_{eff} > 1\,000$**

CCEM.RF-K28.W— RF power from 18 GHz to 26.5 GHz in rectangular waveguide

D.9 SCL uncertainty budgets

Measurement frequency: 18 GHz   Travelling standard: NIM-1

	Quantity	Estimate x_i	Standard uncertainty u_i	Probability Distribution / method of evaluation (A or B)	Sensitivity coefficient c_i	Uncertainty contribution	Degree of freedom
1	K_{Ref}	1.00587	0.00320	Rectangular / B	$\dfrac{\partial K_{UUT}}{\partial K_{Ref}}$		52.20
2a	P_{UUT}	2.853	0.003	Normal / A	$\dfrac{\partial K_{UUT}}{\partial P_{UUT}}$		3
2b	P_{UUT_res}	0.000	0.005	Rectangular / B	$\dfrac{\partial K_{UUT}}{\partial P_{UUT\_res}}$		∞
3a	$P_{Monitor\_UUT}$	3.003	0.001	Normal / A	$\dfrac{\partial K_{UUT}}{\partial P_{Monitor\_UUT}}$		3
3b	$P_{Monitor\_UUT\_res}$	0.000	0.001	Rectangular / B	$\dfrac{\partial K_{UUT}}{\partial P_{Monitor\_UUT\_res}}$		∞
4a	$P_{Monitor\_Ref}$	3.003	0.001	Normal / A	$\dfrac{\partial K_{UUT}}{\partial P_{Monitor\_Ref}}$		3
4b	$P_{Monitor\_Ref\_res}$	0.000	0.001	Rectangular / B	$\dfrac{\partial K_{UUT}}{\partial P_{Monitor\_Ref\_res}}$	Calculated by Numerical Method	∞
5a	P_{Ref}	3.011	0.001	Normal / A	$\dfrac{\partial K_{UUT}}{\partial P_{Ref}}$		3
5b	P_{Ref_res}	0.000	0.001	Rectangular / B	$\dfrac{\partial K_{UUT}}{\partial P_{Ref\_res}}$		∞
6a	Γ_{UUT_real}	-0.1016	0.01264	Normal / B	$\dfrac{\partial K_{UUT}}{\partial \Gamma_{UUT\_real}}$		∞
6b	Γ_{UUT_img}	-0.1384	0.01488	Normal / B	$\dfrac{\partial K_{UUT}}{\partial \Gamma_{UUT\_img}}$		∞
7a	S_{11A_real}	0.00436	0.07113	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{11A\_real}}$		50.04
7b	S_{11A_img}	0.07199	0.07182	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{11A\_img}}$		51.99
8a	S_{12A_real}	-0.84084	0.00704	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{12A\_real}}$		115.55
8b	S_{12A_img}	-0.53096	0.00882	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{12A\_img}}$		70.86
9a	S_{21A_real}	-0.84443	0.00684	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{21A\_real}}$		112.74
9b	S_{21A_img}	-0.51992	0.00824	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{21A\_img}}$	Calculated by Numerical Method	88.14
10a	S_{22A_real}	-0.06567	0.06670	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{22A\_real}}$		52.23
10b	S_{22A_img}	0.01273	0.06601	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{22A\_img}}$		50.11

11a	Γ_{e3_real}	0.06526	0.00865	Normal / B	$\dfrac{\partial K_{UUT}}{\partial \Gamma_{e3\_real}}$		73200
11b	Γ_{e3_img}	0.00468	0.01259	Normal / B	$\dfrac{\partial K_{UUT}}{\partial \Gamma_{e3\_img}}$		45000
12a	Γ_{Ref_real}	0.00829	0.00154	Normal / B	$\dfrac{\partial K_{UUT}}{\partial \Gamma_{Ref\_real}}$		68.89
12b	Γ_{Ref_img}	0.03607	0.00614	Normal / B	$\dfrac{\partial K_{UUT}}{\partial \Gamma_{Ref\_img}}$		50.10

Measurement frequency: __21 GHz__   Travelling standard: __NIM-1__

	Quantity	Estimate x_i	Standard uncertainty u_i	Probability Distribution / method of evaluation (A or B)	Sensitivity coefficient c_i	Uncertainty contribution	Degree of freedom
1	K_{Ref}	1.00596	0.00415	Rectangular / B	$\dfrac{\partial K_{UUT}}{\partial K_{Ref}}$		54.096
2a	P_{UUT}	2.860	0.000	Normal / A	$\dfrac{\partial K_{UUT}}{\partial P_{UUT}}$		3
2b	P_{UUT_res}	0.000	0.005	Rectangular / B	$\dfrac{\partial K_{UUT}}{\partial P_{UUT\_res}}$		∞
3a	$P_{Monitor\_UUT}$	3.001	0.001	Normal / A	$\dfrac{\partial K_{UUT}}{\partial P_{Monitor\_UUT}}$		3
3b	$P_{Monitor\_UUT\_res}$	0.000	0.001	Rectangular / B	$\dfrac{\partial K_{UUT}}{\partial P_{Monitor\_UUT\_res}}$		∞
4a	$P_{Monitor\_Ref}$	3.003	0.001	Normal / A	$\dfrac{\partial K_{UUT}}{\partial P_{Monitor\_Ref}}$		3
4b	$P_{Monitor\_Ref\_res}$	0.000	0.001	Rectangular / B	$\dfrac{\partial K_{UUT}}{\partial P_{Monitor\_Ref\_res}}$	Calculated by Numerical Method	∞
5a	P_{Ref}	3.009	0.001	Normal / A	$\dfrac{\partial K_{UUT}}{\partial P_{Ref}}$		3
5b	P_{Ref_res}	0.000	0.001	Rectangular / B	$\dfrac{\partial K_{UUT}}{\partial P_{Ref\_res}}$		∞
6a	Γ_{UUT_real}	0.07626	0.01238	Normal / B	$\dfrac{\partial K_{UUT}}{\partial \Gamma_{UUT\_real}}$		∞
6b	Γ_{UUT_img}	0.08468	0.01340	Normal / B	$\dfrac{\partial K_{UUT}}{\partial \Gamma_{UUT\_img}}$		∞
7a	S_{11A_real}	-0.00207	0.02978	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{11A\_real}}$		50.09
7b	S_{11A_img}	0.03025	0.03139	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{11A\_img}}$		61.11
8a	S_{12A_real}	0.17841	0.01043	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{12A\_real}}$		64.50
8b	S_{12A_img}	0.97574	0.00611	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{12A\_img}}$		62.78

	Quantity	Estimate	Standard uncertainty	Probability Distribution / method of evaluation	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
9a	S_{21A_real}	0.18859	0.00985	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{21A\_real}}$		74.52
9b	S_{21A_img}	0.97132	0.01001	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{21A\_img}}$		53.82
10a	S_{22A_real}	-0.00645	0.02264	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{22A\_real}}$		51.62
10b	S_{22A_img}	-0.02196	0.02443	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{22A\_img}}$	Calculated by Numerical Method	67.70
11a	Γ_{e3_real}	-0.04193	0.00553	Normal / B	$\dfrac{\partial K_{UUT}}{\partial \Gamma_{e3\_real}}$		38200
11b	Γ_{e3_img}	-0.02853	0.01599	Normal / B	$\dfrac{\partial K_{UUT}}{\partial \Gamma_{e3\_img}}$		40500
12a	Γ_{Ref_real}	-0.04104	0.00412	Normal / B	$\dfrac{\partial K_{UUT}}{\partial \Gamma_{Ref\_real}}$		55.81
12b	Γ_{Ref_img}	-0.04985	0.00493	Normal / B	$\dfrac{\partial K_{UUT}}{\partial \Gamma_{Ref\_img}}$		52.64

Measurement frequency: 24 GHz   Travelling standard: NIM-1

	Quantity	Estimate x_i	Standard uncertainty u_i	Probability Distribution / method of evaluation (A or B)	Sensitivity coefficient c_i	Uncertainty contribution	Degree of freedom
1	K_{Ref}	1.00045	0.00431	Rectangular / B	$\dfrac{\partial K_{UUT}}{\partial K_{Ref}}$		52.473
2a	P_{UUT}	2.883	0.003	Normal / A	$\dfrac{\partial K_{UUT}}{\partial P_{UUT}}$		3
2b	P_{UUT_res}	0.000	0.005	Rectangular / B	$\dfrac{\partial K_{UUT}}{\partial P_{UUT\_res}}$		∞
3a	$P_{Monitor\_UUT}$	3.002	0.002	Normal / A	$\dfrac{\partial K_{UUT}}{\partial P_{Monitor\_UUT}}$		3
3b	$P_{Monitor\_UUT\_res}$	0.000	0.001	Rectangular / B	$\dfrac{\partial K_{UUT}}{\partial P_{Monitor\_UUT\_res}}$		∞
4a	$P_{Monitor\_Ref}$	3.002	0.001	Normal / A	$\dfrac{\partial K_{UUT}}{\partial P_{Monitor\_Ref}}$	Calculated by Numerical Method	3
4b	$P_{Monitor\_Ref\_res}$	0.000	0.001	Rectangular / B	$\dfrac{\partial K_{UUT}}{\partial P_{Monitor\_Ref\_res}}$		∞
5a	P_{Ref}	3.008	0.001	Normal / A	$\dfrac{\partial K_{UUT}}{\partial P_{Ref}}$		3
5b	P_{Ref_res}	0.000	0.001	Rectangular / B	$\dfrac{\partial K_{UUT}}{\partial P_{Ref\_res}}$		∞
6a	Γ_{UUT_real}	0.04994	0.00984	Normal / B	$\dfrac{\partial K_{UUT}}{\partial \Gamma_{UUT\_real}}$		∞
6b	Γ_{UUT_img}	0.08642	0.01509	Normal / B	$\dfrac{\partial K_{UUT}}{\partial \Gamma_{UUT\_img}}$		∞

7a	S_{11A_real}	0.01060	0.01818	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{11A\_real}}$		62.27
7b	S_{11A_img}	0.01395	0.01890	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{11A\_img}}$		70.60
8a	S_{12A_real}	0.71001	0.00904	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{12A\_real}}$		91.46
8b	S_{12A_img}	-0.68738	0.00899	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{12A\_img}}$		104.02
9a	S_{21A_real}	0.70302	0.01064	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{21A\_real}}$	Calculated by Numerical Method	132.10
9b	S_{21A_img}	-0.69717	0.01041	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{21A\_img}}$		121.16
10a	S_{22A_real}	0.01153	0.01507	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{22A\_real}}$		98.55
10b	S_{22A_img}	0.00036	0.01130	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{22A\_img}}$		50.12
11a	$\varGamma_{e3\_real}$	0.01605	0.00744	Normal / B	$\dfrac{\partial K_{UUT}}{\partial \varGamma_{e3\_real}}$		63400
11b	$\varGamma_{e3\_img}$	0.08091	0.01681	Normal / B	$\dfrac{\partial K_{UUT}}{\partial \varGamma_{e3\_img}}$		41500
12a	$\varGamma_{Ref\_real}$	0.04162	0.00501	Normal / B	$\dfrac{\partial K_{UUT}}{\partial \varGamma_{Ref\_real}}$		52.00
12b	$\varGamma_{Ref\_img}$	0.03261	0.00399	Normal / B	$\dfrac{\partial K_{UUT}}{\partial \varGamma_{Ref\_img}}$		55.67

Measurement frequency: 26.5 GHz   Travelling standard: NIM-1

	Quantity	Estimate x_i	Standard uncertainty u_i	Probability Distribution / method of evaluation (A or B)	Sensitivity coefficient c_i	Uncertainty contribution	Degree of freedom
1	K_{Ref}	1.00062	0.00446	Rectangular / B	$\dfrac{\partial K_{UUT}}{\partial K_{Ref}}$		58.96
2a	P_{UUT}	2.803	0.003	Normal / A	$\dfrac{\partial K_{UUT}}{\partial P_{UUT}}$		3
2b	P_{UUT_res}	0.000	0.005	Rectangular / B	$\dfrac{\partial K_{UUT}}{\partial P_{UUT\_res}}$	Calculated by Numerical Method	∞
3a	$P_{Monitor\_UUT}$	3.002	0.001	Normal / A	$\dfrac{\partial K_{UUT}}{\partial P_{Monitor\_UUT}}$		3
3b	$P_{Monitor\_UUT\_res}$	0.000	0.001	Rectangular / B	$\dfrac{\partial K_{UUT}}{\partial P_{Monitor\_UUT\_res}}$		∞
4a	$P_{Monitor\_Ref}$	3.001	0.001	Normal / A	$\dfrac{\partial K_{UUT}}{\partial P_{Monitor\_Ref}}$		3
4b	$P_{Monitor\_Ref\_res}$	0.000	0.001	Rectangular / B	$\dfrac{\partial K_{UUT}}{\partial P_{Monitor\_Ref\_res}}$		∞

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5a	P_{Ref}	3.009	0.001	Normal / A	$\dfrac{\partial K_{UUT}}{\partial P_{Ref}}$		3
5b	P_{Ref_res}	0.000	0.001	Rectangular / B	$\dfrac{\partial K_{UUT}}{\partial P_{Ref\_res}}$		∞
6a	Γ_{UUT_real}	0.11153	0.01655	Normal / B	$\dfrac{\partial K_{UUT}}{\partial \Gamma_{UUT\_real}}$		∞
6b	Γ_{UUT_img}	0.03223	0.00791	Normal / B	$\dfrac{\partial K_{UUT}}{\partial \Gamma_{UUT\_img}}$		∞
7a	S_{11A_real}	0.01703	0.06942	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{11A\_real}}$		50.51
7b	S_{11A_img}	0.06819	0.07171	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{11A\_img}}$		57.20
8a	S_{12A_real}	-0.77659	0.01222	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{12A\_real}}$		99.31
8b	S_{12A_img}	-0.62506	0.01283	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{12A\_img}}$		67.52
9a	S_{21A_real}	-0.78928	0.01721	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{21A\_real}}$		77.04
9b	S_{21A_img}	-0.59491	0.01485	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{21A\_img}}$		106.73
10a	S_{22A_real}	-0.07180	0.07414	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{22A\_real}}$		56.96
10b	S_{22A_img}	0.01164	0.07176	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{22A\_img}}$	Calculated by Numerical Method	50.24
11a	Γ_{e3_real}	0.06356	0.01934	Normal / B	$\dfrac{\partial K_{UUT}}{\partial \Gamma_{e3\_real}}$		50800
11b	Γ_{e3_img}	-0.01990	0.01191	Normal / B	$\dfrac{\partial K_{UUT}}{\partial \Gamma_{e3\_img}}$		85400
12a	Γ_{Ref_real}	-0.05411	0.01067	Normal / B	$\dfrac{\partial K_{UUT}}{\partial \Gamma_{Ref\_real}}$		50.16
12b	Γ_{Ref_img}	-0.01766	0.00370	Normal / B	$\dfrac{\partial K_{UUT}}{\partial \Gamma_{Ref\_img}}$		63.98

Measurement frequency: 18 GHz   Travelling standard: NIM-2

	Quantity	Estimate x_i	Standard uncertainty u_i	Probability Distribution / method of evaluation (A or B)	Sensitivity coefficient c_i	Uncertainty contribution	Degree of freedom
1	K_{Ref}	1.00587	0.00320	Rectangular / B	$\dfrac{\partial K_{UUT}}{\partial K_{Ref}}$	Calculated by Numerical Method	52.204
2a	P_{UUT}	2.838	0.003	Normal / A	$\dfrac{\partial K_{UUT}}{\partial P_{UUT}}$		3

2b	$P_{\text{UUT\_res}}$	0.000	0.005	Rectangular / B	$\dfrac{\partial K_{\text{UUT}}}{\partial P_{\text{UUT\_res}}}$		∞
3a	$P_{\text{Monitor\_UUT}}$	3.003	0.001	Normal / A	$\dfrac{\partial K_{\text{UUT}}}{\partial P_{\text{Monitor\_UUT}}}$		3
3b	$P_{\text{Monitor\_UUT\_res}}$	0.000	0.001	Rectangular / B	$\dfrac{\partial K_{\text{UUT}}}{\partial P_{\text{Monitor\_UUT\_res}}}$		∞
4a	$P_{\text{Monitor\_Ref}}$	3.002	0.001	Normal / A	$\dfrac{\partial K_{\text{UUT}}}{\partial P_{\text{Monitor\_Ref}}}$		3
4b	$P_{\text{Monitor\_Ref\_res}}$	0.000	0.001	Rectangular / B	$\dfrac{\partial K_{\text{UUT}}}{\partial P_{\text{Monitor\_Ref\_res}}}$		∞
5a	P_{Ref}	3.011	0.001	Normal / A	$\dfrac{\partial K_{\text{UUT}}}{\partial P_{\text{Ref}}}$		3
5b	$P_{\text{Ref\_res}}$	0.000	0.001	Rectangular / B	$\dfrac{\partial K_{\text{UUT}}}{\partial P_{\text{Ref\_res}}}$		∞
6a	$\Gamma_{\text{UUT\_real}}$	-0.01516	0.00570	Normal / B	$\dfrac{\partial K_{\text{UUT}}}{\partial \Gamma_{\text{UUT\_real}}}$		∞
6b	$\Gamma_{\text{UUT\_img}}$	-0.04954	0.01639	Normal / B	$\dfrac{\partial K_{\text{UUT}}}{\partial \Gamma_{\text{UUT\_img}}}$		∞
7a	$S_{\text{11A\_real}}$	-0.00673	0.07291	Normal / B	$\dfrac{\partial K_{\text{UUT}}}{\partial S_{\text{11A\_real}}}$		50.05
7b	$S_{\text{11A\_img}}$	0.07365	0.07357	Normal / B	$\dfrac{\partial K_{\text{UUT}}}{\partial S_{\text{11A\_img}}}$		51.88
8a	$S_{\text{12A\_real}}$	0.83846	0.00696	Normal / B	$\dfrac{\partial K_{\text{UUT}}}{\partial S_{\text{12A\_real}}}$		116.07
8b	$S_{\text{12A\_img}}$	0.53571	0.00850	Normal / B	$\dfrac{\partial K_{\text{UUT}}}{\partial S_{\text{12A\_img}}}$		89.43
9a	$S_{\text{21A\_real}}$	0.83900	0.00685	Normal / B	$\dfrac{\partial K_{\text{UUT}}}{\partial S_{\text{21A\_real}}}$		113.48
9b	$S_{\text{21A\_img}}$	0.52651	0.00821	Normal / B	$\dfrac{\partial K_{\text{UUT}}}{\partial S_{\text{21A\_img}}}$		88.96
10a	$S_{\text{22A\_real}}$	-0.06339	0.06718	Normal / B	$\dfrac{\partial K_{\text{UUT}}}{\partial S_{\text{22A\_real}}}$		52.01
10b	$S_{\text{22A\_img}}$	0.02315	0.06661	Normal / B	$\dfrac{\partial K_{\text{UUT}}}{\partial S_{\text{22A\_img}}}$	Calculated by Numerical Method	50.29
11a	$\Gamma_{\text{e3\_real}}$	0.06526	0.00865	Normal / B	$\dfrac{\partial K_{\text{UUT}}}{\partial \Gamma_{\text{e3\_real}}}$		73200
11b	$\Gamma_{\text{e3\_img}}$	0.00468	0.01259	Normal / B	$\dfrac{\partial K_{\text{UUT}}}{\partial \Gamma_{\text{e3\_img}}}$		45000
12a	$\Gamma_{\text{Ref\_real}}$	0.00829	0.00154	Normal / B	$\dfrac{\partial K_{\text{UUT}}}{\partial \Gamma_{\text{Ref\_real}}}$		68.89
12b	$\Gamma_{\text{Ref\_img}}$	0.03607	0.00614	Normal / B	$\dfrac{\partial K_{\text{UUT}}}{\partial \Gamma_{\text{Ref\_img}}}$		50.10

CCEM.RF-K28.W— RF power from 18 GHz to 26.5 GHz in rectangular waveguide

Measurement frequency: <u>21 GHz</u>   Travelling standard: <u>NIM-2</u>

	Quantity	Estimate x_i	Standard uncertainty u_i	Probability Distribution / method of evaluation (A or B)	Sensitivity coefficient c_i	Uncertainty contribution	Degree of freedom
1	K_{Ref}	1.00596	0.00415	Rectangular / B	$\dfrac{\partial K_{UUT}}{\partial K_{Ref}}$		54.096
2a	P_{UUT}	2.770	0.000	Normal / A	$\dfrac{\partial K_{UUT}}{\partial P_{UUT}}$		3
2b	P_{UUT_res}	0.000	0.005	Rectangular / B	$\dfrac{\partial K_{UUT}}{\partial P_{UUT\_res}}$		∞
3a	$P_{Monitor\_UUT}$	3.002	0.001	Normal / A	$\dfrac{\partial K_{UUT}}{\partial P_{Monitor\_UUT}}$		3
3b	$P_{Monitor\_UUT\_res}$	0.000	0.001	Rectangular / B	$\dfrac{\partial K_{UUT}}{\partial P_{Monitor\_UUT\_res}}$		∞
4a	$P_{Monitor\_Ref}$	3.003	0.001	Normal / A	$\dfrac{\partial K_{UUT}}{\partial P_{Monitor\_Ref}}$		3
4b	$P_{Monitor\_Ref\_res}$	0.000	0.001	Rectangular / B	$\dfrac{\partial K_{UUT}}{\partial P_{Monitor\_Ref\_res}}$		∞
5a	P_{Ref}	3.007	0.003	Normal / A	$\dfrac{\partial K_{UUT}}{\partial P_{Ref}}$	Calculated by Numerical Method	3
5b	P_{Ref_res}	0.000	0.001	Rectangular / B	$\dfrac{\partial K_{UUT}}{\partial P_{Ref\_res}}$		∞
6a	Γ_{UUT_real}	0.15515	0.015081	Normal / B	$\dfrac{\partial K_{UUT}}{\partial \Gamma_{UUT\_real}}$		∞
6b	Γ_{UUT_im}	0.12012	0.013548	Normal / B	$\dfrac{\partial K_{UUT}}{\partial \Gamma_{UUT\_img}}$		∞
7a	S_{11A_real}	-0.00347	0.03728	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{11A\_real}}$		50.10
7b	S_{11A_img}	0.03787	0.03857	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{11A\_img}}$		57.10
8a	S_{12A_real}	-0.17003	0.01012	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{12A\_real}}$		73.75
8b	S_{12A_img}	-0.97724	0.00605	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{12A\_img}}$		61.39
9a	S_{21A_real}	-0.17661	0.00983	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{21A\_real}}$		73.77
9b	S_{21A_img}	-0.97188	0.01000	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{21A\_img}}$	Calculated by Numerical Method	53.28
10a	S_{22A_real}	-0.01064	0.02962	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{22A\_real}}$		51.49
10b	S_{22A_img}	-0.02806	0.03085	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{22A\_img}}$		60.02

11a	Γ_{e3_real}	-0.04193	0.00553	Normal / B	$\dfrac{\partial K_{UUT}}{\partial \Gamma_{e3\_real}}$		38200
11b	Γ_{e3_img}	-0.02853	0.01599	Normal / B	$\dfrac{\partial K_{UUT}}{\partial \Gamma_{e3\_img}}$		40500
12a	Γ_{Ref_real}	-0.04104	0.00412	Normal / B	$\dfrac{\partial K_{UUT}}{\partial \Gamma_{Ref\_real}}$		55.81
12b	Γ_{Ref_img}	-0.04985	0.00493	Normal / B	$\dfrac{\partial K_{UUT}}{\partial \Gamma_{Ref\_img}}$		52.64

Measurement frequency: 24 GHz   Travelling standard: NIM-2

	Quantity	Estimate x_i	Standard uncertainty u_i	Probability Distribution / method of evaluation (A or B)	Sensitivity coefficient c_i	Uncertainty contribution	Degree of freedom
1	K_{Ref}	1.00045	0.00431	Rectangular / B	$\dfrac{\partial K_{UUT}}{\partial K_{Ref}}$		52.47
2a	P_{UUT}	2.770	0.000	Normal / A	$\dfrac{\partial K_{UUT}}{\partial P_{UUT}}$		3
2b	P_{UUT_res}	0.000	0.005	Rectangular / B	$\dfrac{\partial K_{UUT}}{\partial P_{UUT\_res}}$		∞
3a	$P_{Monitor\_UUT}$	3.002	0.002	Normal / A	$\dfrac{\partial K_{UUT}}{\partial P_{Monitor\_UUT}}$		3
3b	$P_{Monitor\_UUT\_res}$	0.000	0.001	Rectangular / B	$\dfrac{\partial K_{UUT}}{\partial P_{Monitor\_UUT\_res}}$		∞
4a	$P_{Monitor\_Ref}$	3.001	0.001	Normal / A	$\dfrac{\partial K_{UUT}}{\partial P_{Monitor\_Ref}}$		3
4b	$P_{Monitor\_Ref\_res}$	0.000	0.001	Rectangular / B	$\dfrac{\partial K_{UUT}}{\partial P_{Monitor\_Ref\_res}}$	Calculated by Numerical Method	∞
5a	P_{Ref}	3.007	0.001	Normal / A	$\dfrac{\partial K_{UUT}}{\partial P_{Ref}}$		3
5b	P_{Ref_res}	0.000	0.001	Rectangular / B	$\dfrac{\partial K_{UUT}}{\partial P_{Ref\_res}}$		∞
6a	Γ_{UUT_real}	0.07145	0.01125	Normal / B	$\dfrac{\partial K_{UUT}}{\partial \Gamma_{UUT\_real}}$		∞
6b	Γ_{UUT_img}	0.15373	0.01603	Normal / B	$\dfrac{\partial K_{UUT}}{\partial \Gamma_{UUT\_img}}$		∞
7a	S_{11A_real}	0.01162	0.01911	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{11A\_real}}$		61.94
7b	S_{11A_img}	0.01437	0.01965	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{11A\_img}}$		67.88
8a	S_{12A_real}	-0.71789	0.00883	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{12A\_real}}$		104.03
8b	S_{12A_img}	0.67946	0.00894	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{12A\_img}}$		106.38

	Quantity	Estimate x_i	Standard uncertainty u_i	Probability Distribution / method of evaluation (A or B)	Sensitivity coefficient c_i	Uncertainty contribution	Degree of freedom
9a	S_{21A_real}	-0.71223	0.01061	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{21A\_real}}$		131.05
9b	S_{21A_img}	0.68467	0.01041	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{21A\_img}}$		121.94
10a	S_{22A_real}	0.01158	0.01508	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{22A\_real}}$		98.42
10b	S_{22A_img}	-0.00056	0.01133	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{22A\_img}}$	Calculated by Numerical Method	50.23
11a	Γ_{e3_real}	0.01605	0.00744	Normal / B	$\dfrac{\partial K_{UUT}}{\partial \Gamma_{e3\_real}}$		63400
11b	Γ_{e3_img}	0.08091	0.01681	Normal / B	$\dfrac{\partial K_{UUT}}{\partial \Gamma_{e3\_img}}$		41500
12a	Γ_{Ref_real}	0.04162	0.00501	Normal / B	$\dfrac{\partial K_{UUT}}{\partial \Gamma_{Ref\_real}}$		52.00
12b	Γ_{Ref_img}	0.03261	0.00399	Normal / B	$\dfrac{\partial K_{UUT}}{\partial \Gamma_{Ref\_img}}$		55.67

Measurement frequency: 26.5 GHz   Travelling standard: NIM-2

	Quantity	Estimate x_i	Standard uncertainty u_i	Probability Distribution / method of evaluation (A or B)	Sensitivity coefficient c_i	Uncertainty contribution	Degree of freedom
1	K_{Ref}	1.00062	0.00446	Rectangular / B	$\dfrac{\partial K_{UUT}}{\partial K_{Ref}}$		58.96
2a	P_{UUT}	2.800	0.000	Normal / A	$\dfrac{\partial K_{UUT}}{\partial P_{UUT}}$		3
2b	P_{UUT_res}	0.000	0.005	Rectangular / B	$\dfrac{\partial K_{UUT}}{\partial P_{UUT\_res}}$		∞
3a	$P_{Monitor\_UUT}$	3.002	0.001	Normal / A	$\dfrac{\partial K_{UUT}}{\partial P_{Monitor\_UUT}}$		3
3b	$P_{Monitor\_UUT\_res}$	0.000	0.001	Rectangular / B	$\dfrac{\partial K_{UUT}}{\partial P_{Monitor\_UUT\_res}}$	Calculated by Numerical Method	∞
4a	$P_{Monitor\_Ref}$	3.004	0.001	Normal / A	$\dfrac{\partial K_{UUT}}{\partial P_{Monitor\_Ref}}$		3
4b	$P_{Monitor\_Ref\_res}$	0.000	0.001	Rectangular / B	$\dfrac{\partial K_{UUT}}{\partial P_{Monitor\_Ref\_res}}$		∞
5a	P_{Ref}	3.011	0.001	Normal / A	$\dfrac{\partial K_{UUT}}{\partial P_{Ref}}$		3
5b	P_{Ref_res}	0.000	0.001	Rectangular / B	$\dfrac{\partial K_{UUT}}{\partial P_{Ref\_res}}$		∞
6a	Γ_{UUT_real}	0.04673	0.01117	Normal / B	$\dfrac{\partial K_{UUT}}{\partial \Gamma_{UUT\_real}}$		∞
6b	Γ_{UUT_img}	0.05865	0.01365	Normal / B	$\dfrac{\partial K_{UUT}}{\partial \Gamma_{UUT\_img}}$		∞

7a	S_{11A_real}	0.01723	0.07098	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{11A\_real}}$		50.48
7b	S_{11A_img}	0.06995	0.0732	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{11A\_img}}$		56.88
8a	S_{12A_real}	0.76662	0.01200	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{12A\_real}}$		109.55
8b	S_{12A_img}	0.63747	0.01242	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{12A\_img}}$		97.09
9a	S_{21A_real}	0.77952	0.01708	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{21A\_real}}$		78.06
9b	S_{21A_img}	0.60345	0.01490	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{21A\_img}}$		104.10
10a	S_{22A_real}	-0.07968	0.08119	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{22A\_real}}$		55.79
10b	S_{22A_img}	0.01005	0.07900	Normal / B	$\dfrac{\partial K_{UUT}}{\partial S_{22A\_img}}$	Calculated by Numerical Method	50.15
11a	Γ_{e3_real}	0.06356	0.01934	Normal / B	$\dfrac{\partial K_{UUT}}{\partial \Gamma_{e3\_real}}$		50800
11b	Γ_{e3_img}	-0.01990	0.01191	Normal / B	$\dfrac{\partial K_{UUT}}{\partial \Gamma_{e3\_img}}$		85400
12a	Γ_{Ref_real}	-0.05411	0.01067	Normal / B	$\dfrac{\partial K_{UUT}}{\partial \Gamma_{Ref\_real}}$		50.16
12b	Γ_{Ref_img}	-0.01766	0.00370	Normal / B	$\dfrac{\partial K_{UUT}}{\partial \Gamma_{Ref\_img}}$		63.98

D.10 NMC uncertainty budgets

Travelling Standard: HP K486A Thermistor Mount (serial no.: 1606)

Frequency: 18 GHz

$u(x_i)$	Quantity X_i	Estimate x_i (units)	Standard Uncertainty $u(x_i)$ (units)	Prob Distri (A,B)	Sensitivity Coefficient, c_i (units)	Uncertainty Contribution $c_i*u(x_i)$	DOF
u(1)	K_{Std}	0.8413 (-)	0.010302143 (-)	Normal (B)	1.15E+00 (-)	1.19E-02	∞
u(2)	P_{Std}	0.000811916 (watt)	4.06E-07 (watt)	Normal (B)	-1.19E+03 (watt⁻¹)	-4.85E-04	∞
u(3)	P_{Dut}	0.000933418 (watt)	1.60E-07 (watt)	Normal (B)	1.04E+03 (watt⁻¹)	1.66E-04	∞
u(4)	P_{m_Std}	0.001 (watt)	1.00E-07 (watt)	Normal (B)	9.68E+02 (watt⁻¹)	9.68E-05	∞
u(5)	P_{m_Dut}	0.001 (watt)	1.00E-07 (watt)	Normal (B)	-9.68E+02 (watt⁻¹)	-9.68E-05	∞
u(6)	$\Gamma_{Std}(mag)$	0.199 (-)	0.01 (-)	Normal (B)	-8.79E-02 (-)	-8.79E-04	∞
u(7)	$\Gamma_{Std}(phase)$	0.0174533 (rad)	0.050336239 (rad)	Normal (B)	1.17E-02 (rad⁻¹)	5.88E-04	∞
u(8)	$\Gamma_{Dut}(mag)$	0.167946792 (-)	0.00550039 (-)	Normal (B)	-1.75E-02 (-)	-9.60E-05	∞
u(9)	$\Gamma_{Dut}(phase)$	1.123525869 (rad)	0.040148868 (rad)	Normal (B)	-1.77E-02 (rad⁻¹)	-7.12E-04	∞
u(10)	$\Gamma_{EG}(mag)$	0.055157328 (-)	0.015000397 (-)	Normal (B)	-3.69E-01 (-)	-5.53E-03	∞
u(11)	$\Gamma_{EG}(phase)$	-2.52130037 (rad)	0.095138523 (rad)	Normal (B)	-6.04E-03 (rad⁻¹)	-5.74E-04	∞
u(12)	S_{21A}	0.978195358 (-)	0.0085 (-)	Normal (B)	-9.57E-01 (-)	-8.13E-03	∞
u(13)	Repeatability	0.968363995 (-)	1.02E-04 (-)	Normal (A)	1 (-)	1.02E-04	5
$u_c(K_{Dut})$	Combined standard uncertainty (*k*=1)					**Eff DOF**	
	@ 18 GHz			Normal	0.01547	2.68E+09	
K_{Dut}	**@ 18 GHz = 0.9684**						

Travelling Standard: HP K486A Thermistor Mount (serial no.: 1606)

Frequency: 21 GHz

$u(x_i)$	Quantity X_i	Estimate x_i	Standard Uncertainty	Prob Distri (A,B)	Sensitivity Coefficient,	Uncertainty Contribution	DOF

		(units)	$u(x_i)$ (units)		c_i (units)	$c_i*u(x_i)$	
u(1)	K_{Std}	0.8189 (-)	0.014699042 (-)	Normal (B)	1.18E+00 (-)	1.74E-02	∞
u(2)	P_{Std}	0.000811434 (watt)	4.06E-07 (watt)	Normal (B)	-1.20E+03 (watt^{-1})	-4.86E-04	∞
u(3)	P_{Dut}	0.000943721 (watt)	1.60E-07 (watt)	Normal (B)	1.03E+03 (watt^{-1})	1.65E-04	∞
u(4)	P_{m_Std}	0.001 (watt)	1.00E-07 (watt)	Normal (B)	9.70E+02 (watt^{-1})	9.70E-05	∞
u(5)	P_{m_Dut}	0.001 (watt)	1.00E-07 (watt)	Normal (B)	-9.70E+02 (watt^{-1})	-9.70E-05	∞
u(6)	$\Gamma_{Std}(mag)$	0.159 (-)	0.01 (-)	Normal (B)	-7.04E-02 (-)	-7.04E-04	∞
u(7)	$\Gamma_{Std}(phase)$	3.08923 (rad)	0.063060125 (rad)	Normal (B)	1.41E-02 (rad^{-1})	8.88E-04	∞
u(8)	$\Gamma_{Dut}(mag)$	0.116822186 (-)	0.005502248 (-)	Normal (B)	9.44E-02 (-)	5.19E-04	∞
u(9)	$\Gamma_{Dut}(phase)$	2.731333725 (rad)	0.043657724 (rad)	Normal (B)	-5.30E-03 (rad^{-1})	-2.31E-04	∞
u(10)	$\Gamma_{EG}(mag)$	0.054272763 (-)	0.015000601 (-)	Normal (B)	-3.28E-02 (-)	-4.92E-04	∞
u(11)	$\Gamma_{EG}(phase)$	0.860761470 (rad)	0.154487796 (rad)	Normal (B)	8.78E-03 (rad^{-1})	1.36E-03	∞
u(12)	S_{21A}	0.979913098 (-)	0.009 (-)	Normal (B)	-9.79E-01 (-)	-8.81E-03	∞
u(13)	Repeatability	0.972039593 (-)	1.87E-04 (-)	Normal (A)	1 (-)	1.87E-04	5
$u_c(K_{Dut})$	Combined standard uncertainty (*k*=1)					**Eff DOF**	
	@ 21 GHz			Normal	0.01962	6.08E+08	
K_{Dut}	**@ 21 GHz = 0.9720**						

Travelling Standard: HP K486A Thermistor Mount (serial no.: 1606)

Frequency: 24 GHz

$u(x_i)$	Quantity X_i	Estimate x_i (units)	Standard Uncertainty $u(x_i)$ (units)	Prob Distri (A,B)	Sensitivity Coefficient, c_i (units)	Uncertainty Contribution $c_i*u(x_i)$	DOF
u(1)	K_{Std}	0.7785 (-)	0.014680005 (-)	Normal (B)	1.25E+00 (-)	1.83E-02	∞
u(2)	P_{Std}	0.000764856	4.07E-07	Normal	-1.27E+03	-5.17E-04	∞

$u(x_i)$	Quantity X_i	Estimate x_i (units)	Standard Uncertainty $u(x_i)$ (units)	Prob Distri (A,B)	Sensitivity Coefficient, c_i (units)	Uncertainty Contribution $c_i*u(x_i)$	DOF
		(watt)	(watt)	(B)	(watt^{-1})		
u(3)	P_{Dut}	0.000956265 (watt)	1.60E-07 (watt)	Normal (B)	1.02E+03 (watt^{-1})	1.63E-04	∞
u(4)	P_{m_Std}	0.000999 (watt)	1.00E-07 (watt)	Normal (B)	9.73E+02 (watt^{-1})	9.73E-05	∞
u(5)	P_{m_Dut}	0.001 (watt)	1.00E-07 (watt)	Normal (B)	-9.72E+02 (watt^{-1})	-9.72E-05	∞
u(6)	$\Gamma_{Std}(mag)$	0.244 (-)	0.01 (-)	Normal (B)	-7.62E-02 (-)	-7.62E-04	∞
u(7)	$\Gamma_{Std}(phase)$	0.15708 (rad)	0.041029638 (rad)	Normal (B)	9.93E-03 (rad^{-1})	4.07E-04	∞
u(8)	$\Gamma_{Dut}(mag)$	0.089425703 (-)	0.005503244 (-)	Normal (B)	-6.43E-02 (-)	-3.54E-04	∞
u(9)	$\Gamma_{Dut}(phase)$	2.040751647 (rad)	0.047305 (rad)	Normal (B)	-5.38E-03 (rad^{-1})	-2.55E-04	∞
u(10)	$\Gamma_{EG}(mag)$	0.04519089 (-)	0.015000452 (-)	Normal (B)	-5.25E-01 (-)	-7.87E-03	∞
u(11)	$\Gamma_{EG}(phase)$	-2.790181589 (rad)	0.155372414 (rad)	Normal (B)	4.55E-03 (rad^{-1})	7.07E-04	∞
u(12)	S_{21A}	0.976176922 (-)	0.009 (-)	Normal (B)	-9.72E-01 (-)	-8.75E-03	∞
u(13)	Repeatability	0.971853656 (-)	1.53E-04 (-)	Normal (A)	1 (-)	1.53E-04	5
$u_c(K_{Dut})$	**Combined standard uncertainty (*k*=1)**					**Eff DOF**	
	@ 24 GHz			Normal	0.02182	2.09E+09	
K_{Dut}	**@ 24 GHz = 0.9719**						

Travelling Standard: HP K486A Thermistor Mount (serial no.: 1606)

Frequency: 26.5 GHz

$u(x_i)$	Quantity X_i	Estimate x_i (units)	Standard Uncertainty $u(x_i)$ (units)	Prob Distri (A,B)	Sensitivity Coefficient, c_i (units)	Uncertainty Contribution $c_i*u(x_i)$	DOF
u(1)	K_{Std}	0.6818 (-)	0.014638262 (-)	Normal (B)	1.41E+00 (-)	2.06E-02	∞
u(2)	P_{Std}	0.000701348 (watt)	4.07E-07 (watt)	Normal (B)	-1.37E+03 (watt^{-1})	-5.58E-04	∞
u(3)	P_{Dut}	0.000937339 (watt)	1.60E-07 (watt)	Normal (B)	1.03E+03 (watt^{-1})	1.64E-04	∞
u(4)	P_{m_Std}	0.001 (watt)	1.00E-07 (watt)	Normal (B)	9.61E+02 (watt^{-1})	9.61E-05	∞

u(x_i)		Estimate	Standard Uncertainty	Prob Distri	Sensitivity Coefficient	Uncertainty Contribution	DOF
u(5)	P_{m_Dut}	0.001 (watt)	1.00E-07 (watt)	Normal (B)	-9.61E+02 (watt^{-1})	-9.61E-05	∞
u(6)	Γ_{Std}(mag)	0.163 (-)	0.01 (-)	Normal (B)	1.04E-01 (-)	1.04E-03	∞
u(7)	Γ_{Std}(phase)	-0.890118 (rad)	0.061504684 (rad)	Normal (B)	5.61E-04 (rad^{-1})	3.45E-05	∞
u(8)	Γ_{Dut}(mag)	0.102278835 (-)	0.005503597 (-)	Normal (B)	9.49E-02 (-)	5.22E-04	∞
u(9)	Γ_{Dut}(phase)	1.948373387 (rad)	0.06115409 (rad)	Normal (B)	3.93E-03 (rad^{-1})	2.41E-04	∞
u(10)	Γ_{EG}(mag)	0.053550983 (-)	0.015002097 (-)	Normal (B)	5.30E-01 (-)	7.95E-03	∞
u(11)	Γ_{EG}(phase)	0.806258882 (rad)	0.098725588 (rad)	Normal (B)	4.49E-03 (rad^{-1})	4.44E-04	∞
u(12)	S_{21A}	0.976425377 (-)	0.009 (-)	Normal (B)	-9.65E-01 (-)	-8.68E-03	∞
u(13)	Repeatability	0.958570363 (-)	2.02E-04 (-)	Normal (A)	1 (-)	2.02E-04	5
$u_c(K_{Dut})$	**Combined standard uncertainty (k=1)**					**Eff DOF**	
	@ 26.5 GHz		Normal	0.02380		9.65E+08	
K_{Dut}	**@ 26.5 GHz = 0.9586**						

Travelling Standard: HP K486A Thermistor Mount (serial no.: 05616)

Frequency: 18 GHz

u(x_i)	Quantity X_i	Estimate x_i (units)	Standard Uncertainty u(x_i) (units)	Prob Distri (A,B)	Sensitivity Coefficient, c_i (units)	Uncertainty Contribution $c_i*u(x_i)$	DOF
u(1)	K_{Std}	0.8413 (-)	0.010302143 (-)	Normal (B)	1.17E+00 (-)	1.21E-02	∞
u(2)	P_{Std}	0.000810802 (watt)	4.06E-07 (watt)	Normal (B)	-1.21E+03 (watt^{-1})	-4.94E-04	∞
u(3)	P_{Dut}	0.000949706 (watt)	1.96E-07 (watt)	Normal (B)	1.04E+03 (watt^{-1})	2.03E-04	∞
u(4)	P_{m_Std}	0.000999 (watt)	1.00E-07 (watt)	Normal (B)	9.86E+02 (watt^{-1})	9.86E-05	∞
u(5)	P_{m_Dut}	0.001 (watt)	1.00E-07 (watt)	Normal (B)	-9.85E+02 (watt^{-1})	-9.85E-05	∞
u(6)	Γ_{Std}(mag)	0.199 (-)	0.01 (-)	Normal (B)	-8.94E-02 (-)	-8.94E-04	∞
u(7)	Γ_{Std}(phase)	0.0174533 (rad)	0.050336239 (rad)	Normal (B)	1.19E-02 (rad^{-1})	5.99E-04	∞

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u(8)	$\overline{\Gamma_{\text{Dut}}\text{(mag)}}$	0.049279336 (-)	0.005500122 (-)	Normal (B)	-6.68E-02 (-)	-3.67E-04	∞
u(9)	$\overline{\Gamma_{\text{Dut}}\text{(phase)}}$	1.61316813 (rad)	0.040230731 (rad)	Normal (B)	-4.24E-03 (rad^{-1})	-1.70E-04	∞
u(10)	$\overline{\Gamma_{\text{EG}}\text{(mag)}}$	0.055157328 (-)	0.015000397 (-)	Normal (B)	-3.81E-01 (-)	-5.71E-03	∞
u(11)	$\overline{\Gamma_{\text{EG}}\text{(phase)}}$	-2.52130036 (rad)	0.095138523 (rad)	Normal (B)	7.65E-03 (rad^{-1})	7.28E-04	∞
u(12)	$\overline{S_{21A}}$	0.978195358 (-)	0.0085 (-)	Normal (B)	-9.73E-01 (-)	-8.27E-03	∞
u(13)	Repeatability	0.984941889 (-)	2.43E-04 (-)	Normal (A)	1 (-)	2.43E-04	5
$u_c(K_{\text{Dut}})$	**Combined standard uncertainty (k=1)**					**Eff DOF**	
	@ 18 GHz			Normal	0.01577	8.88E+07	
K_{Dut}	**@ 18 GHz = 0.9849**						

Travelling Standard: HP K486A Thermistor Mount (serial no.: 05616)

Frequency: 21 GHz

u(x_i)	Quantity X_i	Estimate x_i (units)	Standard Uncertainty u(x_i) (units)	Prob Distri (A,B)	Sensitivity Coefficient, c_i (units)	Uncertainty Contribution $c_i*u(x_i)$	DOF
u(1)	$\overline{K_{\text{Std}}}$	0.8189 (-)	0.014699042 (-)	Normal (B)	1.13E+00 (-)	1.67E-02	∞
u(2)	$\overline{P_{\text{Std}}}$	0.000811346 (watt)	4.06E-07 (watt)	Normal (B)	-1.15E+03 (watt^{-1})	-4.65E-04	∞
u(3)	$\overline{P_{\text{Dut}}}$	0.000896213 (watt)	1.96E-07 (watt)	Normal (B)	1.04E+03 (watt^{-1})	2.03E-04	∞
u(4)	$\overline{P_{\text{m\_Std}}}$	0.001 (watt)	1.00E-07 (watt)	Normal (B)	9.29E+02 (watt^{-1})	9.29E-05	∞
u(5)	$\overline{P_{\text{m\_Dut}}}$	0.001001 (watt)	1.00E-07 (watt)	Normal (B)	-9.28E+02 (watt^{-1})	-9.28E-05	∞
u(6)	$\overline{\Gamma_{\text{Std}}\text{(mag)}}$	0.159 (-)	0.01 (-)	Normal (B)	-6.74E-02 (-)	-6.74E-04	∞
u(7)	$\overline{\Gamma_{\text{Std}}\text{(phase)}}$	3.08923 (rad)	0.063060125 (rad)	Normal (B)	1.35E-02 (rad^{-1})	8.50E-04	∞
u(8)	$\overline{\Gamma_{\text{Dut}}\text{(mag)}}$	0.20008218 (-)	0.005502317 (-)	Normal (B)	9.52E-02 (-)	5.24E-04	∞
u(9)	$\overline{\Gamma_{\text{Dut}}\text{(phase)}}$	2.588740306 (rad)	0.043641365 (rad)	Normal (B)	-5.99E-03 (rad^{-1})	-2.61E-04	∞
u(10)	$\overline{\Gamma_{\text{EG}}\text{(mag)}}$	0.054272763 (-)	0.015000601 (-)	Normal (B)	1.25E-01 (-)	1.88E-03	∞

u(11)	Γ_{EG}(phase)	0.860761470 (rad)	0.154487796 (rad)	Normal (B)	7.49E-03 (rad^{-1})	1.16E-03	∞
u(12)	S_{21A}	0.979913098 (-)	0.009 (-)	Normal (B)	-9.37E-01 (-)	-8.43E-03	∞
u(13)	Repeatability	0.930107609 (-)	8.02E-05 (-)	Normal (A)	1 (-)	8.02E-05	5
$u_c(K_{Dut})$	**Combined standard uncertainty (*k*=1)**					**Eff DOF**	
	@ 21 GHz			Normal	0.01886	1.53E+10	
K_{Dut}	**@ 21 GHz = 0.9301**						

Travelling Standard: HP K486A Thermistor Mount (serial no.: 05616)

Frequency: 24 GHz

u(x_i)	Quantity X_i	Estimate x_i (units)	Standard Uncertainty u(x_i) (units)	Prob Distri (A,B)	Sensitivity Coefficient, c_i (units)	Uncertainty Contribution c_i*u(x_i)	DOF
u(1)	K_{Std}	0.7785 (-)	0.014680005 (-)	Normal (B)	1.21E+00 (-)	1.77E-02	∞
u(2)	P_{Std}	0.000766377 (watt)	4.07E-07 (watt)	Normal (B)	-1.23E+03 (watt^{-1})	-4.99E-04	∞
u(3)	P_{Dut}	0.00093254 (watt)	1.96E-07 (watt)	Normal (B)	1.01E+03 (watt^{-1})	1.98E-04	∞
u(4)	P_{m_Std}	0.001001 (watt)	1.00E-07 (watt)	Normal (B)	9.40E+02 (watt^{-1})	9.40E-05	∞
u(5)	P_{m_Dut}	0.001001 (watt)	1.00E-07 (watt)	Normal (B)	-9.40E+02 (watt^{-1})	-9.40E-05	∞
u(6)	Γ_{Std}(mag)	0.244 (-)	0.01 (-)	Normal (B)	-7.38E-02 (-)	-7.38E-04	∞
u(7)	Γ_{Std}(phase)	0.15708 (rad)	0.041029638 (rad)	Normal (B)	9.62E-03 (rad^{-1})	3.95E-04	∞
u(8)	Γ_{Dut}(mag)	0.158293469 (-)	0.005505457 (-)	Normal (B)	-7.10E-02 (-)	-3.91E-04	∞
u(9)	Γ_{Dut}(phase)	2.20097441 (rad)	0.047171462 (rad)	Normal (B)	-7.57E-03 (rad^{-1})	-3.57E-04	∞
u(10)	Γ_{EG}(mag)	0.04519089 (-)	0.015000452 (-)	Normal (B)	-6.33E-01 (-)	-9.50E-03	∞
u(11)	Γ_{EG}(phase)	-2.79018158 (rad)	0.155372414 (rad)	Normal (B)	2.04E-03 (rad^{-1})	3.18E-04	∞
u(12)	S_{21A}	0.976176922 (-)	0.009 (-)	Normal (B)	-9.40E-01 (-)	-8.46E-03	∞
u(13)	Repeatability	0.940426576 (-)	1.44E-04 (-)	Normal (A)	1 (-)	1.44E-04	5

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$u_c(K_{Dut})$	Combined standard uncertainty (k=1)				Eff DOF
	@ 24 GHz	Normal	0.02187		2.66E+09
K_{Dut}	@ 24 GHz = 0.9404				

Travelling Standard: HP K486A Thermistor Mount (serial no.: 05616)

Frequency: 26.5 GHz

$u(x_i)$	Quantity X_i	Estimate x_i (units)	Standard Uncertainty $u(x_i)$ (units)	Prob Distri (A,B)	Sensitivity Coefficient, c_i (units)	Uncertainty Contribution $c_i*u(x_i)$	DOF
u(1)	K_{Std}	0.6818 (-)	0.014638262 (-)	Normal (B)	1.40E+00 (-)	2.05E-02	∞
u(2)	P_{Std}	0.000701785 (watt)	4.07E-07 (watt)	Normal (B)	-1.36E+03 (watt^{-1})	-5.54E-04	∞
u(3)	P_{Dut}	0.000935761 (watt)	1.96E-07 (watt)	Normal (B)	1.02E+03 (watt^{-1})	2.00E-04	∞
u(4)	P_{m_Std}	0.001 (watt)	1.00E-07 (watt)	Normal (B)	9.55E+02 (watt^{-1})	9.55E-05	∞
u(5)	P_{m_Dut}	0.001001 (watt)	1.00E-07 (watt)	Normal (B)	-9.54E+02 (watt^{-1})	-9.54E-05	∞
u(6)	$\Gamma_{Std}(mag)$	0.163 (-)	0.01 (-)	Normal (B)	1.03E-01 (-)	1.03E-03	∞
u(7)	$\Gamma_{Std}(phase)$	-0.890118 (rad)	0.061504684 (rad)	Normal (B)	5.57E-04 (rad^{-1})	3.43E-05	∞
u(8)	$\Gamma_{Dut}(mag)$	0.069975853 (-)	0.00550742 (-)	Normal (B)	9.46E-02 (-)	5.31E-04	∞
u(9)	$\Gamma_{Dut}(phase)$	2.666243164 (rad)	0.061160544 (rad)	Normal (B)	-2.31E-03 (rad^{-1})	-1.41E-04	∞
u(10)	$\Gamma_{EG}(mag)$	0.053550983 (-)	0.015002097 (-)	Normal (B)	4.72E-01 (-)	7.08E-03	∞
u(11)	$\Gamma_{EG}(phase)$	0.806258881 (rad)	0.098725588 (rad)	Normal (B)	-1.75E-03 (rad^{-1})	-1.73E-04	∞
u(12)	S_{21A}	0.976425377 (-)	0.009 (-)	Normal (B)	-9.60E-01 (-)	-8.64E-03	∞
u(13)	Repeatability	0.953497548 (-)	1.54E-04 (-)	Normal (A)	1 (-)	1.54E-04	5
$u_c(K_{Dut})$	Combined standard uncertainty (k=1)					Eff DOF	
	@ 26.5 GHz			Normal	0.02339	2.69E+09	
K_{Dut}	@ 26.5 GHz = 0.9535						

E Recalculated Results

E.1 Recalculated KCRV for NIM-1 (SN 1606) based on revised NPL results

Table E.1.1. Measurements and standard uncertainties (k=1) of NIM-1 (SN 1606) at **18** GHz

Laboratory	Measurements used to calculate the KCRV				
	η_{eff}	$u(\eta_{eff})$ (k=1)	K_C	$u(K_C)$ (k=1)	
NIM	0.9760	0.0009	0.9459	0.0016	
LNE	0.9770	0.0030	0.9490	0.0030	
NPL	0.9727	0.0029	0.9434	0.0028	
PTB	0.9756	0.0013	0.9463	0.0013	
UME	0.9773	0.0014	0.9491	0.0025	
KRISS	0.9763	0.0011	0.9475	0.0012	
NIST	0.9756	0.0023	0.9468	0.0022	
SCL			0.9420	0.0210	
KCRV (revised)	0.9761	0.0005	0.9468	0.0007	

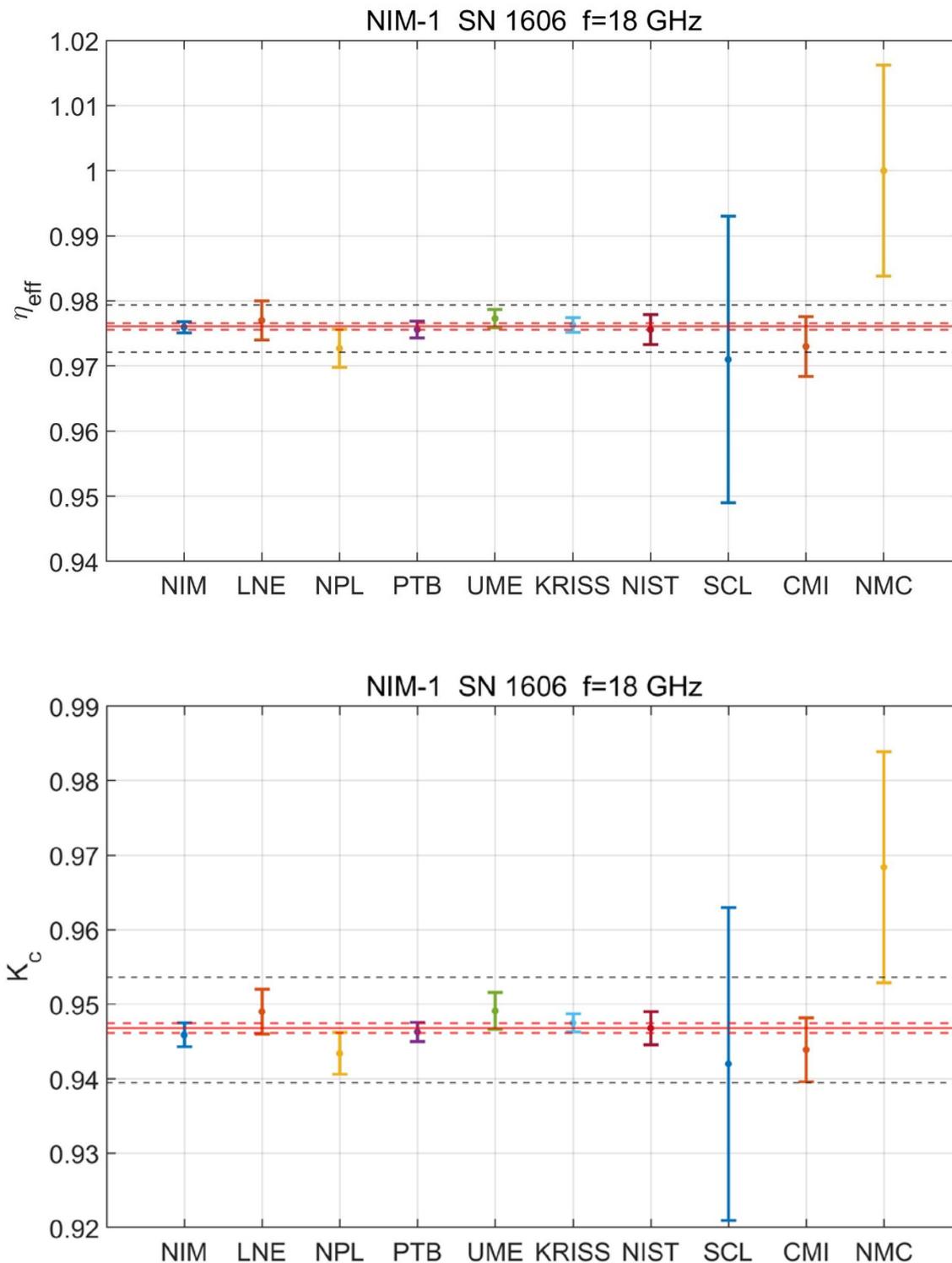| Laboratory	Measurements not used to calculate the KCRV				
	η_{eff}	$u(\eta_{eff})$ (k=1)	K_C	$u(K_C)$ (k=1)	Reason for exclusion
SCL	0.9710	0.0220			Statistical outlier
CMI	0.9730	0.0046	0.9439	0.0043	Traceable to other participant
NMC	1.0000	0.0162	0.9684	0.0155	Traceable to other participant

Figure 7. Effective efficiency and calibration factor of travelling standard NIM-1 at 18 GHz. KCRV (—), u(KCRV) (----), outlier boundary (----)（based on revised NPL results）.

Table E.1.2 Measurements and standard uncertainties (*k*=1) of NIM-1 (SN 1606) at **21** GHz

Laboratory	Measurements used to calculate the KCRV				
	η_{eff}	$u(\eta_{eff})$ (*k*=1)	K_C	$u(K_C)$ (*k*=1)	
NIM	0.9802	0.0008	0.9678	0.0012	
LNE	0.9800	0.0030	0.9680	0.0030	
NPL	0.9791	0.0012	0.9674	0.0013	
PTB	0.9799	0.0015	0.9678	0.0016	
UME	0.9814	0.0015			
KRISS	0.9806	0.0012	0.9681	0.0012	
NIST	0.9814	0.0016			
SCL	0.9810	0.0230	0.9680	0.0220	
KCRV (revised)	0.9803	0.0005	0.9678	0.0006	

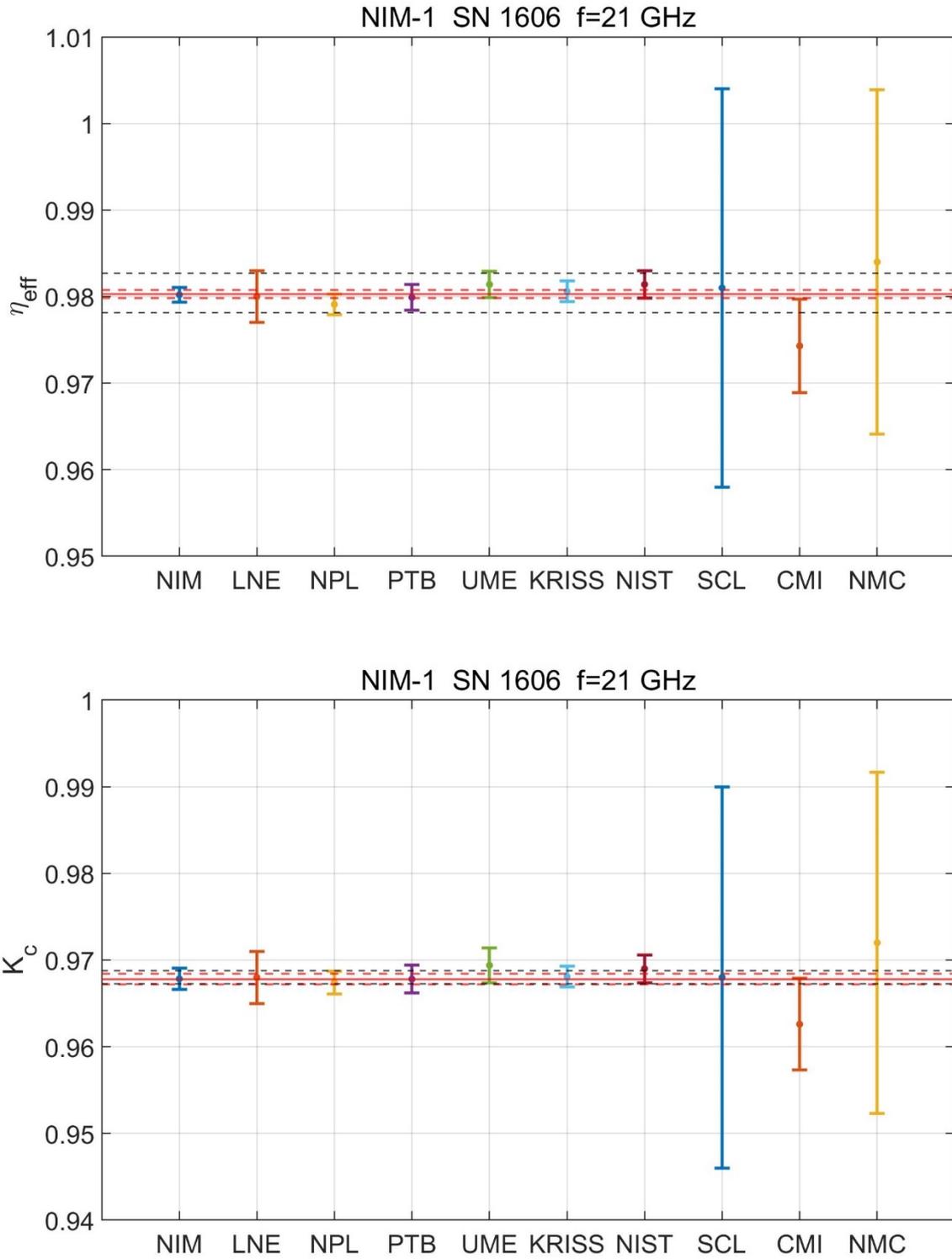| Laboratory	Measurements not used to calculate the KCRV				
	η_{eff}	$u(\eta_{eff})$ (*k*=1)	K_C	$u(K_C)$ (*k*=1)	Reason for exclusion
UME			0.9694	0.0020	Statistical outlier
NIST			0.9690	0.0016	Statistical outlier
CMI	0.9743	0.0054	0.9626	0.0053	Traceable to other participant
NMC	0.9840	0.0199	0.9720	0.0197	Traceable to other participant

Figure 8. Effective efficiency and calibration factor of travelling standard NIM-1 at 21 GHz. KCRV (—), u(KCRV) (----), outlier boundary (----)（based on revised NPL results）.

Table E.1.3. Measurements and combined standard uncertainties ($k=1$) of NIM-1 (SN 1606) at **24** GHz

Laboratory	Measurements used to calculate the KCRV				
	η_{eff}	$u(\eta_{eff})$ ($k=1$)	K_C	$u(K_C)$ ($k=1$)	
NIM	0.9777	0.0008	0.9681	0.0011	
LNE	0.9770	0.0030	0.9670	0.0030	
NPL	0.9775	0.0016	0.9685	0.0016	
PTB	0.9779	0.0012	0.9704	0.0013	
UME	0.9795	0.0015	0.9707	0.0018	
KRISS	0.9785	0.0012	0.9686	0.0012	
NIST	0.9787	0.0019	0.9689	0.0019	
SCL	0.9750	0.0220	0.9650	0.0220	
KCRV (revised)	0.9781	0.0005	0.9690	0.0006	

Laboratory	Measurements not used to calculate the KCRV				
	η_{eff}	$u(\eta_{eff})$ ($k=1$)	K_C	$u(K_C)$ ($k=1$)	Reason for exclusion
CMI	0.9739	0.0054	0.9647	0.0053	Traceable to other participant
NMC	0.9811	0.0221	0.9719	0.0219	Traceable to other participant

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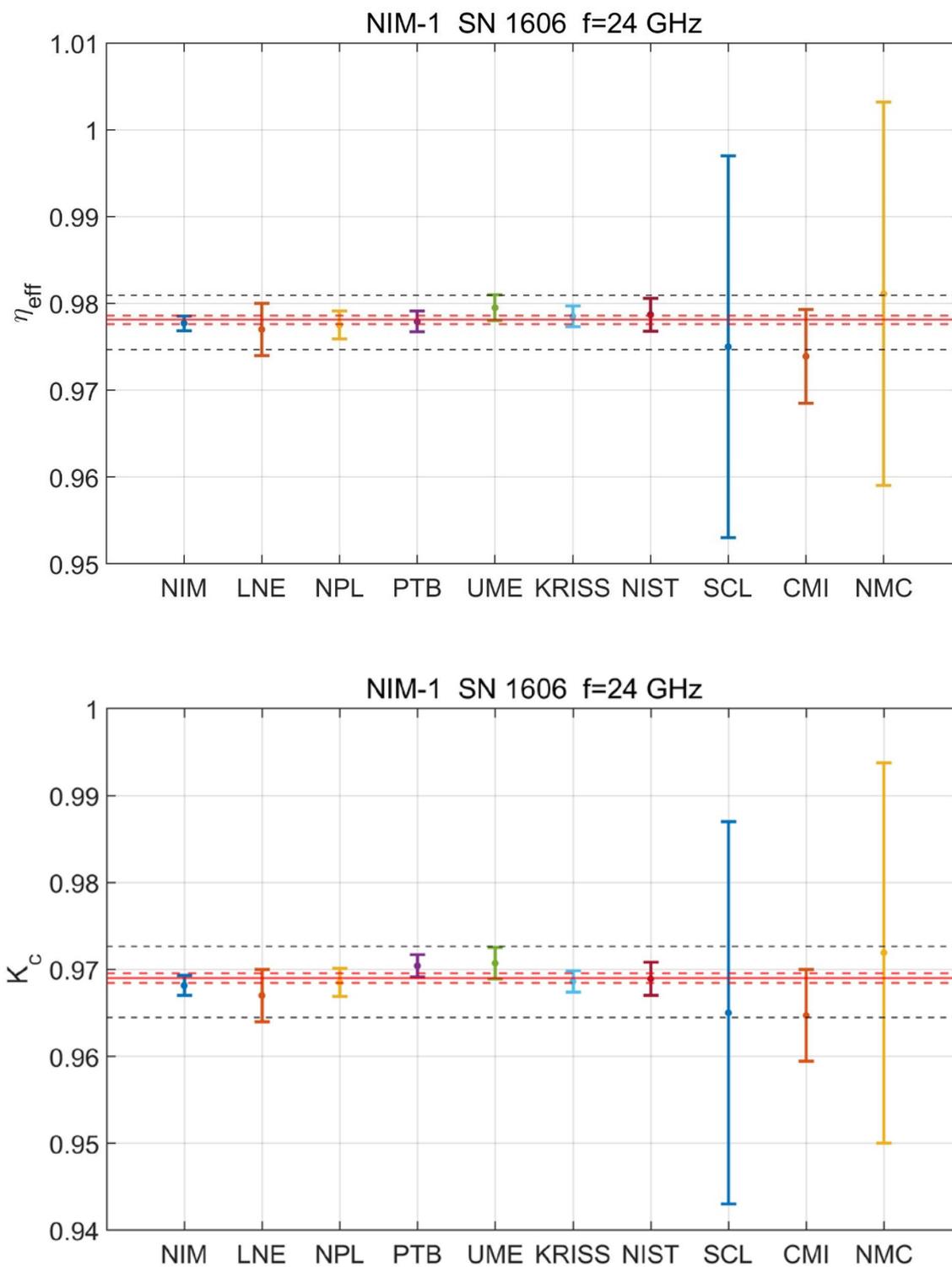

Figure 9. Effective efficiency and calibration factor of travelling standard NIM-1 at 24 GHz. KCRV (—), u(KCRV) (----), outlier boundary (----) （based on revised NPL results）.

Table E.1.4. Measurements and combined standard uncertainties (*k*=1) of NIM-1 (SN 1606) at **26.5** GHz

Laboratory	Measurements used to calculate the KCRV				
	η_{eff}	$u(\eta_{eff})$ (*k*=1)	K_C	$u(K_C)$ (*k*=1)	
NIM	0.9722	0.0009	0.9598	0.0012	
LNE	0.9730	0.0030	0.9610	0.0030	
NPL	0.9715	0.0013	0.9594	0.0013	
PTB	0.9722	0.0014	0.9602	0.0015	
UME	0.9737	0.0015	0.9603	0.0020	
KRISS	0.9727	0.0012	0.9586	0.0013	
NIST	0.9729	0.0019	0.9593	0.0019	
KCRV (revised)	0.9724	0.0005	0.9596	0.0006	

Laboratory	Measurements not used to calculate the KCRV				
	η_{eff}	$u(\eta_{eff})$ (*k*=1)	K_C	$u(K_C)$ (*k*=1)	Reason for exclusion
SCL	0.9670	0.0280	0.9540	0.0270	Statistical outlier
CMI	0.9683	0.0054	0.9560	0.0053	Traceable to other participant
NMC	0.9713	0.0242	0.9586	0.0238	Traceable to other participant

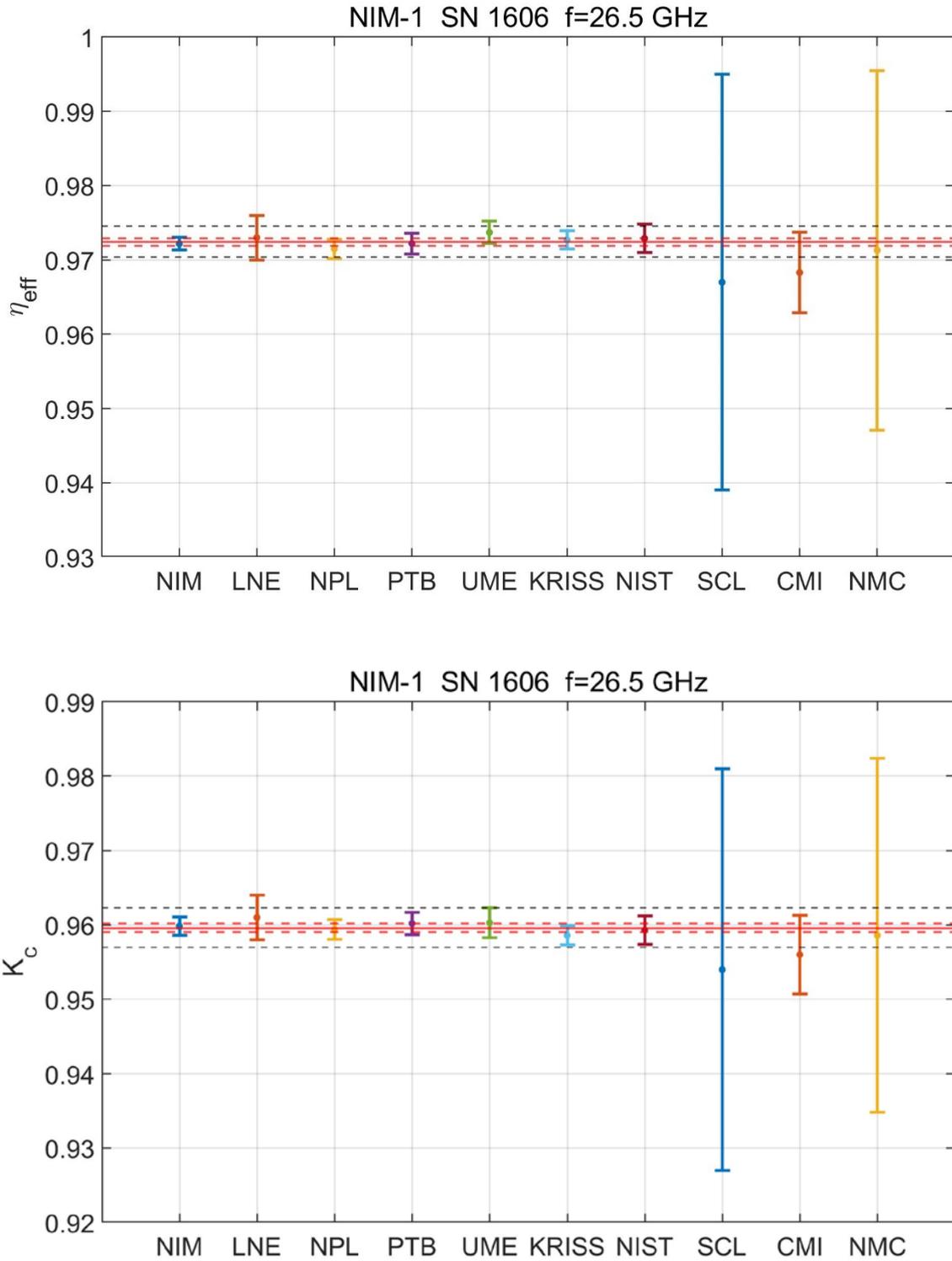*CCEM.RF-K28.W— RF power from 18 GHz to 26.5 GHz in rectangular waveguide*

Figure 10. Effective efficiency and calibration factor of travelling standard NIM-1 at 26.5 GHz. KCRV (—), u(KCRV) (----), outlier boundary (----)（based on revised NPL results）.

E.2 Recalculated KCRV for NIM-2 (SN 05616) based on revised NPL results

Table E.2.1. Measurements and combined standard uncertainties (*k*=1) of NIM-2 (SN 05616) at **18** GHz

| Laboratory | Measurements used to calculate the KCRV | | | | |
	η_{eff}	$u(\eta_{eff})$ (*k*=1)	K_C	$u(K_C)$ (*k*=1)	
NIM	0.9670	0.0009	0.9643	0.0010	
LNE	0.9680	0.0030	0.9650	0.0030	
NPL	0.9670	0.0022	0.9642	0.0022	
PTB	0.9658	0.0011	0.9631	0.0011	
UME	0.9679	0.0014	0.9652	0.0016	
KRISS	0.9679	0.0013	0.9656	0.0013	
NIST	0.9669	0.0017	0.9646	0.0017	
KCRV (revised)	0.9670	0.0005	0.9644	0.0005	

| Laboratory | Measurements not used to calculate the KCRV | | | | |
	η_{eff}	$u(\eta_{eff})$ (*k*=1)	K_C	$u(K_C)$ (*k*=1)	Reason for exclusion
SCL	0.9620	0.0140	0.9590	0.0140	Statistical outlier
CMI	0.9629	0.0045	0.9602	0.0045	Traceable to other participant
NMC	0.9878	0.0160	0.9849	0.0158	Traceable to other participant

CCEM.RF-K28.W— RF power from 18 GHz to 26.5 GHz in rectangular waveguide

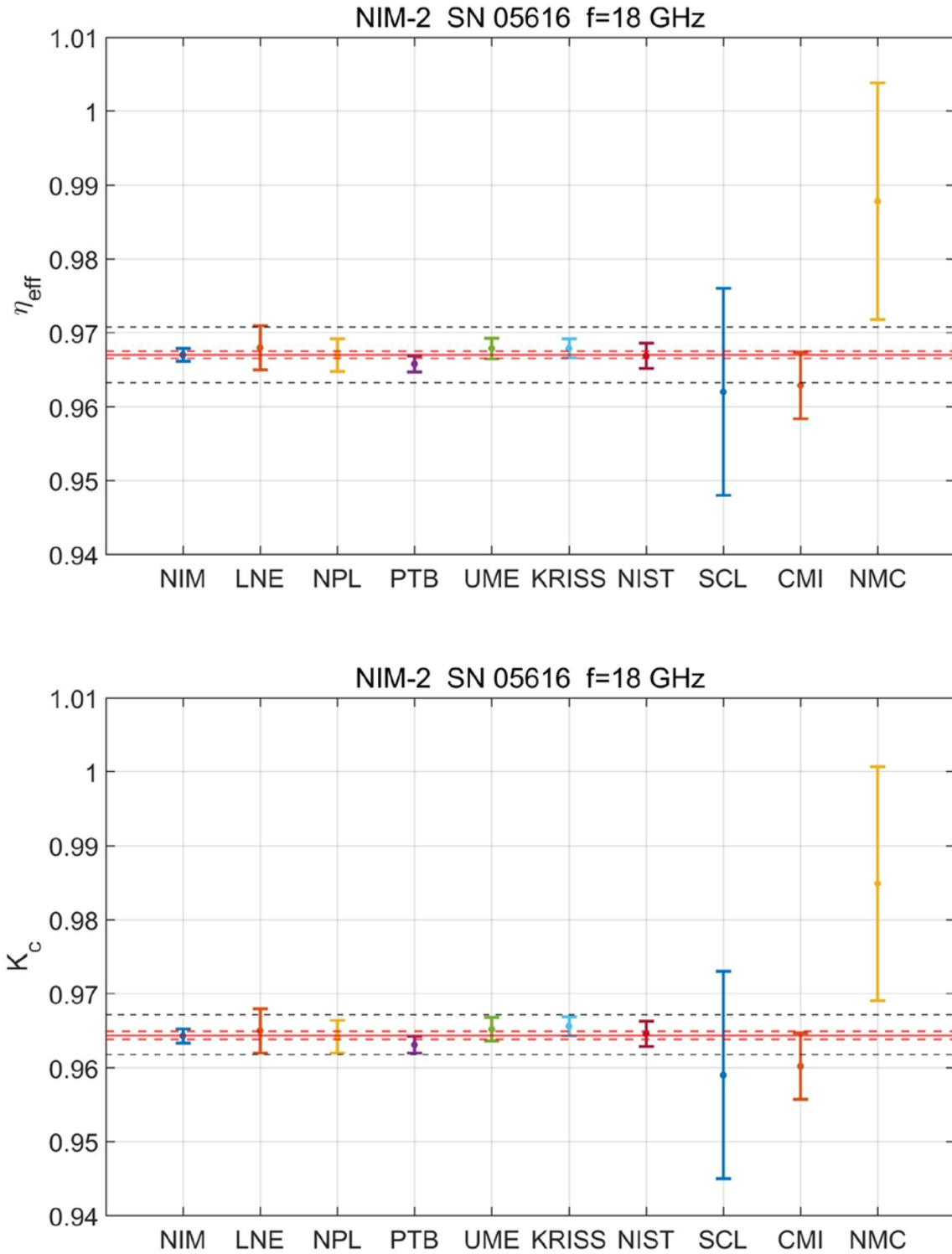
Figure 11. Effective efficiency and calibration factor of travelling standard NIM-2 at 18 GHz. KCRV (—), u(KCRV) (----), outlier boundary (----)（based on revised NPL results）.

Table E.2.2. Measurements and combined standard uncertainties (k=1) of NIM-2 (SN 05616) at **21** GHz

Laboratory	Measurements used to calculate the KCRV				
	η_{eff}	$u(\eta_{eff})$ (k=1)	K_C	$u(K_C)$ (k=1)	
NIM	0.9694	0.0009	0.9337	0.0017	
LNE	0.9690	0.0030	0.9340	0.0030	
NPL	0.9687	0.0013	0.9332	0.0014	
PTB	0.9671	0.0012	0.9302	0.0013	
UME	0.9711	0.0015	0.9352	0.0028	
KRISS	0.9690	0.0012	0.9318	0.0014	
NIST	0.9679	0.0014	0.9312	0.0013	
SCL	0.9710	0.0190	0.9340	0.0170	
KCRV (revised)	0.9689	0.0005	0.9321	0.0006	

Laboratory	Measurements not used to calculate the KCRV				
	η_{eff}	$u(\eta_{eff})$ (k=1)	K_C	$u(K_C)$ (k=1)	Reason for exclusion
CMI	0.9621	0.0055	0.9263	0.0052	Traceable to other participant
NMC	0.9665	0.0198	0.9301	0.0189	Traceable to other participant

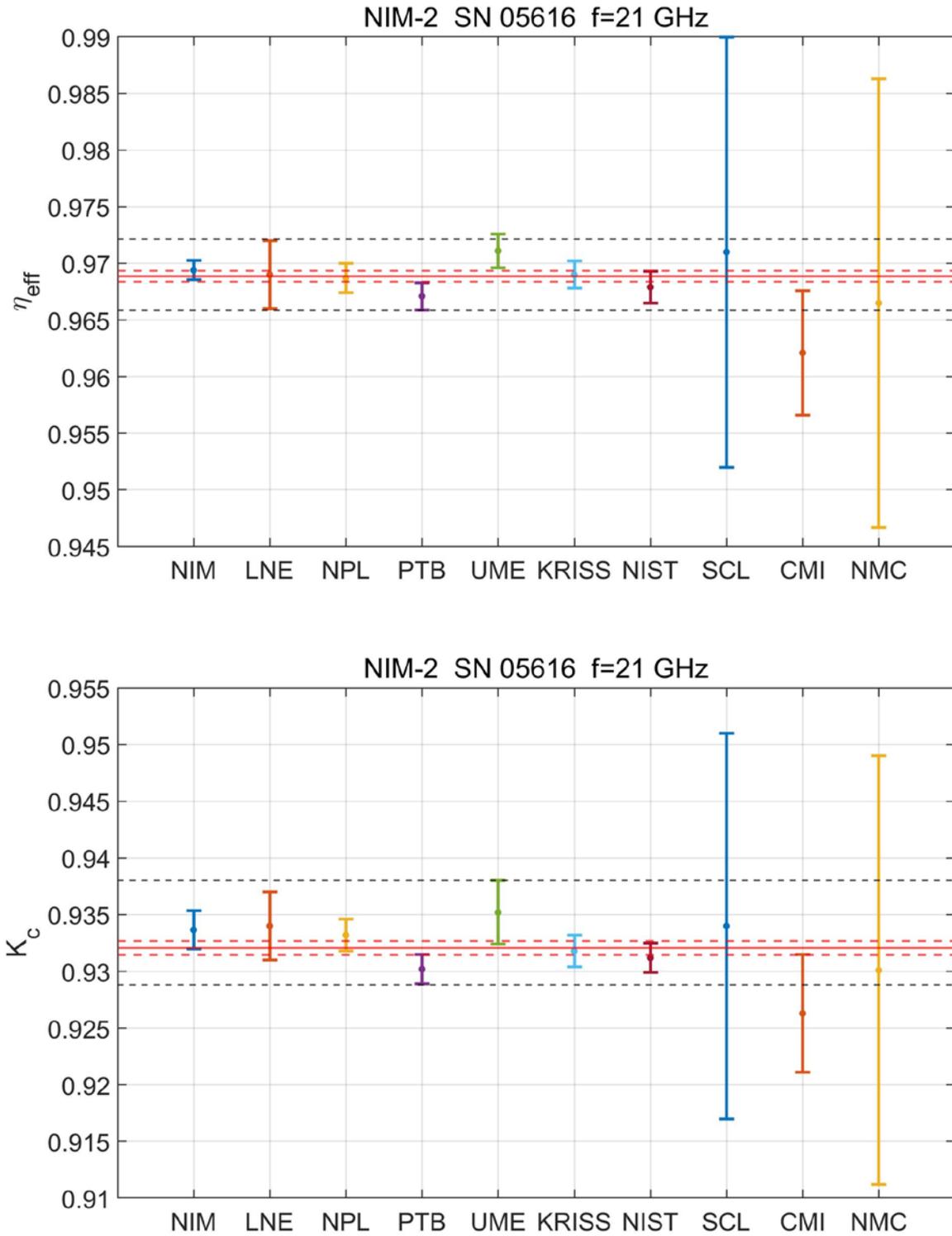*CCEM.RF-K28.W— RF power from 18 GHz to 26.5 GHz in rectangular waveguide*

Figure 12. Effective efficiency and calibration factor of travelling standard NIM-2 at 21 GHz. KCRV (—), u(KCRV) (----), outlier boundary (----)（based on revised NPL results）.

Table E.2.3. Measurements and expanded uncertainties (*k*=1) of NIM-2 (SN 05616) at **24** GHz

Laboratory	Measurements used to calculate the KCRV				
	η_{eff}	$u(\eta_{\text{eff}})$ (*k*=1)	K_{C}	$u(K_{\text{C}})$ (*k*=1)	
NIM	0.9667	0.0009	0.9402	0.0015	
LNE	0.9680	0.0030	0.9410	0.0030	
NPL	0.9665	0.0013	0.9389	0.0014	
PTB	0.9658	0.0011	0.9410	0.0012	
UME	0.9704	0.0015	0.9435	0.0025	
KRISS	0.9679	0.0015	0.9403	0.0016	
NIST	0.9648	0.0020	0.9376	0.0020	
KCRV (revised)	0.9670	0.0005	0.9402	0.0006	

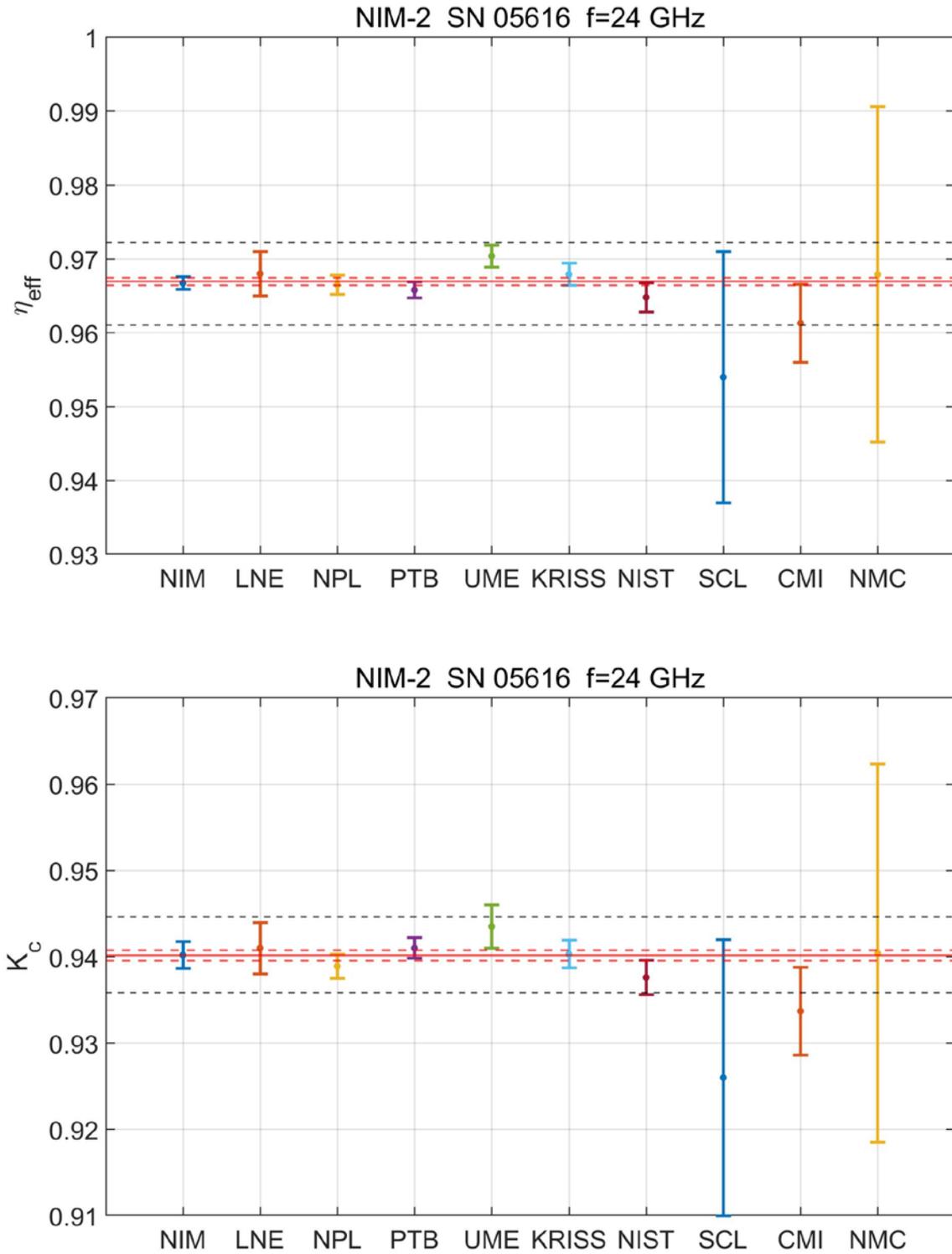| Laboratory	Measurements not used to calculate the KCRV				
	η_{eff}	$u(\eta_{\text{eff}})$ (*k*=1)	K_{C}	$u(K_{\text{C}})$ (*k*=1)	Reason for exclusion
SCL	0.9540	0.0170	0.9260	0.0160	Statistical outlier
CMI	0.9613	0.0053	0.9337	0.0051	Traceable to other participant
NMC	0.9679	0.0227	0.9404	0.0219	Traceable to other participant

Figure 13. Effective efficiency and calibration factor of travelling standard NIM-2 at 24 GHz. KCRV (—),
u(KCRV) (----), outlier boundary (----)（based on revised NPL results）.

Table E.2.4. Measurements and expanded uncertainties (*k*=1) of NIM-2 (SN 05616) at **26.5** GHz

Laboratory	Measurements used to calculate the KCRV				
	η_{eff}	$u(\eta_{eff})$ (*k*=1)	K_C	$u(K_C)$ (*k*=1)	
NIM	0.9626	0.0009	0.9580	0.0010	
LNE	0.9650	0.0030	0.9600	0.0030	
NPL	0.9623	0.0014	0.9573	0.0014	
PTB	0.9609	0.0015	0.9558	0.0015	
UME	0.9655	0.0015	0.9598	0.0017	
KRISS	0.9639	0.0013	0.9578	0.0013	
NIST	0.9599	0.0013	0.9543	0.0014	
SCL	0.9630	0.0250	0.9580	0.0250	
KCRV (revised)	0.9626	0.0005	0.9573	0.0005	

Laboratory	Measurements not used to calculate the KCRV				
	η_{eff}	$u(\eta_{eff})$ (*k*=1)	K_C	$u(K_C)$ (*k*=1)	Reason for exclusion
CMI	0.9570	0.0053	0.9519	0.0053	Traceable to other participant
NMC	0.9591	0.0236	0.9535	0.0234	Traceable to other participant

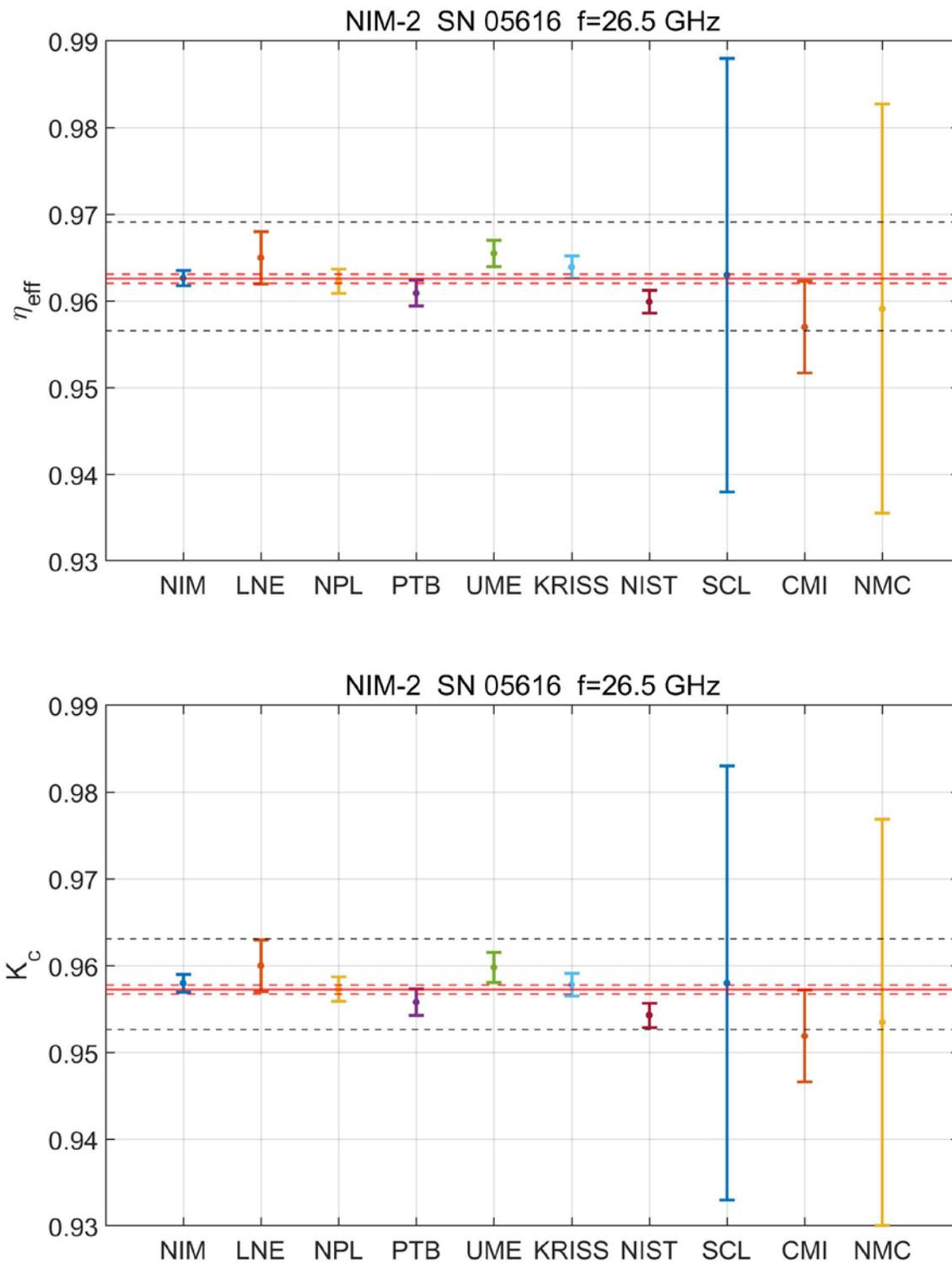Figure 14. Effective efficiency and calibration factor of travelling standard NIM-2 at 26.5 GHz. KCRV (—), u(KCRV) (----), outlier boundary (----)（based on revised NPL results）.