CCEM Key Comparison CCEM.RF-K26

Attenuation at 18 GHz, 26.5 GHz and 40 GHz using a step attenuator

Final Report of the Pilot Laboratory

Anton Widarta

National Metrology Institute of Japan
National Institute of Advanced Industrial Science and Technology
Tsukuba 305-8563
JAPAN

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Abstract

This report summarizes the results of the Key Comparison CCEM.RF-K26 Attenuation at 18 GHz, 26.5 GHz and 40 GHz using a step attenuator which has been performed from January 2015 to February 2018. Fourteen National Metrology Institutes (NMIs) participated in this key comparison, and the Key Comparison Reference Values (KCRVs) were determined from the measurement results of five to ten participating NMIs, depending on the attenuation and frequency.

I. INTRODUCTION

The last Consultative Committee on Electricity and Magnetism (CCEM) on radio frequency attenuation intercomparison between National Metrology Institutions is CCEM-RF-K19.CL, i.e., ‘Attenuation at 60 MHz and 5 GHz using a Type N 50 ohm step attenuator’[1]. However, due to the increasing growth of RF measurement systems such as measuring receivers, spectrum analyzers and vector network analyzers operating beyond 18 GHz, it is necessary to perform a key comparison on radio frequency or microwave attenuation in the frequency range from 18 GHz to 40 GHz or 50 GHz. This frequency range gets a lot of attention recently as it includes spectrum allocated to high band 5G technology as well as to radars used in autonomous vehicles.

Two commercial programmable step attenuators fitted with precision 2.4 mm female connectors were used as traveling standards and measured at 18 GHz, 26.5 GHz, and 40 GHz, i.e., the lower and upper limits of K- and Ka-frequency bands. One of the traveling standards was attached with 10-dB pads on each port in order to obtain measurements with minimal mismatch effects [2][3]. The attenuation measurement values, i.e., 20 dB, 40 dB, 60 dB, 80 dB and 90 dB steps were selected to maximize the potential participants and to permit the participants to demonstrate fully the dynamic range of their measurement facilities.

This Key Comparison was open to all CCEM members and, additionally, Signatories of the Metre Convention. 12 CCEM member laboratories, 1 observer and 1 nonmember participated in this Key Comparison, and the National Metrology Institute of Japan (NMIJ/AIST) served as pilot laboratory which also prepared and provide the travelling standards. Support group members were National Physical Laboratory (NPL), National Institute of Metrology (NIM), National Metrology Centre (NMC-A*STAR), Swiss Federal Office for Metrology and Accreditation (METAS), and Laboratoire national de métrologie et d'essais (LNE), who assisted in reviewing the report.

II. PARTICIPANTS

Anton Widarta
National Metrology Institute of Japan
(NMIJ/AIST)
Tsukuba, **JAPAN**

GAO Qiulai
National Institute of Metrology
(NIM)
Beijing, **CHINA**

Dirk Schubert
Physikalisch-Technische Bundesanstal
(PTB)
Braunschweig, **GERMANY**

Djamel Allal
Laboratoire national de métrologie et d'essais
(LNE)
Trappes, **FRANCE**

Markus Zeier
Swiss Federal Office for Metrology and Accreditation
(METAS)
Bern-Wabern, **SWITZERLAND**

Satya Kesh Dubey
National Physical Laboratory of India
(NPLI)
New Delhi, **INDIA**

Vitaliy Pruglo
All-Russian Scientific Research Institute of Physico-Technical Measurements
(VNIIFTRI)
Mendeleevo, **RUSSIA**

Joo-Gwang Lee
Korea Research Institute of Standard and Science
(KRISS)
Daejeon, **SOUTH KOREA**

John Howes
National Physical Laboratory
(NPL)
Teddington, **UNITED KINGDOM**

Linoh Magagula
National Metrology Institute of South Africa
(NMISA)
Pretoria, **SOUTH AFRICA**

Handan Sakarya
Tubitak Ulusal Metrologi Enstitűsű
(TUBITAK-UME)
Kocaeli, **TURKEY**

Meng Yusong
National Metrology Centre
(NMC-A*STAR)
Singapore**, SINGAPORE**

Karel Drazil
Czech Metrology Institute
(CMI)
Prague, **CZECH REPUBLIC**

Manuel Rodriguez Higuero
Instituto Nacional de Tecnica Aeroespacial
(INTA)
Madrid, **SPAIN**

III. TRAVELLING STANDARDS [4]

Table III-1 details the traveling standards used in this intercomparison. Two programmable step attenuators identified as ATT#1 and ATT#2, fitted with precision 2.4 mm female connectors. Both ports of ATT#2 are attached with 10-dB pads, then they are mounted on an aluminum alloy base. The standards are driven by a control unit which provides both manual and computer control. The travelling standards were circulated among the participants provided with ATA carnet document.

TABLE III-1 TRAVELLING STANDARD DESCRIPTION

Device	Identifier	Manufacturer	Model Number	Serial Number	Attenuation
Step Attenuator	ATT#1	Agilent Technologies	84906L	US42140229	0 to 90 dB in 10 dB steps
Step Attenuator with 10-dB pads	ATT#2	Agilent Technologies	84905M	MY46150135	0 to 60 dB in 10 dB steps
Switch Controller		Agilent Technologies	11713B	MY47361669	

Fig. III-1 Photograph of the traveling standards.

IV. COMPARISON PROTOCOL [4]

A. Incremental Attenuation Measurement

The incremental attenuation [2] in decibels (dB) of the travelling standards from the datum position (0 dB) to the setting value is the primary measurand of this intercomparison. Participants were asked to provide the measurements as indicated in Table IV-1. Table IV-2 shows the controlled switch settings required to set the attenuation step.

TABLE IV-1 ATTENUATION STEP AND FREQUENCY

Device	Attenuation Step [dB]	Frequency [GHz]
ATT#1	0-20, 0-40, 0-60, 0-80, 0-90	18, 26.5, 40
ATT#2	0-20, 0-40, 0-60	18, 26.5, 40

TABLE IV-2 ATTENUATION SETTING OF THE STANDARDS (ATT#1, ATT#2)

Attenuation [dB]	Activated Switch			
	1	2	3	4
0				
20		X		
40	X		X	
60	X	X	X	
80		X	X	X
90	X	X	X	X

B. Reflection Coefficient

The magnitude or complex reflection coefficients of the standards and the measurement system ‘source’ and ‘load’ were requested to be measured for estimating correction and/or uncertainty due to mismatch.

C. Connector Gaging

In order to preserve connector conditions of the standards, center conductor recessions of the standard and the system test port connectors were requested to be measured and recorded. The recession values between (-0.003 to 0.000) inches were recommended for this comparison.

D. Measurement Conditions

1. Room temperature: (23 ± 2) °C
2. Relative humidity: (50 ± 20) %
3. Maximum power incident on the standards: 100 mW.

V. MEASUREMENT DATE AND PROGRESS

TABLE V-1 DATES OF MEASUREMENTS OF THIS INTERCOMPARISON

Laboratory	Date of Measurement	
	Arrival	Dispatch
NMIJ/AIST	10 Jan 2015	03 Feb 2015
NIM	13 Feb 2015	06 Mar 2015
PTB	08 Apr 2015	13 May 2015
LNE	18 May 2015	12 Jun 2015
INTA	16 Jun 2015	07 Jul 2015
METAS	13 Jul 2015	12 Aug 2015
NMISA	17 Aug 2015	07 Sep 2015
CMI	25 Sep 2015	23 Oct 2015
TUBITAK-UME	09 Nov 2015	27 Nov 2015
NMIJ/AIST	10 Dec 2015	18 Feb 2016
NMC-A*STAR	25 Feb 2016	17 Mar 2016
NPLI	25 Apr 2016	18 May 2016
VNIIFTRI	20 Jun 2016	15 Jul 2016
KRISS	15 Nov 2016	10 Jan 2017
NMIJ/AIST	19 Jan 2017	16 May 2017
NPL	23 May 2017	24 Oct 2017
NMIJ/AIST	07 Nov 2017	20 Feb 2018

Measurements were performed at each participant's laboratory between February 2015 and October 2017. Table V-1 shows the date of measurement performed by each participant based on the arrival and dispatch dates of the traveling standards reported to the pilot.

To monitor the stabilities of the traveling standards, NMIJ, as a pilot laboratory, performed measurements to both traveling standards; ATT#1, ATT#2 at the beginning; January 2015 and at the end; February 2018 of this intercomparison as well as when the standards returned to NMIJ at the end of each loop; January 2016 and February 2017.

There was an unexpected problem with the ATT#2 traveling standard as soon as the first loop had been started. One of the 10-dB pads on ATT#2 were not installed properly. NIM informed the pilot that they noticed that connector nut of the 10-dB pad on Port-1 of the ATT#2 was loose or not properly torqued. Although the attenuation values would be change from the initial measured values by the pilot, to ensure further stability of the standard, the pilot decided to ask NIM to properly tighten the connector nut along with adjusting the mounting base before and after tightening as needed. Since the traveling standards were circulated to the participants starting from NIM, these adjustments would not affect other participants. For NMIJ, then the measurements performed on January 2016 would be considered in the results analysis.

Serious problems with the delivery of the traveling standards occurred twice due to the incomplete handling of A.T.A CARNET documents and resulted in the NPL had been unable to take measurements on their original slot as well as on their rescheduled slot. The first was the delivery of the standards from NIM to NPL on March 6, 2015. The standards stuck at Heathrow Airport and finally delivered to NPL on March 31, 2015. However, since NPL was effectively shut down due to the Easter break, they delivered the standards to the next participation laboratory, PTB, without taking measurements to minimize the effect of schedule delays. The second was the delivery of the standards from VNIIFTRI to NPL on July 15, 2016. The standards reached NPL almost 2 months later, and again it was not possible for NPL to take measurements in the remaining time of their rescheduled slot, and then they sent the standards to the next participant laboratory, Nederlands Meetinstituut – Van Swinden Laboratorium (NMi-VSL, the Netherlands). The measurement time slot for NPL was then rescheduled once again at the end of this comparison. These problems were resolved thanks to the hard work of the NPL in processing the A.T.A Carnet documents at the airport, as well as the availability of funds from NPL and NMIJ to cover additional shipping costs incurred.

It could be said that the participants were able to complete their measurements within a three-week timescale, as specified in the protocol. However, it turned out that one week was too short for delivering the traveling standards with an A.T.A. CARNET document attached.

As soon as these measurements were completed, Dr. Widarta of the pilot was assigned to another department and eventually returned to his lab in March 2021, that resulting in a major delay in this reporting.

In accordance with '*Measurement Comparisons in the CIPM MRA*' [5] which serves as a guideline for the conduction of any CIPM Intercomparison Project, it is stated "If, on examination of the complete set of results, the pilot institute finds results that appear to be anomalous, the corresponding participating institutes are invited to check their results for numerical errors but without being informed of the magnitude or sign of the apparent anomaly. If no numerical error is found, the result stands and the complete set is sent in a report to all participants according to Section 8.2". For this report, the pilot laboratory failed to inform participants of potentially anomalous results before the release of draft A. This provided no opportunity for the respective participants to detect errors and resubmit corrected results or withdraw from this comparison once the results had been received by the pilot laboratory.

NMi-VSL withdraw from this comparison after their measurement results, taken from 21 September to 7 November 2016, indicated technical problems that prevented them from being able to submit any of their results to the pilot laboratory for the intercomparison. Hellenic Institute of Metrology (EIM-Greece) and National Institute for Standards (NIS-Egypt) withdrew from this comparison before taking measurements.

METAS results for traveling standard ATT#1 at 60 dB are off but could be ascertained due to the laboratory used the wrong combination of attenuation sections (30 dB+30 dB instead of 10 dB+20 dB+30 dB). The result is therefore not representative for their measurement capabilities. This can be seen from the result for ATT#2 at 60 dB, which is compliant with the key comparison reference value.

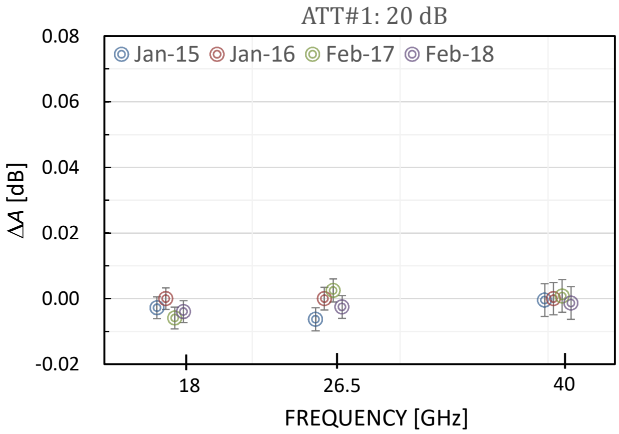
VI. SUMMARY OF MEASUREMENT TECHNIQUES

TABLE VI-1 SUMMARY OF THE MEASUREMENT TECHNIQUES USED BY EACH PARTICIPANT

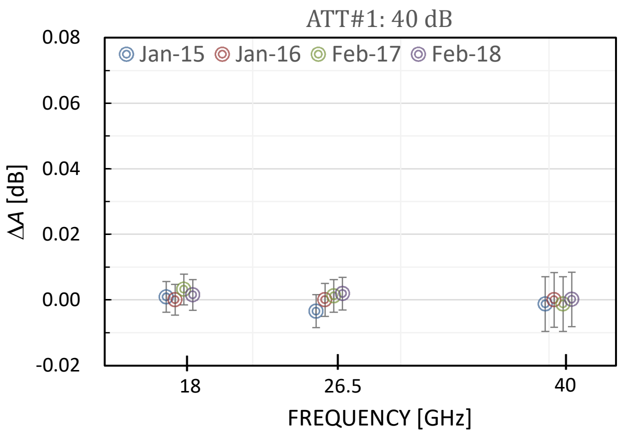
Laboratory	Method	Standard	Source of traceability
NMIJ	IF substitution	IF attenuator standard	LF voltage ratio (NMIJ)
NIM	AF substitution	Inductive voltage divider	LF voltage ratio (NIM)
PTB	DC substitution (to 30 dB) RF series substitution (above 30 dB)	Thermistor mount Reference attenuator	DC voltage (PTB)
LNE	IF substitution	WBCO attenuator	Length (LNE)
INTA	Measuring Receiver	Step attenuator	Attenuation (NIST, NPL)
METAS	VNA	Airlines, Offset-Shorts, Flush-Shorts, WBCO attenuator	Dimensional, material, and electrical properties (METAS)
NMISA	VNA	WBCO attenuator	Overseas NMI (NPL)
CMI	SA (to 26.5 GHz) VNA (40 GHz)	Step attenuator	DC Voltage (CMI)
TUBITAK-UME	VNA	VNA Verification Kit	Overseas NMI (NPL)
NMC-A*STAR	AF Substitution	Inductive voltage divider	LF voltage ratio (NPL)
NPLI	IF substitution	WBCO attenuator	Length (NPLI)
VNIIFTRI	IF substitution	Inductive voltage divider	LF voltage ratio (VNIIFTRI)
KRISS	RF series substitution	RF attenuation standard	DC Voltage (KRISS)
NPL	Voltage ratio / AF substitution	Inductive voltage divider	LF voltage ratio (NPL)

Table VI-1 gives a summary of the measurement techniques employed by each participant. A full description of the methods, as provided by each participant, can be found in Appendix B.

VII. Stability of the Traveling Standards



(a)



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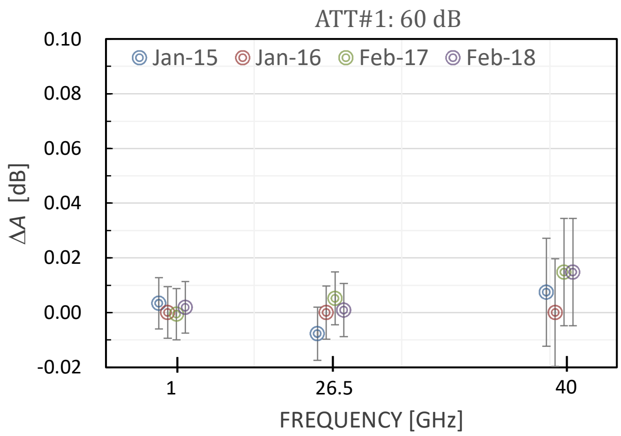
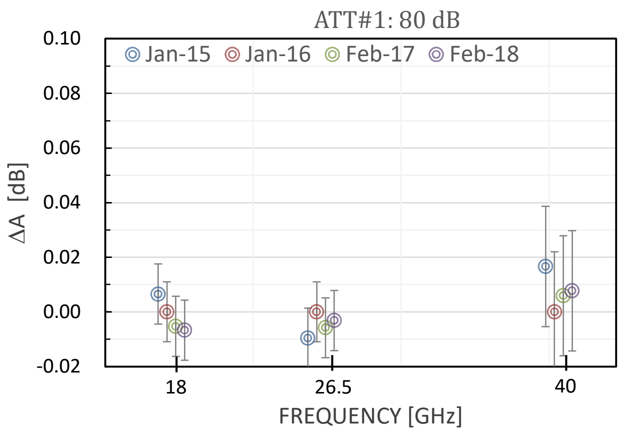
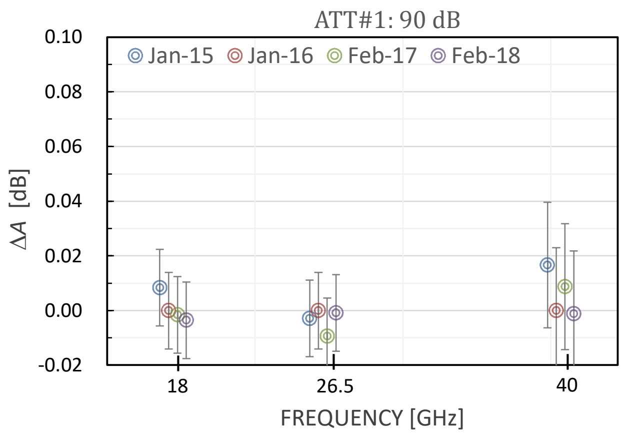


(c)

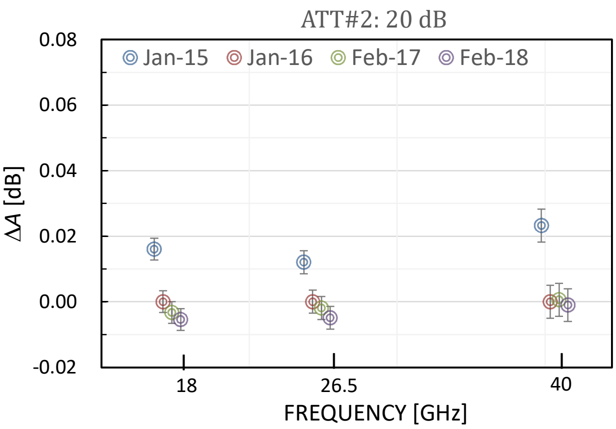


(d)

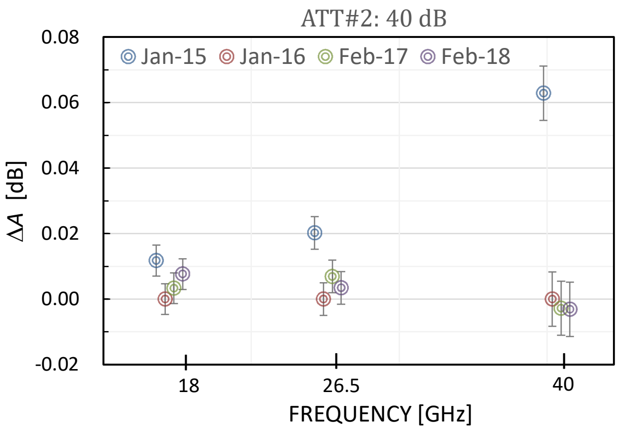


(f)

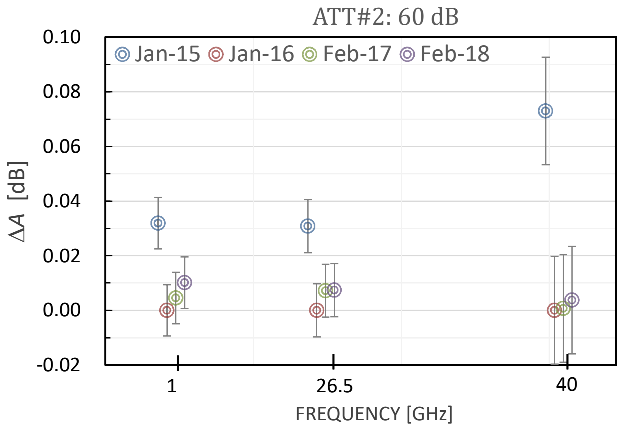
Fig.VII-1. Pilot laboratory measurements of incremental attenuation of the traveling standard ATT#1 (SN: US42140229): (a) 20 dB, (b) 40 dB, (c) 60 dB, (d) 80 dB, (e) 90 dB. The measured attenuation values are normalized to the measured values in January 2016.



(a)



(b)



(c)

Fig. VII-2. Pilot laboratory measurement of incremental attenuation of the traveling standard ATT#2 (SN: MY46150135): (a) 20 dB, (b) 40 dB, (c) 60 dB. The measured attenuation values are normalized to the measured values in January 2016. For visualization purposes, the deviations of the January 2015 are displayed in $\Delta A/8$.

To monitor the stability or shift in values versus time, NMIJ as a pilot laboratory took measurements to both traveling standards four times, i.e., at the beginning (January 2015) and at the end (February 2018) of this comparison, as well as when the standards returned to NMIJ at each end of the loop (January 2016 and February 2017).

Fig. VII-1 shows measurement results of the ATT#1 traveling standard of each incremental attenuation setting, i.e., 20 dB, 40 dB, 60 dB, 80 dB and 90 dB at frequency of 18 GHz, 26.5 GHz, and 40 GHz, respectively. The measured attenuation values are normalized to the ones measured in January 2016 and displayed as deviation (ΔA) in decibels as shown on y-axis. Slight differences or variations in the results were observed, but still within the combined standard uncertainty (k = 1) as indicated by the vertical error bars and did not show significant changes versus time. Therefore, any one of these measurements is sufficient to be included in the calculation of the Key Comparison Reference Values (KCRVs) of the travelling standard ATT#1. In this case, only measurements performed in January 2016 were reported as the NMIJ measurements. Uncertainty due to this variation is then combined into the uncertainty of the KCRV. The details are given as described in Appendix A.

For the traveling standard ATT#2, as shown in Fig. VII-2(a), (b), (c), the initial measurements of January 2015 differed significantly from others, with the maximum difference was 0.58 dB at the 60 dB measurement at 40 GHz. This is due to a change in the assembly condition of the standard ATT#2, where the 10-dB pad on port 1 has been properly re-tightened, followed by re-mounting of the standard to the base as described in section V above. For visualization purposes, the deviations of the January 2015 are displayed in $\Delta A/8$. After this adjustment, the results were stable, no significant shift values versus time. Since this adjustment was made at the first participant's place, then it did not affect other participants. For NMIJ, then measurements performed on January 2016 were reported to include in the calculation of the KCRVs of the travelling standard ATT#2. Uncertainty due to this variation is treated in the same manner as for the ATT#1.

VIII. KEY COMPARISON RESULTS AND DISCUSSION

The measured incremental attenuations from the datum position (0 dB) to 20 dB, 40 dB, 60 dB, 80 dB and 90 dB of the traveling standard ATT#1 and to 20 dB, 40 dB, 60 dB of the traveling standard ATT#2 at frequency of 18 GHz, 26.5 GHz, and 40 GHz, respectively, were reported by the fourteen participating NMIs. Some participants were unable to report a particular attenuation due to their measurement system capabilities or other technical reasons. The reports also included estimates of the Type A and Type B uncertainties and the combined standard uncertainty (at one standard deviation, k=1). All uncertainty budgets provided by the participants can be found in Appendix C.

The measurement results and associated standard uncertainties together with the reference values (KCRVs) and associated standard uncertainties (rounded to three decimal places) can be found in Tables VIII-1 to VIII-24. Each table is followed by a graphical illustration of the reported results and the corresponding KCRV, as on Figures VIII-1 to VIII-24. Results from participants with traceability to other/overseas laboratories were not used to calculate the KCRV. Identification of statistical outliers was examined by the Median of Absolute Deviations (MAD) method [6],[7]. After calculating each KCRV and its standard uncertainty, the Chi-squared test was applied to verify the consistency of the data. Further outlier identification was performed on the failed test results [7],[8]. Details on these evaluation methods can be found in Appendix A. The statistical outlier boundary lines by the MAD method are plotted as dashed black lines. The measurements which finally used to determine the KCRV are indicated by the filled diamond markers.

Among the NMIs whose results were used to calculate the KCRV, the majority used the dedicated attenuation measurement systems, e.g., IF/RF substitution, voltage ratio, etc., while METAS, for all measurements and CMI, for measurements at 40 GHz used commercial VNAs but with comparable reporting uncertainties. However, the results reported by METAS for attenuation steps of 40 dB and higher, were not obtained by means of normal attenuation measurements, but rather by calculations utilizing the S-parameter measurements of the 0 dB, 10 dB, 20 dB, and 30 dB attenuator sections of the traveling standards.

Figure VIII-25 shows the percentage of statistical outliers by the MAD method of the participants included in the KCRV calculations. The total average for ATT#1 was about 22%. For comparison, the average total in CCEM-RF-K19.CL was less than 10%. This can be considered due to the significant increase of the frequency measurements in this intercomparison. However, the total average for ATT#2 was about 11% comparable to the CCEM-RF-K19.CL. It can be said that this proves the effectiveness of attaching 10-dB pads on both ports of ATT#2, which minimized the mismatch errors which tend to increase with increasing frequency.

Degree of equivalence with respect to the key comparison reference value (KCRV) can be found in Tables IX-1 to IX-24, followed by a graphical illustration as on Figures IX-1 to IX-24. While, both degree of equivalences with respect to the reference value and between each of the laboratories can be found in Tables A-1 to A-24.

Appendix A describes the methods used to determine the key comparison reference value (KCRV), and its associated uncertainty, along with the degrees of equivalence with respect to the reference value.

All uncertainty budgets provided by the participants can be found in Appendix C.

A. Results for Travelling Standard ATT#1 (US42140229)

TABLE VIII-1 MEASUREMENTS AND COMBINED STANDARD UNCERTAINTIES (k=1) OF 20 dB INCREMENTAL ATTENUATION OF ATT#1 AT 18 GHz.

Lab_i	Measurements used to calculate the KCRV	
	A_{20_i} (dB)	$u(A_{20\_i})$ (dB)
NMIJ/AIST	19.930	0.003
NIM	19.936	0.003
PTB	19.933	0.003
LNE	19.940	0.010
METAS	19.938	0.005
CMI	19.940	0.017
KRISS	19.933	0.006
Instability of ATT#1 $u(ATT\#1_{\_20})$ (dB)		0.002
KCRV	A_{20_R} (dB)	$u(A_{20\_R})$ (dB)
	19.934	0.003

Lab_i	Measurements not used to calculate the KCRV		
	A_{20_i} (dB)	$u(A_{20\_i})$(dB)	Reason for exclusion
INTA	19.940	0.026	Traceable to other NMI
NMISA	19.931	0.008	Traceable to other NMI
TUBITAK-UME	19.926	0.013	Traceable to other NMI
NMC-A*STAR	19.937	0.002	Traceable to other NMI
NPLI	19.993	0.018	Statistical outlier
VNIIFTRI	19.960	0.020	Statistical outlier
NPL	19.654	0.002	Statistical outlier

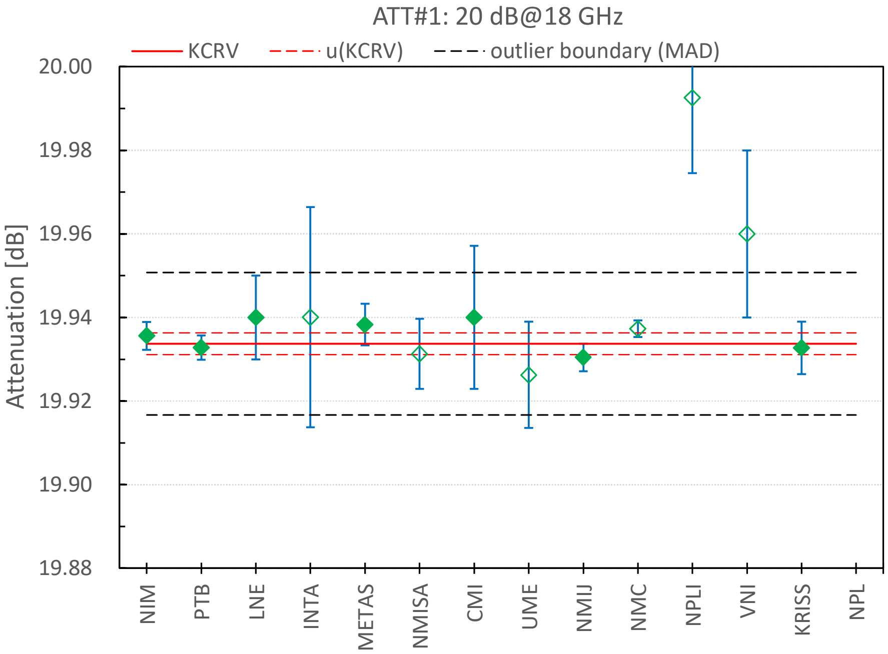


Fig.VIII-1. 20 dB incremental attenuation of ATT#1 at 18 GHz. The filled markers indicate the measurements used to determine the KCRV. Note: A_{20_NPL} = 19.654 dB, $u(A_{20\_NPL})$ = 0.002 dB.

TABLE VIII-2 MEASUREMENTS AND COMBINED STANDARD UNCERTAINTIES (k=1) OF 20 dB INCREMENTAL ATTENUATION OF ATT#1 AT 26.5 GHz.

Lab_i	Measurements used to calculate the KCRV	
	A_{20_i} (dB)	$u(A_{20\_i})$ (dB)
NMIJ/AIST	19.926	0.004
NIM	19.927	0.005
PTB	19.921	0.006
LNE	19.930	0.010
METAS	19.933	0.005
CMI	19.922	0.018
NPLI	19.924	0.017
VNIIFTRI	19.932	0.026
KRISS	19.906	0.008
NPL	19.938	0.010
Instability of ATT#1	$u(ATT\#1_{20})$ (dB)	0.003
KCRV	A_{20_R} (dB)	$u(A_{20\_R})$ (dB)
	19.926	0.003

Lab_i	Measurements not used to calculate the KCRV		
	A_{20_i} (dB)	$u(A_{20\_i})$ (dB)	Reason for exclusion
INTA	19.931	0.024	Traceable to other NMI
NMISA	19.916	0.008	Traceable to other NMI
TUBITAK-UME	19.920	0.015	Traceable to other NMI
NMC-A*STAR	19.932	0.004	Traceable to other NMI

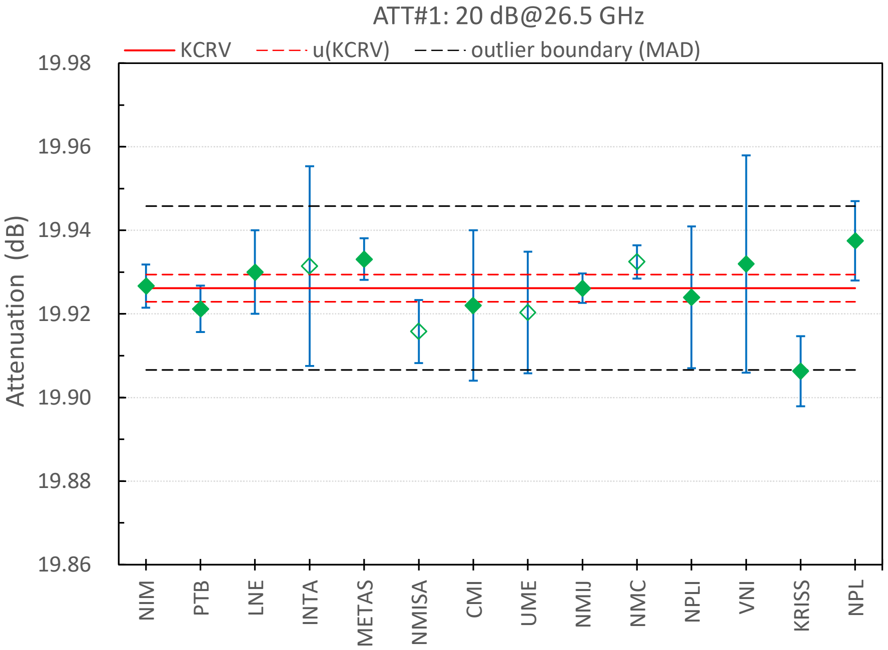


Fig. VIII-2. 20 dB incremental attenuation of ATT#1 at 26.5 GHz. The filled markers indicate the measurements used to determine the KCRV.

TABLE VIII-3 MEASUREMENTS AND COMBINED STANDARD UNCERTAINTIES (k=1) OF 20 dB INCREMENTAL ATTENUATION OF ATT#1 AT 40 GHz.

Lab_i	Measurements used to calculate the KCRV	
	A_{20_i} (dB)	$u(A_{20\_i})$ (dB)
NMIJ/AIST	19.875	0.005
NIM	19.875	0.007
PTB	19.868	0.010
LNE	19.870	0.020
METAS	19.881	0.005
CMI	19.872	0.023
VNIIFTRI	19.876	0.021
KRISS	19.876	0.014
Instability of ATT#1 $u(ATT\#1_{\_20})$ (dB)		0.001
KCRV	A_{20_R} (dB)	$u(A_{20\_R})$ (dB)
	19.876	0.003

Lab_i	Measurements not used to calculate the KCRV		
	A_{20_i} (dB)	$u(A_{20\_i})$ (dB)	Reason for exclusion
INTA	19.850	0.070	Traceable to other NMI
NMISA	19.869	0.010	Traceable to other NMI
TUBITAK-UME	19.866	0.022	Traceable to other NMI
NMC-A*STAR	Not provided	Not provided	Not provided
NPLI	19.907	0.019	Statistical outlier
NPL	19.464	0.008	Statistical outlier

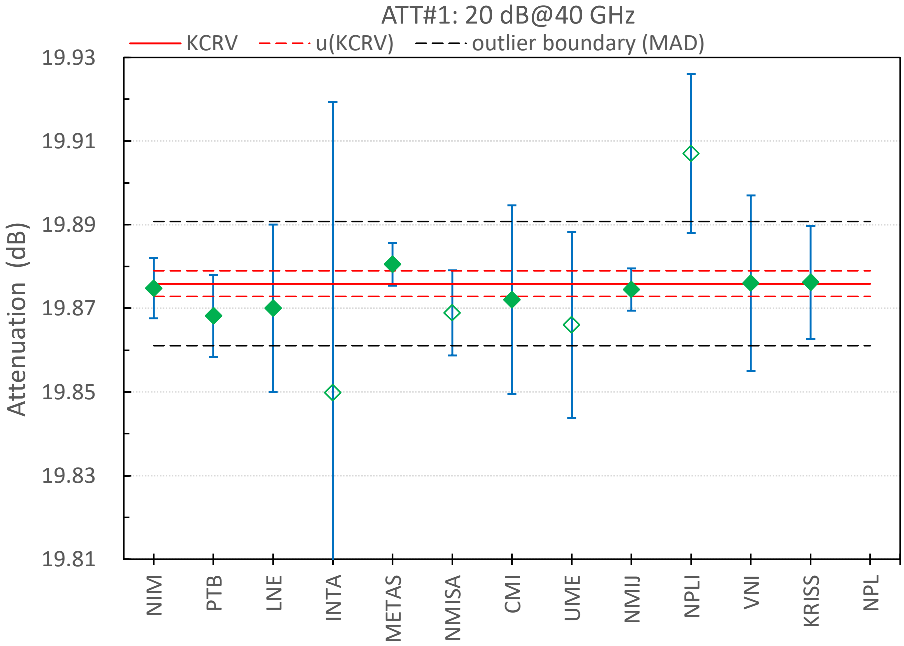


Fig. VIII-3. 20 dB incremental attenuation of ATT#1 at 40 GHz. The filled markers indicate the measurements used to determine the KCRV. Note: A_{20_NPL} = 19.464 dB, $u(A_{20\_NPL})$ = 0.008 dB.

TABLE VIII-4 MEASUREMENTS AND COMBINED STANDARD UNCERTAINTIES (k=1) OF 40 dB INCREMENTAL ATTENUATION OF ATT#1 AT 18 GHz

Lab$_i$	Measurements used to calculate the KCRV	
	A_{40_i} (dB)	$u(A_{40\_i})$ (dB)
NMIJ/AIST	39.961	0.005
NIM	39.969	0.004
PTB	39.957	0.012
LNE	39.980	0.040
METAS	39.959	0.009
CMI	39.947	0.023
KRISS	39.956	0.007
Instability of ATT#1 $u(ATT\#1\_{40})$ (dB)		0.002
KCRV	A_{40_R} (dB)	$u(A_{40\_R})$ (dB)
	39.964	0.003

Lab_i	Measurements not used to calculate the KCRV		
	A_{40_i} (dB)	$u(A_{40\_i})$ (dB)	Reason for exclusion
INTA	39.961	0.032	Traceable to other NMI
NMISA	39.937	0.015	Traceable to other NMI
TUBITAK-UME	39.957	0.013	Traceable to other NMI
NMC-A*STAR	39.958	0.004	Traceable to other NMI
NPLI	40.006	0.029	Statistical outlier
VNIIFTRI	39.819	0.030	Statistical outlier
NPL	39.775	0.003	Statistical outlier

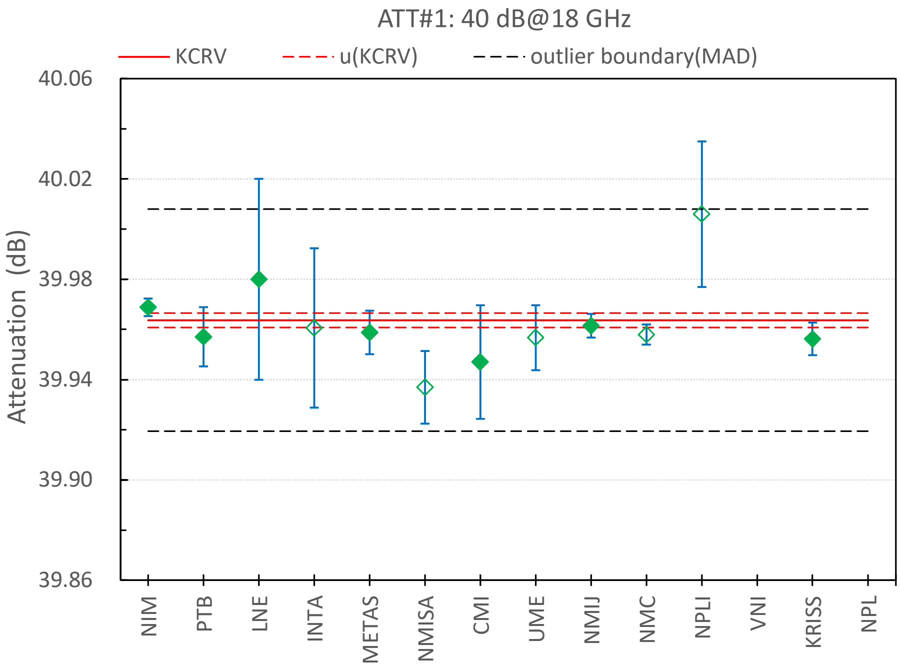


Fig. VIII-4. 40 dB incremental attenuation of ATT#1 at 18 GHz. The filled diamond markers indicate the measurements used to determine the KCRV. Note: A_{40_VNI} = 39.819 dB, $u(A_{40\_VNI})$ = 0.030 dB. A_{40_NPL} = 39.775 dB, $u(A_{40\_NPL})$ = 0.003 dB.

TABLE VIII-5 MEASUREMENTS AND COMBINED STANDARD UNCERTAINTIES (k=1) OF 40 dB INCREMENTAL ATTENUATION OF ATT#1 AT 26.5 GHz

Lab_i	Measurements used to calculate the KCRV	
	A_{40_i} (dB)	$u(A_{40\_i})$ (dB)
NMIJ/AIST	40.045	0.005
NIM	40.057	0.005
PTB	40.023	0.019
LNE	40.060	0.040
METAS	40.044	0.009
CMI	40.036	0.024
NPLI	40.033	0.030
VNIIFTRI	40.047	0.031
KRISS	40.036	0.010
NPL	40.067	0.019
Instability of ATT#1	$u(ATT\#1\_{40})$ (dB)	0.001
KCRV	A_{40_R} (dB)	$u(A_{40\_R})$ (dB)
	40.048	0.003

Lab_i	Measurements not used to calculate the KCRV		
	A_{40_i} (dB)	$u(A_{40\_i})$ (dB)	Reason for exclusion
INTA	40.038	0.031	Traceable to other NMI
NMISA	40.033	0.014	Traceable to other NMI
TUBITAK-UME	40.031	0.016	Traceable to other NMI
NMC-A*STAR	40.045	0.005	Traceable to other NMI

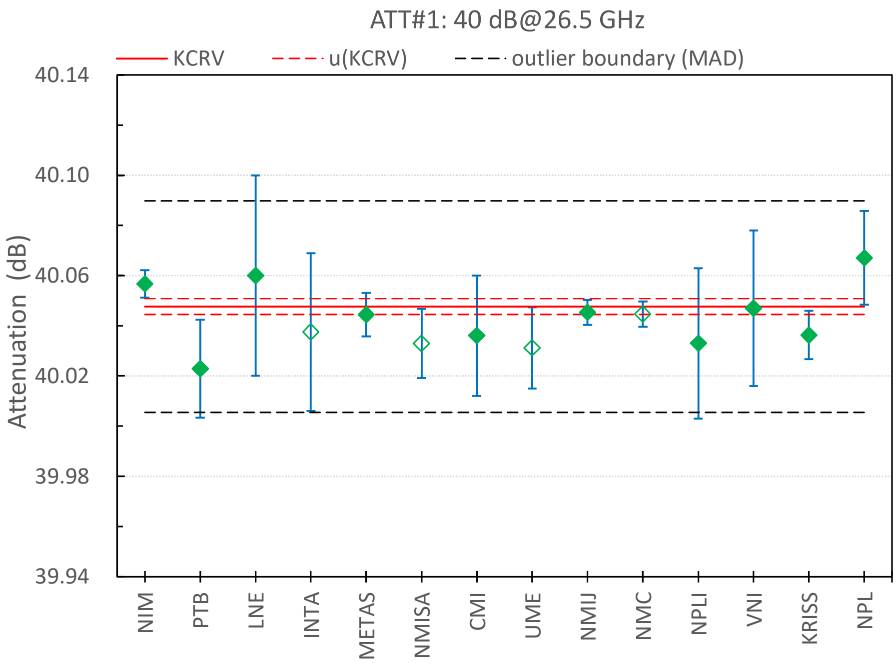


Fig. VIII-5. 40 dB incremental attenuation of ATT#1 at 26.5 GHz. The filled diamond markers indicate the measurements used to determine the KCRV.

TABLE VIII-6 MEASUREMENTS AND COMBINED STANDARD UNCERTAINTIES (k=1) OF 40 dB INCREMENTAL ATTENUATION OF ATT#1 AT 40 GHz

Lab_i	Measurements used to calculate the KCRV	
	A_{40_i} (dB)	$u(A_{40\_i})$ (dB)
NMIJ/AIST	40.254	0.008
NIM	40.260	0.008
PTB	40.241	0.021
LNE	40.260	0.05
METAS	40.240	0.009
CMI	40.233	0.043
VNIIFTRI	40.246	0.027
KRISS	40.271	0.016
Instability of ATT#1	$u(ATT\#1_{\_40})$ (dB)	0.001
KCRV	$A4_{0\_R}$ (dB)	$u(A4_{0\_R})$ (dB)
	40.252	0.005

Lab_i	Measurements not used to calculate the KCRV		
	A_{40_i} (dB)	$u(A_{40\_i})$ (dB)	Reason for exclusion
INTA	40.236	0.075	Traceable to other NMI
NMISA	40.237	0.016	Traceable to other NMI
TUBITAK-UME	40.222	0.028	Traceable to other NMI
NMC-A*STAR	Not provided	Not provided	Not provided
NPLI	40.299	0.051	Statistical outlier
NPL	39.833	0.017	Statistical outlier)

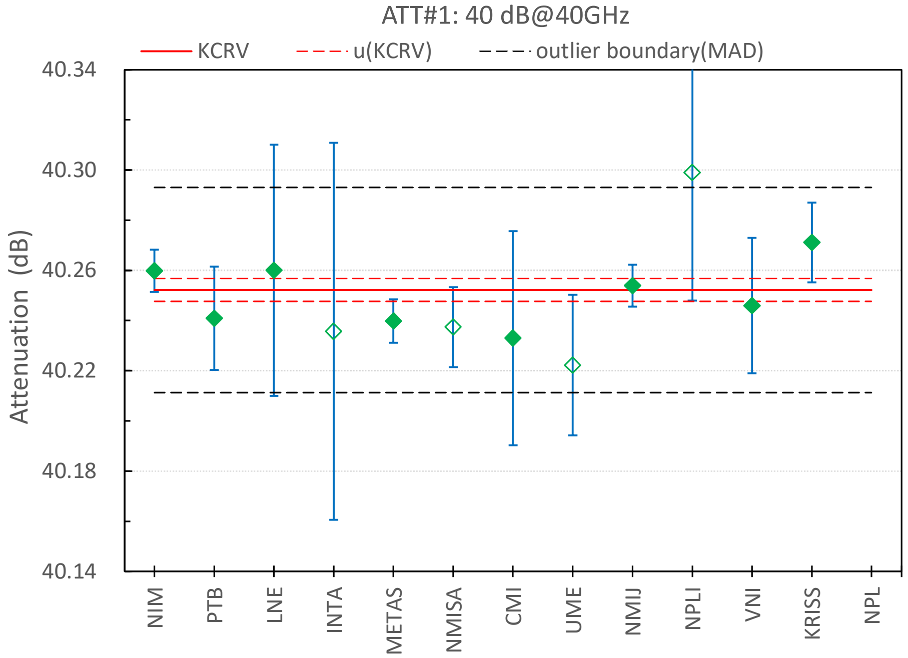


Fig. VIII-6. 40 dB incremental attenuation of ATT#1 at 40 GHz. The filled markers indicate the measurements used to determine the KCRV. Note: A_{40_NPL} = 39.833 dB, $u(A_{40\_NPL})$ = 0.017 dB.

TABLE VIII-7 MEASUREMENTS AND COMBINED STANDARD UNCERTAINTIES (k=1) OF 60 dB INCREMENTAL ATTENUATION OF ATT#1 AT 18 GHz

Lab_i	Measurements used to calculate the KCRV	
	A_{60_i} (dB)	$u(A_{60\_i})$ (dB)
NMIJ/AIST	59.894	0.009
NIM	59.904	0.005
LNE	59.900	0.040
CMI	59.891	0.029
VNIIFTRI	59.910	0.035
KRISS	59.892	0.007
Instability of ATT#1 $u(ATT\#1_{\_60})$ (dB)		0.001
KCRV	A_{60_R} (dB)	$u(A_{60\_R})$ (dB)
	59.900	0.004

Lab_i	Measurements not used to calculate the KCRV		
	A_{60_i} (dB)	$u(A_{60\_i})$ (dB)	Reason for exclusion
INTA	59.891	0.043	Traceable to other NMI
NMISA	59.881	0.080	Traceable to other NMI
TUBITAK-UME	59.897	0.014	Traceable to other NMI
NMC-A*STAR	59.893	0.004	Traceable to other NMI
PTB	59.981	0.010	Statistical outlier
METAS	60.169	0.009	Statistical outlier*
NPLI	60.026	0.046	Statistical outlier
NPL	59.668	0.005	Statistical outlier

* Wrong configuration, see note section V.

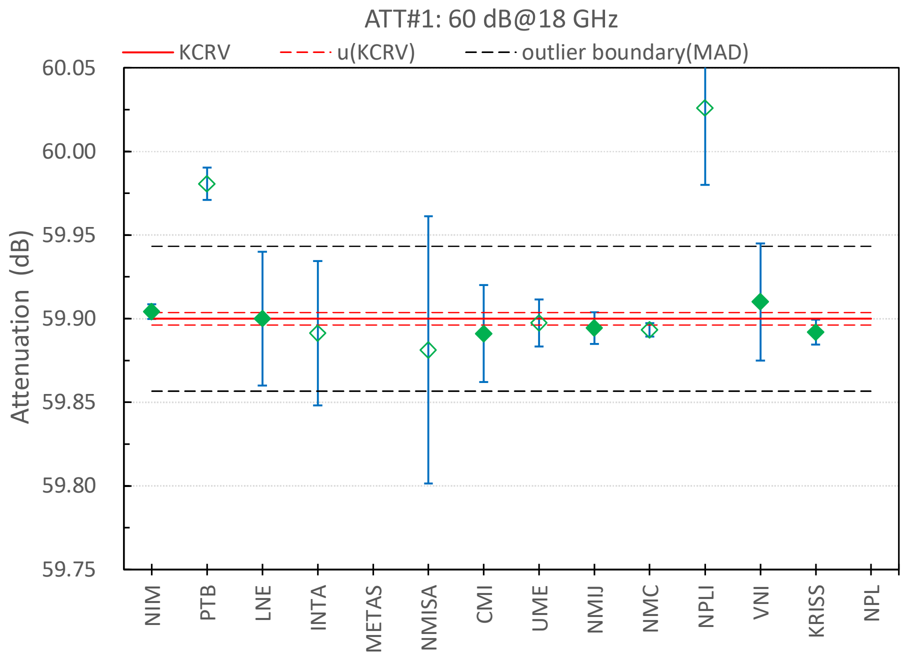


Fig. VIII-7. 60 dB incremental attenuation of ATT#1 at 18 GHz. The filled markers indicate the measurements used to determine the KCRV. Note: *A_{60_METAS} = 60.169 dB, $u(A_{60\_METAS})$ = 0.009 dB. A_{60_NPL} = 59.668 dB, $u(A_{60\_NPL})$ = 0.005 dB. *Wrong configuration, see note section V.

TABLE VIII-8 MEASUREMENTS AND COMBINED STANDARD UNCERTAINTIES (k=1) OF 60 dB INCREMENTAL ATTENUATION OF ATT#1 AT 26.5 GHz

Lab_i	Measurements used to calculate the KCRV	
	A_{60_i} (dB)	$u(A_{60\_i})$ (dB)
NMIJ/AIST	59.976	0.010
NIM	59.987	0.006
PTB	59.961	0.011
LNE	60.000	0.040
CMI	59.980	0.031
VNIIFTRI	59.961	0.038
KRISS	59.969	0.010
Instability of ATT#1	$u(ATT\#1_{\_60})$ (dB)	0.003
KCRV	A_{60_R} (dB)	$u(A_{60\_R})$ (dB)
	59.979	0.005

Lab_i	Measurements not used to calculate the KCRV		
	A_{60_i} (dB)	$u(A_{60\_i})$ (dB)	Reason for exclusion
INTA	59.991	0.045	Traceable to other NMI
NMISA	59.978	0.082	Traceable to other NMI
TUBITAK-UME	59.972	0.016	Traceable to other NMI
NMC-A*STAR	59.981	0.005	Traceable to other NMI
METAS	60.251	0.009	Statistical outlier*
NPLI	60.072	0.045	Statistical outlier
NPL	60.120	0.028	Statistical outlier

*Wrong configuration, see note section V.

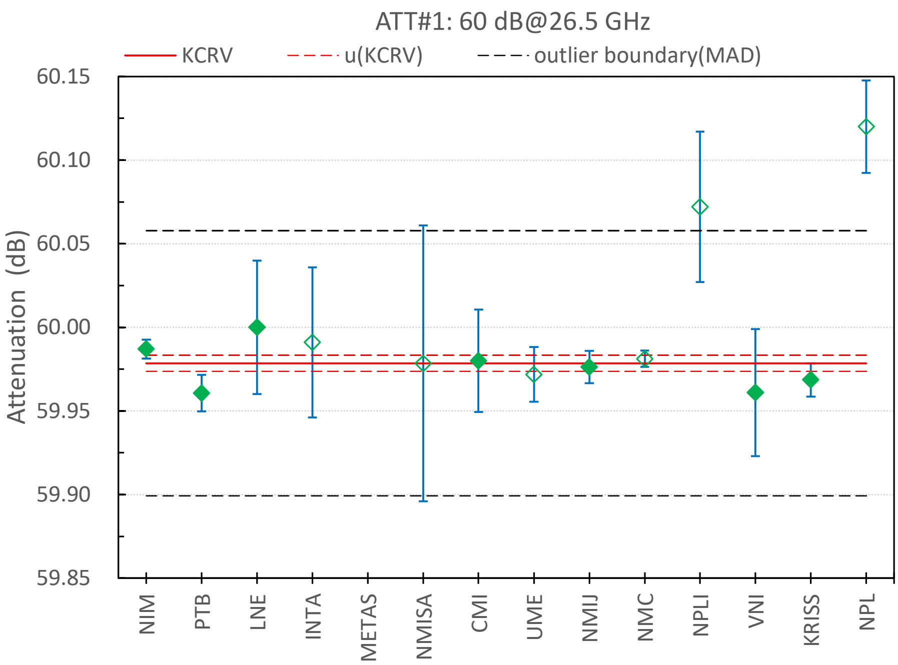


Fig. VIII-8. 60 dB incremental attenuation of ATT#1 at 26.5 GHz. The filled markers indicate the measurements used to determine the KCRV. Note: *A_{60_METAS} = 60.251, $u(A_{60\_METAS})$ = 0.009 dB. *Wrong configuration, see note section V.

TABLE VIII-9 MEASUREMENTS AND COMBINED STANDARD UNCERTAINTIES (k=1) OF 60 dB INCREMENTAL ATTENUATION OF ATT#1 AT 40 GHz

Lab_i	Measurements used to calculate the KCRV	
	A_{60_i} (dB)	$u(A_{60\_i})$ (dB)
NMIJ/AIST	60.097	0.020
NIM	60.099	0.008
PTB	60.045	0.027
LNE	60.110	0.050
CMI	60.079	0.062
VNIIFTRI	60.130	0.035
KRISS	60.081	0.014
Instability of ATT#1	$u(ATT\#1_{\_60})$ (dB)	0.003
KCRV	A_{60_R} (dB)	$u(A_{60\_R})$ (dB)
	60.094	0.007

Lab_i	Measurements not used to calculate the KCRV		
	A_{60_i} (dB)	$u(A_{60\_i})$ (dB)	Reason for exclusion
INTA	60.067	0.075	Traceable to other NMI
NMISA	60.055	0.086	Traceable to other NMI
TUBITAK-UME	60.072	0.027	Traceable to other NMI
NMC-A*STAR	Not provided	Not provided	Not provided
METAS	60.449	0.009	Statistical outlier*
NPLI	60.558	0.059	Statistical outlier)
NPL	59.622	0.024	Statistical outlier

* Wrong configuration, see note section V.

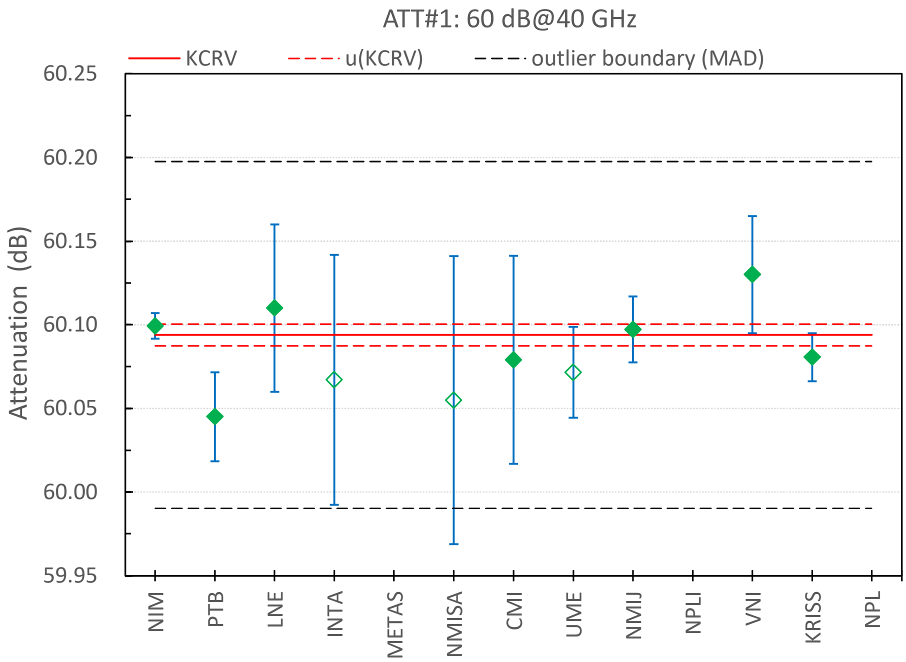


Fig. VIII-9. 60 dB incremental attenuation of ATT#1 at 40 GHz. The filled markers indicate the measurements used to determine the KCRV. Note: *A_{60_METAS} = 60.449 dB, $u(A_{60\_METAS})$ = 0.009 dB. A_{60_NPLI} = 60.558 dB, $u(A_{60\_NPLI})$ = 0.059 dB. A_{60_NPL} = 59.662 dB, $u(A_{60\_NPL})$ = 0.024 dB. *Wrong configuration, see note section V.

TABLE VIII-10 MEASUREMENTS AND COMBINED STANDARD UNCERTAINTIES (k=1) OF 80 dB INCREMENTAL ATTENUATION OF ATT#1 AT 18 GHz

Lab_i	Measurements used to calculate the KCRV	
	A_{80_i} (dB)	$u(A_{80\_i})$ (dB)
NMIJ/AIST	80.095	0.011
NIM	80.104	0.007
LNE	80.110	0.050
METAS	80.100	0.012
CMI	80.091	0.036
KRISS	80.122	0.012
Instability of ATT#1 $u(ATT\#1_{\_80})$ (dB)		0.004
KCRV	A_{80_R} (dB)	$u(A_{80\_R})$ (dB)
	80.104	0.006

Lab_i	Measurements not used to calculate the KCRV		
	A_{80_i} (dB)	$u(A_{80\_i})$ (dB)	Reason for exclusion
INTA	80.095	0.054	Traceable to other NMI
NMISA	80.044	0.549	Traceable to other NMI
TUBITAK-UME	80.097	0.065	Traceable to other NMI
NMC-A*STAR	80.101	0.007	Traceable to other NMI
NPLI	Not provided	Not provided	Not provided
PTB	80.192	0.021	Statistical outlier
VNIIFTRI	80.175	0.180	Statistical outlier
NPL	79.702	0.007	Statistical outlier

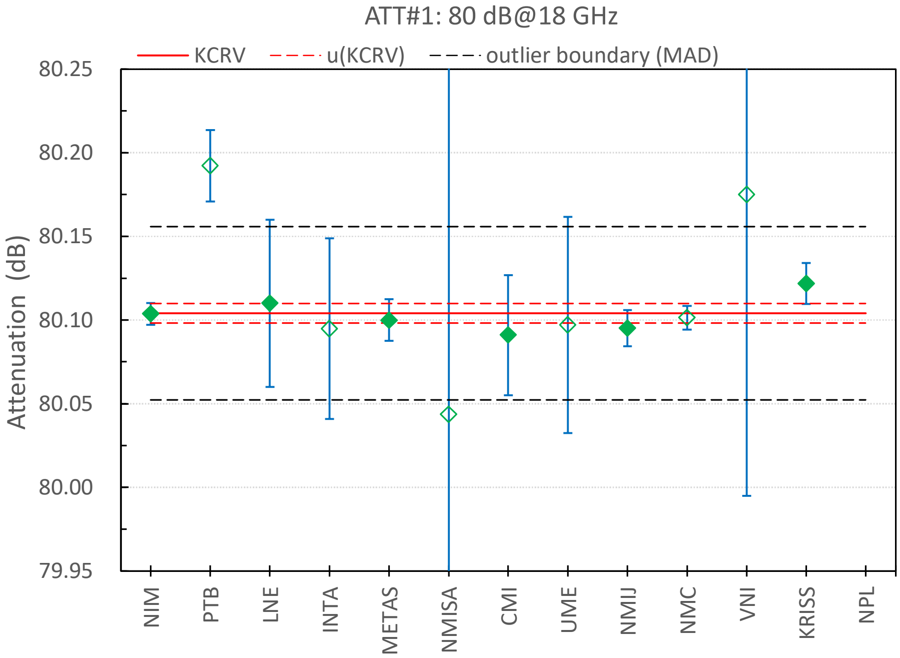


Fig. VIII-10. 80 dB incremental attenuation of ATT#1 at 18 GHz. The filled markers indicate the measurements used to determine the KCRV. Note: $u(A_{80\_NMISA})$ = 0.549 dB. A_{80_NPL} = 79.702 dB, $u(A_{80\_NPL})$ = 0.007 dB.

TABLE VIII-11 MEASUREMENTS AND COMBINED STANDARD UNCERTAINTIES (k=1) OF 80 dB INCREMENTAL ATTENUATION OF ATT#1 AT 26.5 GHz

Lab_i	Measurements used to calculate the KCRV	
	A_{80_i} (dB)	$u(A_{80\_i})$ (dB)
NMIJ/AIST	80.173	0.011
NIM	80.175	0.006
PTB	80.180	0.025
LNE	80.170	0.040
METAS	80.177	0.012
CMI	80.156	0.045
VNIIFTRI	80.190	0.180
Instability of ATT#1 $u(ATT\#1_{\_80})$ (dB)		0.003
KCRV	A_{80_R} (dB)	$u(A_{80\_R})$ (dB)
	80.175	0.006

Lab_i	Measurements not used to calculate the KCRV		
	A_{80_i} (dB)	$u(A_{80\_i})$ (dB)	Reason for exclusion
INTA	80.152	0.053	Traceable to other NMI
NMISA	80.302	0.598	Traceable to other NMI
TUBITAK-UME	80.165	0.066	Traceable to other NMI
NMC-A*STAR	80.170	0.008	Traceable to other NMI
NPLI	Not provided	Not provided	Not provided
KRISS	80.127	0.012	Statistical outlier
NPL	80.221	0.037	Statistical outlier

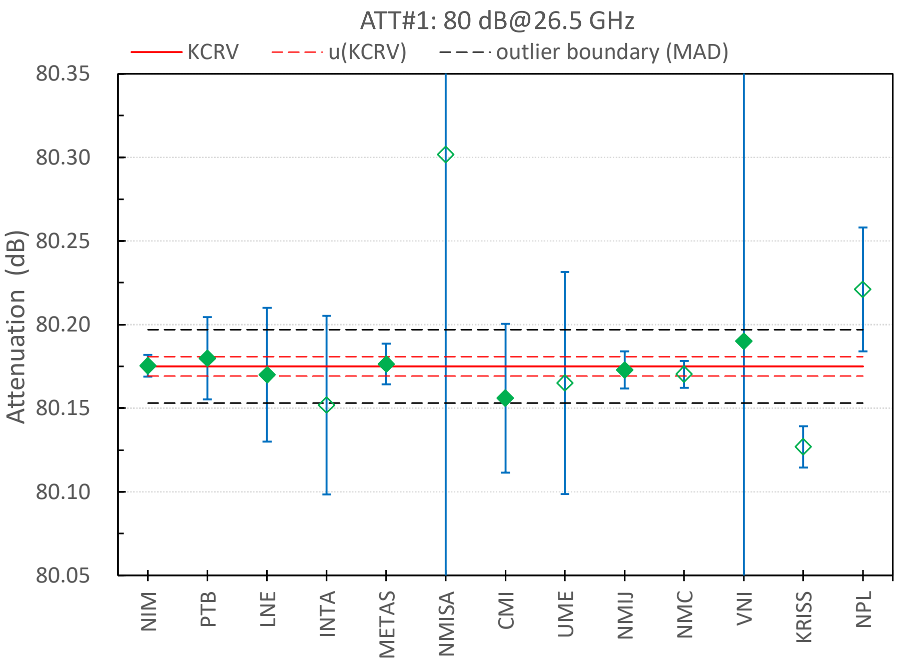


Fig. VIII-11. 80 dB incremental attenuation of ATT#1 at 26.5 GHz. The filled markers indicate the measurements used to determine the KCRV. Note: $u(A_{80\_NMISA})$ = 0.598 dB. $u(A_{80\_VNI})$ = 0.180 dB.

TABLE VIII-12 MEASUREMENTS AND COMBINED STANDARD UNCERTAINTIES (k=1) OF 80 dB INCREMENTAL ATTENUATION OF ATT#1 AT 40 GHz

Lab_i	Measurements used to calculate the KCRV	
	A_{80_i} (dB)	$u(A_{80\_i})$ (dB)
NMIJ/AIST	80.357	0.022
NIM	80.342	0.009
PTB	80.257	0.037
LNE	80.390	0.060
CMI	80.322	0.106
VNIIFTRI	80.310	0.170
Instability of ATT#1	$u(ATT\#1_{\_80})$ (dB)	0.003
KCRV	A_{80_R} (dB)	$u(A_{80\_R})$ (dB)
	80.341	0.008

Lab_i	Measurements not used to calculate the KCRV		
	A_{80_i} (dB)	$u(A_{80\_i})$ (dB)	Reason for exclusion
INTA	80.337	0.139	Traceable to other NMI
NMISA	80.255	0.640	Traceable to other NMI
TUBITAK-UME	80.333	0.145	Traceable to other NMI
NMC-A*STAR	Not provided	Not provided	Not provided
NPLI	Not provided	Not provided	Not provided
NPL	Not provided	Not provided	Not provided
METAS	80.296	0.012	Statistical outlier*
KRISS	80.415	0.018	Statistical outlier*

*After performing the chi-squared test.

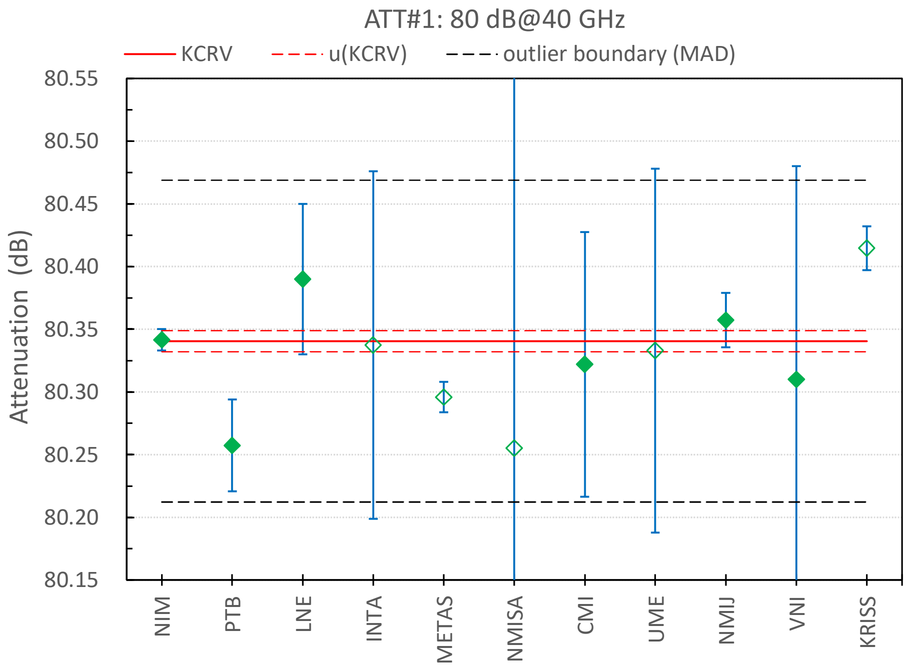


Fig. VIII-12. 80 dB incremental attenuation of ATT#1 at 40 GHz. The filled markers indicate the measurements used to determine the KCRV. Note: $u(A_{80\_NMISA})$ = 0.640 dB.

TABLE VIII-13 MEASUREMENTS AND COMBINED STANDARD UNCERTAINTIES (k=1) OF 90 dB INCREMENTAL ATTENUATION OF ATT#1 AT 18 GHz

Lab_i	Measurements used to calculate the KCRV	
	A_{90_i} (dB)	$u(A_{90\_i})$ (dB)
NMIJ/AIST	90.013	0.014
NIM	90.021	0.009
LNE	90.050	0.040
METAS	90.012	0.016
CMI	90.006	0.047
VNIIFTRI	90.014	0.500
KRISS	90.065	0.015
Instability of ATT#1 $u(ATT\#1\_{90})$ (dB)		0.002
KCRV	A_{90_R} (dB)	$u(A_{90\_R})$ (dB)
	90.026	0.006

Lab_i	Measurements not used to calculate the KCRV		
	A_{90_i} (dB)	$u(A_{90\_i})$ (dB)	Reason for exclusion
INTA	90.015	0.055	Traceable to other NMI
NMISA	89.657	1.477	Traceable to other NMI
TUBITAK-UME	90.010	0.197	Traceable to other NMI
A*STAR	90.013	0.008	Traceable to other NMI
NPLI	Not provided	Not provided	Not provided
PTB	90.122	0.059	Statistical outlier
NPL	90.230	0.009	Statistical outlier

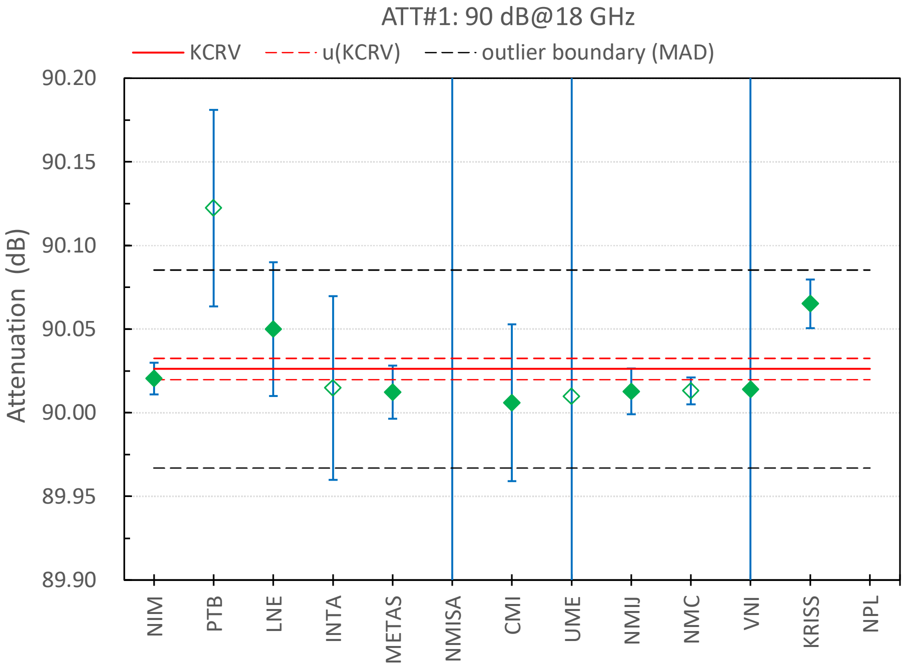


Fig. VIII-13. 90 dB incremental attenuation of ATT#1 at 18 GHz. The filled markers indicate the measurements used to determine the KCRV. Note: A_{90_NMISA} = 89.657 dB, $u(A_{90\_NMISA})$ = 1.477 dB. $u(A_{90\_UME})$ = 0.197 dB, $u(A_{90\_VNI})$ = 0.500 dB. A_{90_NPL} = 90.230 dB, $u(A_{90\_NPL})$ = 0.009 dB.

TABLE VIII-14 MEASUREMENTS AND COMBINED STANDARD UNCERTAINTIES (k=1) OF 90 dB INCREMENTAL ATTENUATION OF ATT#1 AT 26.5 GHz

Lab$_i$	Measurements used to calculate the KCRV	
	A_{90_i} (dB)	$u(A_{90\_i})$ (dB)
NMIJ/AIST	90.159	0.014
NIM	90.161	0.011
PTB	90.156	0.064
METAS	90.158	0.016
VNIIFTRI	90.157	0.520
Instability of ATT#1	$u(ATT\#1_{\_90})$ (dB)	0.005
KCRV	A_{90_R} (dB)	$u(A_{90\_R})$ (dB)
	90.160	0.009

Lab$_i$	Measurements not used to calculate the KCRV		
	A_{90_i} (dB)	$u(A_{90\_i})$ (dB)	Reason for exclusion
INTA	90.155	0.104	Traceable to other NMI
NMISA	90.473	1.675	Traceable to other NMI
TUBITAK-UME	90.146	0.213	Traceable to other NMI
A*STAR	90.152	0.009	Traceable to other NMI
NPLI	Not provided	Not provided	Not provided
LNE	90.190	0.050	Statistical outlier
CMI	90.127	0.092	Statistical outlier
KRISS	90.140	0.017	Statistical outlier
NPL	90.188	0.051	Statistical outlier

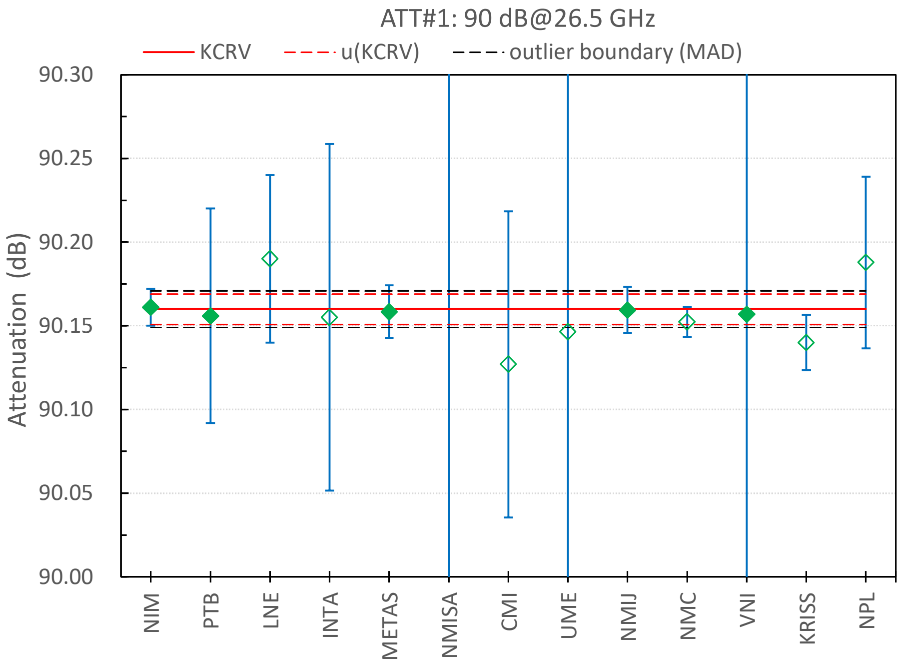


Fig. VIII-14. 90 dB incremental attenuation of ATT#1 at 26.5 GHz. The filled markers indicate the measurements used to determine the KCRV. Note: A_{90_NMISA} = 90.473 dB, $u(A_{90\_NMISA})$ = 1.675 dB. $u(A_{90\_UME})$ = 0.213 dB. $u(A_{90\_VNI})$ = 0.520dB.

TABLE VIII-15 MEASUREMENTS AND COMBINED STANDARD UNCERTAINTIES (k=1) OF 90 dB INCREMENTAL ATTENUATION OF ATT#1 AT 40 GHz

Lab_i	Measurements used to calculate the KCRV	
	A_{90_i} (dB)	$u(A_{90\_i})$ (dB)
NMIJ/AIST	90.413	0.023
NIM	90.403	0.012
PTB	90.523	0.075
LNE	90.330	0.070
CMI	90.312	0.203
VNIIFTRI	90.350	0.520
Instability of ATT#1 $u(ATT\#1_{\_90})$ (dB)		0.006
KCRV	A_{90_R}(dB)	$u(A_{90\_R})$ (dB)
	90.406	0.012

Lab_i	Measurements not used to calculate the KCRV		
	A_{90_i} (dB)	$u(A_{90\_i})$ (dB)	Reason for exclusion
INTA	90.336	0.351	Traceable to other NMI
NMISA	90.418	1.850	Traceable to other NMI
TUBITAK-UME	90.325	0.427	Traceable to other NMI
A*STAR	Not provided	Not provided	Not provided
NPLI	Not provided	Not provided	Not provided
NPL	Not provided	Not provided	Not provided
METAS	90.350	0.016	Statistical outlier*
KRISS	90.498	0.020	Statistical outlier*

*After performing the chi-squared test.

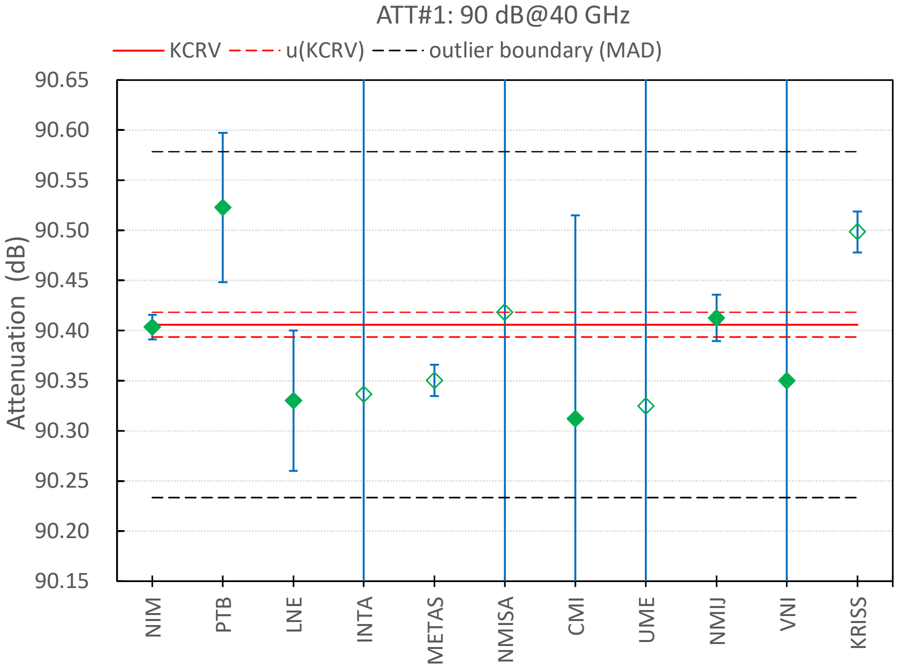


Fig. VIII-15. 90 dB incremental attenuation of ATT#1 at 40 GHz. The filled markers indicate the measurements used to determine the KCRV. Note: $u(A_{90\_INTA})$ = 0.351 dB. $u(A_{90\_NMISA})$ = 1.850 dB. $u(A_{90\_UME})$ = 0.427 dB. $u(A_{90\_VNI})$ = 0.520dB.

B. Results for Travelling Standard ATT#2 (MY46150135)

TABLE VIII-16 MEASUREMENTS AND COMBINED STANDARD UNCERTAINTIES (k=1) OF 20 dB INCREMENTAL ATTENUATION OF ATT#2 AT 18 GHz

Lab_i	Measurements used to calculate the KCRV	
	A_{20_i} (dB)	$u(A_{20\_i})$ (dB)
NMIJ/AIST	19.893	0.003
NIM	19.893	0.003
PTB	19.897	0.004
LNE	19.910	0.010
METAS	19.893	0.005
CMI	19.882	0.016
NPLI	19.874	0.029
VNIIFTRI	19.907	0.012
KRISS	19.903	0.008
Instability of ATT#2	$u(ATT\#2_{\_20})$ (dB)	0.001
KCRV	A_{20_R}(dB)	$u(A_{20\_R})$ (dB)
	19.895	0.002

Lab_i	Measurements not used to calculate the KCRV		
	A_{20_i} (dB)	$u(A_{20\_i})$ (dB)	Reason for exclusion
INTA	19.889	0.066	Traceable to other NMI
NMISA	19.894	0.010	Traceable to other NMI
TUBITAK-UME	19.906	0.014	Traceable to other NMI
A*STAR	19.894	0.003	Traceable to other NMI
NPL	19.929	0.002	Statistical outlier*

*After performing the chi-squared test.

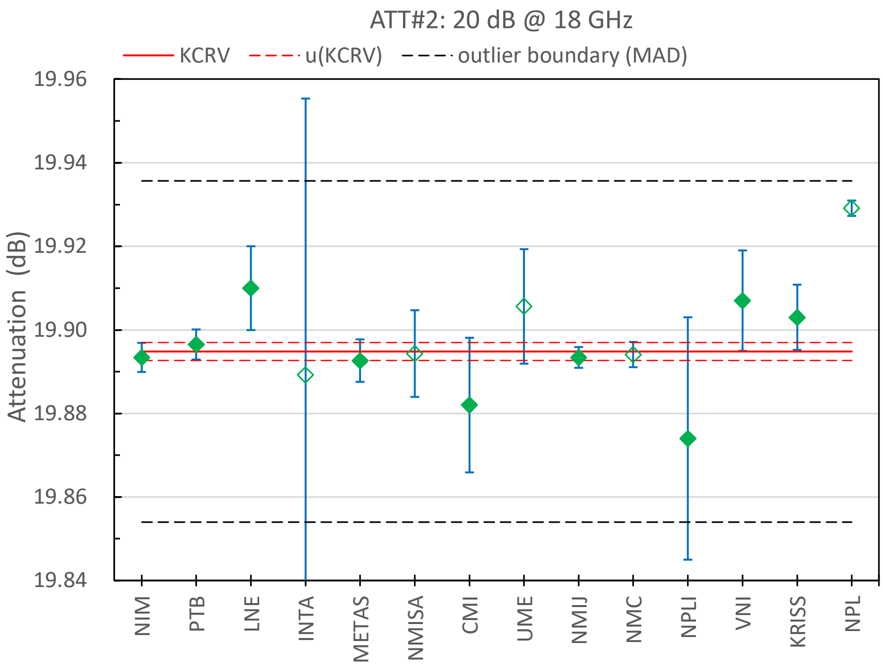


Fig. VIII-16. 20 dB incremental attenuation of ATT#2 at 18 GHz. The filled markers indicate the measurements used to determine the KCRV.

TABLE VIII-17 MEASUREMENTS AND COMBINED STANDARD UNCERTAINTIES (k=1) OF 20 dB INCREMENTAL ATTENUATION OF ATT#2 AT 26.5 GHz

Lab_i	Measurements used to calculate the KCRV	
	A_{20_i} (dB)	$u(A_{20\_i})$ (dB)
NMIJ/AIST	19.940	0.002
NIM	19.935	0.007
PTB	19.948	0.005
LNE	19.950	0.010
METAS	19.939	0.005
CMI	19.940	0.016
NPLI	19.936	0.036
VNIIFTRI	19.944	0.012
KRISS	19.943	0.007
NPL	19.935	0.006
Instability of ATT#2	$u(ATT\#2\_{20})$ (dB)	0.001
KCRV	A_{20_R}(dB)	$u(A_{20\_R})$ (dB)
	19.941	0.002

Lab_i	Measurements not used to calculate the KCRV		
	A_{20_i} (dB)	$u(A_{20\_i})$ (dB)	Reason for exclusion
INTA	19.940	0.086	Traceable to other NMI
NMISA	19.940	0.010	Traceable to other NMI
TUBITAK-UME	19.937	0.013	Traceable to other NMI
NMC-A*STAR	19.937	0.004	Traceable to other NMI

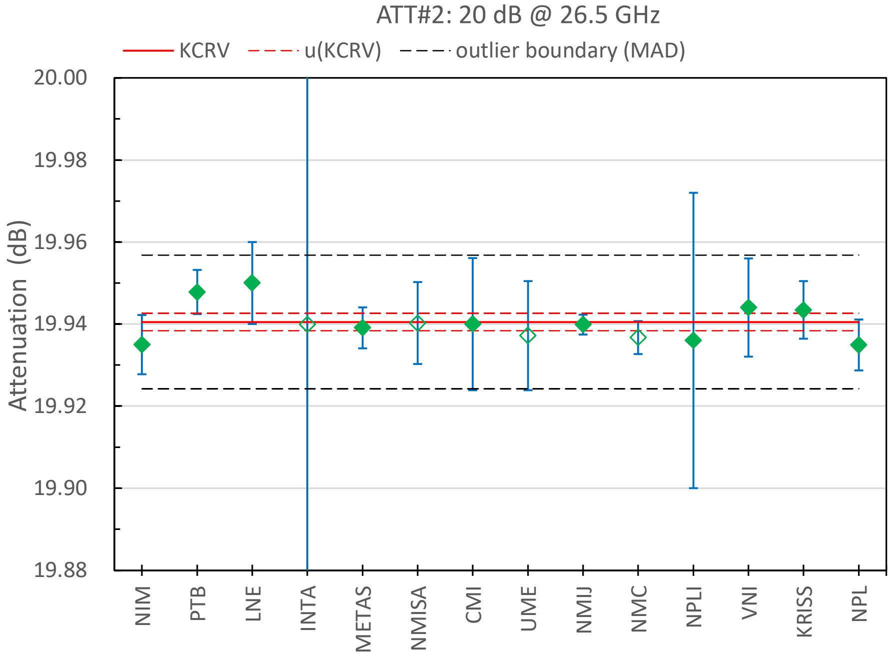


Fig. VIII-17. 20 dB incremental attenuation of ATT#2 at 26.5 GHz. The filled markers indicate the measurements used to determine the KCRV. Note: $u(A_{90\_\mathrm{INTA}})$ = 0.086 dB.

TABLE VIII-18 MEASUREMENTS AND COMBINED STANDARD UNCERTAINTIES (k=1) OF 20 dB INCREMENTAL ATTENUATION OF ATT#2 AT 40 GHz

Lab_i	Measurements used to calculate the KCRV	
	A_{20_i} (dB)	$u(A_{20\_i})$ (dB)
NMIJ/AIST	19.823	0.003
NIM	19.835	0.009
PTB	19.803	0.014
METAS	19.819	0.005
CMI	19.823	0.020
NPLI	19.819	0.040
VNIIFTRI	19.851	0.012
KRISS	19.824	0.009
Instability of ATT#2	$u(ATT\#2_{\_20})$ (dB)	0.001
KCRV	A_{20_R}(dB)	$u(A_{20\_R})$ (dB)
	19.823	0.002

Lab_i	Measurements not used to calculate the KCRV		
	A_{20_i} (dB)	$u(A_{20\_i})$ (dB)	Reason for exclusion
INTA	19.845	0.117	Traceable to other NMI
NMISA	19.810	0.011	Traceable to other NMI
TUBITAK-UME	19.825	0.014	Traceable to other NMI
NMC-A*STAR	Not provided	Not provided	Not provided
LNE	19.850	0.010	Statistical outlier*
NPL	19.788	0.002	Statistical outlier

*After performing the chi-squared test.

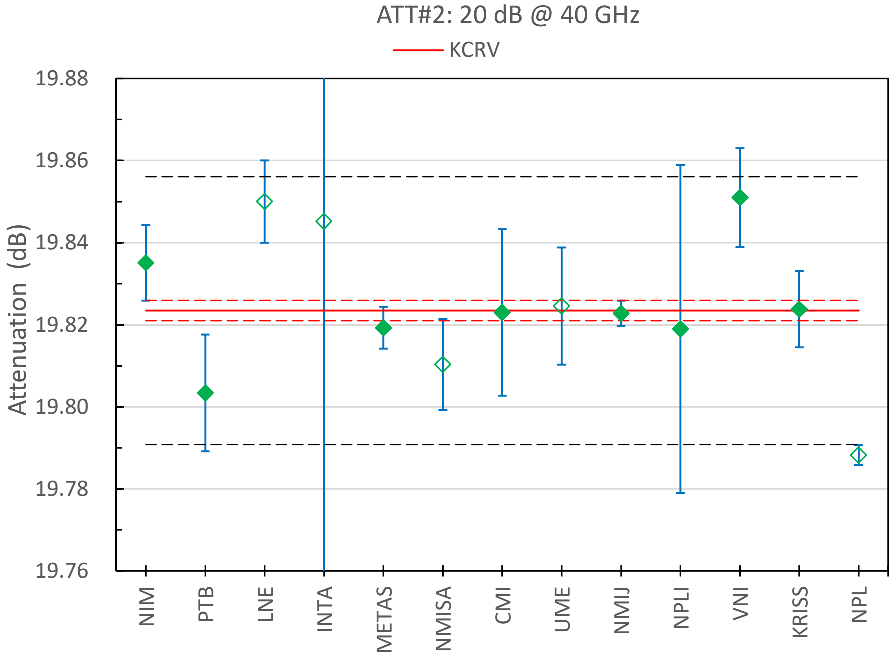


Fig. VIII-18. 20 dB incremental attenuation of ATT#2 at 40 GHz. The filled markers indicate the measurements used to determine the KCRV. Note: $u(A_{90\_\mathrm{INTA}})$ = 0.117 dB.

TABLE VIII-19 MEASUREMENTS AND COMBINED STANDARD UNCERTAINTIES (k=1) OF 40 dB INCREMENTAL ATTENUATION OF ATT#2 AT 18 GHz

Lab_i	Measurements used to calculate the KCRV	
	A_{40_i} (dB)	$u(A_{40\_i})$ (dB)
NMIJ/AIST	40.160	0.004
NIM	40.162	0.004
PTB	40.166	0.012
METAS	40.158	0.009
CMI	40.176	0.023
NPLI	40.159	0.039
VNIIFTRI	40.172	0.021
KRISS	40.162	0.008
Instability of ATT#2	$u(ATT\#2\_{40})$ (dB)	0.002
KCRV	A_{40_R}(dB)	$u(A_{0\_R})$ (dB)
	40.161	0.003

Lab_i	Measurements not used to calculate the KCRV		
	A_{40_i} (dB)	$u(A_{40\_i})$ (dB)	Reason for exclusion
INTA	40.158	0.071	Traceable to other NMI
NMISA	40.157	0.060	Traceable to other NMI
TUBITAK-UME	40.173	0.015	Traceable to other NMI
NMC-A*STAR	40.164	0.004	Traceable to other NMI
LNE	40.200	0.040	Statistical outlier
NPL	40.199	0.003	Statistical outlier

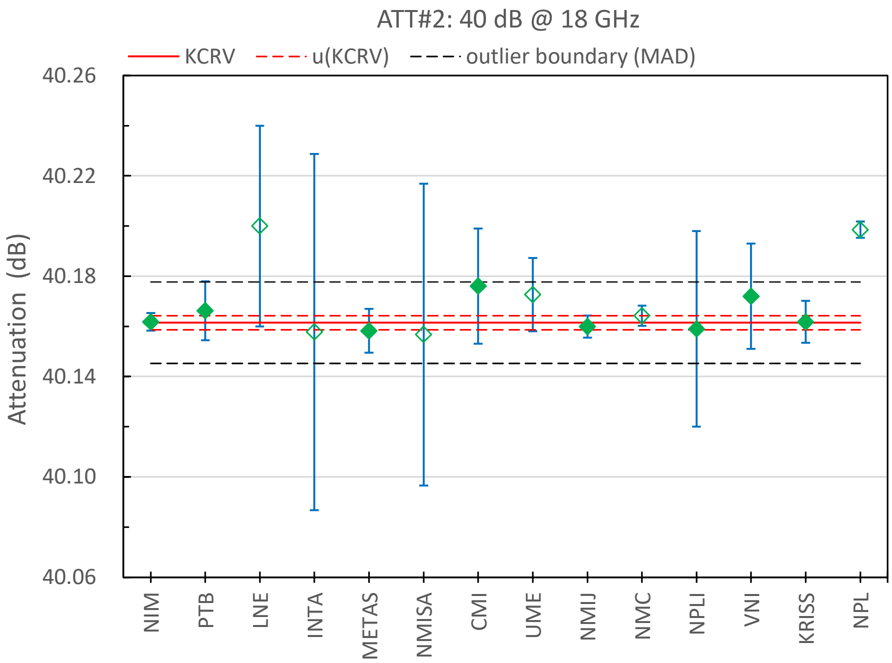


Fig. VIII-19. 40 dB incremental attenuation of ATT#2 at 18 GHz. The filled markers indicate the measurements used to determine the KCRV.

TABLE VIII-20 MEASUREMENTS AND COMBINED STANDARD UNCERTAINTIES (k=1) OF 40 dB INCREMENTAL ATTENUATION OF ATT#2 AT 26.5 GHz

Lab_i	Measurements used to calculate the KCRV	
	A_{40_i} (dB)	$u(A_{40\_i})$ (dB)
NMIJ/AIST	40.170	0.004
NIM	40.169	0.007
PTB	40.188	0.020
LNE	40.180	0.040
METAS	40.166	0.009
CMI	40.150	0.025
NPLI	40.170	0.042
VNIIFTRI	40.169	0.021
KRISS	40.179	0.008
NPL	40.156	0.012
Instability of ATT#2	$u(ATT\#2\_{40})$ (dB)	0.002
KCRV	A_{20_R}(dB)	$u(A_{20\_R})$ (dB)
	40.170	0.004

Lab_i	Measurements not used to calculate the KCRV		
	A_{40_i} (dB)	$u(A_{40\_i})$ (dB)	Reason for exclusion
INTA	40.171	0.101	Traceable to other NMI
NMISA	40.156	0.067	Traceable to other NMI
TUBITAK-UME	40.167	0.015	Traceable to other NMI
A*STAR	40.175	0.006	Traceable to other NMI

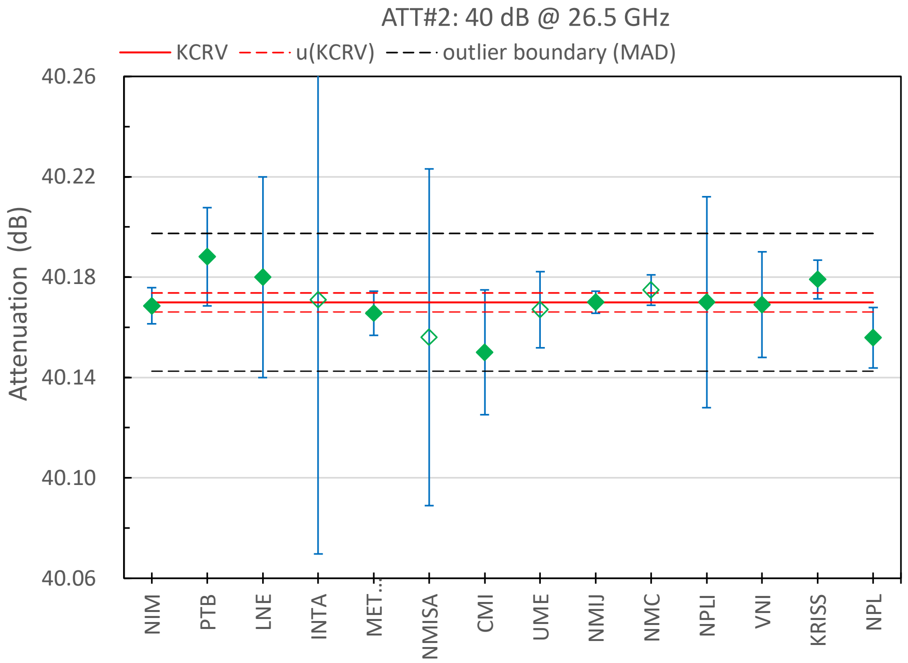


Fig. VIII-20. 40 dB incremental attenuation of ATT#2 at 26.5 GHz. The filled markers indicate the measurements used to determine the KCRV.

TABLE VIII-21 MEASUREMENTS AND COMBINED STANDARD UNCERTAINTIES (k=1) OF 40 dB INCREMENTAL ATTENUATION OF ATT#2 AT 40 GHz

Lab$_i$	Measurements used to calculate the KCRV	
	A_{40_i} (dB)	$u(A_{40\_i})$ (dB)
NMIJ/AIST	39.989	0.006
NIM	40.014	0.009
PTB	39.972	0.019
LNE	40.010	0.040
METAS	40.006	0.010
CMI	39.983	0.042
VNIIFTRI	40.022	0.021
KRISS	39.981	0.010
Instability of ATT#2	$u(ATT\#2\_{40})$ (dB)	0.002
KCRV	A_{20_R}(dB)	$u(A_{20\_R})$ (dB)
	39.996	0.004

Lab$_i$	Measurements not used to calculate the KCRV		
	A_{40_i} (dB)	$u(A_{40\_i})$ (dB)	Reason for exclusion
INTA	40.007	0.071	Traceable to other NMI
NMISA	39.957	0.084	Traceable to other NMI
TUBITAK-UME	39.989	0.020	Traceable to other NMI
A*STAR	Not provided	Not provided	Not provided
NPLI	40.162	0.046	Statistical outlier
NPL	39.934	0.004	Statistical outlier*

*After performing the chi-squared test.

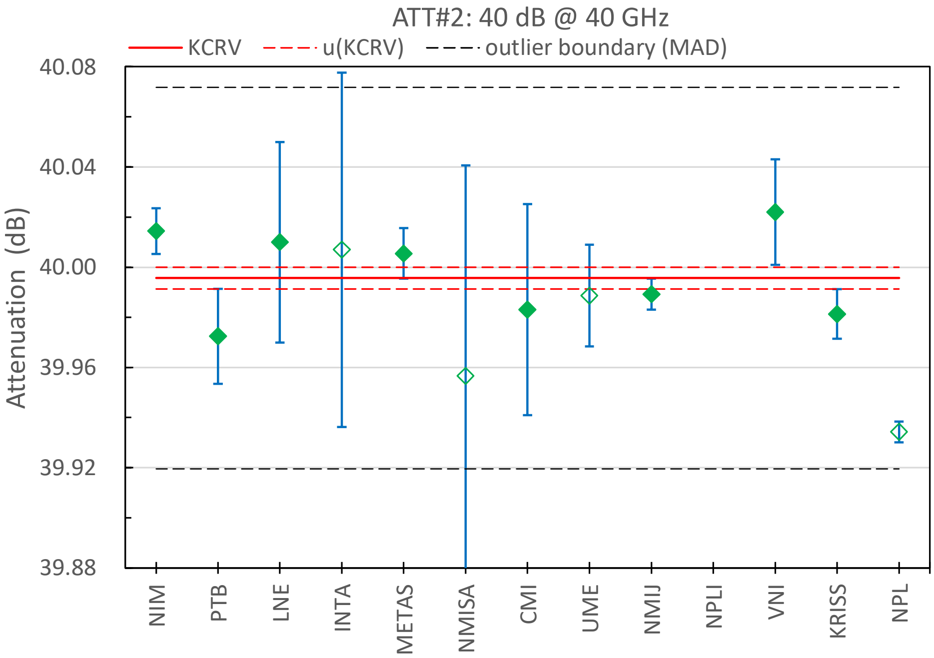


Fig. VIII-21. 40 dB incremental attenuation of ATT#2 at 40 GHz. The filled markers indicate the measurements used to determine the KCRV. Note: A_{40_NPLI} = 40.162 dB, $u(A_{40\_\text{NPLI}})$ = 0.046 dB.

TABLE VIII-22 MEASUREMENTS AND COMBINED STANDARD UNCERTAINTIES (k=1) OF 60 dB INCREMENTAL ATTENUATION OF ATT#2 AT 18 GHz

Lab_i	Measurements used to calculate the KCRV	
	A_{60_i} (dB)	$u(A_{60\_i})$ (dB)
NMIJ/AIST	60.029	0.009
NIM	60.031	0.004
METAS	60.031	0.013
CMI	60.001	0.030
VNIIFTRI	60.048	0.170
KRISS	60.039	0.011
NPL	60.039	0.005
Instability of ATT#2	$u(ATT\#2_{\_60})$ (dB)	0.002
KCRV	A_{60_R}(dB)	$u(A_{60\_R})$ (dB)
	60.034	0.004

Lab_i	Measurements not used to calculate the KCRV		
	A_{60_i} (dB)	$u(A_{60\_i})$ (dB)	Reason for exclusion
INTA	60.025	0.062	Traceable to other NMI
NMISA	59.989	0.566	Traceable to other NMI
TUBITAK-UME	60.048	0.065	Traceable to other NMI
A*STAR	60.033	0.006	Traceable to other NMI
PTB	60.127	0.010	Statistical outlier
LNE	60.080	0.040	Statistical outlier
NPLI	60.181	0.052	Statistical outlier

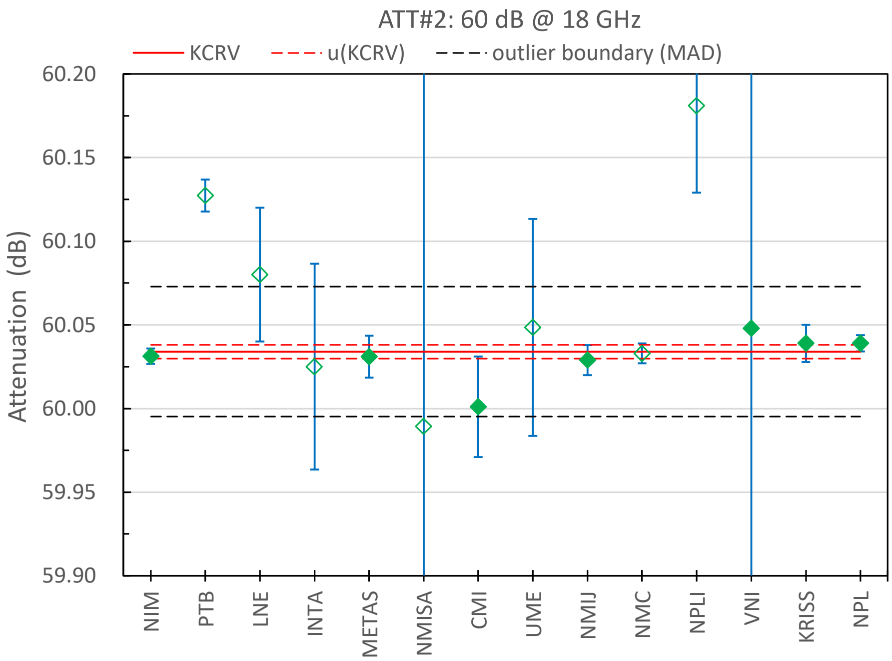


Fig. VIII-22. 60 dB incremental attenuation of ATT#2 at 18 GHz. The filled markers indicate the measurements used to determine the KCRV. Note: $u(A_{60\_NMISA})$ = 0.566 dB. $u(A_{60\_VNI})$ = 0.170 dB.

TABLE VIII-23 MEASUREMENTS AND COMBINED STANDARD UNCERTAINTIES (k=1) OF 60 dB INCREMENTAL ATTENUATION OF ATT#2 AT 26.5 GHz

Lab_i	Measurements used to calculate the KCRV	
	A_{60_i} (dB)	$u(A_{60\_i})$ (dB)
NMIJ/AIST	60.124	0.009
NIM	60.117	0.008
PTB	60.134	0.022
METAS	60.117	0.012
CMI	60.111	0.041
VNIIFTRI	60.141	0.170
KRISS	60.109	0.011
NPL	60.105	0.017
Instability of ATT#2	$u(ATT\#2_{\_60})$ (dB)	0.004
KCRV	A_{60_R}(dB)	$u(A_{60\_R})$ (dB)
	60.117	0.006

Lab_i	Measurements not used to calculate the KCRV		
	A_{60_i} (dB)	$u(A_{60\_i})$ (dB)	Reason for exclusion
INTA	60.114	0.104	Traceable to other NMI
NMISA	59.993	0.605	Traceable to other NMI
TUBITAK-UME	60.144	0.066	Traceable to other NMI
A*STAR	60.131	0.007	Traceable to other NMI
LNE	60.160	0.040	Statistical outlier
NPLI	59.880	0.055	Statistical outlier

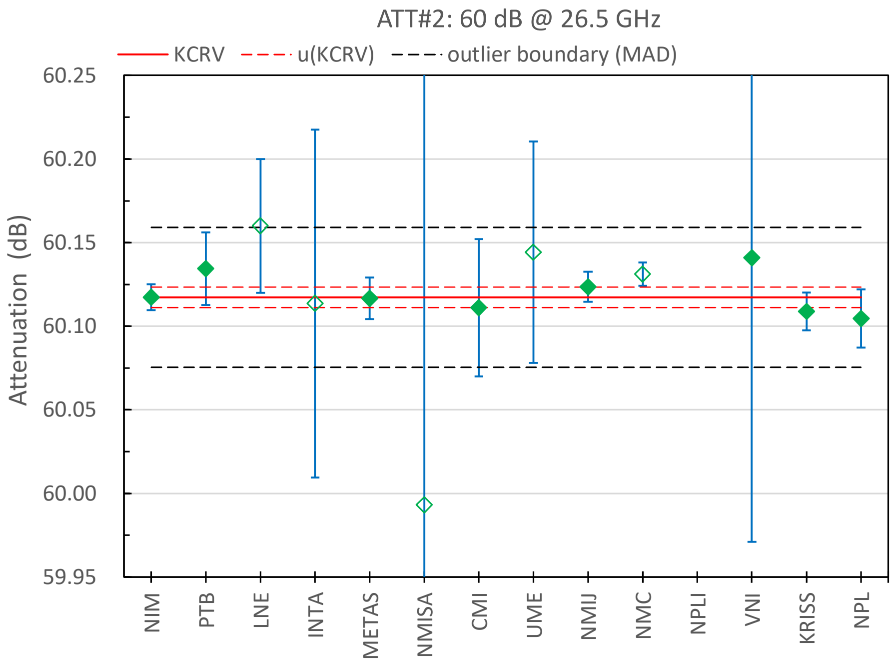


Fig. VIII-23. 60 dB incremental attenuation of ATT#2 at 26.5 GHz. The filled markers indicate the measurements used to determine the KCRV. Note: $u(A_{60\_NMISA})$ = 0.605 dB.

TABLE VIII-24 MEASUREMENTS AND COMBINED STANDARD UNCERTAINTIES (k=1) OF 60 dB INCREMENTAL ATTENUATION OF ATT#2 AT 40 GHz

Lab_i	Measurements used to calculate the KCRV	
	A_{60_i} (dB)	$u(A_{60\_i})$ (dB)
NMIJ/AIST	59.944	0.019
NIM	59.963	0.010
PTB	59.913	0.032
LNE	59.970	0.040
METAS	59.955	0.014
CMI	59.938	0.105
VNIIFTRI	59.965	0.170
Instability of ATT#2	$u(ATT\#2_{\_60})$ (dB)	0.002
KCRV	A_{60_R}(dB)	$u(A_{60\_R})$ (dB)
	59.956	0.007

Lab_i	Measurements not used to calculate the KCRV		
	A_{60_i} (dB)	$u(A_{60\_i})$ (dB)	Reason for exclusion
INTA	59.963	0.075	Traceable to other NMI
NMISA	59.674	0.762	Traceable to other NMI
TUBITAK-UME	59.943	0.145	Traceable to other NMI
A*STAR	Not provided	Not provided	Not provided
NPL	Not provided	Not provided	Not provided
NPLI	60.032	0.058	Statistical outlier
KRISS	59.902	0.014	Statistical outlier*

* After performing the chi-squared test.

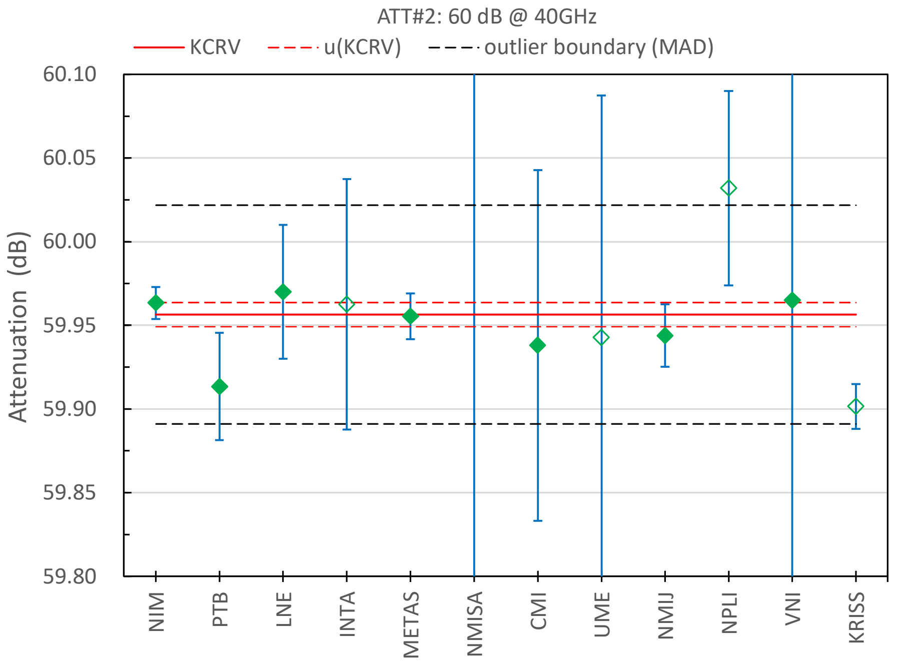


Fig. VIII-24. 60 dB incremental attenuation of ATT#2 at 40 GHz. The filled markers indicate the measurements used to determine the KCRV. Note: A_{60_NMISA} =59.674 dB, $u(A_{60\_NMISA})$ = 0.762 dB. $u(A_{60\_VNI})$ = 0.170 dB.

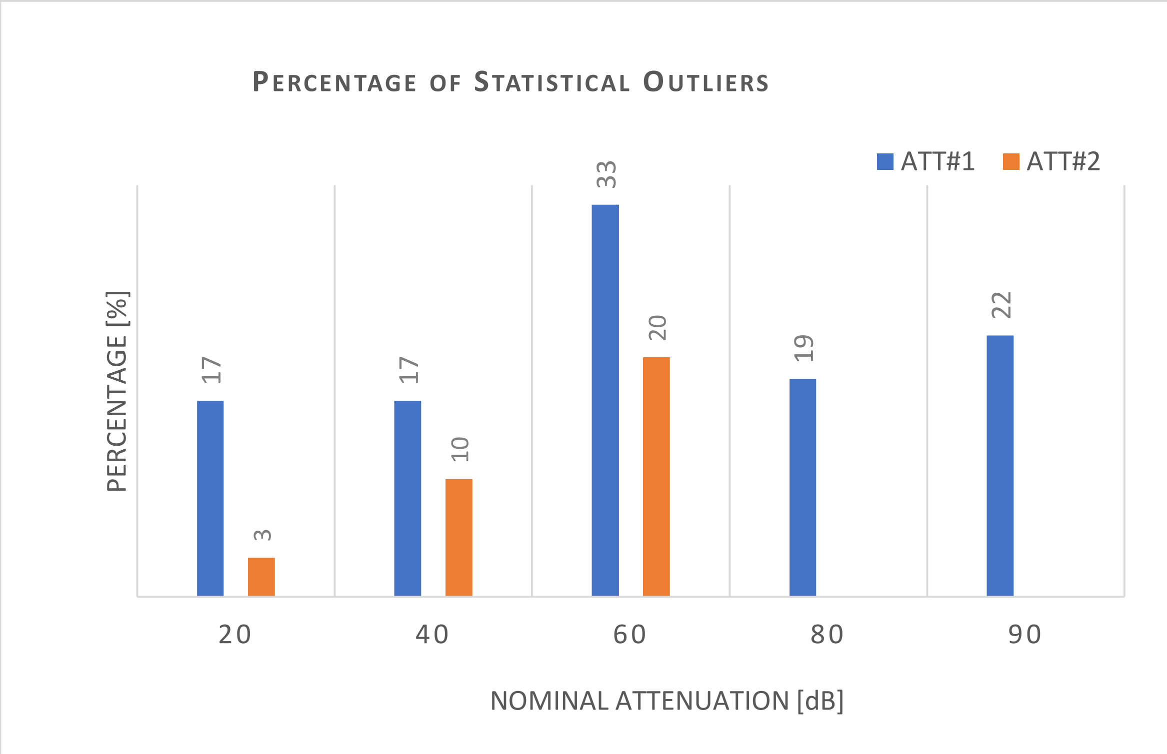


Fig. VIII-25. Percentage of statistical outliers of participants used in calculation of KCRV.

IX DEGREES OF EQUIVALENCE OF THE PARTICIPATING INSTITUTES

A. Travelling Standard ATT#1 (US42140229)

TABLE IX-1 DEGREES OF EQUIVALENCE FOR 20 dB INCREMENTAL ATTENUATION OF ATT#1 AT 18 GHz

Lab_i	DoE with respect to the KCRV	
	D_i (dB)	Ui (dB)
NMIJ/AIST	-0.003	0.004
NIM	0.002	0.004
PTB	-0.001	0.002
LNE	0.006	0.019
INTA	0.006	0.053
METAS	0.005	0.009
NMISA	-0.002	0.014
CMI	0.006	0.034
TUBITAK-UME	-0.007	0.026
NMC-A*STAR	0.004	0.007
NPLI	0.059	0.036
VNIIFTRI	0.026	0.040
KRISS	-0.001	0.011
NPL	-0.279	0.006

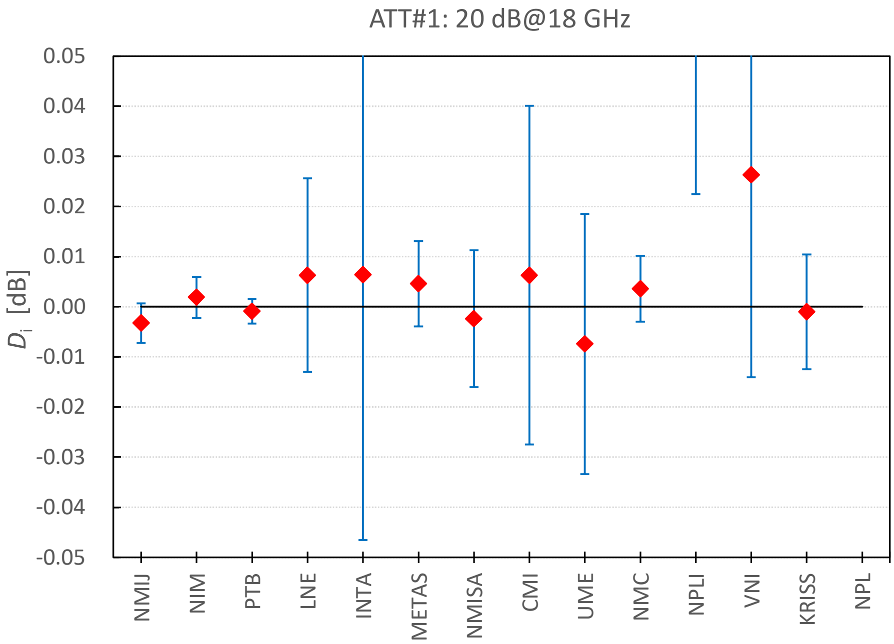


Fig. IX-1 Degrees of equivalence Di and expanded uncertainty Ui (k = 2) with respect to the KCRV for 20 dB incremental attenuation of ATT#1 at 18 GHz. Note: D_{NPLI} = 0.059 dB, U_{NPLI} = 0.036 dB. D_{NPL} = -0.279 dB, U_{NPL} = 0.006 dB.

TABLE IX-2 DEGREES OF EQUIVALENCE FOR 20 dB INCREMENTAL ATTENUATION OF ATT#1 AT 26.5 GHz

Lab$_i$	DoE with respect to the KCRV	
	D_i (dB)	U_i (dB)
NMIJ/AIST	0.000	0.003
NIM	0.001	0.008
PTB	-0.005	0.009
LNE	0.004	0.019
INTA	0.005	0.048
METAS	0.007	0.008
NMISA	-0.010	0.016
CMI	-0.004	0.035
TUBITAK-UME	-0.006	0.030
NMC-A*STAR	0.006	0.010
NPLI	-0.002	0.033
VNIIFTRI	0.005	0.052
KRISS	-0.020	0.015
NPL	0.011	0.018

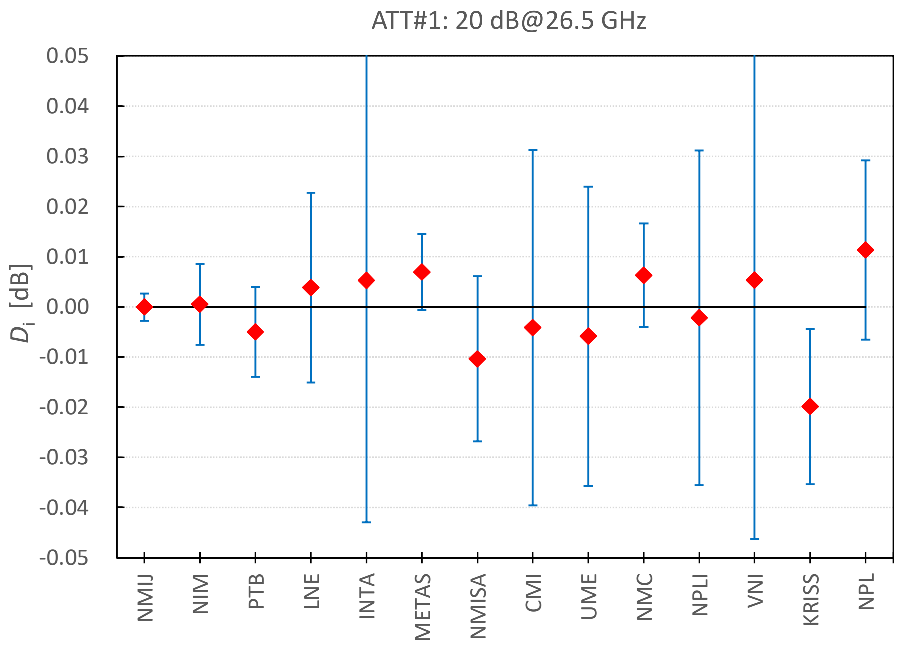


Fig. IX-2 Degrees of equivalence Di and expanded uncertainty Ui (k = 2) with respect to the KCRV for 20 dB incremental attenuation of ATT#1 at 26.5 GHz.

TABLE IX-3 DEGREES OF EQUIVALENCE FOR 20 dB INCREMENTAL ATTENUATION OF ATT#1 AT 40 GHz

Lab$_i$	DoE with respect to the KCRV	
	D_i (dB)	U_i (dB)
NMIJ/AIST	-0.001	0.008
NIM	-0.001	0.013
PTB	-0.008	0.019
LNE	-0.006	0.040
INTA	-0.026	0.139
METAS	0.005	0.008
NMISA	-0.007	0.021
CMI	-0.004	0.045
TUBITAK-UME	-0.010	0.045
NPLI	0.031	0.038
VNIIFTRI	0.000	0.042
KRISS	0.000	0.026
NPL	-0.412	0.018

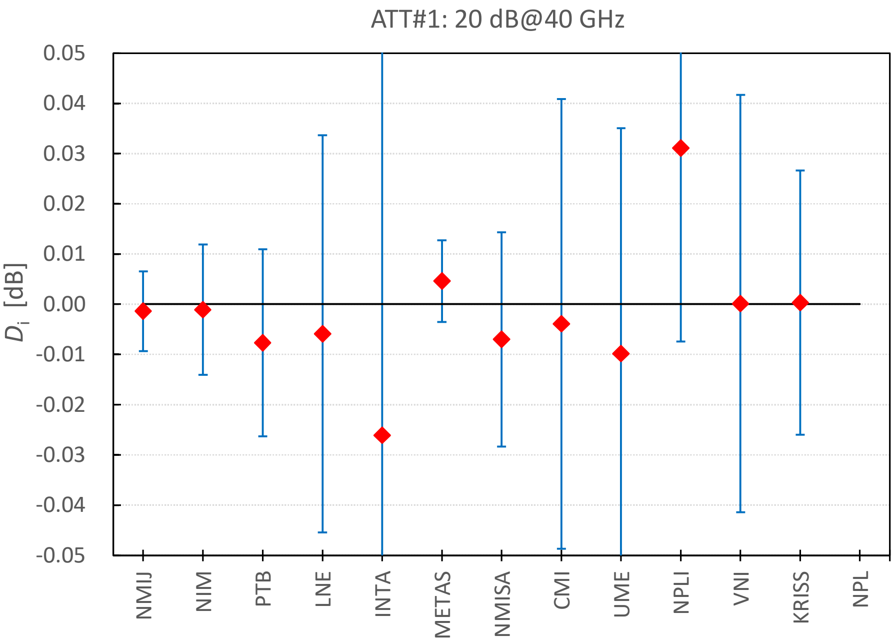


Fig. IX-3 Degrees of equivalence Di and expanded uncertainty Ui (k = 2) with respect to the KCRV for 20 dB incremental attenuation of ATT#1 at 40 GHz. Note: U_{INTA} = 0.139 dB. D_{NPL} = -0.412 dB, U_{NPL} = 0.018 dB.

TABLE IX-4 DEGREES OF EQUIVALENCE FOR 40 dB INCREMENTAL ATTENUATION OF ATT#1 AT 18 GHz

Lab_i	DoE with respect to the KCRV	
	D_i (dB)	U_i (dB)
NMIJ/AIST	-0.002	0.007
NIM	0.005	0.004
PTB	-0.007	0.023
LNE	0.016	0.080
INTA	-0.003	0.064
METAS	-0.005	0.016
NMISA	-0.027	0.030
CMI	-0.017	0.045
TUBITAK-UME	-0.007	0.026
NMC-A*STAR	-0.006	0.010
NPLI	0.042	0.058
VNIIFTRI	-0.145	0.060
KRISS	-0.007	0.012
NPL	-0.189	0.009

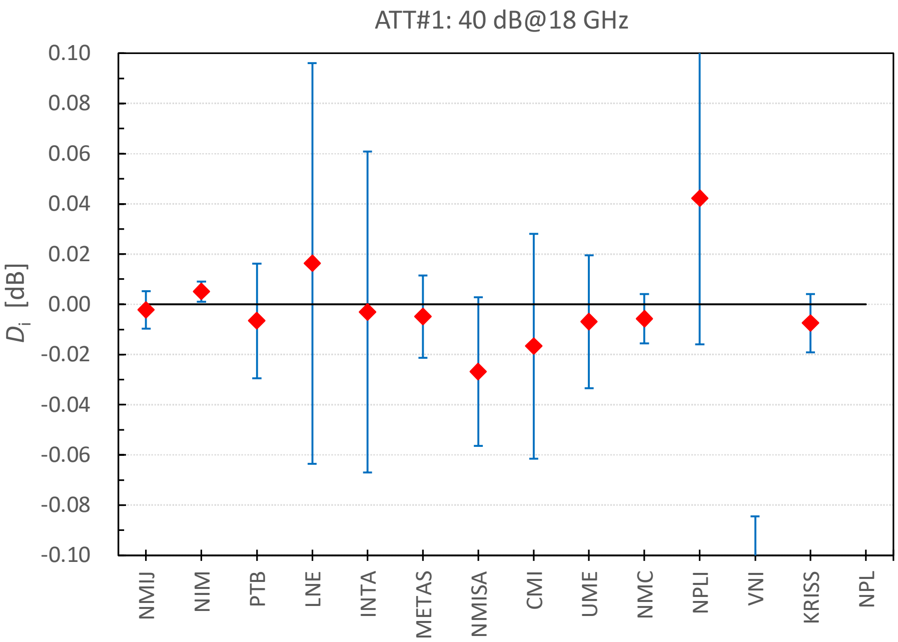


Fig. IX-4 Degrees of equivalence Di and expanded uncertainty Ui (k = 2) with respect to the KCRV for 40 dB incremental attenuation of ATT#1 at 18 GHz. Note: D_{VNI} = -0.145 dB, U_{VNI} = 0.060 dB. D_{NPL} = -0.189 dB, U_{NPL} = 0.009 dB.

TABLE IX-5 DEGREES OF EQUIVALENCE FOR 40 dB INCREMENTAL ATTENUATION OF ATT#1 AT 26.5 GHz

Lab	DoE with respect to the KCRV	
	D_i (dB)	*U*i (dB)
NMIJ/AIST	-0.002	0.010
NIM	0.009	0.011
PTB	-0.025	0.039
LNE	0.012	0.080
INTA	-0.010	0.063
METAS	-0.003	0.017
NMISA	-0.015	0.028
CMI	-0.012	0.048
TUBITAK-UME	-0.017	0.033
NMC-A*STAR	-0.003	0.012
NPLI	-0.015	0.060
VNIIFTRI	-0.001	0.062
KRISS	-0.011	0.019
NPL	0.019	0.033

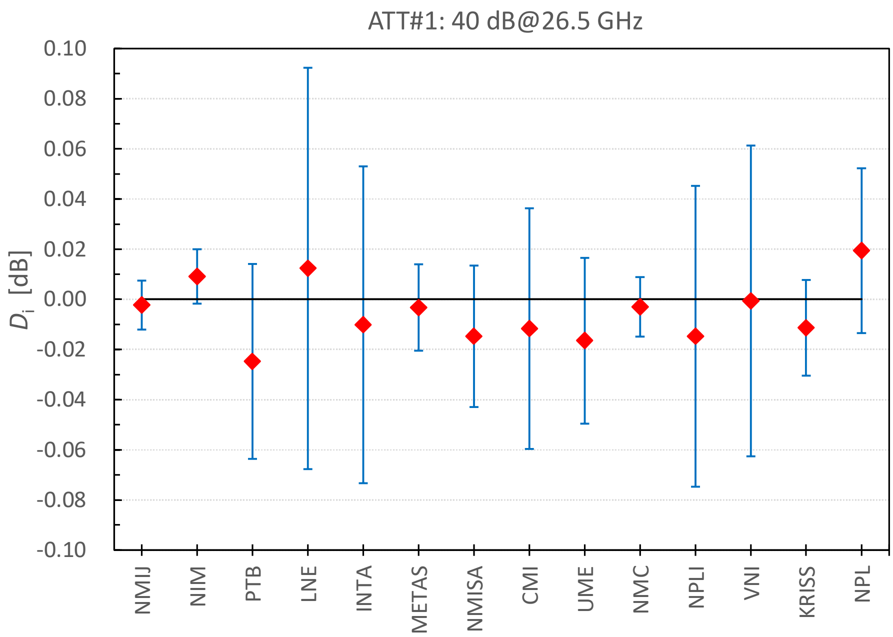


Fig. IX-5 Degrees of equivalence *D*i and expanded uncertainty *U*i ($k = 2$) with respect to the KCRV for 40 dB incremental attenuation of ATT#1 at 26.5 GHz.

TABLE IX-6 DEGREES OF EQUIVALENCE FOR 40 dB INCREMENTAL ATTENUATION OF ATT#1 AT 40 GHz

Lab$_i$	DoE with respect to the KCRV	
	D_i (dB)	U_i (dB)
NMIJ/AIST	0.002	0.014
NIM	0.008	0.014
PTB	-0.011	0.040
LNE	0.008	0.100
INTA	-0.017	0.151
METAS	-0.012	0.015
NMISA	-0.015	0.033
CMI	-0.019	0.085
TUBITAK-UME	-0.030	0.057
NPLI	0.047	0.102
VNIIFTRI	-0.006	0.053
KRISS	0.019	0.030
NPL	-0.420	0.034

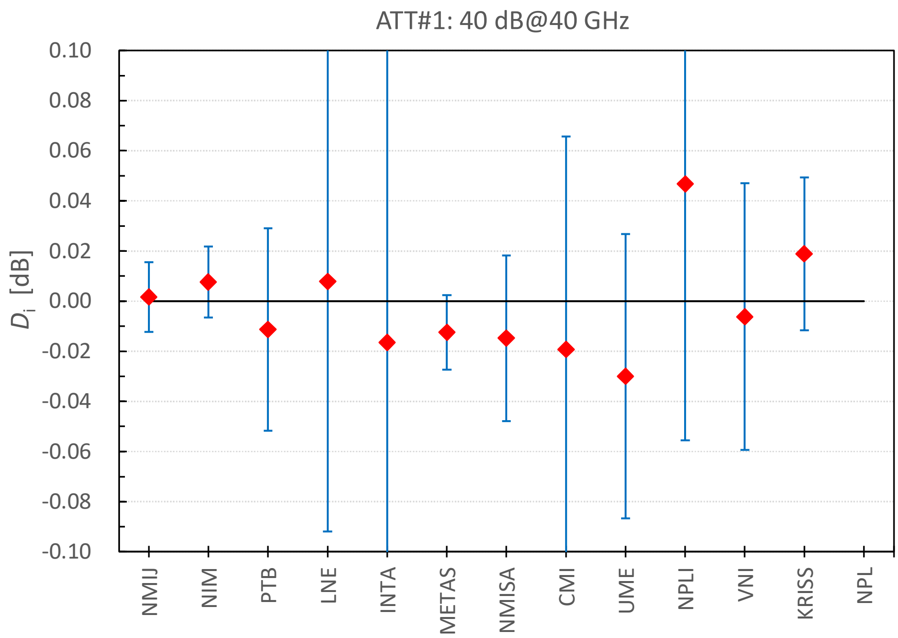


Fig. IX-6 Degrees of equivalence D_i and expanded uncertainty U_i (k = 2) with respect to the KCRV for 40 dB incremental attenuation of ATT#1 at 40 GHz. Note: U_{INTA} = 0.151 dB. D_{NPL} = -0.420 dB, U_{NPL} = 0.034 dB.

TABLE IX-7 DEGREES OF EQUIVALENCE FOR 60 dB INCREMENTAL ATTENUATION OF ATT#1 AT 18 GHz

Lab$_i$	DoE with respect to the KCRV	
	D_i (dB)	U_i (dB)
NMIJ/AIST	-0.006	0.017
NIM	0.004	0.005
PTB	0.081	0.021
LNE	0.000	0.080
INTA	-0.009	0.087
METAS*	0.269	0.019
NMISA	-0.019	0.160
CMI	-0.009	0.058
TUBITAK-UME	-0.002	0.029
NMC-A*STAR	-0.007	0.011
NPLI	0.126	0.092
VNIIFTRI	0.010	0.070
KRISS	-0.008	0.013
NPL	-0.232	0.012

*Wrong configuration, see note section V.

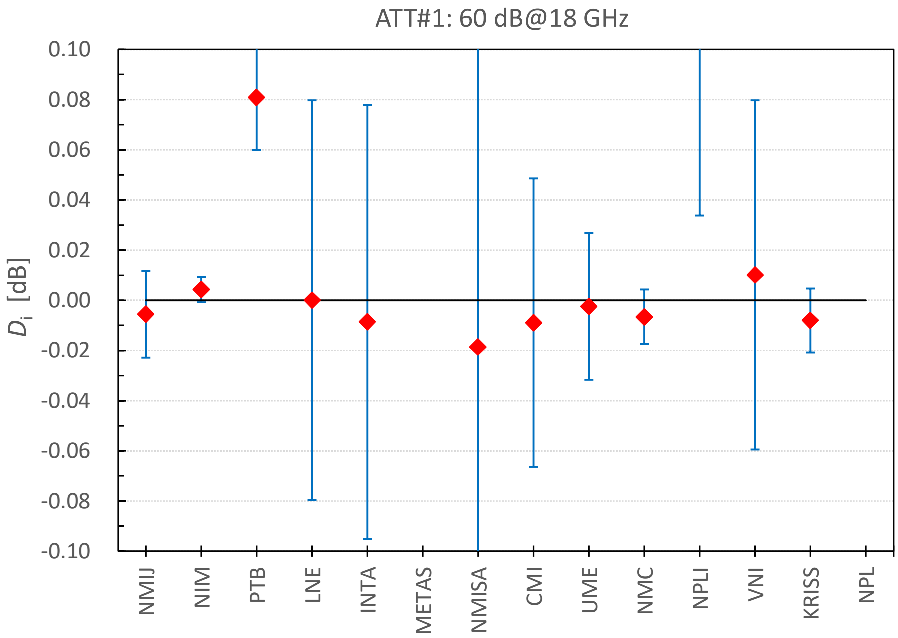


Fig. IX-7 Degrees of equivalence Di and expanded uncertainty Ui (k = 2) with respect to the KCRV for 60 dB incremental attenuation of ATT#1 at 18 GHz. Note: *D_{METAS} = 0.269 dB, U_{METAS} = 0.019 dB. U_{NMISA} = 0.160 dB. D_{NPL} = -0.232 dB, U_{NPL} = 0.012 dB. *Wrong configuration, see note section V.

TABLE IX-8 DEGREES OF EQUIVALENCE FOR 60 dB INCREMENTAL ATTENUATION OF ATT#1 AT 26.5 GHz

Lab$_i$	DoE with respect to the KCRV	
	D_i (dB)	U_i (dB)
NMIJ/AIST	-0.002	0.017
NIM	0.009	0.006
PTB	-0.018	0.019
LNE	0.021	0.079
INTA	0.013	0.090
METAS*	0.272	0.020
NMISA	0.000	0.165
CMI	0.001	0.060
TUBITAK-UME	-0.007	0.034
NMC-A*STAR	0.003	0.014
NPLI	0.093	0.091
VNIIFTRI	-0.018	0.075
KRISS	-0.010	0.017
NPL	0.141	0.056

*Wrong configuration, see note section V.

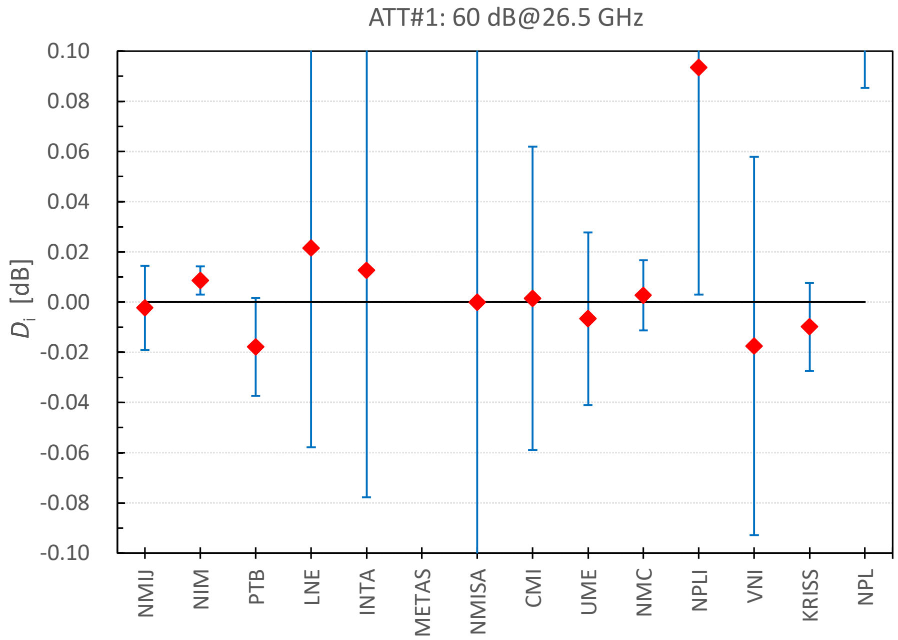


Fig. IX-8 Degrees of equivalence D_i and expanded uncertainty U_i (k = 2) with respect to the KCRV for 60 dB incremental attenuation of ATT#1 at 26.5 GHz. Note: *D_{METAS} =0.272 dB, U_{METAS} = 0.020 dB. U_{NMISA} = 0.165 dB. D_{NPL} = 0.141 dB, U_{NPL} = 0.056 dB. *Wrong configuration, see note section V.

TABLE IX-9 DEGREES OF EQUIVALENCE FOR 60 dB INCREMENTAL ATTENUATION OF ATT#1 AT 40 GHz

Lab$_i$	DoE with respect to the KCRV	
	D_i (dB)	U_i (dB)
NMIJ/AIST	0.003	0.037
NIM	0.005	0.008
PTB	-0.049	0.052
LNE	0.016	0.099
INTA	-0.027	0.150
METAS*	0.355	0.022
NMISA	-0.039	0.173
CMI	-0.015	0.124
TUBITAK-UME	-0.022	0.056
NPLI	0.464	0.119
VNIIFTRI	0.036	0.069
KRISS	-0.013	0.026
NPL	-0.472	0.051

*Wrong configuration, see note section V.

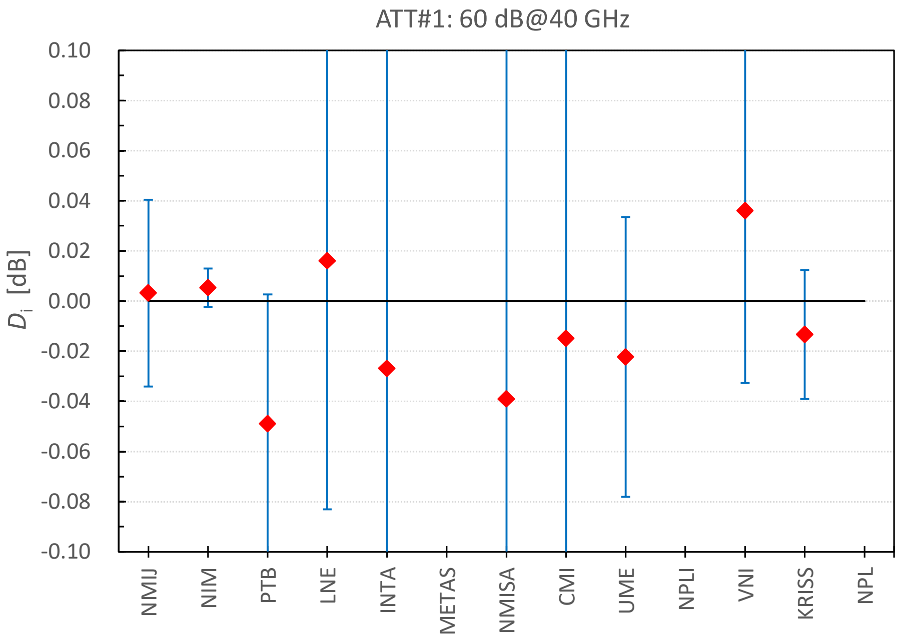


Fig. IX-9 Degrees of equivalence Di and expanded uncertainty Ui (k = 2) with respect to the KCRV for 60 dB incremental attenuation of ATT#1 at 40 GHz. Note: U_{INTA} = 0.150 dB. *D_{METAS} = 0.355dB, U_{METAS} = 0.022 dB. U_{NMISA} = 0.173 dB. U_{CMI} = 0.124 dB. D_{NPLI} = 0.464 dB, U_{NPLI} = 0.119 dB. D_{NPL} = -0.472 dB, U_{NPL} = 0.051 dB. *Wrong configuration, see note section V.

TABLE IX-10 DEGREES OF EQUIVALENCE FOR 80 dB INCREMENTAL ATTENUATION OF ATT#1 AT 18 GHz

Lab$_i$	DoE with respect to the KCRV	
	D_i (dB)	U_i (dB)
NMIJ/AIST	-0.009	0.018
NIM	0.000	0.006
PTB	0.088	0.044
LNE	0.006	0.099
INTA	-0.009	0.109
METAS	-0.004	0.022
NMISA	-0.060	1.097
CMI	-0.013	0.071
TUBITAK-UME	-0.007	0.130
NMC-A*STAR	-0.003	0.018
VNIIFTRI	0.071	0.360
KRISS	0.018	0.021
NPL	-0.402	0.017

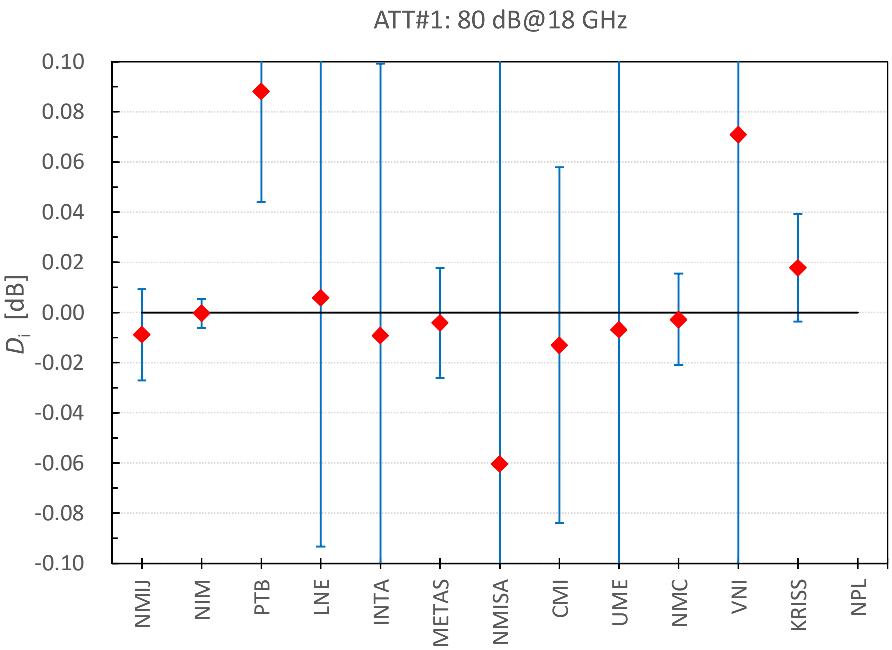


Fig. IX-10 Degrees of equivalence Di and expanded uncertainty Ui (k = 2) with respect to the KCRV for 80 dB incremental attenuation of ATT#1 at 18 GHz. Note: U_{NMISA} = 1.097 dB. U_{UME}= 0.130 dB. U_{VNI}= 0.360 dB. D_{NPL} = -0.402 dB, U_{NPL} = 0.017 dB.

TABLE IX-11 DEGREES OF EQUIVALENCE FOR 80 dB INCREMENTAL ATTENUATION OF ATT#1 AT 26.5 GHz

Lab$_i$	DoE with respect to the KCRV	
	D_i (dB)	Ui (dB)
NMIJ/AIST	-0.002	0.022
NIM	0.000	0.012
PTB	0.005	0.049
LNE	-0.005	0.080
INTA	-0.023	0.108
METAS	0.002	0.024
NMISA	0.127	1.196
CMI	-0.019	0.089
TUBITAK-UME	-0.010	0.133
NMC-A*STAR	-0.005	0.020
VNIIFTRI	0.015	0.360
KRISS	-0.048	0.027
NPL	0.046	0.075

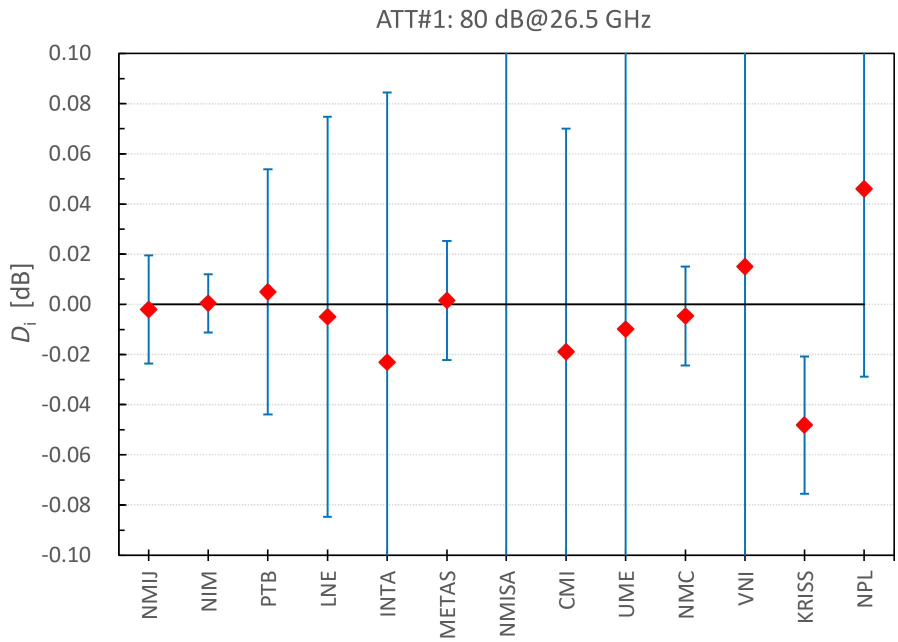


Fig. IX-11 Degrees of equivalence Di and expanded uncertainty Ui (k = 2) with respect to the KCRV for 80 dB incremental attenuation of ATT#1 at 26.5 GHz. Note: U_NMISA = 1.196 dB. U_UME= 0.133 dB. U_VNI= 0.360 dB.

TABLE IX-12 DEGREES OF EQUIVALENCE FOR 80 dB INCREMENTAL ATTENUATION OF ATT#1 AT 40 GHz

Lab$_i$	DoE with respect to the KCRV	
	D_i (dB)	U_i (dB)
NMIJ/AIST	0.017	0.040
NIM	0.001	0.004
PTB	-0.083	0.071
LNE	0.049	0.119
INTA	-0.003	0.278
METAS	-0.045	0.029
NMISA	-0.085	1.280
CMI	-0.019	0.210
TUBITAK-UME	-0.008	0.291
VNIIFTRI	-0.031	0.340
KRISS	0.074	0.039

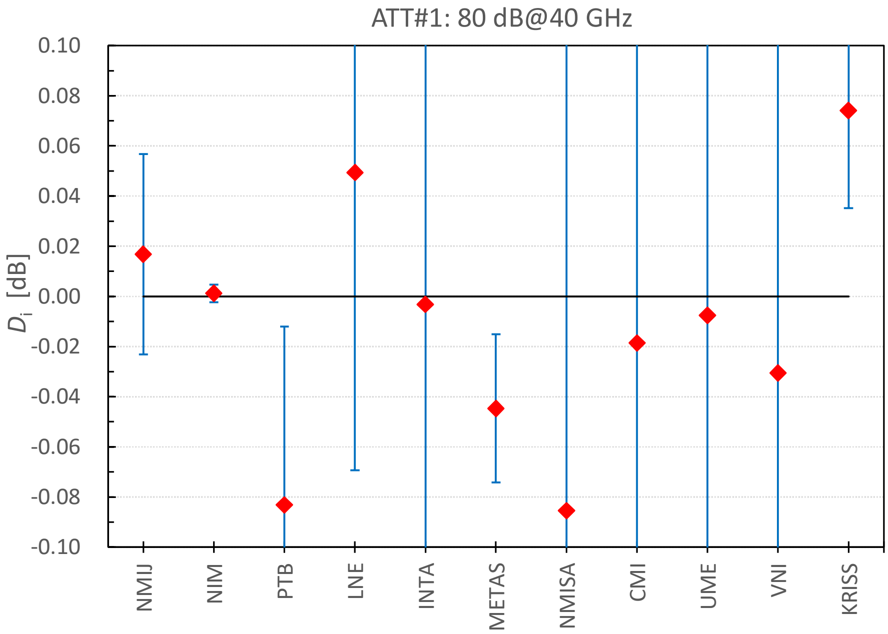


Fig. IX-12 Degrees of equivalence Di and expanded uncertainty Ui (k = 2) with respect to the KCRV for 80 dB incremental attenuation of ATT#1 at 40 GHz. Note: U_{INTA} = 0. 278 dB. U_{NMISA} = 1.280 dB. U_{CMI} = 0.210 dB. U_{UME} = 0.291 dB. U_{VNI}= 0.340 dB.

TABLE IX-13 DEGREES OF EQUIVALENCE FOR 90 dB INCREMENTAL ATTENUATION OF ATT#1 AT 18 GHz

Lab$_i$	DoE with respect to the KCRV	
	D_i (dB)	U_i (dB)
NMIJ/AIST	-0.013	0.027
NIM	-0.006	0.019
PTB	0.096	0.118
LNE	0.024	0.080
INTA	-0.011	0.111
METAS	-0.014	0.032
NMISA	-0.369	2.954
CMI	-0.020	0.094
TUBITAK-UME	-0.016	0.394
NMC-A*STAR	-0.013	0.020
VNIIFTRI	-0.012	1.000
KRISS	0.039	0.029
NPL	0.203	0.022

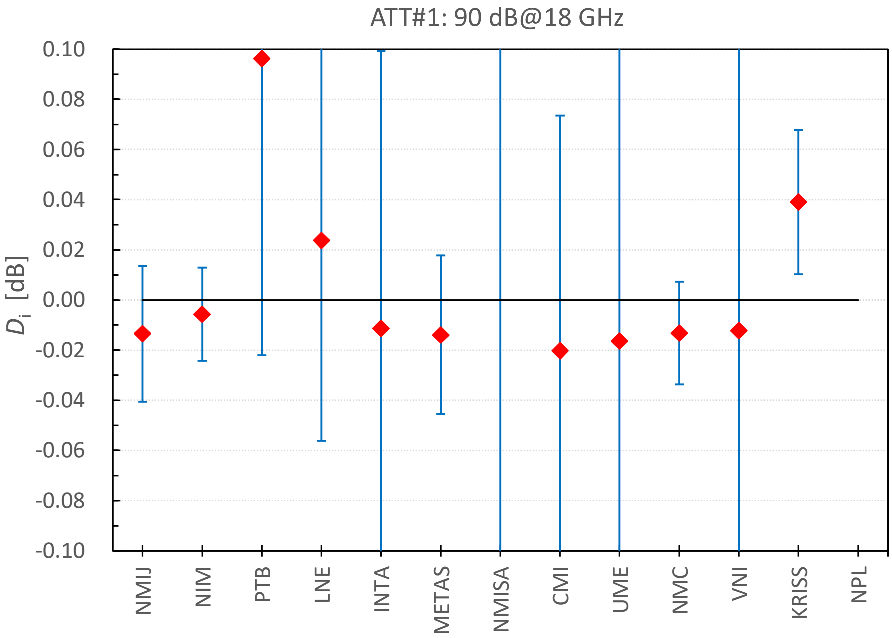


Fig. IX-13 Degrees of equivalence Di and expanded uncertainty Ui (k = 2) with respect to the KCRV for 90 dB incremental attenuation of ATT#1 at 18 GHz. Note: U_{INTA} = 0.111 dB. U_{NMISA} = 2.954 dB. U_{UME} = 0.394 dB. U_{VNI}= 1.000 dB, D_{NPL} = 0.203 dB, U_{NPL} = 0.022 dB.

TABLE IX-14 DEGREES OF EQUIVALENCE FOR 90 dB INCREMENTAL ATTENUATION OF ATT#1 AT 26.5 GHz

Lab$_i$	DoE with respect to the KCRV	
	D_i (dB)	Ui (dB)
NMIJ/AIST	0.000	0.020
NIM	0.001	0.013
PTB	-0.004	0.127
LNE	0.030	0.102
INTA	-0.005	0.208
METAS	-0.002	0.026
NMISA	0.313	3.350
CMI	-0.033	0.184
TUBITAK-UME	-0.013	0.427
NMC-A*STAR	-0.008	0.026
VNIIFTRI	-0.003	1.040
KRISS	-0.020	0.038
NPL	0.028	0.104

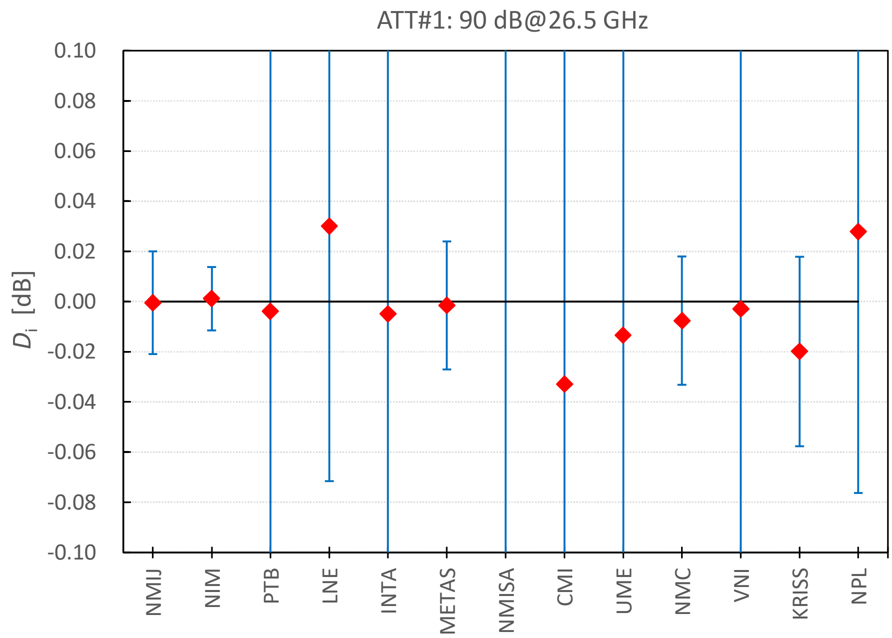


Fig. IX-14 Degrees of equivalence Di and expanded uncertainty Ui (k = 2) with respect to the KCRV for 90 dB incremental attenuation of ATT#1 at 26.5 GHz. Note: U_{PTB} = 0.127 dB. U_{INTA} = 0.208 dB. D_{NMISA} = 0.313 dB, U_{NMISA} = 3.350 dB. U_{CMI} =0.184 dB. U_{UME} = 0.427 dB. U_{VNI}= 1.040 dB.

TABLE IX-15 DEGREES OF EQUIVALENCE FOR 90 dB INCREMENTAL ATTENUATION OF ATT#1 AT 40 GHz

Lab_i	DoE with respect to the KCRV	
	D_i (dB)	Ui (dB)
NMIJ/AIST	0.007	0.039
NIM	-0.002	0.004
PTB	0.117	0.147
LNE	-0.076	0.138
INTA	-0.069	0.701
METAS	-0.056	0.040
NMISA	0.012	3.699
CMI	-0.094	0.405
TUBITAK-UME	-0.081	0.854
VNIIFTRI	-0.056	1.040
KRISS	0.093	0.048

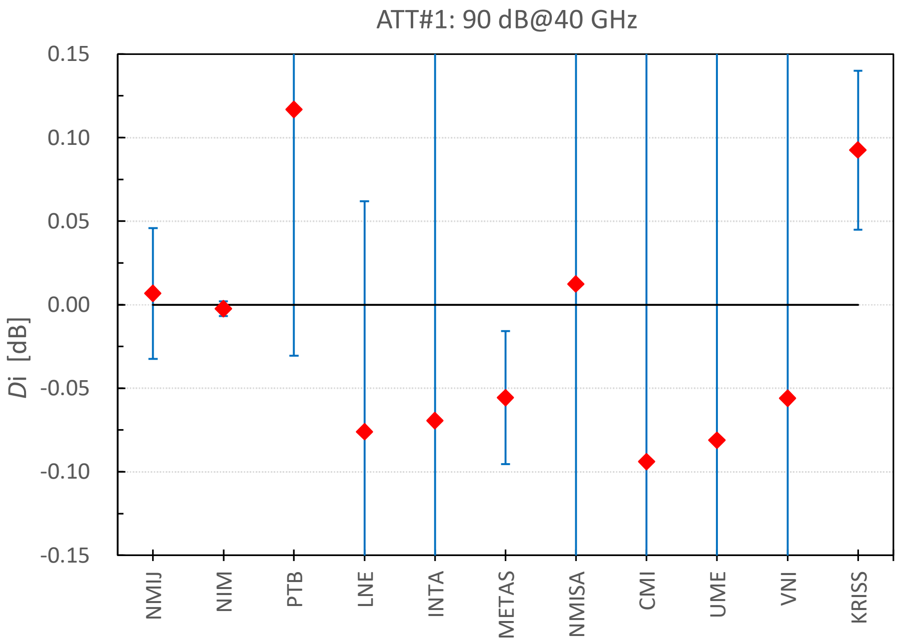


Fig. IX-15 Degrees of equivalence Di and expanded uncertainty Ui (k = 2) with respect to the KCRV for 90 dB incremental attenuation of ATT#1 at 40 GHz. Note: U_{INTA} = 0.701 dB. U_{NMISA} = 3.699 dB. U_{CMI} =0.405 dB. U_{UME} = 0.854 dB. U_{VNI}= 1.040 dB.

B. Travelling Standard ATT#2 (MY46150135)

TABLE IX-16 DEGREES OF EQUIVALENCE FOR 20 dB INCREMENTAL ATTENUATION OF ATT#2 AT 18 GHz

Lab$_i$	DoE with respect to the KCRV	
	D_i (dB)	U_i (dB)
NMIJ	-0.001	0.003
NIM	-0.001	0.005
PTB	0.002	0.006
LNE	0.015	0.020
INTA	-0.006	0.132
METAS	-0.002	0.009
NMISA	-0.001	0.021
CMI	-0.013	0.032
TUBITAK-UME	0.011	0.028
A*STAR	-0.001	0.007
NPLI	-0.021	0.058
VNIIFTRI	0.012	0.024
KRISS	0.008	0.015
NPL	0.034	0.006

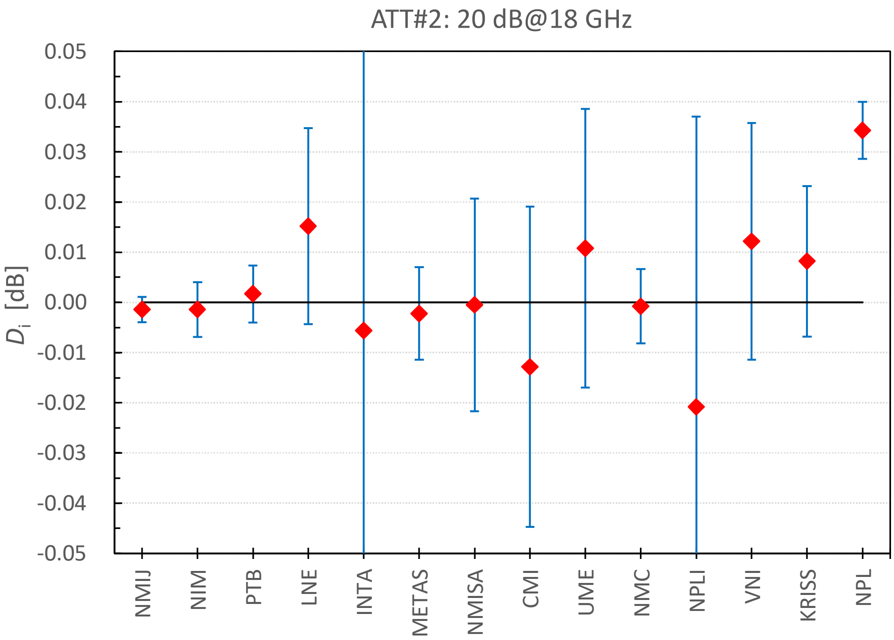


Fig. IX-16 Degrees of equivalence Di and expanded uncertainty Ui (k = 2) with respect to the KCRV for 20 dB incremental attenuation of ATT#2 at 18 GHz. Note: U_{INTA} = 0.132 dB.

TABLE IX-17 DEGREES OF EQUIVALENCE FOR 20 dB INCREMENTAL ATTENUATION OF ATT#2 AT 26.5 GHz

Lab$_i$	DoE with respect to the KCRV	
	D_i (dB)	U_i (dB)
NMIJ	-0.001	0.002
NIM	-0.006	0.014
PTB	0.007	0.010
LNE	0.009	0.020
INTA	-0.001	0.172
METAS	-0.001	0.009
NMISA	0.000	0.020
CMI	-0.001	0.032
TUBITAK-UME	-0.003	0.027
NMC-A*STAR	-0.004	0.009
NPLI	-0.005	0.072
VNIIFTRI	0.003	0.024
KRISS	0.003	0.013
NPL	-0.006	0.012

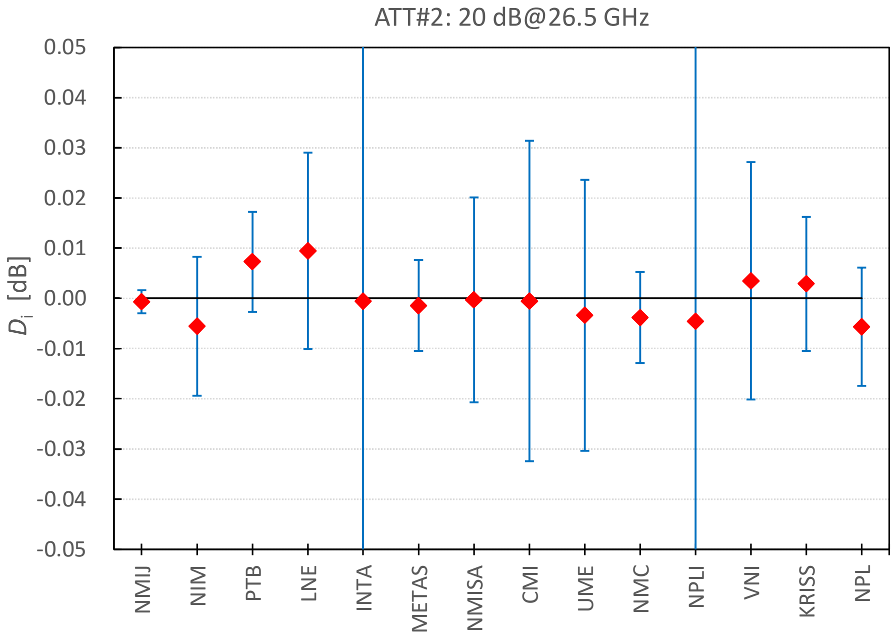


Fig. IX-17 Degrees of equivalence Di and expanded uncertainty Ui (k = 2) with respect to the KCRV for 20 dB incremental attenuation of ATT#2 at 26.5 GHz. Note: U_{INTA} = 0.172 dB. U_{NPLI}= 0.072 dB.

TABLE IX-18 DEGREES OF EQUIVALENCE FOR 20 dB INCREMENTAL ATTENUATION OF ATT#2 AT 40 GHz

Lab_i	DoE with respect to the KCRV	
	D_i (dB)	U_i (dB)
NMIJ	-0.001	0.004
NIM	0.012	0.018
PTB	-0.020	0.028
LNE	0.027	0.021
INTA	0.022	0.233
METAS	-0.004	0.009
NMISA	-0.013	0.023
CMI	0.000	0.040
TUBITAK-UME	0.001	0.029
NPLI	-0.004	0.080
VNIIFTRI	0.028	0.023
KRISS	0.000	0.018
NPL	-0.035	0.007

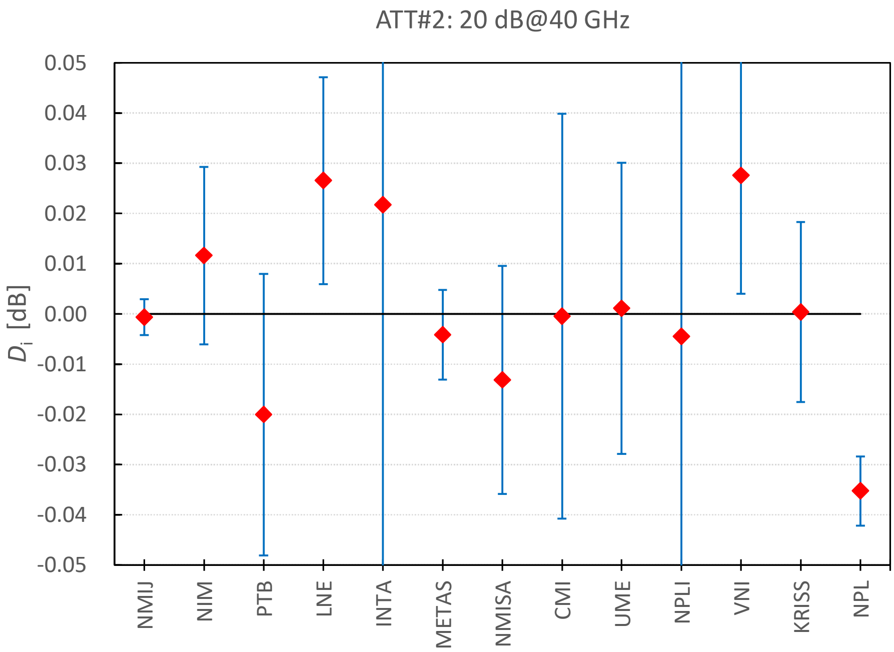


Fig. IX-18 Degrees of equivalence D_i and expanded uncertainty U_i (k = 2) with respect to the KCRV for 20 dB incremental attenuation of ATT#2 at 40 GHz. Note: U_{INTA} = 0.233 dB. U_{NPLI}= 0.080 dB.

TABLE IX-19 DEGREES OF EQUIVALENCE FOR 40 dB INCREMENTAL ATTENUATION OF ATT#2 AT 18 GHZ

Lab$_i$	DoE with respect to the KCRV	
	D_i (dB)	U_i (dB)
NMIJ/AIST	-0.001	0.007
NIM	0.000	0.004
PTB	0.005	0.023
LNE	0.039	0.080
INTA	-0.004	0.142
METAS	-0.003	0.017
NMISA	-0.005	0.120
CMI	0.015	0.046
TUBITAK-UME	0.011	0.030
NMC-A*STAR	0.003	0.010
NPLI	-0.002	0.078
VNIIFTRI	0.011	0.042
KRISS	0.000	0.016
NPL	0.037	0.009

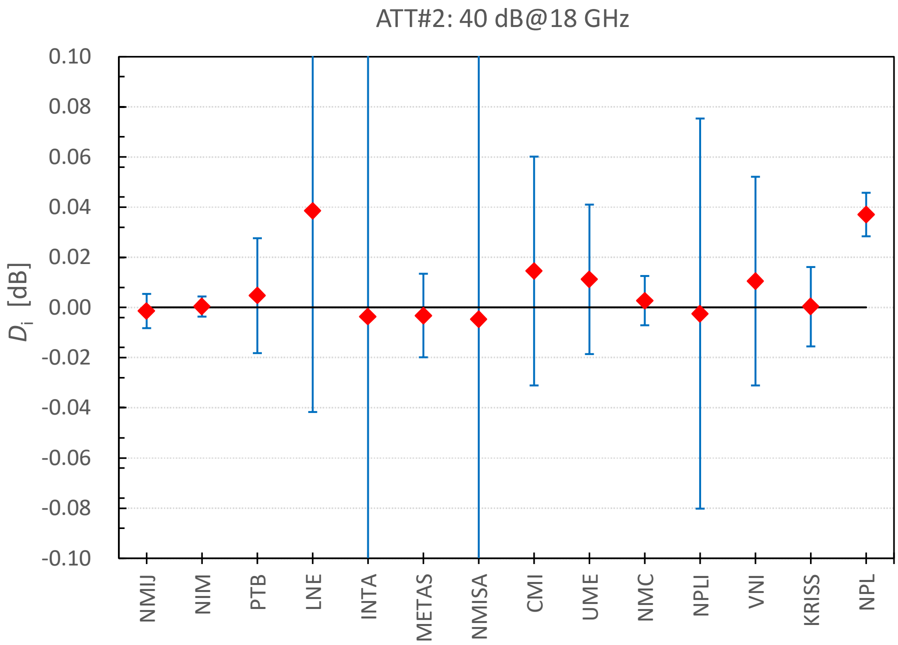


Fig. IX-19 Degrees of equivalence *D*i and expanded uncertainty *U*i ($k = 2$) with respect to the KCRV for 40 dB incremental attenuation of ATT#2 at 18 GHz. Note: U_{INTA} = 0.142 dB. U_{NMISA}= 0.120 dB.

TABLE IX-20 DEGREES OF EQUIVALENCE FOR 40 dB INCREMENTAL ATTENUATION OF ATT#2 AT 26.5 GHz

Lab$_i$	DoE with respect to the KCRV	
	D_{i} (dB)	Ui (dB)
NMIJ	0.000	0.005
NIM	-0.001	0.015
PTB	0.018	0.038
LNE	0.010	0.080
INTA	0.001	0.203
METAS	-0.004	0.016
NMISA	-0.014	0.134
CMI	-0.020	0.049
TUBITAK-UME	-0.003	0.031
NMC-A*STAR	0.005	0.014
NPLI	0.000	0.084
VNIIFTRI	-0.001	0.041
KRISS	0.009	0.013
NPL	-0.014	0.023

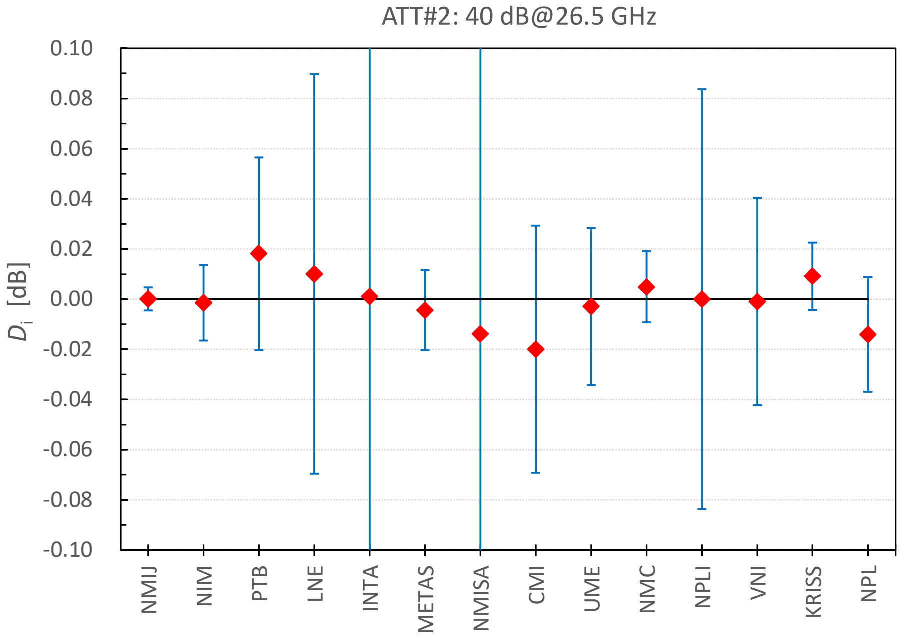


Fig. IX-20 Degrees of equivalence Di and expanded uncertainty Ui (k = 2) with respect to the KCRV for 40 dB incremental attenuation of ATT#2 at 26.5 GHz. Note: U_{INTA} = 0.203 dB. U_{NMISA}= 0.134 dB.

TABLE IX-21 DEGREES OF EQUIVALENCE FOR 40 dB INCREMENTAL ATTENUATION OF ATT#2 AT 40 GHz

Lab$_i$	DoE with respect to the KCRV	
	D_i (dB)	U_i (dB)
NMIJ	-0.006	0.009
NIM	0.019	0.016
PTB	-0.023	0.037
LNE	0.014	0.080
INTA	0.011	0.142
METAS	0.010	0.018
NMISA	-0.039	0.168
CMI	-0.013	0.084
TUBITAK-UME	-0.007	0.041
NPLI	0.166	0.092
VNIIFTRI	0.026	0.041
KRISS	-0.014	0.018
NPL	-0.061	0.012

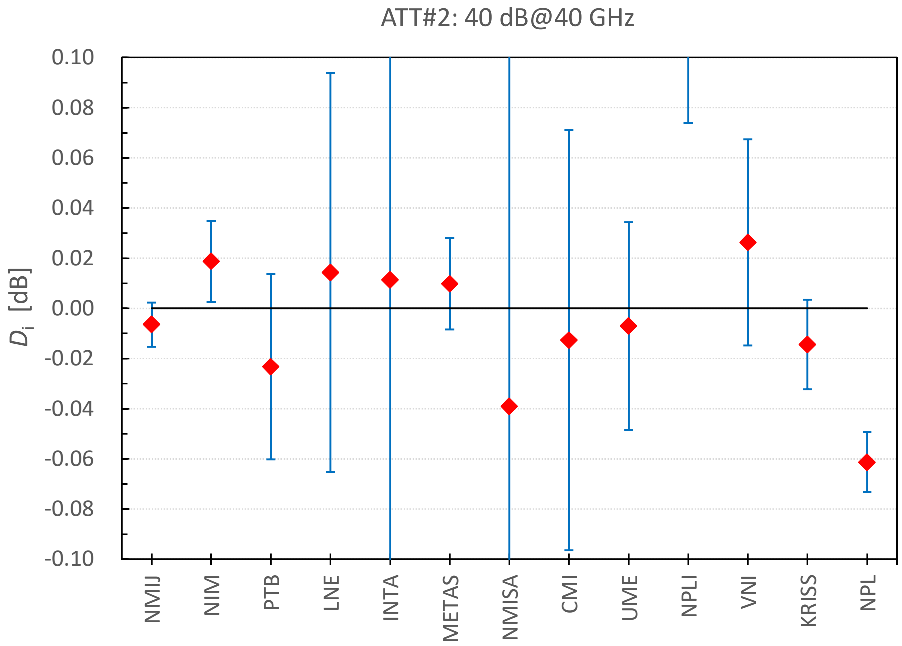


Fig. IX-21 Degrees of equivalence Di and expanded uncertainty Ui (k = 2) with respect to the KCRV for 40 dB incremental attenuation of ATT#2 at 40GHz. Note: U_{INTA} = 0.142 dB. U_{NMISA} = 0.168 dB, D_{NPLI} = 0.166 dB, U_{NPLI} = 0.092 dB.

TABLE IX-22 DEGREES OF EQUIVALENCE FOR 60 dB INCREMENTAL ATTENUATION OF ATT#2 AT 18 GHz

Lab$_i$	DoE with respect to the KCRV	
	D_i (dB)	U_i (dB)
NMIJ	-0.005	0.016
NIM	-0.003	0.005
PTB	0.093	0.021
LNE	0.046	0.080
INTA	-0.009	0.123
METAS	-0.003	0.024
NMISA	-0.045	1.133
CMI	-0.033	0.060
TUBITAK-UME	0.014	0.130
NMC-A*STAR	-0.001	0.014
NPLI	0.147	0.104
VNIIFTRI	0.014	0.340
KRISS	0.005	0.021
NPL	0.005	0.006

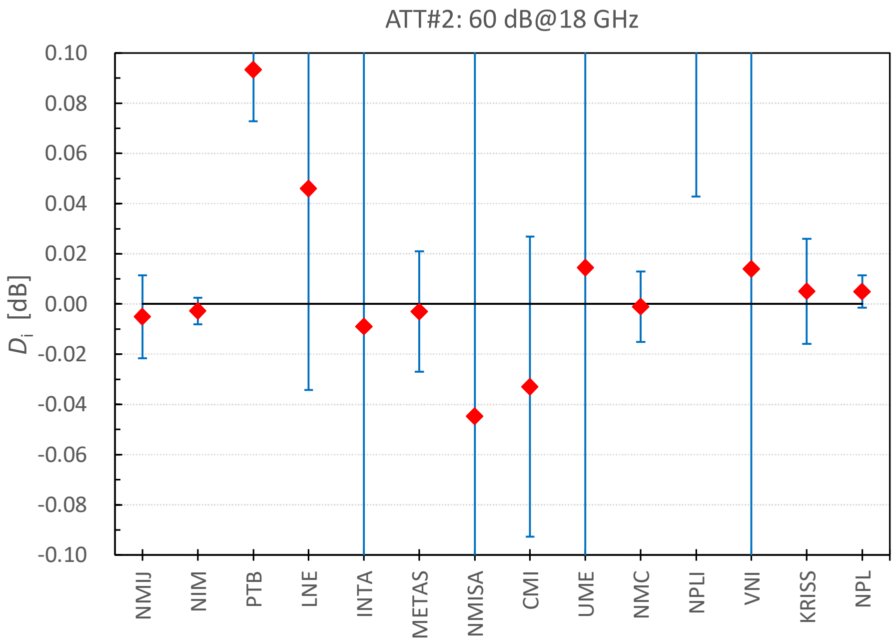


Fig. IX-22 Degrees of equivalence Di and expanded uncertainty Ui (k = 2) with respect to the KCRV for 40 dB incremental attenuation of ATT#2 at18 GHz. Note: U_{INTA} = 0.123 dB. U_{NMISA} = 1.133 dB, U_{UME} = 0.130 dB, D_{NPLI} = 0.147 dB, U_{NPLI} = 0.104 dB, U_{VNI} = 0.340 dB.

TABLE IX-23 DEGREES OF EQUIVALENCE FOR 60 dB INCREMENTAL ATTENUATION OF ATT#2 AT 26.5 GHz

Lab$_i$	DoE with respect to the KCRV	
	D_i (dB)	Ui (dB)
NMIJ	0.006	0.013
NIM	0.000	0.009
PTB	0.017	0.042
LNE	0.043	0.081
INTA	-0.004	0.208
METAS	-0.001	0.022
NMISA	-0.124	1.210
CMI	-0.006	0.081
TUBITAK-UME	0.027	0.133
NMC-A*STAR	0.014	0.019
NPLI	-0.237	0.111
VNIIFTRI	0.024	0.340
KRISS	-0.008	0.019
NPL	-0.013	0.033

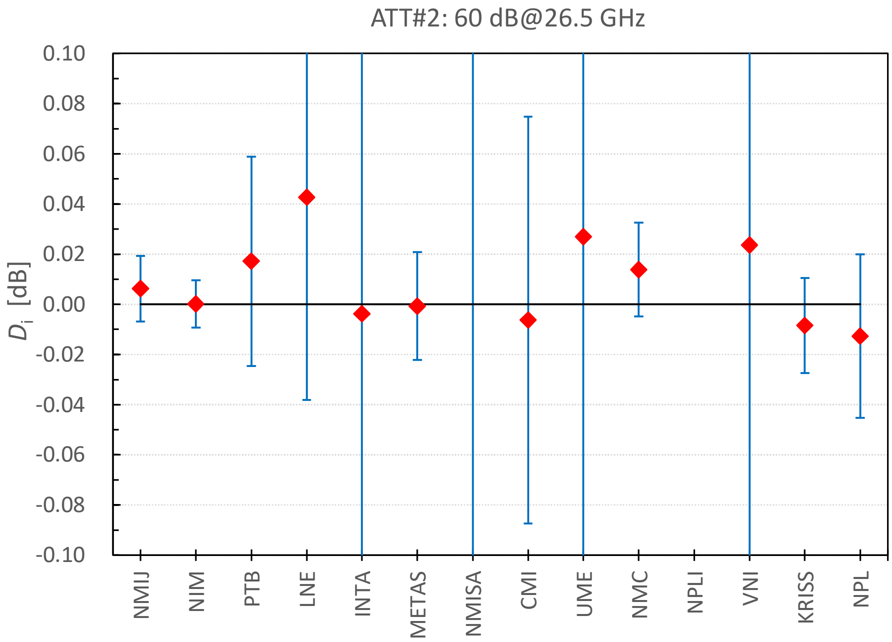


Fig. IX-23 Degrees of equivalence Di and expanded uncertainty Ui (k = 2) with respect to the KCRV for 60 dB incremental attenuation of ATT#2 at 26.5GHz. Note: U_{INTA} = 0.208 dB. D_{NMISA} = -0.124 dB, U_{NMISA} = 1.210 dB, U_{UME} = 0.133 dB, D_{NPLI} = -0.237 dB, U_{NPLI} = 0.111 dB, U_{VNI} = 0.340 dB.

TABLE IX-24 DEGREES OF EQUIVALENCE FOR 60 dB INCREMENTAL ATTENUATION OF ATT#2 AT 40 GHz

Lab$_i$	DoE with respect to the KCRV	
	D_i (dB)	Ui (dB)
NMIJ/AIST	-0.013	0.034
NIM	0.007	0.013
PTB	-0.043	0.062
LNE	0.014	0.079
INTA	0.006	0.151
METAS	-0.001	0.023
NMISA	-0.283	1.523
CMI	-0.018	0.209
TUBITAK-UME	-0.014	0.290
NPLI	0.076	0.117
VNIIFTRI	0.009	0.340
KRISS	-0.055	0.031

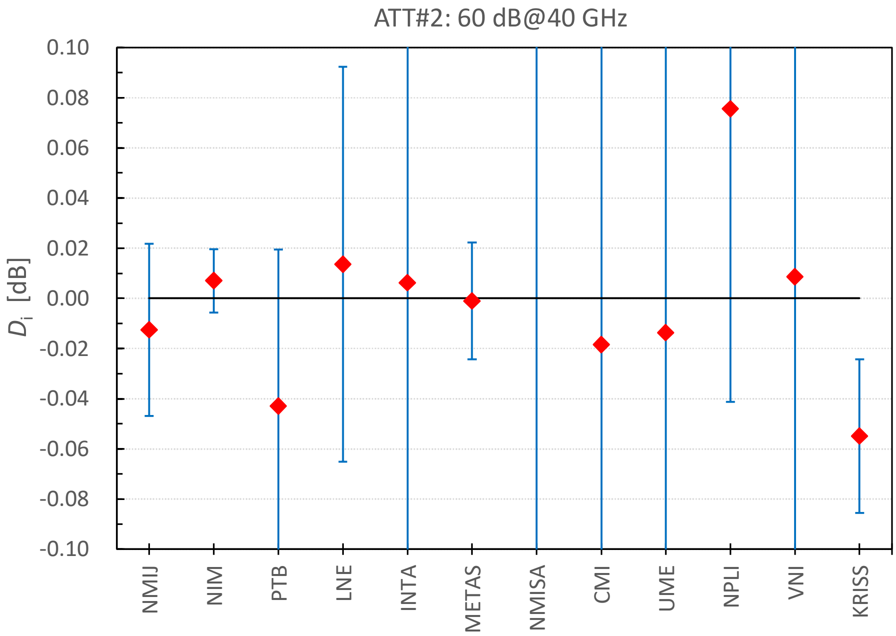


Fig. IX-24 Degrees of equivalence Di and expanded uncertainty Ui (k = 2) with respect to the KCRV for 60 dB incremental attenuation of ATT#2 at 40 GHz. Note: U_{INTA} = 0.151 dB. D_{NMISA} = -0.283 dB, U_{NMISA} = 1.523 dB, U_{CMI} = 0.209 dB, U_{UME} = 0.290 dB, U_{VNI} = 0.340 dB.

X CONCLUSION

Key Comparison CCEM.RF-K26 Attenuation at 18 GHz, 26.5 GHz and 40 GHz using a step attenuator has been performed from January 2015 to February 2018.

Fourteen NMIs participated in this intercomparison, and the KCRVs were determined from the measurement results of five to ten NMIs, depending on the attenuation and frequency. Among the NMIs whose results were considered in calculation of the KCRVs, the majority of NMIs performed measurements with the dedicated attenuation measurement systems (IF/RF substitution, voltage ratio, etc.), whereas two NMIs used commercial VNAs.

Two traveling standards, identified as ATT#1 and ATT#2, were circulated, and both remained stable throughout the entire comparison. The traveling standard ATT#2 equipped with 10-dB pads to minimize mismatch errors proved its effectiveness by showing a significant reduction in the number of statistical outliers.

All measurements specified in the protocol, attenuation steps of 20 dB, 40 dB, 60 dB, 80 dB and 90 dB of the traveling standard ATT#1 and of 20 dB, 40 dB, 60 dB of the traveling standard ATT#2 at frequency of 18 GHz, 26.5 GHz, and 40 GHz, respectively, were calculated for each KCRV. The MAD method and the Chi-squared test were used to test for presence of outliers and data inconsistencies. The reported results were related to the KCRV by calculating the Degrees of Equivalence and their expanded uncertainties.

XI References

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8. M.G. Cox, "The evaluation of key comparison data," Metrologia, 39, 589 – 595.

Appendix A – Treatment of the results [1]

Key comparison **CCEM.RF-K26**

MEASURANDS: Attenuation

Pilot Laboratory: NMIJ (Japan)

A_{x_i} result of measurement of x dB attenuation step carried out by laboratory i.

$u(A_{x\_i})$ combined uncertainty of A_{x_i} reported by laboratory i.

where, x=20, 40, 60, 80 or 90, indicates the measured attenuation step.

The key comparison reference values (KCRVs), A_{x_R}, for this comparison are calculated using the weighted mean from the results of the participants. Data outlying results are excluded in obtaining KCRV.

The identification of data outliers is first examined using the Median of Absolute Deviations (MAD) [6], [7] which is defined as

$$\sigma \approx S(MAD) \equiv k_1\ median_j\{|Y_j - Y_{med}|\}, \tag{1}$$

where k_1 is a multiplier determined by simulation and Y_{med} is the median of the sample $\{Y_i\}$. According to [7], the value of k_1 for 8, 9 and 10 participants are 1.671, 1.633 and 1.626, respectively. A value of Y_j, which differs from the median by more than 2.5 times $S(MAD)$, is considered an outlier, and this criterion may be used to test each point:

$$|Y_i - Y_{med}| > 2.5 \times S(MAD). \tag{2}$$

Should the inequality (2) be true for any point Y_i, this point is identified as an outlier.

The KCRVs, A_{x_R}, for this comparison is calculated using the weighted mean [7][8] from the results of the participants as follows:

$$A_{x\_R} = \left(\sum_{i=1}^{N\prime} \frac{A_{x\_i}}{u^2(A_{x\_i})}\right) \times \left(\sum_{i=1}^{N\prime} \frac{1}{u^2(A_{x\_i})}\right)^{-1} , \tag{3}$$

where x = 20, 40, 60, 80 or 90 and N' is the number of participants after inconsistent data has been identified and discarded as in (2).

The combined uncertainties associated with the KCRV are obtained as follows, which also includes the standard uncertainty of the traveling standard $u(ATT\#1, 2_x)$ due to instability or variations during circulation to all participants.

$$u(A_{x\_R}) = \left(\sum_{i=1}^{N'} \frac{1}{u^2(A_{x\_i})} + u^2\,(ATT\#1, 2_x) \right)^{-1/2} . \tag{4}$$

The degrees of equivalence ΔA_{x_i} of each laboratory with respect to the reference value are given by

$$D_i = \Delta_{A_{x\_i}} = A_{x\_i} - A_{x\_R} \; . \tag{5}$$

The expanded uncertainty in ΔA_{x_i} is given by

$$U_i = U(\Delta_{A_{x\_i}}) = 2.0\sqrt{u^2(A_{x\_i}) - u^2(A_{x\_R})} \; . \tag{6}$$

The Chi-squared test [7],[8] is then performed to check that the data are consistent. If this data consistency check fails, further data re-identification followed by re-calculation of the KCRV are performed until the test succeeds. In this case, data removal is conducted from the one with the largest $| D_i / U_i|$ value.

If A_{x_i} is not used in the calculation of the KCRV, then the expanded uncertainty in ΔA_{x_i} is given by

$$U_i = U(\Delta_{A_{x\_i}}) = 2.0\sqrt{u^2(A_{x\_i}) + u^2(A_{x\_R})} \; . \tag{7}$$

The factor 2.0 in (6) and (7) gives 95 % coverage under the assumption of normality.

Appendix B – Technical Reports from participating laboratories

The following reports on the measurement techniques were received from the participating laboratories.

B.1 NMIJ Measurements (Anton P. Widarta)

Measurements

All attenuation measurements were carried out using the NMIJ RF attenuation measurement working standard system works on principle of intermediate frequency (IF=30 MHz) substitution technique by employing a resistive step attenuators assembly as an IF reference standard and a general-purpose receiver as a sensitive level detector (*A. Widarta in Proceedings ICEE 2008, Okinawa, Japan, July, 2008 and A. Widarta et al. in 2014 CPEM Conf. Dig., Rio de Janeiro, Brazil, July 2014)*.

The device under test was inserted between the test ports were impedance tuned using slide-screw tuner directly connected to the coaxial isolators. Each tuner-isolator assembly was mounted in a sturdy shield box to minimize the leakage or crosstalk effects. The reflection coefficients of the test ports and the device under test were also measured and used to calculate the mismatch uncertainty. Single step measurement technique, which uses a good linear range of the mixer, i.e. -20 dBm to -80 dBm, was used for measurements up to 60 dB. The double step measurement technique was used for measurements of attenuation higher than 60 dB in order to keep the noise effect relatively small *(A. Widarta in 2012 CPEM Conf. Dig., Washington DC, USA, July 2012)*

Traceability

Attenuation traceability of the system is ensured by calibrating the IF reference standard using the originally developed 'NMIJ Precision IF Attenuation Measurement System,' with an inductive voltage divider (IVD) as the reference standard (*A. Widarta et al., IEEE-TIM, 52-2, pp.302-305, April 2003*). Voltage ratio of the IVD is traceable to the Japan National Standard for Low Frequency Voltage Ratio.

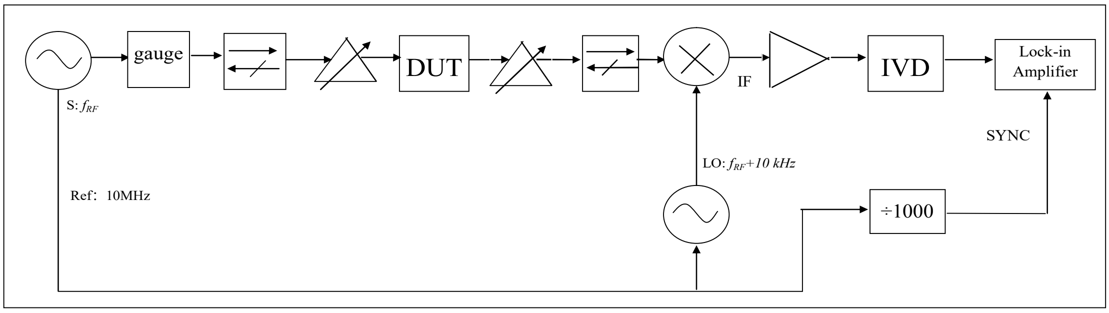
Reflection coefficient or impedance traceability was provided by NMIJ S-parameter standard group.

Uncertainty Sources

The measurement uncertainties were evaluated using the GUM, include the type A standard uncertainty or the standard deviation of the mean and the type B standard uncertainty, which consists of the systemic uncertainties as follows: 1. Reference Standard, 2. System Linearity, 3. Leakage, 4. Drift, 5. Digital Reading Resolution, 6. Stability, 7. Block Gauge (for measurements of attenuation higher than 60 dB using the double step technique) and 8. Mismatch.

B.2 NIM Measurements (GAO Qiulai)

The attenuation standard at NIM adopts audio substitution using Inductive Voltage Divider (IVD) as reference standard. The principle of the system is shown in the following figure.



The RF signal goes through device under test (DUT) and incidents a double balanced mixer. The IF frequency of the mixer can be 10 kHz when RF and LO frequencies are set to be f_{RF} and f_{RF} +10 kHz. The IF signal goes through the IVD and is measured with a Lock-in Amplifier (LA). The ratio value of the IVD is set based on the IF signal measurement result to compensate the attenuation change in the RF channel. The measured attenuation is derived from the ratio value of the IVD since the mixer can be considered as linear device in magnitude when the LO level is 30 dB higher than the RF signal. Therefore, the attenuation can be expressed by

$$A = 20 \log_{10} \frac{D_2}{D_1} (dB) \quad ,$$

where the D1 and D2 are ratio values of the IVD when the attenuator is set at its datum and measured positions.

The attenuation standard is single-channel system. The signal source and LO source are locked together to a 10 MHz reference. IF synchronization (SYNC) signal is obtained from a frequency divider in which the 10 MHz reference of the signal source is divided by 1000. Therefore the correlation between the IF signal and IF SYNC is fair good at RF frequency below 40 GHz.

A pair of automatic tuners is used as test ports in order to improve the mismatch uncertainty. The other port of the tuner is connected with two isolators. The reflection coefficients of the test ports are less than 0.01 after they are calibrated with a VNA previously. In addition, a gauge connected to RF source directly is used for RF partial substitution to improve non-linearity and noise uncertainties.

The All devices in the system are traced to related standard at NIM. The IVD is traced to AC ratio standard. The signal sources are traced to signal generator standard. The LA is calibrated base on the operation manual.

The measurement uncertainty is consisting of reference standard, mismatch, system linearity, leakage, resolution, connector repeatability, attenuator stability contributions are and experimental standard uncertainty of the mean of 10 measurements. For the calculation of mismatch uncertainty, two formulas were adopted. For the travelling standard ATT#1, following formula was adopted

$$u_{MIS} = \frac{8.686}{\sqrt{2}}[|\Gamma_G|^2(|s_{11b}|^2 + |s_{11e}|^2) + |\Gamma_L|^2(|s_{22b}|^2 + |s_{22e}|^2) + |\Gamma_G|^2|\Gamma_L|^2(|s_{21b}|^4 + |s_{21e}|^4)]^{1/2}$$

Since For the travelling standard ATT#2 were connected two fixed attenuators, therefore following formula was adopted for calculation of the mismatch uncertainty.

$$u_{mis} = \frac{8.686}{\sqrt{2}}\{|\Gamma_G|^2(|S_{11b} - S_{11e}|^2) + |\Gamma_L|^2|s_{22b} - S_{22e}|^2\}^{\frac{1}{2}}$$

Reference

I.A. Harris, C. Eng. and F.L. Warner, “Re-examination of mismatch uncertainty when measuring microwave power and attenuation” IEE PROC., Vol. 128, pt. H, No. 1 FEBRURY 1981, pp. 35-41

B.3 PTB Measurements (Dirk Schubert)

Power Ratio

The PTB RF standard attenuation measuring equipment for attenuation values up to 30 dB is working with the power ratio method using DC substitution. A stabilized RF power of 10 mW is fed into the DUT. The power transmitted through the DUT is measured with a thermistor mount which is connected to a self-balancing bolometer bridge. The bridge voltages are measured using two digital voltmeters. The attenuation is calculated from two power levels, which correspond to the ON and OFF settings of the DUT. Source and load side of the insertion point for the DUT are matched with tuners. Traceability to the German national standard for DC voltage is achieved by calibration of the digital voltmeters

RF Series Substitution

The PTB RF standard attenuation measuring equipment for attenuation values above 30 dB is working with the RF series substitution method. A stabilized RF power of 10 mW is fed into the DUT. The power transmitted through the DUT is detected with a sensitive receiver. The attenuation of the DUT is measured by comparison with a chain of reference attenuators which are calibrated with the power ratio method. The small difference between DUT and reference chain is measured using the receivers synchronous detector only. The attenuation is calculated from the value of the reference chain and the measured difference between DUT and reference chain. Source and load side of the insertion point for the DUT are matched with tuners. Traceability to national standards is achieved by calibration of the synchronous detector and the components of the reference chain with the power ratio setup which again is traceable to the German national standard for DC voltage.

B.4 LNE Measurements (D. Allal, R. Picou, M. Bunel)

Measurement technique

All measurements were carried out using an IF substitution method at 30 MHz. A TEGAM VM7 attenuation measurement system was used.

The measurement system was well matched by using impedance tuners at both ports and possibly fixed attenuators in order to minimize mismatch uncertainty. The reflection coefficient was measured using a vector network analyser.

Traceability route

A comparison among four methods (Power ratio method up to 20 dB, LF substitution after square-law detection, IF substitution, VNA) is performed periodically. A WBCO attenuator is used to perform a check measurement at each 20 dB step for any attenuation range higher than 20 dB.

B.5 INTA Measurements (Manuel R. Higuero)

Measurements

Measurement of Voltage Reflection Coefficient was made with an HP 8510C Vector Network Analyser, traceable at that time to NPL via calibrated air lines and a calibrated step attenuator, and making use of a verification kit (also traceable to NPL at that time) in order to verify the measurements.

Measurement of incremental Insertion Loss was made with an Agilent N5531S Measuring Receiver and an Agilent E8257D Signal Generator. Use was made also of two padding attenuators for measurement of Att #1 under test.

Traceability

- For the N5531S Measuring Receiver the linearity contribution was characterized making use of the above-mentioned calibrated step attenuator (traceable to NIST). The rest of uncertainty contributions were taken from the manufacturer specifications, as well as the way to combine them together. Load Match was dependent on the attenuation introduced by the receiver at each measurement level, and was combined with the [S]-parameters of the padding attenuators and / or cables used (traceable to NPL via the VNA).
- For the E8257D Signal Generator, the ripple technique was used with the aid of a calibrated airline (traceable to NPL) in order to measure its Voltage Reflection Coefficient. Source Match was combined with the [S]-parameters of the padding attenuators and / or cables used (traceable to NPL via the VNA).

B.6 METAS Measurements (Michael Wollensack)

Measurements

The scattering parameters were measured using a vector network analyzer (VNA). The VNA has been error corrected with an over-determined calibration technique including Opens, Offset-Shorts, Flush-Shorts and Loads.

Traceability to SI units: Above 500 MHz the traceability of these measurements is established by a set of primary calibration standards (Airlines, Offset-Shorts and Flush-Shorts). The model of each primary standard includes imperfections of the coaxial connector. Dimensional measurements, material properties and electrical measurements serve as input to EM-field simulations, analytical equations and optimization which result in the S-parameters of each primary standard.

The incremental attenuation is the absolute difference between each attenuation step and the 0 dB state.

The linearity of the VNA is characterized with a known step attenuator which was measured with a WBCO system.

To reduce the uncertainty for higher attenuation states the single section are measured and the other combinations are computed, see http://cp.literature.agilent.com/litweb/pdf/5991-1268EN.pdf

B.7 NMISA Measurements (Linoh Magagula)

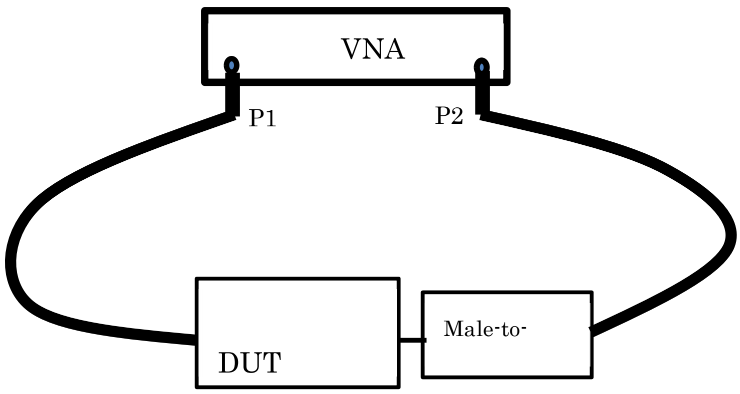
Traceability and measurement technique

Measurements for attenuation and reflection coefficients were performed with an Agilent E8361C VNA. The VNA was calibrated using the SOLT calibration technique employing Agilent 85056A mechanical standards. The attenuation results are traceable to the national standard, the WBCO piston attenuation standard (traceable to other parameters), via a precision measuring receiver and step attenuator, through the linearity calibration of the VNA system.

The WBCO attenuator was calibrated overseas using a parallel substitution system against their national WBCO attenuation standard.

The reflection coefficients results are traceable to physical dimensions of airline standards which were determined by dimensional metrology systems at an overseas NMI.

The VNA calibration and DUT measurements were done at the end of test port cables, which were connected to the two VNA ports. That is, 2.4 mm Agilent flexible test port cables were connected to the VNA ports and a relevant adapter used at the end of the cables to enable suitable connection of the travelling standards.



B.8 CMI Measurements (Karel Dražil)

Method of measurement

Incremental attenuation of the travelling standards was obtained by two alternative ways.

1. Results based on the VNA measurement (data supplied for all three frequencies but only 40 GHz data are intended to be used for the KCRV evaluation)

Measurement of S-parameters was performed using the vector network analyzer Agilent E8364B and calibration kit 85056A. The VNA was calibrated using the SOLR technique where the female-to-female adaptor was used as the “unknown THRU“. The incremental attenuation was computed as the ratio of the S_{21} values (or difference in dB) for the setting value and 0 dB positions.

2. Results based on the spectrum analyzer measurement (18 GHz and 26.5 GHz)

Measurement was performed using spectrum analyzer Agilent E4440A with power splitter and levelling power meter. Power level approximately of 6 dBm was applied to the input of the travelling standards. The systematic errors due to mismatch have been removed by the vector corrections based on S-parameter measurement of the travelling standards and another parts of the instrumentation.

Traceability of the measurement

Measurements are traceable to the Czech national standards. Attenuation measurements are traced back to the standard for DC voltage. Traceable relative power measurements in the range up to (25 – 30) dB are realized by DC substitution utilizing thermistor mounts (8478B, K486A, R486A) and self-balancing bridge (HP 432A). The bridge voltages are measured using digital voltmeters. Linearity of the VNA is checked using step attenuators characterized with the help of thermistor mounts in combination with sensitive receiver or power sensor. Linearity of the spectrum analyzer is calibrated successively in several steps utilizing the thermistor mount with the help of the (uncalibrated) step attenuator. Measurements of reflection coefficient are traceable to SI units through dimensional measurements of the reference coaxial air line and offset shorts.

B.9 TÜBİTAK-UME Measurements (Handan Sakarya and Murat Celep)

Measurement Method

TÜBİTAK UME used VNA to measure the parameters of the comparison standards. To connect the comparison standards to the VNA port 1 (f), 2.4 mm m-m adapter and 2.4 mm flexible cable pairs were used at port 1 and port 2. The R&S ZVA50 VNA with port 1 (m) and port 2 (m) is calibrated using Agilent 85056A calibration kit using firmware (TOSM – Thru, Open Short Match) calibration software. IF bandwidth, power and average are set to 10 Hz, 0 dBm and 5 respectively.
Reflection coefficients of the comparison standards were measured one by one with VNA port 2 after one port calibration was done.
A software program written in Visual Basic is used for obtaining the corrected data from the VNA. Further data analysis is done in spreadsheets with excel macro program incremental attenuation of the travelling standards was obtained by two alternative ways.

Reference used in the measurements

Rohde & Schwarz ZVA50 Network Analyzer used during the measurements of travelling standards. The Agilent 85057B Verification Kit with Serial No 3105A00521 was calibrated by NPL-UK.

B.10 A*STAR Measurements (Neo Hoon, Meng Yusong)

Method of Measurement

The travelling devices were measured at the National Metrology Centre at 18 GHz and 26.5 GHz under the ambient conditions stated above. The incremental attenuation was measured with an audio frequency substitution (5kHz) attenuation measurement system. The magnitude of reflection coefficients of the travelling standards and measurement system 'source' and 'load' were measured with a vector network analyser.

The audio frequency substitution attenuation is traceable to an inductive voltage divider (serial no.: M2010506), which is traceable to National Physical Laboratory (NPL_UK).

During the measurement, the RF signal was connected to port 1 of the travelling standard. The incremental attenuation (in dB) is from the datum position (0 dB) to the setting value. Single step measurement technique is used for attenuation up to 30 dB. However, double step measurement technique, which is switching the variable attenuator into and out from the circuit, is used for attenuation greater than 30 dB.

The magnitude of reflection coefficient of the travelling standards and measurement system 'source' and 'load' were used to calculate the mismatch uncertainty.

The setup for the audio frequency substitution attenuation measurement system is as shown in Figure 1.

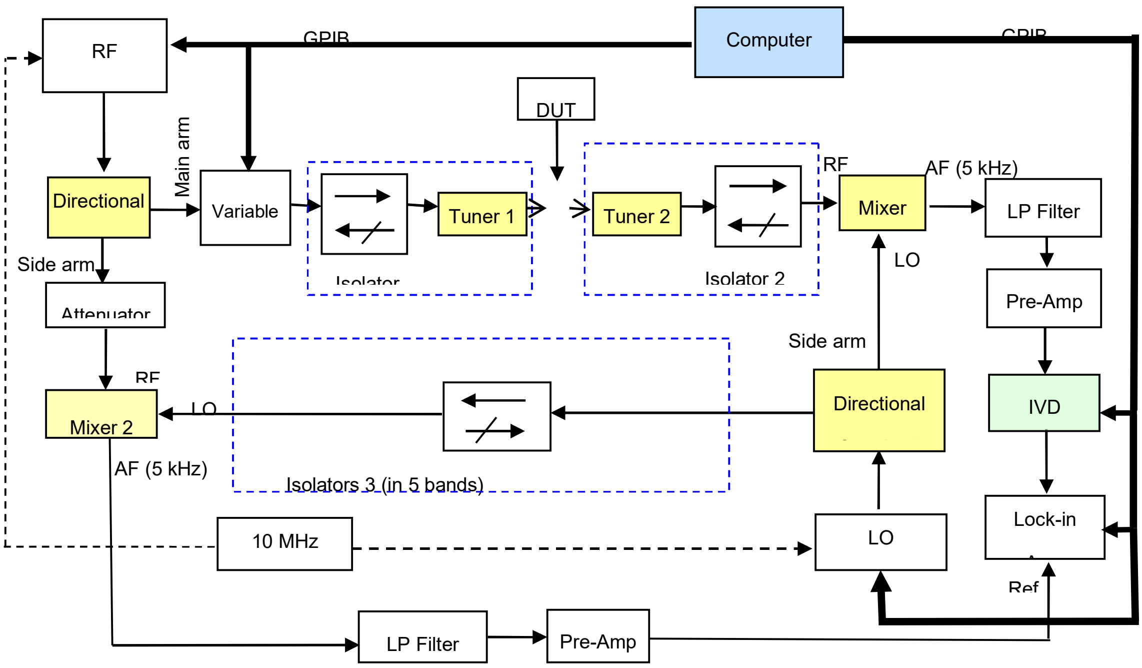


Figure 1 : AF Substitution Attenuation Measurement System

B.11 NPLI Measurements (Jyoti Chauhan, Satya Kesh Dubey **)**

Measurement description:

The two traveling standards(Step Attenuator, 84906L; Step Attenuator with 10-dB pads, 84905M) received for the comparison were checked for their pin depths. The incremental attenuation in dB of the two travelling standards from the datum position (0 dB) to the setting value has been measured using 30 MHz IF substitution technique for the three frequency points i.e., 18 GHz, 26.5 GHz and 40 GHz.

The incremental attenuation of the traveling standard has been measured five times for each attenuation step and the mean value has been reported. The combined standard uncertainty has been calculated and reported accordingly [1, 2].

The magnitude of complex reflection coefficients of the standards and the measurement system 'source' and 'load' have been measured at the above frequency points using a Vector Network Analyser (Anritsu VNA MS4645B) System, which has been calibrated(SOLT method) using a 2.4mm Calibration kit and the precision coaxial airline. The expanded uncertainty in the measured reflection coefficient magnitude has been calculated [3].

Traceability route:

The measured attenuation(dB) for the nominal step of the step attenuator is traceable to the 30 MHz WBCO attenuator of NPL India through 30MHz attenuator and signal calibrator and the VNA based reflection coefficient magnitude measurement is traceable to the Dimension metrology at NPL India through transfer standards coaxial airlines and calibration kit components.

References:

1.'Evaluation of measurement data-Guide to the expression of uncertainty in measurement' Gum document 'First edition September 2008, JCGM 100: 2008.

2. 'Calibration of two port RF Network by 30MHz IF Substitution technique', Document No.3, Document manual, Metrological activities, NPLI, Calibration procedure no. D#5.10c/Doc.3/CP#01, Issue No.4, 11.12.2011.

3. Guidelines on the Evaluation of Vector Network Analyzers(VNA)", Calibration Guide Euramet cg-12 Version 2.0 (03/2011).

B.12 VNIIFTRI Measurements (Vitaliy Pruglo)

Measurement description:

Measurements of attenuation of the attenuator ATT#1 was taken with additional pads when enabled at its input attenuator 5,6 dB and at its output attenuator 10 dB.

Measurements of attenuation of the attenuator ATT#2 was taken without additional pads.

As comparator was used the vector network analyzer R&S ZVA50.

The following analyzer settings were used:

- central frequency selected from the range 18, 26,5, 40 GHz
- span is 2 MHz.
- bandwidth of the intermediate frequency filter is 10 Hz.
- output signal power minus 10 dBm.;
- the R&S ZVA50 VNA with port 1 (m) and port 2 (m) is calibrated using R&S ZV-Z224 calibration kit using firmware (TOSM – Thru, Open Short Match) calibration software.;
- "smoothing" with an aperture of 20%.

Math mode was used to indicate differential attenuation. The accumulation mode was not used.

Measurements of reflectance were also conducted on the vector network analyzer R&S ZVA50. The calibration of the analyzer in the measurement mode of the reflections was performed using the kit R&S ZV-Z224.

The linearity of the analyzer was checked using the traceable to the reference GET 193-2011 of circuit, consisting of the following combination sequentially connected attenuators: input attenuators 84904M, 84905M, pad attenuator on 10 dB, attenuators 84904M, 84905M and pad attenuator on 10 dB.

Traceability route:

The unit of attenuation is traced to the ratio of AC voltages with a frequency of 1 kHz reproduced by an inductive divider from the state primary standard of the unit of attenuation, VNIIFTRI.

The unit of complex reflection coefficients is traceable to the state primary standard of the unit of wave impedance in coaxial, SNIIM.

B.13 KRISS Measurements (Joo-Gwang Lee)

A brief description of measurement technique

We measure the attenuation of the inter-comparison devices using an RF series substitution technique as shown in Figure 1. The STD-3 is coaxial-type attenuation standard, composed of 4 steps of build-up chain of power measurement and operating from 26.5 GHz to 40 GHz. For the measurement of 18 GHz to 26.5 GHz, the STD-2 is used. Its measurement scheme and uncertainty is fully described in reference 1. The overall system has a dynamic range over 80 dB. We attach pads or tuners between the output of DUT and the input of receiving system to reduce the mismatch.

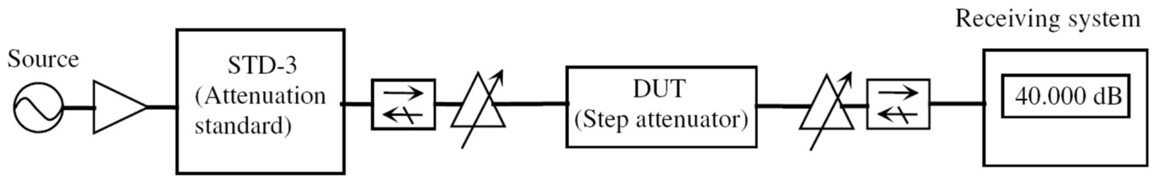


Figure 1. Block diagram of the attenuation measurement system.

The traceability route for the attenuation measurements

The KRISS attenuation standards are traceable, via calibrated dc voltmeters, to the KRISS national standards for dc voltage.

Reference

1. J. G. Lee et al, "Novel attenuation standards at microwave frequencies and evaluation of their uncertainty," *Measurement Science and Technology*, vol. 18, pp. 1929-1933, May. 2007.

B.13 NPL (Niall O'Grady, John Howes)

Measurement Technique

For the duration of the measurement process the laboratory was maintained at a stable temperature that is within the accredited range 23.0 ± 1.5 °C. The travelling standards were allowed to acclimatise for a period of 24 hours prior to measurement.

The attenuation steps were measured on the NPL Primary Attenuator Calibrators which use the Voltage Ratio Method. The NPL attenuation standards are traceable, via calibrated inductive voltage dividers and AC voltmeters, to the UK national standards for low frequency voltage ratio. The attenuation reference standard used for these measurements was an inductive voltage divider operating at 10 kHz.

In the Voltage Ratio method, a continuous wave signal from a synthesized source is passed through the travelling standard, which is inserted between carefully matched tuner-isolator pairs (providing a match of 1 mUnit to a transmission line with characteristic impedance of 50 Ω) and then fed into a highly linear double balanced mixer. A second synthesized source provides the local oscillator power to the mixer.

The two synthesized sources are operated at frequencies that are 10 kHz apart and, since they are both locked to the same 10 MHz crystal controlled oscillator, an extremely stable 10 kHz IF is produced. After amplification, the IF signal is measured with a precision AC digital voltmeter (DVM).

At the DVM a datum of 1V is found by adjusting the RF level whilst at the travelling standard's datum setting. During measurements, the resultant reduced IF signal at a given attenuation setting is taken.

The attenuation value is then calculated via the following equation.

$$Attenuation = 20\log_{10}(Datum\_Signal/Attenuated\_Signal) + C$$

Where C is a correction factor in dB for the non-linearity of the IF amplifier and the DVM.

Uncertainty

In accordance with the Guide to the Expression of Uncertainty in Measurement (GUM) published by the International Standards Organisation (ISO), the uncertainty budget for the attenuation measurements has been provided, detailing the contributions to the total uncertainty as well as stating the respective degrees of freedom (DoF).

The uncertainties of the attenuation and reflection coefficient measurements have been reported at k =1 and k =2 respectively.

The uncertainty budget of reflection coefficient measurements is comprised solely of the uncertainty in the calibration of the VNA used to obtain said measurements. As such all of these measurements have exactly **zero degrees of freedom**.

A table below indicates the type of each source of uncertainty and indicates the corresponding shorthand used in the tabulation of results.

Source of Uncertainty	**Shorthand**	**Type of Uncertainty Evaluation**
Random	u_Type-A	A
Inductive Voltage Divider (reference standard)	u_IVD	B
Mismatch	u_mis	B
System Linearity (including effects of noise)	u_nonl	B
Leakage	u_leak	B
Digital Voltmeter Calibration	u_DMM	B

Appendix C – Uncertainty budgets

C.1 – NMIJ uncertainty budget

Table C.1.1 Uncertainty budget for attenuation step measurements of ATT#1

(a) at 18 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6	SU C7	SU C8	SU C9
20	0.0033	0.0005	0.0010	0.0000	0.0006	0.0003	0.0020	-	0.0022	0.0004
40	0.0047	0.0013	0.0010	0.0000	0.0006	0.0003	0.0040	-	0.0018	0.0003
60	0.0094	0.0023	0.0032	0.0003	0.0006	0.0003	0.0080	-	0.0029	0.0006
80	0.0108	0.0013	0.0032	0.0030	0.0006	0.0003	0.0080	0.0047	0.0029	0.0006
90	0.0136	0.0023	0.0032	0.0090	0.0006	0.0003	0.0080	0.0047	0.0013	0.0011
	Type	B	B	B	B	B	B	A	B	A

(b) at 26.5 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6	SU C7	SU C8	SU C9
20	0.0035	0.0005	0.0010	0.0000	0.0006	0.0003	0.0027	-	0.0019	0.0002
40	0.0050	0.0013	0.0010	0.0000	0.0006	0.0003	0.0040	-	0.0023	0.0003
60	0.0097	0.0023	0.0032	0.0003	0.0006	0.0003	0.0080	-	0.0037	0.0006
80	0.0112	0.0013	0.0032	0.0030	0.0006	0.0003	0.0080	0.0050	0.0037	0.0007
90	0.0137	0.0023	0.0032	0.0090	0.0006	0.0003	0.0080	0.0050	0.0010	0.0005
	Type	B	B	B	B	B	B	A	B	A

(c) at 40 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6	SU C7	SU C8	SU C9
20	0.0050	0.0005	0.0018	0.0000	0.0006	0.0003	0.0020	-	0.0042	0.0002
40	0.0083	0.0013	0.0018	0.0000	0.0006	0.0003	0.0055	-	0.0057	0.0005
60	0.0197	0.0023	0.0036	0.0003	0.0006	0.0003	0.0180	-	0.0068	0.0007
80	0.0217	0.0023	0.0036	0.0030	0.0006	0.0003	0.0180	0.0083	0.0068	0.0015
90	0.0231	0.0023	0.0036	0.0090	0.0006	0.0003	0.0180	0.0083	0.0060	0.0021
	Type	B	B	B	B	B	B	A	B	A

Key
Step: attenuation step in dB
SU_C1: reference standard in dB
SU_C2: system linearity in dB
SU_C3: leakage in dB
SU_C4: drift in dB
SU_C5: digital reading resolution in dB
SU_C6: stability in dB
SU_C7: block gauge in dB
SU_C8: mismatch in dB
SU_C9: experimental standard uncertainty of the mean of 10 measurement in dB

Table C.1.2 Uncertainty budget for attenuation step measurements of ATT#2

(a) at 18 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6	SU C7	SU C8
20	0.0025	0.0005	0.0010	0.0000	0.0006	0.0003	0.0020	0.0007	0.0003
40	0.0044	0.0013	0.0010	0.0000	0.0006	0.0003	0.0040	0.0006	0.0005
60	0.0090	0.0023	0.0032	0.0003	0.0006	0.0003	0.0080	0.0006	0.0007
	Type	B	B	B	B	B	B	B	A

(b) at 26.5 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6	SU C7	SU C8
20	0.0024	0.0005	0.0010	0.0000	0.0006	0.0003	0.0020	0.0003	0.0002
40	0.0044	0.0013	0.0010	0.0000	0.0006	0.0003	0.0040	0.0004	0.0005
60	0.0090	0.0023	0.0032	0.0003	0.0006	0.0003	0.0080	0.0004	0.0007
	Type	B	B	B	B	B	B	B	A

(c) at 40 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6	SU C7	SU C8
20	0.0030	0.0005	0.0018	0.0000	0.0006	0.0003	0.0020	0.0011	0.0003
40	0.0062	0.0013	0.0018	0.0000	0.0006	0.0003	0.0055	0.0014	0.0005
60	0.0186	0.0023	0.0036	0.0003	0.0006	0.0003	0.0180	0.0014	0.0009
	Type	B	B	B	B	B	B	B	A

Key

Step: attenuation step in dB
SU_tot: combined standard uncertainty (k = 1) in dB
SU_C1: reference standard in dB
SU_C2: system linearity in dB
SU_C3: leakage in dB
SU_C4: drift in dB
SU_C5: digital reading resolution in dB
SU_C6: stability in dB
SU_C7: mismatch in dB
SU_C8: experimental standard uncertainty of the mean of 10 measurement in dB

C.2 – NIM uncertainty budget

Table C.2.1 Uncertainty budget for attenuation step measurements of ATT#1

(a) at 18 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6	SU C7
20	0.0033	0.0021	0.0021	0.0006	0.0000	0.0003	0.0011	0.0005
40	0.0035	0.0023	0.0023	0.0006	0.0000	0.0003	0.0011	0.0005
60	0.0045	0.0022	0.0037	0.0006	0.0003	0.0003	0.0011	0.0005
80	0.0065	0.0040	0.0040	0.0006	0.0028	0.0003	0.0011	0.0005
90	0.0094	0.0019	0.0019	0.0006	0.0089	0.0003	0.0011	0.0010
	Type	B	B	B	B	B	B	A

(b) at 26.5 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6	SU C7
20	0.0052	0.0005	0.0050	0.0006	0.0000	0.0003	0.0011	0.0005
40	0.0055	0.0005	0.0053	0.0006	0.0000	0.0003	0.0011	0.0005
60	0.0056	0.0005	0.0054	0.0006	0.0003	0.0003	0.0011	0.0005
80	0.0065	0.0007	0.0057	0.0006	0.0028	0.0003	0.0011	0.0005
90	0.0111	0.0016	0.0062	0.0006	0.0089	0.0003	0.0011	0.0010
	Type	B	B	B	B	B	B	A

(c) at 40 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6	SU C7
20	0.0072	0.0005	0.0070	0.0006	0.0000	0.0003	0.0011	0.0005
40	0.0084	0.0005	0.0083	0.0006	0.0000	0.0003	0.0011	0.0005
60	0.0076	0.0005	0.0074	0.0006	0.0003	0.0003	0.0011	0.0005
80	0.0086	0.0007	0.0080	0.0006	0.0028	0.0003	0.0011	0.0005
90	0.0125	0.0016	0.0084	0.0006	0.0089	0.0003	0.0011	0.0010
	Type	B	B	B	B	B	B	A

Key

Step: attenuation step in dB
SU_tot: combined standard uncertainty (k = 1) in dB
SU_C1: reference standard in dB
SU_C2: mismatch in dB
SU_C3: system linearity in dB
SU_C4: leakage in dB
SU_C5: resolution in dB
SU_C6: connector repeatbility in dB
SU_C7: experimental standard uncertainty of the mean of 10 measurement

Table C.2.2 Uncertainty budget for attenuation step measurements of ATT#2

(a) at 18 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6	SU C7	SU C8
20	0.0035	0.0005	0.0010	0.0006	0.0000	0.0003	0.0011	0.0030	0.0005
40	0.0035	0.0005	0.0010	0.0006	0.0003	0.0003	0.0011	0.0030	0.0005
60	0.0045	0.0007	0.0010	0.0006	0.0028	0.0003	0.0011	0.0030	0.0005
	Type	B	B	B	B	B	B	A	A

(b) at 26.5 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6	SU C7	SU C8
20	0.0072	0.0005	0.0010	0.0006	0.0000	0.0003	0.0011	0.0070	0.0005
40	0.0072	0.0005	0.0010	0.0006	0.0003	0.0003	0.0011	0.0070	0.0005
60	0.0078	0.0007	0.0010	0.0006	0.0028	0.0003	0.0011	0.0070	0.0005
	Type	B	B	B	B	B	B	A	A

(c) at 40 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6	SU C7	SU C8
20	0.0092	0.0005	0.0010	0.0006	0.0000	0.0003	0.0011	0.0090	0.0005
40	0.0092	0.0005	0.0010	0.0006	0.0003	0.0003	0.0011	0.0090	0.0005
60	0.0096	0.0007	0.0010	0.0006	0.0028	0.0003	0.0011	0.0090	0.0005
	Type	B	B	B	B	B	B	A	A

Key

Step: attenuation step in dB
SU_tot: combined standard uncertainty (k = 1) in dB
SU_C1: reference standard in dB
SU_C2: mismatch in dB
SU_C3: system linearity in dB
SU_C4: leakage in dB
SU_C5: resolution in dB
SU_C6: connector repeatability in dB
SU_C7: attenuator stability
SU_C8: experimental standard uncertainty of the mean of 10 measurement

C.3– PTB uncertainty budget

Table C.3.1 Uncertainty budget for attenuation step measurements of ATT#1

(a) at 18 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6
20	0.00289	0.00004	0.00115	0.00265			
40	0.01178	0.00184	0.00058	0.00356	0.01068	0.00289	0.00015
60	0.00967	0.00180	0.00058	0.00309	0.00831	0.00289	0.00175
80	0.02129	0.00260	0.00058	0.00523	0.01087	0.00289	0.01710
90	0.05879	0.00258	0.00058	0.00507	0.01009	0.00289	0.05756
	Type	B	B	B	B	B	B

(b) at 26.5 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6
20	0.00554	0.00006	0.00115	0.00542			
40	0.01947	0.00313	0.00058	0.01165	0.01455	0.00462	0.00017
60	0.01088	0.00299	0.00058	0.00589	0.00705	0.00462	0.00183
80	0.02460	0.00607	0.00058	0.00663	0.01227	0.00462	0.01876
90	0.06402	0.00629	0.00058	0.00623	0.00834	0.00462	0.06268
	Type	A	B	B	B	B	B

(c) at 40 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6
20	0.00982	0.00014	0.00115	0.00975			
40	0.02067	0.00387	0.00058	0.01231	0.01507	0.00577	0.00020
60	0.02662	0.00296	0.00058	0.01741	0.01896	0.00577	0.00190
80	0.03656	0.00297	0.00058	0.01931	0.02204	0.00577	0.02087
90	0.07463	0.00328	0.00058	0.02194	0.02320	0.00577	0.06712
	Type	A	B	B	B	B	B

Key

Step: attenuation step in dB
SU_tot: combined standard uncertainty ($k = 1$) in dB
SU_C1: statistical analysis of observations dB
SU_C2: linearity in dB
SU_C3: mismatch in dB
SU_C4: reference attenuators in dB
SU_C5: cable flexure in dB
SU_C6: crosstalk and noise in dB

Table C.3.2 Uncertainty budget for attenuation step measurements of ATT#2

(a) at 18 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6
20	0.00358	0.00028	0.00173	0.00312			
40	0.01179	0.00099	0.00058	0.00390	0.01068	0.00289	0.00015
60	0.00959	0.00091	0.00058	0.00322	0.00831	0.00289	0.00175
	Type	A	B	B	B	B	B

(b) at 26.5 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6
20	0.00540	0.00178	0.00173	0.00480			
40	0.01957	0.00365	0.00058	0.01168	0.01455	0.00462	0.00017
60	0.02176	0.00571	0.00058	0.00586	0.00705	0.00462	0.01831
	Type	A	B	B	B	B	B

(c) at 40 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6
20	0.01422	0.00156	0.00058	0.00630	0.01124	0.00577	0.00002
40	0.01897	0.00241	0.00058	0.00965	0.01507	0.00577	0.00020
60	0.03204	0.00401	0.00058	0.01604	0.01896	0.00577	0.01898
	Type	A	B	B	B	B	B

Key

Step: attenuation step in dB

SU_tot: combined standard uncertainty (k = 1) in dB

SU_C1: statistical analysis of observations dB

SU_C2: linearity in dB

SU_C3: mismatch in dB

SU_C4: reference attenuators in dB

SU_C5: cable flexure in dB

SU_C6: crosstalk and noise in dB

C.4– LNE uncertainty budget

Table C.4.1 Uncertainty budget for attenuation step measurements of ATT#1

(a) at 18 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6	SU C7	SU C8	SU C9
20	0.01	0.00001	0.00004	-	0.0006	0.0011	0.0002	0.00023	0.0000	-
40	0.04	0.0016	0.0002	0.0003	0.0011	0.0010	0.0003	0.00023	0.0000	-
60	0.04	0.0032	0.0002	0.0004	0.0020	0.0013	0.0003	0.00023	0.0032	-
80	0.05	0.0049	0.0004	0.0007	0.0013	0.0050	0.0003	0.0002	0.0047	0.0071
90	0.04	0.0057	0.0004	0.0015	0.0020	0.0013	0.0003	0.0002	0.0022	0.0041
	Type	B	B	B	B	B	B	A	A	B

(b) at 26.5 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6	SU C7	SU C8	SU C9
20	0.01	0.00001	0.00004	-	0.0006	0.0014	0.0002	0.00023	0.0018	-
40	0.04	0.0016	0.0002	0.0003	0.0011	0.0038	0.0003	0.00023	0.0016	-
60	0.04	0.0032	0.0002	0.0004	0.0020	0.0037	0.0003	0.00023	0.0021	-
80	0.04	0.0049	0.0004	0.0007	0.0013	0.0025	0.0003	0.0002	0.0041	0.0047
90	0.05	0.0057	0.0004	0.0015	0.0020	0.0037	0.0003	0.0002	0.0057	0.0063
	Type	B	B	B	B	B	B	A	A	B

(b) at 40 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6	SU C7	SU C8	SU C9
20	0.02	0.00001	0.00004	-	0.0006	0.0031	0.0002	0.00023	0.0018	-
40	0.05	0.0016	0.0002	0.0003	0.0011	0.0060	0.0003	0.00023	0.0034	-
60	0.05	0.0032	0.0002	0.0004	0.0020	0.0060	0.0003	0.00023	0.0040	-
80	0.06	0.0049	0.0004	0.0007	0.0013	0.0047	0.0003	0.0002	0.0085	0.0068
90	0.07	0.0057	0.0004	0.0015	0.0020	0.0060	0.0003	0.0002	0.0092	0.0085
	Type	B	B	B	B	B	B	A	A	B

Key
Step: attenuation step in dB
SU_tot: combined standard uncertainty (k = 1) in dB
SU_C1: IF reference standard (*voltmeters) in dB
SU_C2: resolution (*power ratio) in dB
SU_C3: noise in dB
SU_C4: linearity in dB
SU_C5: mismatch in dB
SU_C6: stability in dB
SU_C7: repeatablity in dB
SU_C8: connection repeatablity in dB
SU_C9: additional attenuation in dB

Table C.4.2 Uncertainty budget for attenuation step measurements of ATT#2

(a) at 18 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6	SU C7	SU C8
20	0.01	0.00001	0.00004	-	0.0006	0.0009	0.0002	0.00023	0.0018
40	0.04	0.0016	0.0002	0.0003	0.0011	0.0012	0.0003	0.00023	0.0013
60	0.04	0.0032	0.0002	0.0004	0.0020	0.0012	0.0003	0.00023	0.0019
	Type	B	B	B	B	B	B	A	A

(b) at 26.5 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6	SU C7	SU C8
20	0.01	0.00001	0.00004	-	0.0006	0.0014	0.0002	0.00023	0.0000
40	0.04	0.0016	0.0002	0.0003	0.0011	0.0020	0.0003	0.00023	0.0038
60	0.04	0.0032	0.0002	0.0004	0.0020	0.0021	0.0003	0.00023	0.0009
	Type	B	B	B	B	B	B	A	A

(c) at 40 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6	SU C7	SU C8
20	0.01	0.00001	0.00004	-	0.0006	0.0011	0.0002	0.00023	0.0022
40	0.04	0.0016	0.0002	0.0003	0.0011	0.0013	0.0003	0.00023	0.0066
60	0.04	0.0032	0.0002	0.0004	0.0020	0.0013	0.0003	0.00023	0.0044
	Type	B	B	B	B	B	B	A	A

Key
Step: attenuation step in dB
SU_tot: combined standard uncertainty (k = 1) in dB
SU_C1: IF reference standard (*voltmeters) in dB
SU_C2: resolution (*power ratio) in dB
SU_C3: noise in dB
SU_C4: linearity in dB
SU_C5: mismatch in dB
SU_C6: stability in dB
SU_C7: repeatablity in dB
SU_C8: connection repeatablity in dB

C.5– INTA uncertainty budget

Table C.5.1 Uncertainty budget for attenuation step measurements of ATT#1

(a) at 18 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6	SU C7
20	0.026	0.003	0.027	0.019	0.001			0.025
40	0.032	0.005	0.025	0.029	0.001			0.035
60	0.043	0.008	0.024	0.039	0.007	0.031		0.045
80	0.054	0.011	0.027	0.049	0.008	0.031	0.031	0.055
90	0.055	0.012	0.012	0.054	0.010	0.031	0.031	0.060
	Type	B	B	B	A	B	B	B

(b) at 26.5 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6	SU C7
20	0.024	0.003	0.022	0.019	0.001			0.025
40	0.031	0.005	0.024	0.029	0.001			0.035
60	0.045	0.008	0.031	0.039	0.002	0.031		0.045
80	0.053	0.011	0.026	0.049	0.006	0.031	0.031	0.055
90	0.104	0.012	0.029	0.054	0.016	0.031	0.031	0.158
	Type	B	B	B	A	B	B	B

(4) at 40 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6	SU C7
20	0.070	0.003	0.095	0.019	0.002			0.025
40	0.075	0.005	0.096	0.029	0.002	0.031		0.035
60	0.075	0.008	0.090	0.039	0.002	0.031		0.045
80	0.139	0.011	0.092	0.049	0.004	0.031	0.031	0.201
90	0.351	0.012	0.097	0.054	0.005	0.031	0.031	0.591
	Type	B	B	B	A	B	B	B

Key

Step: attenuation step in dB
SU_tot: combined standard uncertainty ($k = 1$) in dB
SU_C1: IF reference standard in dB
SU_C2: Mismatch in dB
SU_C3: Linearity in dB
SU_C4: Repeatability in dB
SU_C5: Range2_uncertainty in dB
SU_C6: Range3_uncertainty in dB
SU_C7: Accuracy in dB

Table C.5.2 Uncertainty budget for attenuation step measurements of ATT#2

(a) at 18 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6	SU C7
20	0.066	0.003	0.090	0.019	0.000			0.025
40	0.071	0.005	0.093	0.029	0.002			0.035
60	0.062	0.008	0.067	0.039	0.004	0.031		0.045
	Type	B	B	B	A	B	B	B

(b) at 26.5 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6	SU C7
20	0.086	0.003	0.119	0.019	0.001			0.025
40	0.101	0.005	0.136	0.029	0.002	0.031		0.035
60	0.104	0.008	0.136	0.039	0.002	0.031		0.045
	Type	B	B	B	A	B	B	B

(4) at 40 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6	SU C7
20	0.117	0.003	0.163	0.019	0.001			0.025
40	0.071	0.005	0.089	0.029	0.001	0.031		0.035
60	0.075	0.008	0.090	0.039	0.002	0.031		0.045
	Type	B	B	B	A	B	B	B

Key

Step: attenuation step in dB
SU_tot: combined standard uncertainty (k = 1) in dB
SU_C1: IF reference standard in dB
SU_C2: Mismatch in dB
SU_C3: Linearity in dB
SU_C4: Repeatability in dB
SU_C5: Range2_uncertainty in dB
SU_C6: Range3_uncertainty in dB
SU_C7: Accuracy in dB

C.6– METAS uncertainty budget

Table C.6.1 Uncertainty budget for attenuation step measurements of ATT#1

(a) at 18 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5
20	0.0050	0.0001	0.0003	0.0003	0.0050	0.0001
40	0.0087	0.0001	0.0002	0.0006	0.0086	0.0001
60	0.0089	0.0001	0.0005	0.0004	0.0089	0.0001
80	0.0124	0.0001	0.0005	0.0006	0.0124	0.0002
90	0.0159	0.0001	0.0001	0.0009	0.0159	0.0002
	Type	A	B	B	B	A

(b) at 26.5 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5
20	0.0050	0.0001	0.0003	0.0005	0.0050	0.0001
40	0.0087	0.0002	0.0004	0.0009	0.0086	0.0001
60	0.0086	0.0002	0.0005	0.0006	0.0086	0.0001
80	0.0122	0.0002	0.0005	0.0009	0.0121	0.0002
90	0.0157	0.0001	0.0003	0.0014	0.0157	0.0002
	Type	A	B	B	B	A

(4) at 40 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5
20	0.0051	0.0003	0.0010	0.0006	0.0050	0.0002
40	0.0087	0.0004	0.0014	0.0010	0.0085	0.0004
60	0.0086	0.0004	0.0013	0.0007	0.0085	0.0005
80	0.0121	0.0004	0.0013	0.0011	0.0120	0.0005
90	0.0156	0.0004	0.0014	0.0016	0.0155	0.0005
	Type	A	B	B	B	A

Key

Step: attenuation step in dB

SU_tot: combined standard uncertainty (k = 1) in dB

SU_C1: connector repeatability in dB

SU_C2: calibration standards in dB

SU_C3: VNA drift in dB

SU_C4: VNA linearity in dB

SU_C5: VNA noise in dB

Table C.6.2 Uncertainty budget for attenuation step measurements of ATT#2

(a) at 18 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5
20	0.0051	0.0001	0.0001	0.0004	0.0051	0.0001
40	0.0088	0.0001	0.0001	0.0011	0.0087	0.0004
60	0.0125	0.0001	0.0001	0.0014	0.0124	0.0004
	Type	A	B	B	B	A

(b) at 26.5 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5
20	0.0050	0.0001	0.0001	0.0006	0.0050	0.0002
40	0.0088	0.0001	0.0001	0.0014	0.0087	0.0004
60	0.0124	0.0001	0.0001	0.0019	0.0123	0.0004
	Type	A	B	B	B	A

(c) at 40 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5
20	0.0051	0.0001	0.0003	0.0007	0.0050	0.0006
40	0.0101	0.0001	0.0003	0.0029	0.0095	0.0019
60	0.0137	0.0001	0.0003	0.0038	0.0130	0.0020
	Type	A	B	B	B	A

Key

Step: attenuation step in dB
SU_tot: combined standard uncertainty (k = 1) in dB
SU_C1: connector repeatability in dB
SU_C2: calibration standards in dB
SU_C3: VNA drift in dB
SU_C4: VNA linearity in dB
SU_C5: VNA noise in dB

C.7– NMISA uncertainty budget

Table C.7.1 Uncertainty budget for attenuation step measurements of ATT#1

(a) at 18 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6
20	0.0084	0.0100	0.0019	0.0010	0.0056	0.0008	0.0010
40	0.0145	0.0200	0.0018	0.0096	0.0066	0.0008	0.0010
60	0.0800	0.1000	0.0019	0.0950	0.0069	0.0008	0.0010
80	0.5486	0.2000	0.0037	0.9224	0.0639	0.0008	0.0010
90	1.4770	0.2000	0.0017	2.5347	0.1636	0.0008	0.0010
	Type	A	A	A	B	A	A

(b) at 26.5 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6
20	0.0075	0.0100	0.0041	0.0010	0.0023	0.0008	0.0010
40	0.0138	0.0200	0.0042	0.0101	0.0019	0.0008	0.0010
60	0.0825	0.1000	0.0045	0.0997	0.0118	0.0008	0.0010
80	0.5978	0.2000	0.0049	0.9829	0.1482	0.0008	0.0010
90	1.6752	0.2000	0.0054	2.8378	0.3294	0.0008	0.0010
	Type	A	A	A	B	A	A

(c) at 40 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6
20	0.0102	0.0100	0.0074	0.0010	0.0037	0.0008	0.0010
40	0.0159	0.0200	0.0083	0.0109	0.0029	0.0008	0.0010
60	0.0862	0.1000	0.0077	0.1063	0.0162	0.0008	0.0010
80	0.6397	0.2000	0.0076	1.0313	0.2034	0.0008	0.0010
90	1.8497	0.2000	0.0082	2.9610	0.6967	0.0008	0.0010
	Type	A	A	A	B	A	A

Key
Step: attenuation step in dB
SU_tot: combined standard uncertainty (k = 1) in dB
SU_C1: linearity in dB
SU_C2: mismatch in dB
SU_C3: isolation in dB
SU_C4: random in dB
SU_C5: ambient condition in dB
SU_C6: cable flexing in dB

Table C.7.2 Uncertainty budget for attenuation step measurements of ATT#2

(a) at 18 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6
20	0.0104	0.0100	0.0024	0.0099	0.0059	0.0008	0.0010
40	0.0601	0.0200	0.0026	0.1016	0.0083	0.0008	0.0010
60	0.5663	0.1000	0.0024	0.9485	0.1434	0.0008	0.0010
	Type	A	A	A	B	A	A

(b) at 26.5 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6
20	0.0100	0.0100	0.0045	0.0106	0.0028	0.0008	0.0010
40	0.0671	0.0200	0.0044	0.1083	0.0208	0.0008	0.0010
60	0.6052	0.1000	0.0044	1.0086	0.1543	0.0008	0.0010
	Type	A	A	A	B	A	A

(c) at 40 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6
20	0.0111	0.0100	0.0043	0.0132	0.0034	0.0008	0.0010
40	0.0840	0.0200	0.0042	0.1337	0.0309	0.0008	0.0010
60	0.7616	0.1000	0.0042	1.2147	0.2913	0.0008	0.0010
	Type	A	A	A	B	A	A

Key

Step: attenuation step in dB
SU_tot: combined standard uncertainty (k = 1) in dB
SU_C1: linearity in dB
SU_C2: mismatch in dB
SU_C3: isolation in dB
SU_C4: random in dB
SU_C5: ambient condition in dB
SU_C6: cable flexing in dB

C.8– CMI uncertainty budget

Table C.8.1 Uncertainty budget for attenuation step measurements of ATT#1

(a) at 18 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4
20	0.0171	0.0009	0.0059	0.0160	0.0012
40	0.0226	0.0016	0.0047	0.0220	0.0013
60	0.0290	0.0048	0.0056	0.0280	0.0020
80	0.0359	0.0041	0.0052	0.0340	0.0094
90	0.0469	0.0090	0.0047	0.0370	0.0269
	Type	A	B	B	B

(b) at 26.5 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4
20	0.0180	0.0011	0.0080	0.0160	0.0012
40	0.0240	0.0018	0.0092	0.0220	0.0015
60	0.0306	0.0090	0.0075	0.0280	0.0037
80	0.0446	0.0055	0.0094	0.0340	0.0267
90	0.0915	0.0215	0.0075	0.0370	0.0805
	Type	A	B	B	B

(c) at 40 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4
20	0.0226	0.0007	0.0102	0.0199	0.0031
40	0.0427	0.0031	0.0136	0.0402	0.0036
60	0.0622	0.0092	0.0103	0.0601	0.0085
80	0.1055	0.0300	0.0169	0.0803	0.0591
90	0.2029	0.0328	0.0142	0.0903	0.1781
	Type	A	B	B	B

Key

Step: attenuation step in dB

SU_tot: combined standard uncertainty (k = 1) in dB

For measurements at 18 GHz and 26.5 GHz,

SU_C1: repeatability in dB

SU_C2: vector correction unc in dB

SU_C3: linearity in dB

SU_C4: noise and leakage in dB

For measurements at 40 GHz

SU_C1: repeatability in dB

SU_C2: mismatch in dB

SU_C3: linearity in dB

SU_C4: noise in dB

Table C.8.2 Uncertainty budget for attenuation step measurements of ATT#2

(a) at 18 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4
20	0.0161	0.0003	0.0005	0.0160	0.0013
40	0.0230	0.0061	0.0004	0.0221	0.0021
60	0.0301	0.0056	0.0004	0.0280	0.0096
	Type	A	B	B	B

(b) at 26.5 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4
20	0.0161	0.0014	0.0005	0.0160	0.0015
40	0.0249	0.0110	0.0004	0.0220	0.0040
60	0.0410	0.0097	0.0005	0.0280	0.0284
	Type	A	B	B	B

(c) at 40 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4
20	0.0203	0.0012	0.0023	0.0198	0.0037
40	0.0421	0.0083	0.0030	0.0400	0.0099
60	0.1049	0.0483	0.0028	0.0599	0.0713
	Type	A	B	B	B

Key

Step: attenuation step in dB
SU_tot: combined standard uncertainty (k = 1) in dB
For measurements at 18 GHz and 26.5 GHz,
SU_C1: repeatability in dB
SU_C2: vector correction unc in dB
SU_C3: linearity in dB
SU_C4: noise and leakage in dB
For measurements at 40 GHz
SU_C1: repeatability in dB
SU_C2: mismatch in dB
SU_C3: linearity in dB
SU_C4: noise in dB

C.9– TUBITAK-UME uncertainty budget

Table C.9.1 Uncertainty budget for attenuation step measurements of ATT#1

(a) at 18 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6	SU C7
20	0.013	0.0029	0.0103	0.0001	0.0000	0.0019	0.0024	0.0062
40	0.013	0.0033	0.0103	0.0006	0.0000	0.0023	0.0024	0.0062
60	0.014	0.0020	0.0103	0.0063	0.0000	0.0021	0.0024	0.0062
80	0.065	0.0043	0.0103	0.0631	0.0000	0.0052	0.0024	0.0062
90	0.197	0.0147	0.0103	0.1960	0.0000	0.0019	0.0024	0.0062
	Type	A	B	B	B	B	B	B

(b) at 26.5 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6	SU C7
20	0.015	0.0028	0.0103	0.0001	0.0000	0.0041	0.0065	0.0062
40	0.016	0.0073	0.0103	0.0006	0.0000	0.0048	0.0065	0.0062
60	0.016	0.0035	0.0103	0.0063	0.0000	0.0056	0.0065	0.0062
80	0.066	0.0145	0.0103	0.0631	0.0000	0.0051	0.0065	0.0062
90	0.213	0.0658	0.0516	0.1960	0.0000	0.0070	0.0065	0.0062
	Type	A	B	B	B	B	B	B

(c) at 40 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6	SU C7
20	0.022	0.0098	0.0103	0.0001	0.0000	0.0141	0.0074	0.0062
40	0.028	0.0176	0.0103	0.0015	0.0000	0.0165	0.0074	0.0062
60	0.027	0.0103	0.0103	0.0145	0.0000	0.0148	0.0074	0.0062
80	0.145	0.0154	0.0103	0.1428	0.0000	0.0147	0.0074	0.0062
90	0.427	0.0761	0.0516	0.4168	0.0000	0.0162	0.0074	0.0062
	Type	A	B	B	B	B	B	B

Key

Step: attenuation step in dB
SU_tot: combined standard uncertainty (k = 1) in dB
SU_C1: repeatability in dB
SU_C2: linearity in dB
SU_C3: isolation in dB
SU_C4: noise in dB
SU_C5: mismatch dB
SU_C6: mismatch 0 dB in dB
SU_C7: cable flexure in dB

Table C.9.2 Uncertainty budget for attenuation step measurements of ATT#2

(a) at 18 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6	SU C7
20	0.014	0.0050	0.0103	0.0006	0.0000	0.0025	0.0034	0.0062
40	0.015	0.0028	0.0103	0.0063	0.0000	0.0029	0.0034	0.0062
60	0.065	0.0081	0.0103	0.0631	0.0000	0.0027	0.0034	0.0062
	Type	A	B	B	B	B	B	B

(b) at 26.5 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6	SU C7
20	0.013	0.0020	0.0103	0.0006	0.0000	0.0036	0.0040	0.0062
40	0.015	0.0041	0.0103	0.0063	0.0000	0.0036	0.0040	0.0062
60	0.066	0.0153	0.0103	0.0631	0.0000	0.0036	0.0040	0.0062
	Type	A	B	B	B	B	B	B

(c) at 40 GHz

SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6	SU C7
0.014	0.0025	0.0103	0.0015	0.0000	0.0044	0.0056	0.0062
0.020	0.0028	0.0103	0.0145	0.0000	0.0040	0.0056	0.0062
0.145	0.0188	0.0103	0.1428	0.0000	0.0042	0.0056	0.0062
Type	A	B	B	B	B	B	B

Key

Step: attenuation step in dB
SU_tot: combined standard uncertainty (k = 1) in dB
SU_C1: repeatability in dB
SU_C2: linearity in dB
SU_C3: isolation in dB
SU_C4: noise in dB
SU_C5: mismatch dB
SU_C6: mismatch 0 dB in dB
SU_C7: cable flexure in dB

C.10– A*STAR uncertainty budget

Table C.10.1 Uncertainty budget for attenuation step measurements of ATT#1

(a) at 18 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6
20	0.002	0.0004	0.0014	0.0006	0.0006	0.0000	0.0011
40	0.004	0.0004	0.0025	0.0006	0.0010	0.0027	0.0006
60	0.004	0.0004	0.0025	0.0006	0.0010	0.0027	0.0009
80	0.007	0.0004	0.0024	0.0010	0.0040	0.0040	0.0010
90	0.008	0.0004	0.0015	0.0010	0.0060	0.0040	0.0011
	Type	B	B	B	B	B	A

(b) at 26.5 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6
20	0.004	0.0004	0.0029	0.0006	0.0006	0.0000	0.0013
40	0.005	0.0004	0.0024	0.0006	0.0010	0.0030	0.0011
60	0.005	0.0004	0.0026	0.0006	0.0010	0.0030	0.0012
80	0.008	0.0004	0.0031	0.0010	0.0040	0.0043	0.0025
90	0.009	0.0004	0.0035	0.0010	0.0060	0.0043	0.0017
	Type	B	B	B	B	B	A

Key

Step: attenuation step in dB

SU_tot: combined standard uncertainty ($k = 1$) in dB

SU_C1: IF reference standard in dB

SU_C2: mismatch in dB

SU_C3: linearity in dB

SU_C4: receiver fluctuation in dB

SU_C5: reference Setting in dB

SU_C6: repeatability in dB

Table C.10.2 Uncertainty budget for attenuation step measurements of ATT#2

(a) at 18 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6
20	0.003	0.0004	0.0019	0.0006	0.0010	0.0000	0.0005
40	0.004	0.0004	0.0019	0.0006	0.0010	0.0025	0.0018
60	0.006	0.0004	0.0018	0.0010	0.0040	0.0025	0.0023
	Type	B	B	B	B	B	A

(b) at 26.5 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6
20	0.004	0.0004	0.0027	0.0006	0.0010	0.0000	0.0022
40	0.006	0.0004	0.0026	0.0006	0.0010	0.0035	0.0022
60	0.007	0.0004	0.0027	0.0010	0.0040	0.0035	0.0016
	Type	B	B	B	B	B	A

Key

Step: attenuation step in dB
SU_tot: combined standard uncertainty (k = 1) in dB
SU_C1: IF reference standard in dB
SU_C2: mismatch in dB
SU_C3: linearity in dB
SU_C4: receiver fluctuation in dB
SU_C5: reference Setting in dB
SU_C6: repeatability in dB

C.11– NPLI uncertainty budget

Table C.11.1 Uncertainty budget for attenuation step measurements of ATT#1

(a) at 18 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6
20	0.018	0.0070	0.0119	0.0115	0.0003	0.0002	0.0004
40	0.029	0.0140	0.0087	0.0231	0.0003	0.0016	0.0003
60	0.046	0.0210	0.0127	0.0346	0.0003	0.0159	0.0006
	Type	B	B	B	B	B	A

(b) at 26.5 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6
20	0.017	0.0070	0.0093	0.0115	0.0003	0.0002	0.0003
40	0.030	0.0140	0.0127	0.0231	0.0003	0.0016	0.0005
60	0.045	0.0210	0.0104	0.0347	0.0003	0.0160	0.0004
	Type	B	B	B	B	B	A

(c) at 40 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6
20	0.019	0.0070	0.0133	0.0115	0.0003	0.0002	0.0003
40	0.051	0.0140	0.0421	0.0233	0.0003	0.0016	0.0004
60	0.059	0.0210	0.0387	0.0349	0.0003	0.0168	0.0011
	Type	B	B	B	B	B	A

Key

Step: attenuation step in dB
SU_tot: combined standard uncertainty (k = 1) in dB
SU_C1: IF reference standard in dB
SU_C2: mismatch in dB
SU_C3: linearity in dB
SU_C4: null meter sensitivity in dB
SU_C5: isolation in dB
SU_C6: repeatability in dB

Table C.11.2 Uncertainty budget for attenuation step measurements of ATT#2

(a) at 18 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6
20	0.029	0.0070	0.0256	0.0115	0.0003	0.0002	0.0002
40	0.039	0.0140	0.0281	0.0233	0.0003	0.0016	0.0003
60	0.052	0.0210	0.0264	0.0349	0.0003	0.0168	0.0004
	Type	B	B	B	B	B	A

(b) at 26.5 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6
20	0.036	0.0070	0.0333	0.0115	0.0003	0.0002	0.0005
40	0.042	0.0140	0.0315	0.0233	0.0003	0.0016	0.0008
60	0.055	0.0210	0.0329	0.0349	0.0003	0.0168	0.0004
	Type	B	B	B	B	B	A

(c) at 40 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6
20	0.040	0.0070	0.0371	0.0115	0.0003	0.0002	0.0002
40	0.046	0.0140	0.0368	0.0233	0.0003	0.0016	0.0005
60	0.058	0.0210	0.0375	0.0349	0.0003	0.0168	0.0015
	Type	B	B	B	B	B	A

Key
Step: attenuation step in dB
SU_tot: combined standard uncertainty (k = 1) in dB
SU_C1: IF reference standard in dB
SU_C2: mismatch in dB
SU_C3: linearity in dB
SU_C4: null meter sensitivity in dB
SU_C5: isolation in dB
SU_C6: repeatability in dB

C.12– VNIIFTRI uncertainty budget

Table C.12.1 Uncertainty budget for attenuation step measurements of ATT#1

(a) at 18 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4
20	0.02	0.01	0.03	0	0.01
40	0.03	0.02	0.03	0	0.01
60	0.035	0.03	0.03	0	0.01
80	0.18	0.04	0.03	0.3	0.01
90	0.5	0.05	0.03	0.9	0.01
	Type	B	B	B	A

(b) at 26.5 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4
20	0.026	0.01	0.03	0	0.01
40	0.031	0.02	0.04	0	0.01
60	0.038	0.03	0.04	0	0.01
80	0.18	0.04	0.05	0.3	0.01
90	0.52	0.045	0.05	0.9	0.01
	Type	B	B	B	A

(c) at 40 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4
20	0.021	0.01	0.03	0	0.01
40	0.027	0.02	0.03	0	0.01
60	0.035	0.03	0.03	0	0.01
80	0.17	0.04	0.03	0.3	0.01
90	0.52	0.045	0.03	0.9	0.01
	Type	B	B	B	A

Key

Step: attenuation step in dB
SU_tot: combined standard uncertainty ($k = 1$) in dB
SU_C1: uncertainty due to the nonlinearity of a measuring path and noise, (dB)
SU_C2: uncertainty due to mismatch, (dB)
SU_C3: uncertainty due to spurious relations and interference, (dB)
SU_C4: uncertainty due to repeatability, (dB)

Table C.12.2 Uncertainty budget for attenuation step measurements of ATT#2

(a) at 18 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4
20	0.012	0.01	0	0	0.01
40	0.021	0.02	0	0	0.01
60	0.17	0.03	0	0.3	0.01
	Type	B	B	B	A

(b) at 26.5 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4
20	0.012	0.01	0	0	0.01
40	0.021	0.02	0	0	0.01
60	0.17	0.03	0	0.3	0.01
	Type	B	B	B	A

(c) at 40 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4
20	0.012	0.01	0	0	0.01
40	0.021	0.02	0	0	0.01
60	0.17	0.03	0	0.3	0.01
	Type	B	B	B	A

Key

Step: attenuation step in dB
SU_tot: combined standard uncertainty (k = 1) in dB
SU_C1: uncertainty due to the nonlinearity of a measuring path and noise, (dB)
SU_C2: uncertainty due to mismatch, (dB)
SU_C3: uncertainty due to spurious relations and interference, (dB)
SU_C4: uncertainty due to repeatability, (dB)

C.13– KRISS uncertainty budget

Table C.13.1 Uncertainty budget for attenuation step measurements of ATT#1

(a) at 18 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6	SU C7
20	0.0063	0.0008	0.0034	0.0050	0.0004	0.0000	0.0017	0.0001
40	0.0065	0.0016	0.0042	0.0040	0.0004	0.0001	0.0023	0.0001
60	0.0074	0.0020	0.0048	0.0046	0.0004	0.0008	0.0023	0.0001
80	0.0122	0.0041	0.0048	0.0073	0.0004	0.0070	0.0023	0.0001
90	0.0145	0.0034	0.0038	0.0043	0.0004	0.0112	0.0029	0.0058
	Type	A	B	B	B	B	B	B

(b) at 26.5 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6	SU C7
20	0.0084	0.0013	0.0034	0.0073	0.0004	0.0000	0.0017	0.0001
40	0.0096	0.0013	0.0042	0.0082	0.0004	0.0001	0.0023	0.0001
60	0.0100	0.0015	0.0048	0.0083	0.0004	0.0007	0.0023	0.0001
80	0.0124	0.0029	0.0048	0.0082	0.0004	0.0070	0.0023	0.0001
90	0.0165	0.0029	0.0038	0.0090	0.0004	0.0112	0.0029	0.0058
	Type	A	B	B	B	B	B	B

(c) at 40 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6	SU C7
20	0.0135	0.0017	0.0034	0.0129	0.0004	0.0000	0.0006	0.0001
40	0.0159	0.0018	0.0042	0.0152	0.0004	0.0001	0.0006	0.0001
60	0.0144	0.0029	0.0048	0.0132	0.0004	0.0009	0.0012	0.0001
80	0.0175	0.0031	0.0048	0.0144	0.0004	0.0079	0.0017	0.0001
90	0.0204	0.0037	0.0038	0.0148	0.0004	0.0112	0.0029	0.0058
	Type	A	B	B	B	B	B	B

Key

Step: attenuation step in dB
SU_tot: combined standard uncertainty (k = 1) in dB
SU_C1: experimental standard uncertainty of the mean of 10 measurements in dB
SU_C2: standard attenuator in dB
SU_C3: mismatch in dB
SU_C4: resolution in dB
SU_C5: leakage in dB
SU_C6: stability in dB
SU_C7: linearity in dB

Table C.13.2 Uncertainty budget for attenuation step measurements of ATT#2

(a) at 18 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6	SU C7
20	0.0078	0.0012	0.0034	0.0065	0.0004	0.0001	0.0023	0.0001
40	0.0084	0.0013	0.0042	0.0067	0.0004	0.0007	0.0023	0.0001
60	0.0111	0.0015	0.0048	0.0066	0.0004	0.0070	0.0023	0.0001
	Type	A	B	B	B	B	B	B

(b) at 26.5 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6	SU C7
20	0.0070	0.0012	0.0034	0.0058	0.0004	0.0002	0.0017	0.0001
40	0.0077	0.0012	0.0042	0.0058	0.0004	0.0009	0.0023	0.0001
60	0.0113	0.0016	0.0048	0.0058	0.0004	0.0079	0.0023	0.0001
	Type	A	B	B	B	B	B	B

(c) at 40 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6	SU C7
20	0.0093	0.0025	0.0034	0.0083	0.0004	0.0001	0.0006	0.0001
40	0.0099	0.0033	0.0042	0.0083	0.0004	0.0009	0.0006	0.0001
60	0.0135	0.0046	0.0048	0.0094	0.0004	0.0071	0.0012	0.0001
	Type	A	B	B	B	B	B	B

Key

Step: attenuation step in dB
SU_tot: combined standard uncertainty ($k = 1$) in dB
SU_C1: experimental standard uncertainty of the mean of 10 measurements in dB
SU_C2: standard attenuator in dB
SU_C3: mismatch in dB
SU_C4: resolution in dB
SU_C5: leakage in dB
SU_C6: stability in dB
SU_C7: linearity in dB

C.14– NPL uncertainty budget

Table C.14.1 Uncertainty budget for attenuation step measurements of ATT#1

(a) at 18 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6
20	0.0019	0.00061	0.00001	0.00032	0.00009	0.00136	0.00108
40	0.0032	0.00108	0.00001	0.00047	0.00017	0.00276	0.00099
60	0.0046	0.00151	0.00001	0.00061	0.00025	0.00413	0.00105
80	0.0065	0.00224	0.00001	0.00076	0.00104	0.00552	0.00206
90	0.0090	0.00487	0.00001	0.00091	0.00391	0.00625	0.00070
	Type	A	B	B	B	B	B

(b) at 26.5 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6
20	0.0095	0.00256	0.00001	0.00033	0.00003	0.00898	0.00123
40	0.0187	0.00426	0.00001	0.00048	0.00005	0.01804	0.00165
60	0.0277	0.00556	0.00001	0.00064	0.00008	0.02707	0.00159
80	0.0370	0.00761	0.00001	0.00080	0.00033	0.03613	0.00205
90	0.0513	0.03119	0.00001	0.00093	0.00124	0.04061	0.00225
	Type	A	B	B	B	B	B

(c) at 40 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6
20	0.0084	0.00134	0.00001	0.00031	0.00001	0.00787	0.00238
40	0.0166	0.00181	0.00001	0.00046	0.00002	0.01610	0.00317
60	0.0244	0.00240	0.00001	0.00060	0.00002	0.02410	0.00257
	Type	A	B	B	B	B	B

Key

Step: attenuation step in dB
SU_tot: combined standard uncertainty (k = 1) in dB
SU_C1: random in dB
SU_C2: Inductive Voltage Divider (reference standard) in dB
SU_C3: digital voltmeter calibration in dB
SU_C4: leakage in dB
SU_C5: system linearity (including effects of noise) in dB
SU_C6: mismatch in dB

Table C.14.2 Uncertainty budget for attenuation step measurements of ATT#2

(a) at 18 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6
20	0.00185	0.00061	0.00001	0.00033	0.00001	0.00138	0.00097
40	0.00325	0.00107	0.00001	0.00048	0.00002	0.00279	0.00109
60	0.00485	0.00218	0.00001	0.00064	0.00008	0.00416	0.00099
	Type	A	B	B	B	B	B

(b) at 26.5 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6
20	0.00625	0.00260	0.00001	0.00033	0.00001	0.00541	0.00171
40	0.01205	0.00478	0.00001	0.00048	0.00002	0.01090	0.00168
60	0.01740	0.00569	0.00001	0.00064	0.00002	0.01631	0.00170
	Type	A	B	B	B	B	B

(c) at 40 GHz

Step	SU tot	SU C1	SU C2	SU C3	SU C4	SU C5	SU C6
20	0.0024	0.00032	0.00001	0.00032	0.00000	0.00183	0.00141
40	0.0042	0.00111	0.00001	0.00047	0.00000	0.00369	0.00137
	Type	A	B	B	B	B	B

Key

Step: attenuation step in dB
SU_tot: combined standard uncertainty (k = 1) in dB
SU_C1: random in dB
SU_C2: Inductive Voltage Divider (reference standard) in dB
SU_C3: digital voltmeter calibration in dB
SU_C4: leakage in dB
SU_C5: system linearity (including effects of noise) in dB
SU_C6: mismatch in dB