CCEM.RF-K9 KEY COMPARISON:

International comparison of thermal noise standards between 12.4 GHz and 18 GHz (GT-RF/99-1)

Final Report

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Abstract

An international comparison of thermal noise-power measurements has been carried out among five national metrology institutes between 12.4 and 18 GHz. Four transfer standards were measured. The following national institutes participated: BNM-LCIE (France), NPL (United Kingdom), PTB (Germany), NIST (United States of America) and VNIIFTRI (Russia). The Bureau National de Métrologie - Laboratoire Central des Industries Electriques (France) acted as the pilot laboratory for the comparison.

I. INTRODUCTION

The measurement comparison was initiated by Euromet among BNM-LCIE, PTB and NPL, under the Euromet 329 project. Its aim was to verify the facilities present in European national metrology institutes for the measurement of radioelectrical noise temperature at national standards level of accuracy in the IEC R140 waveguide range. The Euromet 329 project was extended by the Working Group on Radio-Frequency Quantities (Groupe de Travail pour les grandeurs aux Radio-Fréquences GT-RF) of the Comité Consultatif d'Electricité-Magnétisme (CCEM), an advisory committee of the Comité International des Poids et Mesures (CIPM) to a GT-RF Key comparison. Two additional institutes, NIST and VNIIFTRI joined the comparison, which becomes the GT-RF/99-1 comparison, also identified under the reference CCEM.RF-K9.

The following national metrology institutes participated in this Key comparison:

A. Bureau National de Métrologie - Laboratoire Central des Industries Electriques (BNM-LCIE), Fontenay-aux-Roses, France

B. National Physical Laboratory (NPL), Teddington, United Kingdom

C. Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany.

D. National Institute of Standards and Technology (NIST), Boulder, United States of America

E. All-Russian Scientific Research Institute for Physical-Technical and Radiotechnical Measurements (VNIIFTRI), Moscow, Russia.

The Bureau National de Métrologie - Laboratoire Central des Industries Electriques acted as the pilot laboratory for the comparison. Four transfer standards have circulated for measurement by participants. Measurements were started in April 1997 and were completed in December 2000.

II. Traveling Standards

Four traveling standards were used in the comparison, kindly given by NPL and PTB:

- Noise standard in waveguide with output IEC R140 flange
- Noise standard in coaxial line with output PC-7 connector and associated to a precision adapter PC-7/R140

TSA1:

Waveguide R140 Noise generator with noise source power supply (Nore Microwave Gas Discharge Tube type NTM16-18/7L + transition NTL16-18 R100/R140, output flange R140, 14…16 dB ENR. Noise Tube Power Supply: Nore Microwave type NM5, 125 mA), supplied by PTB.

TSA2:

Waveguide R140 Noise generator with noise source power supply (Nore Gas Discharge Tube Noise Source NTM16/7 + taper R100/R140, 15 dB ENR. Power Supply Nore type NM5), supplied by NPL.

TSB1:

Coaxial PC-7 noise generator associated to a precision coaxial to waveguide adapter (Hewlett-Packard Coaxial Noise Source HP346A opt 002, output connector PC-7, 14…16 dB ENR, Maury Microwave coaxial-waveguide adapter PC-7 / R140 type P229A2. Input power +28 VDC, 30 mA), supplied by PTB.

TSB2:

Coaxial PC-7 noise generator associated to a precision coaxial to waveguide adapter (Hewlett-Packard Coaxial Noise Source HP346A, output connector PC-7, 5 dB ENR, + coaxial-waveguide adapter PC-7 / R140), supplied by NPL.

III. THE COMPARISON SCHEME

The traveling standards were circulated to the participating institutes according to the scheduled scheme described in Table III.1:

Institute	Step number	Plot's legend	Traveling standards	Time period
NPL	Step 1	NPL 1	TSA2, TSB2	April 1997
PTB	Step 1	PTB 1	TSA1, TSB1	June 1997
BNM-LCIE	Step 2	BNM-LCIE 2	TSA1, TSB1, TSA2, TSB2	September 1997
PTB	Step 3	PTB 3	TSA2, TSB2	February 1998
NPL	Step 3	NPL 3	TSA1, TSB1	May 1998
BNM-LCIE	Step 4	BNM-LCIE 4	TSA1, TSB1, TSA2, TSB2	January 1999
NPL	Step 5	NPL 5	TSA2, TSB2	March-April 1999
PTB	Step 5	PTB 5	TSA1, TSB1	April 1999
NIST	Step 6	NIST 6	TSA1, TSB1, TSA2, TSB2	April 2000
VNIIFTRI	Step 7	VNIIFTRI 7	TSA1, TSB1, TSA2, TSB2	Sept-Oct 2000
BNM-LCIE	Step 8	BNM-LCIE 8	TSA1, TSB1, TSA2, TSB2	December 2000

Table III.1: Circulation scheme

IV. RADIOELECTRIC NOISE TEMPERATURE

The fundamental quantity describing a microwave noise source is the available noise temperature T in Kelvin, or the Excess Noise Ratio (ENR) expressed in decibels, and given by the following formula:

$$\mathbf{ENR(dB)= 10.log\frac{T - T_0}{T_0}} \qquad (1)$$

Where T_0 is an arbitrary noise temperature, given as 290 K.

V. QUANTITIES TO BE MEASURED

The required parameters of each traveling standard, to be measured are:

Γ: magnitude of the reflection coefficient measured at its reference plane*, expressed in linear unit.
T: available noise temperature, expressed in Kelvin (K).
ENR: Excess Noise Ratio, expressed in decibels (dB).

The uncertainties ΔT and ΔENR are global uncertainties given to one standard deviation (1 σ) The main contributions in the uncertainty budget are also given.

These parameters have been measured at the following five frequency points: 12.4, 13.5, 15, 17.5 and 18 GHz except for one participant (VNIIFTRI) who carried out measurements at four frequency points: 12.4, 13.5, 15 and 17.5 GHz.

* The reference planes were the waveguide flanges for TSA1 and TSA2. For TSB1 and TSB2, two reference planes were used: the waveguide flange (when the coaxial-waveguide adapter PC-7 / R140 was connected) and the PC 7 connector, output connectors of TSB1 and TSB2.

VI. Measurement Methods and Environmental Conditions

A. BNM-LCIE

The traveling standards were compared against BNM-LCIE's working noise standard which has direct traceability to BNM-LCIE Primary Noise Standards (hot primary standard 1000 K). The noise measurements were made on the BNM-LCIE R140 Dicke-type radiometer [1].
The noise power of the PC-7 noise sources was determined by calculation considering the measured S parameters of the adapters.

B. NPL

The traveling standards were compared against NPL's working noise standard which has direct traceability to UK Primary Noise Standards. The noise measurements were made on the NPL WG 18 radiometer according to the procedures laid down in NPL Procedure Document QPCEM/B/085.
The NPL radiometer is a single-sideband radiometer.
The reflection coefficients were measured on network analysers according to the procedures laid down in NPL Procedure Document QPCEM/B/093.

C. PTB

An RF-switching Dicke-type radiometer for the waveguide band R140 with RF attenuator at the input was used. The measurement input and the noise source output are separately tuned for $|\Gamma|=0$. The unknown sources are calibrated against a working standard of about 10000 K, which is calibrated with reference to the PTB hot primary standard (650 K).
The noise power of the PC-7 noise sources was determined by calculation considering the measured S parameters of the adapters.
The room temperature was 23 °C.

D. NIST

All noise-temperature measurements were made on the NIST WR-62 (R140) waveguide radiometer. It is an isolated, total-power radiometer of the same design as the WR-28 system described in [2]. It is effectively a double sideband system with 20 MHz bandwidth and IF frequency 10 MHz. The two standards used are an ambient standard described in [2] and a WR-62 cryogenic horn standard described in [3]. The standards used are national primary standards. Reflection coefficients were measured on the six-port reflectometer built into the radiometer system [2]. For noise temperature at the PC-7 plane, the noise temperature was measured at the R140 waveguide plane, and a correction was made for the adapter effect. The adapters were characterized using a one-port method developed by Daywitt [4]. Details of the uncertainty analysis for NIST noise-temperature measurements are given in [5].

E. VNIIFTRI

The procedure of comparisons was complicated because of discrepancies of the standards IEC and Russia on the dimensions of waveguides, on frequency ranges of a means of measurements (in particular, in Russia upper bound of a frequency range is 17.44 instead of 18 GHz), and also because of features of VNIIFTRI reference standards.

The CCEM.RF-K9 protocol stipulates the comparisons with the national transfer standard of each participant laboratory. Such standards at VNIIFTRI are represented by neon gas-discharge noise generators. The generators and neon tubes for them were selected from those serially produced before 1991.

ENR unreproducibility for the neon tubes when switching on and off is about 0.02 dB (due to 150-200 mA anode current). To reduce the influence of this factor and to improve the reliability the transfer standard is made of a ten tubes group, switched on in turn. The ENR of this standard is about 18 dB. It is carried out with a 16x8 mm or 11x5.5 mm waveguide section (accordingly for the 12.05-17.44 or 17.44-25.96 GHz frequency range). This noise generator scatters a thermal power up to 60 W, so the temperature of the output flange reaches 60-70 °C. This last circumstance creates an additional uncertainty in the observed data of 1-1.5% because of a thermal drift while the comparisons of gas-discharge noise source with semiconductor generators **TSB1, 2**.

The elimination of the influence of the above-mentioned factors considerably complicates a procedure of measurements. That's why all the transfer standards were compared directly with the cryogenic primary standard PS. The exception is for 18 GHz, when the comparison with PS was carried out only for **TSB2.** ENR for the remaining standards was defined by means of comparison with the **TSB2'**s ENR level. The reason of such decision is the feature of a radiometer characteristic on frequency 18 GHz (noted below).

The PS (waveguide 16x8 mm) represents a sliding termination together with a matching tuner immersed in liquid nitrogen and connected to an output section with sealing window and output flange by means of a heat-shield waveguide. The tuner ensures the alignment of complex reflection coefficients of the compared devices.

The measurements were made by means of a DSB radiometer with a pilot signal. To the input of it were connected: reflectometer, matching tuner, rotary-vane attenuator RVA (situated in between insulators), directional coupler for delivery of the noise pulse-modulated (meander 80 Hz) pilot signal and low-noise amplifier LNA. To reduce the influence of the system's non-linearity the measured signal with ENR more than 5 dB was attenuated on 10±0.01 dB by means of RVA. However usage of RVA on 18 GHz has appeared impossible because of growth on this frequency of uncertainty of attenuation measurements up to ±0.1 dB.

The resulting signal from LNA output goes to a balanced mixer. After an IF amplification (the spectrum of intermediate frequencies is 20-40 MHz) and square-law detection the ratio

$$A = \frac{\text{noise temperature of a pilot signal}}{\text{operating noise temperature of system}}$$

is measured. For this purpose the intensity of signals relevant to adjacent half-periods of modulation are approximately balanced by means of a discrete precision resistive divider (at a residual unbalance in 1-2 %), then detected by a synchronous detector and flattened. This procedure is executed for all the objects connected to the radiometer's input at two close values of transmission factors **?** of the resistive divider. To calculate the **A** value the information about **K** factors and about values of voltages of a residual unbalance relevant **K** is transmitted to the digital computer.

The prototypes of the primary standard and radiometer are described in [6], [7].

The available noise temperature of the coaxial noise sources at the reference plane of their output connectors (PC-7) was measured by method [8], using **TSA2** as a reference source.

The discrepancies in the IEC's and Russian standards on waveguide dimensions and frequency ranges of measuring devices have established the additional complications while comparisons (in particular the 17,44 GHz upper bound of a frequency range instead of 18 GHz). Because of the discrepancy in the IEC's and Russian waveguide connector dimensions standards additional adapters (the transient waveguides with the $\lambda_g/4$ length for 18 GHz) were manufactured. The calculated value of the return loss at 12,4-18,0 GHz is not less than 44 dB, measured attenuation is not more than 10^{-3} dB. Therefore correction factor on losses in the additional adapter is not taken into account.

VII. MEASUREMENT RESULTS

The measurement results are plotted in Figures 7.1 to 7.6. Uncertainty limits have been plotted as combined type A and type B uncertainty limits expressed as ± 1 standard deviation of the mean.

In the legend on the right of the plots, the numerical index following the name of the institute corresponds to the step index of the circulation scheme (Table III.1).

The complete set of measurement results including uncertainties, provided by the participating institutes are reported in tables 1.1 to 8.6 and presented in appendices A.1 to A.5. In these appendices, tables are identified as Table x.y, where x corresponds to the step number and y to the number of traveling standard.

Table x.1 for Source TSA1 output flange R140
Table x.2 for Source TSB1 output flange R140
Table x.3 for Source TSB1 output connector PC-7
Table x.4 for Source TSA2 output flange R140
Table x.5 for Source TSB2 output flange R140
Table x.6 for Source TSB2 output connector PC-7

The uncertainties tables are denoted U.Step.i

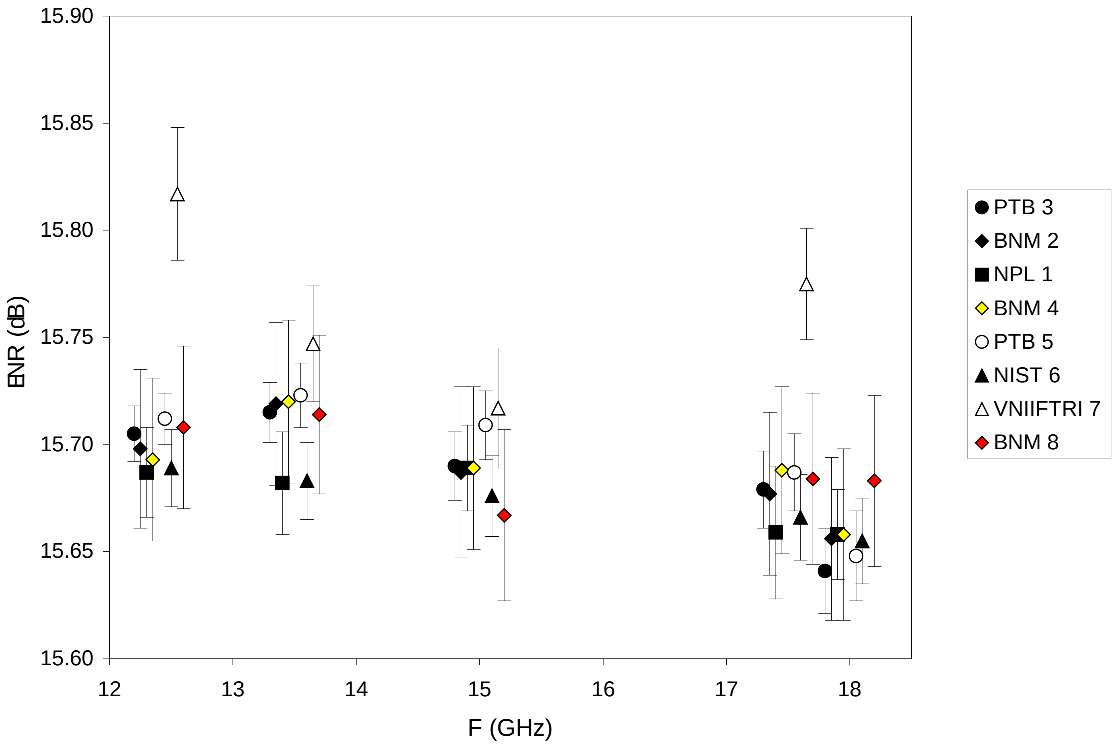

Figure 7.1: TSA1 standard at its output flange R140

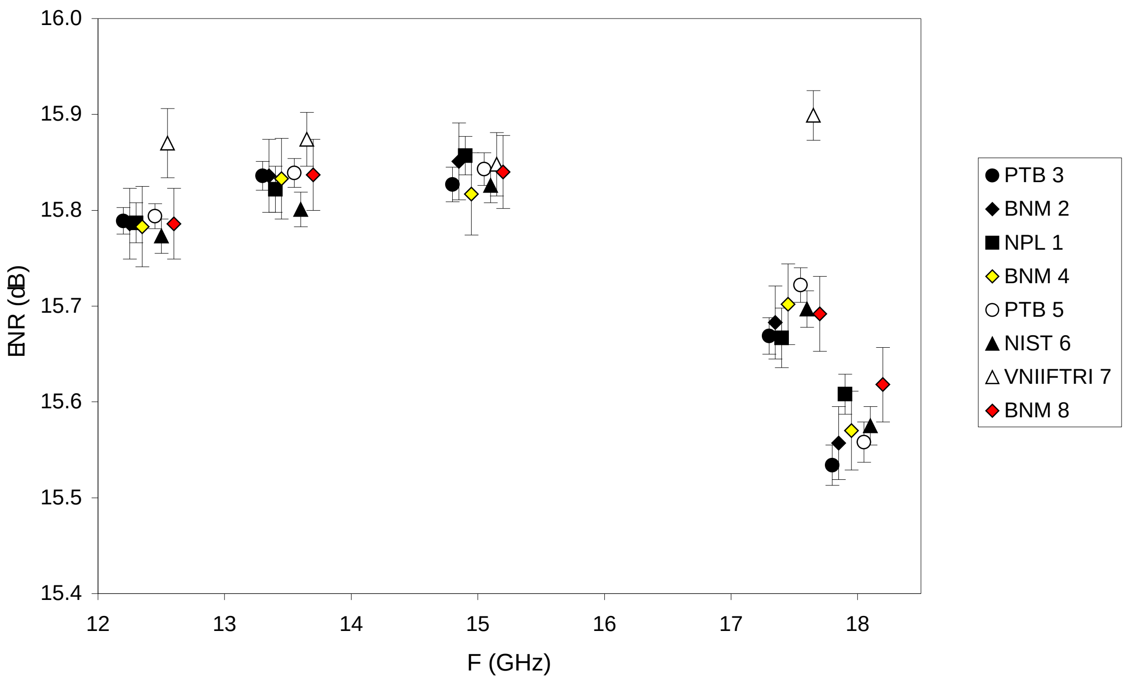

Figure 7.2: TSB1 standard at its output flange R140

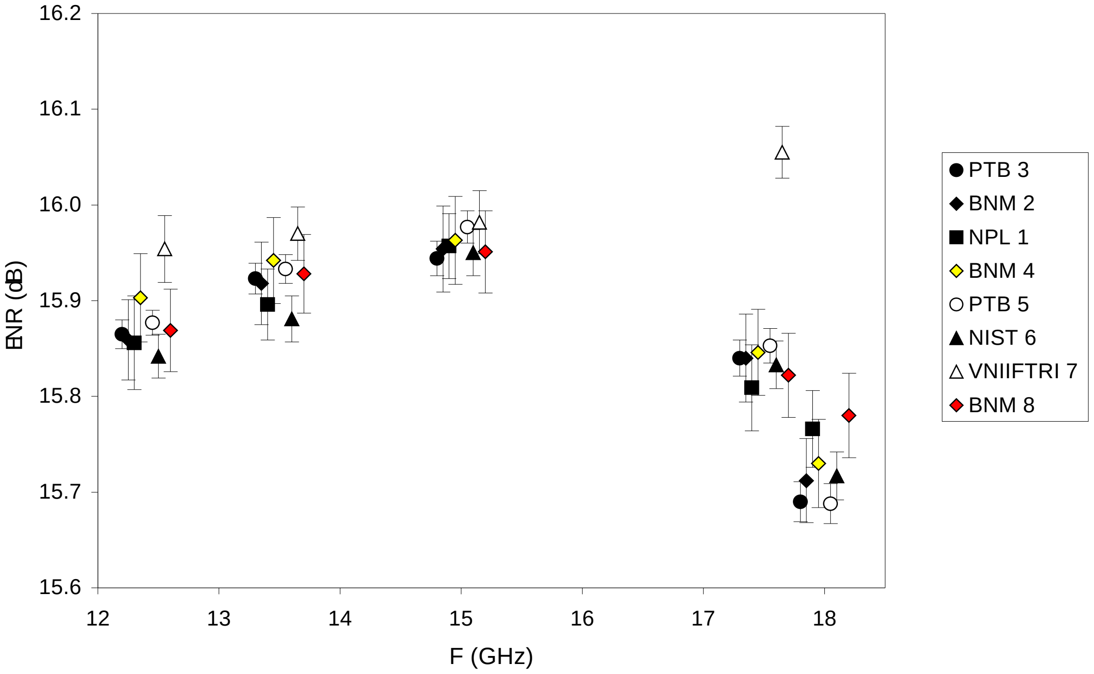

Figure 7.3: TSB1 standard at its output connector PC7

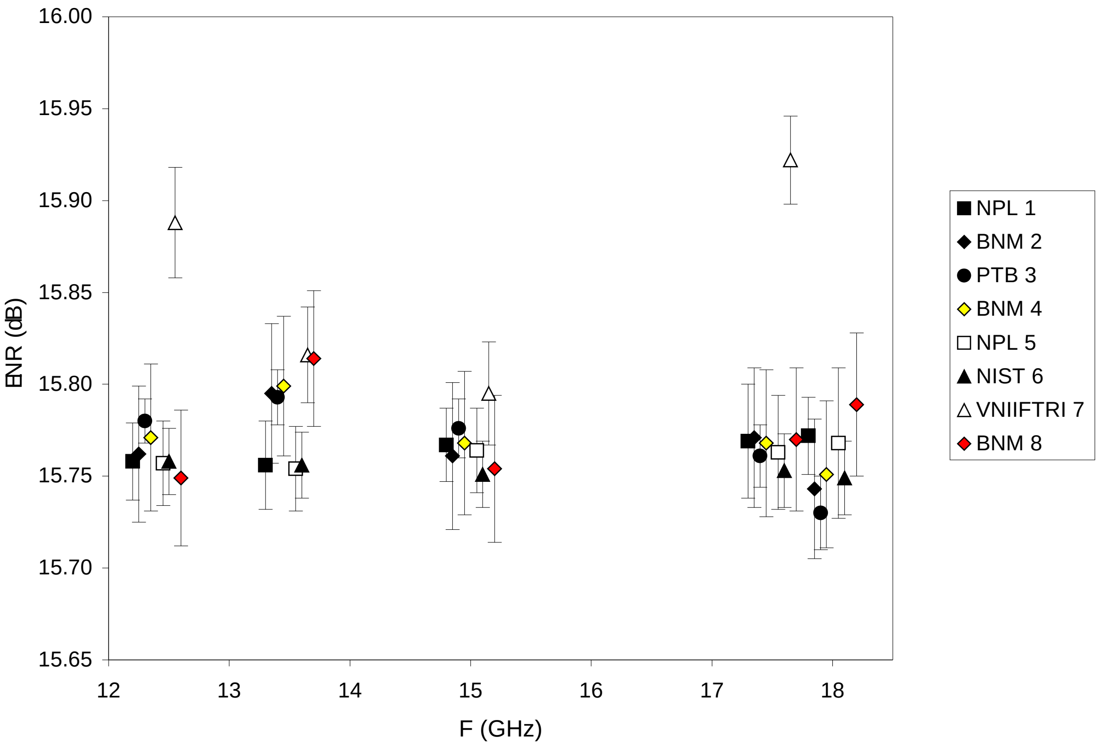

Figure 7.4: TSA2 standard at its output flange R140

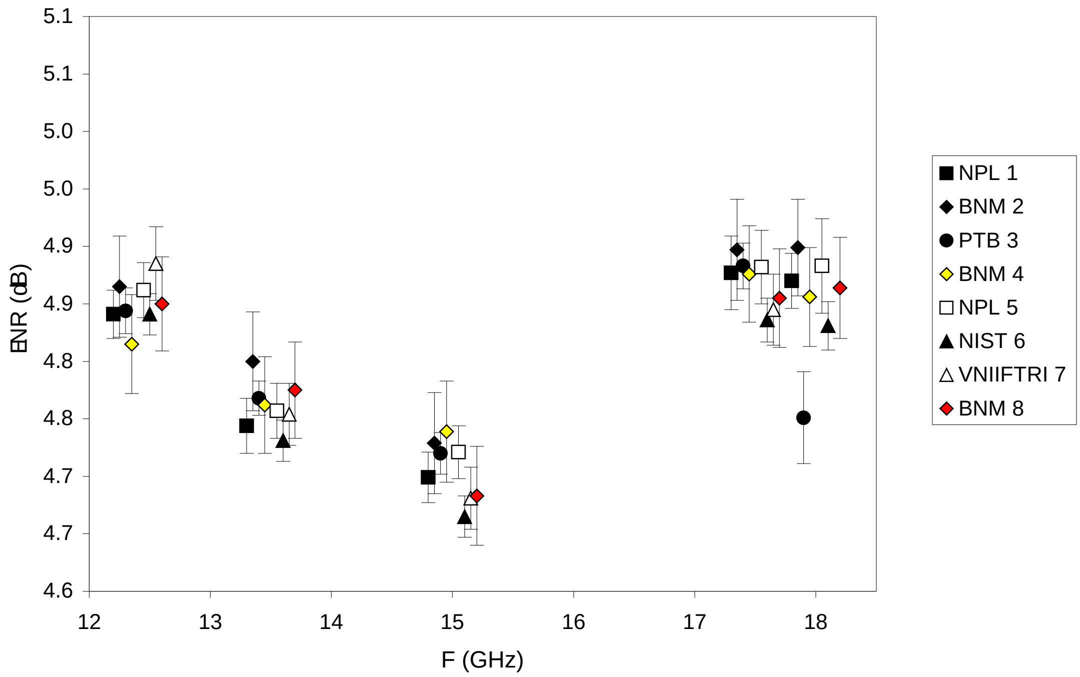

Figure 7.5: TSB2 standard at its output flange R140

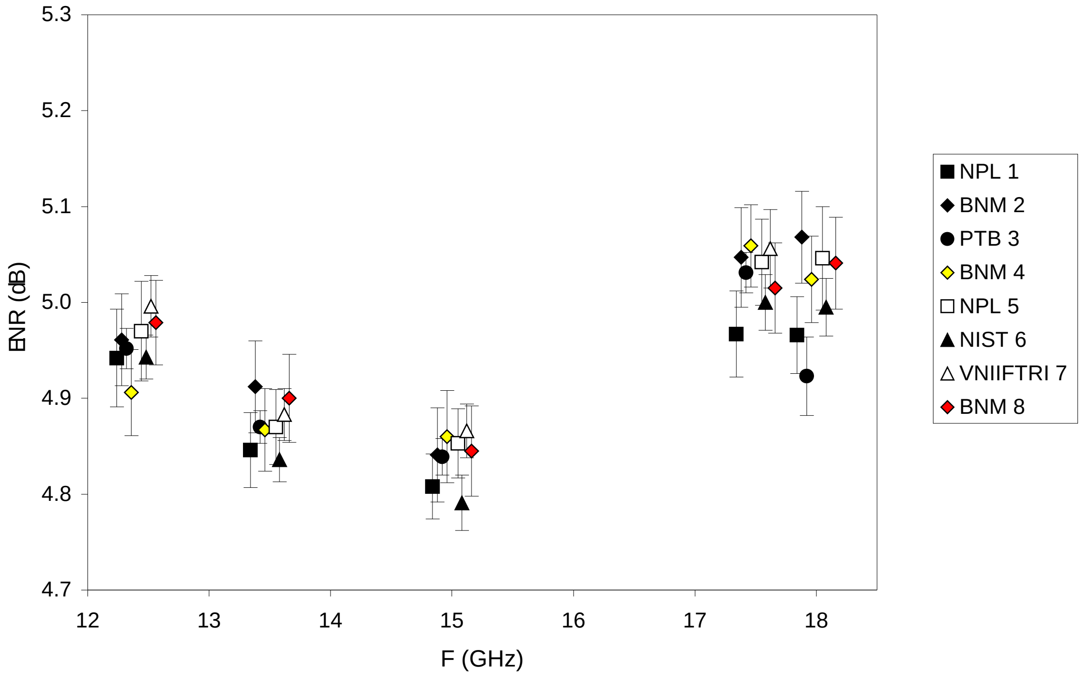

Figure 7.6: TSB2 standard at its output connector PC7

VIII. Reference Value and Degree of Equivalence: Graphical Data

The calculation of the Key Comparison Reference Value (KCRV) and the degree of equivalence are based on Randa's document [9]. The identification of outliers also followed the prescription in [9]. The coverage factor used in that prescription assumes a large sample, whereas the present comparison comprises only five participants. However, in the present case the practical effect of using the appropriate small-sample coverage factor would be small in the Key Comparison Reference Values, and we therefore decided to use the prescription of [9] unmodified, as originally agreed.

The numerical values are reported in tables presented in Appendix A.6
The following symbols are used in these tables:

KCRV: Key Comparison Reference Value
u_{KCRV}: standard uncertainty on the KCRV
Y_i: Reference value for the Lab i; value to take into account in the calculation of the KCRV(one value for each institute). It means that this value is the average value of the ENR given by the institute i. For example, $Y_i(BNM) = \frac{ENR(Step2) + ENR(Step4) + ENR(Step8)}{3}$.
$u(Y_i)$: uncertainty on Y_i. Also averaged
Δ_i: Degree of equivalence
$U_{\Delta i}$: Expanded uncertainty (k=2) on Δ_i

Figures 8.1.1.a to 8.6.5.b give the degrees of equivalence: each plot shows the degree of equivalence of each laboratory with respect to the KCRV, for a given noise source at a given frequency.
Both weighted and unweighted cases are considered.
For the cases presenting outliers, additional plots are presented including these outliers in the calculation.
The plotted uncertainties are extended uncertainties (k=2).

The complete data are reported in Appendix A.6.

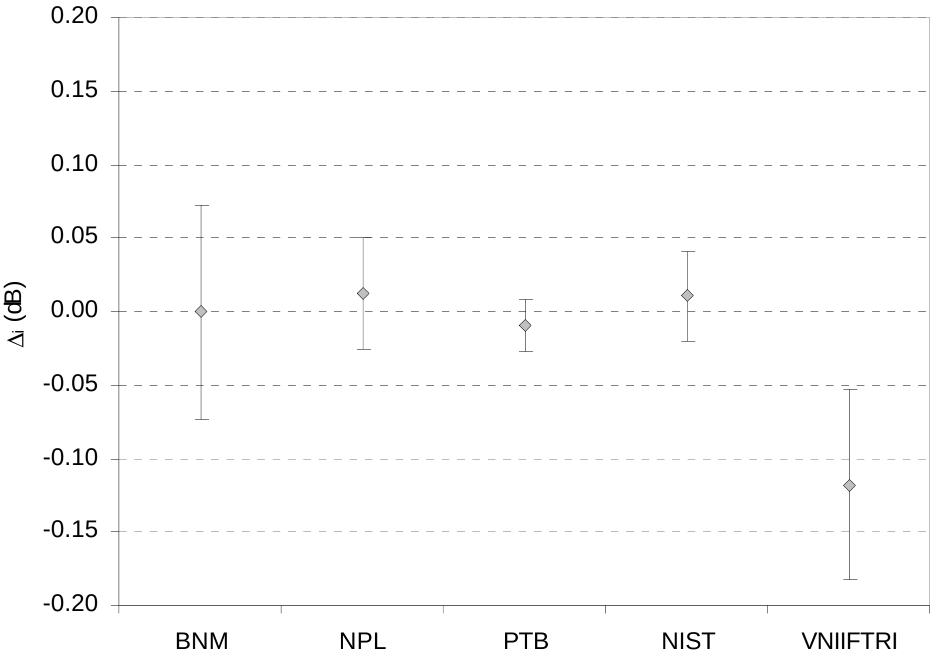

Figure 8.1.1.a: TSA1 output flange R140, F = 12.4 GHz, weighted

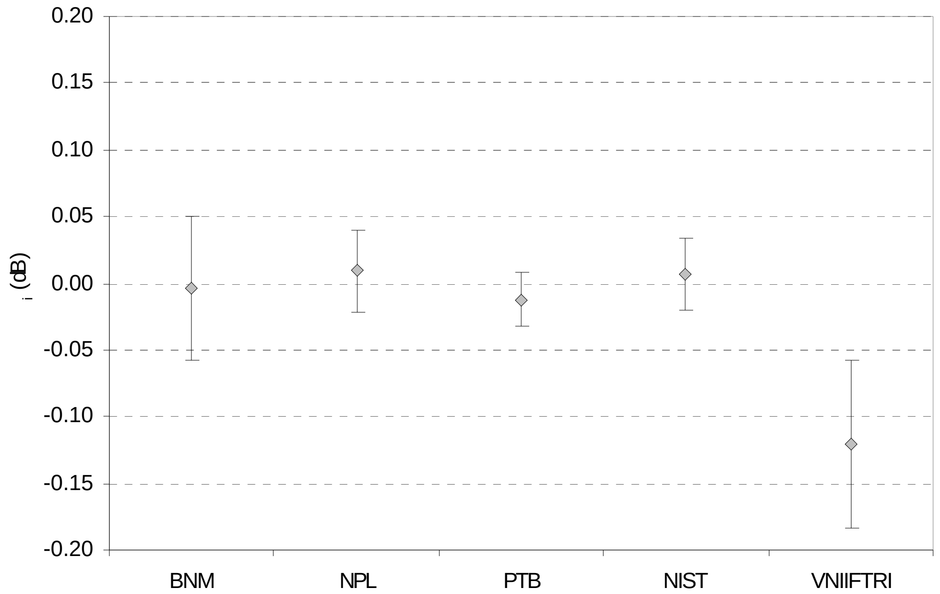

Figure 8.1.1.b: TSA1 output flange R140, F = 12.4 GHz, unweighted

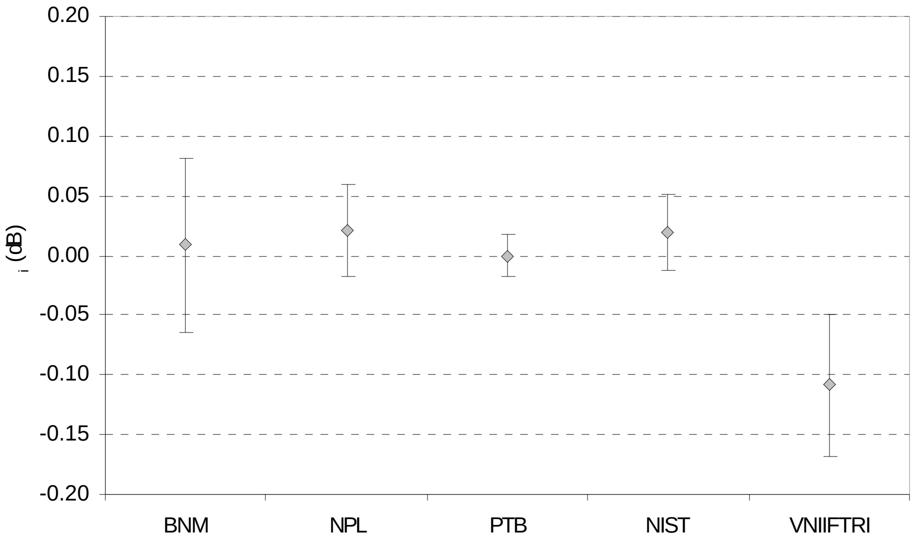

Figure 8.1.1.c: TSA1 output flange R140, F = 12.4 GHz, weighted, outliers included

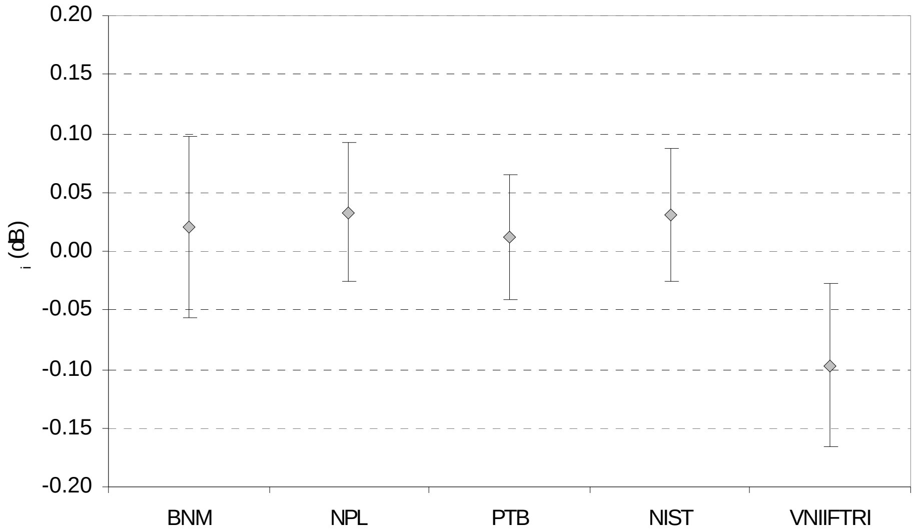

Figure 8.1.1.d: TSA1 output flange R140, F = 12.4 GHz, unweighted, outliers included

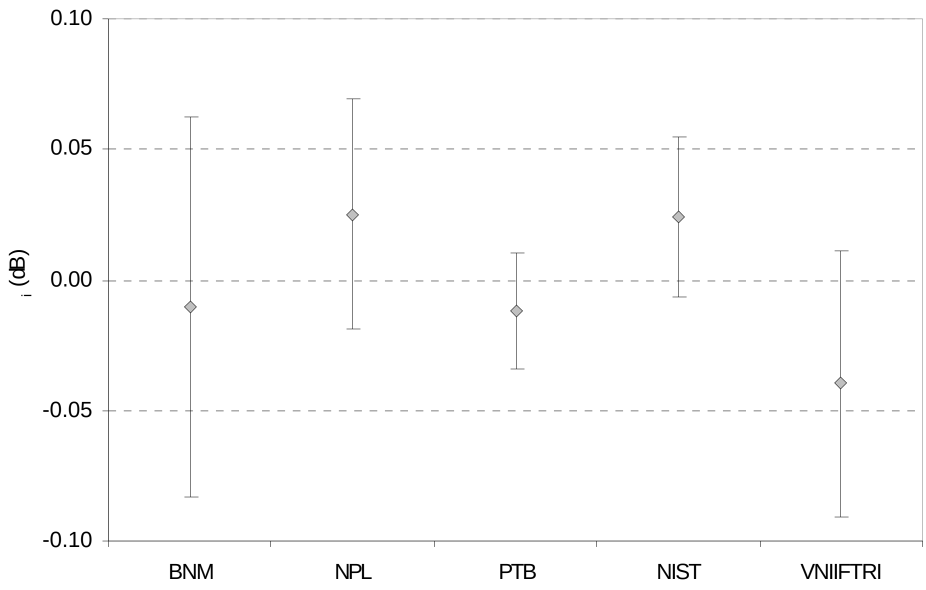

Figure 8.1.2.a: TSA1 output flange R140, F = 13.5 GHz, weighted

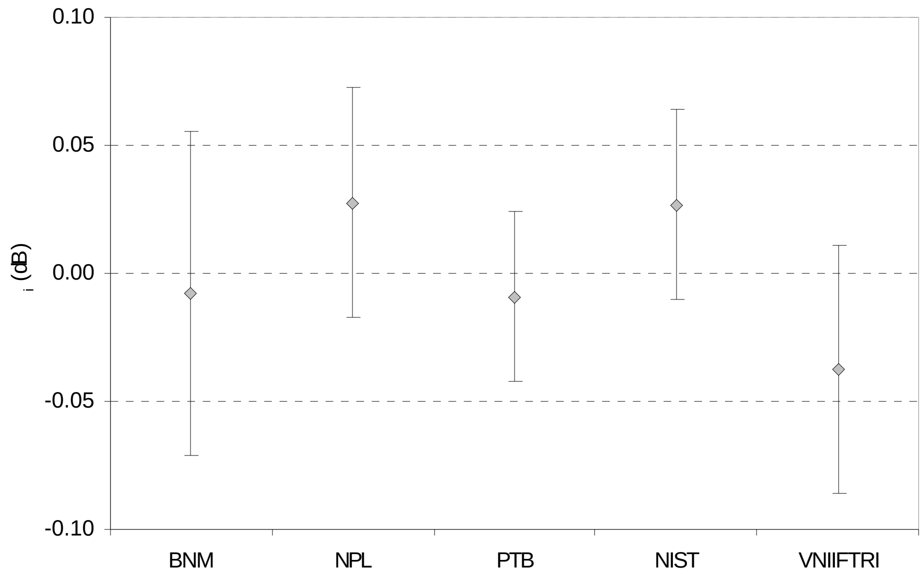

Figure 8.1.2.b: TSA1 output flange R140, F = 13.5 GHz, unweighted

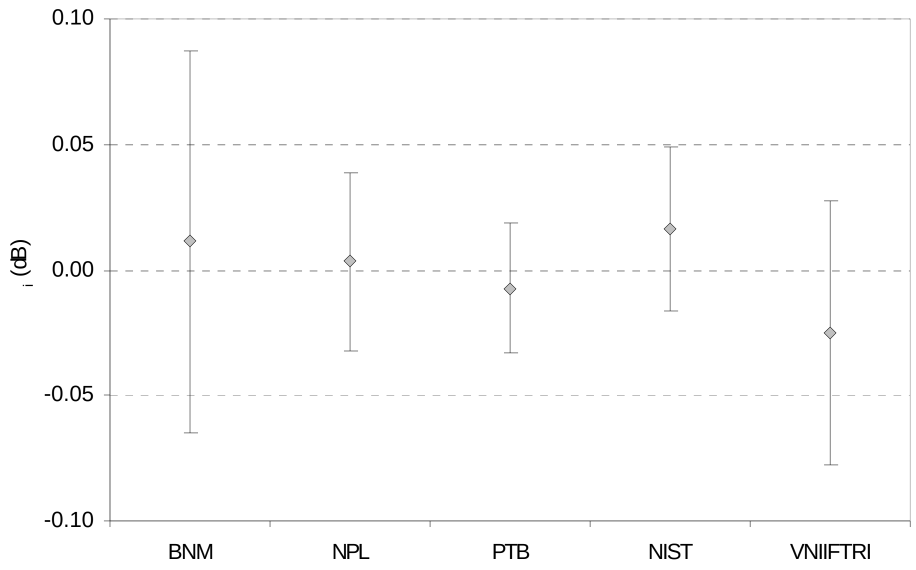

Figure 8.1.3.a: TSA1 output flange R140, F = 15 GHz, weighted

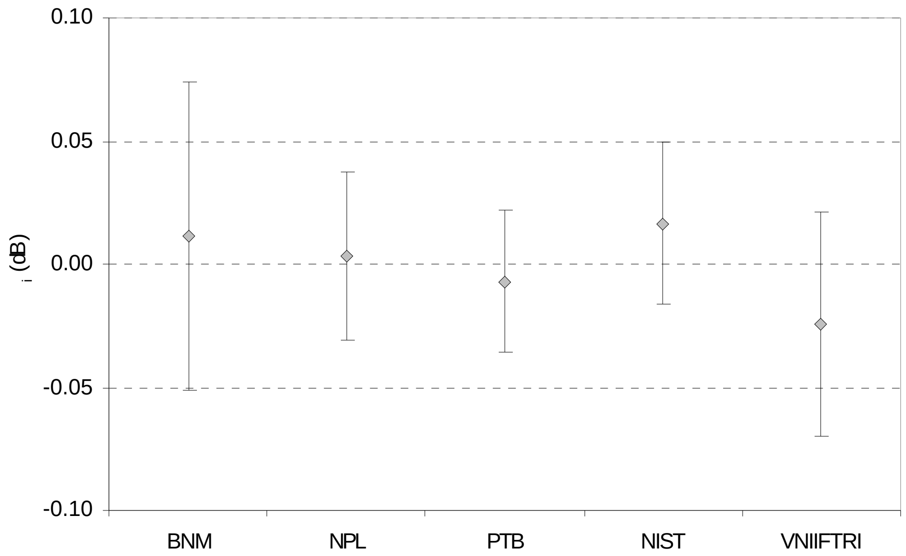

Figure 8.1.3.b: TSA1 output flange R140, F = 15 GHz, unweighted

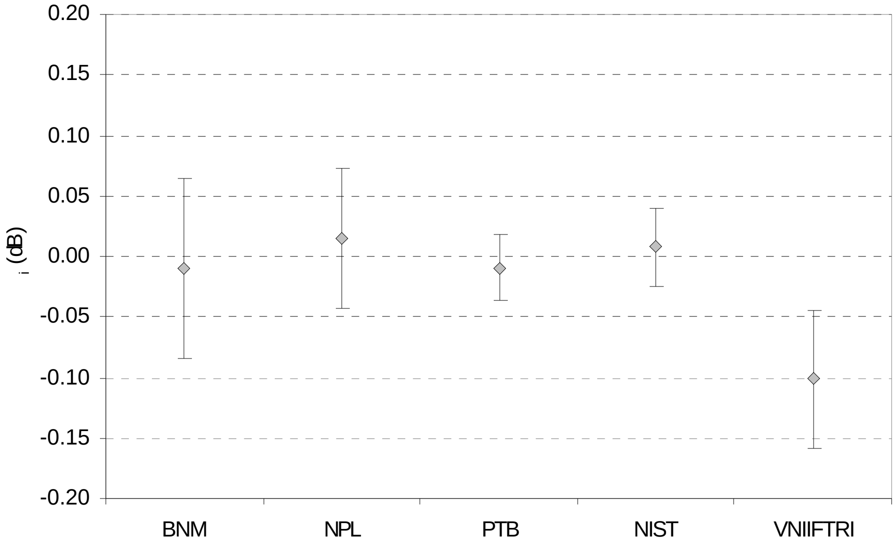

Figure 8.1.4.a: TSA1 output flange R140, F = 17.5 GHz, weighted

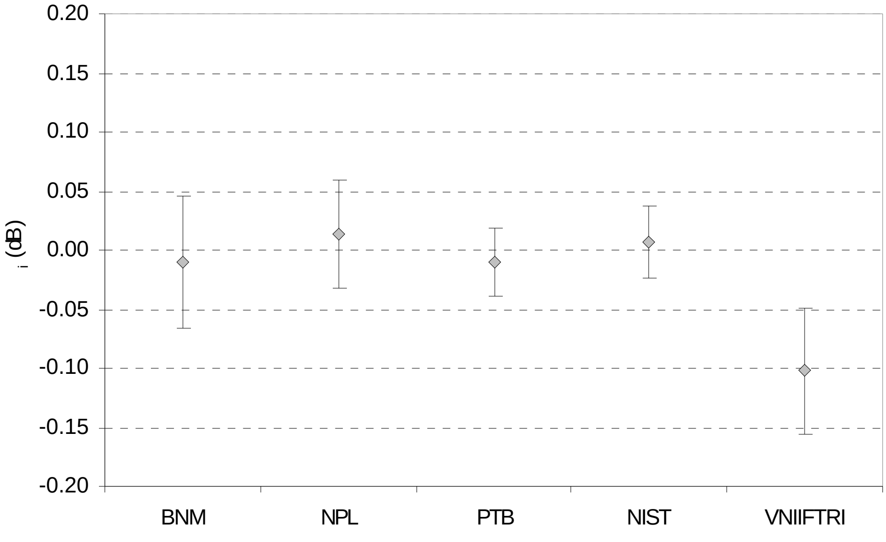

Figure 8.1.4.b: TSA1 output flange R140, F = 17.5 GHz, unweighted

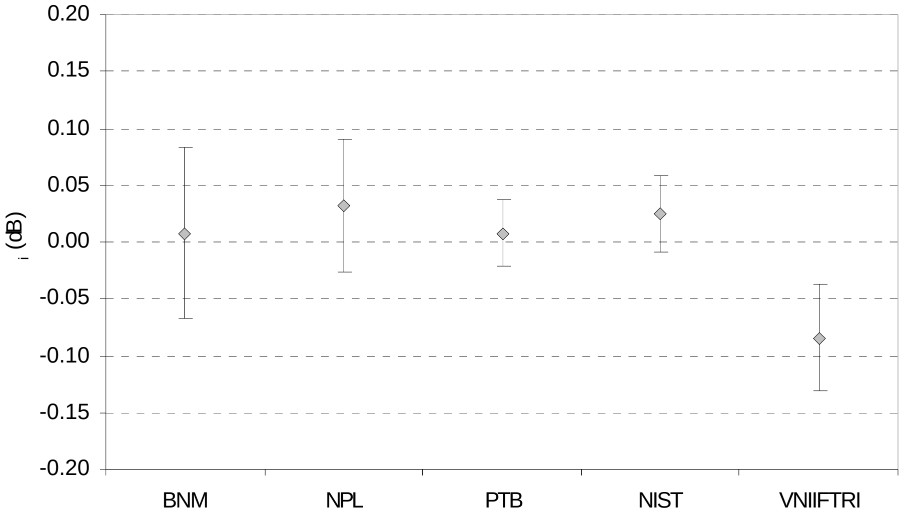

Figure 8.1.4.c: TSA1 output flange R140, F = 17.5 GHz, weighted, outliers included

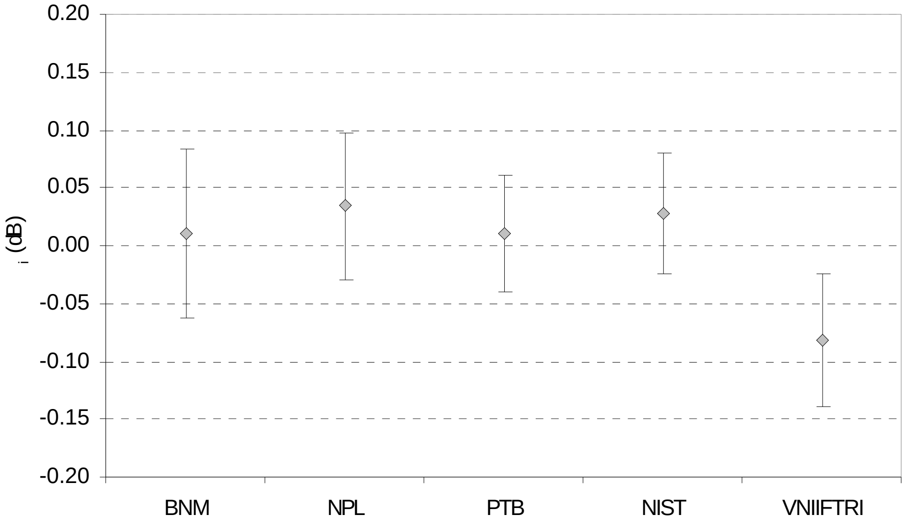

Figure 8.1.4.d: TSA1 output flange R140, F = 17.5 GHz, unweighted, outliers included

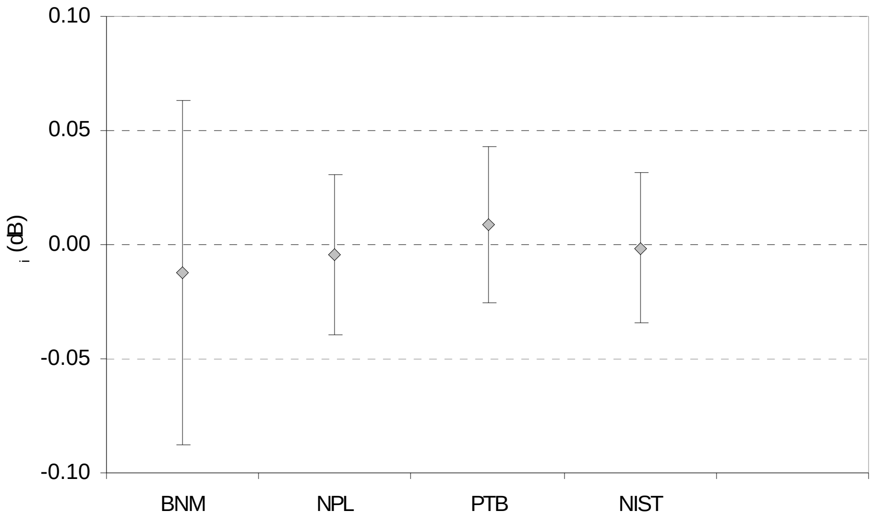

Figure 8.1.5.a: TSA1 output flange R140, F = 18 GHz, weighted

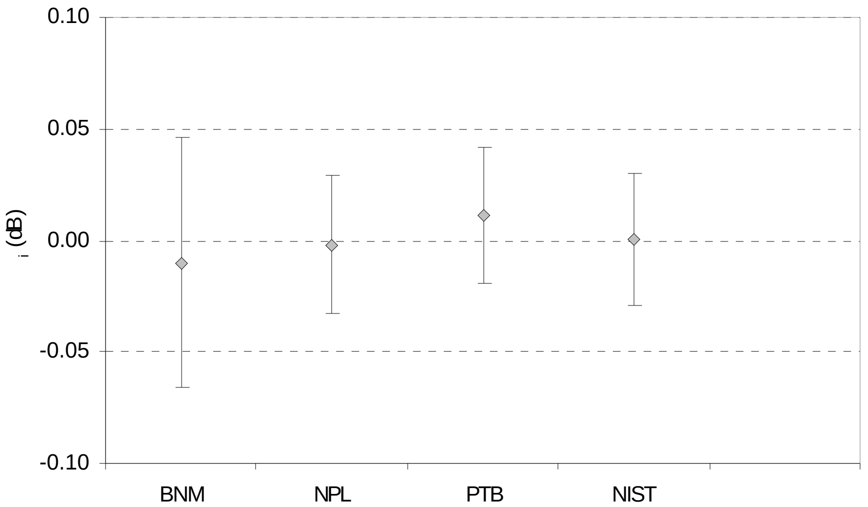

Figure 8.1.5.b: TSA1 output flange R140, F = 18 GHz, unweighted

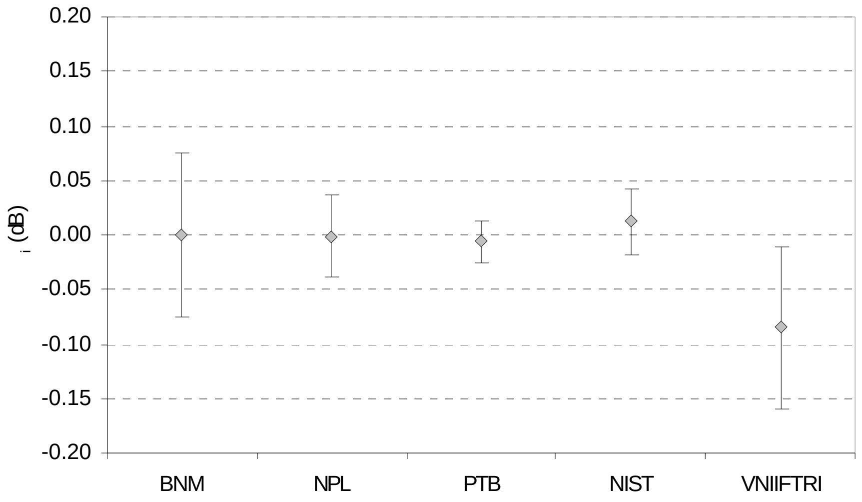

Figure 8.2.1.a: TSB1 output adapter PC-7/R140, F = 12.4 GHz, weighted

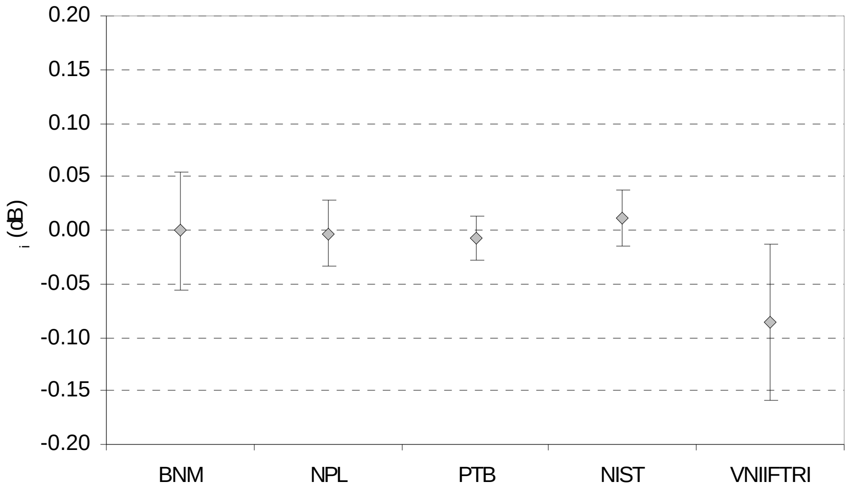

Figure 8.2.1.b: TSB1 output adapter PC-7/R140, F = 12.4 GHz, unweighted

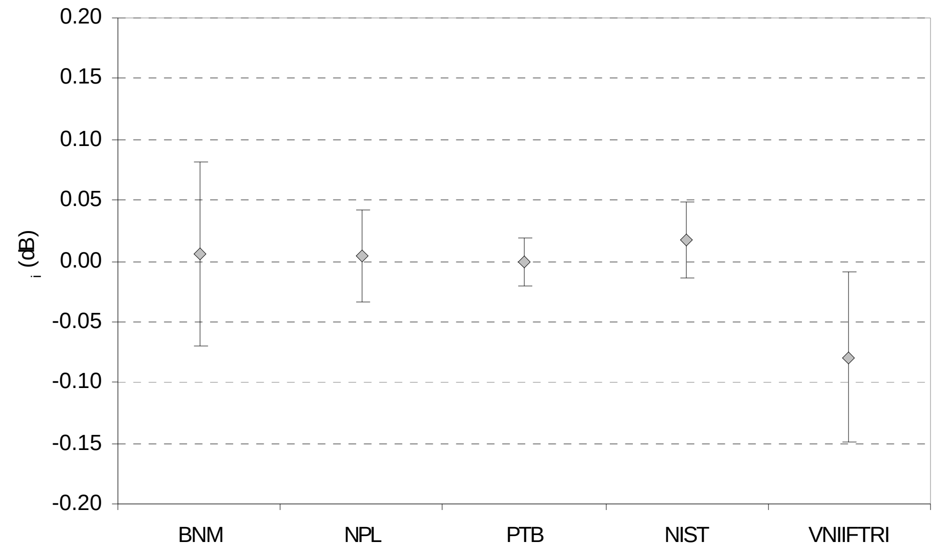

Figure 8.2.1.c: TSB1 output adapter PC-7/R140, F = 12.4 GHz, weighted, outliers included

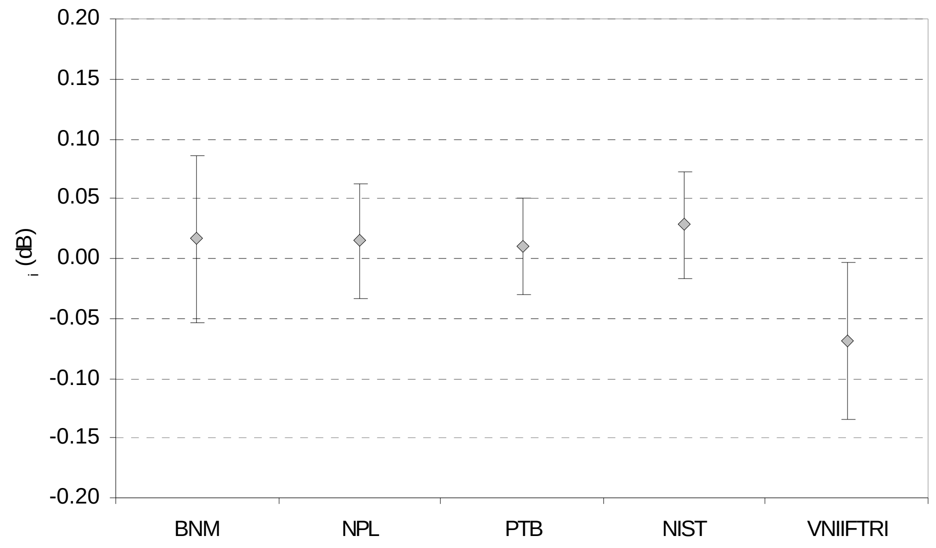

Figure 8.2.1.d: TSB1 output adapter PC-7/R140, F = 12.4 GHz, unweighted, outliers included

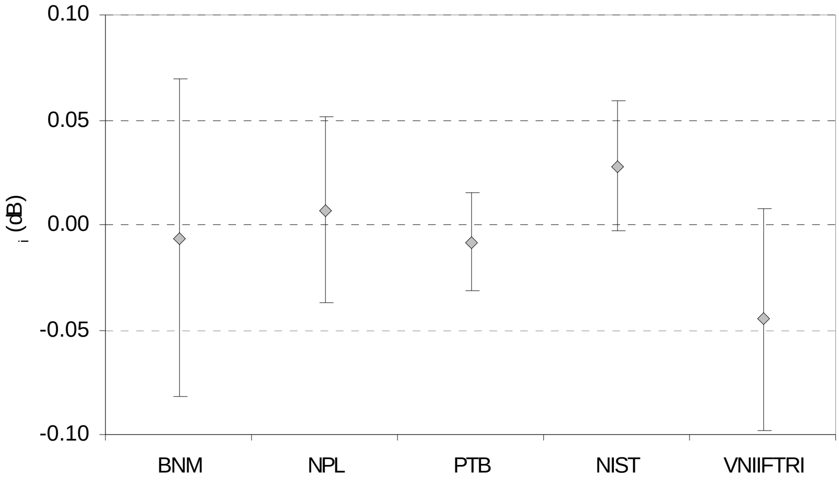

Figure 8.2.2.a: TSB1 output adapter PC-7/R140, F = 13.5 GHz, weighted

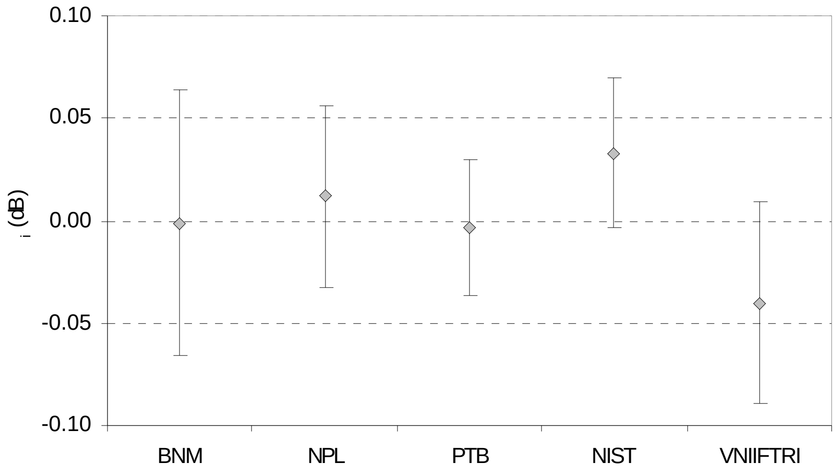

Figure 8.2.2.b: TSB1 output adapter PC-7/R140, F = 13.5 GHz, unweighted

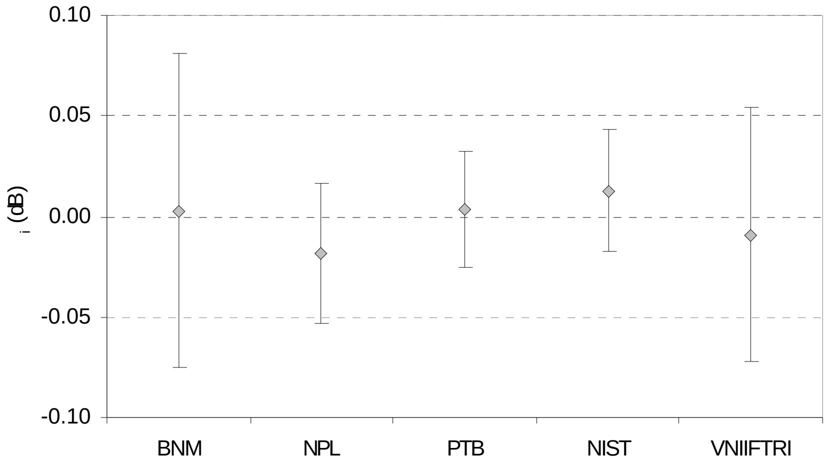

Figure 8.2.3.a: TSB1 output adapter PC-7/R140, F = 15 GHz, weighted

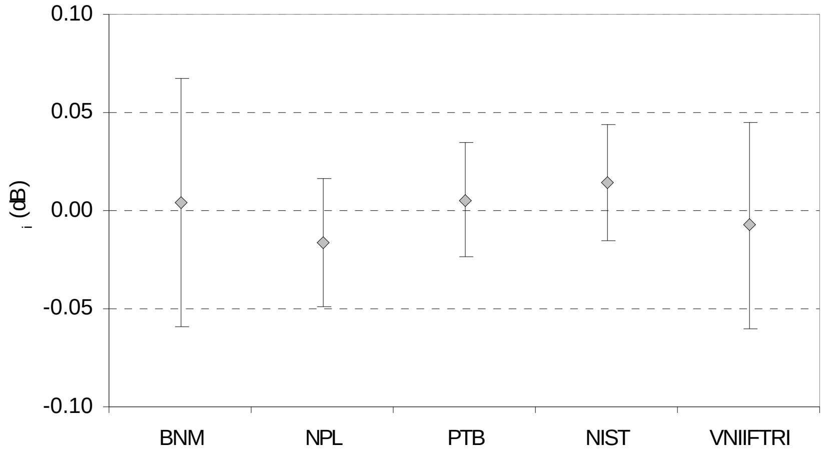

Figure 8.2.3.b: TSB1 output adapter PC-7/R140, F = 15 GHz, unweighted

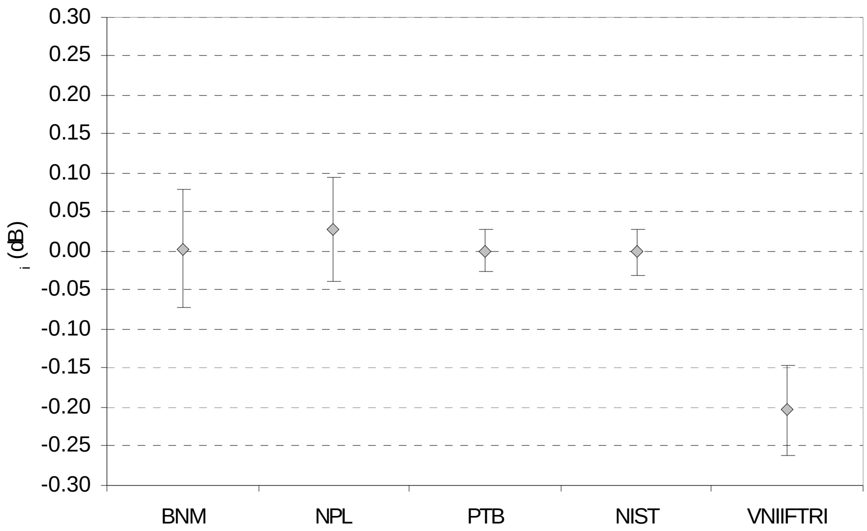

Figure 8.2.4.a: TSB1 output adapter PC-7/R140, F = 17.5 GHz, weighted

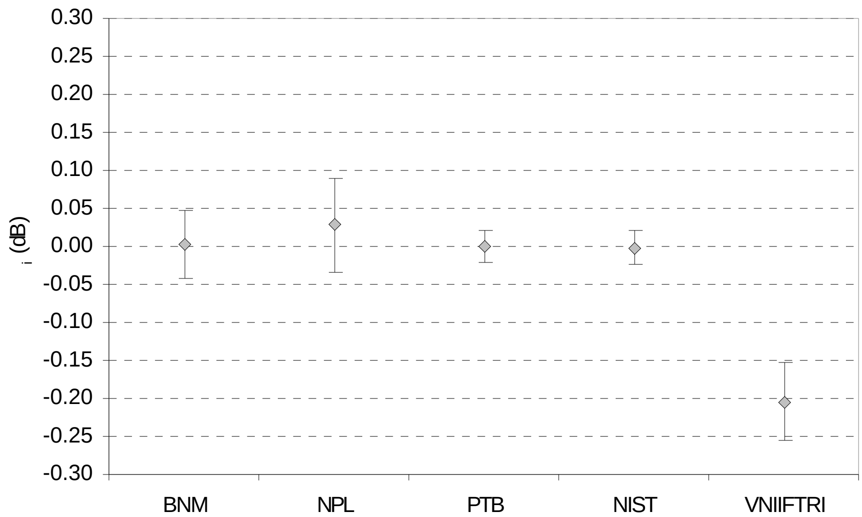

Figure 8.2.4.b: TSB1 output adapter PC-7/R140, F = 17.5 GHz, unweighted

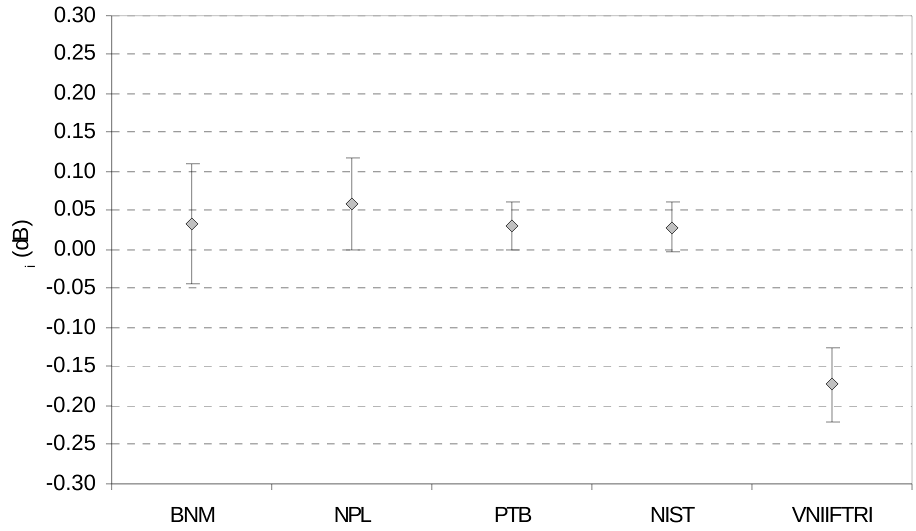

Figure 8.2.4.c: TSB1 output adapter PC-7/R140, F = 17.5 GHz, weighted, outliers included

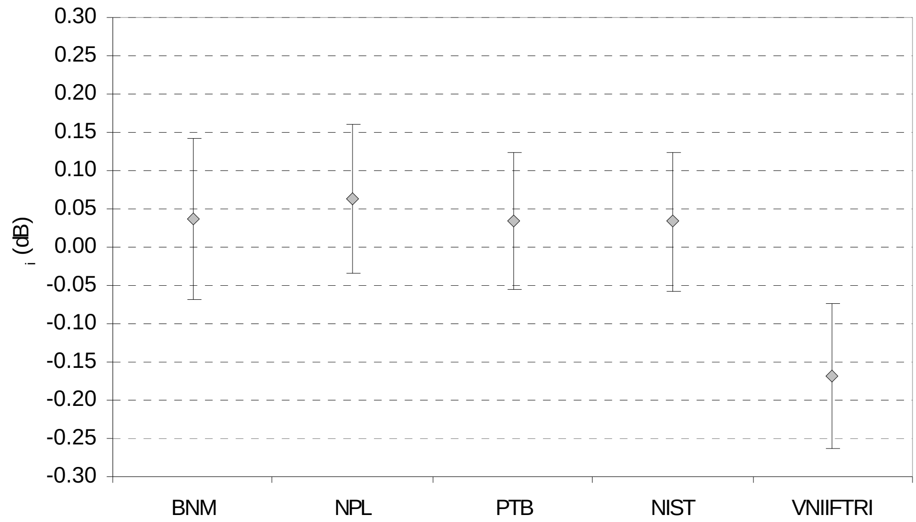

Figure 8.2.4.d: TSB1 output adapter PC-7/R140, F = 17.5 GHz, unweighted, outliers included

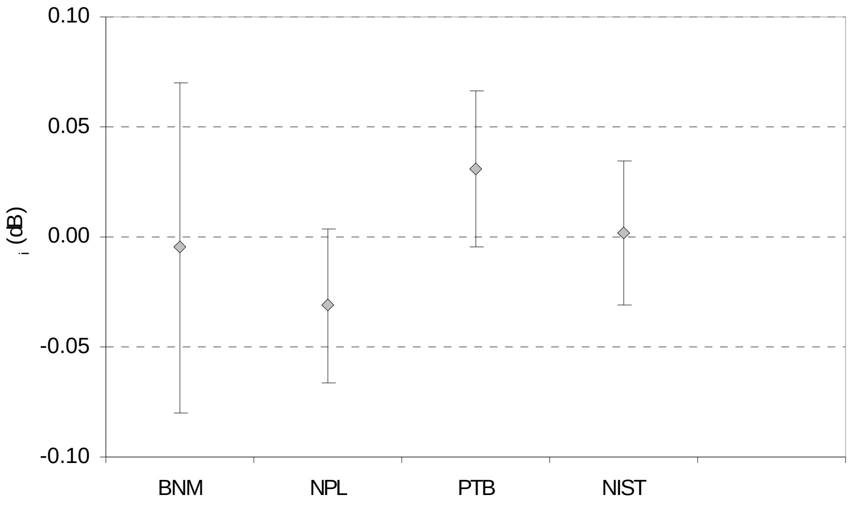

Figure 8.2.5.a: TSB1 output adapter PC-7/R140, F = 18 GHz, weighted

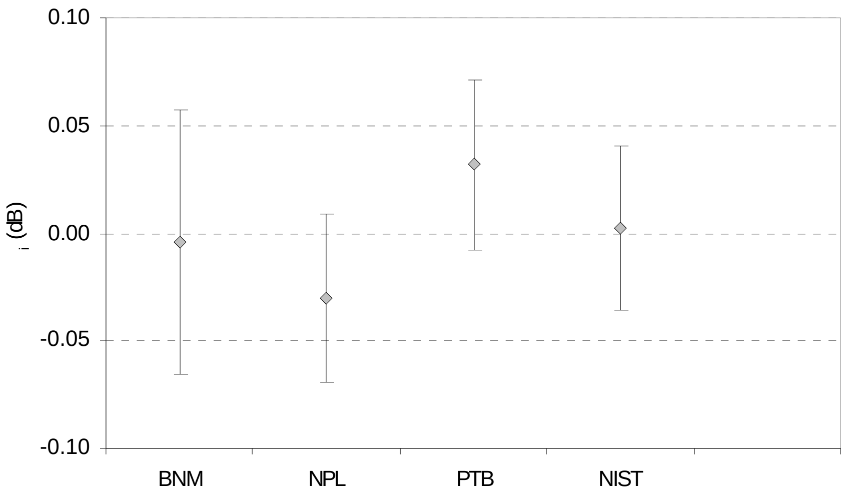

Figure 8.2.5.b: TSB1 output adapter PC-7/R140, F = 18 GHz, unweighted

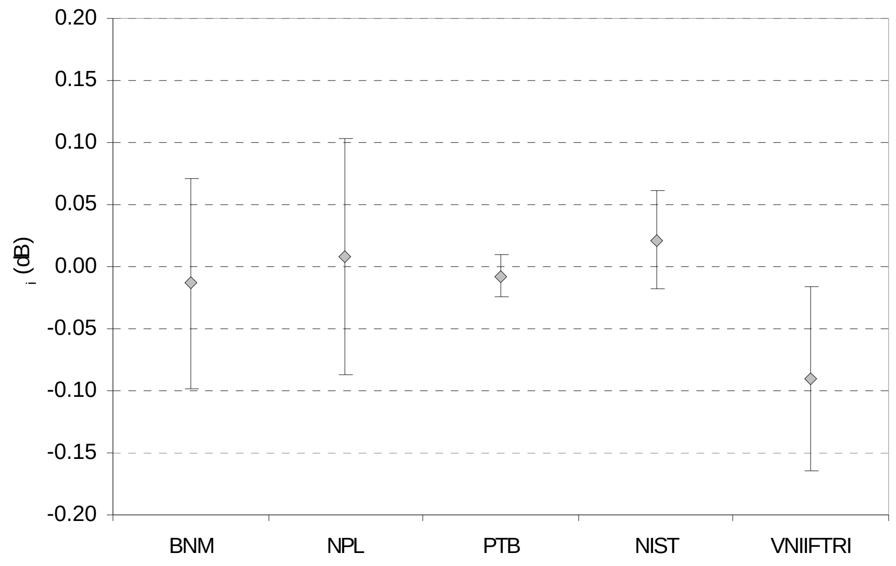

Figure 8.3.1.a: TSB1 output connector PC-7, F = 12.4 GHz, weighted

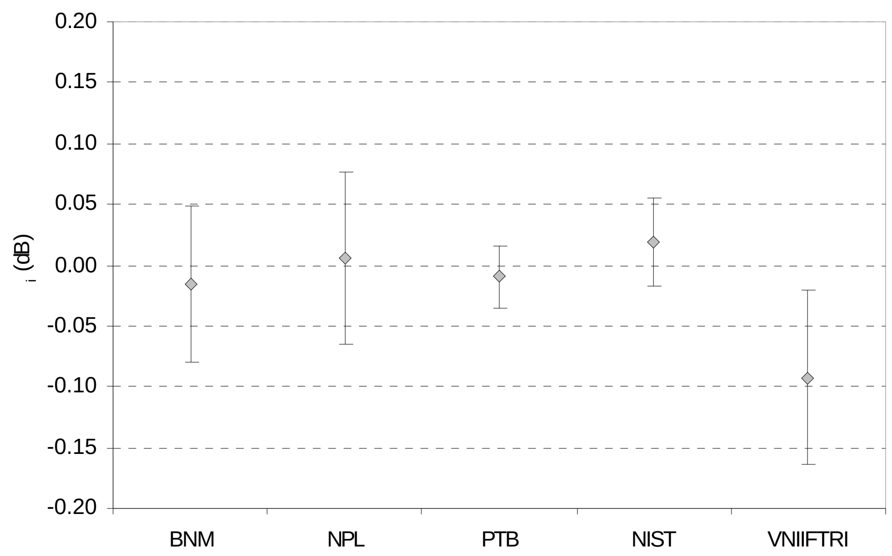

Figure 8.3.1.b: TSB1 output connector PC-7, F = 12.4 GHz, unweighted

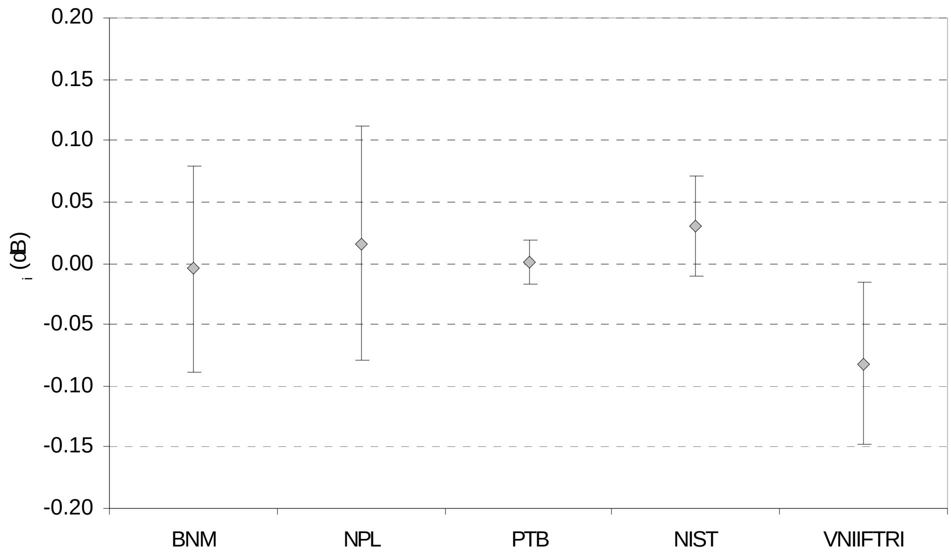

Figure 8.3.1.c: TSB1 output connector PC-7, F = 12.4 GHz, weighted, outliers included

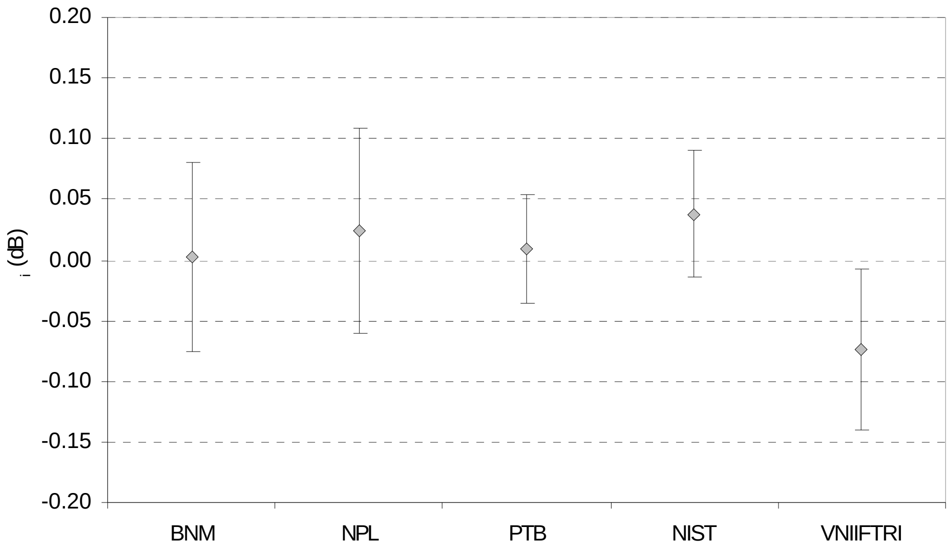

Figure 8.3.1.d: TSB1 output connector PC-7, F = 12.4 GHz, unweighted, outliers included

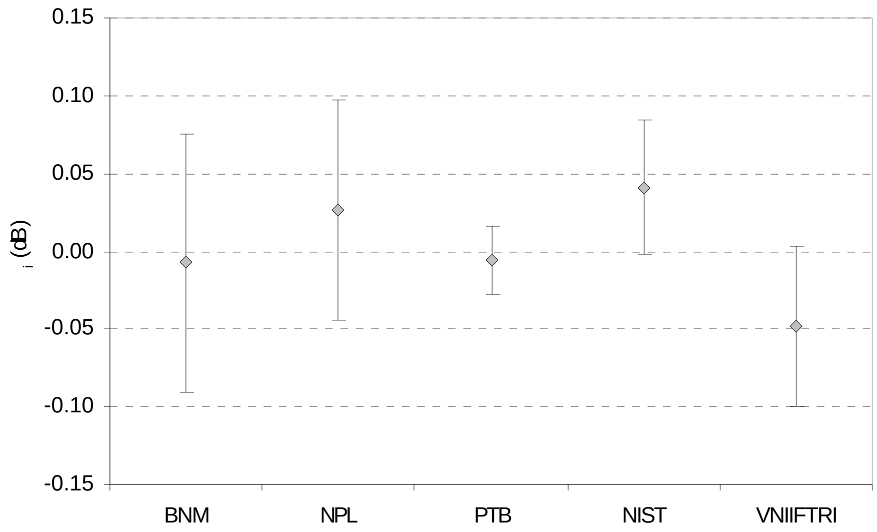

Figure 8.3.2.a: TSB1 output connector PC-7, F = 13.5 GHz, weighted

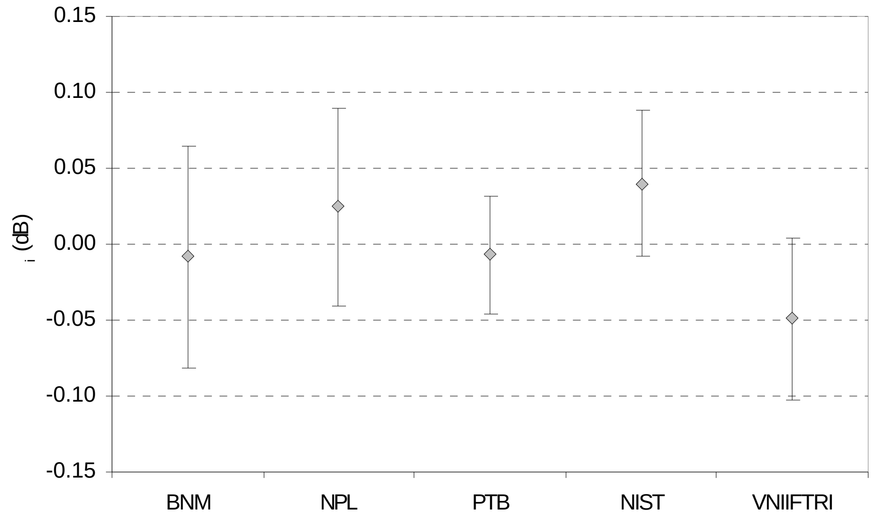

Figure 8.3.2.b: TSB1 output connector PC-7, F = 13.5 GHz, unweighted

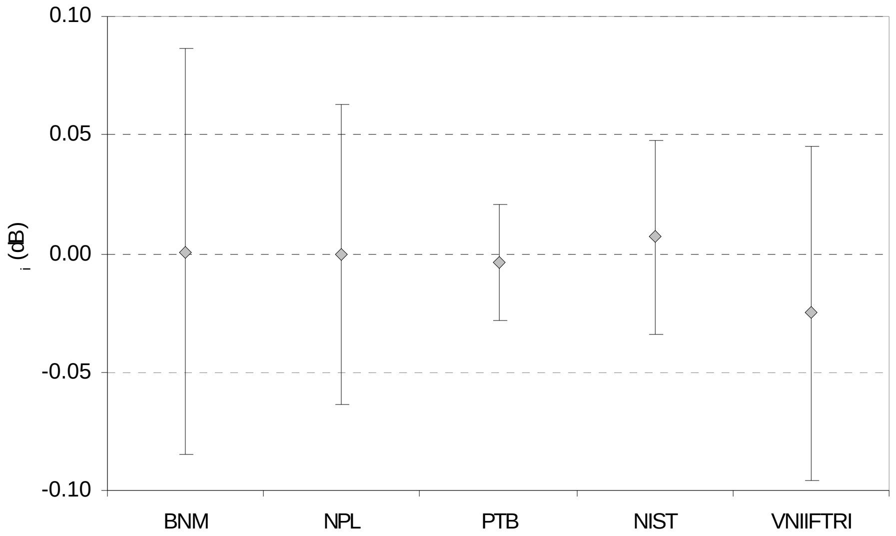

Figure 8.3.3.a: TSB1 output connector PC-7, F = 15 GHz, weighted

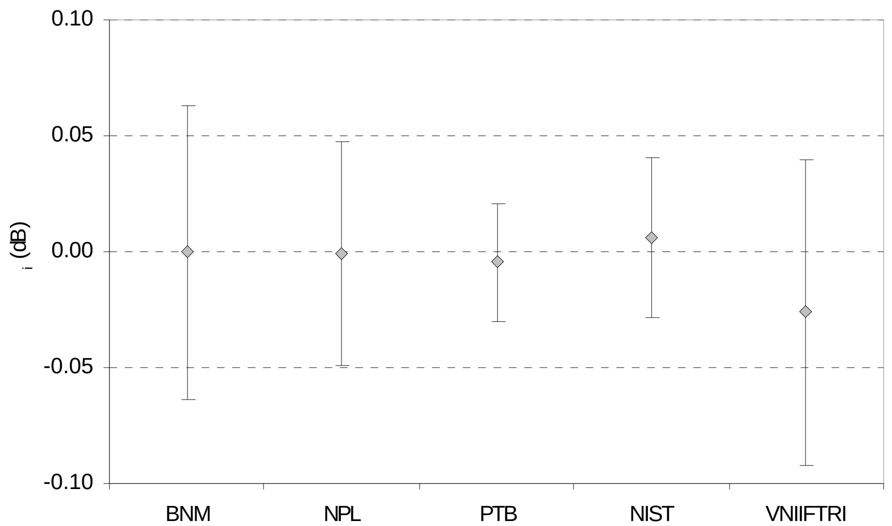

Figure 8.3.3.b: TSB1 output connector PC-7, F = 15 GHz, unweighted

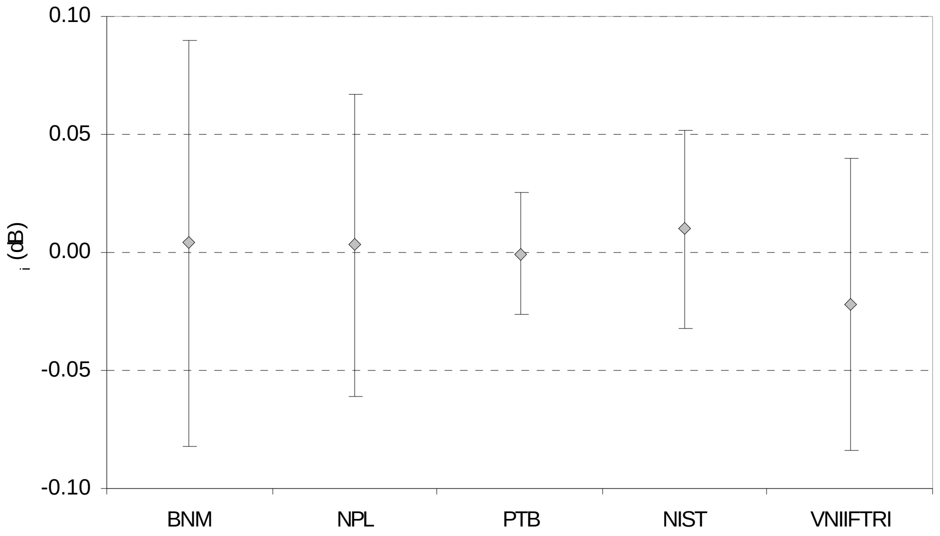

Figure 8.3.3.c: TSB1 output connector PC-7, F = 15 GHz, weighted, outliers included

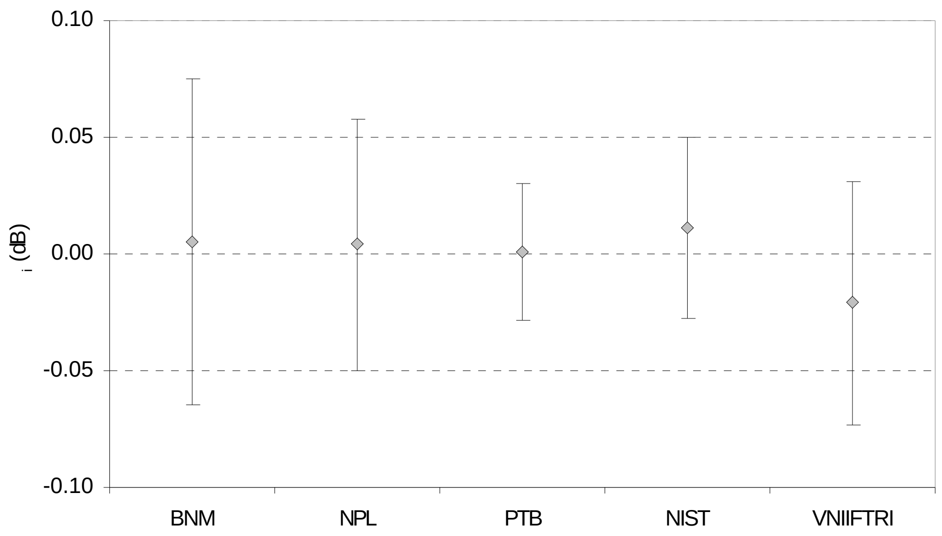

Figure 8.3.3.d: TSB1 output connector PC-7, F = 15 GHz, unweighted, outliers included

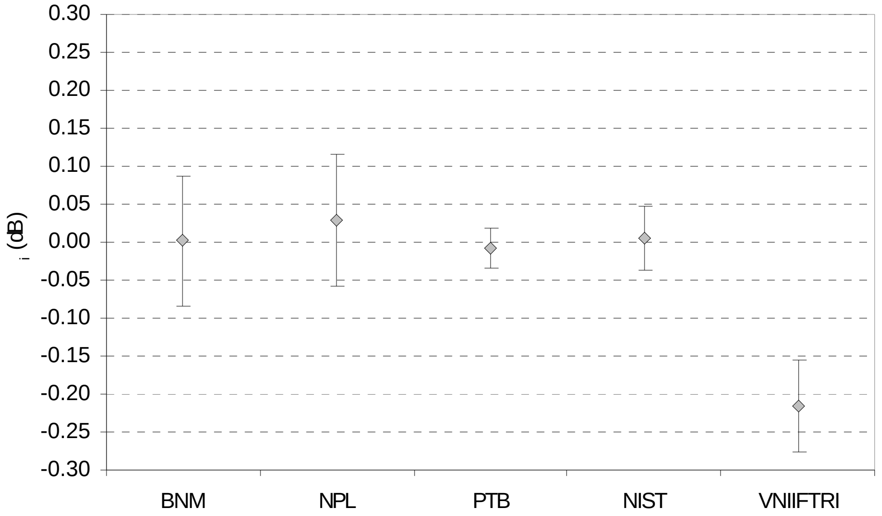

Figure 8.3.4.a: TSB1 output connector PC-7, F = 17.5 GHz, weighted

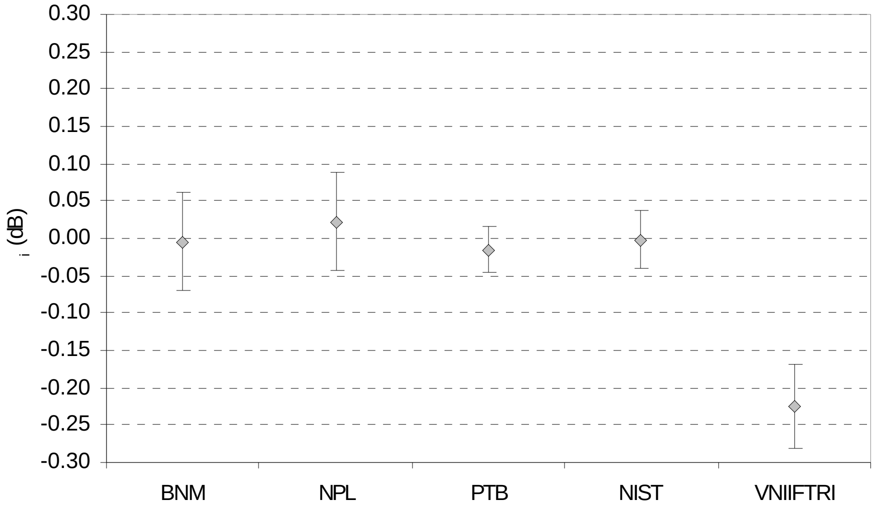

Figure 8.3.4.b: TSB1 output connector PC-7, F = 17.5 GHz, unweighted

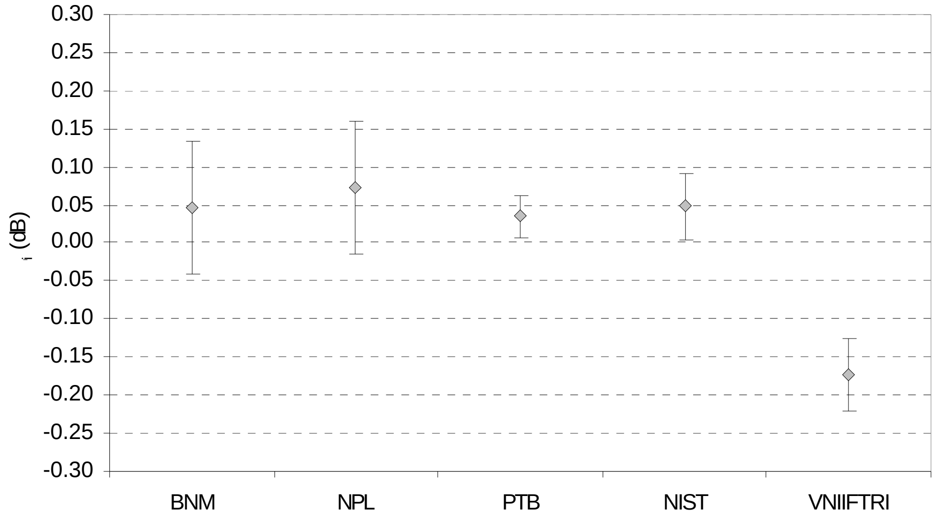

Figure 8.3.4.c: TSB1 output connector PC-7, F = 17.5 GHz, weighted, outliers included

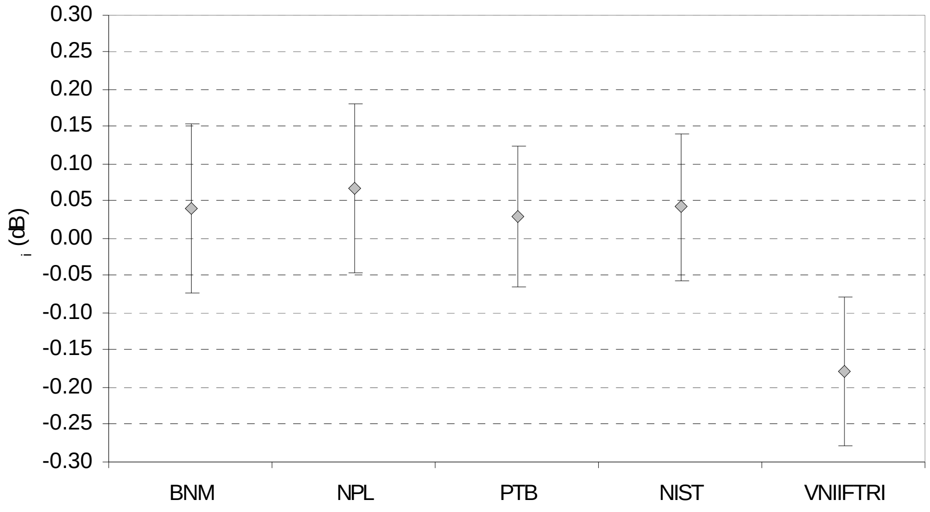

Figure 8.3.4.d: TSB1 output connector PC-7, F = 17.5 GHz, unweighted, outliers included

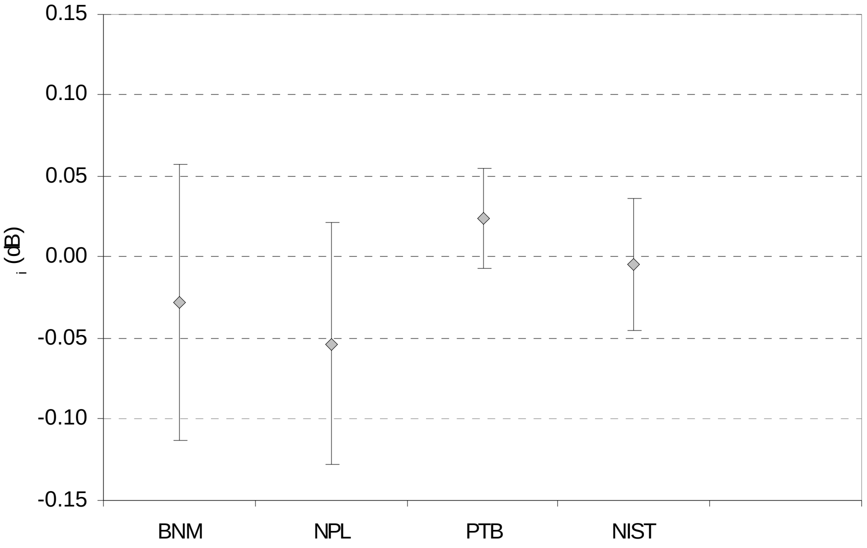

Figure 8.3.5.a: TSB1 output connector PC-7, F = 18 GHz, weighted

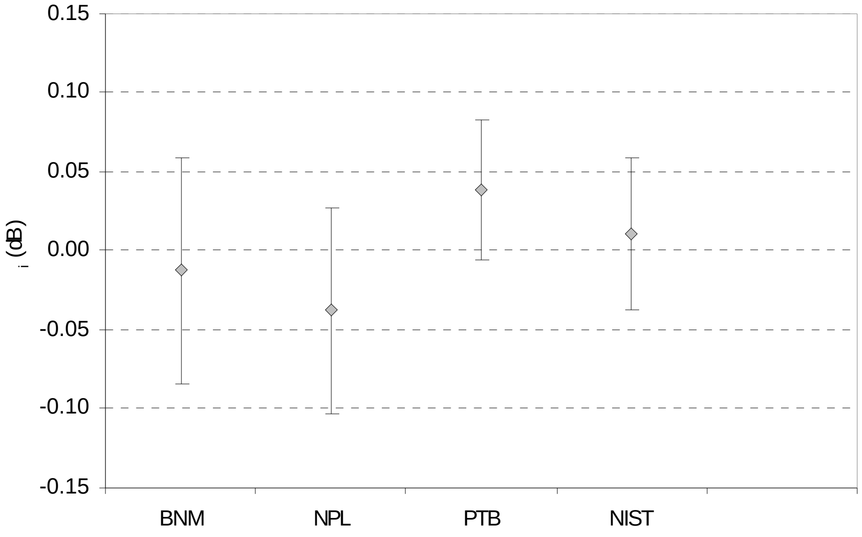

Figure 8.3.5.b: TSB1 output connector PC-7, F = 18 GHz, unweighted

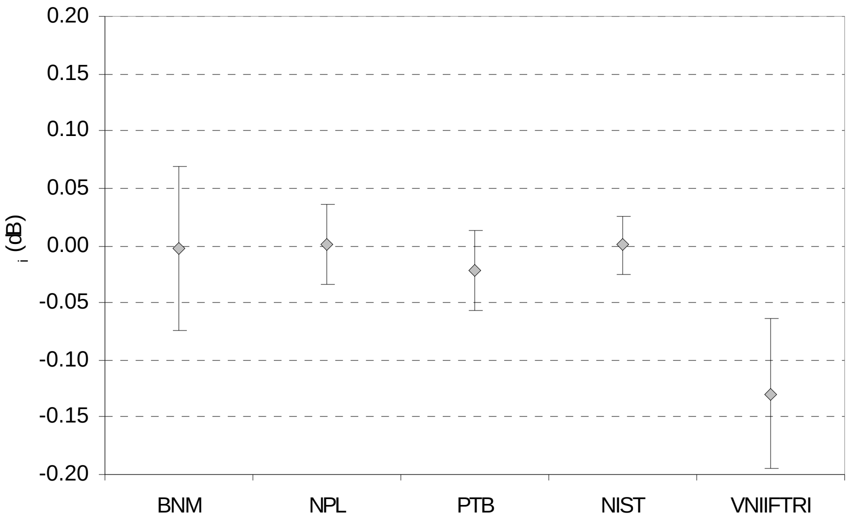

Figure 8.4.1.a: TSA2 output flange R140, F = 12.4 GHz, weighted

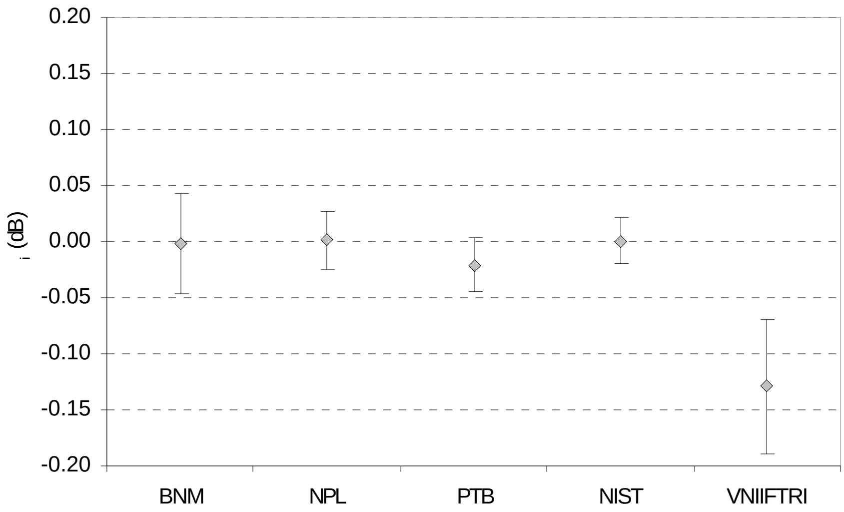

Figure 8.4.1.b: TSA2 output flange R140, F = 12.4 GHz, unweighted

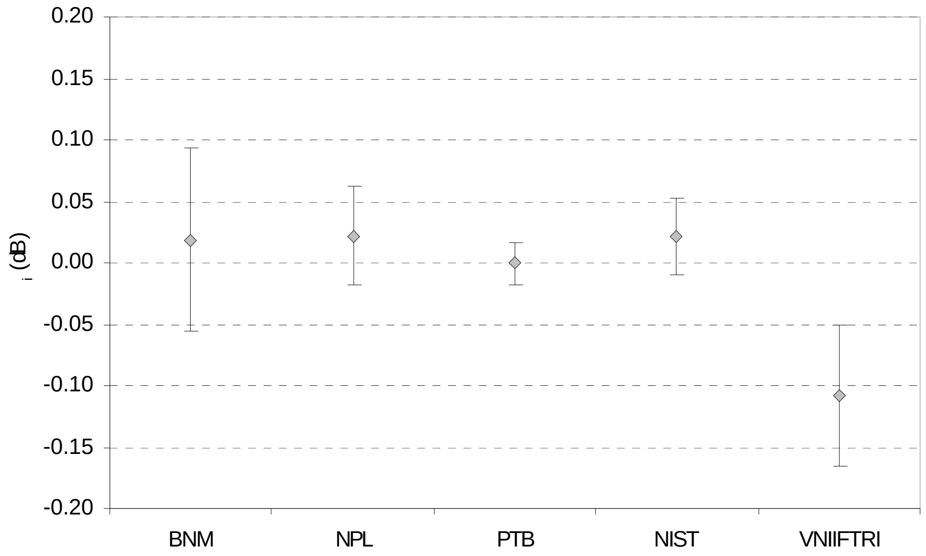

Figure 8.4.1.c: TSA2 output flange R140, F = 12.4 GHz, weighted, outliers included

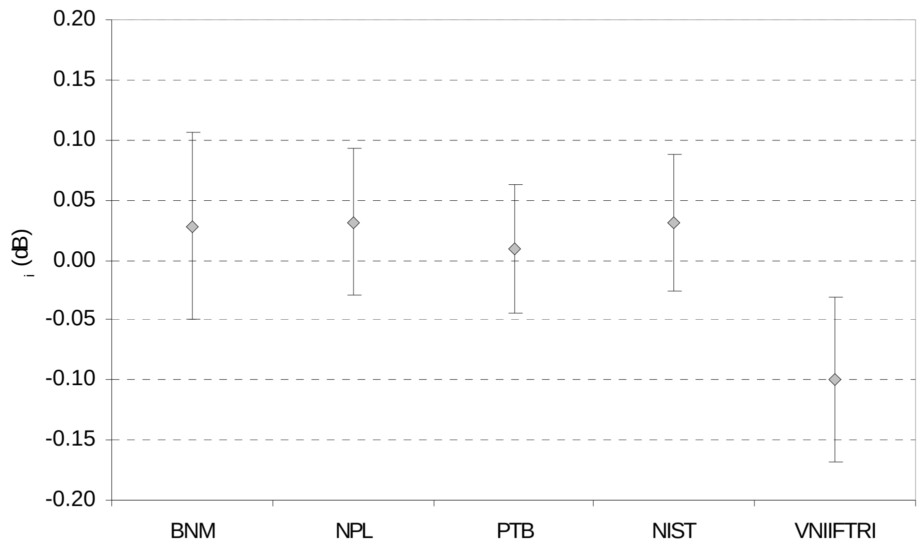

Figure 8.4.1.d: TSA2 output flange R140, F = 12.4 GHz, unweighted, outliers included

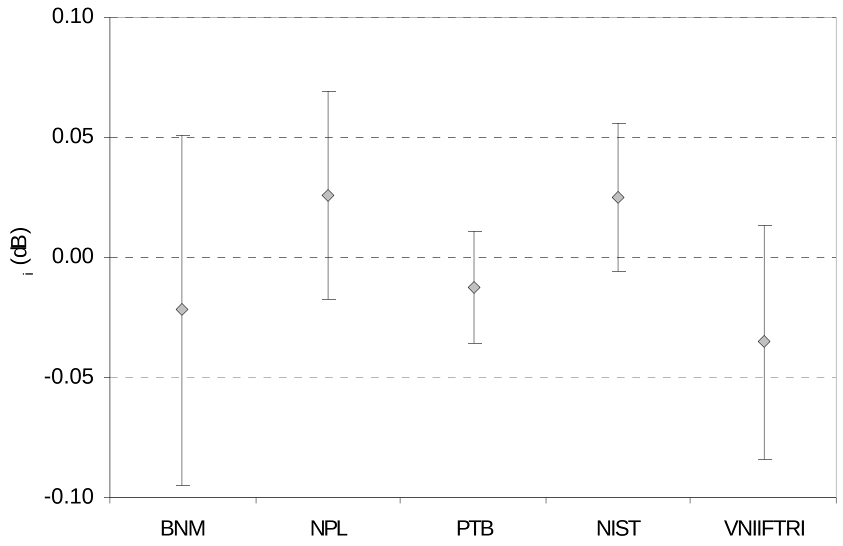

Figure 8.4.2.a: TSA2 output flange R140, F = 13.5 GHz, weighted

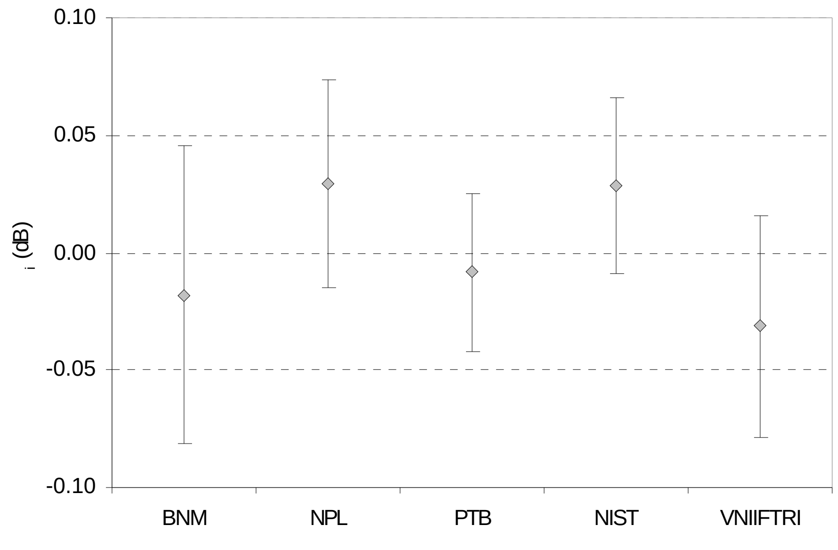

Figure 8.4.2.b: TSA2 output flange R140, F = 13.5 GHz, unweighted

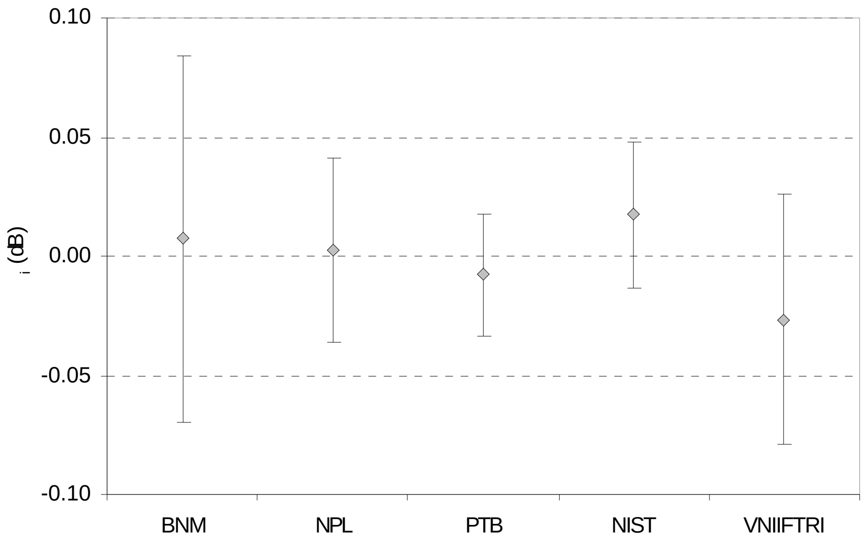

Figure 8.4.3.a: TSA2 output flange R140, F = 15 GHz, weighted

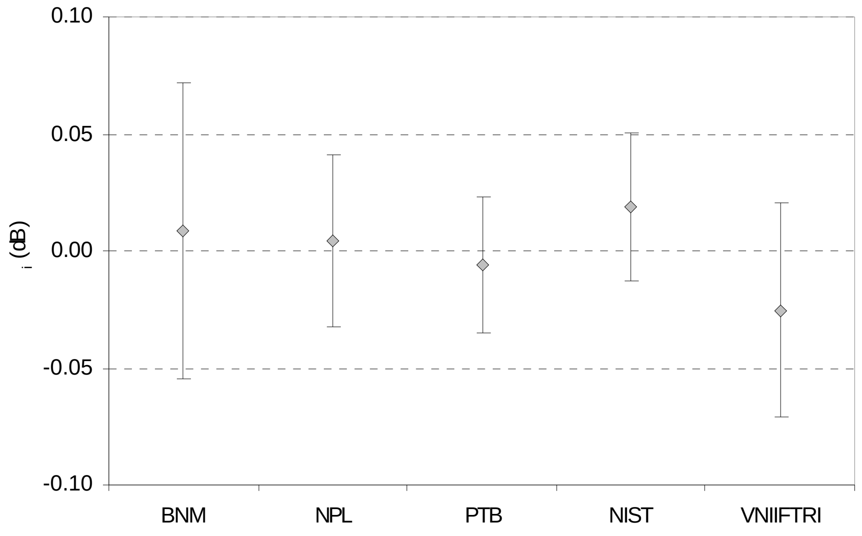

Figure 8.4.3.b: TSA2 output flange R140, F = 15 GHz, unweighted

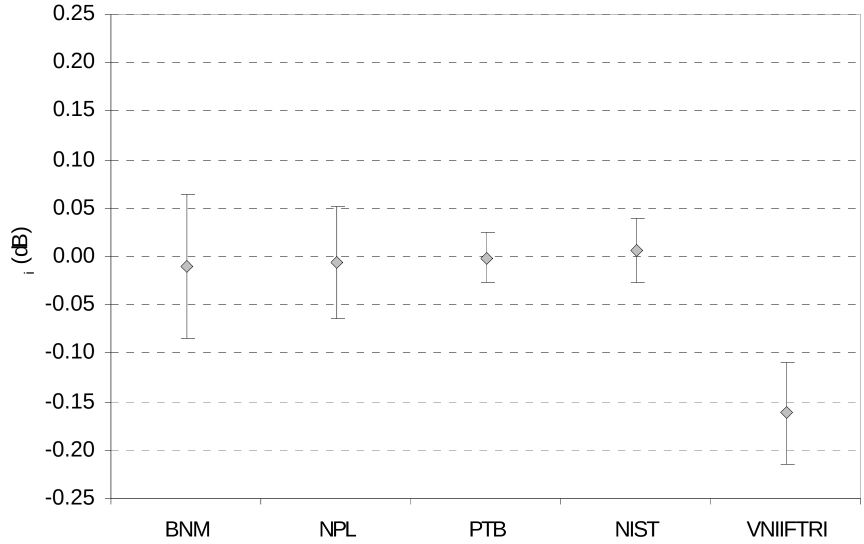

Figure 8.4.4.a: TSA2 output flange R140, F = 17.5 GHz, weighted

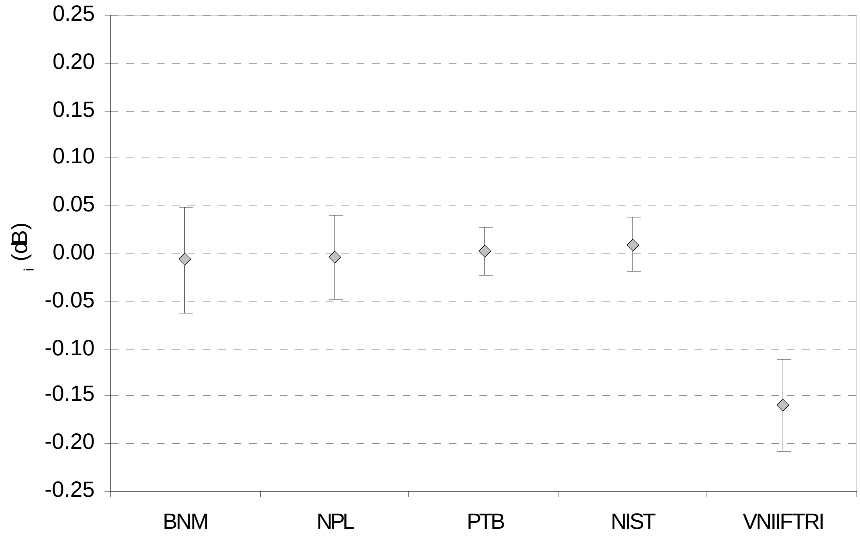

Figure 8.4.4.b: TSA2 output flange R140, F = 17.5 GHz, unweighted

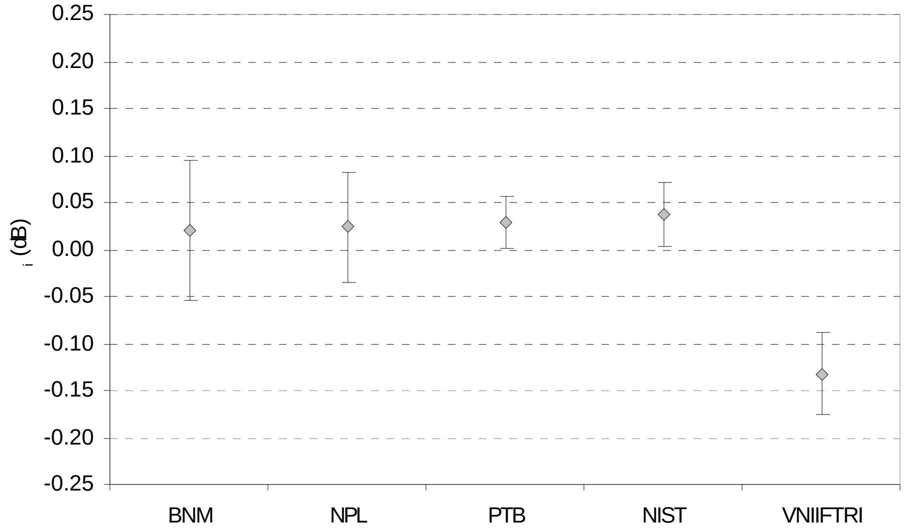

Figure 8.4.4.c: TSA2 output flange R140, F = 17.5 GHz, weighted, outliers included

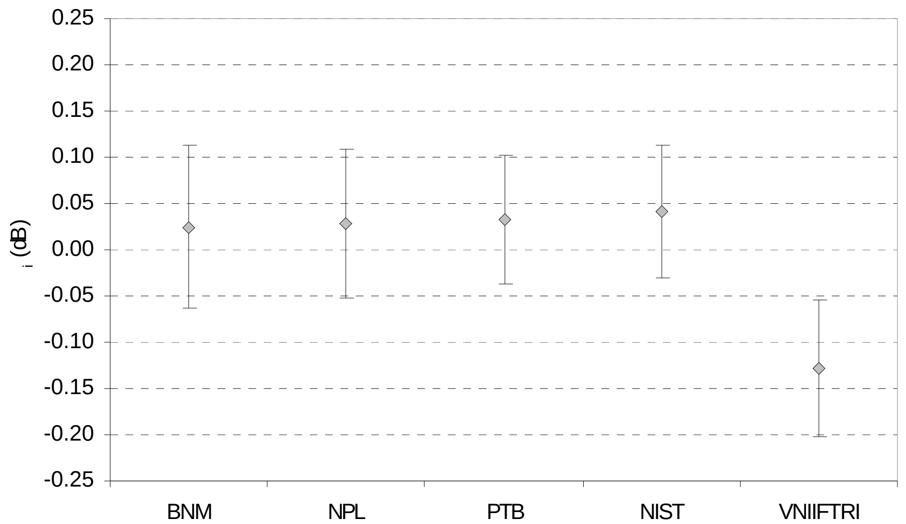

Figure 8.4.4.d: TSA2 output flange R140, F = 17.5 GHz, unweighted, outliers included

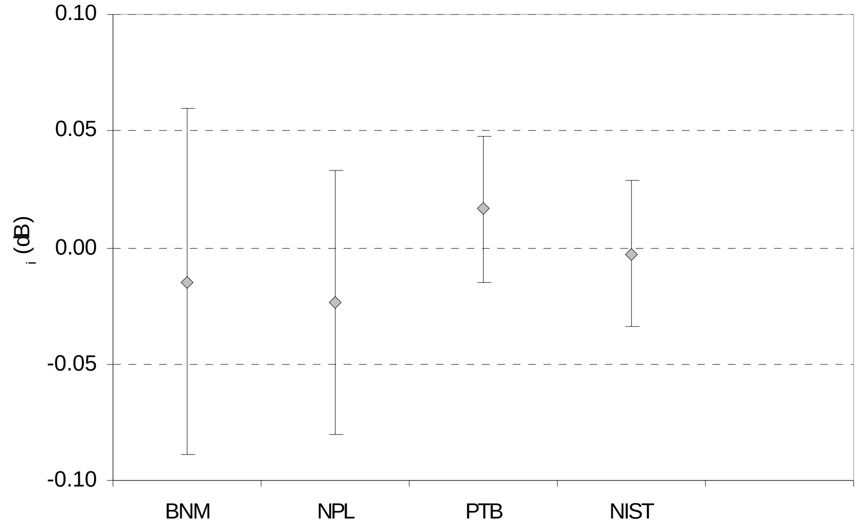

Figure 8.4.5.a: TSA2 output flange R140, F = 18 GHz, weighted

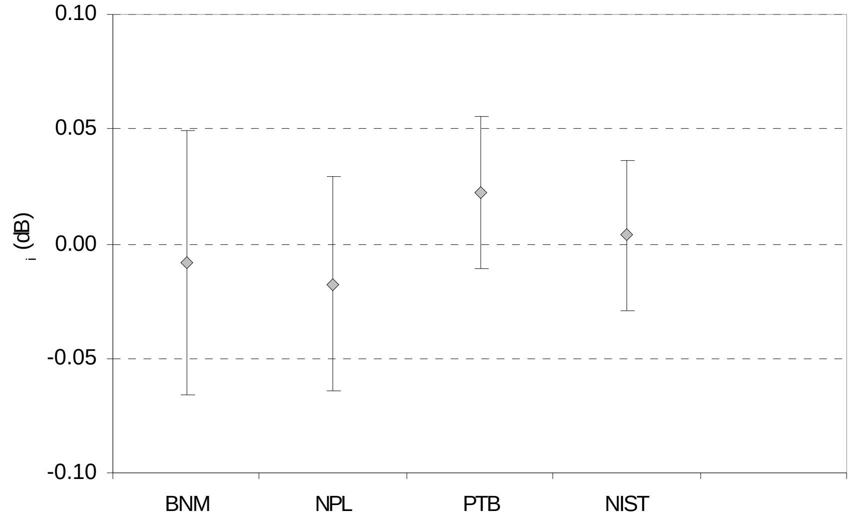

Figure 8.4.5.b: TSA2 output flange R140, F = 18 GHz, unweighted

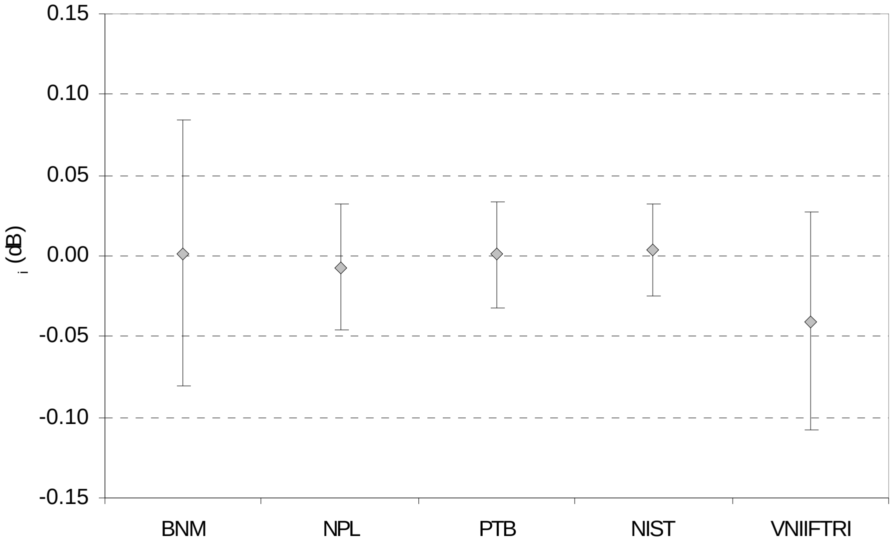

Figure 8.5.1.a: TSB2 output adapter PC-7/R140, F = 12.4 GHz, weighted

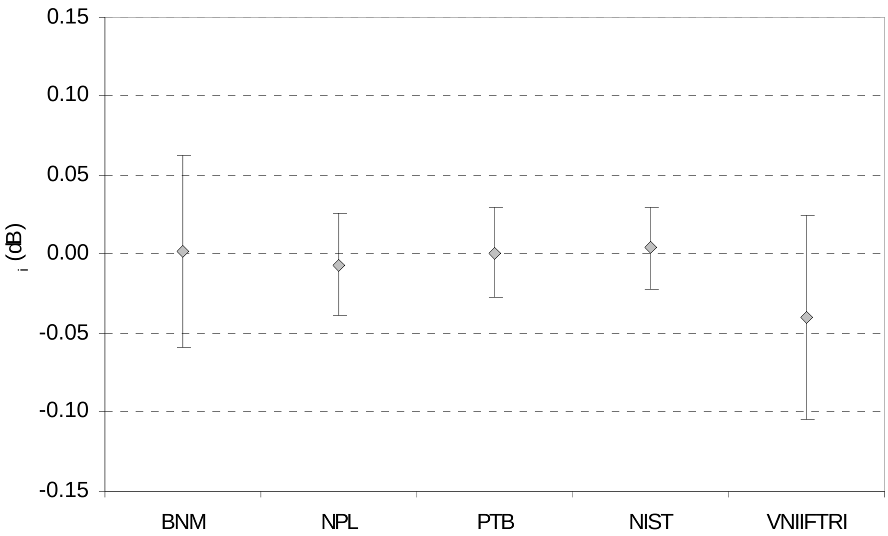

Figure 8.5.1.b: TSB2 output adapter PC-7/R140, F = 12.4 GHz, unweighted

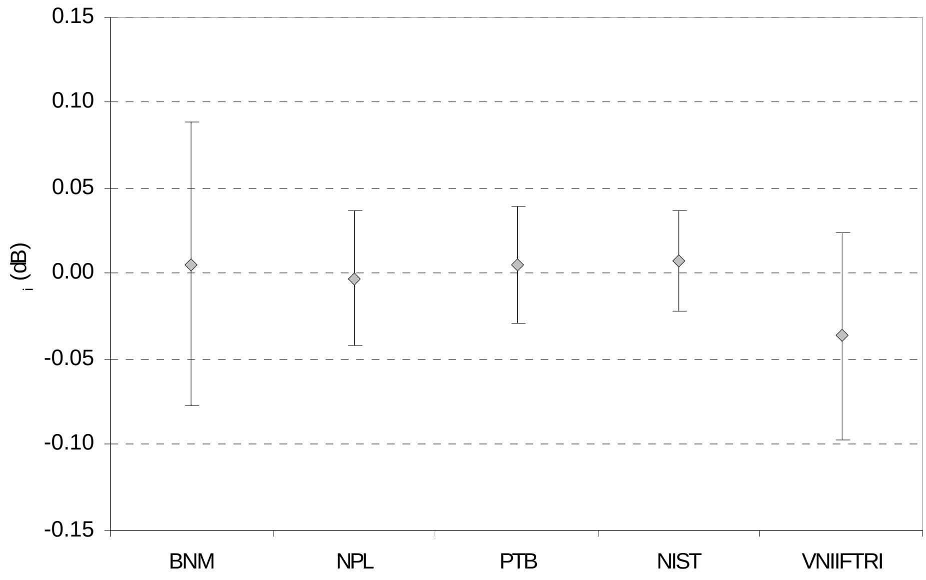

Figure 8.5.1.c: TSB2 output adapter PC-7/R140, F = 12.4 GHz, weighted, outliers included

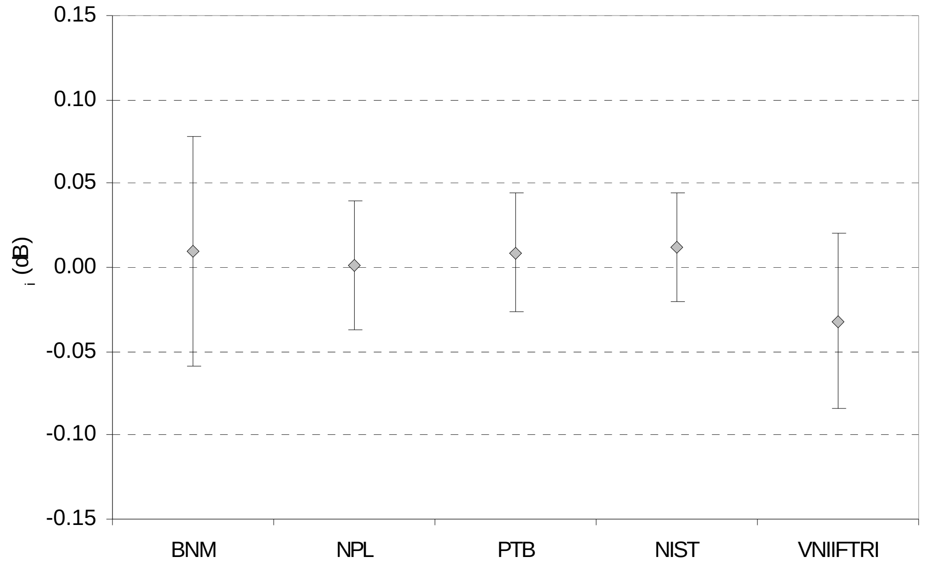

Figure 8.5.1.d: TSB2 output adapter PC-7/R140, F = 12.4 GHz, unweighted, outliers included

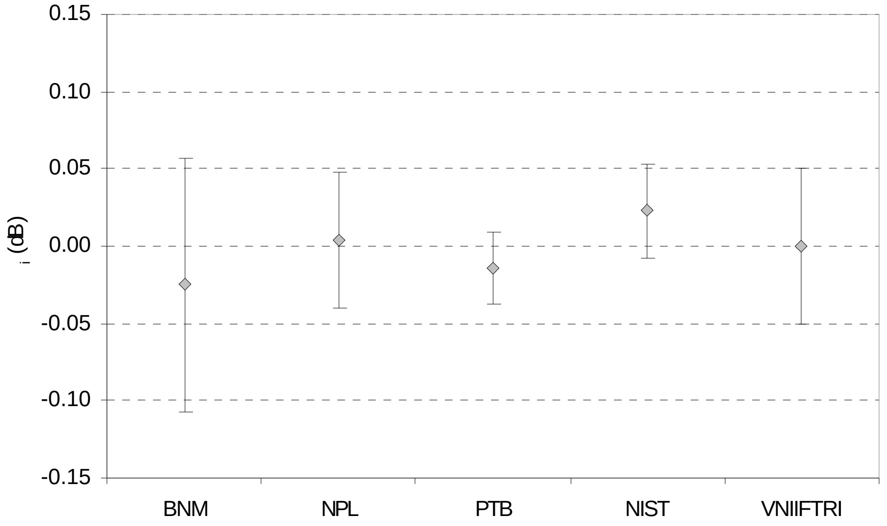

Figure 8.5.2.a: TSB2 output adapter PC-7/R140, F = 13.5 GHz, weighted

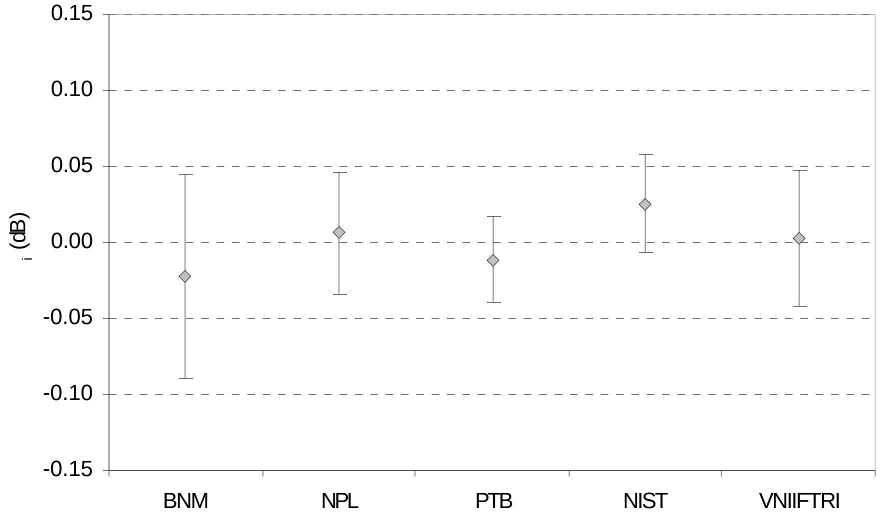

Figure 8.5.2.b: TSB2 output adapter PC-7/R140, F = 13.5 GHz, unweighted

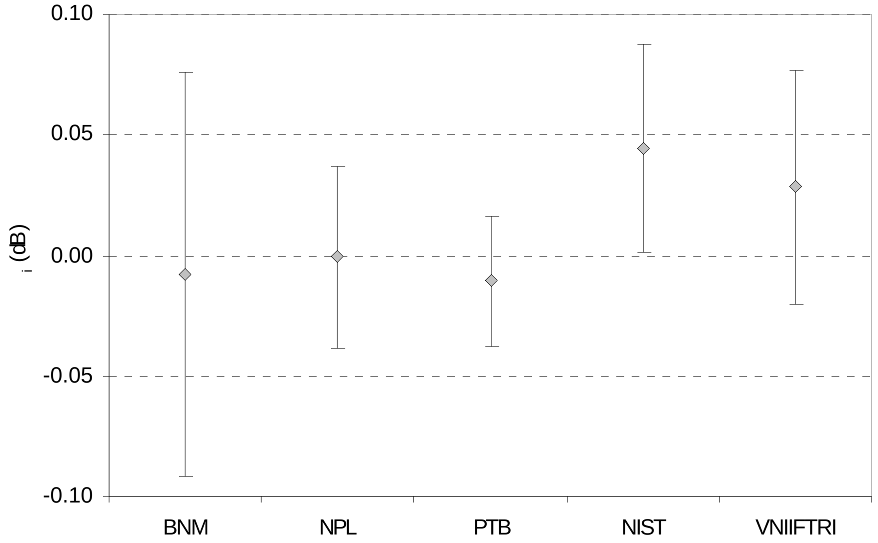

Figure 8.5.3.a: TSB2 output adapter PC-7/R140, F = 15 GHz, weighted

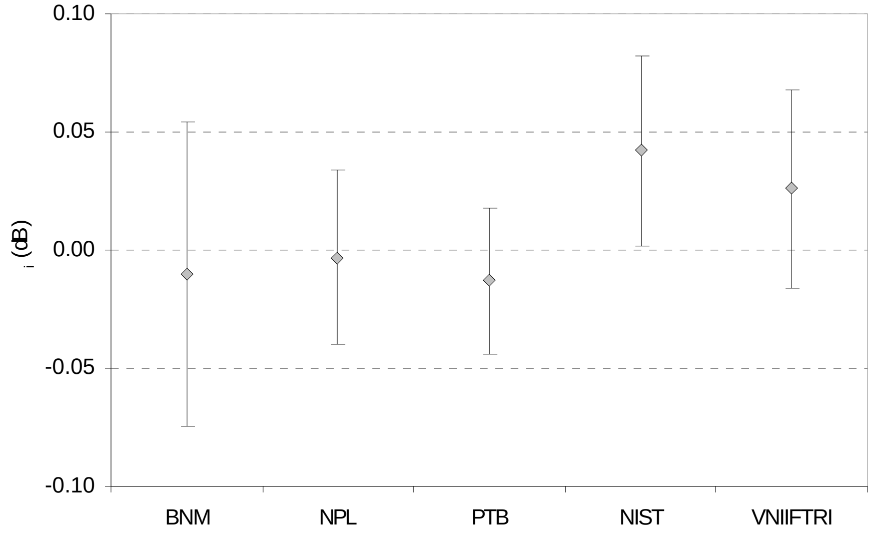

Figure 8.5.3.b: TSB2 output adapter PC-7/R140, F = 15 GHz, unweighted

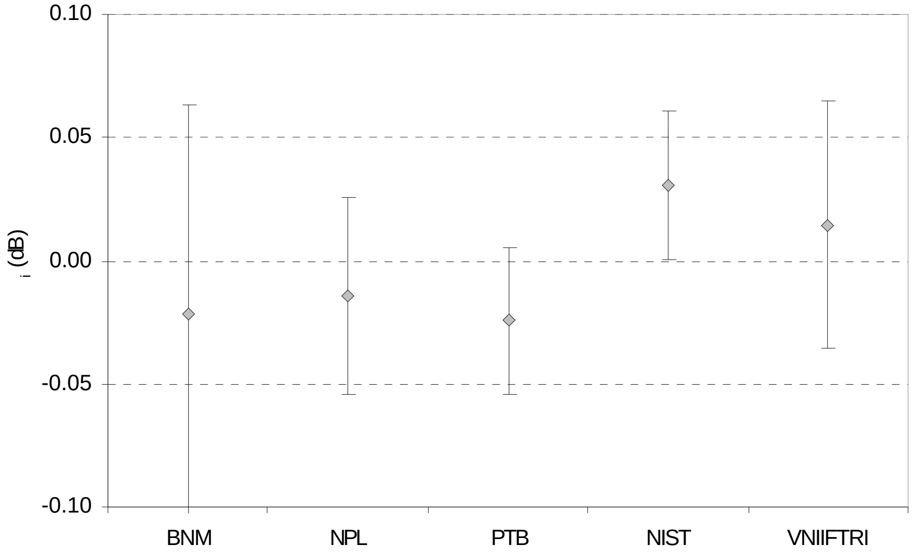

Figure 8.5.3.c: TSB2 output adapter PC-7/R140, F = 15 GHz, weighted, outliers included

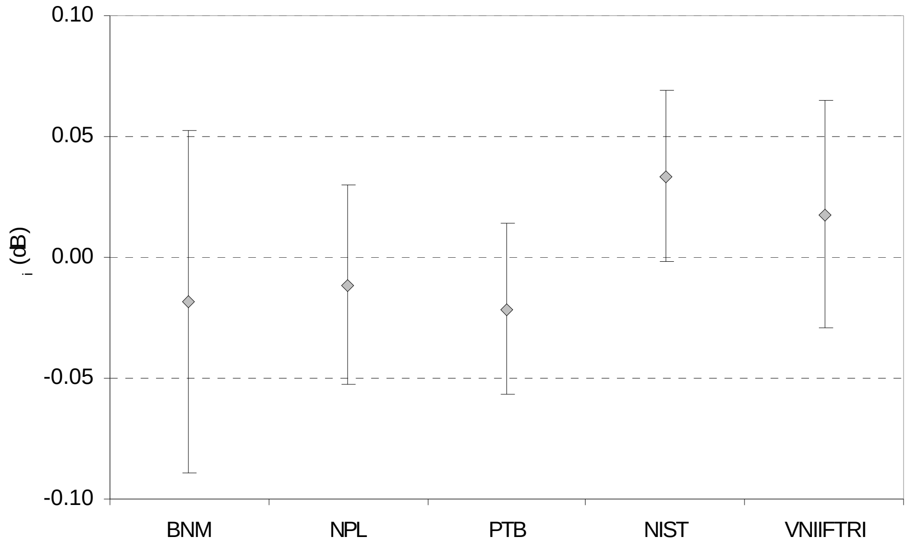

Figure 8.5.3.d: TSB2 output adapter PC-7/R140, F = 15 GHz, unweighted, outliers included

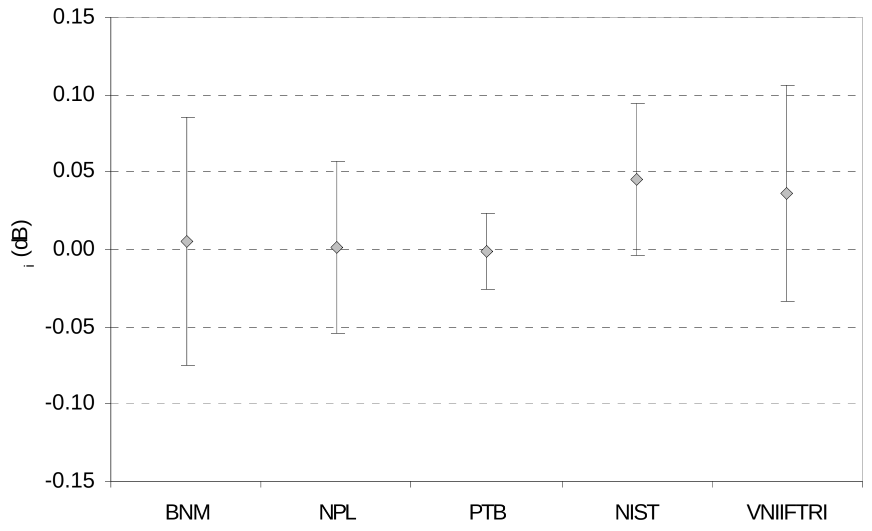

Figure 8.5.4.a: TSB2 output adapter PC-7/R140, F = 17.5 GHz, weighted

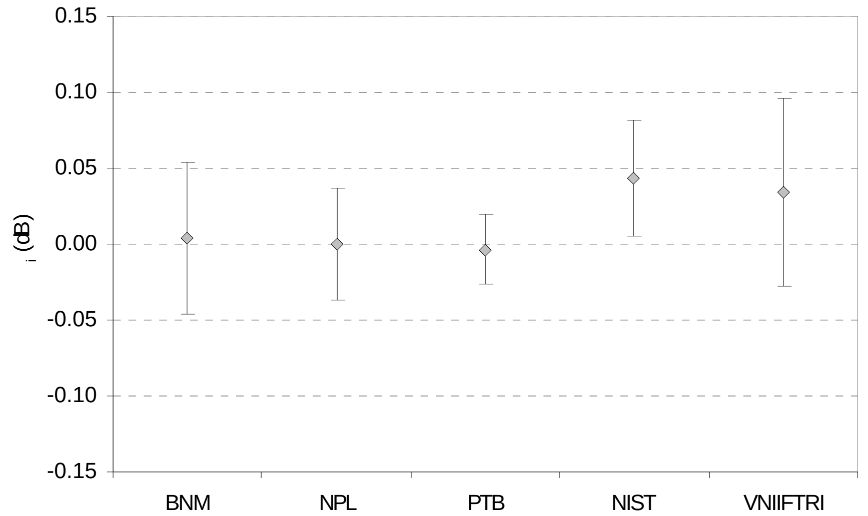

Figure 8.5.4.b: TSB2 output adapter PC-7/R140, F = 17.5 GHz, unweighted

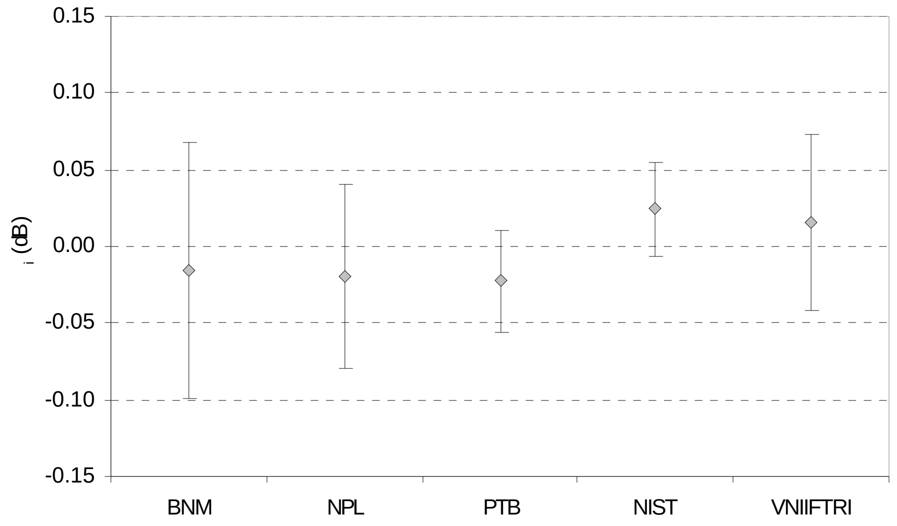

Figure 8.5.4.c: TSB2 output adapter PC-7/R140, F = 17.5 GHz, weighted, outliers included

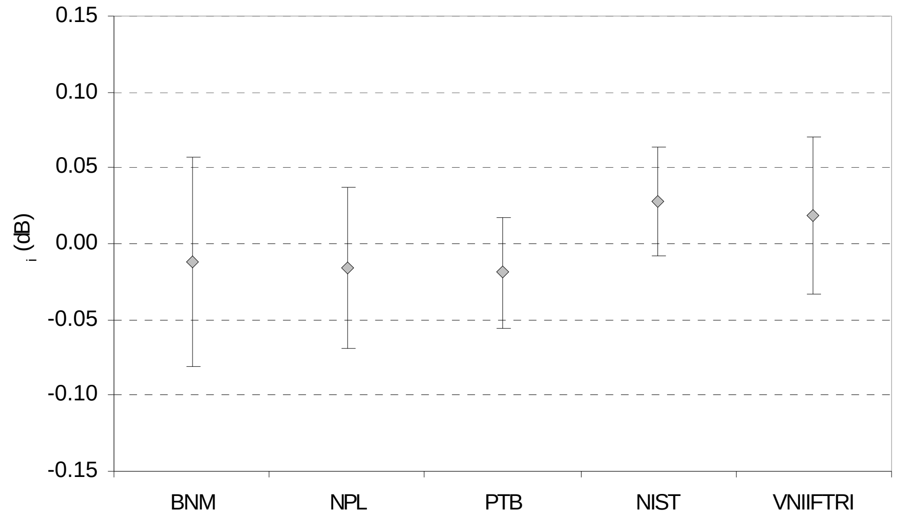

Figure 8.5.4.d: TSB2 output adapter PC-7/R140, F = 17.5 GHz, unweighted, outliers included

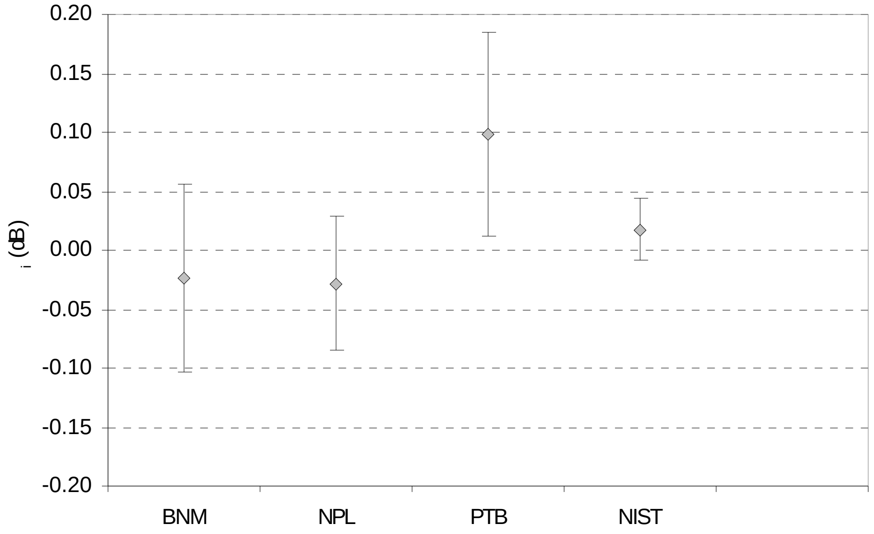

Figure 8.5.5.a: TSB2 output adapter PC-7/R140, F = 18 GHz, weighted

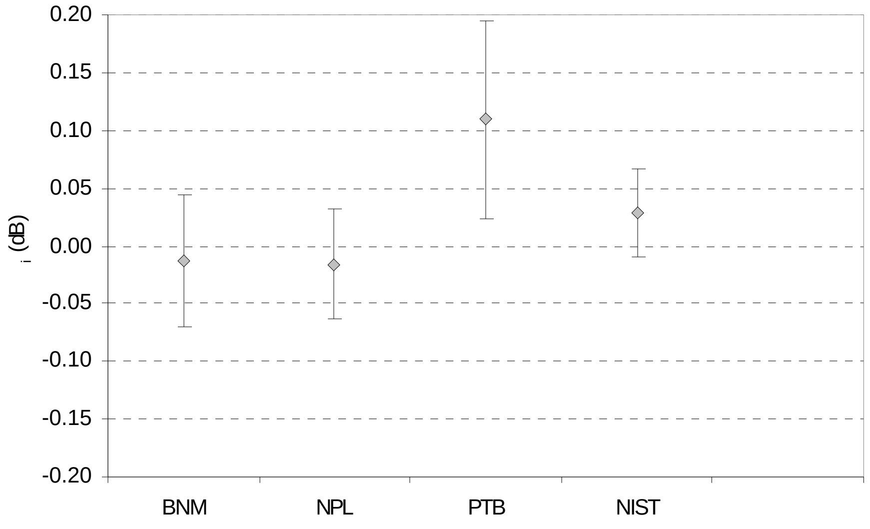

Figure 8.5.5.b: TSB2 output adapter PC-7/R140, F = 18 GHz, unweighted

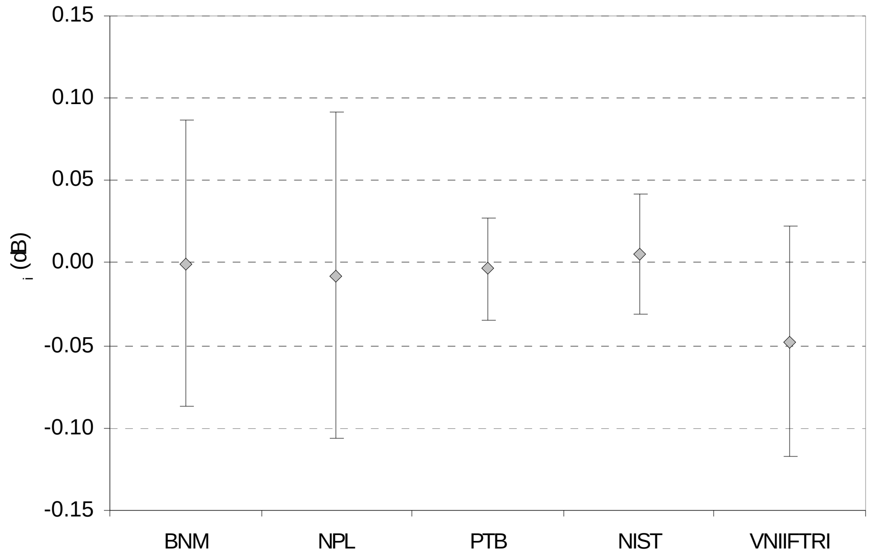

Figure 8.6.1.a: TSB2 output connector PC-7, F = 12.4 GHz, weighted

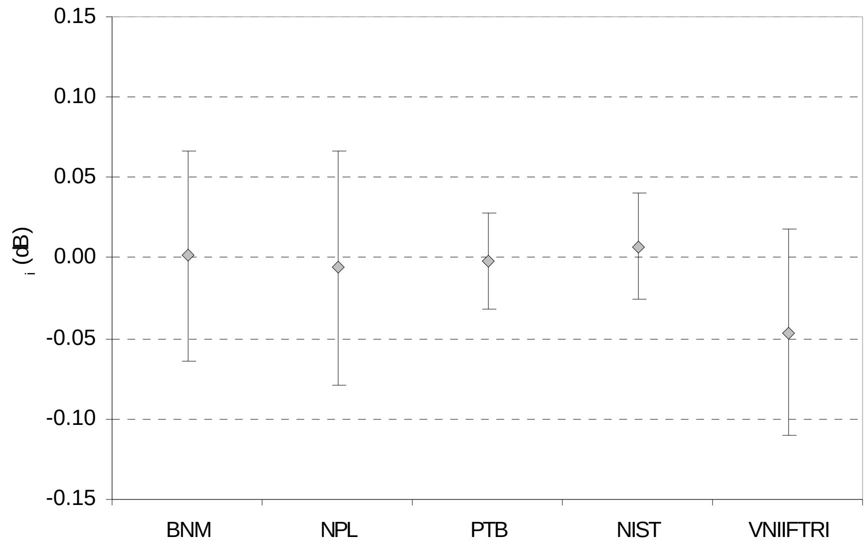

Figure 8.6.1.b: TSB2 output connector PC-7, F = 12.4 GHz, unweighted

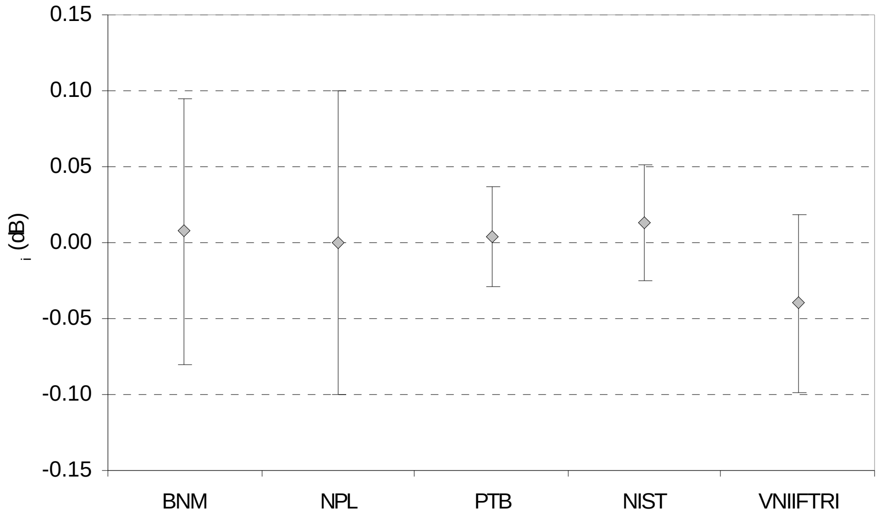

Figure 8.6.1.c: TSB2 output connector PC-7, F = 12.4 GHz, weighted, outliers included

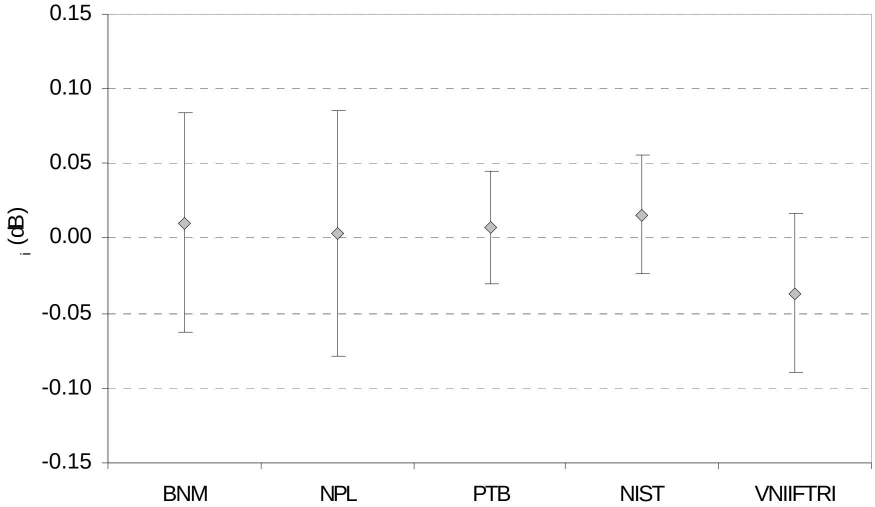

Figure 8.6.1.d: TSB2 output connector PC-7, F = 12.4 GHz, unweighted, outliers included

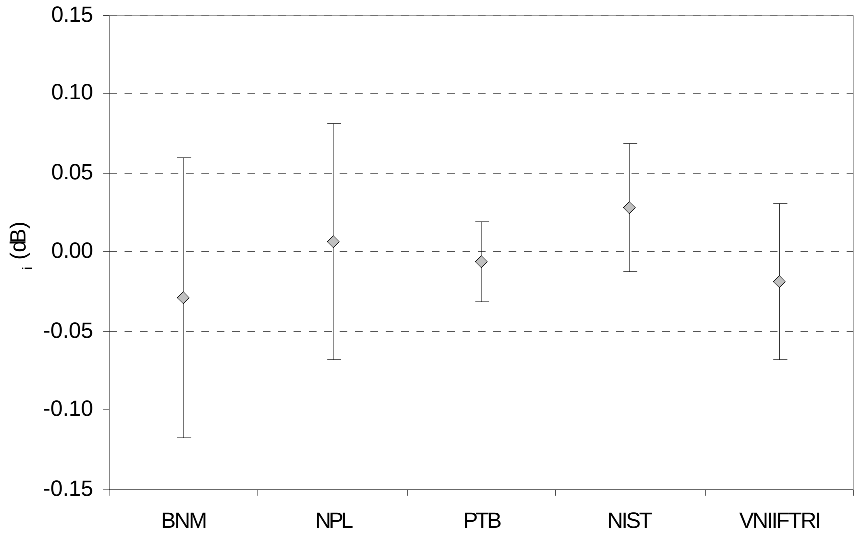

Figure 8.6.2.a: TSB2 output connector PC-7, F = 13.5 GHz, weighted

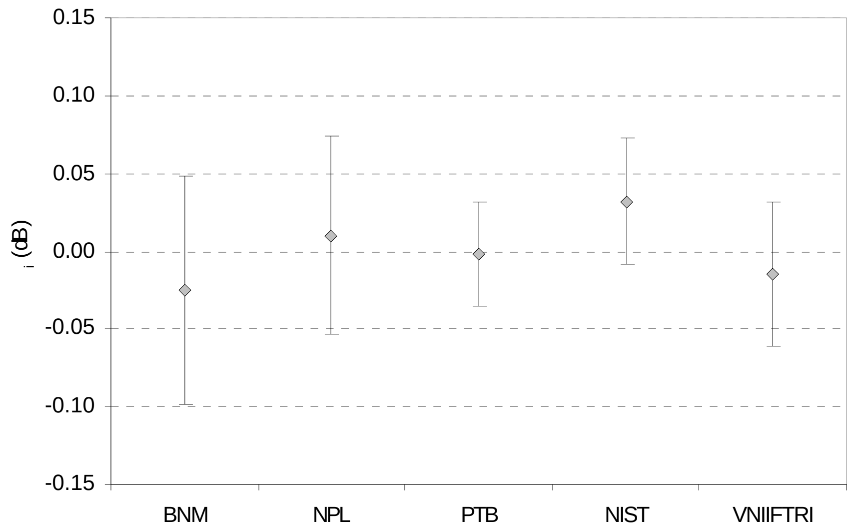

Figure 8.6.2.b: TSB2 output connector PC-7, F = 13.5 GHz, unweighted

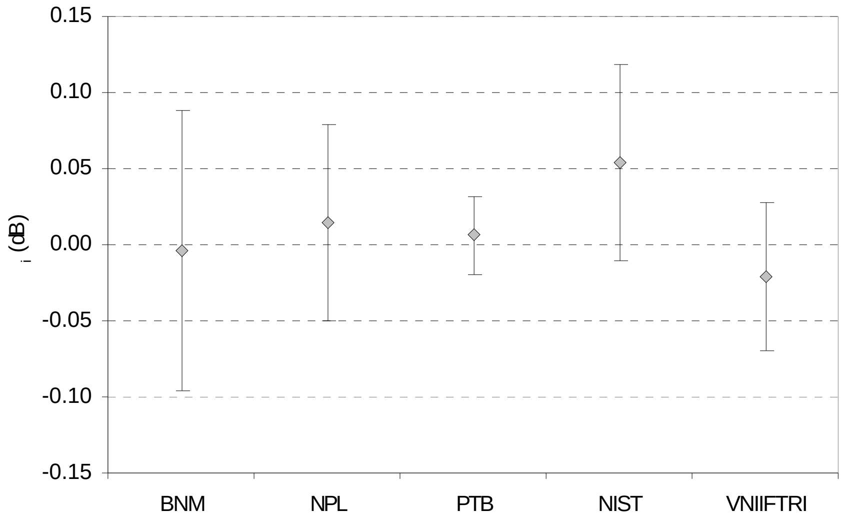

Figure 8.6.3.a: TSB2 output connector PC-7, F = 15 GHz, weighted

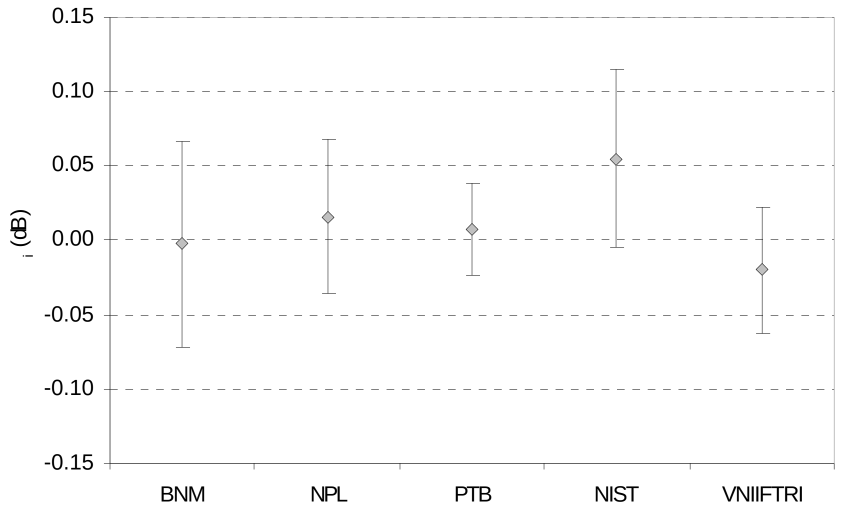

Figure 8.6.3.b: TSB2 output connector PC-7, F = 15 GHz, unweighted

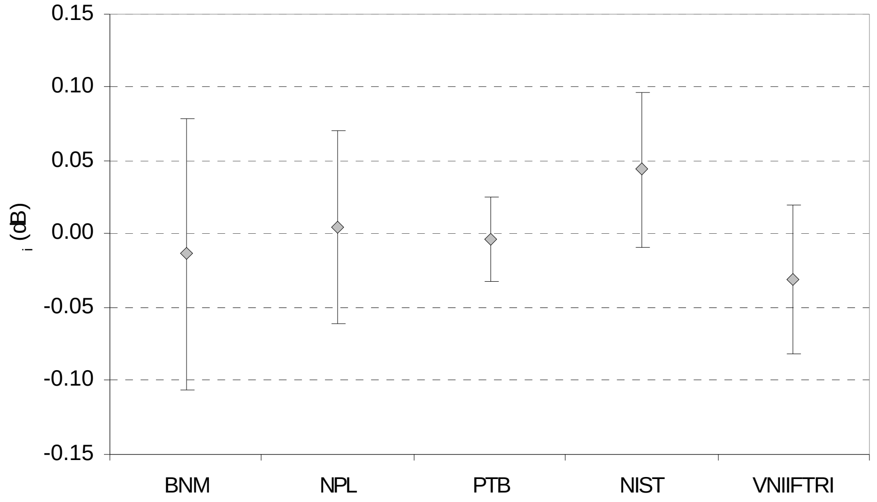

Figure 8.6.3.c: TSB2 output connector PC-7, F = 15 GHz, weighted, outliers included

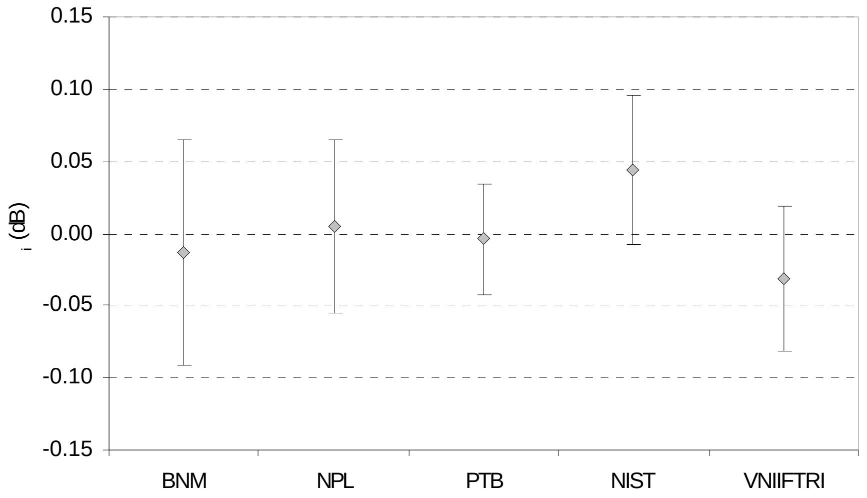

Figure 8.6.3.d: TSB2 output connector PC-7, F = 15 GHz, unweighted, outliers included

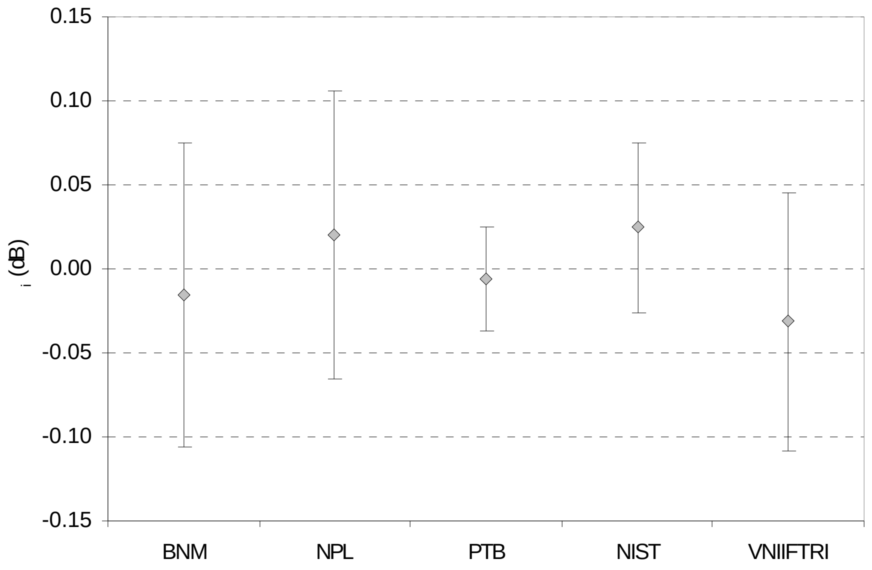

Figure 8.6.4.a: TSB2 output connector PC-7, F = 17.5 GHz, weighted

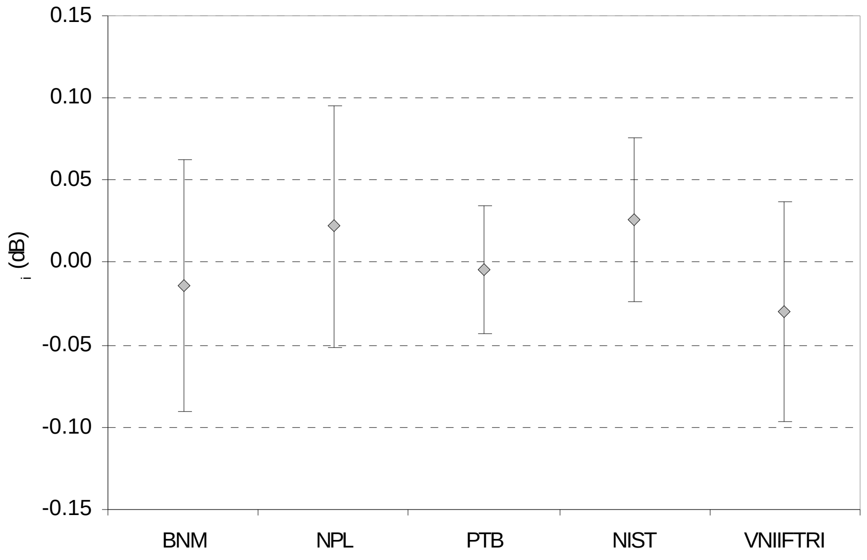

Figure 8.6.4.b: TSB2 output connector PC-7, F = 17.5 GHz, unweighted

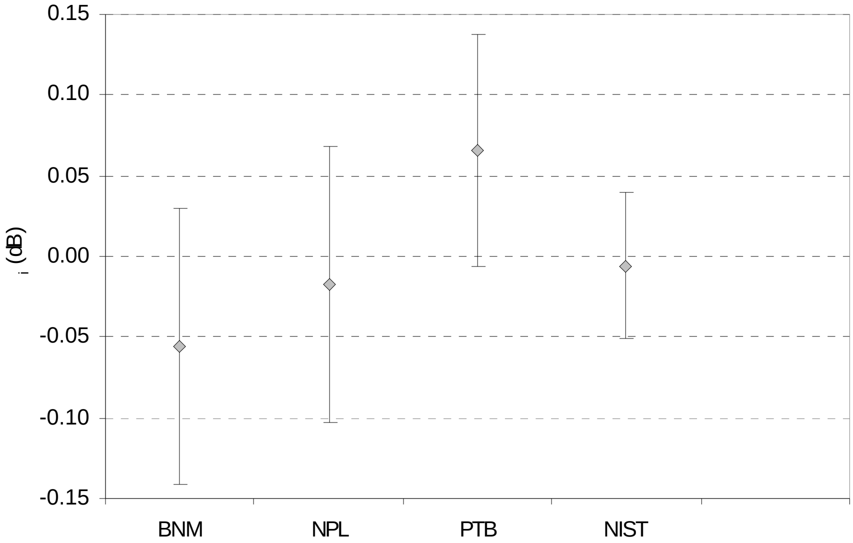

Figure 8.6.5.a: TSB2 output connector PC-7, F = 18 GHz, weighted

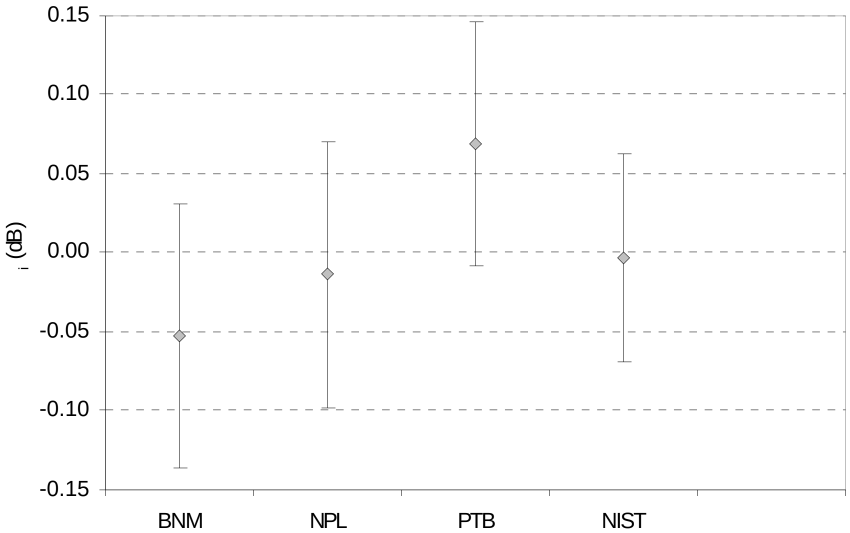

Figure 8.6.5.b: TSB2 output connector PC-7, F = 18 GHz, unweighted

IX. Conclusion

A measurement comparison of thermal noise-power measurements has been carried out among five national metrology institutes on waveguide between 12.4 and 18 GHz. The participants were BNM-LCIE (France), NPL (United Kingdom), PTB (Germany), NIST (United States of America) and VNIIFTRI (Russia). The Bureau National de Métrologie - Laboratoire Central des Industries Electriques (France) acted as the pilot laboratory for the comparison. A very good agreement was found between four participants in measuring noise temperature of four thermal noise transfer standards. Only VNIIFTRI, which uses different waveguide standards present significant differences, in comparison to the four other institutes, especially at the higher frequencies.

An additional exercise has been done for the calculation of the KCRV and the degree of equivalence. This work is presented here for open discussions between the participants.

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A.1 NPL Results

A.1.1 NPL Measurements

Transfer Standard: TSA2 **Reference Plane:** output flange R140

Date of calibration: April 1997
Room Temperature: (23±0.5) °C Room Humidity: (50±10)%

F (GHz)	Γ	T (K)	ΔT(K)	ENR (dB)	ΔENR(dB)
12.4	0.011	11208	52	15.758	0.021
13.5	0.005	11205	60	15.756	0.024
15.0	0.006	11231	51	15.767	0.020
17.5	0.004	11236	78	15.769	0.031
18.0	0.006	11245	53	15.772	0.021

Table 1.4

Transfer Standard: TSB2 **Reference Plane:** output adapter PC-7/R140

Date of calibration: April 1997
Room Temperature: (23±0.5) °C Room Humidity: (50±10)%

F (GHz)	Γ	T (K)	ΔT(K)	ENR (dB)	ΔENR(dB)
12.4	0.073	1174	4.36	4.841	0.021
13.5	0.042	1155	4.82	4.744	0.024
15.0	0.061	1146	4.24	4.699	0.022
17.5	0.047	1181	6.48	4.877	0.032
18.0	0.024	1180	4.86	4.870	0.024

Table 1.5

Transfer Standard: TSB2 **Reference Plane:** output connector PC-7

Date of calibration: April 1997
Room Temperature: (23±0.5) °C Room Humidity: (50±10)%

F (GHz)	Γ	T (K)	ΔT(K)	ENR (dB)	ΔENR(dB)
12.4	0.043	1195	11	4.942	0.051
13.5	0.048	1175	8	4.846	0.039
15.0	0.055	1167	7	4.808	0.034
17.5	0.059	1200	9	4.967	0.045
18.0	0.060	1200	8	4.966	0.040

Table 1.6

Transfer Standard: TSA1 **Reference Plane:** output flange R140

Date of calibration: May 1998
Room Temperature: (25±0.5) °C Room Humidity: (42±10)%

F (GHz)	Γ	T (K)	ΔT(K)	ENR (dB)	ΔENR(dB)
12.4	0.0074	11033	51	15.687	0.021
13.5	0.0076	11020	59	15.682	0.024
15.0	0.0079	11036	50	15.689	0.020
17.5	0.0030	10962	76	15.659	0.031
18.0	0.0093	10961	51	15.658	0.021

Table 3.1

Transfer Standard: TSB1 **Reference Plane:** output adapter PC-7/R140

Date of calibration: May 1998
Room Temperature: (25±0.5) °C Room Humidity: (37±10)%

F (GHz)	Γ	T (K)	ΔT(K)	ENR (dB)	ΔENR(dB)
12.4	0.0400	11282	52	15.787	0.021
13.5	0.0400	11370	61	15.822	0.024
15.0	0.0640	11461	53	15.857	0.020
17.5	0.0340	10982	76	15.667	0.031
18.0	0.0120	10838	51	15.608	0.021

Table 3.2

Transfer Standard: TSB1 **Reference Plane:** output connector PC-7

Date of calibration: May 1998
Room Temperature: (25±0.5) °C Room Humidity: (37±10)%

F (GHz)	Γ	T (K)	ΔT(K)	ENR (dB)	ΔENR(dB)
12.4	0.0440	11459	126	15.856	0.049
13.5	0.0530	11561	97	15.896	0.037
15.0	0.0610	11720	89	15.957	0.034
17.5	0.0320	11337	113	15.809	0.045
18.0	0.0200	11229	101	15.766	0.040

Table 3.3

Transfer Standard: TSA2 **Reference Plane:** output flange R140

Date of calibration: March-April 1999
Room Temperature: (23±1) °C Room Humidity: (27±10)%

F (GHz)	Γ	T (K)	ΔT(K)	ENR (dB)	ΔENR(dB)
12.4	0.011	11207	57	15.757	0.023
13.5	0.006	11201	58	15.754	0.023
15.0	0.007	11226	57	15.764	0.023
17.5	0.004	11223	79	15.763	0.031
18.0	0.006	11240	100	15.768	0.041

Table 5.4

Transfer Standard: TSB2 **Reference Plane:** output adapter PC-7/R140

Date of calibration: March-April 1999
Room Temperature: (23±1) °C Room Humidity: (26±10)%

F (GHz)	Γ	T (K)	ΔT(K)	ENR (dB)	ΔENR(dB)
12.4	0.073	1178.3	4.8	4.862	0.024
13.5	0.046	1157.1	4.7	4.757	0.024
15.0	0.060	1150.0	4.6	4.721	0.023
17.5	0.045	1182.6	6.5	4.882	0.032
18.0	0.027	1182.7	8.5	4.883	0.041

Table 5.5

Transfer Standard: TSB2 **Reference Plane:** output connector PC-7

Date of calibration: March-April 1999
Room Temperature: (23±1) °C Room Humidity: (26±10)%

F (GHz)	Γ	T (K)	ΔT(K)	ENR (dB)	ΔENR(dB)
12.4	0.042	1201.0	11	4.970	0.052
13.5	0.049	1180.1	8	4.870	0.039
15.0	0.056	1176.5	7.4	4.853	0.036
17.5	0.059	1215.9	9.6	5.042	0.045
18.0	0.061	1217.0	12	5.046	0.054

Table 5.6

A.1.2 NPL Uncertainties

The radiometer used for the intercomparison is the NPL WG18 (WR62, R140) radiometer which is a Dicke radiometer with a built in working standard which is calibrated periodically using a hot thermal standard. The equation for the radiometer is:

$$T_u = (T_w - T_a)\frac{Y}{Q} + T_a$$

where T_u is the unknown temperature, T_a is ambient temperature, Y is the Y factor (in linear units) obtained when comparing the unknown with the working standard and Q is given by:

$$Q = \frac{\left(1 - |\Gamma_u|^2\right)}{|1 - S_{11}\Gamma_u|^2}$$

where G_u is the reflection coefficient of the unknown device and S_{11} is the input reflection coefficient of the radiometer.
If G_u is represented by its magnitude ?, and its phase $?_u$, and S11 by its magnitude, |S11| and phase $?_{11}$, then we have:

$$Q = \frac{\left(1 - |\Gamma_u|^2\right)}{1 - 2|S_{11}|\rho\cos(\theta_{11} + \theta_u) + |S_{11}|^2\rho^2}$$

This equation can be used to generate values ?Q by offsetting the values of ?, $?_u$, |S11| and $?_{11}$ by their uncertainties.
By partial differentiation we have:

$$X_1 = \frac{\delta T_{ux}}{\delta T_w}.\Delta T_w = \left(\frac{Y}{Q}\right).\Delta T_w$$

$$X_2 = \frac{\delta T_u}{\delta T_a}.\Delta T_a = \left(1 - \frac{Y}{Q}\right).\Delta T_a$$

$$X_3 = \frac{\delta T_x}{\delta Y}.\Delta Y = \frac{(T_w - T_a)}{Q}.\Delta Y$$

$$X_4 = \frac{\delta T_x}{\delta Q}.\Delta Q_1 = -(T_w - T_a).\frac{Y}{Q^2}.\Delta Q_1$$

$$X_5 = \frac{\delta T_x}{\delta Q}.\Delta Q_2 = -(T_w - T_a).\frac{Y}{Q^2}.\Delta Q_2$$

$$X_6 = \frac{\delta T_x}{\delta Q}.\Delta Q_3 = -(T_w - T_a).\frac{Y}{Q^2}.\Delta Q_3$$

$$X_7 = \frac{\delta T_x}{\delta Q}.\Delta Q_4 = -(T_w - T_a).\frac{Y}{Q^2}.\Delta Q_4$$

where the values Q_1, Q_2, Q_3 and Q_4 are obtained by offsetting each of ?, $?_u$, |S11| and $?_{11}$ by their uncertainties.

A sample calculation for TSB2 at its waveguide port at 12.4 GHz is given below. The uncertainty on the VRC magnitude is assumed to ±0.002 and the uncertainty on the phase is given by [$\sin^{-1}(0.01/|\Gamma|)$]° in phase. If the magnitude |Γ| is less than its uncertainty then the phase uncertainty is 180°. The uncertainty due to flange repeatability is assumed to be proportional to the device ENR and is therefore calculated from $\Delta T = \frac{\log_e(10)}{10}\left(T_u - 290\right)$

Freq = 12.4 GHz Tu = 1178.30 Q = 0.99

Symbol	**Actual values**	**Source of uncertainty**	**Uncertainty value ±**	**? Q ±**	**Probability distribution**	**Divisor**	**Coefficient c_i**	**U_i(T)±K**	**v_i or v_{eff}**
Tw	11221.00	Working standard	28.20		Normal	1.00	0.08	2.27	8
Ta	297.38	Ambient temperature	0.50		Normal	1.00	0.92	0.46	8
Y	-10.97	Y factor	0.0010		Normal	1.00	202.84	0.20	8
?	0.07	Device VRC magnitude	0.002	-0.00039	Normal	1.00	-880.92	0.35	8
?u	39.60	Device VRC phase	1.60	0.00017	Normal	1.00	-880.92	-0.15	8
S_{11}	0.05	Radiometer VRC magnitude	0.002	-0.00014	Normal	1.00	-880.92	0.13	8
$?_{11}$	-159.38	Radiometer VRC phase	2.30	0.00025	Normal	1.00	-880.92	-0.22	8
		Connector repeatability	0.0030		Rectangular	1.73	204.54	0.35	8
		Type A			Normal	1.00		0.24	9.00
		Combined standard uncertainty			Normal			2.41	>1000
		Expanded uncertainty			Normal (k=2)			4.82	

Table U.5.5: Uncertainty for TSB2 at waveguide plane

A similar table for TSA2 is shown below:
Freq = 12.4 GHz Tu = 11206.93 Q = 1.00

Symbol	Actual values	Source of uncertainty	Uncertainty value ±	? Q ±	Probability distribution	Divisor	Coefficient c_i	$U_i(T)$ ±K	v_i or v_{eff}
Tw	11221.00	Working standard	28.20		Normal	1.00	1.00	28.16	8
Ta	297.91	Ambient temperature	0.50		Normal	1.00	0.00	0.00	8
Y	-0.01	Y factor	0.0010		Normal	1.00	2511.89	2.51	8
?	0.01	Device VRC magnitude	0.0020	-0.00016	Normal	1.00	-10909.02	1.76	8
?u	-75.97	Device VRC phase	10.19	-0.00015	Normal	1.00	-10909.02	1.65	8
S_{11}	0.05	Radiometer VRC magnitude	0.0020	-0.00003	Normal	1.00	-10909.02	0.28	8
$?_{11}$	-159.38	Radiometer VRC phase	2.33	-0.00004	Normal	1.00	-10909.02	0.40	8
		Connector repeatability	0.0030		Rectangular	1.73	2513.72	4.35	8
		Type A			Normal	1.00		0.67	9.00
		Combined standard uncertainty			Normal			28.72	>1000
		Expanded uncertainty			Normal (k=2)			57.44	

Table U.5.4: Uncertainty for TSA2 at waveguide plane

Finally, the adaptor de-embedding uncertainty must be considered.
Here the equation is:

$$T_c = \frac{\left(T_{w/g} - T_a\right)}{APTF} + T_a$$

Where T_c denotes the temperature at the coaxial plane, $T_{w/g}$ at the waveguide plane, T_a is the ambient temperature and the APTF is the available power transfer factor of the waveguide to coaxial adaptor. This can be found be several techniques. For this intercomparison, the method of three known (waveguide) loads attached at the waveguide port was used. Reflection coefficient measurements made at the coaxial port allow the necessary S parameters (S_{11}, S_{22} and $S_{12}.S_{21}$) to be calculated.
By partial differentiation we have:

$$\frac{\partial T_c}{\partial T_a} = 1 - \frac{1}{APTF}$$

$$\frac{\partial T_c}{\partial T_{w/g}} = \frac{1}{APTF}$$

$$\frac{\partial T_c}{\partial APTF} = \frac{\left(T_{w/g} - T_a\right)}{APTF^2}$$

The table below shows the uncertainty for TSB2 at the coaxial plane at a frequency of 12.4 GHz.

Symbol	**Actual values**	**Source of uncertainty**	**Uncertainty value ±**	**Probability distribution**	**Divisor**	**Coefficient c_i**	**U_i(T)±K**	**v_i or v_{eff}**
Tu	1178.310	Noise temperature at waveguide plane	2.400	Normal	1.000	1.025	2.461	8
Ta	297.380	Ambient temperature	0.500	Rectangular	1.732	-0.025	-0.007	8
APTF	0.975	APTF	0.011	Normal	2.000	926.304	4.875	8
		Type A	0.240	Normal	1.000	1.025	0.246	9.000
		Combined standard uncertainty		Normal			5.466	>1000
		Expanded uncertainty		Normal (k=2)			10.932	

Table U.5.6: Uncertainty for TSB2 at coaxial plane

Here, the type A uncertainty is the Type A uncertainty of the waveguide measurements and the coefficient used is the same as the coefficient for the noise temperature. The difference between the uncertainty for the noise temperature at waveguide plane quoted in Table 3 above and the equivalent value for TSB2 at the waveguide plane quoted in Table 1 arises because the value in Table 3 excludes the Type A component which is separately accounted for in the calculation Table 3.

A.2 PTB RESULTS
A.2.1 PTB Measurements

Transfer Standard: TSA1 **Reference Plane:** output flange R140

Date of calibration: June 1997
Room Temperature: 23°C Room Humidity:

F (GHz)	Γ	T (K)	ΔT(K)	ENR (dB)	ΔENR(dB)
12.4	0.010	11076	32	15.705	0.013
13.5	0.007	11102	36	15.715	0.014
15.0	0.008	11039	40	15.690	0.016
17.5	0.004	11012	44	15.679	0.018
18.0	0.009	10920	50	15.641	0.020

Table 1.1

Transfer Standard: TSB1 **Reference Plane:** output adapter PC-7/R140

Date of calibration: June 1997
Room Temperature: 23°C Room Humidity:

F (GHz)	Γ	T (K)	ΔT(K)	ENR (dB)	ΔENR(dB)
12.4	0.045	11287	36	15.789	0.014
13.5	0.040	11408	39	15.836	0.015
15.0	0.063	11383	45	15.827	0.018
17.5	0.032	10989	46	15.669	0.019
18.0	0.016	10660	50	15.534	0.021

Table 1.2

Transfer Standard: TSB1 **Reference Plane:** output connector PC-7

Date of calibration: June 1997
Room Temperature: 23°C Room Humidity:

F (GHz)	Γ	T (K)	ΔT(K)	ENR (dB)	ΔENR(dB)
12.4	0.032	11481	38	15.865	0.015
13.5	0.037	11631	41	15.923	0.016
15.0	0.065	11688	47	15.944	0.018
17.5	0.032	11417	49	15.840	0.019
18.0	0.017	11039	52	15.690	0.021

Table 1.3

Transfer Standard: TSA2 **Reference Plane:** output flange R140

Date of calibration: February 1998
Room Temperature: 23°C Room Humidity:

F (GHz)	Γ	T (K)	ΔT(K)	ENR (dB)	ΔENR(dB)
12.4	0.012	11264	31	15.780	0.012
13.5	0.008	11298	37	15.793	0.015
15.0	0.005	11255	41	15.776	0.016
17.5	0.006	11218	44	15.761	0.017
18.0	0.001	11140	50	15.730	0.020

Table 3.4

Transfer Standard: TSB2 **Reference Plane:** output adapter PC-7/R140

Date of calibration: February 1998
Room Temperature: 23°C Room Humidity:

F (GHz)	Γ	T (K)	ΔT(K)	ENR (dB)	ΔENR(dB)
12.4	0.069	1174.7	4.1	4.844	0.020
13.5	0.044	1159.4	3.1	4.768	0.015
15.0	0.059	1149.8	3.6	4.720	0.018
17.5	0.043	1182.6	4.1	4.883	0.020
18.0	0.032	1156.0	8.0	4.751	0.040

Table 3.5

Transfer Standard: TSB2 **Reference Plane:** output connector PC-7

Date of calibration: February 1998
Room Temperature: 23°C Room Humidity:

F (GHz)	Γ	T (K)	ΔT(K)	ENR (dB)	ΔENR(dB)
12.4	0.043	1197.0	4.4	4.952	0.021
13.5	0.046	1180.0	3.4	4.870	0.017
15.0	0.055	1173.6	3.9	4.839	0.019
17.5	0.062	1213.6	4.4	5.031	0.021
18.0	0.062	1191.0	8.6	4.923	0.041

Table 3.6

Transfer Standard: TSA1 **Reference Plane:** output flange R140

Date of calibration: April 1999
Room Temperature: 23°C Room Humidity:

F (GHz)	Γ	T (K)	ΔT(K)	ENR (dB)	ΔENR(dB)
12.4	0.011	11095	30	15.712	0.012
13.5	0.007	11121	36	15.723	0.015
15.0	0.011	11086	40	15.709	0.016
17.5	0.008	11033	43	15.687	0.018
18.0	0.013	10936	50	15.648	0.021

Table 5.1

Transfer Standard: TSB1 **Reference Plane:** output adapter PC-7/R140

Date of calibration: April 1999
Room Temperature: 23°C Room Humidity:

F (GHz)	Γ	T (K)	ΔT(K)	ENR (dB)	ΔENR(dB)
12.4	0.042	11301	32	15.794	0.013
13.5	0.041	11414	38	15.839	0.015
15.0	0.067	11425	43	15.843	0.017
17.5	0.033	11120	44	15.722	0.018
18.0	0.012	10719	49	15.558	0.021

Table 5.2

Transfer Standard: TSB1 **Reference Plane:** output connector PC-7

Date of calibration: April 1999
Room Temperature: 23°C Room Humidity:

F (GHz)	Γ	T (K)	ΔT(K)	ENR (dB)	ΔENR(dB)
12.4	0.038	11513	34	15.877	0.013
13.5	0.042	11658	39	15.933	0.015
15.0	0.067	11773	44	15.977	0.017
17.5	0.036	11450	46	15.853	0.018
18.0	0.028	11034	52	15.688	0.021

Table 5.3

A.2.2 PTB Uncertainties (in K)

Transfer Source: TSA1 **Reference plane:** R140

F(GHz)	12.4	13.5	15.0	17.5	18.0
Standard*	29.3	35.1	38.9	42.4	48.5
Ambient*	0.00274	0.00277	0.00318	0.00279	0.00275
Mismatch after Tuning*	2.04	0.967	0.577	0.681	1.26
Attenuation with Standard*	1.24	1.24	1.24	1.23	1.22
Attenuation with unknown*	-1.24	-1.24	-1.24	-1.23	-1.22
Tuner Attenuation Variation*	0.0	0.0	2.96	0.0	3.25
Source Power*	1.39	1.42	1.47	1.45	1.40
Resolution*	11.3	6.12	7.33	9.94	13.4
Null Detector (Type A)	0.548	1.38	4.79	2.13	0.586
Total	32	36	40	44	50

* Type B

Table U.1.1

Transfer Source: TSB1 **Reference plane:** R140

F(GHz)	12.4	13.5	15.0	17.5	18.0
Standard*	30.1	36.1	40.1	42.4	46.0
Ambient*	0.000536	0.000428	-0.000416	0.00303	0.00549
Mismatch after Tuning*	2.96	2.13	1.76	1.28	1.38
Attenuation with Standard*	1.27	1.28	1.28	1.23	1.19
Attenuation with unknown*	-1.27	-1.28	-1.28	-1.23	-1.19
Tuner Attenuation Variation*	4.37	10.5	14.9	11.1	4.12
Source Power*	13.9	8.21	9.44	6.21	-15.2
Resolution*	11.5	6.29	7.56	9.92	13.1
Null Detector (Type A)	1.63	1.85	4.93	4.53	2.52
Total	36	39	45	46	50

* Type B

Table U.1.2

Transfer Source: TSB1 **Reference plane:** PC-7

F(GHz)	12.4	13.5	15.0	17.5	18.0
Unknown Ref. Wg. Plane*	36.6	39.8	46.2	47.8	51.8
Ambient Temp.Adapter*	0.1	0.1	0.1	0.1	0.1
Attenuation Adapter*	6.44	7.83	6.56	6.40	7.42
Mismatch of Unknown*	3.58	4.2	7.44	3.56	1.83
Tuned Mism. Of Unk. + Ad.*	1.00	1.20	1.44	0.71	0.54
Phase of Reflection*	4.96	4.84	3.42	4.11	3.16
Total	38	41	47	49	52

* Type B

Table U.1.3

Transfer Source: TSA2 **Reference plane:** R140

F(GHz)	12.4	13.5	15.0	17.5	18.0
Standard*	29.8	35.8	39.8	43.3	49.4
Ambient*	0.000773	0.000721	0.000916	0.000624	0.000477
Mismatch after Tuning*	3.03	0.483	0.734	0.719	0.682
Attenuation with Standard*	1.26	1.27	1.26	1.26	1.25
Attenuation with unknown*	-1.26	-1.27	-1.26	-1.26	-1.25
Tuner Attenuation Variation*	0	2.35	-1.68	0	0
Source Power*	1.84	1.46	1.5	1.5	1.54
Resolution*	6.14	6.61	6.51	6.19	6.95
Null Detector (Type A)	4.11	2.27	3.13	3.03	6.77
Total	31	37	41	44	50

* Type B

Table U.3.4

Transfer Source: TSB2 **Reference plane:** R140

F(GHz)	12.4	13.5	15.0	17.5	18.0
Standard*	2.39	2.81	3.09	3.51	4.14
Ambient*	0.106	0.106	0.107	0.106	0.106
Mismatch after Tuning*	0.64	0.171	0.161	0.121	0.140
Attenuation with Standard*	0.101	0.0994	0.0983	0.102	0.0990
Attenuation with unknown*	-0.202	-0.199	-0.197	-0.204	-0.198
Tuner Attenuation Variation*	0.698	0.950	1.07	1.11	0.920
Source Power*	2.92	0.188	0.690	0.206	6.43
Resolution*	0.922	0.664	0.582	1.39	1.87
Null Detector (Type A)	0.830	0.336	1.03	0.967	0.564
Total	4.1	3.1	3.6	4.1	8.0

* Type B

Table U.3.5

Transfer Source: TSB2 **Reference plane:** PC-7

F(GHz)	12.4	13.5	15	17.5	18
Unknown Ref. Wg. Plane*	4.20	3.17	3.70	4.24	8.32
Ambient Temp.Adapter*	0.1	0.1	0.1	0.1	0.1
Attenuation Adapter*	0.622	0.611	0.505	0.528	0.618
Mismatch of Unknown*	0.388	0.407	0.484	0.571	0.557
Tuned Mism. Of Unk. + Ad.*	0.142	0.101	0.116	0.086	0.080
Phase of Reflection*	1.16	0.939	1.17	0.92	2.05
Total	4.4	3.4	3.9	4.4	8.6

* Type B

Table U.3.6

Transfer Source: TSA1 **Reference plane:** R140

F(GHz)	12.4	13.5	15.0	17.5	18.0
Standard*	29.3	35.2	39.1	42.5	48.9
Ambient*	0.00254	0.00526	0.00268	0.00256	0.00260
Mismatch after Tuning*	5.28	0.911	1.27	1.27	1.53
Attenuation with Standard*	1.24	1.25	1.24	1.24	1.22
Attenuation with unknown*	-1.24	-1.25	-1.24	-1.24	-1.22
Tuner Attenuation Variation*	0.33	-3.31	1.65	-2.63	2.93
Source Power*	1.41	1.40	1.43	1.42	1.37
Resolution*	2.9	3.12	3.92	6.42	6.42
Null Detector (Type A)	3.39	2.48	4.27	3.18	3.24
Total	30	36	40	43	50

* Type B

Table U.5.1

Transfer Source: TSB1 **Reference plane:** R140

F(GHz)	12.4	13.5	15.0	17.5	18.0
Standard*	29.9	36.2	40.3	42.9	47.9
Ambient*	0.000385	-0.000491	-0.000860	0.00165	0.00490
Mismatch after Tuning*	8.6	3.31	3.62	2.31	2.51
Attenuation with Standard*	1.27	1.28	1.28	1.25	1.20
Attenuation with unknown*	-1.27	-1.28	-1.28	-1.25	-1.20
Tuner Attenuation Variation*	5.05	9.18	13.6	6.95	1.91
Source Power*	3.28	2.18	2.63	-0.665	0.137
Resolution*	2.96	3.21	4.04	6.48	6.29
Null Detector (Type A)	2.92	1.69	2.75	3.16	6.13
Total	32	38	43	44	49

* Type B

Table U.5.2

Transfer Source: TSB1 **Reference plane:** PC-7

F(GHz)	12.4	13.5	15.0	17.5	18.0
Unknown Ref. Wg. Plane*	32.6	37.8	42.3	45.3	50.5
Ambient Temp.Adapter*	0.1	0.1	0.1	0.1	0.1
Attenuation Adapter*	6.46	7.85	6.61	6.42	7.42
Mismatch of Unknown*	4.27	4.78	7.72	4.02	3.01
Tuned Mism. Of Unk. + Ad.*	0.92	1.085	1.70	0.89	0.768
Phase of Reflection*	6.00	5.22	3.60	3.77	6.44
Total	34	39	44	46	52

* Type B

Table U.5.3

A.3 BNM-LCIE RESULTS
A.3.1 BNM-LCIE Measurements

Transfer Standard: TSA1 **Reference Plane:** output flange R140

Date of calibration: September 1997
Room Temperature: (23±1) °C Room Humidity: < 60%

F (GHz)	Γ	T (K)	ΔT(K)	ENR (dB)	ΔENR(dB)
12.4	0.009	11060	92	15.698	0.037
13.5	0.009	11111	95	15.719	0.038
15.0	0.010	11033	98	15.687	0.040
17.5	0.005	11008	94	15.677	0.038
18.0	0.010	10955	92	15.656	0.038

Table 2.1

Transfer Standard: TSB1 **Reference Plane:** output adapter PC-7/R140

Date of calibration: September 1997
Room Temperature: (23±1) °C Room Humidity: < 60%

F (GHz)	Γ	T (K)	ΔT(K)	ENR (dB)	ΔENR(dB)
12.4	0.041	11279	94	15.786	0.037
13.5	0.042	11408	98	15.836	0.038
15.0	0.067	11447	103	15.851	0.040
17.5	0.032	11023	94	15.683	0.038
18.0	0.015	10715	90	15.557	0.038

Table 2.2

Transfer Standard: TSB1 **Reference Plane:** output connector PC-7

Date of calibration: September 1997
Room Temperature: (23±1) °C Room Humidity: < 60%

F (GHz)	Γ	T (K)	ΔT(K)	ENR (dB)	ΔENR(dB)
12.4	0.038	11465	107	15.859	0.042
13.5	0.044	11619	113	15.918	0.043
15.0	0.064	11715	119	15.954	0.045
17.5	0.033	11418	117	15.840	0.046
18.0	0.033	11095	108	15.712	0.044

Table 2.3

Transfer Standard: TSA2 **Reference Plane:** output flange R140

Date of calibration: September 1997
Room Temperature: (23±1) °C Room Humidity: < 60%

F (GHz)	Γ	T (K)	ΔT(K)	ENR (dB)	ΔENR(dB)
12.4	0.011	11219	93	15.762	0.037
13.5	0.005	11302	97	15.795	0.038
15.0	0.004	11218	100	15.761	0.040
17.5	0.006	11242	96	15.771	0.038
18.0	0.003	11171	94	15.743	0.038

Table 2.4

Transfer Standard: TSB2 **Reference Plane:** output adapter PC-7/R140

Date of calibration: September 1997
Room Temperature: (23±1) °C Room Humidity: < 60%

F (GHz)	Γ	T (K)	ΔT(K)	ENR (dB)	ΔENR(dB)
12.4	0.075	1179.0	8.9	4.865	0.044
13.5	0.045	1165.7	8.7	4.800	0.043
15.0	0.058	1151.6	8.7	4.729	0.044
17.5	0.041	1185.5	9.2	4.897	0.044
18.0	0.032	1186.1	8.6	4.899	0.042

Table 2.5

Transfer Standard: TSB2 **Reference Plane:** output connector PC-7

Date of calibration: September 1997
Room Temperature: (23±1) °C Room Humidity: < 60%

F (GHz)	Γ	T (K)	ΔT(K)	ENR (dB)	ΔENR(dB)
12.4	0.038	1198.9	10.1	4.961	0.048
13.5	0.045	1188.7	10	4.912	0.048
15.0	0.056	1174.2	9.9	4.841	0.049
17.5	0.055	1217.0	11.1	5.047	0.052
18.0	0.055	1221.6	10.2	5.068	0.048

Table 2.6

Transfer Standard: TSA1 **Reference Plane:** output flange R140

Date of calibration: January 1999
Room Temperature: (23±1) °C Room Humidity: < 60%

F (GHz)	Γ	T (K)	ΔT(K)	ENR (dB)	ΔENR(dB)
12.4	0.006	11047	95	15.693	0.038
13.5	0.005	11114	96	15.720	0.038
15.0	0.006	11037	95	15.689	0.038
17.5	0.008	11035	97	15.688	0.039
18.0	0.009	10961	99	15.658	0.040

Table 4.1

Transfer Standard: TSB1 **Reference Plane:** output adapter PC-7/R140

Date of calibration: January 1999
Room Temperature: (23±1) °C Room Humidity: < 60%

F (GHz)	Γ	T (K)	ΔT(K)	ENR (dB)	ΔENR(dB)
12.4	0.041	11272	107	15.783	0.042
13.5	0.042	11400	108	15.833	0.042
15.0	0.067	11358	111	15.817	0.043
17.5	0.032	11070	105	15.702	0.042
18.0	0.015	10746	100	15.570	0.041

Table 4.2

Transfer Standard: TSB1 **Reference Plane:** output connector PC-7

Date of calibration: January 1999
Room Temperature: (23±1) °C Room Humidity: < 60%

F (GHz)	Γ	T (K)	ΔT(K)	ENR (dB)	ΔENR(dB)
12.4	0.046	11580	121	15.903	0.046
13.5	0.039	11682	119	15.942	0.045
15.0	0.062	11737	122	15.963	0.046
17.5	0.036	11433	117	15.846	0.045
18.0	0.015	11139	116	15.730	0.046

Table 4.3

Transfer Standard: TSA2 **Reference Plane:** output flange R140

Date of calibration: January 1999
Room Temperature: (23±1) °C Room Humidity: < 60%

F (GHz)	Γ	T (K)	ΔT(K)	ENR (dB)	ΔENR(dB)
12.4	0.011	11242	102	15.771	0.040
13.5	0.004	11313	97	15.799	0.038
15.0	0.004	11235	99	15.768	0.039
17.5	0.010	11234	102	15.768	0.040
18.0	0.008	11192	101	15.751	0.040

Table 4.4

Transfer Standard: TSB2 **Reference Plane:** output adapter PC-7/R140

Date of calibration: January 1999
Room Temperature: (23±1) °C Room Humidity: < 60%

F (GHz)	Γ	T (K)	ΔT(K)	ENR (dB)	ΔENR(dB)
12.4	0.072	1168.8	8.8	4.815	0.043
13.5	0.044	1158.2	8.5	4.762	0.042
15.0	0.057	1153.6	8.8	4.739	0.044
17.5	0.043	1181.2	8.7	4.876	0.042
18.0	0.026	1177.2	8.9	4.856	0.043

Table 4.5

Transfer Standard: TSB2 **Reference Plane:** output connector PC-7

Date of calibration: January 1999
Room Temperature: (23±1) °C Room Humidity: < 60%

F (GHz)	Γ	T (K)	ΔT(K)	ENR (dB)	ΔENR(dB)
12.4	0.072	1187.4	9.4	4.906	0.045
13.5	0.044	1179.4	8.9	4.867	0.043
15.0	0.057	1178.0	9.9	4.860	0.048
17.5	0.043	1219.6	9.3	5.059	0.043
18.0	0.026	1212.1	9.6	5.024	0.045

Table 4.6

Transfer Standard: TSA1 **Reference Plane:** output flange R140

Date of calibration: December 2000
Room Temperature: (23±1) °C Room Humidity: < 60%

F (GHz)	Γ	T (K)	ΔT(K)	ENR (dB)	ΔENR(dB)
12.4	0.007	11083	95	15.708	0.038
13.5	0.006	11100	93	15.714	0.037
15.0	0.006	10983	99	15.667	0.040
17.5	0.008	11025	99	15.684	0.040
18.0	0.009	11022	97	15.683	0.040

Table 8.1

Transfer Standard: TSB1 **Reference Plane:** output adapter PC-7/R140

Date of calibration: December 2000
Room Temperature: (23±1) °C Room Humidity: < 60%

F (GHz)	Γ	T (K)	ΔT(K)	ENR (dB)	ΔENR(dB)
12.4	0.039	11279	96	15.786	0.037
13.5	0.043	11409	97	15.837	0.037
15.0	0.063	11417	100	15.840	0.038
17.5	0.034	11044	99	15.692	0.039
18.0	0.017	10864	98	15.618	0.039

Table 8.2

Transfer Standard: TSB1 **Reference Plane:** output connector PC-7

Date of calibration: December 2000
Room Temperature: (23±1) °C Room Humidity: < 60%

F (GHz)	Γ	T (K)	ΔT(K)	ENR (dB)	ΔENR(dB)
12.4	0.040	11493	107	15.869	0.043
13.5	0.043	11646	105	15.928	0.041
15.0	0.064	11704	111	15.951	0.043
17.5	0.039	11371	109	15.822	0.044
18.0	0.033	11266	107	15.780	0.044

Table 8.3

Transfer Standard: TSA2 **Reference Plane:** output flange R140

Date of calibration: December 2000
Room Temperature: (23±1) °C Room Humidity: < 60%

F (GHz)	Γ	T (K)	ΔT(K)	ENR (dB)	ΔENR(dB)
12.4	0.007	11187	93	15.749	0.037
13.5	0.008	11351	94	15.814	0.037
15.0	0.008	11199	100	15.754	0.040
17.5	0.009	11240	98	15.770	0.039
18.0	0.005	11289	99	15.789	0.039

Table 8.4

Transfer Standard: TSB2 **Reference Plane:** output adapter PC-7/R140

Date of calibration: December 2000
Room Temperature: (23±1) °C Room Humidity: < 60%

F (GHz)	Γ	T (K)	ΔT(K)	ENR (dB)	ΔENR(dB)
12.4	0.064	1176	8.4	4.850	0.041
13.5	0.043	1161	8.4	4.775	0.042
15.0	0.057	1143	8.4	4.683	0.043
17.5	0.044	1177	8.8	4.855	0.043
18.0	0.022	1179	9.0	4.864	0.044

Table 8.5

Transfer Standard: TSB2 **Reference Plane:** output connector PC-7

Date of calibration: December 2000
Room Temperature: (23±1) °C Room Humidity: < 60%

F (GHz)	Γ	T (K)	ΔT(K)	ENR (dB)	ΔENR(dB)
12.4	0.044	1203	9.2	4.979	0.044
13.5	0.045	1186	9.5	4.900	0.046
15.0	0.054	1175	9.6	4.845	0.047
17.5	0.060	1210	10.0	5.015	0.047
18.0	0.062	1216	10.2	5.041	0.048

Table 8.6

A.3.2 BNM-LCIE Uncertainties

We use a switching radiometer where the standard and unknown noise sources are connected successively for comparison [1].
The radiometer equation gives the unknown noise temperature:

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

where
T_a: ambient temperature (K)
T_s: standard noise temperature (K)
A_s-A_x: variation of the attenuation (in dB) read on the calibrated attenuator
S_{11}: reflection coefficient at the radiometer input
ρ_s: reflection coefficient of the standard source
ρ_x: reflection coefficient of the unknown source
Γ_s: magnitude of ρ_s
Γ_x: magnitude of ρ_x

The ENR is given by

$$\mathrm{ENR}_x(\mathrm{dB}) = 10\log\frac{T_x(\mathrm{K}) - 290\mathrm{K}}{290\mathrm{K}}$$

The formula that gives the uncertainty on T_x is:

$$\begin{aligned}\Delta T_x &= 10^{\frac{A_s - A_x}{10}}\,\Delta T_s \quad \text{(standard)}\\
&+ \left(1 - 10^{\frac{A_s - A_x}{10}}\right)\Delta T_a \quad \text{(ambient)}\\
&+ 0.23\cdot 10^{\frac{A_s - A_x}{10}}\,(T_s - T_a)\,\Delta(A_s - A_x) \quad \text{(attenuation measurement)}\\
&+ (T_s - T_a)10^{\frac{A_s - A_x}{10}}\left[2|S_{11}|(\Gamma_s + \Gamma_x)\right] \quad \text{(mismatch)}\\
&+ 2\cdot 10^{\frac{A_s - A_x}{10}}\,(T_s - T_a)\,\Gamma_s\Delta\Gamma_s \quad \text{(standard reflection coefficient)}\\
&+ 2\cdot 10^{\frac{A_s - A_x}{10}}\,(T_s - T_a)\,\Gamma_x\Delta\Gamma_x \quad \text{(unknown reflection coefficient)}\end{aligned}$$

And the uncertainty on ENR is:

$$\Delta\mathrm{ENR}_x(\mathrm{dB}) = 10\log\left(1 + \frac{\Delta Tx(\mathrm{K})}{Tx(\mathrm{K}) - 290\mathrm{K}}\right)$$

As an example, uncertainties for TSB1 (at R140-waveguide plane and PC7-coaxial plane) are given in the tables below.

Source: TSB1
Reference plane: R140

F(GHz)	12.4	13.5	15	17.5	18
Standard	88	87	88	89	87
Ambient	0.1	0.1	0.1	0.1	0.1
Attenuation Meas.	23	24	24	25	23
Mismatch	16	18	22	26	25
Refl.factor Standard	2	3	3	4	3
Refl.factor Unknown	6	5	5	7	8
Adapter	0	0	0	0	0
Total Type B	93	92	96	97	94
Type A	25	28	27	20	25
Total	96	97	100	99	98

Table U.8.7

Source: TSB1
Reference plane: PC-7

F(GHz)	12.4	13.5	15	17.5	18
Standard	88	87	88	89	87
Ambient	0.1	0.1	0.1	0.1	0.1
Attenuation Meas.	23	24	24	25	23
Mismatch	16	18	22	26	25
Refl.factor Standard	2	3	3	4	3
Refl.factor Unknown	6	5	5	7	8
Adapter	50	50	50	50	50
Total Type B	106	105	108	109	107
Type A	25	24	27	20	25
Total	109	108	112	111	110

Table U.8.8

A.4 NIST RESULTS
A.4.1 NIST Measurements

Transfer Standard: TSA1 **Reference Plane:** output flange R140

Date of calibration: April 2000
Room Temperature: (23±0.5) °C Room Humidity: (40±5)%

F (GHz)	Γ	T (K)	ΔT(K)	ENR (dB)	ΔENR(dB)
12.4	0.0081	11038	44	15.689	0.018
13.5	0.0038	11023	44	15.683	0.018
15.0	0.0070	11006	47	15.676	0.019
17.5	0.0021	10981	49	15.666	0.020
18.0	0.0096	10953	50	15.655	0.020

Table 6.1

Transfer Standard: TSB1 **Reference Plane:** output adapter PC-7/R140

Date of calibration: April 2000
Room Temperature: (23±0.5) °C Room Humidity: (40±5)%

F (GHz)	Γ	T (K)	ΔT(K)	ENR (dB)	ΔENR(dB)
12.4	0.0418	11246	45	15.773	0.018
13.5	0.0389	11318	46	15.801	0.018
15.0	0.0637	11382	47	15.826	0.018
17.5	0.0282	11058	48	15.697	0.019
18.0	0.0181	10759	47	15.575	0.020

Table 6.2

Transfer Standard: TSB1 **Reference Plane:** output connector PC-7

Date of calibration: April 2000
Room Temperature: (23±0.5) °C Room Humidity: (40±5)%

F (GHz)	Γ	T (K)	ΔT(K)	ENR (dB)	ΔENR(dB)
12.4	0.038	11422	60	15.842	0.023
13.5	0.042	11524	61	15.881	0.024
15.0	0.063	11704	64	15.950	0.024
17.5	0.036	11399	63	15.833	0.025
18.0	0.034	11108	63	15.717	0.025

Table 6.3

<u>Transfer Standard:</u> TSA2 **<u>Reference Plane:</u>** output flange R140

Date of calibration: April 2000
Room Temperature: (23±0.5) °C Room Humidity: (40±5)%

F (GHz)	Γ	T (K)	ΔT(K)	ENR (dB)	ΔENR(dB)
12.4	0.0082	11210	44	15.758	0.018
13.5	0.0078	11204	44	15.756	0.018
15.0	0.0059	11193	46	15.751	0.018
17.5	0.0058	11196	49	15.753	0.020
18.0	0.0036	11187	51	15.749	0.020

Table 6.4

<u>Transfer Standard:</u> TSB2 **<u>Reference Plane:</u>** output adapter PC-7/R140

Date of calibration: April 2000
Room Temperature: (23±0.5) °C Room Humidity: (40±5)%

F (GHz)	Γ	T (K)	ΔT(K)	ENR (dB)	ΔENR(dB)
12.4	0.0662	1174	4	4.841	0.018
13.5	0.0313	1152	4	4.731	0.018
15.0	0.0558	1139	4	4.665	0.018
17.5	0.0467	1173	4	4.836	0.019
18.0	0.0229	1172	4	4.831	0.021

Table 6.5

<u>Transfer Standard:</u> TSB2 **<u>Reference Plane:</u>** output connector PC-7

Date of calibration: April 2000
Room Temperature: (23±0.5) °C Room Humidity: (40±5)%

F (GHz)	Γ	T (K)	ΔT(K)	ENR (dB)	ΔENR(dB)
12.4	0.043	1195	5	4.943	0.023
13.5	0.046	1173	5	4.836	0.023
15.0	0.055	1164	6	4.791	0.029
17.5	0.060	1207	6	5.000	0.029
18.0	0.059	1206	6	4.995	0.030

Table 6.6

A.4.2 NIST Uncertainties

Source: TSA1 Reference plane: R140

F(GHz)	12.4	13.5	15	17.5	18
Cryogenic Std.	8.3	8.3	8.3	8.2	8.2
Ambient Std.	5.1	5.1	5.1	5.1	5.0
Y factors	4.3	4.3	4.3	4.3	4.3
Mismatch factors	2.8	7.2	5.6	6.0	3.4
Path difference	30.1	30.1	29.9	29.9	29.8
Isolation	3.0	3.0	3.0	3.0	2.8
Connector var.	26.0	27.2	28.6	30.9	31.2
Broadband Mismatch	0.0	0.1	0.2	0.1	0.1
Nonlinearity	6.6	6.6	6.6	6.6	6.6
Adapter	0	0	0	0	0
Total Type B	41.9	43.1	43.8	45.2	45.1
Type A	13.5	10.9	16.2	18.0	21.1
Total	44.1	44.5	46.7	48.7	49.8

Table U.6.1

Source: TSB1 Reference plane: R140

F(GHz)	12.4	13.5	15	17.5	18
Cryogenic Std.	8.4	8.5	8.5	8.3	8.1
Ambient Std.	5.2	5.2	5.2	5.1	4.9
Y factors	4.4	4.4	4.4	4.3	4.2
Mismatch factors	8.7	11.2	10.1	10.1	1.8
Path difference	30.7	30.9	31.1	30.2	29.3
Isolation	3.1	3.1	3.2	2.9	2.8
Connector var.	26.7	28.0	29.6	31.1	30.7
Broadband Mismatch	0.1	0.2	0.6	0.4	0.1
Nonlinearity	6.7	6.8	6.8	6.6	6.5
Adapter	0	0	0	0	0
Total Type B	43.5	45.0	46.1	46.2	44.2
Type A	11.0	7.3	9.9	11.4	16.6
Total	44.9	45.6	47.2	47.6	47.2

Table U.6.2

Source: TSB1 Reference plane: PC-7

F(GHz)	12.4	13.5	15	17.5	18
Cryogenic Std.	8.6	8.6	8.8	8.6	8.3
Ambient Std.	5.3	5.3	5.4	5.2	5.1
Y factors	4.5	4.5	4.6	4.4	4.3
Mismatch factors	8.8	11.4	10.4	10.4	1.9
Path difference	31.2	31.5	32.0	31.1	30.2
Isolation	3.2	3.1	3.3	3.0	2.9
Connector var.	27.1	28.5	30.5	32.1	31.7
Broadband Mismatch	0.1	0.2	0.6	0.5	0.1
Nonlinearity	6.9	6.9	7.0	6.8	6.7
Adapter	39.6	40.0	41.1	40.1	39.1
Total Type B	59.4	60.9	62.8	62.3	60.1
Type A	11.2	7.4	10.2	11.8	17.1
Total	60.4	61.3	63.6	63.4	62.5

Table U.6.3

Source: TSA2 Reference plane: R140

F(GHz)	12.4	13.5	15	17.5	18
Cryogenic Std.	8.4	8.4	8.4	8.4	8.4
Ambient Std.	5.2	5.2	5.1	5.2	5.1
Y factors	4.4	4.4	4.4	4.4	4.4
Mismatch factors	2.2	5.0	5.5	6.3	3.4
Path difference	30.6	30.6	30.6	30.6	30.5
Isolation	3.1	3.1	3.1	3.1	3.1
Connector var.	26.6	27.7	29.1	31.5	31.9
Broadband Mismatch	0.0	0.1	0.2	0.1	0.1
Nonlinearity	6.7	6.7	6.7	6.7	6.7
Adapter	0	0	0	0	0
Total Type B	42.6	43.5	44.5	46.1	46.1
Type A	10.4	9.0	12.9	15.0	21.9
Total	43.9	44.4	46.3	48.5	51.0

Table U.6.4

Source: TSB2 Reference plane: R140

F(GHz)	12.4	13.5	15	17.5	18
Cryogenic Std.	0.7	0.7	0.6	0.7	0.7
Ambient Std.	0.5	0.5	0.5	0.5	0.5
Y factors	0.4	0.3	0.3	0.4	0.4
Mismatch factors	0.8	0.5	0.7	0.3	0.5
Path difference	2.5	2.4	2.4	2.5	2.5
Isolation	0.3	0.3	0.3	0.3	0.3
Connector var.	2.1	2.2	2.3	2.5	2.6
Broadband Mismatch	0.0	0.0	0.0	0.0	0.0
Nonlinearity	0.7	0.7	0.7	0.7	0.7
Adapter	0	0	0	0	0
Total Type B	3.6	3.5	3.5	3.8	3.8
Type A	0.6	0.6	0.8	0.9	1.8
Total	3.6	3.5	3.6	3.9	4.2

Table U.6.5

Source: TSB2 Reference plane: PC-7

F(GHz)	12.4	13.5	15	17.5	18
Cryogenic Std.	0.7	0.7	0.7	0.7	0.7
Ambient Std.	0.5	0.5	0.5	0.5	0.5
Y factors	0.4	0.4	0.4	0.4	0.4
Mismatch factors	0.8	0.5	0.7	0.3	0.5
Path difference	2.5	2.5	2.4	2.6	2.6
Isolation	0.3	0.3	0.3	0.3	0.3
Connector var.	2.2	2.2	2.3	2.6	2.7
Broadband Mismatch	0.0	0.0	0.0	0.0	0.0
Nonlinearity	0.7	0.7	0.7	0.7	0.7
Adapter	3.1	3.1	4.5	4.7	4.7
Total Type B	4.8	4.7	5.8	6.1	6.1
Type A	0.6	0.7	0.8	1.0	1.9
Total	4.8	4.7	5.8	6.2	6.4

Table U.6.6

A.5 VNIIFTRI RESULTS

A.5.1 VNIIFTRI Measurements

Transfer Standard: TSA1 **Reference Plane:** output flange R140

Date of calibration: 06.09-16.10.2000
Room Temperature: (24±3) °C Room Humidity: (67±4)%

F (GHz)	Γ	T (K)	ΔT(K)	ENR (dB)	ΔENR(dB)
12.4	0.004	11360	79	15.817	0.031
13.5	0.004	11181	68	15.747	0.027
15.0	0.005	11106	70	15.717	0.028
17.5	0.012	11252	66	15.775	0.026

Table 7.1

Transfer Standard: TSB1 **Reference Plane:** output adapter PC-7/R140

Date of calibration: 03.09-06.10.2000
Room Temperature: (24±3) °C Room Humidity: (67±4)%

F (GHz)	Γ	T (K)	ΔT(K)	ENR (dB)	ΔENR(dB)
12.4	0.041	11495	93	15.870	0.036
13.5	0.040	11505	72	15.874	0.028
15.0	0.066	11437	85	15.848	0.033
17.5	0.037	11570	67	15.899	0.026

Table 7.2

Transfer Standard: TSB1 **Reference Plane:** output connector PC-7

Date of calibration: 29.09-16.10.2000
Room Temperature: (24±3) °C Room Humidity: (67±4)%

F (GHz)	Γ	T (K)	ΔT(K)	ENR (dB)	ΔENR(dB)
12.4	0.027	11715	94	15.954	0.035
13.5	0.054	11755	75	15.970	0.028
15.0	0.058	11787	88	15.982	0.033
17.5	0.032	11982	72	16.055	0.027

Table 7.3

Transfer Standard: TSA2 **Reference Plane:** output flange R140

Date of calibration: 10.09-16.10.2000
Room Temperature: (24±3) °C Room Humidity: (67±4)%

F (GHz)	Γ	T (K)	ΔT(K)	ENR (dB)	ΔENR(dB)
12.4	0.007	11541	78	15.888	0.030
13.5	0.006	11356	66	15.816	0.026
15.0	0.004	11302	71	15.795	0.028
17.5	0.007	11630	63	15.922	0.024

Table 7.4

Transfer Standard: TSB2 **Reference Plane:** output adapter PC-7/R140

Date of calibration: 27.08-06.10.2000
Room Temperature: (24±3) °C Room Humidity: (67±4)%

F (GHz)	Γ	T (K)	ΔT(K)	ENR (dB)	ΔENR(dB)
12.4	0.058	1183	6.7	4.885	0.032
13.5	0.038	1157	5.3	4.754	0.027
15.0	0.056	1142	5.4	4.681	0.027
17.5	0.047	1175	6.4	4.845	0.031

Table 7.5

Transfer Standard: TSB2 **Reference Plane:** output connector PC-7

Date of calibration: 29.09-16.10.2000
Room Temperature: (24±3) °C Room Humidity: (67±4)%

F (GHz)	Γ	T (K)	ΔT(K)	ENR (dB)	ΔENR(dB)
12.4	0.051	1206	6.7	4.996	0.032
13.5	0.064	1183	5.5	4.883	0.027
15.0	0.072	1179	5.6	4.866	0.028
17.5	0.105	1219	8.7	5.056	0.041

Table 7.6

A.5.2 VNIIFTRI Uncertainties

Main contributions in the uncertainty budget

The main uncertainty sources of measured noise temperature NT and designations of uncertainty components* (for TSA1, TSA2, TSB1, TSB2)		U_i/u_i
1. Uncertainty of a mean NT on five measurements	u_a	
2. NT uncertainty of a primary standard PS, or (on 18 GHz) working standard TSB2	U_1	$\sqrt{3}$
3. Discrepancy of PS and TS reflection coefficients	U_2	$\sqrt{2}$
4. Uncertainty because of reflections from an input of a radiometer at comparisons with PS, or at comparisons with TSB2 - uncertainty of correction factor on a difference of quadrates of reflection coefficients modules of transfer standards	U_3	$\sqrt{2}$
5 Uncertainty of measurement of attenuation by RVA	U_4	$\sqrt{3}$
6. Uncertainty of correction factor on non-linearity of a radiometer	U_5	$\sqrt{3}$
7. Uncertainty of a transmission ratio of a resistive divider	U_6	$\sqrt{3}$
8. Uncertainty of temperature of a «room» load or of a RVA vane	U_7	$\sqrt{3}$

*u_a – standard uncertainty of type A; U_i and u_i – maximum allowed and standard uncertainties
of type B.

Table 7

Numerical evaluations of main uncertainty components U_i, u_a, and also combined uncertainties u_c for TSA1, TSA2, TSB1, TSB2 (in K)										
Comparison method	F(GHz)	U_1	U_2	U_3	U_4	U_5	U_6	U_7	u_a	u_c
TSA1/PS	12.4	5.9	4.5	14.7	25.5	25.5	104.6	51.8	28.1	76.9
	13.5	5.9	2.6	9.7	25.2	25.2	79.3	51.1	30.2	66.1
	15.0	5.9	7.8	21.1	25.0	25.0	85.1	50.7	27.0	68.5
	17.5	5.9	10.5	16.8	25.2	25.2	83.9	51.2	56.0	83.7
TSA1/TSB2	18.0	63.6	15.8	14.5	0.0	25.5	18.3	11.2	8.8	68.7
TSA2/PS	12.4	6.1	4.8	10.3	25.9	25.9	104.6	52.5	20.2	74.2
	13.5	6.0	5.4	12.4	25.4	25.4	79.3	51.6	20.3	62.8
	15.0	6.0	4.8	16.0	25.4	25.4	85.1	51.7	12.7	63.7
	17.5	6.0	5.2	14.7	26.1	26.1	83.9	53.0	36.0	72.0
TSA2/TSB2	18.0	64.9	16.1	14.8	0.0	26.1	18.3	11.4	9.0	70.0
TSB1/PS	12.4	5.8	26.6	9.5	25.6	25.6	104.6	52.0	52.8	90.5
	13.5	5.8	23.4	8.6	25.7	25.7	79.3	52.2	21.6	65.2
	15.0	5.8	84.0	18.8	25.8	25.8	85.1	52.3	25.8	90.3
	17.5	5.8	37.1	19.9	26.0	26.0	83.9	52.7	33.2	75.7
TSB1/TSB2	18.0	62.5	15.5	14.3	0.0	25.1	18.3	11.0	8.6	67.5
TSB2/PS	12.4	0.5	3.9	0.7	0.0	2.0	8.0	5.1	1.7	6.7
	13.5	0.5	2.6	0.7	0.0	2.0	5.8	4.9	1.4	5.3
	15.0	0.5	3.1	0.6	0.0	1.9	5.5	4.9	1.6	5.4
	17.5	0.5	3.5	1.1	0.0	2.0	5.9	5.0	3.2	6.4
	18.0	0.5	1.4	0.7	0.0	2.1	6.2	5.2	0.7	5.2

Table 8

The main uncertainty sources of measured noise temperature NT and designations of uncertainty components for coaxial TS at their output PC-7 connectors		U_i/u_i
1. Uncertainty of a mean NT on five pairs of measurements	u_a'	
2. NT uncertainty of TSB1 or TSB2 at their output R140 flanges	U_1'	$\sqrt{3}$
3. Discrepancy of reflection coefficients	U_2'	$\sqrt{2}$
4. Uncertainty of correction factor on a difference of quadrates of reflection coefficients modules of transfer standards	U_3'	$\sqrt{2}$
5. Uncertainty of a transmission ratio of a resistive divider	U_4'	$\sqrt{3}$

* See note to table 7

Table 9*

Numerical evaluations of main uncertainty components U_i', u_a', and combined uncertainties u_c' for TSB1c, TSB2c (in K)							
Measurements procedure	F(GHz)	U_1'	U_2'	U_3'	U_4'	u_a'	u_c'
a) TSB1 → TSA2 b) $TSB1_c$ → $TSA2_{wc1}$	12.4	92.8	15.1	7.5	2.4	1.6	93.6
	13.5	72.2	25.1	10.8	2.9	3.0	74.8
	15.0	84.6	25.8	18.4	0.0	1.1	87.5
	17.5	67.4	20.7	30.1	2.8	1.2	72.2
	18.0	70.2	38.6	42.9	0.0	3.3	81.3
a) TSB2 → TSA2 b) $TSB2_c$ → $TSA2_{wc2}$	12.4	6.6	0.1	1.6	1.2	0.1	6.7
	13.5	5.4	0.1	1.5	1.0	0.4	5.5
	15.0	5.3	0.0	2.2	1.6	0.4	5.6
	17.5	6.3	0.2	6.2	5.7	0.3	8.7
	18.0	5.3	0.0	4.0	4.3	0.3	6.7

Designations: $TSB1_c$ or $TSB2_c$ - TSB1 or TSB2 without their PC7/R140 adapter, $TSA2_{wc1}$ - TSA2 with the TSB1 adapter; $TSA2_{wc2}$ - TSA2 with the TSB2 adapter.

Table 10

Influence of switching of the standard TSB1 on the radiometer input

F (GHz)	Experimental standard deviation of the mean of the five measurements (dB)		
	at switching in a plane:		at absence of the switching
	between input of a radiometer and TSB1 output with the additional adapter	of output PC-7 connector with simultaneous rotational displacements of the coaxial standard on 90°	
12.4	0.0006	0.0012	0.0005
18.0	0.0013	0.0021	0.0007

Table 11

A.6. KCRV and Degrees of Equivalence: Numerical Data

A.6.1.a: Weighted case
Source: TSA1
Reference plane: R140

12.4 GHz

KCRV	u_{KCRV}
15.699	0.009

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	15.700	0.038	0.000	0.073	no
NPL	15.687	0.021	0.012	0.038	no
PTB	15.709	0.013	-0.009	0.017	no
NIST	15.689	0.018	0.010	0.031	no
VNIIFTRI	*15.817*	*0.031*	*-0.118*	*0.065*	*yes*

13.5 GHz

KCRV	u_{KCRV}
15.707	0.009

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	15.718	0.038	-0.010	0.073	no
NPL	15.682	0.024	0.025	0.044	no
PTB	15.719	0.015	-0.012	0.022	no
NIST	15.683	0.018	0.024	0.031	no
VNIIFTRI	15.747	0.027	-0.040	0.051	no

15 GHz

KCRV	u_{KCRV}
15.692	0.009

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	15.681	0.039	0.011	0.076	no
NPL	15.689	0.020	0.003	0.035	no
PTB	15.700	0.016	-0.007	0.026	no
NIST	15.676	0.019	0.016	0.033	no
VNIIFTRI	15.717	0.028	-0.025	0.053	no

17.5 GHz

KCRV	u_{KCRV}
15.674	0.012

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	15.683	0.039	-0.009	0.074	no
NPL	15.659	0.031	0.015	0.057	no
PTB	15.683	0.018	-0.009	0.027	no
NIST	15.666	0.020	0.008	0.032	no
VNIIFTRI	*15.775*	*0.026*	*-0.101*	*0.057*	*yes*

18 GHz

KCRV	u_{KCRV}
15.654	0.011

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	15.666	0.039	-0.012	0.075	no
NPL	15.658	0.021	-0.004	0.035	no
PTB	15.645	0.021	0.009	0.034	no
NIST	15.655	0.020	-0.001	0.033	no

A.6.1.b: Unweighted case
Source: TSA1
Reference plane: R140

12.4 GHz

KCRV	u_{KCRV}
15.696	0.005

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	15.700	0.038	-0.004	0.054	no
NPL	15.687	0.021	0.009	0.031	no
PTB	15.709	0.013	-0.012	0.020	no
NIST	15.689	0.018	0.007	0.027	no
VNIIFTRI	*15.817*	*0.031*	*-0.121*	*0.063*	*yes*

13.5 GHz

KCRV	u_{KCRV}
15.710	0.012

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	15.718	0.038	-0.008	0.063	no
NPL	15.682	0.024	0.028	0.045	no
PTB	15.719	0.015	-0.009	0.033	no
NIST	15.683	0.018	0.027	0.037	no
VNIIFTRI	15.747	0.027	-0.037	0.049	no

15 GHz

KCRV	u_{KCRV}
15.693	0.007

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	15.681	0.039	0.012	0.063	no
NPL	15.689	0.020	0.004	0.034	no
PTB	15.700	0.016	-0.007	0.029	no
NIST	15.676	0.019	0.017	0.033	no
VNIIFTRI	15.717	0.028	-0.024	0.046	no

17.5 GHz

KCRV	u_{KCRV}
15.673	0.006

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	15.683	0.039	-0.010	0.056	no
NPL	15.659	0.031	0.014	0.045	no
PTB	15.683	0.018	-0.010	0.028	no
NIST	15.666	0.020	0.007	0.031	no
VNIIFTRI	*15.775*	*0.026*	*-0.102*	*0.053*	*yes*

18 GHz

KCRV	u_{KCRV}
15.656	0.004

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	15.666	0.039	-0.010	0.056	no
NPL	15.658	0.021	-0.002	0.031	no
PTB	15.645	0.021	0.011	0.030	no
NIST	15.655	0.020	0.001	0.030	no

A.6.1.c: Weighted case, outliers included
Source: TSA1
Reference plane: R140

12.4 GHz

KCRV	u_{KCRV}
15.708	0.009

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$
BNM	15.700	0.038	0.009	0.073
NPL	15.687	0.021	0.021	0.038
PTB	15.709	0.013	0.000	0.018
NIST	15.689	0.018	0.019	0.032
VNIIFTRI	15.817	0.031	-0.109	0.060

17.5 GHz

KCRV	u_{KCRV}
15.691	0.011

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$
BNM	15.683	0.039	0.008	0.075
NPL	15.659	0.031	0.032	0.058
PTB	15.683	0.018	0.008	0.029
NIST	15.666	0.020	0.025	0.034
VNIIFTRI	15.775	0.026	-0.084	0.047

A.6.1.d: Unweighted case, outliers included
Source: TSA1
Reference plane: R140

12.4 GHz

KCRV	u_{KCRV}
15.720	0.024

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$
BNM	15.700	0.038	0.021	0.076
NPL	15.687	0.021	0.033	0.059
PTB	15.709	0.013	0.012	0.053
NIST	15.689	0.018	0.031	0.056
VNIIFTRI	15.817	0.031	-0.097	0.069

17.5 GHz

KCRV	u_{KCRV}
15.693	0.021

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$
BNM	15.683	0.039	0.010	0.074
NPL	15.659	0.031	0.034	0.064
PTB	15.683	0.018	0.010	0.050
NIST	15.666	0.020	0.027	0.052
VNIIFTRI	15.775	0.026	-0.082	0.058

A.6.2.a: Weighted case
Source: TSB1
Reference plane: PC-7/R140

12.4 GHz

KCRV	u_{KCRV}
15.785	0.009

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	15.785	0.039	0.000	0.075	no
NPL	15.787	0.021	-0.002	0.038	no
PTB	15.792	0.014	-0.006	0.020	no
NIST	15.773	0.018	0.012	0.031	no
VNIIFTRI	*15.870*	*0.036*	*-0.085*	*0.074*	*yes*

13.5 GHz

KCRV	u_{KCRV}
15.829	0.009

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	15.835	0.039	-0.006	0.076	no
NPL	15.822	0.024	0.007	0.044	no
PTB	15.838	0.015	-0.008	0.023	no
NIST	15.801	0.018	0.028	0.031	no
VNIIFTRI	15.874	0.028	-0.045	0.053	no

15 GHz

KCRV	u_{KCRV}
15.839	0.010

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	15.836	0.040	0.003	0.078	no
NPL	15.857	0.020	-0.018	0.035	no
PTB	15.835	0.018	0.004	0.029	no
NIST	15.826	0.018	0.013	0.030	no
VNIIFTRI	15.848	0.033	-0.009	0.063	no

17.5 GHz

KCRV	u_{KCRV}
15.696	0.013

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	15.692	0.040	0.004	0.075	no
NPL	*15.667*	*0.031*	*0.029*	*0.067*	*yes*
PTB	15.696	0.019	0.000	0.027	no
NIST	15.697	0.019	-0.001	0.028	no
VNIIFTRI	*15.899*	*0.026*	*-0.203*	*0.058*	*yes*

18 GHz

KCRV	u_{KCRV}
15.577	0.011

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	15.582	0.039	-0.005	0.075	no
NPL	15.608	0.021	-0.031	0.035	no
PTB	15.546	0.021	0.031	0.035	no
NIST	15.575	0.020	0.002	0.033	no

A.6.2.b: Unweighted case
Source: TSB1
Reference plane: PC-7/R140

12.4 GHz

KCRV	u_{KCRV}
15.784	0.004

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	15.785	0.039	-0.001	0.055	no
NPL	15.787	0.021	-0.003	0.031	no
PTB	15.792	0.014	-0.007	0.021	no
NIST	15.773	0.018	0.011	0.027	no
VNIIFTRI	*15.870*	*0.036*	*-0.086*	*0.072*	*yes*

13.5 GHz

KCRV	u_{KCRV}
15.834	0.012

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	15.835	0.039	-0.001	0.065	no
NPL	15.822	0.024	0.012	0.044	no
PTB	15.838	0.015	-0.004	0.033	no
NIST	15.801	0.018	0.033	0.037	no
VNIIFTRI	15.874	0.028	-0.040	0.050	no

15 GHz

KCRV	u_{KCRV}
15.840	0.005

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	15.836	0.040	0.004	0.063	no
NPL	15.857	0.020	-0.017	0.033	no
PTB	15.835	0.018	0.005	0.029	no
NIST	15.826	0.018	0.014	0.030	no
VNIIFTRI	15.848	0.033	-0.008	0.052	no

17.5 GHz

KCRV	u_{KCRV}
15.695	0.001

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	15.692	0.040	0.003	0.046	no
NPL	*15.667*	*0.031*	*0.028*	*0.062*	*yes*
PTB	15.696	0.019	-0.001	0.022	no
NIST	15.697	0.019	-0.002	0.022	no
VNIIFTRI	*15.899*	*0.026*	*-0.204*	*0.052*	*yes*

18 GHz

KCRV	u_{KCRV}
15.578	0.013

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	15.582	0.039	-0.004	0.061	no
NPL	15.608	0.021	-0.030	0.039	no
PTB	15.546	0.021	0.032	0.039	no
NIST	15.575	0.020	0.003	0.038	no

A.6.2.c: Weighted case, outliers included
Source: TSB1
Reference plane: PC-7/R140

12.4 GHz

KCRV	u_{KCRV}
15.791	0.009

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$
BNM	15.785	0.039	0.006	0.075
NPL	15.787	0.021	0.004	0.038
PTB	15.792	0.014	-0.001	0.020
NIST	15.773	0.018	0.018	0.031
VNIIFTRI	15.870	0.036	-0.079	0.070

17.5 GHz

KCRV	u_{KCRV}
15.726	0.011

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$
BNM	15.692	0.040	0.034	0.076
NPL	15.667	0.031	0.059	0.058
PTB	15.696	0.019	0.031	0.030
NIST	15.697	0.019	0.029	0.031
VNIIFTRI	15.899	0.026	-0.173	0.047

A.6.2.d: Unweighted case, outliers included
Source: TSB1
Reference plane: PC-7/R140

12.4 GHz

KCRV	u_{KCRV}
15.801	0.017

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$
BNM	15.785	0.039	0.016	0.069
NPL	15.787	0.021	0.014	0.048
PTB	15.792	0.014	0.010	0.041
NIST	15.773	0.018	0.028	0.045
VNIIFTRI	15.870	0.036	-0.069	0.066

17.5 GHz

KCRV	u_{KCRV}
15.730	0.043

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$
BNM	15.692	0.040	0.038	0.105
NPL	15.667	0.031	0.063	0.098
PTB	15.696	0.019	0.035	0.090
NIST	15.697	0.019	0.033	0.090
VNIIFTRI	15.899	0.026	-0.169	0.094

A.6.3.a: Weighted case
Source: TSB1
Reference plane: PC-7

12.4 GHz

KCRV	u_{KCRV}
15.864	0.011

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	15.877	0.044	-0.013	0.084	no
NPL	15.856	0.049	0.008	0.095	no
PTB	15.871	0.014	-0.007	0.017	no
NIST	15.842	0.023	0.022	0.040	no
VNIIFTRI	*15.954*	*0.035*	*-0.090*	*0.074*	*yes*

13.5 GHz

KCRV	u_{KCRV}
15.922	0.011

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	15.929	0.043	-0.007	0.083	no
NPL	15.896	0.037	0.026	0.071	no
PTB	15.928	0.016	-0.006	0.022	no
NIST	15.881	0.024	0.041	0.043	no
VNIIFTRI	15.970	0.028	-0.048	0.052	no

15 GHz

KCRV	u_{KCRV}
15.957	0.013

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	15.956	0.045	0.001	0.086	no
NPL	15.957	0.034	0.000	0.063	no
PTB	15.961	0.018	-0.004	0.024	no
NIST	15.950	0.024	0.007	0.041	no
VNIIFTRI	*15.982*	*0.033*	*-0.025*	*0.071*	*yes*

17.5 GHz

KCRV	u_{KCRV}
15.838	0.013

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	15.836	0.045	0.002	0.086	no
NPL	15.809	0.045	0.029	0.086	no
PTB	15.847	0.019	-0.008	0.025	no
NIST	15.833	0.025	0.005	0.042	no
VNIIFTRI	*16.055*	*0.027*	*-0.217*	*0.060*	*yes*

18 GHz

KCRV	u_{KCRV}
15.713	0.014

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	15.741	0.045	-0.028	0.085	no
NPL	15.766	0.040	-0.053	0.075	no
PTB	15.689	0.021	0.024	0.031	no
NIST	15.717	0.025	-0.004	0.041	no

A.6.3.b: Unweighted case
Source: TSB1
Reference plane: PC-7

12.4 GHz

KCRV	u_{KCRV}
15.862	0.008

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	15.877	0.044	-0.016	0.064	no
NPL	15.856	0.049	0.005	0.071	no
PTB	15.871	0.014	-0.010	0.025	no
NIST	15.842	0.023	0.019	0.036	no
VNIIFTRI	*15.954*	*0.035*	*-0.093*	*0.072*	*yes*

13.5 GHz

KCRV	u_{KCRV}
15.921	0.015

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	15.929	0.043	-0.008	0.073	no
NPL	15.896	0.037	0.025	0.065	no
PTB	15.928	0.016	-0.007	0.039	no
NIST	15.881	0.024	0.040	0.048	no
VNIIFTRI	15.970	0.028	-0.049	0.053	no

15 GHz

KCRV	u_{KCRV}
15.956	0.002

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	15.956	0.045	0.000	0.063	no
NPL	15.957	0.034	-0.001	0.048	no
PTB	15.961	0.018	-0.005	0.025	no
NIST	15.950	0.024	0.006	0.034	no
VNIIFTRI	*15.982*	*0.033*	*-0.026*	*0.066*	*yes*

17.5 GHz

KCRV	u_{KCRV}
15.831	0.008

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	15.836	0.045	-0.005	0.066	no
NPL	15.809	0.045	0.022	0.066	no
PTB	15.847	0.019	-0.015	0.031	no
NIST	15.833	0.025	-0.002	0.039	no
VNIIFTRI	*16.055*	*0.027*	*-0.224*	*0.056*	*yes*

18 GHz

KCRV	u_{KCRV}
15.728	0.016

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	15.741	0.045	-0.013	0.071	no
NPL	15.766	0.040	-0.038	0.065	no
PTB	15.689	0.021	0.039	0.044	no
NIST	15.717	0.025	0.011	0.048	no

A.6.3.c: Weighted case, outliers included
Source: TSB1
Reference plane: PC-7

12.4 GHz

KCRV	u_{KCRV}
15.872	0.011

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$
BNM	15.877	0.044	-0.005	0.085
NPL	15.856	0.049	0.016	0.096
PTB	15.871	0.014	0.001	0.018
NIST	15.842	0.023	0.030	0.041
VNIIFTRI	15.954	0.035	-0.082	0.067

15 GHz

KCRV	u_{KCRV}
15.960	0.012

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$
BNM	15.956	0.045	0.004	0.086
NPL	15.957	0.034	0.003	0.064
PTB	15.961	0.018	-0.001	0.026
NIST	15.950	0.024	0.010	0.042
VNIIFTRI	15.982	0.033	-0.022	0.062

17.5 GHz

KCRV	u_{KCRV}
15.881	0.012

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$
BNM	15.836	0.045	0.045	0.087
NPL	15.809	0.045	0.072	0.087
PTB	15.847	0.019	0.035	0.028
NIST	15.833	0.025	0.048	0.044
VNIIFTRI	16.055	0.027	-0.174	0.048

A.6.3.d: Unweighted case, outliers included
Source: TSB1
Reference plane: PC-7

12.4 GHz

KCRV	u_{KCRV}
15.880	0.019

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$
BNM	15.877	0.044	0.003	0.078
NPL	15.856	0.049	0.024	0.085
PTB	15.871	0.014	0.009	0.045
NIST	15.842	0.023	0.038	0.053
VNIIFTRI	15.954	0.035	-0.074	0.067

15 GHz

KCRV	u_{KCRV}
15.961	0.005

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$
BNM	15.956	0.045	0.005	0.070
NPL	15.957	0.034	0.004	0.054
PTB	15.961	0.018	0.001	0.029
NIST	15.950	0.024	0.011	0.039
VNIIFTRI	15.982	0.033	-0.021	0.052

17.5 GHz

KCRV	u_{KCRV}
15.876	0.045

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$
BNM	15.836	0.045	0.040	0.114
NPL	15.809	0.045	0.067	0.114
PTB	15.847	0.019	0.029	0.095
NIST	15.833	0.025	0.043	0.098
VNIIFTRI	16.055	0.027	-0.179	0.100

A.6.4.a: Weighted case
Source: TSA2
Reference plane: R140

12.4 GHz

KCRV	u_{KCRV}
15.758	0.013

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	15.761	0.038	-0.003	0.071	no
NPL	15.758	0.022	0.001	0.035	no
PTB	*15.780*	*0.012*	*-0.022*	*0.036*	*yes*
NIST	15.758	0.018	0.000	0.025	no
VNIIFTRI	*15.888*	*0.030*	*-0.130*	*0.065*	*yes*

13.5 GHz

KCRV	u_{KCRV}
15.781	0.009

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	15.803	0.038	-0.022	0.073	no
NPL	15.755	0.024	0.026	0.043	no
PTB	15.793	0.015	-0.012	0.024	no
NIST	15.756	0.018	0.025	0.031	no
VNIIFTRI	15.816	0.026	-0.035	0.049	no

15 GHz

KCRV	u_{KCRV}
15.768	0.010

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	15.761	0.040	0.007	0.077	no
NPL	15.766	0.022	0.003	0.039	no
PTB	15.776	0.016	-0.008	0.026	no
NIST	15.751	0.018	0.017	0.031	no
VNIIFTRI	15.795	0.028	-0.027	0.053	no

17.5 GHz

KCRV	u_{KCRV}
15.760	0.011

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	15.770	0.039	-0.010	0.075	no
NPL	15.766	0.031	-0.006	0.058	no
PTB	15.761	0.017	-0.001	0.025	no
NIST	15.753	0.020	0.007	0.033	no
VNIIFTRI	*15.922*	*0.024*	*-0.162*	*0.053*	*yes*

18 GHz

KCRV	u_{KCRV}
15.746	0.012

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	15.761	0.039	-0.015	0.074	no
NPL	15.770	0.031	-0.024	0.057	no
PTB	15.730	0.020	0.016	0.032	no
NIST	15.749	0.020	-0.003	0.032	no

A.6.4.b: Unweighted case
Source: TSA2
Reference plane: R140

12.4 GHz

KCRV	u_{KCRV}
15.759	0.001

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	15.761	0.038	-0.002	0.044	no
NPL	15.758	0.022	0.001	0.025	no
PTB	*15.780*	*0.012*	*-0.021*	*0.024*	*yes*
NIST	15.758	0.018	0.001	0.021	no
VNIIFTRI	*15.888*	*0.030*	*-0.129*	*0.060*	*yes*

13.5 GHz

KCRV	u_{KCRV}
15.785	0.012

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	15.803	0.038	-0.018	0.063	no
NPL	15.755	0.024	0.030	0.044	no
PTB	15.793	0.015	-0.008	0.034	no
NIST	15.756	0.018	0.029	0.037	no
VNIIFTRI	15.816	0.026	-0.031	0.047	no

15 GHz

KCRV	u_{KCRV}
15.770	0.007

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	15.761	0.040	0.009	0.063	no
NPL	15.766	0.022	0.004	0.037	no
PTB	15.776	0.016	-0.006	0.029	no
NIST	15.751	0.018	0.019	0.032	no
VNIIFTRI	15.795	0.028	-0.025	0.046	no

17.5 GHz

KCRV	u_{KCRV}
15.762	0.004

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	15.770	0.039	-0.007	0.056	no
NPL	15.766	0.031	-0.004	0.044	no
PTB	15.761	0.017	0.001	0.025	no
NIST	15.753	0.020	0.009	0.029	no
VNIIFTRI	*15.922*	*0.024*	*-0.160*	*0.049*	*yes*

18 GHz

KCRV	u_{KCRV}
15.753	0.009

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	15.761	0.039	-0.009	0.058	no
NPL	15.770	0.031	-0.018	0.047	no
PTB	15.730	0.020	0.022	0.033	no
NIST	15.749	0.020	0.003	0.033	no

A.6.4.c: Weighted case, outliers included
Source: TSA2
Reference plane: R140

12.4 GHz

KCRV	u_{KCRV}
15.779	0.008

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$
BNM	15.761	0.038	0.019	0.074
NPL	15.758	0.022	0.022	0.041
PTB	15.780	0.012	-0.001	0.017
NIST	15.758	0.018	0.021	0.032
VNIIFTRI	15.888	0.030	-0.109	0.058

17.5 GHz

KCRV	u_{KCRV}
15.790	0.010

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$
BNM	15.770	0.039	0.020	0.075
NPL	15.766	0.031	0.024	0.058
PTB	15.761	0.017	0.029	0.027
NIST	15.753	0.020	0.037	0.034
VNIIFTRI	15.922	0.024	-0.132	0.043

A.6.4.d: Unweighted case, outliers included
Source: TSA2
Reference plane: R140

12.4 GHz

KCRV	u_{KCRV}
15.789	0.025

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$
BNM	15.761	0.038	0.028	0.077
NPL	15.758	0.022	0.031	0.061
PTB	15.780	0.012	0.009	0.054
NIST	15.758	0.018	0.031	0.057
VNIIFTRI	15.888	0.030	-0.099	0.068

17.5 GHz

KCRV	u_{KCRV}
15.794	0.032

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$
BNM	15.770	0.039	0.025	0.088
NPL	15.766	0.031	0.028	0.080
PTB	15.761	0.017	0.033	0.069
NIST	15.753	0.020	0.041	0.071
VNIIFTRI	15.922	0.024	-0.128	0.074

A.6.5.a: Weighted case
Source: TSB2
Reference plane: PC-7/R140

12.4 GHz

KCRV	u_{KCRV}
4.845	0.011

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	4.843	0.043	0.001	0.082	no
NPL	4.852	0.023	-0.007	0.039	no
PTB	4.844	0.020	0.001	0.033	no
NIST	4.841	0.018	0.004	0.028	no
VNIIFTRI	*4.885*	*0.032*	*-0.040*	*0.068*	*yes*

13.5 GHz

KCRV	u_{KCRV}
4.754	0.009

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	4.779	0.042	-0.025	0.083	no
NPL	4.751	0.024	0.003	0.044	no
PTB	4.768	0.015	-0.014	0.023	no
NIST	4.731	0.018	0.023	0.031	no
VNIIFTRI	4.754	0.027	0.000	0.051	no

15 GHz

KCRV	u_{KCRV}
4.709	0.012

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	4.717	0.044	-0.008	0.084	no
NPL	4.710	0.023	-0.001	0.038	no
PTB	4.720	0.018	-0.011	0.027	no
NIST	*4.665*	*0.018*	*0.044*	*0.043*	*yes*
VNIIFTRI	4.681	0.027	0.028	0.048	no

17.5 GHz

KCRV	u_{KCRV}
4.881	0.016

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	4.876	0.043	0.005	0.080	no
NPL	4.880	0.032	0.002	0.056	no
PTB	4.883	0.020	-0.002	0.025	no
NIST	*4.836*	*0.019*	*0.045*	*0.049*	*yes*
VNIIFTRI	*4.845*	*0.031*	*0.036*	*0.070*	*yes*

18 GHz

KCRV	u_{KCRV}
4.849	0.016

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	4.873	0.043	-0.024	0.080	no
NPL	4.877	0.033	-0.028	0.056	no
PTB	*4.751*	*0.040*	*0.098*	*0.086*	*yes*
NIST	4.831	0.021	0.018	0.026	no

A.6.5.b: Unweighted case
Source: TSB2
Reference plane: PC-7/R140

12.4 GHz

KCRV	u_{KCRV}
4.845	0.002

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	4.843	0.043	0.002	0.061	no
NPL	4.852	0.023	-0.007	0.032	no
PTB	4.844	0.020	0.001	0.029	no
NIST	4.841	0.018	0.004	0.026	no
VNIIFTRI	*4.885*	*0.032*	*-0.040*	*0.064*	*yes*

13.5 GHz

KCRV	u_{KCRV}
4.757	0.008

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	4.779	0.042	-0.023	0.068	no
NPL	4.751	0.024	0.006	0.041	no
PTB	4.768	0.015	-0.011	0.028	no
NIST	4.731	0.018	0.026	0.032	no
VNIIFTRI	4.754	0.027	0.003	0.045	no

15 GHz

KCRV	u_{KCRV}
4.707	0.009

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	4.717	0.044	-0.010	0.064	no
NPL	4.710	0.023	-0.003	0.036	no
PTB	4.720	0.018	-0.013	0.031	no
NIST	*4.665*	*0.018*	*0.042*	*0.040*	*yes*
VNIIFTRI	4.681	0.027	0.026	0.042	no

17.5 GHz

KCRV	u_{KCRV}
4.880	0.002

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	4.876	0.043	0.003	0.050	no
NPL	4.880	0.032	0.000	0.037	no
PTB	4.883	0.020	-0.003	0.023	no
NIST	*4.836*	*0.019*	*0.043*	*0.038*	*yes*
VNIIFTRI	*4.845*	*0.031*	*0.035*	*0.062*	*yes*

18 GHz

KCRV	u_{KCRV}
4.860	0.015

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	4.873	0.043	-0.013	0.058	no
NPL	4.877	0.033	-0.016	0.048	no
PTB	*4.751*	*0.040*	*0.109*	*0.085*	*yes*
NIST	4.831	0.021	0.029	0.038	no

A.6.5.c: Weighted case, outliers included
Source: TSB2
Reference plane: PC-7/R140

12.4 GHz

KCRV	u_{KCRV}
4.849	0.010

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$
BNM	4.843	0.043	0.006	0.083
NPL	4.852	0.023	-0.003	0.040
PTB	4.844	0.020	0.005	0.034
NIST	4.841	0.018	0.008	0.029
VNIIFTRI	4.885	0.032	-0.036	0.060

15 GHz

KCRV	u_{KCRV}
4.696	0.010

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$
BNM	4.717	0.044	-0.021	0.085
NPL	4.710	0.023	-0.014	0.040
PTB	4.720	0.018	-0.024	0.030
NIST	4.665	0.018	0.031	0.030
VNIIFTRI	4.681	0.027	0.015	0.050

17.5 GHz

KCRV	u_{KCRV}
4.860	0.011

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$
BNM	4.876	0.043	-0.016	0.083
NPL	4.880	0.032	-0.019	0.060
PTB	4.883	0.020	-0.023	0.033
NIST	4.836	0.019	0.024	0.031
VNIIFTRI	4.845	0.031	0.015	0.058

A.6.5.d: Unweighted case, outliers included
Source: TSB2
Reference plane: PC-7/R140

12.4 GHz

KCRV	u_{KCRV}
4.853	0.008

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$
BNM	4.843	0.043	0.010	0.068
NPL	4.852	0.023	0.001	0.039
PTB	4.844	0.020	0.009	0.035
NIST	4.841	0.018	0.012	0.032
VNIIFTRI	4.885	0.032	-0.032	0.052

15 GHz

KCRV	u_{KCRV}
4.699	0.011

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$
BNM	4.717	0.044	-0.018	0.071
NPL	4.710	0.023	-0.011	0.041
PTB	4.720	0.018	-0.021	0.035
NIST	4.665	0.018	0.034	0.035
VNIIFTRI	4.681	0.027	0.018	0.047

17.5 GHz

KCRV	u_{KCRV}
4.864	0.010

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$
BNM	4.876	0.043	-0.012	0.069
NPL	4.880	0.032	-0.016	0.053
PTB	4.883	0.020	-0.019	0.037
NIST	4.836	0.019	0.028	0.035
VNIIFTRI	4.845	0.031	0.019	0.052

A.6.6.a: Weighted case
Source: TSB2
Reference plane: PC-7

12.4 GHz

KCRV	u_{KCRV}
4.949	0.014

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	4.949	0.046	0.000	0.087	no
NPL	4.956	0.052	-0.007	0.099	no
PTB	4.952	0.021	-0.003	0.031	no
NIST	4.943	0.023	0.006	0.036	no
VNIIFTRI	*4.996*	*0.032*	*-0.047*	*0.070*	*yes*

13.5 GHz

KCRV	u_{KCRV}
4.864	0.011

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	4.893	0.046	-0.029	0.089	no
NPL	4.858	0.039	0.006	0.075	no
PTB	4.870	0.017	-0.006	0.025	no
NIST	4.836	0.023	0.028	0.040	no
VNIIFTRI	4.883	0.027	-0.019	0.049	no

15 GHz

KCRV	u_{KCRV}
4.845	0.014

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	4.849	0.048	-0.004	0.092	no
NPL	4.831	0.035	0.014	0.064	no
PTB	4.839	0.019	0.006	0.026	no
NIST	*4.791*	*0.029*	*0.054*	*0.064*	*yes*
VNIIFTRI	4.866	0.028	-0.021	0.049	no

17.5 GHz

KCRV	u_{KCRV}
5.025	0.014

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	5.040	0.047	-0.016	0.090	no
NPL	5.005	0.045	0.020	0.085	no
PTB	5.031	0.021	-0.006	0.031	no
NIST	5.000	0.029	0.025	0.051	no
VNIIFTRI	5.056	0.041	-0.031	0.077	no

18 GHz

KCRV	u_{KCRV}
4.989	0.020

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	5.044	0.047	-0.055	0.085	no
NPL	5.006	0.047	-0.017	0.085	no
PTB	4.923	0.041	0.066	0.072	no
NIST	4.995	0.030	-0.006	0.045	no

A.6.6.b: Unweighted case
Source: TSB2
Reference plane: PC-7

12.4 GHz

KCRV	u_{KCRV}
4.950	0.003

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	4.949	0.046	0.001	0.065	no
NPL	4.956	0.052	-0.006	0.073	no
PTB	4.952	0.021	-0.002	0.030	no
NIST	4.943	0.023	0.007	0.033	no
VNIIFTRI	*4.996*	*0.032*	*-0.046*	*0.064*	*yes*

13.5 GHz

KCRV	u_{KCRV}
4.868	0.010

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	4.893	0.046	-0.025	0.073	no
NPL	4.858	0.039	0.010	0.064	no
PTB	4.870	0.017	-0.002	0.033	no
NIST	4.836	0.023	0.032	0.041	no
VNIIFTRI	4.883	0.027	-0.015	0.046	no

15 GHz

KCRV	u_{KCRV}
4.846	0.008

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	4.849	0.048	-0.003	0.070	no
NPL	4.831	0.035	0.016	0.052	no
PTB	4.839	0.019	0.007	0.031	no
NIST	*4.791*	*0.029*	*0.055*	*0.060*	*yes*
VNIIFTRI	4.866	0.028	-0.020	0.042	no

17.5 GHz

KCRV	u_{KCRV}
5.026	0.011

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	5.040	0.047	-0.014	0.076	no
NPL	5.005	0.045	0.022	0.073	no
PTB	5.031	0.021	-0.005	0.039	no
NIST	5.000	0.029	0.026	0.050	no
VNIIFTRI	5.056	0.041	-0.030	0.067	no

18 GHz

KCRV	u_{KCRV}
4.992	0.025

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$	Outlier
BNM	5.044	0.047	-0.052	0.084	no
NPL	5.006	0.047	-0.014	0.084	no
PTB	4.923	0.041	0.069	0.077	no
NIST	4.995	0.030	-0.003	0.066	no

A.6.6.c: Weighted case, outliers included
Source: TSB2
Reference plane: PC-7

12.4 GHz

KCRV	u_{KCRV}
4.956	0.013

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$
BNM	4.949	0.046	0.008	0.088
NPL	4.956	0.052	0.000	0.100
PTB	4.952	0.021	0.004	0.033
NIST	4.943	0.023	0.013	0.038
VNIIFTRI	4.996	0.032	-0.040	0.059

15 GHz

KCRV	u_{KCRV}
4.835	0.012

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$
BNM	4.849	0.048	-0.014	0.093
NPL	4.831	0.035	0.005	0.065
PTB	4.839	0.019	-0.004	0.029
NIST	4.791	0.029	0.044	0.052
VNIIFTRI	4.866	0.028	-0.031	0.050

A.6.6.d: Unweighted case, outliers included
Source: TSB2
Reference plane: PC-7

12.4 GHz

KCRV	u_{KCRV}
4.959	0.009

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$
BNM	4.949	0.046	0.010	0.073
NPL	4.956	0.052	0.003	0.082
PTB	4.952	0.021	0.007	0.038
NIST	4.943	0.023	0.016	0.040
VNIIFTRI	4.996	0.032	-0.037	0.053

15 GHz

KCRV	u_{KCRV}
4.835	0.012

Lab_i	Y_i	$u(Y_i)$	Δ_i	$U_{\Delta i}$
BNM	4.849	0.048	-0.014	0.078
NPL	4.831	0.035	0.005	0.060
PTB	4.839	0.019	-0.004	0.039
NIST	4.791	0.029	0.044	0.051
VNIIFTRI	4.866	0.028	-0.031	0.050

Key Comparison CCEM.RF-K9

Degrees of equivalence

Measurand: Excess Noise Ratio (ENR) expressed in decibels (dB), at 12.4 GHz, 13.5 GHz, 15 GHz, 17.5 GHz and 18 GHz

The Key Comparison Reference Value, KCRV, was calculated as the unweighted mean of the participants results,

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

and its standard uncertainty is,

$$u_{KCRV} = \left(\frac{1}{N(N-1)}\sum_{i=1}^{N}\left(ENR_i - KCRV\right)^2\right)^{0.5}$$

where N is the number of participating laboratories

The degree of equivalence of each laboratory with respect to the KCRV is given by

$$D_i = KCRV - ENR_i$$

and its expanded uncertainty (k = 2) is

$U_i = 2\left(u_{KCRV}^2 + \left(1 - \frac{2}{N'}\right)u_i^2\right)^{0.5}$ for laboratories included in KCRV computation, or

$U_i = 2\left(u_i^2 + u_{KCRV}^2\right)^{0.5}$ for laboratories not included in KCRV computation (outliers),

where N’ is the number of laboratories included in KCRV computation

The degree of equivalence between two laboratories is given by

$$D_{ij} = D_i - D_j$$

and its expanded uncertainty (k = 2) is,

$$U_{ij} = 2\left(u_i^2 + u_j^2\right)^{0.5}$$

Noise source TSA1, reference plane: R140

Degrees of equivalence at 12.4 GHz

Lab *i* ⇓	D_i (dB)	U_i (dB)	BNM D_{ij} (dB)	BNM U_{ij} (dB)	NPL D_{ij} (dB)	NPL U_{ij} (dB)	PTB D_{ij} (dB)	PTB U_{ij} (dB)	NIST D_{ij} (dB)	NIST U_{ij} (dB)	VNIIFTRI D_{ij} (dB)	VNIIFTRI U_{ij} (dB)
BNM	-0.004	0.054			-0.013	0.086	0.009	0.079	-0.011	0.083	0.117	0.098
NPL	0.009	0.031	0.013	0.086			0.022	0.049	0.002	0.055	0.130	0.075
PTB	-0.012	0.020	-0.009	0.079	-0.022	0.049			-0.020	0.044	0.108	0.067
NIST	0.007	0.027	0.011	0.083	-0.002	0.055	0.020	0.044			0.128	0.072
VNIIFTRI	-0.121	0.063	-0.117	0.098	-0.130	0.075	-0.108	0.067	-0.128	0.072		

Degrees of equivalence at 13.5 GHz

Lab *i* ⇓	D_i (dB)	U_i (dB)	BNM D_{ij} (dB)	BNM U_{ij} (dB)	NPL D_{ij} (dB)	NPL U_{ij} (dB)	PTB D_{ij} (dB)	PTB U_{ij} (dB)	NIST D_{ij} (dB)	NIST U_{ij} (dB)	VNIIFTRI D_{ij} (dB)	VNIIFTRI U_{ij} (dB)
BNM	-0.008	0.063			-0.036	0.089	0.001	0.081	-0.035	0.083	0.029	0.093
NPL	0.028	0.045	0.036	0.089			0.037	0.056	0.001	0.060	0.065	0.072
PTB	-0.009	0.033	-0.001	0.081	-0.037	0.056			-0.036	0.046	0.028	0.061
NIST	0.027	0.037	0.035	0.083	-0.001	0.060	0.036	0.046			0.064	0.065
VNIIFTRI	-0.037	0.049	-0.029	0.093	-0.065	0.072	-0.028	0.061	-0.064	0.065		

Degrees of equivalence at 15 GHz

Lab *i* ⇓	D_i (dB)	U_i (dB)	BNM D_{ij} (dB)	BNM U_{ij} (dB)	NPL D_{ij} (dB)	NPL U_{ij} (dB)	PTB D_{ij} (dB)	PTB U_{ij} (dB)	NIST D_{ij} (dB)	NIST U_{ij} (dB)	VNIIFTRI D_{ij} (dB)	VNIIFTRI U_{ij} (dB)
BNM	0.012	0.063			0.008	0.088	0.019	0.085	-0.005	0.087	0.036	0.097
NPL	0.004	0.034	-0.008	0.088			0.011	0.051	-0.013	0.055	0.028	0.069
PTB	-0.007	0.029	-0.019	0.085	-0.011	0.051			-0.024	0.050	0.018	0.064
NIST	0.017	0.033	0.005	0.087	0.013	0.055	0.024	0.050			0.041	0.068
VNIIFTRI	-0.024	0.046	-0.036	0.097	-0.028	0.069	-0.018	0.064	-0.041	0.068		

Degrees of equivalence at 17.5 GHz

Lab *i* ⇓	D_i (dB)	U_i (dB)	BNM D_{ij} (dB)	BNM U_{ij} (dB)	NPL D_{ij} (dB)	NPL U_{ij} (dB)	PTB D_{ij} (dB)	PTB U_{ij} (dB)	NIST D_{ij} (dB)	NIST U_{ij} (dB)	VNIIFTRI D_{ij} (dB)	VNIIFTRI U_{ij} (dB)
BNM	-0.010	0.056			-0.024	0.100	0.000	0.086	-0.017	0.088	0.092	0.094
NPL	0.014	0.045	0.024	0.100			0.024	0.072	0.007	0.074	0.116	0.081
PTB	-0.010	0.028	0.000	0.086	-0.024	0.072			-0.017	0.054	0.092	0.063
NIST	0.007	0.031	0.017	0.088	-0.007	0.074	0.017	0.054			0.109	0.066
VNIIFTRI	-0.102	0.053	-0.092	0.094	-0.116	0.081	-0.092	0.063	-0.109	0.066		

Degrees of equivalence at 18 GHz

Lab *i* ⇓	D_i (dB)	U_i (dB)	BNM D_{ij} (dB)	BNM U_{ij} (dB)	NPL D_{ij} (dB)	NPL U_{ij} (dB)	PTB D_{ij} (dB)	PTB U_{ij} (dB)	NIST D_{ij} (dB)	NIST U_{ij} (dB)
BNM	-0.010	0.056			-0.008	0.089	-0.021	0.089	-0.011	0.088
NPL	-0.002	0.031	0.008	0.089			-0.013	0.059	-0.003	0.058
PTB	0.011	0.030	0.021	0.089	0.013	0.059			0.010	0.057
NIST	0.001	0.030	0.011	0.088	0.003	0.058	-0.010	0.057		

Noise source TSB1, reference plane: PC-7/R140

Degrees of equivalence at 12.4 GHz

Lab *j* ⇒

Lab *i* ⇓			BNM		NPL		PTB		NIST		VNIIFTRI	
	D_i (dB)	U_i (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)
BNM	-0.001	0.055			0.002	0.088	0.007	0.082	-0.012	0.085	0.085	0.106
NPL	-0.003	0.031	-0.002	0.088			0.004	0.050	-0.014	0.055	0.083	0.083
PTB	-0.007	0.021	-0.007	0.082	-0.004	0.050			-0.018	0.045	0.079	0.077
NIST	0.011	0.027	0.012	0.085	0.014	0.055	0.018	0.045			0.097	0.080
VNIIFTRI	-0.086	0.072	-0.085	0.106	-0.083	0.083	-0.079	0.077	-0.097	0.080		

Degrees of equivalence at 13.5 GHz

Lab *j* ⇒

Lab *i* ⇓			BNM		NPL		PTB		NIST		VNIIFTRI	
	D_i (dB)	U_i (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)
BNM	-0.001	0.065			-0.013	0.092	0.002	0.084	-0.034	0.086	0.039	0.096
NPL	0.012	0.044	0.013	0.092			0.016	0.057	-0.021	0.060	0.052	0.074
PTB	-0.004	0.033	-0.002	0.084	-0.016	0.057			-0.037	0.047	0.037	0.064
NIST	0.033	0.037	0.034	0.086	0.021	0.060	0.037	0.047			0.073	0.067
VNIIFTRI	-0.040	0.050	-0.039	0.096	-0.052	0.074	-0.037	0.064	-0.073	0.067		

Degrees of equivalence at 15 GHz

Lab *j* ⇒

Lab *i* ⇓			BNM		NPL		PTB		NIST		VNIIFTRI	
	D_i (dB)	U_i (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)
BNM	0.004	0.063			0.021	0.090	-0.001	0.088	-0.010	0.088	0.012	0.104
NPL	-0.017	0.033	-0.021	0.090			-0.022	0.053	-0.031	0.054	-0.009	0.077
PTB	0.005	0.029	0.001	0.088	0.022	0.053			-0.009	0.050	0.013	0.075
NIST	0.014	0.030	0.010	0.088	0.031	0.054	0.009	0.050			0.022	0.075
VNIIFTRI	-0.008	0.052	-0.012	0.104	0.009	0.077	-0.013	0.075	-0.022	0.075		

Degrees of equivalence at 17.5 GHz

Lab *j* ⇒

Lab *i* ⇓			BNM		NPL		PTB		NIST		VNIIFTRI	
	D_i (dB)	U_i (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)
BNM	0.003	0.046			-0.025	0.101	0.003	0.088	0.005	0.088	0.207	0.095
NPL	0.028	0.062	0.025	0.101			0.028	0.072	0.030	0.073	0.232	0.081
PTB	-0.001	0.022	-0.003	0.088	-0.028	0.072			0.002	0.053	0.204	0.064
NIST	-0.002	0.022	-0.005	0.088	-0.030	0.073	-0.002	0.053			0.202	0.064
VNIIFTRI	-0.204	0.052	-0.207	0.095	-0.232	0.081	-0.204	0.064	-0.202	0.064		

Degrees of equivalence at 18 GHz

Lab *j* ⇒

Lab *i* ⇓			BNM		NPL		PTB		NIST	
	D_i (dB)	U_i (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)
BNM	-0.004	0.061			0.026	0.089	-0.036	0.089	-0.007	0.088
NPL	-0.030	0.039	-0.026	0.089			-0.062	0.059	-0.033	0.058
PTB	0.032	0.039	0.036	0.089	0.062	0.059			0.029	0.058
NIST	0.003	0.038	0.007	0.088	0.033	0.058	-0.029	0.058		

Noise source TSB1, reference plane: PC-7

Degrees of equivalence at 12.4 GHz

Lab *i* ⇓ / Lab *j* ⇒

			BNM		NPL		PTB		NIST		VNIIFTRI	
	D_i (dB)	U_i (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)
BNM	-0.016	0.064			-0.021	0.131	-0.006	0.092	-0.035	0.099	0.077	0.112
NPL	0.005	0.071	0.021	0.131			0.015	0.102	-0.014	0.108	0.098	0.120
PTB	-0.010	0.025	0.006	0.092	-0.015	0.102			-0.029	0.054	0.083	0.075
NIST	0.019	0.036	0.035	0.099	0.014	0.108	0.029	0.054			0.112	0.084
VNIIFTRI	-0.093	0.072	-0.077	0.112	-0.098	0.120	-0.083	0.075	-0.112	0.084		

Degrees of equivalence at 13.5 GHz

Lab *i* ⇓ / Lab *j* ⇒

			BNM		NPL		PTB		NIST		VNIIFTRI	
	D_i (dB)	U_i (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)
BNM	-0.008	0.073			-0.033	0.113	-0.001	0.091	-0.048	0.098	0.041	0.103
NPL	0.025	0.065	0.033	0.113			0.032	0.080	-0.015	0.088	0.074	0.093
PTB	-0.007	0.039	0.001	0.091	-0.032	0.080			-0.047	0.057	0.042	0.064
NIST	0.040	0.048	0.048	0.098	0.015	0.088	0.047	0.057			0.089	0.074
VNIIFTRI	-0.049	0.053	-0.041	0.103	-0.074	0.093	-0.042	0.064	-0.089	0.074		

Degrees of equivalence at 15 GHz

Lab *i* ⇓ / Lab *j* ⇒

			BNM		NPL		PTB		NIST		VNIIFTRI	
	D_i (dB)	U_i (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)
BNM	0.000	0.063			0.001	0.112	0.004	0.096	-0.006	0.101	0.026	0.111
NPL	-0.001	0.048	-0.001	0.112			0.003	0.076	-0.007	0.083	0.025	0.095
PTB	-0.005	0.025	-0.004	0.096	-0.003	0.076			-0.011	0.059	0.021	0.075
NIST	0.006	0.034	0.006	0.101	0.007	0.083	0.011	0.059			0.032	0.082
VNIIFTRI	-0.026	0.066	-0.026	0.111	-0.025	0.095	-0.021	0.075	-0.032	0.082		

Degrees of equivalence at 17.5 GHz

Lab *i* ⇓ / Lab *j* ⇒

			BNM		NPL		PTB		NIST		VNIIFTRI	
	D_i (dB)	U_i (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)
BNM	-0.005	0.066			-0.027	0.127	0.011	0.097	-0.003	0.103	0.219	0.105
NPL	0.022	0.066	0.027	0.127			0.037	0.097	0.024	0.103	0.246	0.105
PTB	-0.015	0.031	-0.011	0.097	-0.037	0.097			-0.013	0.062	0.209	0.065
NIST	-0.002	0.039	0.003	0.103	-0.024	0.103	0.013	0.062			0.222	0.074
VNIIFTRI	-0.224	0.056	-0.219	0.105	-0.246	0.105	-0.209	0.065	-0.222	0.074		

Degrees of equivalence at 18 GHz

Lab *i* ⇓ / Lab *j* ⇒

			BNM		NPL		PTB		NIST	
	D_i (dB)	U_i (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)
BNM	-0.013	0.071			0.025	0.120	-0.052	0.099	-0.024	0.102
NPL	-0.038	0.065	-0.025	0.120			-0.077	0.090	-0.049	0.094
PTB	0.039	0.044	0.052	0.099	0.077	0.090			0.028	0.065
NIST	0.011	0.048	0.024	0.102	0.049	0.094	-0.028	0.065		

Noise source TSA2, reference plane: R140

Degrees of equivalence at 12.4 GHz

Lab *j* ⇒

Lab *i* ⇓			BNM		NPL		PTB		NIST		VNIIFTRI	
	D_i (dB)	U_i (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)
BNM	-0.002	0.044			-0.003	0.088	0.019	0.080	-0.003	0.084	0.127	0.097
NPL	0.001	0.025	0.003	0.088			0.022	0.050	0.000	0.057	0.131	0.074
PTB	-0.021	0.024	-0.019	0.080	-0.022	0.050			-0.022	0.043	0.108	0.065
NIST	0.001	0.021	0.003	0.084	0.000	0.057	0.022	0.043			0.130	0.070
VNIIFTRI	-0.129	0.060	-0.127	0.097	-0.131	0.074	-0.108	0.065	-0.130	0.070		

Degrees of equivalence at 13.5 GHz

Lab *j* ⇒

Lab *i* ⇓			BNM		NPL		PTB		NIST		VNIIFTRI	
	D_i (dB)	U_i (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)
BNM	-0.018	0.063			-0.048	0.089	-0.010	0.081	-0.047	0.083	0.013	0.092
NPL	0.030	0.044	0.048	0.089			0.038	0.056	0.001	0.059	0.061	0.070
PTB	-0.008	0.034	0.010	0.081	-0.038	0.056			-0.037	0.047	0.023	0.060
NIST	0.029	0.037	0.047	0.083	-0.001	0.059	0.037	0.047			0.060	0.063
VNIIFTRI	-0.031	0.047	-0.013	0.092	-0.061	0.070	-0.023	0.060	-0.060	0.063		

Degrees of equivalence at 15 GHz

Lab *j* ⇒

Lab *i* ⇓			BNM		NPL		PTB		NIST		VNIIFTRI	
	D_i (dB)	U_i (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)
BNM	0.009	0.063			0.004	0.090	0.015	0.086	-0.010	0.087	0.034	0.097
NPL	0.004	0.037	-0.004	0.090			0.011	0.054	-0.015	0.056	0.030	0.071
PTB	-0.006	0.029	-0.015	0.086	-0.011	0.054			-0.025	0.048	0.019	0.064
NIST	0.019	0.032	0.010	0.087	0.015	0.056	0.025	0.048			0.044	0.067
VNIIFTRI	-0.025	0.046	-0.034	0.097	-0.030	0.071	-0.019	0.064	-0.044	0.067		

Degrees of equivalence at 17.5 GHz

Lab *j* ⇒

Lab *i* ⇓			BNM		NPL		PTB		NIST		VNIIFTRI	
	D_i (dB)	U_i (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)
BNM	-0.007	0.056			-0.004	0.100	-0.009	0.085	-0.017	0.088	0.152	0.092
NPL	-0.004	0.044	0.004	0.100			-0.005	0.071	-0.013	0.074	0.156	0.078
PTB	0.001	0.025	0.009	0.085	0.005	0.071			-0.008	0.052	0.161	0.059
NIST	0.009	0.029	0.017	0.088	0.013	0.074	0.008	0.052			0.169	0.062
VNIIFTRI	-0.160	0.049	-0.152	0.092	-0.156	0.078	-0.161	0.059	-0.169	0.062		

Degrees of equivalence at 18 GHz

Lab *j* ⇒

Lab *i* ⇓			BNM		NPL		PTB		NIST	
	D_i (dB)	U_i (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)
BNM	-0.009	0.058			0.009	0.100	-0.031	0.088	-0.012	0.088
NPL	-0.018	0.047	-0.009	0.100			-0.040	0.074	-0.021	0.074
PTB	0.022	0.033	0.031	0.088	0.040	0.074			0.019	0.057
NIST	0.003	0.033	0.012	0.088	0.021	0.074	-0.019	0.057		

Noise source TSB2, reference plane: PC-7/R140

Degrees of equivalence at 12.4 GHz

Lab *i* ⇓			Lab *j* ⇒ BNM		NPL		PTB		NIST		VNIIFTRI	
	D_i (dB)	U_i (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)
BNM	0.002	0.061			0.008	0.096	0.001	0.094	-0.002	0.093	0.042	0.107
NPL	-0.007	0.032	-0.008	0.096			-0.007	0.060	-0.010	0.058	0.034	0.078
PTB	0.001	0.029	-0.001	0.094	0.007	0.060			-0.003	0.054	0.041	0.075
NIST	0.004	0.026	0.002	0.093	0.010	0.058	0.003	0.054			0.044	0.073
VNIIFTRI	-0.040	0.064	-0.042	0.107	-0.034	0.078	-0.041	0.075	-0.044	0.073		

Degrees of equivalence at 13.5 GHz

Lab *i* ⇓			Lab *j* ⇒ BNM		NPL		PTB		NIST		VNIIFTRI	
	D_i (dB)	U_i (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)
BNM	-0.023	0.068			-0.029	0.097	-0.011	0.090	-0.048	0.092	-0.025	0.100
NPL	0.006	0.041	0.029	0.097			0.018	0.057	-0.019	0.060	0.003	0.072
PTB	-0.011	0.028	0.011	0.090	-0.018	0.057			-0.037	0.047	-0.014	0.062
NIST	0.026	0.032	0.048	0.092	0.019	0.060	0.037	0.047			0.023	0.065
VNIIFTRI	0.003	0.045	0.025	0.100	-0.003	0.072	0.014	0.062	-0.023	0.065		

Degrees of equivalence at 15 GHz

Lab *i* ⇓			Lab *j* ⇒ BNM		NPL		PTB		NIST		VNIIFTRI	
	D_i (dB)	U_i (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)
BNM	-0.010	0.064			-0.007	0.098	0.003	0.094	-0.052	0.094	-0.036	0.103
NPL	-0.003	0.036	0.007	0.098			0.010	0.058	-0.045	0.058	-0.029	0.070
PTB	-0.013	0.031	-0.003	0.094	-0.010	0.058			-0.055	0.051	-0.039	0.065
NIST	0.042	0.040	0.052	0.094	0.045	0.058	0.055	0.051			0.016	0.065
VNIIFTRI	0.026	0.042	0.036	0.103	0.029	0.070	0.039	0.065	-0.016	0.065		

Degrees of equivalence at 17.5 GHz

Lab *i* ⇓			Lab *j* ⇒ BNM		NPL		PTB		NIST		VNIIFTRI	
	D_i (dB)	U_i (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)
BNM	0.003	0.050			0.003	0.107	0.007	0.095	-0.040	0.094	-0.031	0.106
NPL	0.000	0.037	-0.003	0.107			0.003	0.075	-0.043	0.074	-0.035	0.089
PTB	-0.003	0.023	-0.007	0.095	-0.003	0.075			-0.047	0.055	-0.038	0.074
NIST	0.043	0.038	0.040	0.094	0.043	0.074	0.047	0.055			0.009	0.073
VNIIFTRI	0.035	0.062	0.031	0.106	0.035	0.089	0.038	0.074	-0.009	0.073		

Degrees of equivalence at 18 GHz

Lab *i* ⇓			Lab *j* ⇒ BNM		NPL		PTB		NIST	
	D_i (dB)	U_i (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)	D_{ij} (dB)	U_{ij} (dB)
BNM	-0.013	0.058			0.003	0.108	-0.122	0.117	-0.042	0.096
NPL	-0.016	0.048	-0.003	0.108			-0.126	0.103	-0.045	0.077
PTB	0.109	0.085	0.122	0.117	0.126	0.103			0.080	0.090
NIST	0.029	0.038	0.042	0.096	0.045	0.077	-0.080	0.090		

Noise source TSB2, reference plane: PC-7

Degrees of equivalence at 12.4 GHz

Lab *i* ⇓ / Lab *j* ⇒

Lab i	D_i (dB)	U_i (dB)	BNM D_{ij} (dB)	BNM U_{ij} (dB)	NPL D_{ij} (dB)	NPL U_{ij} (dB)	PTB D_{ij} (dB)	PTB U_{ij} (dB)	NIST D_{ij} (dB)	NIST U_{ij} (dB)	VNIIFTRI D_{ij} (dB)	VNIIFTRI U_{ij} (dB)
BNM	0.001	0.065			0.007	0.138	0.003	0.101	-0.006	0.102	0.047	0.112
NPL	-0.006	0.073	-0.007	0.138			-0.004	0.111	-0.013	0.113	0.040	0.121
PTB	-0.002	0.030	-0.003	0.101	0.004	0.111			-0.009	0.062	0.044	0.077
NIST	0.007	0.033	0.006	0.102	0.013	0.113	0.009	0.062			0.053	0.079
VNIIFTRI	-0.046	0.064	-0.047	0.112	-0.040	0.121	-0.044	0.077	-0.053	0.079		

Degrees of equivalence at 13.5 GHz

Lab *i* ⇓ / Lab *j* ⇒

Lab i	D_i (dB)	U_i (dB)	BNM D_{ij} (dB)	BNM U_{ij} (dB)	NPL D_{ij} (dB)	NPL U_{ij} (dB)	PTB D_{ij} (dB)	PTB U_{ij} (dB)	NIST D_{ij} (dB)	NIST U_{ij} (dB)	VNIIFTRI D_{ij} (dB)	VNIIFTRI U_{ij} (dB)
BNM	-0.025	0.073			-0.035	0.120	-0.023	0.097	-0.057	0.102	-0.010	0.106
NPL	0.010	0.064	0.035	0.120			0.012	0.085	-0.022	0.091	0.025	0.095
PTB	-0.002	0.033	0.023	0.097	-0.012	0.085			-0.034	0.057	0.013	0.064
NIST	0.032	0.041	0.057	0.102	0.022	0.091	0.034	0.057			0.047	0.071
VNIIFTRI	-0.015	0.046	0.010	0.106	-0.025	0.095	-0.013	0.064	-0.047	0.071		

Degrees of equivalence at 15 GHz

Lab *i* ⇓ / Lab *j* ⇒

Lab i	D_i (dB)	U_i (dB)	BNM D_{ij} (dB)	BNM U_{ij} (dB)	NPL D_{ij} (dB)	NPL U_{ij} (dB)	PTB D_{ij} (dB)	PTB U_{ij} (dB)	NIST D_{ij} (dB)	NIST U_{ij} (dB)	VNIIFTRI D_{ij} (dB)	VNIIFTRI U_{ij} (dB)
BNM	-0.003	0.070			-0.018	0.119	-0.010	0.103	-0.058	0.112	0.017	0.111
NPL	0.016	0.052	0.018	0.119			0.009	0.080	-0.039	0.091	0.035	0.090
PTB	0.007	0.031	0.010	0.103	-0.009	0.080			-0.048	0.069	0.027	0.068
NIST	0.055	0.060	0.058	0.112	0.039	0.091	0.048	0.069			0.075	0.081
VNIIFTRI	-0.020	0.042	-0.017	0.111	-0.035	0.090	-0.027	0.068	-0.075	0.081		

Degrees of equivalence at 17.5 GHz

Lab *i* ⇓ / Lab *j* ⇒

Lab i	D_i (dB)	U_i (dB)	BNM D_{ij} (dB)	BNM U_{ij} (dB)	NPL D_{ij} (dB)	NPL U_{ij} (dB)	PTB D_{ij} (dB)	PTB U_{ij} (dB)	NIST D_{ij} (dB)	NIST U_{ij} (dB)	VNIIFTRI D_{ij} (dB)	VNIIFTRI U_{ij} (dB)
BNM	-0.014	0.076			-0.036	0.131	-0.009	0.104	-0.040	0.111	0.016	0.125
NPL	0.022	0.073	0.036	0.131			0.026	0.099	-0.005	0.107	0.051	0.122
PTB	-0.005	0.039	0.009	0.104	-0.026	0.099			-0.031	0.072	0.025	0.092
NIST	0.026	0.050	0.040	0.111	0.005	0.107	0.031	0.072			0.056	0.100
VNIIFTRI	-0.030	0.067	-0.016	0.125	-0.051	0.122	-0.025	0.092	-0.056	0.100		

Degrees of equivalence at 18 GHz

Lab *i* ⇓ / Lab *j* ⇒

Lab i	D_i (dB)	U_i (dB)	BNM D_{ij} (dB)	BNM U_{ij} (dB)	NPL D_{ij} (dB)	NPL U_{ij} (dB)	PTB D_{ij} (dB)	PTB U_{ij} (dB)	NIST D_{ij} (dB)	NIST U_{ij} (dB)
BNM	-0.052	0.084			-0.038	0.133	-0.121	0.125	-0.049	0.112
NPL	-0.014	0.084	0.038	0.133			-0.083	0.125	-0.011	0.112
PTB	0.069	0.077	0.121	0.125	0.083	0.125			0.072	0.102
NIST	-0.003	0.066	0.049	0.112	0.011	0.112	-0.072	0.102		