CCEM RF KEY COMPARISON CCEM.RF-K22.W

Noise in waveguide between 18 GHz and 26.5 GHz

Final Report

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Abstract

This report summarises the results of the Key Comparison CCEM.RF-K22.W on noise temperature, performed between October 2007 and February 2011. In this comparison, the available noise temperature of three noise sources was determined by six National Metrology Institutes (NMIs) in the frequency range from 18 GHz to 26.5 GHz.

CONTENTS

1. INTRODUCTION

The Mutual Recognition Arrangement (MRA) states that the metrological equivalence of national measurements standards will be determined by a set of key comparisons chosen and organised by the Consultative Committees of the CIPM, working together with the BIPM and the Regional Metrology Organisations (RMOs).

As part of this process, “the CIPM Consultative Committee for Electricity and Magnetism (CCEM) carried out the key comparison CCEM.RF-K22.W on noise measurement in waveguide between 18 GHz and 26.5 GHz.

This comparison was piloted by the Laboratoire National de Métrologie et d’Essais (LNE).

2. PARTICIPANTS AND ORGANISATION OF THE COMPARISON

2.1.List of participants

The participating institutes are listed in the following table.

Table 1: List of participants

Acronym	National Metrology Institute	Country	Contact
KRISS	Korea Research Institute of Standards and Science	Republic of Korea	Tae-Weon Kang twkang@kriss.re.kr
LNE	Laboratoire National de Métrologie et d’Essais	France	Djamel Allal djamel.allal@lne.fr
NIST	National Institute of Standards and Technology	United States of America	Dave Walker dwalker@boulder.nist.gov
NMIJ/AIST	National Metrology Institute of Metrology/Advanced Industrial Science and Technology	Japan	Yozo Shimada yozo.shimada@aist.go.jp
NPL	National Physical Laboratory	United Kingdom	Stephen Protheroe stephen.protheroe@npl.co.uk
VNIIFTRI	All-Russian Scientific Research Institute for Physical-Technical and Radiotechnical Measurements	Russian Federation	Rinadij Uzdin l120@vniiftri.ru

2.2.Comparison schedule

The comparison loop was initially planned to last 14 months with time slots of two months allocated to each participant, for measurements and transportation to the next participant [1].

However, due to problems described in section 2.4, a second comparison loop has been added and the comparison lasted longer. Finally, the measurements started in October 2007 and ended in February 2011.

The effective dates of measurements are summarized in tables 2 and 3 below, for the two comparison loops respectively.

Table 2: Dates of measurement for the first comparison loop

Laboratory	**Date of measurement**
LNE (France)	October 2007
NPL (United Kingdom)	December 2007
NIST (United States of America)	February 2008
NMIJ/AIST (Japan)	July 2008
KRISS (Republic of Korea)	September 2008
VNIIFTRI (Russian Federation)	June 2009
LNE (France)	September 2009

Table 3: Dates of measurement for the second comparison loop

Laboratory	**Date of measurement**
LNE (France)	October 2008
NIST (United States of America)	February 2009
NMIJ/AIST (Japan)	April 2009
KRISS (Republic of Korea)	June 2009
VNIIFTRI (Russian Federation)	December 2009
NPL (United Kingdom)	February 2011

2.3.Organisation of the comparison

The comparison was organised by the pilot laboratory. The travelling standards were circulated in two loops. The pilot laboratory had to measure the standards both at the beginning and at the end of each loop.

2.4.Unexpected incidents

During the first half of the first comparison loop, a lack of reliability of one travelling (standard "K22.W.1.waveguide", see description in section 3) has been noticed by the first two participants and confirmed by the third participant (NIST, see comparison schedule below).

Hence, decision was taken to remove "K22.W.1.waveguide" from the comparison protocol and to arrange a second loop with a supplementary noise source with identifier K22.W.3.waveguide (see description in section 3.1), supplied by NMIJ/AIST, delaying the first time schedule by 10 more months.

Apart from that, during this comparison and due to successive breakdowns of their measurement system and for economic reasons, the pilot laboratory has taken the decision to stop all activities related to noise temperature measurement and consequently to withdraw all its CMC lines from the BIPM database.

This situation has posed a problem with regard to the technical protocol of the comparison [1] because LNE as the pilot laboratory, was supposed to measure each travelling standard at the beginning and then at the end of the measurement loop in order to confirm the stability of the travelling standards. This could not be achieved as the measurement system failed at the end of the second measurement loop and has not been repaired; but fortunately this will not affect the Key Comparison Reference Value since it was stipulated in the technical protocol that this last measurement should not be taken into account in the calculation.

Finally, one of the participants, NPL, had to postpone their measurements of the second loop due to modifications of their measurement system which had prevented them from carrying out any measurement for several months.

All these problems have prolonged considerably the duration of this comparison.

3. Travelling standards and measurement instructions

3.1. Description of the standards

The travelling standards of the comparison were initially two solid-state noise sources, both of nominal ENR value of 15 dB and both to be powered by 28 V DC through a BNC connection.

The first one with identifier K22.W.1.waveguide was an IEC R220 waveguide noise source and the second one with identifier K22.W.2.coaxial was a 3.5 mm male coaxial noise source. A third travelling standard with identifier K22.W.2.waveguide has been obtained from the combination of the second one with a female 3.5 mm to R220 adapter, constituting a waveguide noise source.

As explained in section 2.4, a supplementary noise source has been added in the comparison. This new travelling standard has identifier K22.W.3.waveguide and was supplied by NMIJ/AIST and obtained from the combination of a male 3.5 mm coaxial noise source with a female 3.5 mm coaxial to R220 waveguide adapter, also to be powered by 28 V DC through a BNC connection.

The three initial travelling standards and the supplementary one are described in table 3 below.

Table 4: Description of the travelling standards

Comparison identifier	Type
K22.W.1.waveguide	QUINSTAR QNS-FB15LK, SN 7362001
K22.W.2.waveguide	AGILENT 346C, SN MY44420626 (with adapter)
K22.W.2.coaxial	AGILENT 346C, SN MY44420626 (without adapter)
K22.W.3.waveguide	NOISE/COM NC346C, SN P404 (with adapter)

3.2. Quantities to be measured and conditions of measurement

The main quantity to be measured in the comparison was the available noise temperature of the noise standards in kelvin (K).

In addition, the complex valued reflection coefficient of the standards in linear units had to be measured.

Depending on the type of radiometer used, coaxial or waveguide, travelling standard K22.W.2.waveguide or K22.W.2.coaxial respectively is calibrated after adapter evaluation.

Measurements have been carried out at the four following frequencies: 18 GHz, 22 GHz, 25.8 GHz and 26.5 GHz.

Note that due to the use of a different waveguide size, VNIIFTRI did not carry out measurements at 26.5 GHz and that KRISS did not carry out measurements at the particular frequency of 25.8 GHz, compatible with the Russian standard on waveguide sizes.

3.3.Deviations from the protocol.

Due to the problem mentioned in section 4 and related with the pilot laboratory, the protocol could not be strictly applied, especially; the check measurements could not be carried out by the pilot laboratory.

4. Methods of measurement

Table 2 summarizes the individual measurement methods employed by each participant. The detailed descriptions provided by the participants are given in Appendix C.

Table 5: Summary of the measurement techniques used the participants

Laboratory	Method	Reference standards	Possible external source of traceability
KRISS	Total power radiometer	-Cryogenic and ambient standards at 18 GHz -Diode noise sources at 22 GHz and 26.5 GHz	- Traceable to NPL at 22 GHz and 26.5 GHz
LNE	Switching radiometer	Hot standard	-
NIST	Total power radiometer	Cryogenic and ambient standards	-
NMIJ/AIST	Total power radiometer	Cryogenic and ambient standards	Traceable to NIST for the cryogenic standard
NPL	Total power radiometer	Hot standard and ambient standards	-
VNIIFTRI	radiometer	Cryogenic standard	-

5. Measurement results

5.1. Results of the participating institutes

The measured available noise temperature and the reflection coefficient of three travelling standards, as described in lines 2 to 4 of Table 4, were reported by the participating laboratories. The measurement techniques used by the different participants are described in the technical reports in Appendix A.

Both quantities were measured at 18 GHz, 22 GHz, 25.8 GHz and 26.5 GHz and the results for the available noise temperature at these four frequencies are presented for full analysis in this section. Indeed, as the reflection coefficient is regarded only as an auxiliary measurement quantity, the corresponding reference value has not been determined.

Participants were also asked to provide estimates of the Type A and Type B uncertainties and the combined standard uncertainty of the available noise temperature at the aforementioned frequencies and the uncertainty budgets provided by the participants can be found in Appendix B.

The comparison results are presented in Tables 6 to 18, including the following data:

- Reflection coefficient (magnitude and phase) of travelling standard
- Available noise temperature and its standard uncertainty
- Key Comparison Reference Value (KCRV) and its standard uncertainty
- Degree of Equivalence and its expanded (k = 2) uncertainty

Graphical illustrations of the reported results with their standard uncertainty are also presented, together with the corresponding KCRV and its standard uncertainty, as green dashed lines and the outlier limits as red dashed lines.

The outlier limits, the KCRV and Degrees of Equivalence with their uncertainties are determined according to [2], as described below.

For each comparison result, if the value T_i of a participant differs from the median T_M by more than $2.5K_n median\{|T_i - T_M|\}$, then T_i is taken as outlier. The multiplier K_n is given in Table 1 of [2] and depends on the number of participants.

Then, the KCRV is given by

$$KCRV = \frac{1}{N'}\sum_{i=1}^{N'} T_i$$

where N' is the number of participants, excluding:

- the outliers,
- and the participants who are traceable to another participant. Thereby, based on the information given in Table 5, NMIJ/AIST data are not used for the KCRV calculation at any frequency, and KRISS data are not used at frequencies higher than 18 GHz.

For both cases, data are italicized in Tables 6 to 18. The outliers' data are furthermore highlighted in grey.

The combined standard uncertainty of KCRV is given by

$$u_{KCRV} = \sqrt{\frac{1}{N'^2}\sum_{i=1}^{N'} u_{T_i}^2}$$

where u_{T_i} is the combined standard uncertainty of the *i*th participant.

The deviation of a participant from the KCRV is given by

$$\Delta_i = T_i - KCRV$$

If T_i is not taken in the calculation of the KCRV, then the expanded uncertainty of this deviation is given by

$$U_{\Delta_i} = 2 \times \sqrt{u_{T_i}^2 + u_{KCRV}^2} \ ,$$

Otherwise the expanded uncertainty is given by

$$U_{\Delta_i} = 2 \times \sqrt{\left(1 - \frac{2}{N'}\right) u_{T_i}^2 + u_{KCRV}^2} \ .$$

Both the deviation and its expanded uncertainty define the degree of equivalence of the participant's result relative to the KCRV.

Finally, the reported measurements results for each laboratory are summarized in Tables 6 to 18 below.

5.1.1. Results for travelling standard K22.W.2.waveguide

Table 6: Measurements, combined standard uncertainties and degree of equivalence for K22.W.2.waveguide at 18 GHz

Laboratory	|Γ|	ϕ_Γ (°)	T (K)	u_T (K)	Δ (K)	U_Δ (K)
KRISS	0.025	-101	7160	156	44	262
LNE	*0.029*	-	*7433*	*84*	*317*	*196*
NIST	0.029	-94	7131	30	15	111
NMIJ/AIST	*0.031*	*-92*	*7229*	*69*	*113*	*147*
NPL	0.031	-93	6994	103	-122	189
VNIIFTRI	0.028	-95	7180	54	64	131
					KCRV	u_{KCRV}
					7116	50

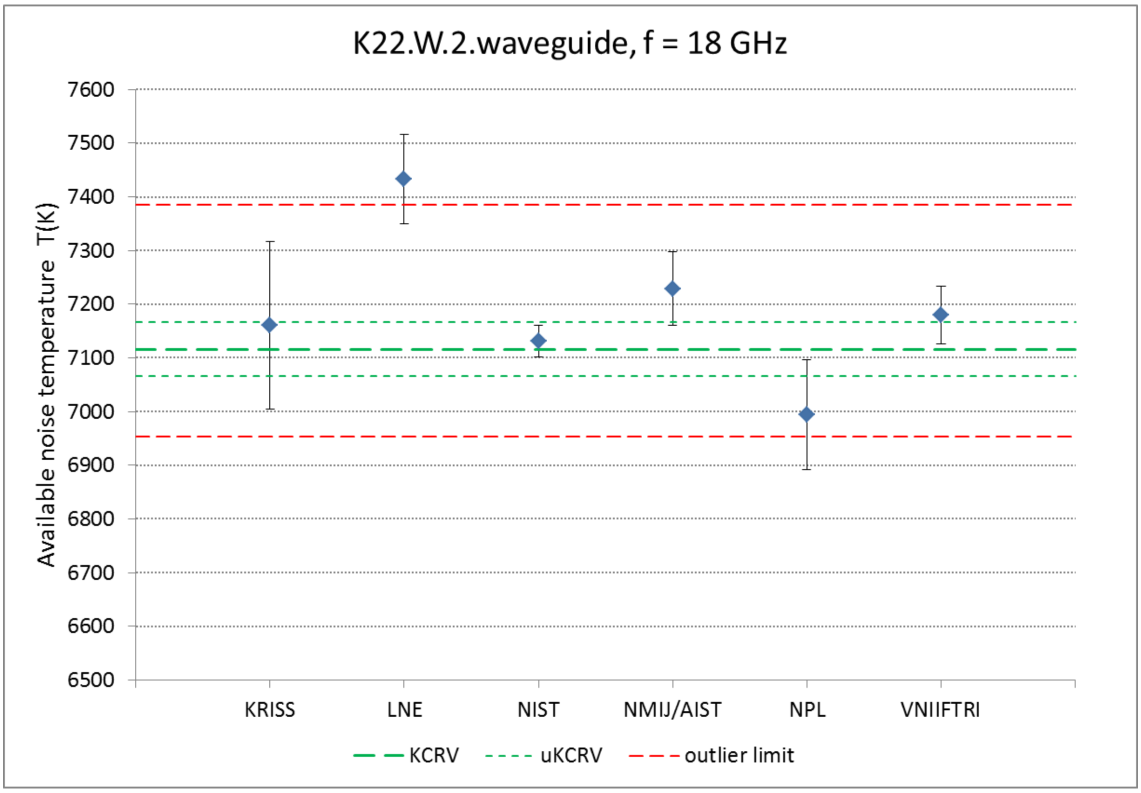

Fig. 1: Measurement of available noise temperature with combined standard uncertainty for K22.W.2.waveguide at 18 GHz

Table 7: Measurements, combined standard uncertainties and degree of equivalence for K22.W.2.waveguide at 22 GHz

Laboratory	$\|\Gamma\|$	ϕ_Γ (°)	T (K)	u_T (K)	Δ (K)	U_Δ (K)
KRISS	*0.055*	*44*	*8776*	*246*	*83*	*406*
LNE	0.055	-	8784	63	91	117
NIST	0.053	42	8630	41	-63	87
NMIJ/AIST	*0.054*	*44*	*8711*	*85*	*18*	*149*
NPL	0.053	43	8699	34	6	78
VNIIFTRI	0.057	42	8660	67	-33	123
					KCRV	u_{KCRV}
					8693	27

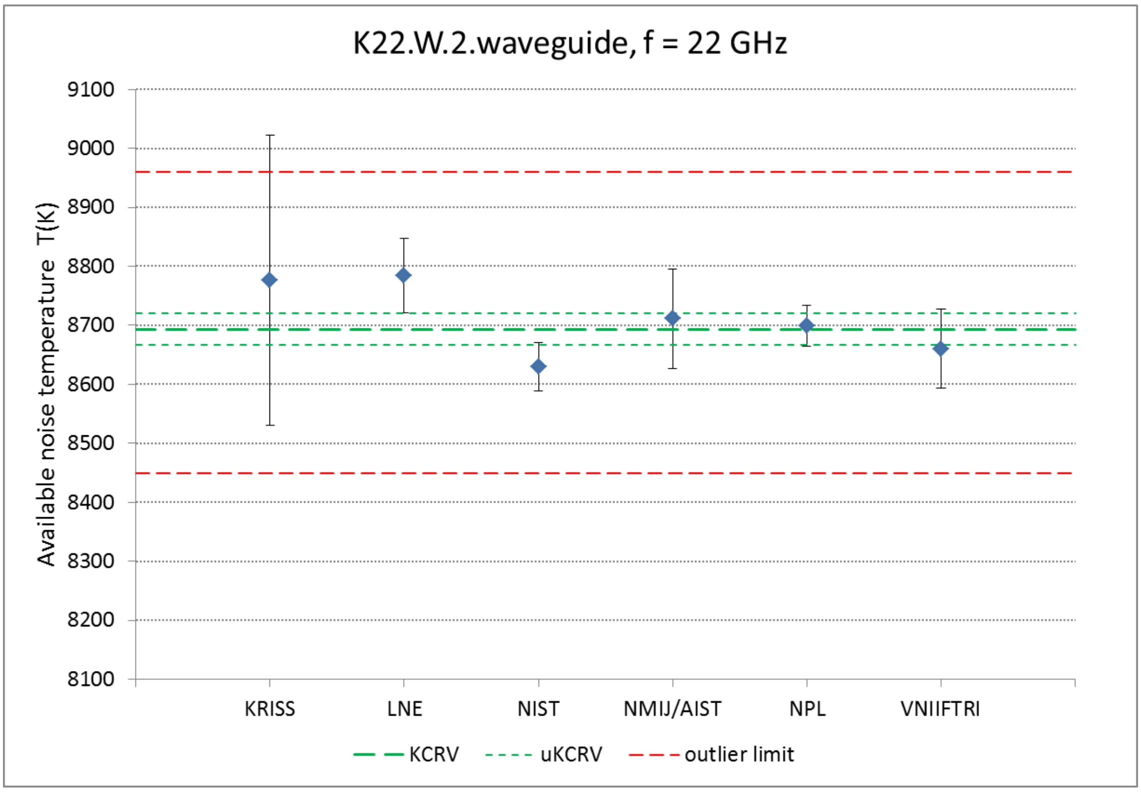

Fig. 2: Measurement of available noise temperature with combined standard uncertainty for K22.W.2.waveguide at 22 GHz

Table 8: Measurements, combined standard uncertainties and degree of equivalence for K22.W.2.waveguide at 25.8 GHz

Laboratory	$\|\Gamma\|$	ϕ_Γ (°)	T (K)	u_T (K)	Δ (K)	U_Δ (K)
KRISS	-	-	-	-	-	-
LNE	0.042	-	11297	71	32	132
NIST	0.039	-23	11177	55	-88	112
NMIJ/AIST	*0.040*	*-23*	*11436*	*147*	*171*	*239*
NPL	0.042	-25	11207	55	-58	112
VNIIFTRI	0.045	-16	11380	98	115	169
					KCRV	u_{KCRV}
					11265	36

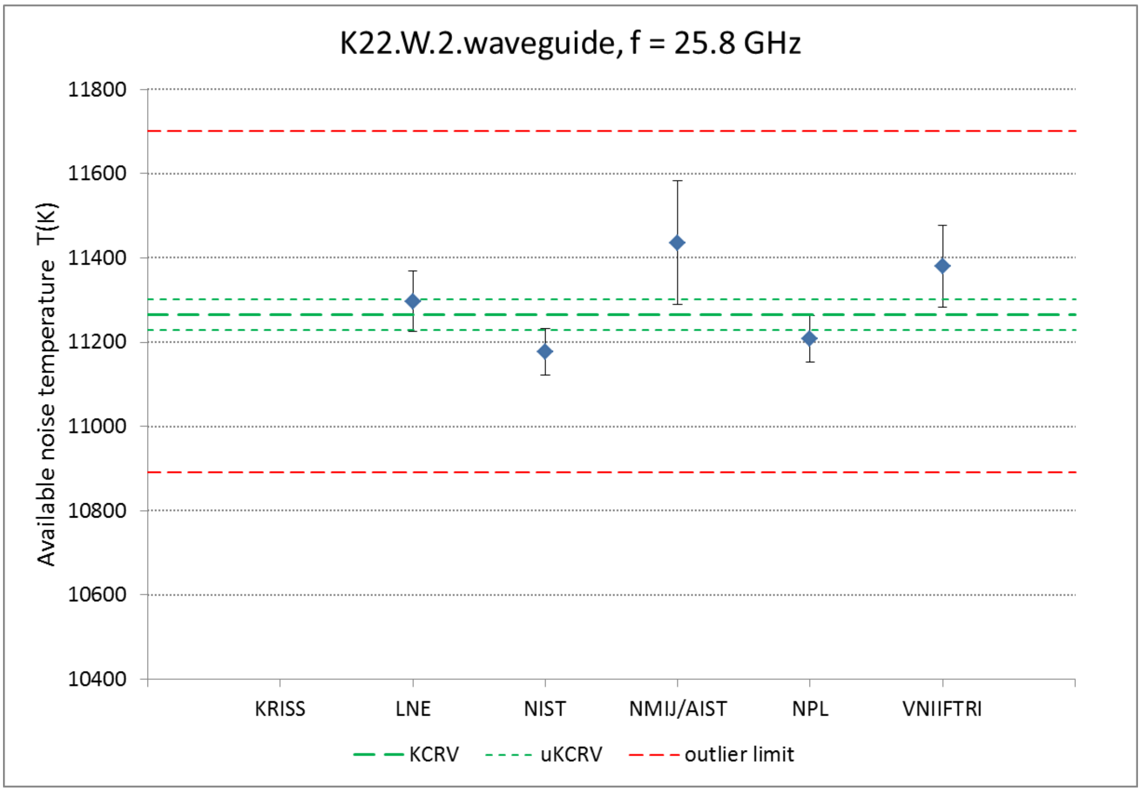

Fig. 3: Measurement of available noise temperature with combined standard uncertainty for K22.W.2.waveguide at 25.8 GHz

Table 9: Measurements, combined standard uncertainties and degree of equivalence for K22.W.2.waveguide at 26.5 GHz

Laboratory	$\|\Gamma\|$	ϕ_Γ (°)	T (K)	u_T (K)	Δ (K)	U_Δ (K)
KRISS	*0.042*	*-166*	*10376*	*288*	*26*	*413*
LNE	0.053	-	10401	67	51	117
NIST	0.040	-171	10292	53	-58	102
NMIJ/AIST	*0.041*	*-174*	*10609*	*136*	*259*	*281*
NPL	0.044	-172	10357	52	7	101
VNIIFTRI	-	-	-	-	-	-
					KCRV	u_{KCRV}
					10350	34

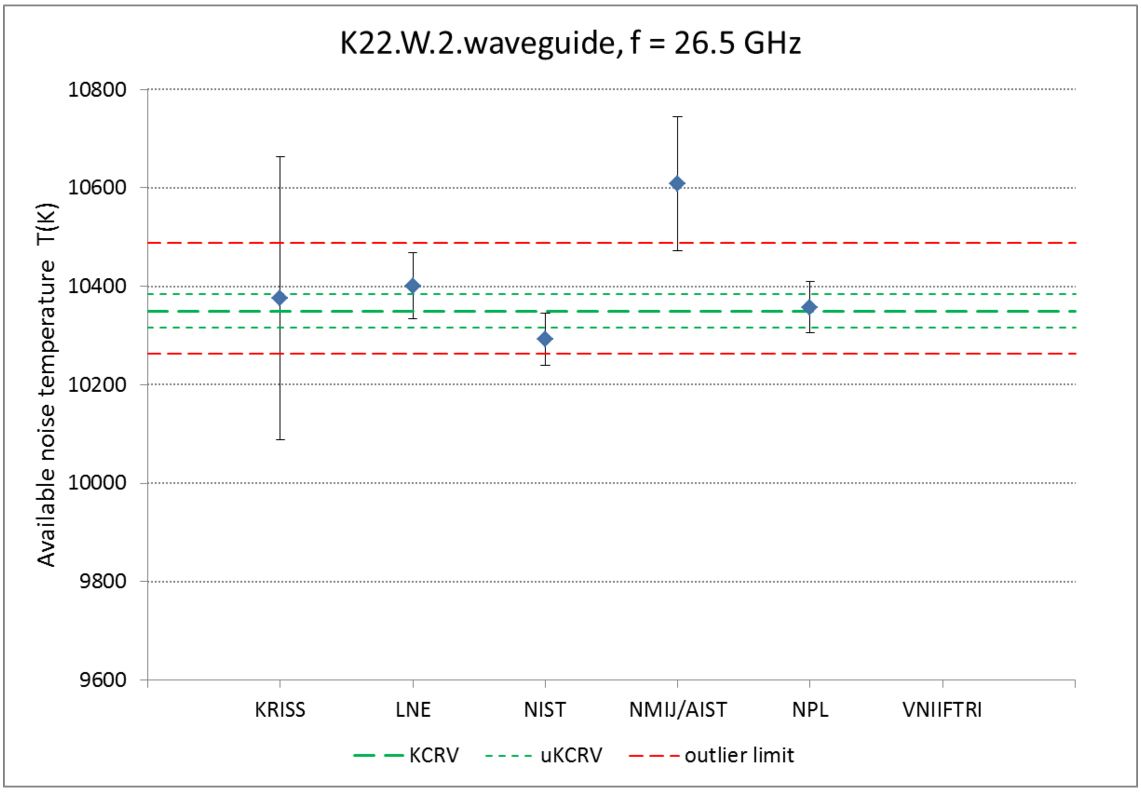

Fig. 4: Measurement of available noise temperature with combined standard uncertainty for K22.W.2.waveguide at 26.5 GHz

5.1.2. Results for travelling standard K22.W.2.coaxial

Table 10: Measurements, combined standard uncertainties and degree of equivalence for K22.W.2.coaxial at 18 GHz

Laboratory	$\|\Gamma\|$	ϕ_Γ (°)	T (K)	u_T (K)	Δ (K)	U_Δ (K)
KRISS	0.028	64	7324	148	89	245
LNE	-	-	-	-	-	-
NIST	0.035	81	7264	38	29	137
NMIJ/AIST	*0.034*	*80*	*7363*	*89*	*128*	*179*
NPL	0.030	77	7118	111	-117	202
VNIIFTRI	-	-	-	-	-	-
					KCRV	u_{KCRV}
					7235	63

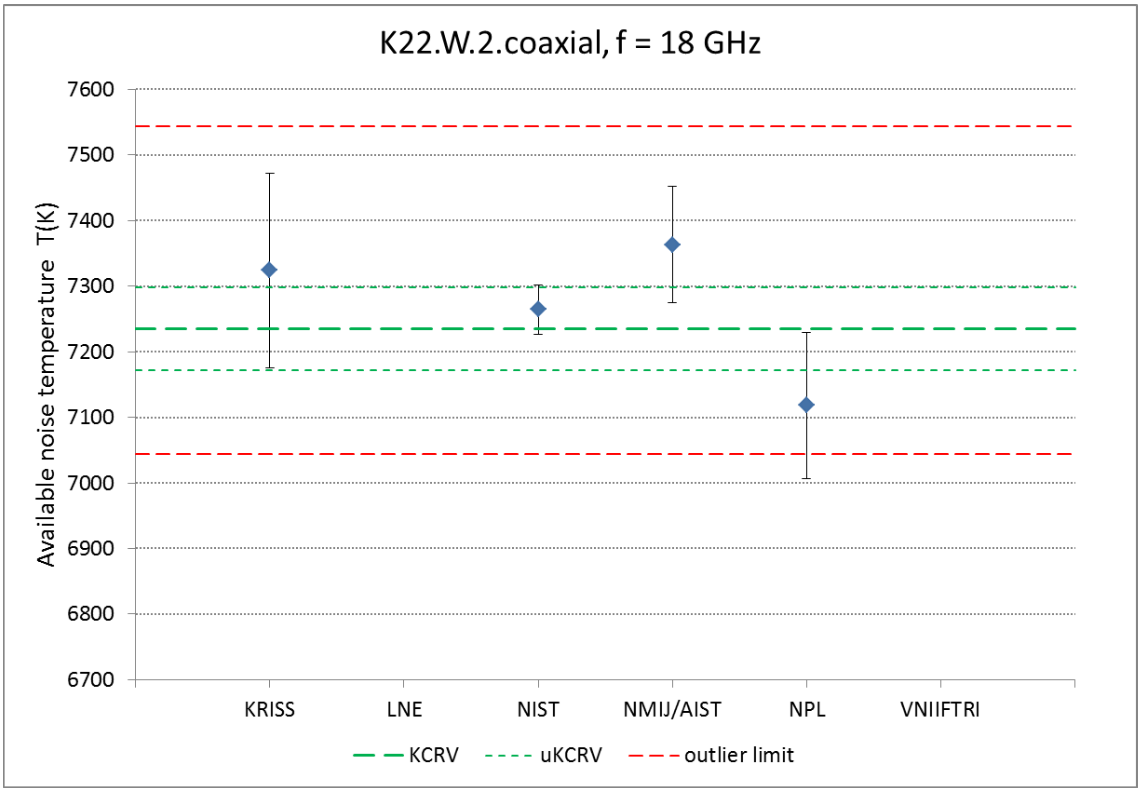

Fig. 5: Measurement of available noise temperature with combined standard uncertainty for K22.W.2.coaxial at 18 GHz

Table 11: Measurements, combined standard uncertainties and degree of equivalence for K22.W.2.coaxial at 22 GHz

Laboratory	$\|\Gamma\|$	ϕ_Γ (°)	T (K)	u_T (K)	Δ (K)	U_Δ (K)
KRISS	*0.037*	*79*	*8951*	*238*	*108*	*344*
LNE	-	-	-	-	-	-
NIST	0.039	73	8827	50	-16	99
NMIJ/AIST	*0.041*	*75*	*8903*	*111*	*60*	*172*
NPL	0.034	65	8859	44	16	93
VNIIFTRI	-	-	-	-	-	-
					KCRV	u_{KCRV}
					8843	34

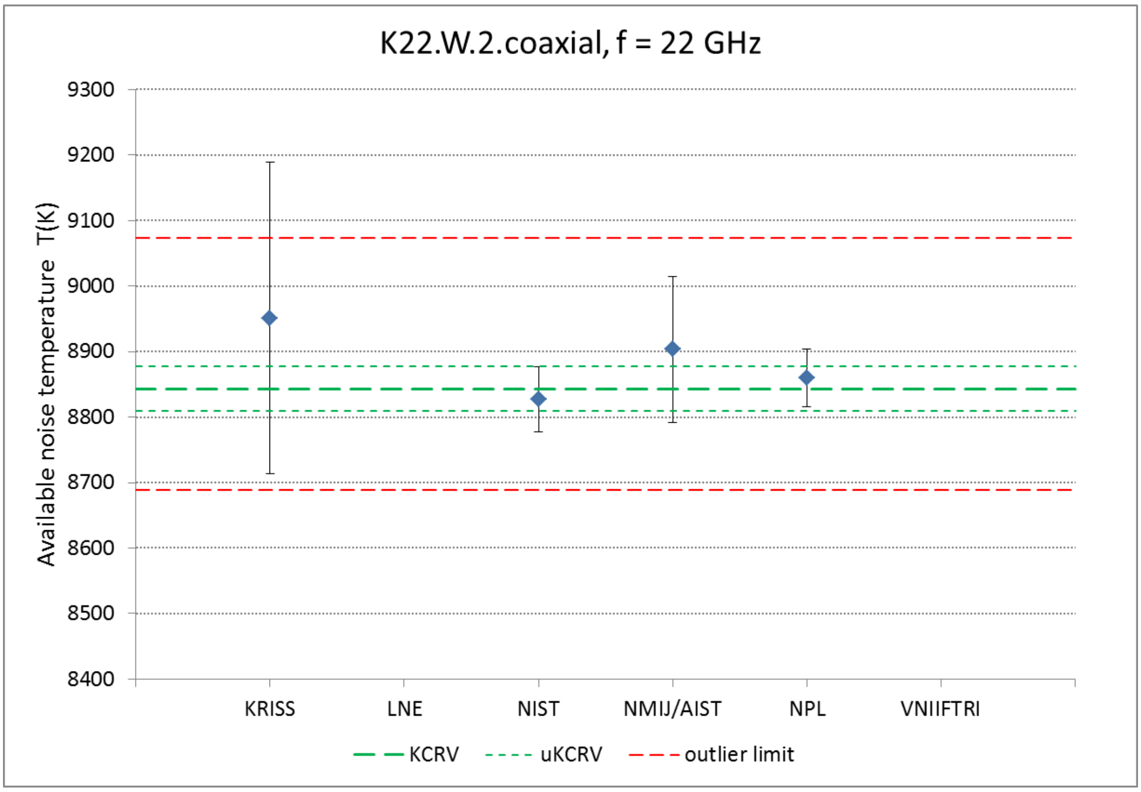

Fig. 6: Measurement of available noise temperature with combined standard uncertainty for K22.W.2.coaxial at 22 GHz

Table 12: Measurements, combined standard uncertainties and degree of equivalence for K22.W.2.coaxial at 25.8 GHz

Laboratory	$\|\Gamma\|$	ϕ_Γ (°)	T (K)	u_T (K)	Δ (K)	U_Δ (K)
KRISS	-	-	-	-	-	-
LNE	-	-	-	-	-	-
NIST	0.050	31	11503	67	31	125
NMIJ/AIST	*0.050*	*151*	*11713*	*176*	*241*	*226*
NPL	0.043	158	11441	69	-31	127
VNIIFTRI	-	-	-	-	-	-
					KCRV	u_{KCRV}
					11472	49

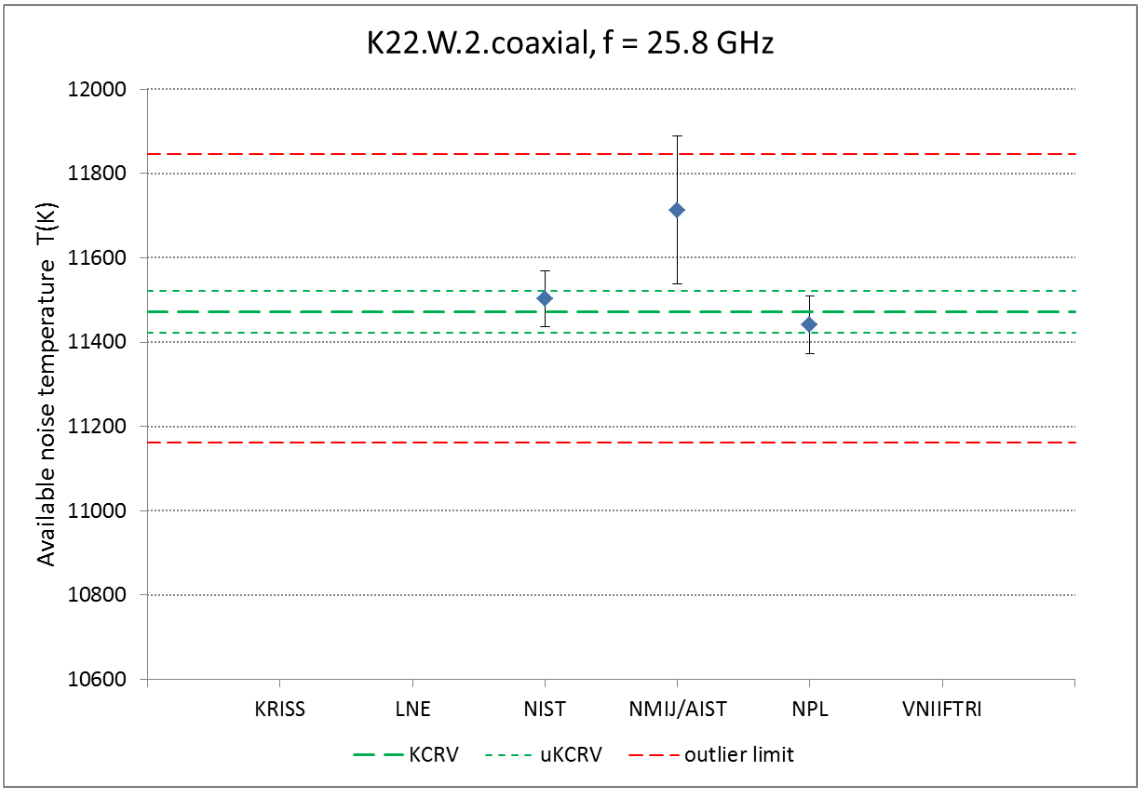

Fig. 7: Measurement of available noise temperature with combined standard uncertainty for K22.W.2.coaxial at 25.8 GHz

Table 13: Measurements, combined standard uncertainties and degree of equivalence for K22.W.2.coaxial at 26.5 GHz

Laboratory	$\|\Gamma\|$	ϕ_Γ (°)	T (K)	u_T (K)	Δ (K)	U_Δ (K)
KRISS	*0.043*	*99*	*10654*	*279*	*64*	*336*
LNE	-	-	-	-	-	-
NIST	0.051	101	10609	64	19	119
NMIJ/AIST	*0.048*	*102*	*10875*	*165*	*285*	*343*
NPL	0.042	98	10571	64	-19	119
VNIIFTRI	-	-	-	-	-	-
					KCRV	u_{KCRV}
					10590	46

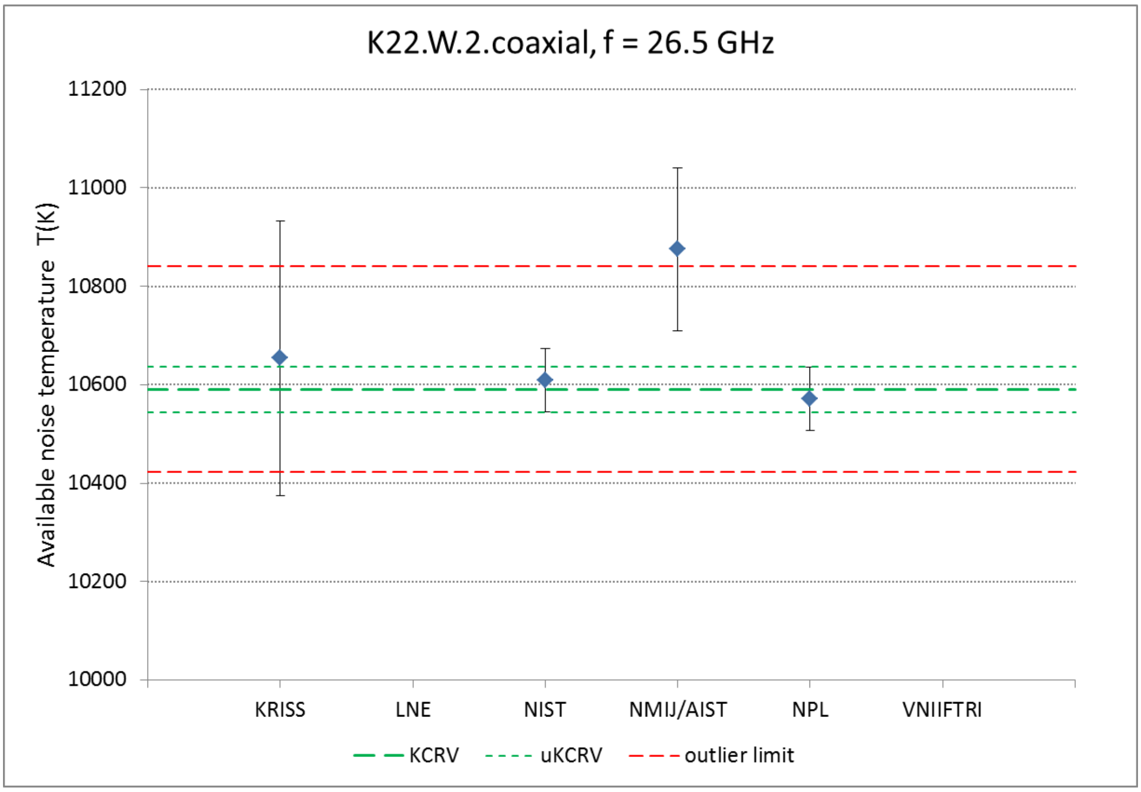

Fig. 8: Measurement of available noise temperature with combined standard uncertainty for K22.W.2.coaxial at 26.5 GHz

5.1.3. Results for travelling standard K22.W.3.waveguide

Table 14: Measurements, combined standard uncertainties and degree of equivalence for K22.W.3.waveguide at 18 GHz

Laboratory	$\lvert\Gamma\rvert$	ϕ_Γ (°)	T (K)	u_T (K)	Δ (K)	U_Δ (K)
KRISS	0.075	-161	13215	281	37	463
LNE	*0.217*	-	*13629*	*108*	*451*	*267*
NIST	0.092	-156	13047	56	-131	179
NMIJ/AIST	*0.073*	*-159*	*13096*	*131*	*-82*	*256*
NPL	0.077	-159	13259	55	81	178
VNIIFTRI	0.076	-160	13190	99	12	219
					KCRV	u_{KCRV}
					13178	78

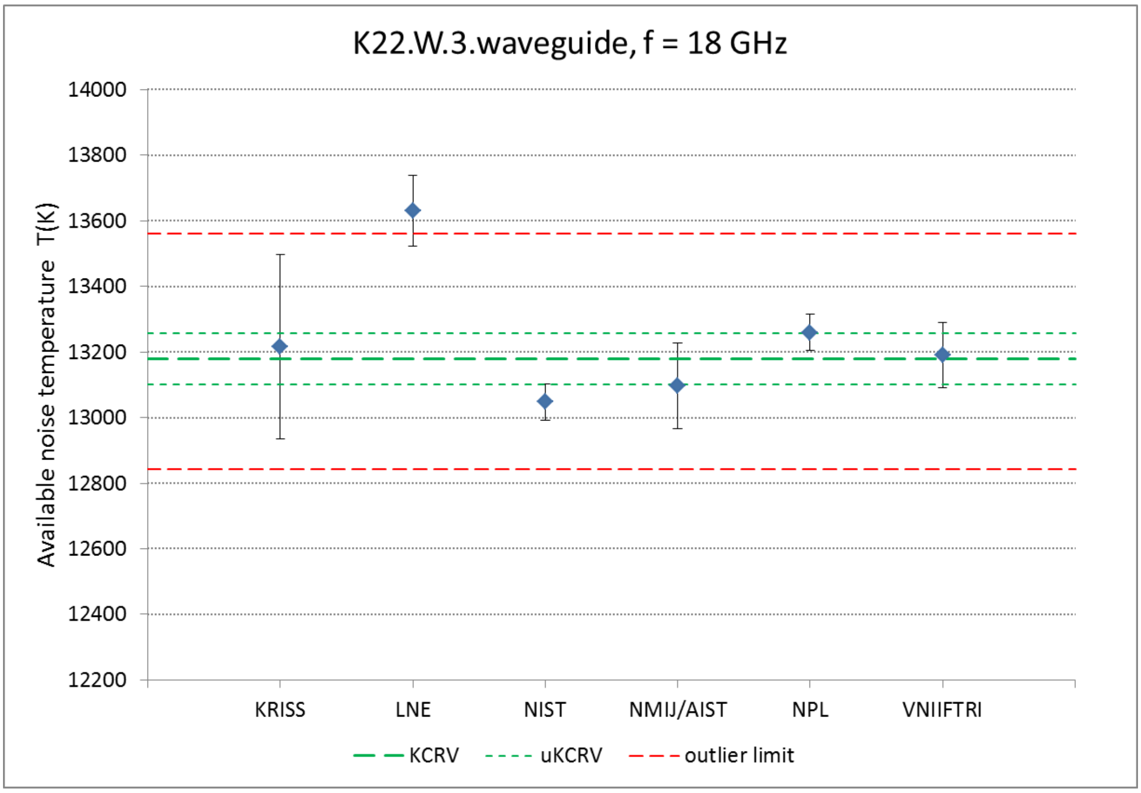

Fig. 9: Measurement of available noise temperature with combined standard uncertainty for K22.W.3.waveguide at 18 GHz

Table 15: Measurements, combined standard uncertainties and degree of equivalence for K22.W.3.waveguide at 22 GHz

Laboratory	$\|\Gamma\|$	ϕ_Γ (°)	T (K)	u_T (K)	Δ (K)	U_Δ (K)
KRISS	*0.139*	*-57*	*10709*	*292*	*244*	*481*
LNE	0.149	-	10276	72	-189	132
NIST	0.152	-58	10598	57	133	111
NMIJ/AIST	*0.142*	*-58*	*10487*	*107*	*22*	*185*
NPL	0.138	-58	10584	51	119	103
VNIIFTRI	0.138	-58	10400	52	-65	104
					KCRV	u_{KCRV}
					10465	30

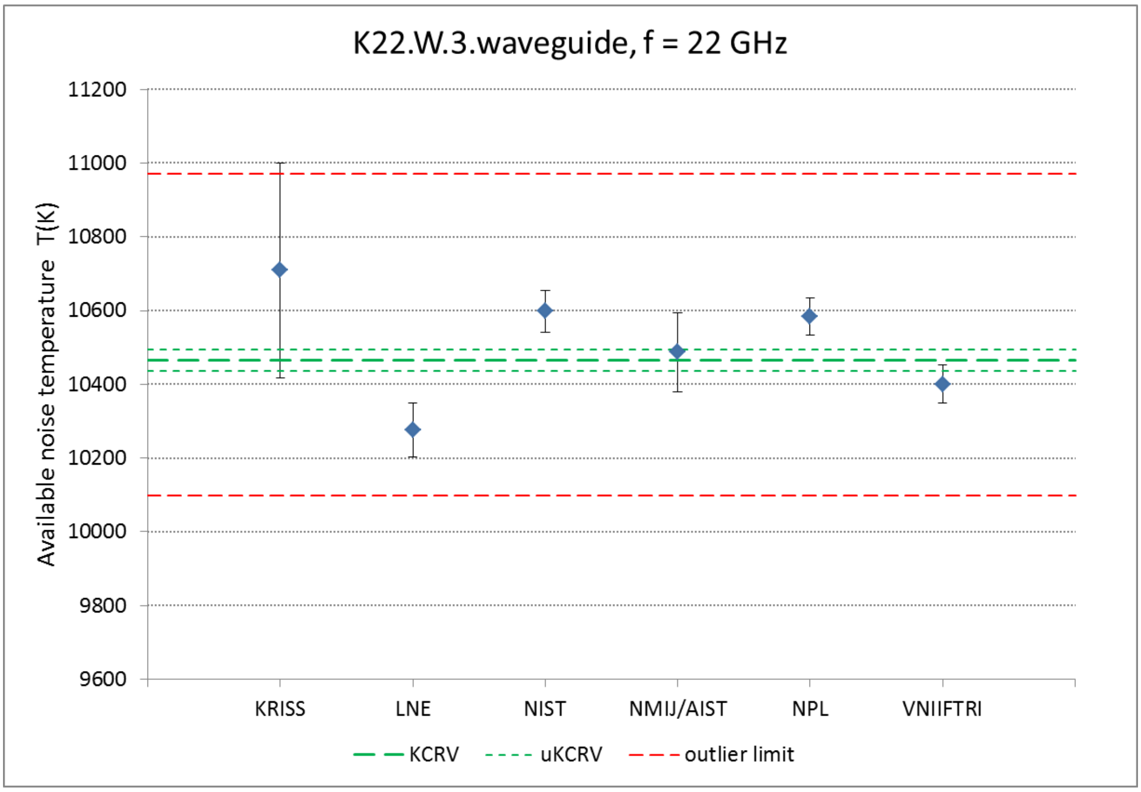

Fig. 10: Measurement of available noise temperature with combined standard uncertainty for K22.W.3.waveguide at 22 GHz

Table 16: Measurements, combined standard uncertainties and degree of equivalence for K22.W.3.waveguide at 25.8 GHz

Laboratory	$\|\Gamma\|$	ϕ_Γ (°)	T (K)	u_T (K)	Δ (K)	U_Δ (K)
KRISS	-	-	-	-	-	-
LNE	*0.094*	-	*8071*	*50*	*-101*	*115*
NIST	0.040	-146	8163	39	-9	79
NMIJ/AIST	*0.042*	*-168*	*8174*	*115*	*2*	*173*
NPL	0.049	-156	8164	37	-8	77
VNIIFTRI	0.071	139	8190	62	18	105
					KCRV	u_{KCRV}
					8172	28

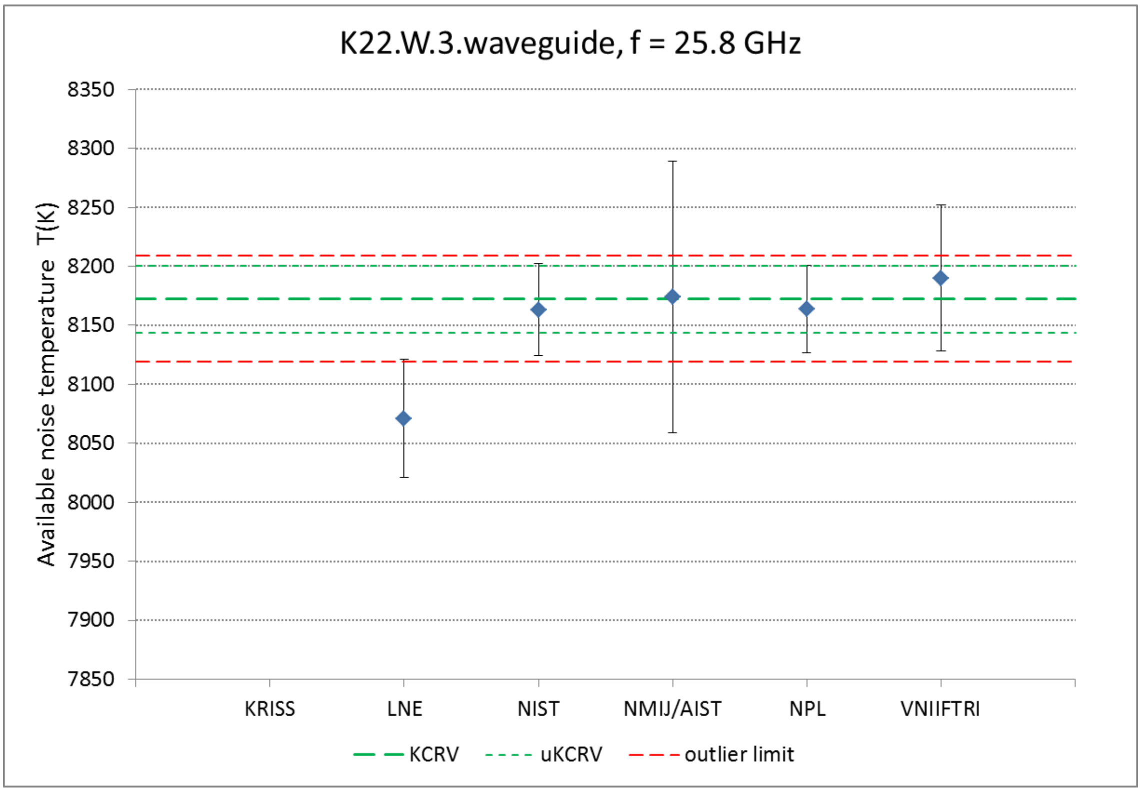

Fig. 11: Measurement of available noise temperature with combined standard uncertainty for K22.W.3.waveguide at 25.8 GHz

Table 17: Measurements, combined standard uncertainties and degree of equivalence for K22.W.3.waveguide at 26.5 GHz

Laboratory	$\lvert\Gamma\rvert$	ϕ_Γ (°)	T (K)	u_T (K)	Δ (K)	U_Δ (K)
KRISS	*0.014*	*155*	*7450*	*190*	*99*	*298*
LNE	0.145	-	7418	48	67	88
NIST	0.011	-147	7317	35	-34	72
NMIJ/AIST	*0.010*	*138*	*7370*	*98*	*19*	*159*
NPL	0.021	166	7317	32	-34	68
VNIIFTRI	-	-	-	-	-	-
					KCRV	u_{KCRV}
					7351	23

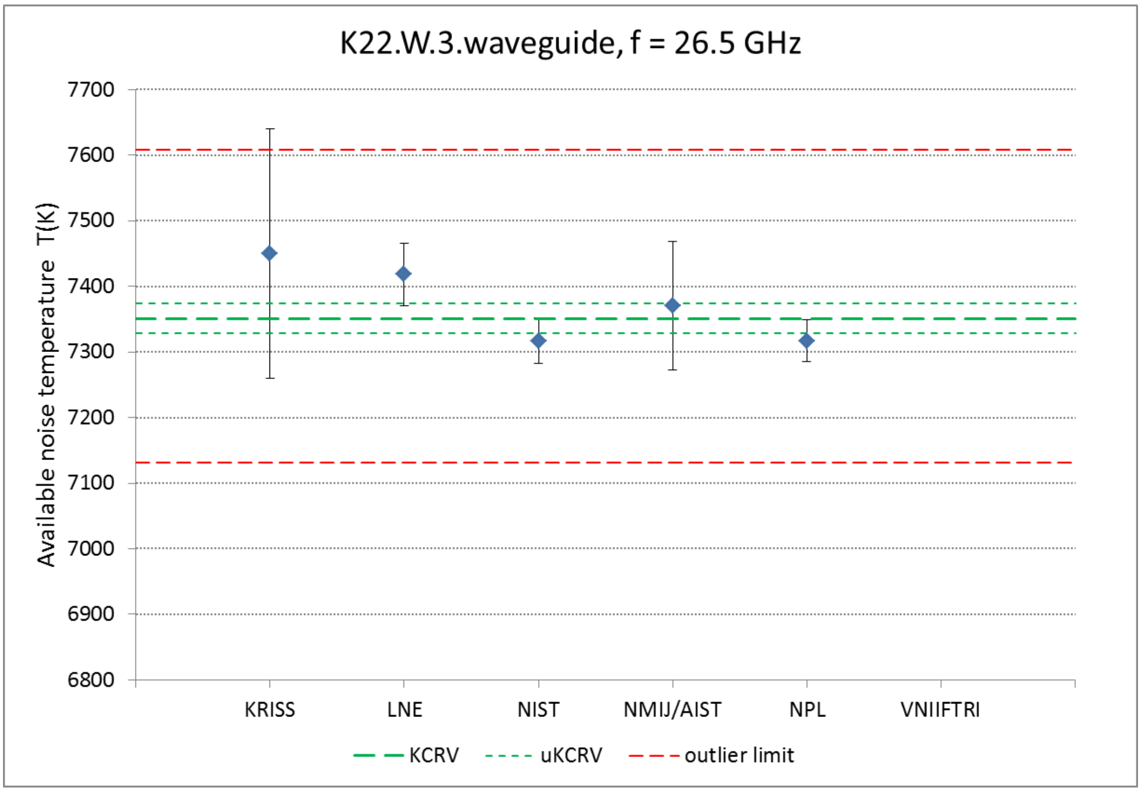

Fig. 12: Measurement of available noise temperature with combined standard uncertainty for K22.W.3.waveguide at 26.5 GHz

6. CONCLUSION

In this comparison, available noise temperature of three noise sources, two in waveguide and one in coaxial line were determined at four frequencies in the band from 18 GHz to 26.5 GHz, by six National Metrology Institutes (NMIs) between October 2007 and February 2011. Four participants used national primary standards, while one participant had one working standard traceable to another participant for all frequencies and a second participant who was traceable to another participant above 18 GHz.

During the comparison, instability has been noticed on one of the travelling standards, so it was replaced with a supplementary noise source, which prolonged the duration of the comparison. Moreover, breakdown of the pilot laboratory measurement system during the comparison has prevented any possible check of stability of the travelling standards during the comparison progress.

The reported results have been used to calculate the Key Comparison Reference Value (KCRV) for the three travelling standards and for all frequencies. Despite the problems mentioned above and a comparison that was much longer than initially planned, the results show generally good agreement among the participants as illustrated by the data given for the Degrees of Equivalence and their expanded uncertainties.

References

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A. Technical Reports from the participating laboratories

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

A.1. KRISS report

Available noise temperature

At 18 GHz, the two standard noise sources are a 7-mm cryogenic noise source and an ambient termination. A 7-mm coaxial total power radiometer was used to measure the noise power using appropriate adapters as follows;

- for the travelling standard, K22.W.2.coaxial, a 3.5 mm (female) –7 mm adapter.
- for the travelling standard, K22.W.2.waveguide, a 3.5 mm (female)–WR42 adapter provided by the pilot laboratory (HP K281C, MY46040120) was used. The adapter was evaluated using the adapter removal method and embedded to obtain the noise temperature (NT) of the travelling standard, K22.W.2.waveguide.
- for the travelling standard K22.W.3.waveguide, a cascaded adapter, WR42–3.5 mm (male) adapter and 3.5 mm (female) –7 mm adapter.

At 22 GHz and 26.5 GHz, a set of diode noise sources calibrated at National Physical Laboratory (NPL), United Kingdom, were used. Since a diode noise source with 15 dB ENR is commercially available, a 10 dB attenuator was combined with the noise source to make a cold noise source. The efficiency, i.e., the dissipative component of the 10 dB attenuator was obtained from the measured scattering parameters. The noise power was measured using a commercial noise figure analyzer, Agilent N8975A. At 22 GHz and 26.5 GHz, the following adapters were used;

- for the travelling standard, K22.W.2.coaxial, no adapter was used.
- for the travelling standard, K22.W.2.waveguide, a 3.5 mm (female)–WR42 adapter provided by the pilot laboratory (HP K281C, MY46040120) was used.
- for the travelling standard K22.W.3.waveguide, a WR42–3.5(male) adapter was used to measure the noise power and de-embedded to obtain the noise temperature (NT) of the travelling standard.

The control of all instruments and the measurement were done by a system controller via GPIB.

The reflection coefficients

The reflection coefficient of the travelling standards was measured using a vector network analyzer and the results are reported as complex values.

The control of all instruments and the measurement were done by a system controller via GPIB.

A.2. LNE Report

The traveling standards were compared against LNE's IEC R220 hot (nominal 1000 K) primary noise standard. The noise measurements were made on the BNM-LCIE R220 Dicke-type radiometer [3] by comparing successively LNE noise standard and the travelling noise standard to a said reference noise source.

For each standard, the attenuation of a calibrated attenuator located at the input of the radiometer is set to A_s and A_x, so as to cancel the difference between the noise standard and the reference noise source levels, respectively. The difference $\Delta = A_s - A_x$ in dB between the two attenuation settings is used to determine the available noise temperature T_x of the travelling standard, knowing the available noise temperature T_s of LNE standard. Additional parameters used for the determination of T_x are the ambient/attenuator temperature T_a and a mismatch term including reflection coefficients S_{11}, ρ_x and ρ_s of the radiometer input, the travelling noise standard and LNE noise standard respectively, as shown in the radiometer equation below. Not shown in the equation below but also taken into account, is the imbalance between the two radiometer arms connected alternatively to the standard and the unknown noise sources.

$$T_x = (T_s - T_a)10^{\frac{\Delta}{10}} \left|\frac{1 - S_{11}\rho_x}{1 - S_{11}\rho_s}\right| \frac{1 - |\rho_s|^2}{1 - |\rho_x|^2} + T_a$$

A.3. NIST Report

The noise temperature measured and reported is the available noise temperature, defined to be the available noise power per unit bandwidth divided by Boltzmann's constant. For noise temperatures above T_0 = 290 K, we also report the excess noise ratio delivered into a reflectionless load (ENR_0). It is defined by

$$ENR_0(dB) \equiv 10\log_{10}\left(\frac{T(1-|\Gamma|^2) - T_0}{T_0}\right),$$

where T is the available noise temperature, and Γ is the reflection coefficient of the device under test. If the available ENR is desired, it can be computed directly from the available noise temperature by

$$ENR_{av}(dB) \equiv 10\log_{10}\left(\frac{T - T_0}{T_0}\right).$$

For most devices, the difference between ENR_0 and ENR_{av} is very small. NIST noise-temperature measurements are performed on total-power radiometers, using two primary thermal noise standards, one of which is at ambient temperature and one of which is at cryogenic (liquid nitrogen) temperature. These national primary standards are traceable to the SI unit kelvin (through calibrated thermistors and the boiling temperature of liquid nitrogen). For measurements at 30 and 60 MHz, tunable coaxial standards [4] are used. From 1 to 12.4 GHz, coaxial standards [5] are used, and for 12.4 GHz and above, waveguide/horn standards [6, 7] are used. The radiometers themselves are described in references [4, 8-10]. The NIST radiometers are double-sideband, total-power radiometers. The IF frequency is 0 (*i.e.*, the LO frequency is set to the measurement frequency), and the IF bandwidth B_{IF} ranges from 5 MHz to 20 MHz, depending on the particular radiometer. Thus the reported noise temperature represents an average over a frequency range of 2 BIF centered at the measurement frequency.

At least three independent measurements (including separate system calibrations, where applicable) of the noise temperature are made at each frequency. The noise source is allowed to warm up before any measurements are made. For many connector types and frequencies, the measurements are made through adapters. The procedure for characterizing the adapter and removing its effect is described in references [11, 12].

A.4. NMIJ/AIST Report

METHOD

The noise temperature measurements were made on the NMIJ total-power radiometer [16] for WR-42 waveguide band. The travelling standard was compared with an ambient standard and a cryogenic standard. The radiometer is a heterodyne system with 30 MHz IF signal. The IF signal is detected through the step attenuator (IF ATT). The noise powers of devices under test and the standards are proportional to the attenuation of the IF ATT. Then, the noise temperature was determined from the attenuation. For the coaxial noise source with an adapter, the noise temperature was measured at waveguide plane. The noise temperature of the coaxial plane was determined by a correction of the adapter efficiency. The adapter efficiency was evaluated by the one-port method [17]. The cooling water of about 23 °C was circulated to the radiometer to stabilize the thermal fluctuation of the system.

TRACEABILITY

NMIJ has been equipped with a cryogenic noise source and an ambient noise source for the reference standards. The cryogenic noise source is traceable to NIST noise standard. The temperature of the ambient noise source is measured by a thermocouple which is traceable to the Japan national standard of temperature.

A.5. NPL Report

The travelling standards were calibrated using a radiometer against an NPL transfer standard which has direct traceability to UK Primary Noise Standards.

The results quoted are in terms of equivalent available noise temperature which implies that when multiplied by Boltzmann's constant the values calculated would represent the power spectral density (W/Hz) delivered to a conjugately-matched load. Each result represents the average value measured over a 10 MHz bandwidth centred on the quoted frequency. The frequency accuracy is estimated to be ±1 part in 10^6.

The reflection coefficient measurements were performed using a calibrated Vector Network Analyser whose performance was verified using traceably calibrated impedance audit standards. The uncertainty on the quoted measurements is estimated to be 0.01 in magnitude and $[2\sin^{-1}(0.005/|\Gamma|)]°$ in phase. If the magnitude $|\Gamma|$ is less than its uncertainty then the phase uncertainty is 180°.

The device temperature was measured using a platinum resistance thermometer attached to the outer case. The calibration results are valid for the device temperature stated.

A.6. VNIIFTRI Report

The TRAVELING STANDARDS were compared against the cryogenic primary standard PS. The PS represents a waveguide absorbing load (rectangular waveguide 11x5.5 mm) immersed in liquid nitrogen and connected to an output section with sealing window and output flange by means of a heat-shield waveguide.

The noise measurements were made by means of a radiometer with a pilot signal [19]. It is a double sideband system with input calibrated attenuator, IF frequency 30 MHz, bandwidth 10 MHz and NFA as equivalent noise figure meter. To improve comparison the adjustable matching tuner was excluded from radiometer input circuit. Instead of it the complex reflection coefficients of the compared devices and radiometer input were measured on Agilent Technologies Network Analyzer E8363B. The mismatch correction was performed on these results.

The PS and radiometer are similar physically to described in [18, 19].

As in the previous comparison the differences of the IEC and Russia standards on the dimensions of waveguides have led to the necessity of making additional adapters. To reduce the influence of the adapter the technique was used with a reconnection of this adapter, similar to that described in [20].

Unfortunately noise temperature at the PC-3.5 plane of K22.W.2 was not measured through the absence of high-quality waveguide-coaxial adapter.

B. Uncertainty budgets

B.1. KRISS Uncertainty budgets

K22.W.2.waveguide at 18 GHz

No.	Components of uncertainty	c_i	$u(x_i)$	$\|c_i\|u(x_i)$, K	Distribution
1	7-mm ambient standard	35.24	0.2309 K	8	rectangular
2	7-mm cryogenic standard	-32.54	0.8340 K	27	normal
3	Y-factor including nonlinearity, Y1=Ns1/Ns2	-37285 K	0.0037	138	rectangular
4	Y-factor including nonlinearity, Y2=Ns1/Nx	-66620 K	0.0003	20	rectangular
5	Mismatch correction between the STD1 and the TPR	10495 K	0.0012	13	normal
6	Mismatch correction between the STD2 and the TPR	-3179 K	0.0013	4	normal
7	Mismatch correction between the DUT and the TPR	7362 K	0.0008	6	normal
8	Adapter de-embedding to obtain Te, the NT of the coaxial TS, K22.W.2.coaxial. Evaluation of the adapter (3.5 mm (f)-GPC7 adapter, NOISE#1)	-7146 K	0.005	36	normal
9	Type A uncertainty	1	12 K	12	normal
10	*Adapter embedding* to obtain the NT of the waveguide TS, K22.W.2.waveguide, Evaluation of the adapter (*KC artifact*): 3.5 mm(f)-WR42	7028 K	0.0068	48	normal
	Combined standard uncertainty (k=1)			156	normal

K22.W.2.waveguide at 22 GHz

No.	Components of uncertainty	c_i	$u(x_i)$	$\lvert c_i \rvert u(x_i)$, K	Distribution
1	3.5-mm noise source STD3-1	0.9991	55 K	55	normal
2	3.5-mm noise source STD3-2 with a 10 dB-attenuator ATT3-2	-0.0033	33 K	0	normal
2.1	15-dB ENR 3.5-mm noise source	0.00854	65 K	1	normal
2.2	The dissipative components of the 10-dB attenuator	10764 K	0.0031	33	normal
3	Y-factor including nonlinearity, Y1=Ns1/Ns2	-3286 K	0.0639	210	rectangular
4	Y-factor including nonlinearity, Y2=Ns1/Nx	-9044 K	0.0097	88	rectangular
5	Mismatch correction between the STD1 and the noise figure analyzer	9656 K	0.0033	32	normal
6	Mismatch correction between the STD2 and the noise figure analyzer	-5 K	0.0024	0	normal
7	Mismatch correction between the DUT and the noise figure analyzer	9611 K	0.0031	30	normal
8	Type A uncertainty	1	8 K	8	normal
9	*Adapter embedding* to obtain the NT of the waveguide TS, K22.W.2.waveguide, Evaluation of the adapter (*KC artifact*): 3.5 mm (f)-WR42	8655 K	0.0069	59	normal
	Combined standard uncertainty (k=1)			246	normal

K22.W.2.waveguide at 26.5 GHz

No.	Components of uncertainty	c_i	$u(x_i)$	$\lvert c_i \rvert u(x_i)$, K	Distribution
1	3.5-mm noise source STD3-1	0.9234	80 K	74	normal
2	3.5-mm noise source STD3-2 with a 10 dB-attenuator ATT3-2	0.0722	24 K	2	normal
2.1	15-dB ENR 3.5-mm noise source	0.0738	55 K	4	normal
2.2	The dissipative components of the 10-dB attenuator	7554 K	0.0031	24	normal
3	Y-factor including nonlinearity, Y1=Ns1/Ns2	-2027 K	0.1198	243	rectangular
4	Y-factor including nonlinearity, Y2=Ns1/Nx	-9948 K	0.0113	112	rectangular
5	Mismatch correction between the STD1 and the noise figure analyzer	10896 K	0.0018	20	normal
6	Mismatch correction between the STD2 and the noise figure analyzer	77 K	0.0011	0	normal
7	Mismatch correction between the DUT and the noise figure analyzer	10916 K	0.0013	14	normal
8	Type A uncertainty	1	19.9	20	normal
9	*Adapter embedding* to obtain the NT of the waveguide TS, K22.W.2.waveguide, Evaluation of the adapter (*KC artifact*): 3.5 mm (f)-WR42	10359 K	0.0068	71	normal
	Combined standard uncertainty (k=1)			288	normal

K22.W.2.coaxial at 18 GHz

No.	Components of uncertainty	c_i	$u(x_i)$	$\|c_i\|u(x_i)$, K	Distribution
1	7-mm ambient standard	35.24	0.2309 K	8	rectangular
2	7-mm cryogenic standard	-32.54	0.8340 K	27	normal
3	Y-factor including nonlinearity, Y1=Ns1/Ns2	-37285 K	0.0037	138	rectangular
4	Y-factor including nonlinearity, Y2=Ns1/Nx	-66620 K	0.0003	20	rectangular
5	Mismatch correction between the STD1 and the TPR	10495 K	0.0012	13	normal
6	Mismatch correction between the STD2 and the TPR	-3179 K	0.0013	4	normal
7	Mismatch correction between the DUT and the TPR	7362 K	0.0008	6	normal
8	Adapter de-embedding to obtain Te, the NT of the coaxial TS, K22.W.2.coaxial. Evaluation of the adapter (3.5 mm (f)-GPC7 adapter, NOISE#1)	-7146 K	0.0050	36	normal
9	Type A uncertainty	1	12 K	12	normal
	Combined standard uncertainty (k=1)			148	normal

K22.W.2.coaxial at 22 GHz

No.	Components of uncertainty	c_i	$u(x_i)$	$\|c_i\|u(x_i)$, K	Distribution
1	3.5-mm noise source STD3-1	0.9991	55 K	55	normal
2	3.5-mm noise source STD3-2 with a 10 dB-attenuator ATT3-2	-0.0033	34 K	0	normal
2.1	15-dB ENR 3.5-mm noise source	0.0978	65 K	6	normal
2.2	The dissipative components of the 10-dB attenuator	10764 K	0.0031	33	normal
3	Y-factor including nonlinearity, Y1=Ns1/Ns2	-3286 K	0.0639	210	rectangular
4	Y-factor including nonlinearity, Y2=Ns1/Nx	-9044 K	0.0097	88	rectangular
5	Mismatch correction between the STD1 and the noise figure analyzer	9656 K	0.0033	32	normal
6	Mismatch correction between the STD2 and the noise figure analyzer	-5 K	0.0024	0	normal
7	Mismatch correction between the DUT and the noise figure analyzer	9611 K	0.0031	30	normal
8	Type A uncertainty	1	8 K	8	normal
	Combined standard uncertainty (k=1)			238	normal

K22.W.2.coaxial at 26.5 GHz

No.	Components of uncertainty	c_i	$u(x_i)$	$\lvert c_i \rvert u(x_i)$, K	Distribution
1	3.5-mm noise source STD3-1	0.9234	80 K	74	normal
2	3.5-mm noise source STD3-2 with a 10 dB-attenuator ATT3-2	0.0722	25 K	2	normal
2.1	15-dB ENR 3.5-mm noise source	0.0998	55 K	5	normal
2.2	The dissipative components of the 10-dB attenuator	7554 K	0.0031	24	normal
3	Y-factor including nonlinearity, Y1=Ns1/Ns2	-2027 K	0.1198	243	rectangular
4	Y-factor including nonlinearity, Y2=Ns1/Nx	-9948 K	0.0113	112	rectangular
5	Mismatch correction between the STD1 and the noise figure analyzer	10896 K	0.0018	20	normal
6	Mismatch correction between the STD2 and the noise figure analyzer	77 K	0.0011	0	normal
7	Mismatch correction between the DUT and the noise figure analyzer	10916 K	0.0013	14	normal
8	Type A uncertainty	1	20 K	20	normal
	Combined standard uncertainty (k=1)			279	normal

K22.W.3.waveguide at 18 GHz

No.	Components of uncertainty	c_i	$u(x_i)$	$\|c_i\|u(x_i)$, K	Distribution
1	7-mm ambient standard	66.39	0.2309 K	15	rectangular
2	7-mm cryogenic standard	-57.47	0.8340 K	48	normal
3	Y-factor including nonlinearity, Y1=Ns1/Ns2	-70015 K	0.0037	259	rectangular
4	Y-factor including nonlinearity, Y2=Ns1/Nx	-189852 K	0.0002	38	rectangular
5	Mismatch correction between the STD1 and the total power radiometer	19140 K	0.0004	8	normal
6	Mismatch correction between the STD2 and the total power radiometer	-59 K	0.0003	0	normal
7	Mismatch correction between the DUT and the total power radiometer	13828 K	0.0004	6	normal
8	Adapter de-embedding to obtain the NT of the waveguide TS, K22.W.3.waveguide, Evaluation of the adapter (cascaded WR42-3.5 mm (f) adapter and 3.5 mm (m)-GPC7 adapter, NOISE#31)	-12919 K	0.0068	88	normal
9	Type A uncertainty	1	11 K	11	normal
	Combined standard uncertainty (k=1)			281	normal

K22.W.3.waveguide at 22 GHz

No.	Components of uncertainty	c_i	$u(x_i)$	$\|c_i\|u(x_i)$, K	Distribution
1	3.5-mm noise source STD3-1	1.2406	55 K	68	normal
2	3.5-mm noise source STD3-2 with a 10 dB-attenuator ATT3-2	-0.0390	35 K	1	normal
2.1	15-dB ENR 3.5-mm noise source	0.09979	65 K	6	normal
2.2	The dissipative components of the 10-dB attenuator	10983 K	0.0031	34	normal
3	Y-factor including nonlinearity, Y1=Ns1/Ns2	-3844 K	0.0659	253	rectangular
4	Y-factor including nonlinearity, Y2=Ns1/Nx	-12448 K	0.0083	103	rectangular
5	Mismatch correction between the STD1 and the noise figure analyzer	11080 K	0.0012	13	normal
6	Mismatch correction between the STD2 and the noise figure analyzer	-264.5 K	0.0003	0	normal
7	Mismatch correction between the DUT and the noise figure analyzer	11054 K	0.0009	10	normal
8	Adapter de-embedding to obtain the NT of the waveguide TS, K22.W.3.waveguide: Evaluation of the adapter (WR42-3.5 mm (m))	-10624 K	0.0069	73	normal
9	Type A uncertainty	1	20 K	20	normal
	Combined standard uncertainty (k=1)			292	normal

K22.W.3.waveguide at 26.5 GHz

No.	Components of uncertainty	c_i	$u(x_i)$	$\lvert c_i \rvert u(x_i)$, K	Distribution
1	3.5-mm noise source STD3-1	0.5973	80 K	48	normal
2	3.5-mm noise source STD3-2 with a 10 dB-attenuator ATT3-2	0.5541	25 K	14	normal
2.1	15-dB ENR 3.5-mm noise source	0.1021	55 K	6	normal
2.2	The dissipative components of the 10-dB attenuator	7722 K	0.0031	24	normal
3	Y-factor including nonlinearity, Y1=Ns1/Ns2	-1521 K	0.1068	159	rectangular
4	Y-factor including nonlinearity, Y2=Ns1/Nx	-4552 K	0.0167	73	rectangular
5	Mismatch correction between the STD1 and the noise figure analyzer	7074 K	0.0028	18	normal
6	Mismatch correction between the STD2 and the noise figure analyzer	447.5 K	0.0021	1	normal
7	Mismatch correction between the DUT and the noise figure analyzer	7442 K	0.0013	9	normal
8	Adapter de-embedding to obtain the NT of the waveguide TS, K22.W.3.waveguide: Evaluation of the adapter (WR42-3.5 mm (m))	-7313 K	0.0069	50	normal
9	Type A uncertainty	1	15 K	15	normal
	Combined standard uncertainty (k=1)			190	normal

B.2. LNE Uncertainty budgets

K22.W.2.waveguide

Frequency (GHz)	18	22	25.8	26.5
Standard noise temperature T_s (K)	2	2	2	2
Ambient temperature T_a (K)	0.2	0.2	0.2	0.2
“Radiometer to standard” link (dB)	0.006	0.005	0.004	0.004
“Radiometer to unknown” link (dB)	0.003	0.001	0.001	0.005
Attenuation difference Δ (dB)	0.02	0.02	0.02	0.02
Standard reflection coefficient ρ_s	0.01	0.01	0.01	0.01
Unknown reflection coefficient ρ_x	0.001	0.001	0.001	0.001
Radiometer reflection coefficient S_{11}	0.001	0.001	0.001	0.001

K22.W.3.waveguide

Frequency (GHz)	18	22	25.8	26.5
Standard noise temperature T_s (K)	2	2	2	2
Ambient temperature T_a (K)	0.2	0.2	0.2	0.2
“Radiometer to standard” link (dB)	0.003	0.001	0.001	0.005
“Radiometer to unknown” link (dB)	0.006	0.004	0.001	0.001
Attenuation difference Δ (dB)	0.02	0.02	0.02	0.02
Standard reflection coefficient ρ_s	0.01	0.01	0.01	0.01
Unknown reflection coefficient ρ_x	0.001	0.001	0.001	0.001
Radiometer reflection coefficient S_{11}	0.001	0.001	0.001	0.001

B.3. NIST Uncertainty budgets

The combined standard uncertainty is composed of type-A and type-B uncertainties [13, 14]. Type-A uncertainties (u_A) are those that are measured and determined by statistical methods, such as the standard deviation of the mean of several independent measurements of the quantity of interest. Type-B uncertainties (u_B) are those determined by other means, such as estimates of systematic uncertainties. The uncertainty reported is the expanded uncertainty, given by

$$U = 2\sqrt{u_A^2 + u_B^2}\,.$$

This corresponds approximately to a 95% confidence level. Details of the uncertainty analysis can be found in references [8-10, 15].

B.4. NMIJ/AIST Uncertainty budgets

K22.W.2.waveguide

Standard uncertainty components	Source of uncertainty	Value of standard uncertainty			
		18 GHz	22 GHz	25.8 GHz	26.5 GHz
u_1	Cryogenic std.	42.1	50.9	93.3	85.1
u_2	Ambient std.	3.3	4.0	5.3	4.9
u_3	Mismatch for DUT	2.7	6.4	29.5	29.8
u_4	Mismatch for cryogenic std.	-1.7	-4.6	-11.9	-8.3
u_5	Mismatch for ambient std.	-11.8	-18.3	-38.6	-34.0
u_6	Attenuation for DUT	7.1	8.4	10.9	10.1
u_7	Attenuation for cryogenic std.	-29.6	-35.6	-59.9	-58.0
u_8	Attenuation for ambient std.	-36.7	-43.9	-70.8	-68.1
u_9	Linearity	20.7	25.2	33.7	30.8
u_{10}	Internal noise correction	2.1	0.8	5.4	2.2
u_{11}	Adapter	0.0	0.0	0.0	0.0
	Type A	8.5	15.2	19.3	12.9
Combined standard uncertainty		68.6	84.5	146.6	136.4
Expanded uncertainty (k=2)		137.2	169.0	293.2	272.8

K22.W.2.coaxial

Standard uncertainty components	Source of uncertainty	Value of standard uncertainty			
		18 GHz	22 GHz	25.8 GHz	26.5 GHz
u_1	Cryogenic std.	42.9	52.0	95.6	87.3
u_2	Ambient std.	3.4	4.1	5.4	5.0
u_3	Mismatch for DUT	2.8	6.6	30.2	30.5
u_4	Mismatch for cryogenic std.	-1.7	-4.7	-12.2	-8.5
u_5	Mismatch for ambient std.	-12.1	-18.8	-39.6	-34.9
u_6	Attenuation for DUT	7.2	8.6	11.2	10.3
u_7	Attenuation for cryogenic std.	-30.2	-36.4	-61.4	-59.5
u_8	Attenuation for ambient std.	-37.4	-44.9	-72.5	-69.9
u_9	Linearity	21.1	25.8	34.6	31.6
u_{10}	Internal noise correction	2.1	0.8	5.6	2.2
u_{11}	Adapter	55.4	69.5	91.2	86.8
	Type A	8.7	15.5	19.7	13.3
Combined standard uncertainty		89.2	110.9	175.8	164.6
Expanded uncertainty (k=2)		178.4	221.8	351.6	329.2

K22.W.3.waveguide

Standard uncertainty components	Source of uncertainty	Value of standard uncertainty			
		18 GHz	22 GHz	25.8 GHz	26.5 GHz
u_1	Cryogenic std.	77.6	61.6	65.9	58.2
u_2	Ambient std.	6.1	4.8	3.8	3.4
u_3	Mismatch for DUT	8.7	32.1	28.8	16.8
u_4	Mismatch for cryogenic std.	-3.5	-5.6	-8.4	-5.3
u_5	Mismatch for ambient std.	-21.0	-21.5	-28.1	-22.5
u_6	Attenuation for DUT	12.2	9.7	8.0	7.4
u_7	Attenuation for cryogenic std.	-55.3	-43.6	-42.4	-39.9
u_8	Attenuation for ambient std.	-67.5	-53.5	-50.6	-47.4
u_9	Linearity	38.2	30.6	23.8	21.1
u_{10}	Internal noise correction	3.2	0.0	3.4	2.0
u_{11}	Adapter	0.0	0.0	0.0	0.0
	Type A	36.0	16.9	45.3	30.8
Combined standard uncertainty		130.8	106.9	114.5	97.5
Expanded uncertainty (k=2)		261.6	213.7	228.9	195.1

B.5. NPL Uncertainty budgets

K22.W.2.waveguide

Frequency (GHz)	18.0	22.0	25.8	26.5
Known Noise Standard	102.4	33.5	53.3	51.0
Ambient Standard	0.1	0.0	0.0	0.0
Y-Factor (Known Std)	1.6	1.9	2.6	2.5
Y-Factor (Unknown Std)	1.4	2.0	2.5	2.5
Mismatch	5.5	3.1	12.1	7.3
Adaptor Temperature	0.0	0.0	0.0	0.0
Adaptor Loss	0.0	0.0	0.0	0.0
Type A	11.4	0.6	1.0	2.9
RSS	103.2	33.7	54.8	51.7

K22.W.2.coaxial

Frequency (GHz)	18.0	22.0	25.8	26.5
Known Noise Standard	104.3	34.1	54.5	52.1
Ambient Standard	0.1	0.0	0.0	0.0
Y-Factor (Known Std)	1.4	2.0	2.6	2.5
Y-Factor (Unknown Std)	1.6	2.0	2.6	2.5
Mismatch	5.5	3.2	12.3	7.4
Adaptor Temperature	0.0	0.0	0.0	0.0
Adaptor Loss	34.9	26.6	39.9	36.4
Type A	11.4	0.6	1.0	2.9
RSS	110.8	43.5	68.7	64.1

K22.W.3.waveguide

Frequency (GHz)	18.0	22.0	25.8	26.5
Known Noise Standard	54.2	45.8	35.4	30.8
Ambient Standard	0.2	0.0	0.1	0.1
Y-Factor (Known Std)	3.6	3.1	2.3	2.2
Y-Factor (Unknown Std)	3.9	3.4	2.1	1.8
Mismatch	5.5	22.3	9.2	6.4
Adaptor Temperature	0.0	0.0	0.0	0.0
Adaptor Loss	0.0	0.0	0.0	0.0
Type A	0.9	0.8	0.4	0.5
RSS	54.8	51.2	36.7	31.6

B.6. VNIIFTRI Uncertainty budgets

K22.W.2.waveguide

F(GHz)	18.0	22.0	25.8
Cryogenic Std.	5.9	6.3	7.5
Ambient Std.	5.2	6.2	8.2
Attenuation	13.6	16.0	21.2
Y factors	13.5	46.9	72.3
Isolation	8.5	4.0	28.1
Mismatch factors	40.2	51.5	76.1
Broadband Mismatch	13.4	17.2	25.4
Nonlinearity	5.9	9.7	16.6
Adapter de-embedding	20.9	27.0	39.1
Total Type B	50.3	64.3	94.1
Type A	19.8	18.0	26.6
Total	54.1	66.7	97.8

K22.W.3.waveguide

F(GHz)	18.0	22.0	25.8
Cryogenic Std.	11.1	7.7	5.5
Ambient Std.	9.9	7.5	5.9
Attenuation	25.5	19.5	15.4
Y factors	25.6	58.3	83.0
Isolation	16.2	4.9	18.6
Mismatch factors	59.1	17.2	40.3
Broadband Mismatch	19.7	5.7	13.4
Nonlinearity	11.1	11.8	12.0
Adapter de-embedding	39.2	32.9	28.3
Total Type B	80.2	45.6	55.6
Type A	57.8	25.6	28.1
Total	98.8	52.3	62.3