CCEM KEY COMPARISON CCEM.RF-K18.CL (GT-RF/00-1)

Noise in 50 Ω coaxial line at frequencies up to 1 GHz

Final Report

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ABSTRACT

A measurement comparison of noise temperature has been carried out between four National Metrology Laboratories in coaxial line at 30 MHz, 60 MHz and 1 GHz. The identification of this intercomparison is CCEM.RF-K18.CL. Two noise sources have been measured. The following four national laboratories participated in this intercomparison: NPL (United Kingdom), NIST (United States of America), BNM-LNE (France) and VNIIFTRI (Russia). The National Physical Laboratory (United Kingdom) acted as the pilot laboratory for the comparison. It can be seen that, there is generally good agreement between the laboratories.

1 Introduction

In January 2000, NPL submitted to GT-RF members a proposal to undertake an intercomparison of noise temperature in coaxial lines at frequencies 30 MHz, 60 MHz and 1 GHz. This proposal was formally accepted at the BIPM meeting in 2000 and assigned the designation GT-RF/00-1, which was subsequently re-labelled as CCEM.RF-K18.CL. The protocol, designated GT-RF/01-12, was agreed at the following meeting in 2001 and the participants announced: NPL (pilot laboratory), NIST, BNM-LNE and VNIIFTRI.

The participants reported results for noise temperature measurements of the two travelling standards at all frequencies, as well as reporting the voltage reflection coefficient of the travelling standards. All reported results are included in this report.

2 Travelling Standards

The travelling standards provided by the pilot laboratory were two solid-state noise sources with GPC-7 connectors: an HP346A Opt 002, with a nominal ENR of 5 dB (serial no. 4124A06260), and an HP346B Opt 002, with a nominal ENR of 15 dB (serial no. 4124A16660). Both standards were powered by 28 V DC. This voltage was monitored and maintained as close to 28 V as is practicable.

The devices are 21 mm by 140 mm by 30 mm (0.8 in by 5.5 in by 1.2 in) and weigh 108 grams (3.5 oz). The DC power is supplied via a BNC connector.

The participants were asked to provide a measurement of the noise temperature for each of the travelling standards and, if possible, to measure the voltage reflection coefficient and provide this in full complex value or, if this was not possible, magnitude only.

3 Comparison Protocol and Schedule

The travelling standards were circulated to the participants, who were asked to provide a measurement of the noise temperature of the travelling standards at frequencies of 30 MHz, 60 MHz and 1 GHz. The participants were also asked to provide a measurement of the voltage reflection coefficient (VRC) of both standards at each frequency.

Owing to delays in the procurement of the travelling standards and in customs, the timetable was not strictly adhered to and hence the comparison took place between February 2002 and September 2003, the initial and final measurements being carried out by the pilot laboratory, NPL.

The table below gives the date of measurement at each of the participating laboratories.

Laboratory	Date of Measurement
NPL (UK)	February 2002
NIST (USA)	September 2002
BNM-LNE (France)	November 2002
VNIIFTRI (Russia)	March 2003
NPL (UK)	September 2003

4 Methods of Measurement

4.1 NPL Measurements

The travelling standards, operating at (28.00 ± 0.01) V DC, were calibrated against the NPL Working Noise Standards, which have direct traceability to UK Primary Noise Standards. The noise measurements were made according to the procedures laid down in NPL Procedure Document QPCEM/B/080.

The reflection coefficients were measured on network analysers according to the procedures laid down in NPL Procedure Document QPCEM/B/093. The uncertainties on these measurements are estimated at 0.01 in magnitude and $[\sin^{-1}(0.01/|\Gamma|)]^\circ$ in phase. If the magnitude, $|\Gamma|$, is less than its uncertainty, then the phase uncertainty is stated as ±180°.

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 2 MHz bandwidth centred on the quoted frequency accurate to ±1 kHz.

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. The reported ambient temperature is that of the ambient temperature of the radiometer.

4.2 NIST Measurements

NIST noise-temperature measurements are performed on total-power radiometers, using two primary thermal noise standards, one of which is at ambient temperature and the other of which is at cryogenic (liquid nitrogen) temperature. For measurements at 30 and 60 MHz, tuneable coaxial standards [1] are used; and from 1 to 12.4 GHz, broadband coaxial standards [2] are used. All the NIST radiometers are total-power radiometers. At 1 GHz and above [3] the measurements are double sideband, at baseband, and the bandwidth of each sideband is 5 MHz. At 30 MHz and 60 MHz [1,4], the power is measured directly, using band-pass filters centred at the measurement frequency, with bandwidths of 0.77 MHz for 30 MHz and 1.38 MHz for 60 MHz. At least three independent measurements of the noise temperature of each noise source were made at each frequency. Because the 30 MHz and 60 MHz radiometer has type-N connectors, whereas the travelling standards have GPC-7 connectors, the measurements at 30 MHz and 60 MHz were made through adaptors, resulting in a small increase in the uncertainty. The procedure for characterizing the adaptor and removing its effect is described in references [5,6]. The uncertainty analysis can be found in references [3,4,7].

The laboratory was maintained at (23.0 ± 0.5) °C and (40 ± 5) % relative humidity during the measurements.

At 30 MHz and 60 MHz the reflection coefficient is measured on a low-frequency impedance meter. During the course of this comparison, a software error was found that resulted in incorrect values for the impedance (and reflection coefficient) of the device under test (DUT). The error has now been corrected, but the NIST results for the reflection coefficient at 30 MHz and 60 MHz in this comparison are wrong. Fortunately, because the ambient and cryogenic standards are tuned to have the same impedance as the DUT, as measured by the same impedance meter, the actual value of the impedance (or reflection coefficient) of the DUT does not affect the measured noise temperature. At 1 GHz the reflection coefficient is measured on a vector network analyser, and that result is not affected by any (known) error.

It is for this reason that NIST have withdrawn their reflection coefficient measurement results at 30 MHz and 60 MHz.

4.3 BNM-LNE Measurements

The travelling standards were compared against BNM's working noise standard (Ailtech Noise Generator, Type 7616) with PC-7 connector, which has traceability to the UK Primary Noise Standard.

The noise measurements were made on the BNM-LNE Dicke-type radiometer at a room temperature of (23 ± 1.5) °C using a supply voltage of (28.00 ± 0.17) V.

The measurements are double sideband at 1000 MHz, and single sideband at 30 MHz and 60 MHz, with noise filter bandwidths of 30 MHz and 60 MHz respectively.

4.4 VNIIFTRI Measurements

The travelling standards HP346A and HP346B were compared against the VNIIFTRI cryogenic noise standard [8]. The comparison frequency points, f_c, the values of intermediate frequencies, IF_1 and IF_2, and IF_2 bandwidth are given as:

Comparison frequency f_c, MHz	IF_1, MHz	IF_2, MHz	IF_2 bandwidth, MHz
30, 60	150	10	0.3
1000	2050	30	3

Each radiometer contains on its input: a matching tuner, a directional coupler (used as a reflectometer with an auxiliary sinusoidal signal source), a second matching tuner and a low-noise amplifier.

Adjustment of the first tuner decreases the reflected signal by 25 dB, ensuring a residual difference of voltage reflection coefficient, $|\Delta\Gamma|$, no greater than 0.018.

Digital signal processing at the square-law detector output of the radiometer reduces the equation for the unknown noise temperature to $T_u = (T_s - T_a)\cdot Y + T_a$, where T_s is the cryogenic standard noise temperature. The equation and its remaining designations are identical to the expression for a Dicke radiometer [9].

The cryogenic noise standard and the inputs of the comparators have Type N connectors, so the losses in the additional adapters were taken into account according to reference [10].

To correct for the non-linearities in the radiometer, the measured noise levels of each device were stored and these levels were reproduced as closely as possible, with an accuracy not worse than 1%, using an auxiliary noise source and a step attenuator.

Voltage reflection coefficient magnitudes of the comparison devices were measured on an analogue measuring set (type R4-11) with an absolute uncertainty of approximately 0.02.

The noise measurements were made according to the procedures laid down in VNIIFTRI Procedure Document [11].

5 Discussion of the Results

The results were presented to the pilot laboratory in the form of a noise temperature measurement and the magnitude of the reflection coefficient. Participants were asked to provide separately the uncertainties obtained from Type A and Type B evaluations and the expanded uncertainty (at 95% confidence level) for the noise temperature. The measurement results and associated expanded uncertainties together with the reference values and associated expanded uncertainties are shown in Figures 1 – 3 for the HP346A device and Figures 4 – 6 for the HP346B device.

The complete set of measurements for each participant can be found in Appendix A, along with associated expanded uncertainties and degrees of equivalence with respect to the key comparison reference value and between participants.

Along with the measurement results, participants were asked to provide details of the various contributions towards the measurement uncertainty for the noise temperature only. These uncertainty budgets may be found in Appendix B.

The expanded uncertainties quoted in the results are derived by multiplying the combined standard uncertainties by a coverage factor of 2.0, which is sufficient to provide a level of confidence for this expanded uncertainty of approximately 95 % for all participants.[1]

The KCRV for the noise temperature at each frequency was determined by the unweighted mean of the reported results, excluding any outliers. This method was chosen, as it was believed that all four participants would provide similar results and uncertainties.

In the period of time between February 2002 and September 2003, when NPL's measurements were carried out, components were replaced in NPL's noise temperature measurement system, which required it to be re-calibrated. Because of this, it was decided to use only NPL's second measurement in the calculation of the KCRV, as it is more representative of NPL's current measurement capabilities.

BNM-LNE's noise temperature standard is traceable to UK National Standards via NPL; therefore there is correlation associated with these measurements. However, due to the re-calibration of NPL's noise measurement system between the measurement of BNM-LNE's standard at NPL and NPL's second measurement of the travelling standards, the correlation associated with these measurements will be significantly reduced (it will not be eradicated entirely).

It is believed that this correlation is low enough to be insignificant. In fact, a comparison of the KCRVs obtained with and without BNM-LNE's measurements shows insignificant changes and for this reason it was decided to include BNM-LNE's measurement results in the calculation of the KCRV.

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[1] A coverage factor, k, of 2.0 is sufficient assuming all Type B uncertainty contributions have infinite degrees of freedom. NIST states finite degrees of freedom but provides uncertainties for both the finite and infinite cases (see Appendix B). For consistency, the NIST results for $k = 2.0$ were used in this report.

The method used to determine outliers was that described in [13], see Appendix A. If a result was considered an outlier, it was not used in the calculation of the KCRV. Results not used in the computation of the KCRV are identified in Appendix A using ***bold, italic typeface*.**

Comparison of possible variants of the KCRV and degree of equivalence estimations showed that the inclusion or exclusion of certain participants (even outliers) in the calculation changes the results by a small amount, less than the uncertainty in the KCRV or degree of equivalence. In conclusion, considering the small number of participants in this comparison, there was general satisfactory agreement among the results.

The reflection coefficients were measured as secondary quantities and do not form part of the object of this comparison; hence there is no KCRV for this measurand. The reported reflection coefficients can be seen in Tables A.1 through A.6 in Appendix A.

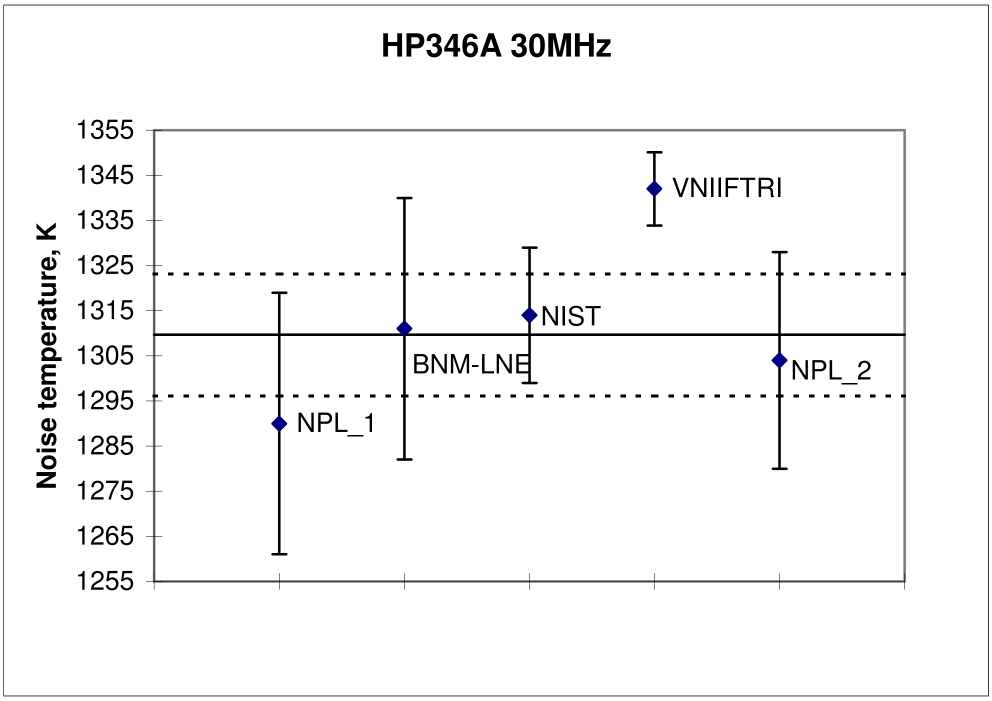

Fig 1: The measured noise temperature of the HP346A at 30 MHz and its associated expanded uncertainty supplied by each laboratory together with the KCRV and its associated expanded uncertainty.

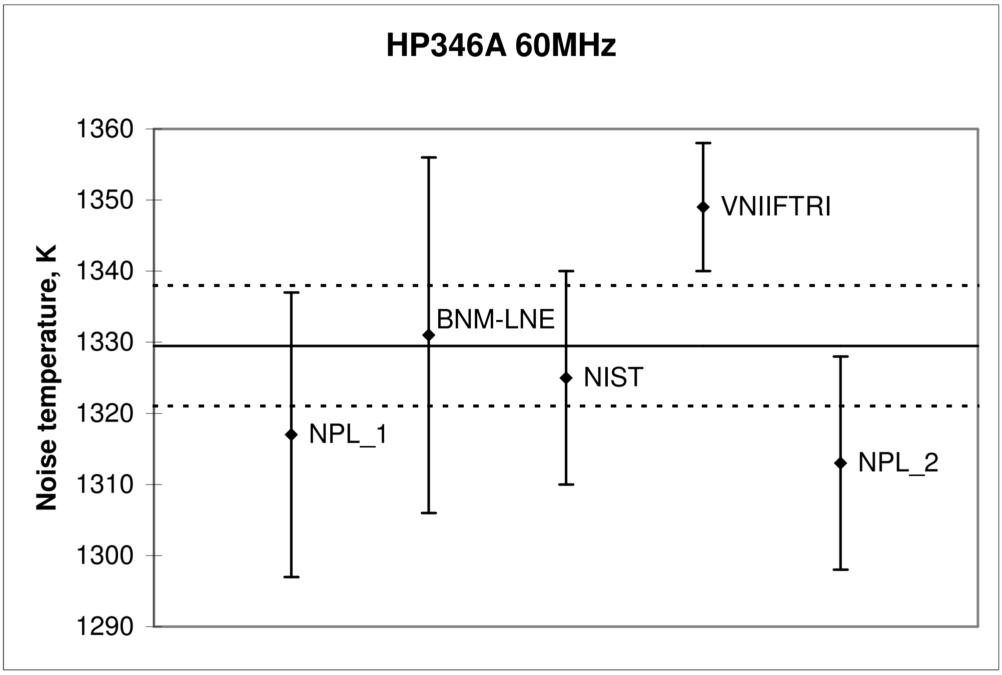

Fig 2: The measured noise temperature of the HP346A at 60 MHz and its associated expanded uncertainty supplied by each laboratory together with the KCRV and its associated expanded uncertainty.

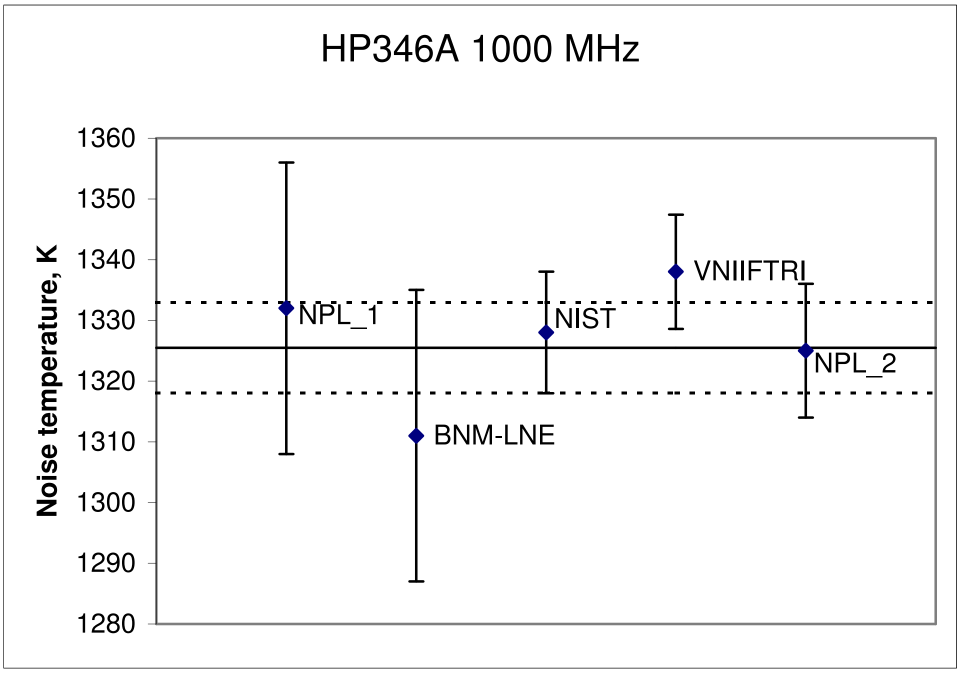

Fig 3: The measured noise temperature of the HP346A at 1 GHz and its associated expanded uncertainty supplied by each laboratory together with the KCRV and its associated expanded uncertainty.

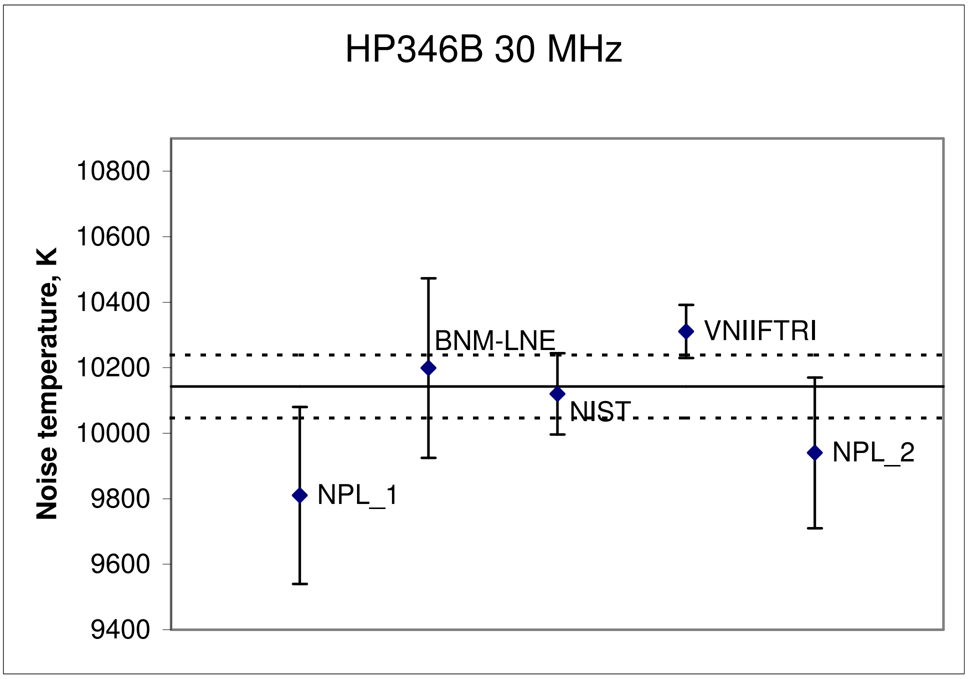

Fig 4: The measured noise temperature of the HP346B at 30 MHz and its associated expanded uncertainty supplied by each laboratory together with the KCRV and its associated expanded uncertainty.

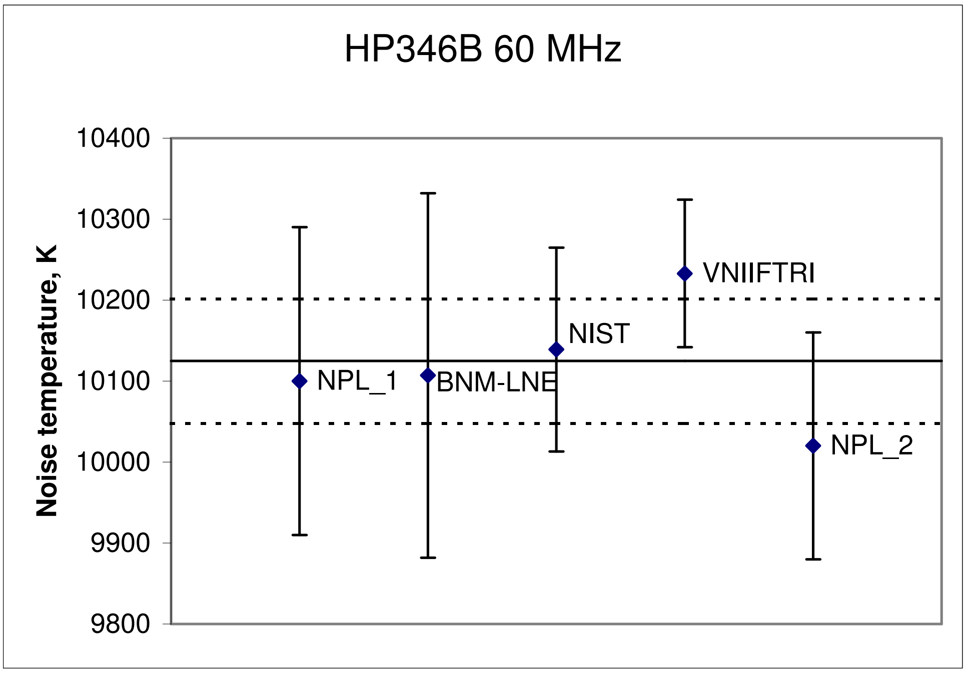

Fig 5: The measured noise temperature of the HP346B at 60 MHz and its associated expanded uncertainty supplied by each laboratory together with the KCRV and its associated expanded uncertainty.

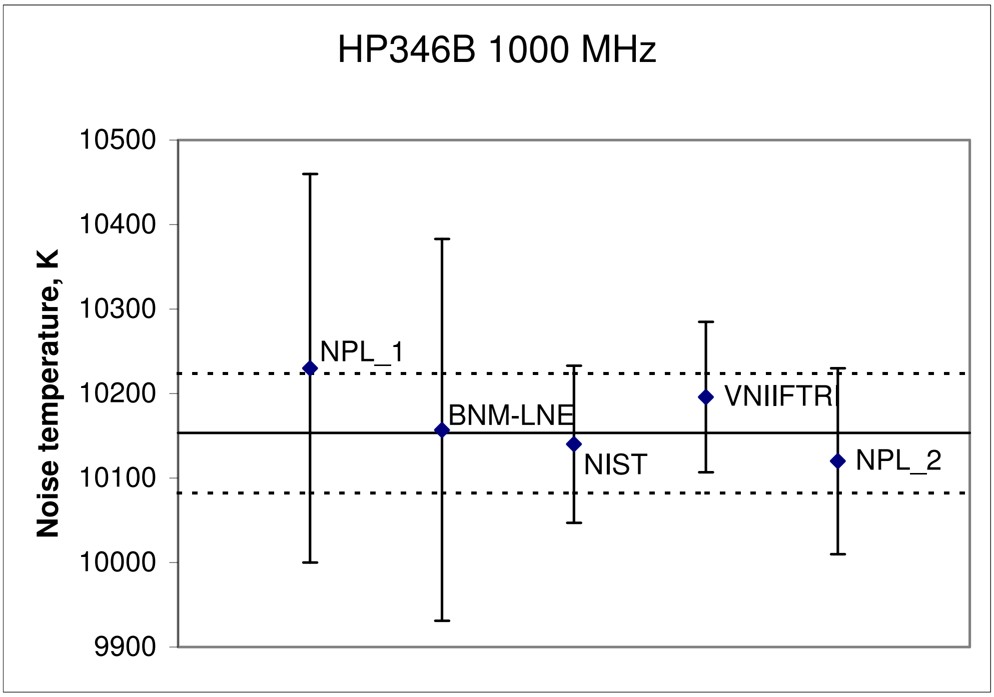

Fig 6: The measured noise temperature of the HP346B at 1 GHz and its associated expanded uncertainty supplied by each laboratory together with the KCRV and its associated expanded uncertainty.

6 Acknowledgements

The authors would like to thank Zdenka Rabuzin-Prpic (NPL), Alexis Litwin (BNM-LNE) and George Free (NIST) for carrying out the measurements of the travelling standards at their respective laboratories.

7 References

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Appendix A

Key comparison **CCEM.RF-K18.CL**

MEASURANDS: Noise Temperature and Voltage Reflection Coefficient

Pilot Laboratory: NPL (UK)

T_i	result of measurement of noise temperature carried out by laboratory *i*.
$U(T_i)$	expanded uncertainty of T_i reported by laboratory *i*.
$\lvert\Gamma_i\rvert$	result of measurement of magnitude of voltage reflection coefficient carried out by laboratory *i*.

Outlying results were excluded in obtaining the KCRV. Outliers were identified using the Median of Absolute Deviations [13], defined by

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

where k_1 is a multiplier determined by simulation (2.019 for 4 participants) and Y_{med} is the median of the sample $\{Y_i\}$. A value of Y_j, which differs from the median by more than $2.5S(MAD)$, is considered an outlier, and this criterion may be used to test each point:

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

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

Outlying results are highlighted in the tables in ***bold italic typeface***.

The key comparison reference values for this comparison are calculated using the unweighted mean from the results of the participants as follows:

$$T_R = \frac{T_{NPL\_2} + T_{NIST} + T_{VNIIFTRI} + T_{BNM-LNE}}{4}\,. \tag{3}$$

If any laboratory's results were considered to be outliers, they were not used in this calculation and hence the denominator was adjusted accordingly.

The expanded uncertainties associated with the KCRV were obtained using

$$U(T_R) = 2.0\sqrt{\frac{1}{N^2}\sum_i u^2(T_i)}\ , \tag{4}$$

where N is the number of laboratories used to determine the KCRV, T_i is the reported measurement result from each laboratory (excluding outliers) and 2.0 is the coverage factor used to obtain the expanded uncertainty [14].

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

$$\Delta_{Ti} = T_R - T_i\,. \tag{5}$$

If T_i is an outlier, then the expanded uncertainty in Δ_{Ti} is given by

$$U(\Delta_{Ti}) = 2.0\sqrt{u^2(T_i) + u^2(T_R)}\ , \tag{6}$$

where $u(T_R)$ is the combined standard uncertainty of the KCRV and equivalent to $U(T_R)/2.0$.

If T_i is not an outlier, then the expanded uncertainty in Δ_{Ti} is given by

$$U(\Delta_{Ti}) = 2.0\sqrt{u^2(T_R) + \left(1 - \frac{2}{N}\right)u^2(T_i)} \tag{7}$$

owing to the existence of correlation between the KCRV and the measured value T_i.

The degrees of equivalence between laboratories, Δ_{Tij}, are given by

$$\Delta_{Tij} = T_j - T_i\,. \tag{8}$$

The associated expanded uncertainty, $U(\Delta_{Tij})$, was determined using equation (6), replacing $u^2(T_R)$ with $u^2(T_j)$.

Equation (6) cannot be used to derive the uncertainty in the degree of equivalence between NPL and BNM-LNE due to BNM-LNE's results having traceability to NPL, therefore it is decided not to include a degree of equivalence between NPL and BNM-LNE [2].

Full results can be seen in Tables A.1 to A.6. Degree of equivalence with respect to the reference value and between each of the participants can be found in Tables A.7 to A.12 and in graphical form in Figs 7 and 8.

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[2] The correlation makes little difference to the KCRV, but its effect is more significant in the calculation of the uncertainty in the degree of equivalence and even a small correlation coefficient of 0.1 can change the value of the uncertainty by approximately 5 %.

<table>
<tr><td rowspan="2">Lab i</td><td colspan="3">Results and Expanded Uncertainty for HP346A device at 30 MHz</td></tr>
<tr><td>$|\Gamma_i|$</td><td>T_i (K)</td><td>$U(T_i)$ (K)</td></tr>
<tr><td>NPL_1</td><td>0.003</td><td>1290</td><td>29</td></tr>
<tr><td>BNM-LNE</td><td>0.003</td><td>1311</td><td>29</td></tr>
<tr><td>NIST</td><td>Withdrawn</td><td>1314</td><td>15</td></tr>
<tr><td>VNIIFTRI</td><td>0.005</td><td>***1342***</td><td>8.1</td></tr>
<tr><td>NPL_2</td><td>0.003</td><td>1304</td><td>24</td></tr>
<tr><td colspan="4"></td></tr>
<tr><td></td><td>T_R(K)</td><td colspan="2">$U(T_R)$ (K)</td></tr>
<tr><td>KCRV</td><td>1310</td><td colspan="2">14</td></tr>
</table>

Table A.1

<table>
<tr><td rowspan="2">Lab i</td><td colspan="3">Results and Expanded Uncertainty for HP346A device at 60 MHz</td></tr>
<tr><td>$|\Gamma_i|$</td><td>T_i (K)</td><td>$U(T_i)$ (K)</td></tr>
<tr><td>NPL_1</td><td>0.003</td><td>1317</td><td>20</td></tr>
<tr><td>BNM-LNE</td><td>0.003</td><td>1331</td><td>25</td></tr>
<tr><td>NIST</td><td>Withdrawn</td><td>1325</td><td>15</td></tr>
<tr><td>VNIIFTRI</td><td>0.005</td><td>1349</td><td>9</td></tr>
<tr><td>NPL_2</td><td>0.002</td><td>1313</td><td>15</td></tr>
<tr><td colspan="4"></td></tr>
<tr><td></td><td>T_R(K)</td><td colspan="2">$U(T_R)$ (K)</td></tr>
<tr><td>KCRV</td><td>1330</td><td colspan="2">9</td></tr>
</table>

Table A.2

<table>
<tr><td rowspan="2">Lab i</td><td colspan="3">Results and Expanded Uncertainty for HP346A device at 1 GHz</td></tr>
<tr><td>$|\Gamma_i|$</td><td>T_i (K)</td><td>$U(T_i)$ (K)</td></tr>
<tr><td>NPL_1</td><td>0.005</td><td>1332</td><td>24</td></tr>
<tr><td>BNM-LNE</td><td>0.004</td><td>1311</td><td>24</td></tr>
<tr><td>NIST</td><td>0.005</td><td>1328</td><td>10</td></tr>
<tr><td>VNIIFTRI</td><td>0.01</td><td>1338</td><td>9.4</td></tr>
<tr><td>NPL_2</td><td>0.005</td><td>1325</td><td>11</td></tr>
<tr><td colspan="4"></td></tr>
<tr><td></td><td>T_R(K)</td><td colspan="2">$U(T_R)$ (K)</td></tr>
<tr><td>KCRV</td><td>1326</td><td colspan="2">7</td></tr>
</table>

Table A.3

Lab i	Results and Expanded Uncertainty for HP346B device at 30 MHz		
	$\|\Gamma_i\|$	T_i (K)	$U(T_i)$ (K)
NPL_1	0.03	9810	270
BNM-LNE	0.01	10199	274
NIST	Withdrawn	10120	124
VNIIFTRI	0.015	10311	81
NPL_2	0.011	9940	230

	T_R(K)	$U(T_R)$ (K)
KCRV	10143	97

Table A.4

Lab i	Results and Expanded Uncertainty for HP346B device at 60 MHz		
	$\|\Gamma_i\|$	T_i (K)	$U(T_i)$ (K)
NPL_1	0.007	10100	190
BNM-LNE	0.007	10107	225
NIST	Withdrawn	10139	126
VNIIFTRI	0.01	10233	91
NPL_2	0.008	10020	140

	T_R(K)	$U(T_R)$ (K)
KCRV	10125	77

Table A.5

Lab i	Results and Expanded Uncertainty for HP346B device at 1 GHz		
	$\|\Gamma_i\|$	T_i (K)	$U(T_i)$ (K)
NPL_1	0.023	10230	230
BNM-LNE	0.022	10157	226
NIST	0.023	10140	93
VNIIFTRI	0.025	10196	89
NPL_2	0.023	10120	110

	T_R(K)	$U(T_R)$ (K)
KCRV	10153	71

Table A.6

Lab j ⇒

Lab i ⇓	KCRV		NPL		BNM-LNE		NIST		VNIIFTRI	
	Δ_{Ti}	$U(\Delta_{Ti})$	Δ_{Tij}	$U(\Delta_{Tij})$	Δ_{Tij}	$U(\Delta_{Tij})$	Δ_{Tij}	$U(\Delta_{Tij})$	Δ_{Tij}	$U(\Delta_{Tij})$
NPL	6	19					10	28	38	25
BNM-LNE	-1	22					3	33	31	30
NIST	-4	16	-10	28	-3	33			28	17
VNIIFTRI	-32	16	-38	25	-31	30	-28	17		

Table A.7: Degrees of Equivalence for noise temperature of device HP346A (low temperature) at 30 MHz

Lab j ⇒

Lab i ⇓	KCRV		NPL		BNM-LNE		NIST		VNIIFTRI	
	Δ_{Ti}	$U(\Delta_{Ti})$	Δ_{Tij}	$U(\Delta_{Tij})$	Δ_{Tij}	$U(\Delta_{Tij})$	Δ_{Tij}	$U(\Delta_{Tij})$	Δ_{Tij}	$U(\Delta_{Tij})$
NPL	17	14					12	21	36	17
BNM-LNE	-1	20					-6	29	18	27
NIST	5	14	-12	21	6	29			24	17
VNIIFTRI	-19	11	-36	17	-18	27	-24	17		

Table A.8: Degrees of Equivalence for noise temperature of device HP346A (low temperature) at 60 MHz

Lab j ⇒

Lab i ⇓	KCRV		NPL		BNM-LNE		NIST		VNIIFTRI	
	Δ_{Ti}	$U(\Delta_{Ti})$	Δ_{Tij}	$U(\Delta_{Tij})$	Δ_{Tij}	$U(\Delta_{Tij})$	Δ_{Tij}	$U(\Delta_{Tij})$	Δ_{Tij}	$U(\Delta_{Tij})$
NPL	1	10					3	15	13	14
BNM-LNE	15	19					17	26	27	26
NIST	-2	10	-3	15	-17	26			10	14
VNIIFTRI	-12	10	-13	14	-27	26	-10	14		

Table A.9: Degrees of Equivalence for noise temperature of device HP346A (low temperature) at 1 GHz

Lab $j \Rightarrow$

Lab i ⇓	KCRV		NPL		BNM-LNE		NIST		VNIIFTRI	
	Δ_{Ti}	$U(\Delta_{Ti})$	Δ_{Tij}	$U(\Delta_{Tij})$	Δ_{Tij}	$U(\Delta_{Tij})$	Δ_{Tij}	$U(\Delta_{Tij})$	Δ_{Tij}	$U(\Delta_{Tij})$
NPL	203	189					180	261	371	244
BNM-LNE	-56	217					-79	301	112	286
NIST	23	131	-180	261	79	301			191	148
VNIIFTRI	-168	112	-371	244	-112	286	-191	148		

Table A.10: Degrees of Equivalence for noise temperature of device HP346B (high temperature) at 30 MHz

Lab $j \Rightarrow$

Lab i ⇓	KCRV		NPL		BNM-LNE		NIST		VNIIFTRI	
	Δ_{Ti}	$U(\Delta_{Ti})$	Δ_{Tij}	$U(\Delta_{Tij})$	Δ_{Tij}	$U(\Delta_{Tij})$	Δ_{Tij}	$U(\Delta_{Tij})$	Δ_{Tij}	$U(\Delta_{Tij})$
NPL	105	125					119	188	213	167
BNM-LNE	18	177					32	258	126	243
NIST	-14	118	-119	188	-32	258			94	155
VNIIFTRI	-108	100	-213	167	-126	243	-94	155		

Table A.11: Degrees of Equivalence for noise temperature of device HP346B (high temperature) at 60 MHz

Lab $j \Rightarrow$

Lab i ⇓	KCRV		NPL		BNM-LNE		NIST		VNIIFTRI	
	Δ_{Ti}	$U(\Delta_{Ti})$	Δ_{Tij}	$U(\Delta_{Tij})$	Δ_{Tij}	$U(\Delta_{Tij})$	Δ_{Tij}	$U(\Delta_{Tij})$	Δ_{Tij}	$U(\Delta_{Tij})$
NPL	33	105					20	144	76	141
BNM-LNE	-4	175					-17	244	39	243
NIST	13	96	-20	144	17	244			56	129
VNIIFTRI	-43	95	-76	141	-39	243	-56	129		

Table A.12: Degrees of Equivalence for noise temperature of device HP346B (high temperature) at 1 GHz

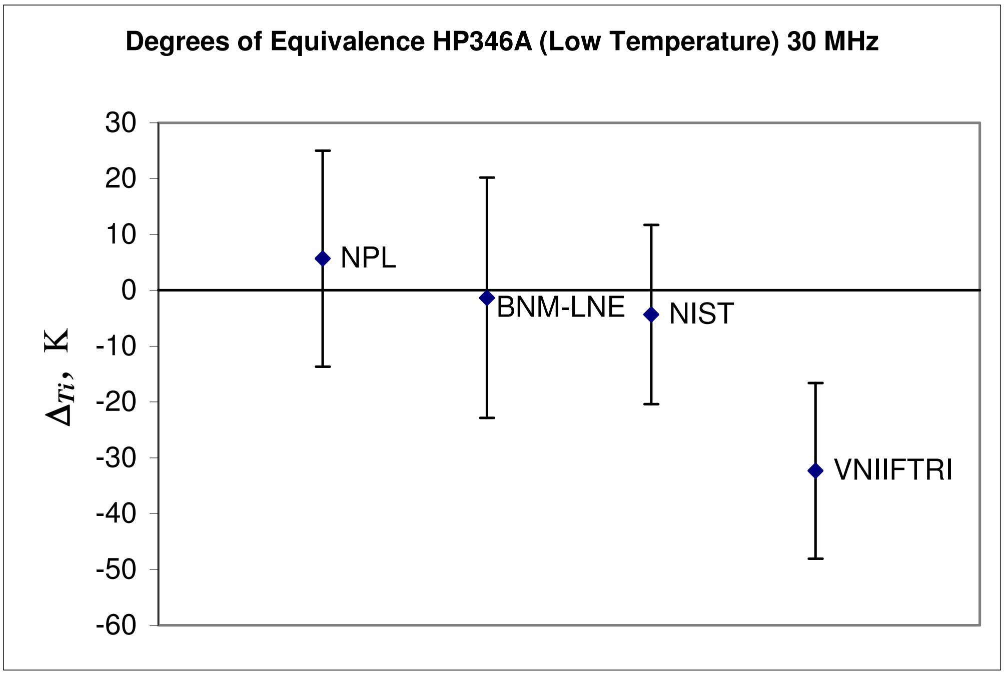

Fig 7a: Degrees of Equivalence with respect to the reference value for noise temperature of device HP346A (low temperature) at 30 MHz and their associated uncertainties

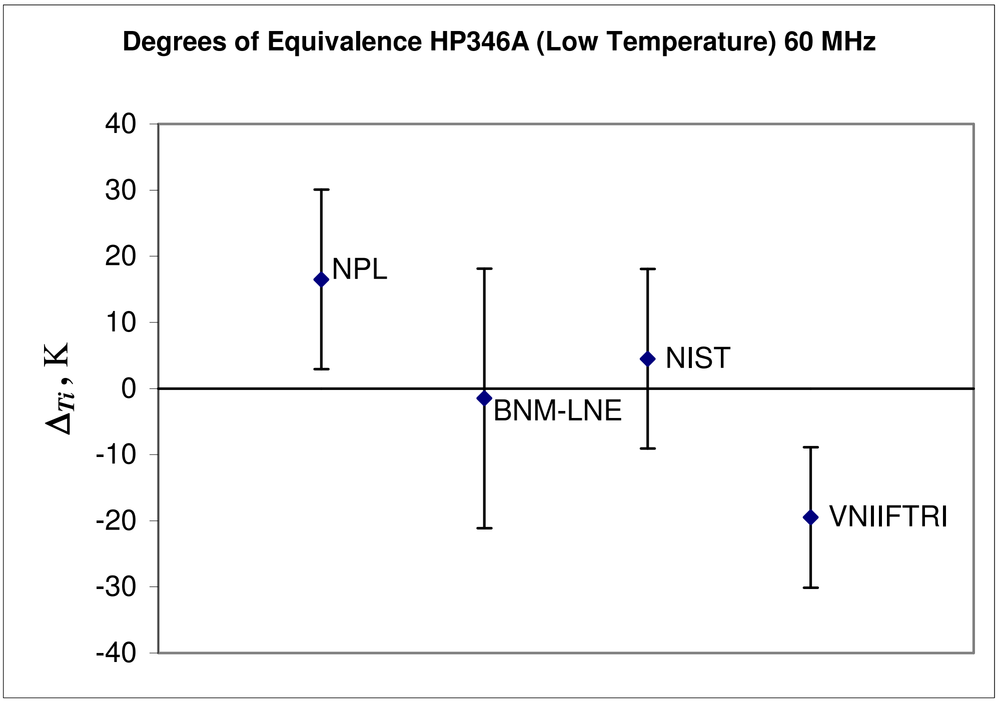

Fig 7b: Degrees of Equivalence with respect to the reference value for noise temperature of device HP346A (low temperature) at 60 MHz and their associated uncertainties

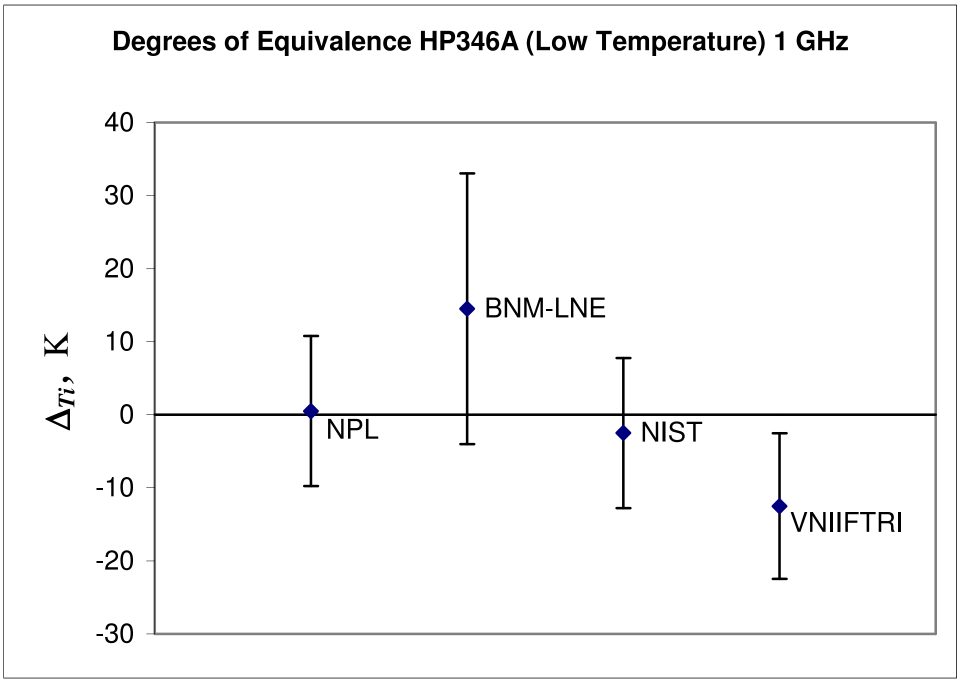

Fig 7c: Degrees of Equivalence with respect to the reference value for noise temperature of device HP346A (low temperature) at 1 GHz and their associated uncertainties

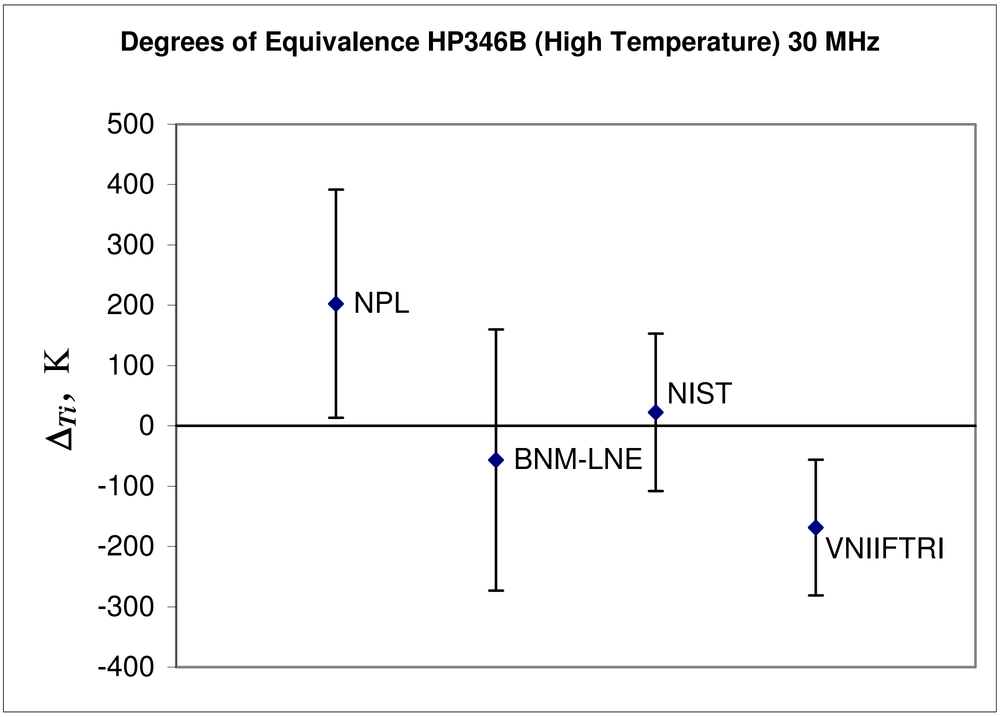

Fig 8a: Degrees of Equivalence with respect to the reference value for noise temperature of device HP346B (high temperature) at 30 MHz and their associated uncertainties

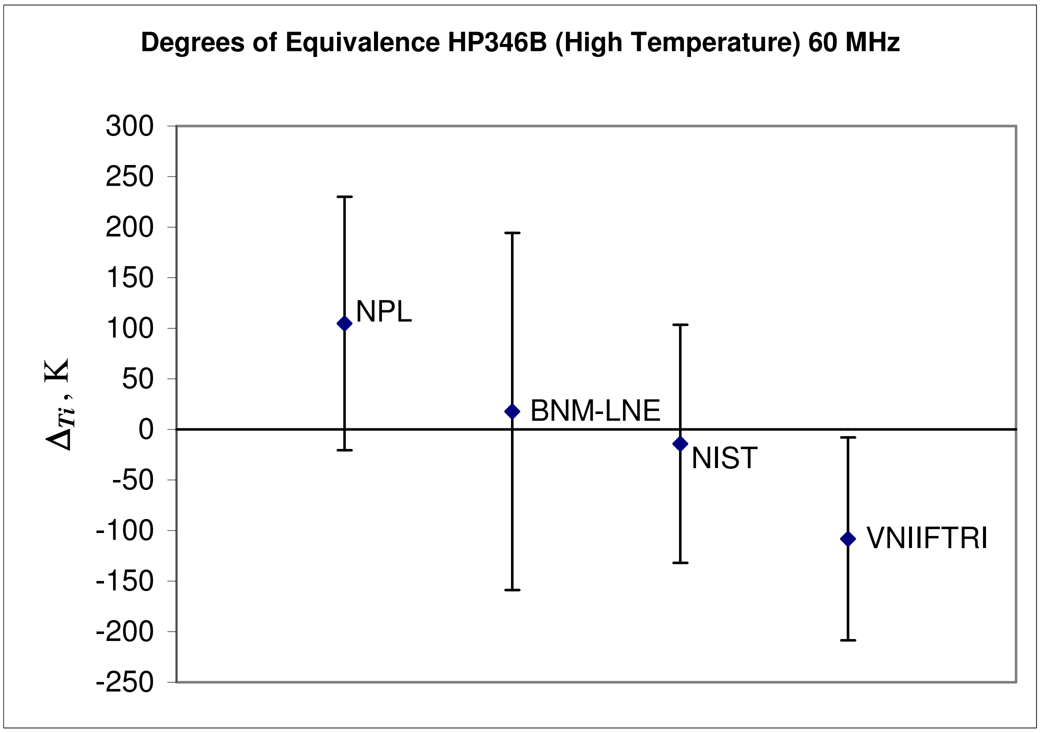

Fig 8b: Degrees of Equivalence with respect to the reference value for noise temperature of device HP346B (high temperature) at 60 MHz and their associated uncertainties

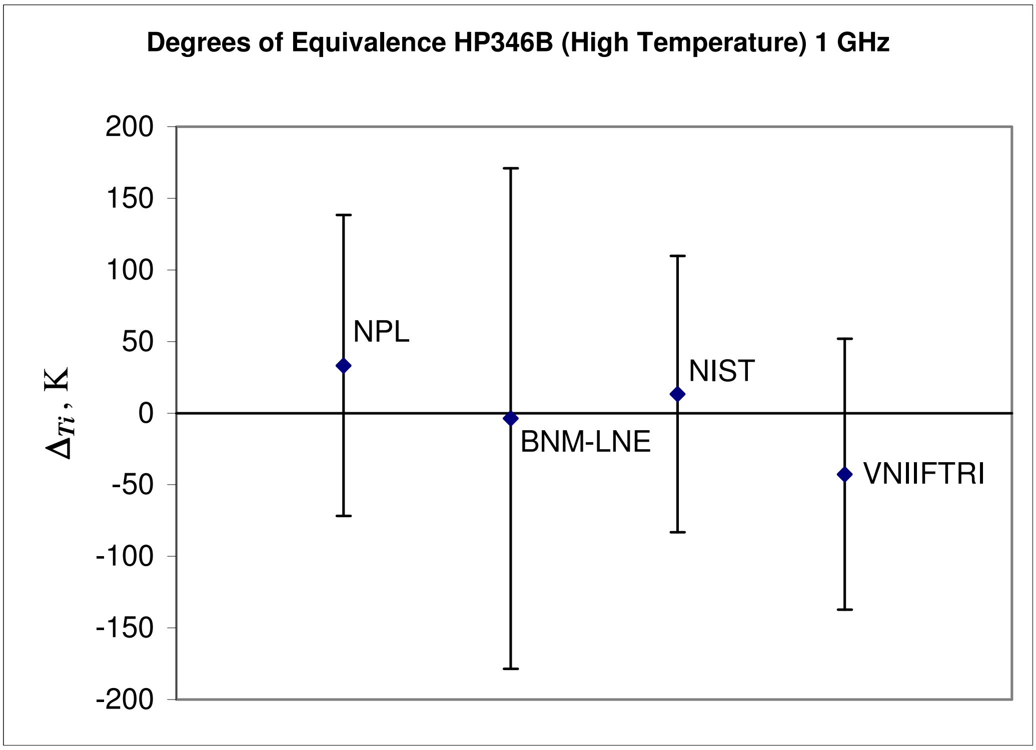

Fig 8c: Degrees of Equivalence with respect to the reference value for noise temperature of device HP346B (high temperature) at 1 GHz and their associated uncertainties

Appendix B

The tables in this appendix give details of the uncertainty contributions appropriate to the measurement of noise temperature for each of the participants, as provided by each of the participants.

BNM-LNE Uncertainties

Degrees of freedom are 58 for type A uncertainty and ∞ for type B uncertainties for all of BNM-LNE's measurements.

Table B.1: Uncertainty in measurement of noise temperature of HP346A at 30 MHz

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$
Standard	10340 K	120 K	Gaussian	0.101032	12.124 K
Ambient	296.15 K	1.5 K	Gaussian	0.898968	1.348 K
Attenuation	-9.955 dB	0.03 dB	Gaussian	233.3923	7.002 K
Mismatch	0.03	0.005	Gaussian	30.44247	0.152 K
Standard reflect.	0.008	0.005	Gaussian	16.23599	0.081 K
Unknown reflect.	0.003	0.005	Gaussian	6.088495	0.030 K
Type A			Gaussian		2.841 K
Combined uncertainty (1 σ)					14.4 K
Expanded uncertainty (2 σ)					29 K

Table B.2: Uncertainty in measurement of noise temperature of HP346A at 60 MHz

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$
Standard	10680 K	95 K	Gaussian	0.099656	9.467 K
Ambient	296.15 K	1.5 K	Gaussian	0.900344	1.351 K
Attenuation	-10.015 dB	0.03 dB	Gaussian	238.0076	7.140 K
Mismatch	0.054	0.005	Gaussian	31.04447	0.155 K
Standard reflect.	0.008	0.005	Gaussian	16.55705	0.083 K
Unknown reflect.	0.003	0.005	Gaussian	6.208894	0.031 K
Type A			Gaussian		2.152 K
Combined uncertainty (1 σ)					12.1 K
Expanded uncertainty (2 σ)					25 K

Table B.3: Uncertainty in measurement of noise temperature of HP346A at 1 GHz

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$
Standard	10190 K	90 K	Gaussian	0.102457	9.221 K
Ambient	296.15 K	1.5 K	Gaussian	0.897543	1.346 K
Attenuation	-9.895 dB	0.03 dB	Gaussian	233.1493	6.994 K
Mismatch	0.073	0.005	Gaussian	38.52032	0.193 K
Standard reflect.	0.013	0.005	Gaussian	26.35601	0.132 K
Unknown reflect.	0.004	0.005	Gaussian	8.109542	0.041 K
Type A			Gaussian		0.716 K
Combined uncertainty (1 σ)					11.7 K
Expanded uncertainty (2 σ)					24 K

Table B.4: Uncertainty in measurement of noise temperature of HP346B at 30 MHz

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$
Standard	10340 K	120 K	Gaussian	0.986036	118.32 K
Ambient	296.15 K	1.5 K	Gaussian	0.013964	0.0209 K
Mismatch	0.03	0.005	Gaussian	237.68646	1.188 K
Attenuation	-0.06107 dB	0.03 dB	Gaussian	2277.829	68.33 K
Standard reflect.	0.008	0.005	Gaussian	158.4576	0.792 K
Unknown reflect.	0.01	0.005	Gaussian	198.072	0.990 K
Type A			Gaussian		6.448 K
Combined uncertainty (1 σ)					136.8 K
Expanded uncertainty (2 σ)					274 K

Table B.5: Uncertainty in measurement of noise temperature of HP346B at 60 MHz

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$
Standard	10680 K	95 K	Gaussian	0.944688	89.75 K
Ambient	296.15 K	1.5 K	Gaussian	0.055312	0.083 K
Attenuation	-0.247 dB	0.03 dB	Gaussian	2256.184	67.69 K
Mismatch	0.054	0.005	Gaussian	215.8089	1.079 K
Standard reflect.	0.008	0.005	Gaussian	156.9519	0.785 K
Unknown reflect.	0.007	0.005	Gaussian	137.333	0.687 K
Type A			Gaussian		4.381 K
Combined uncertainty (1 σ)					112.5 K
Expanded uncertainty (2 σ)					225 K

Table B.6: Uncertainty in measurement of noise temperature of HP346B at 1 GHz

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$
Standard	10190 K	90 K	Gaussian	0.9977	89.79 K
Ambient	296.15 K	1.5 K	Gaussian	0.0023	0.00345 K
Attenuation	-0.010 dB	0.03 dB	Gaussian	2270.352	68.11 K
Mismatch	0.073	0.005	Gaussian	375.1016	1.876 K
Standard reflect.	0.013	0.005	Gaussian	256.6485	1.283 K
Unknown reflect.	0.022	0.005	Gaussian	434.3282	2.172 K
Type A			Gaussian		2.472 K
Combined uncertainty (1 σ)					112.8 K
Expanded uncertainty (2 σ)					226 K

NIST Uncertainties

Table B.7: Uncertainties in measurement of noise temperature of HP346A at 30 MHz

Source (i)	Type	$u_T(i)$ (K)	Eff. Degr. Of Freedom (DOF)
Cryogenic Std	B	1.02	8
Ambient Std	B	0.57	8
Mismatch Factor	B	5.82	8
Path Asymmetry	B	0.71	8
Linearity	B	1.31	8
Y-Factor	B	0.41	8
Adaptor	B	4.07	8
Type-A	A	0.46	17

Combined Standard Uncertainty: $u_T = 7.4$K Effective DOF = 16.8

$k(95\%) = 2.11$

$U(k=2) = 15$K

$U(k=2.11) = 16$K

Table B.8: Uncertainties in measurement of noise temperature of HP346A at 60 MHz

Source (i)	Type	$u_T(i)$ (K)	Eff. Degr. Of Freedom (DOF)
Cryogenic Std	B	1.64	8
Ambient Std	B	0.60	8
Mismatch Factor	B	5.87	8
Path Asymmetry	B	0.91	8
Linearity	B	1.32	8
Y-Factor	B	0.52	8
Adaptor	B	4.12	8
Type-A	A	1.21	11

Combined Standard Uncertainty: $u_T = 7.7$K Effective DOF = 16.8

$k(95\%) = 2.11$

$U(k=2) = 15$K

$U(k=2.11) = 16$K

Table B.9: Uncertainties in measurement of noise temperature of HP346A at 1 GHz

Source (i)	Type	u_T(i) (K)	Eff. Degr. Of Freedom (DOF)
Cryogenic Std	B	2.99	8
Ambient Std	B	0.58	8
Mismatch Factor	B	1.01	8
Path Asymmetry	B	3.51	8
Linearity	B	1.33	8
Y-Factor	B	0.41	8
Adaptor	B	0.11	8
Type-A	A	0.33	5

Combined Standard Uncertainty: u_T = 5.0K Effective DOF = 20.7

k(95%) = 2.09

U(*k*=2) = 10K

U(*k*=2.11) = 10K

Table B.10: Uncertainties in measurement of noise temperature of HP346B at 30 MHz

Source (i)	Type	u_T(i) (K)	Eff. Degr. Of Freedom (DOF)
Cryogenic Std	B	9.8	8
Ambient Std	B	4.6	8
Mismatch Factor	B	44.8	8
Path Asymmetry	B	6.9	8
Linearity	B	10.1	8
Y-Factor	B	3.9	8
Adaptor	B	39.3	8
Type-A	A	4.5	11

Combined Standard Uncertainty: u_T = 62K Effective DOF = 18.5

k(95%) = 2.10

U(*k*=2) = 124K

U(*k*=2.11) = 130K

Table B.11: Uncertainty in measurement of noise temperature of HP346B at 60 MHz

Source (i)	Type	u_T(i) (K)	Eff. Degr. Of Freedom (DOF)
Cryogenic Std	B	12.6	8
Ambient Std	B	4.6	8
Mismatch Factor	B	44.9	8
Path Asymmetry	B	6.9	8
Linearity	B	10.1	8
Y-Factor	B	4.0	8
Adaptor	B	39.4	8
Type-A	A	7.6	17

Combined Standard Uncertainty: u_T = 63K Effective DOF = 19.3

k(95%) = 2.09

U(*k*=2) = 126K

U(*k*=2.11) = 132K

Table B.12: Uncertainty in measurement of noise temperature of HP346B at 1 GHz

Source (i)	Type	u_T(i) (K)	Eff. Degr. Of Freedom (DOF)
Cryogenic Std	B	28.5	8
Ambient Std	B	4.7	8
Mismatch Factor	B	8.9	8
Path Asymmetry	B	33.5	8
Linearity	B	10.1	8
Y-Factor	B	4.0	8
Adaptor	B	0.8	8
Type-A	A	3.3	5

Combined Standard Uncertainty: u_T = 46.5K Effective DOF = 19.3

k(95%) = 2.09

U(*k*=2) = 93K

U(*k*=2.11) = 97K

VNIIFTRI Uncertainties

Table B.13: VNIIFTRI's procedure for estimating uncertainties

<table>
<tr><th colspan="2">Uncertainties,
sources and standard uncertainties designations u_i</th><th colspan="4">Input quantities and uncertainties</th><th>Estimation procedure</th></tr>
<tr><td>Cryogenic Standard</td><td>u_0</td><td colspan="4">Uncertaintiy of output noise temperature T_s: σT_s=(0.13…0.17) K</td><td>$u_0 = y \cdot \boldsymbol{\sigma} T_s$</td></tr>
<tr><td>Ambient Standard</td><td>u_1</td><td colspan="4">Uncertainties of ambient standard noise temperature T_a:
measurement ΔT_a=0.3 K, gradients ΔT_{gr}=0.2 K</td><td>$u_1 = (y+1) \cdot \sqrt{(\Delta T_a / \sqrt{3})^2 + (\Delta T_{gr} / \sqrt{3})^2}$</td></tr>
<tr><td>Mismatch</td><td>u_2</td><td colspan="4">Mismatch factors: residual inequalities of VRC $\boldsymbol{\Gamma}_s$, $\boldsymbol{\Gamma}_u$, $\boldsymbol{\Gamma}_a$ of compared devices
$\Delta\Gamma_s = |\boldsymbol{\Gamma}_s - \boldsymbol{\Gamma}_a| \leq 0.018$, $\Delta\Gamma_u = |\boldsymbol{\Gamma}_u - \boldsymbol{\Gamma}_a| \leq 0.018$;
$\boldsymbol{\Gamma}_L$ - VRC of radiometer input;
$|\boldsymbol{\Gamma}_L - \boldsymbol{\Gamma}_a^*|$ =(0.020…0.049)</td><td>$u_2 = (2|\Gamma_L - \Gamma_0^*| / \sqrt{3}) \sqrt{(T_u \Delta\Gamma_u)^2 + (y T_a \Delta\Gamma_s)^2}$</td></tr>
<tr><td>-"-</td><td>u_3</td><td colspan="4">Variation of radiometer noise level:
$\Delta T_{test} \leq 2$ K if $\Delta\Gamma_{test}$=0.1 (upper estimate)</td><td>$u_3 = \Delta T_{test} (\Delta\Gamma_u / \Delta\Gamma_{test})$</td></tr>
<tr><td rowspan="4">Variation of losses in a matching tuner ("back-to-back" method [5])</td><td rowspan="4">u_4</td><td>F(MHz)</td><td>30</td><td>60</td><td>1000</td><td rowspan="4">$u_4 = \frac{T_u - T_a}{4.34} \frac{\boldsymbol{\Delta}_{test}}{\sqrt{3}} \frac{|\boldsymbol{\Gamma}_{real}|}{|\boldsymbol{\Gamma}|_{test}}$</td></tr>
<tr><td>$|\Gamma|_{test}$</td><td>0.13</td><td>0.13</td><td>0.33</td></tr>
<tr><td>Δ_{test}, (dB)</td><td>0.03</td><td>0.03</td><td>0.02</td></tr>
<tr><td>$|\Gamma_{real}|$</td><td>0.05</td><td>0.07</td><td>0.1</td></tr>
<tr><td>Adaptor losses</td><td>u_5</td><td colspan="4">σ_{ad}=(0.005…0.01) dB - standard uncertainty of measurement of adaptor losses, Δ_{ad}=(0.004…0.01) dB - nonreproducibility of these losses at repeated connections of the adapter</td><td>$u_5 = \frac{T_u - T_a}{4.34} \sqrt{\boldsymbol{\sigma}_{ad}^2 + (\frac{\Delta_{ad}}{\sqrt{3}})^2}$</td></tr>
<tr><td>Radiometer Non-linearity "nlin"</td><td>u_6</td><td colspan="4">Δ_{att}=0.01 dB - attenuation accuracy of a standard step attenuator at measurement of overfalls of noise levels; σ_{nlin}=(0.002…0.006) dB - Type A uncertainty at nonlinearity measurement; δ_{nlin}=nonlin/3=(0.002…0.008) dB - residual uncertainty of nonlinearity.</td><td>$u_6 = \frac{T_u - T_a}{4.34} \sqrt{\boldsymbol{\sigma}_{nlin}^2 + (\frac{\Delta_{att}}{\sqrt{3}})^2 + (\frac{\boldsymbol{\delta}_{nlin}}{\sqrt{3}})^2}$</td></tr>
<tr><td>Non-reproducibility of repeated measurements</td><td>u_7</td><td colspan="4">Type B uncertainty</td><td>The uncertainty u_7 was valued on standard deviation of 3-4 experimental results received per different days.</td></tr>
<tr><td>Type A</td><td>u_8</td><td colspan="4"></td><td>Standard uncertainty of the mean for one typical measurement result at observations number not less than 8.</td></tr>
</table>

Table B.14: Uncertainty in measurement of noise temperature of HP346A at 30 MHz, 60 MHz and 1 GHz

Source of uncertainty	Standard uncertainty value ±K at F (MHz)			
	u_i	30	60	1000
Cryogenic Standard	u_0	0.71	0.71	1.38
Ambient Standard	u_1	1.84	1.83	1.85
Mismatch	u_2	0.79	0.79	1.38
Variation of radiometer noise	u_3	1.70	1.69	1.71
Variation of losses in a matching transformer	u_4	1.58	2.20	0.83
Adapter	u_5	1.32	1.75	2.45
Non-linearity.	u_6	1.87	1.86	1.92
Non-reproducibility of repeated measurements	u_7	0.58	0.29	0.30
Type A	u_8	1.00	1.25	1.26
Total (combined standard uncertainty)		4.06	4.51	4.71
Expanded uncertainty		8.11	9.01	9.42

Table B.15: Uncertainty in measurement of noise temperature of HP346B at 30 MHz, 60 MHz and 1 GHz

Source of uncertainty	u_i	Uncertainty value ±K at F (MHz)		
		30	60	1000
Cryogenic Standard	u_0	6.9	6.9	13.5
Ambient Standard	u_1	15.0	15.00	15.0
Mismatch	u_2	10.3	8.6	17.0
Variation of radiometer noise	u_3	16.4	16.4	16.4
Variation of losses in a matching transformer	u_4	15.3	21.4	8.0
Adapter	u_5	12.8	17.0	23.6
Non-linearity.	u_6	19.0	20.0	17.8
Non-reproducibility of repeated measurements	u_7	9.9	5.0	2.0
Type A	u_8	12.2	16.2	8.0
Total (combined standard uncertainty)		40.7	45.3	44.4
Expanded uncertainty		81.4	90.6	88.8

NPL Uncertainties

Uncertainties in the first NPL measurement (March 2002)

Table B.16: Uncertainties in measurement of noise temperature of HP346A at 30 MHz

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$
Standard	8818 K	120 K	0.1163	14.0 K
Ambient	296.36 K	0.25 K	0.88	0.22 K
Y-factor	-9.427 dB	0.001 dB	780.3161	0.780 K
Mismatch	0.978498	0.00166	1013.092	1.679 K
Connector repeatability				0.11 K
Type A				1.32 K
Combined uncertainty (1 σ)				14.2 K
Expanded uncertainty (2 σ)				29 K

Table B.17: Uncertainties in measurement of noise temperature of HP346A at 60 MHz

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$
Standard	9213 K	85 K	0.114191	9.71 K
Ambient	296.294 K	0.25 K	0.88	0.22 K
Y-factor	-9.431 dB	0.001 dB	650.935	0.651 K
Mismatch	0.998382	0.00057	1019.863	0.58 K
Connector repeatability				0.12 K
Type A				1.26 K
Combined uncertainty (1 σ)				9.84 K
Expanded uncertainty (2 σ)				20 K

Table B.18: Uncertainties in measurement of noise temperature of HP346A at 1 GHz

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$
Standard	9346 K	105 K	0.114323	12.0 K
Ambient	296.312 K	0.25 K	0.89	0.22 K
Y-factor	-9.422 dB	0.001 dB	780.3161	0.78 K
Mismatch	0.999272	0.00030	1035.344	0.312 K
Connector repeatability				0.12 K
Type A				0.67 K
Combined uncertainty (1 σ)				12.1 K
Expanded uncertainty (2 σ)				24 K

Table B.19: Uncertainties in measurement of noise temperature of HP346B at 30 MHz

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$
Standard	8818 K	120 K	1.1164	133.97 K
Ambient	296.659 K	0.25 K	0.1164	0.03 K
Y-factor	0.391 dB	0.001 dB	4931.51	4.932 K
Mismatch	0.980140	0.00150	9706.019	14.6 K
Connector repeatability				0.11 K
Type A				7.33 K
Combined uncertainty (1 σ)				135 K
Expanded uncertainty (2 σ)				270 K

Table B.20 Uncertainties in measurement of noise temperature of HP346B at 60 MHz

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$
Standard	9213 K	85 K	1.100745	93.56 K
Ambient	296.407 K	0.25 K	0.100745	0.03 K
Y-factor	0.410 dB	0.001 dB	4837.11	4.837 K
Mismatch	0.998492	0.00045	9829.752	4.443 K
Connector repeatability				1.13 K
Type A				12.66 K
Combined uncertainty (1 σ)				94.7 K
Expanded uncertainty (2 σ)				190 K

Table B.21: Uncertainties in measurement of noise temperature of HP346B at 1 GHz

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$
Standard	9346 K	105 K	1.0963	115.11 K
Ambient	296.477 K	0.25 K	0.0963	0.03 K
Y-factor	0.3941 dB	0.001 dB	4843.785	4.844 K
Mismatch	0.998795	0.00032	9933.221	3.159 K
Connector repeatability				1.14 K
Type A				5.55 K
Combined uncertainty (1 σ)				115 K[3]
Expanded uncertainty (2 σ)				230 K

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[3] Actual figure is close to 115.39 K, but for the purposes of this exercise has been rounded.

Uncertainties in the second NPL measurements (September 2003)

Table B.22: Uncertainties in measurement of noise temperature of HP346A at 30 MHz

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$
Standard	8922 K	101 K	0.1167	11.8 K
Ambient	296.846 K	0.25 K	0.88	0.22 K
Y-factor	-9.3949 dB	0.001 dB	784.7208	0.785 K
Mismatch	0.985094	0.00120	1021.690	1.022 K
Connector repeatability				0.12 K
Type A				0.22 K
Combined uncertainty (1 σ)				11.9 K
Expanded uncertainty (2 σ)				24 K

Table B.23: Uncertainties in measurement of noise temperature of HP346A at 60 MHz

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$
Standard	9099 K	64.0 K	0.1154	7.39 K
Ambient	296.922 K	0.25 K	0.88	0.22 K
Y-factor	-9.3858 dB	0.001 dB	648.1035	0.648 K
Mismatch	0.997902	0.00055	1018.194	0.555 K
Connector repeatability				0.12 K
Type A				0.12 K
Combined uncertainty (1 σ)				7.44 K
Expanded uncertainty (2 σ)				15 K

Table B.24: Uncertainties in measurement of noise temperature of HP346A at 1 GHz

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$
Standard	9030 K	47.0 K	0.1177	5.53 K
Ambient	296.850 K	0.25 K	0.88	0.22 K
Y-factor	-9.2917 dB	0.001 dB	624.4073	0.624 K
Mismatch	0.999758	0.00012	1028.52	0.126 K
Connector repeatability				0.12 K
Type A				0.07 K
Combined uncertainty (1 σ)				5.58 K
Expanded uncertainty (2 σ)				11 K

Table B.25: Uncertainties in measurement of noise temperature of HP346B at 30 MHz

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$
Standard	8922 K	101 K	0.1175	112.87 K
Ambient	296.913 K	0.25 K	0.1175	0.03 K
Y-factor	0.4258 dB	0.001 dB	4978.771	4.979 K
Mismatch	0.987041	0.00140	9764.814	13.640 K
Connector repeatability				1.11 K
Type A				1.07 K
Combined uncertainty (1 σ)				114 K
Expanded uncertainty (2 σ)				230 K

Table B.26: Uncertainties in measurement of noise temperature of HP346B at 60 MHz

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$
Standard	9099 K	64.0 K	1.0950	70.69 K
Ambient	296.922 K	0.25 K	0.0950	0.03 K
Y-factor	0.4209 dB	0.001 dB	4749.031	4.749 K
Mismatch	0.997552	0.00049	9662.039	4.792 K
Connector repeatability				1.12 K
Type A				0.90 K
Combined uncertainty (1 σ)				71.0 K
Expanded uncertainty (2 σ)				140 K

Table B.27: Uncertainties in measurement of noise temperature of HP346B at 1 GHz

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$
Standard	9030 K	47.0 K	1.1250	52.86 K
Ambient	296.585 K	0.25 K	0.1250	0.03 K
Y-factor	0.50900 dB	0.001 dB	4794.038	4.794 K
Mismatch	0.999375	0.00020	9831.664	1.938 K
Connector repeatability				1.13 K
Type A				0.70 K
Combined uncertainty (1 σ)				53.2 K
Expanded uncertainty (2 σ)				110 K