

# **Comparison on the Effective Efficiency Measurement of Thermistor Mounts in Coaxial Lines up to 18 GHz Final**

**EURAMET Project 1512**

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## INTRODUCTION

During the EURAMET SC-RFMW meeting held in Istanbul in 2015 the National Metrology Institute of Egypt (NIS) requested a comparison for effective efficiency to validate their newly established Type N micro-calorimeter (10 MHz to 18 GHz). Upon NIS' request, several other NMIs that have primary power measurement capability in this band; including NPL, PTB, NIS, LNE, INRIM, VSL and NQIS expressed interest in participating in such a comparison. After the discussions, NPL, PTB, NIS, NMISA and TÜBİTAK UME decided to participate and TÜBİTAK UME has been chosen as the pilot the comparison.

The comparison was originally planned to start in 2017. However, because of the supply chain challenges for acquiring Keysight 8478B power sensors which are chosen to be used in the comparison, the start date was delayed to 2018. The comparison devices are supplied by both the pilot (TÜBİTAK UME) and one of the participants (PTB).

In this comparison, we aim to compare the primary level effective efficiency for Type-N thermistor power sensors in the frequency range 10 MHz to 18 GHz. Two commercial thermistor mounts were used as the travelling standards. The following document outlines the general procedure for the coordination and reporting of the comparison with reference to the "EURAMET Guide on Comparisons" [1]. Each participant followed their own local measurement procedures while performing their measurements.

Once all the participant laboratories completed their measurements and reported to the pilot laboratory (TÜBİTAK UME), the pilot laboratory analysed the results, performed the calculation of the degrees of equivalence and comparison reference values. Then the pilot laboratory prepared the comparison report draft and circulated it to the participant laboratories for review and feedbacks.

## 1. TRAVELLING STANDARD

A pair of commercial thermistor mounts (HP/Agilent/Keysight 8478B sensors) were used as the travelling standards in the comparison. The details of the 8478B sensors are given below:

- Frequency range: 10 MHz to 18 GHz
- Connector type: Type N male
- Input impedance: 50  $\Omega$
- Operating resistance: 200  $\Omega$  (unbalanced)
- Power range with HP/Agilent/Keysight 432A model power meter: 1  $\mu$ W to 10 mW
- Maximum average power: 10 mW
- Output connector: Mates with HP/Agilent/Keysight 432A/N432A power meter cable
- Weight: Net 140 g

A picture of the thermistor mounts is shown in Fig. 1.



Figure 1. HP/Agilent 8478B thermistor mount

A brief information about the travelling standards is presented in Table 1. The standards are identified as STD#1 and STD#2.

Table 1. Information about travelling standards

Identification	Model	Manufacturer	Serial Number	Connector and characteristic impedance	Frequency range
STD#1 (UME)	8478B	Agilent Technologies	3318A25528	Type N male, 50 $\Omega$	10 MHz – 18 GHz
STD#2 (PTB)	8478B	HP	2106A24217	Type N male, 50 $\Omega$	10 MHz – 18 GHz

## 2. PARTICIPANT LABORATORIES

A list of participating institutes, the contact persons and their addresses is given in Table 2.

Table 2. List of participant and contacts

Acronym of Institute	Country	Contact Person	Shipping Address	E-mail/Fax/Telephone
TUBITAK UME	Turkey	Erkan DANACI	TÜBİTAK Ulusal Metroloji Enstitüsü (UME) TÜBİTAK Gebze Yerleşkesi Barış Mah. Dr. Zeki Acar Cad. No:1 41470 Gebze-Kocaeli, TURKEY	<a href="mailto:erkan.danaci@tubitak.gov.tr">erkan.danaci@tubitak.gov.tr</a> Tel: +90 (262) 679 5000-4500 Fax: +90 (262) 6795001
PTB	Germany	Rolf Judaschke	Physikalisch-Technische Bundesanstalt High Frequency Measurement Techniques 2.22 Bundesallee 100 D-38116 Braunschweig Germany	<a href="mailto:rolf.judaschke@ptb.de">rolf.judaschke@ptb.de</a> Phone: +49 531 592 2220 Fax: +49 531 592 2228
NPL	UK	Daniel Stokes	National Physical Laboratory Hampton Road Teddington Middlesex TW11 0LW UK	<a href="mailto:Daniel.Stokes@npl.co.uk">Daniel.Stokes@npl.co.uk</a> Phone: +44 (0) 20 8943 6322
NIS	Egypt	AbdelRahman Sallam	NIS National Institute for Standards of Egypt 36 Tersa Street, P.O:136 Al Haram, El-Giza Egypt	<a href="mailto:sallam2050@gmail.com">sallam2050@gmail.com</a> Phone: +20 1554135885 Fax: +202 33867452
NMISA	South Africa	Linoh Magagula	National Metrology Institute of South Africa (NMISA) CSIR Campus, Building 5 Meiring Naude Rd Brummeria 0184 Pretoria South Africa	<a href="mailto:Imagagula@nmisa.org">Imagagula@nmisa.org</a> Phone: +27 12 841 4342

### 3. TIME SCHEDULE

The comparison started in September 2018.

At the beginning of the circulation, TÜBİTAK UME performed the first effective efficiency measurement of both of the travelling standards (Table 3), and then initiated the circulation of the traveling standards.

Total measurement time of the standards at each institute was estimated to be around 4 weeks with a 2 week travelling time between each participant.

Table 3. Comparison schedule

Time period	Task	Institute
September 2018 (4 weeks)	The first measurement	TÜBİTAK UME
October 2018 (4 weeks)	Transport to PTB	
December 2018- January 2019 (4 weeks)	The second measurement	PTB
February 2019 (2 weeks)	Transport to NPL	
February - May 2019 (4 weeks)	The third measurement	NPL
June 2019 (2 weeks)	Transport to NIS	
June-July 2019 (2 weeks)	The fourth measurement	NIS
August 2019 (4 weeks)	Transport to NMISA	
December 2019 - January 2020 (4 weeks)	The fifth measurement	NMISA
February 2020 (4 weeks)	Transport to TÜBİTAK UME	
June 2020 (4 weeks)	The last measurement	TÜBİTAK UME

## 4. MEASUREMENT TECHNIQUE

The goal of this study is to compare the effective efficiency of a bolometric type thermistor standard by using primary level equipment as the participating laboratories routinely establish them.

### 4.1. Measurements

Each laboratory performed the effective efficiency measurements according to their own procedures. The measurement frequencies for this comparison were 50 MHz, 500 MHz, 1 GHz, 2 GHz, 4 GHz, 6 GHz, 8 GHz, 10 GHz, 12 GHz, 14 GHz, 16 GHz and 18 GHz.

The effective efficiency is defined as follows (Eq. 1):

$$\text{Effective Efficiency} = \frac{\text{DC substitute power}}{\text{Absorbed Power at calibration frequency}} \quad (1)$$

Voltage reflection coefficients (VRCs) of both travelling standards were measured and reported both in magnitude and phase as a part of this comparison.

Calibration factor is defined as follows (Eq. 2):

$$\text{Calibration Factor} = \text{Effective Efficiency} * (1 - \text{VRC}^2) \quad (2)$$

In order to verify the condition of the connectors of the travelling standards, the pin depth characterization of Type-N RF connectors on each travelling standards was done prior to the measurement of the effective efficiency. The pin depths should be between  $0.207 + 0.0005$  and  $0.207 + 0.0027$  inch [2], indicating that the centre pin was recessed from the plane of the outer conductor. There was no any protrusion during the comparison.

Suggested environmental conditions for the measurements were  $(23 \pm 1)$  °C for ambient temperature and  $(50 \pm 20)$  %rh for relative humidity.

### 4.2. Uncertainty Evaluation

Each participant laboratory should perform an uncertainty analysis for the effective efficiency of each of the travelling standards. A breakdown of the uncertainty contributions should be given as part of the measurement report. The reported uncertainty should be expanded uncertainty with a coverage factor of  $k=2$  or greater, and it must be clearly indicated in the report. . The uncertainty should be given as an absolute value to avoid any confusion for the comparison of the measurements.

The uncertainty evaluation should be handled in accordance with the “Guide to the Expression of Uncertainty in Measurement (GUM) published by the International Standards Organization (ISO) [3].

## 5. COMPARISON EVALUATION and CALCULATION of REFERENCE VALUES

Comparison reference value (CRV) was calculated as a weighted mean of the participant laboratories results and the comparison results were evaluated according to the Ref [4].

### 5.1. The Comparison Reference Value

Comparison reference values ( $x_{CRV}$ ) and associated uncertainties  $u(x_{CRV})$  were calculated using the measurements result of participants' values as given below as Eq. 3 and Eq. 4, respectively.

$$x_{CRV} = \sum_1^N \frac{x_i}{u(x_i)^2} \quad (3)$$

$$u(x_{CRV}) = \sum_1^N \frac{1}{u(x_i)^2} \quad (4)$$

where  $u(x_i)$  is uncertainty value of the participant in  $k=1$  confidential level.

The comparison Reference Values ( $x_{CRV}$ ) were calculated for each measurement point using the weighted mean.

The expanded uncertainty of the Comparison Reference Values ( $x_{CRV}$ ) was calculated by:

$$U(x_{CRV}) = 2 \times u(x_{CRV}) \quad (5)$$

The results were presented in Section 6.

### 5.2. Degree of Equivalences ( $D_i$ ) and Normalised Errors ( $E_n$ )

The results of the comparison are reported as the degrees of equivalence and the normalised error between a participant's result and the Comparison Reference Values ( $x_{CRV}$ ).

The degree of equivalence of each participant ( $D_i$ ), was calculated as:

$$D_i = x_i - x_{CRV} \quad (6)$$

where  $x_i$  is the corrected result of the participants due to the drift of the travelling standard with time, and  $x_{CRV}$  is the Comparison Reference Value.

The expanded uncertainty of the degree of equivalence for a participant's result ( $U(D_i)$ ), was calculated as:

$$U(D_i) = \sqrt{U(x_i)^2 + U(x_{CRV})^2} \quad (7)$$

$$U(D_i) = \sqrt{U(x_i)^2 - U(x_{CRV})^2} \quad (8)$$

where  $U(x_i)$  is the expanded uncertainty of the corrected results of each participant and  $U(x_{CRV})$  is the expanded uncertainty of the Comparison Reference Value. Equation (7) was used where the participant result does not contribute to the Comparison Reference Value. Due to the correlation with the Comparison Reference Value, Equation (8) was used where the participant result contributes to the Comparison Reference Value.

For each participant's result, the normalised errors ( $E_n$ ) were calculated as:

$$E_n = \frac{x_i - x_{CRV}}{\sqrt{U(x_i)^2 - U(x_{CRV})^2}} = \frac{D_i}{U(D_i)} \quad (9)$$

$$E_n = \frac{x_i - x_{CRV}}{\sqrt{U(x_i)^2 + U(x_{CRV})^2}} = \frac{D_i}{U(D_i)} \quad (10)$$

Equation (9) was used for the results which contribute to the Comparison Reference Value. Equation (10) was used for the participant results which are excluded from the Comparison Reference Value.

The participant results were regarded as satisfactory if  $|E_n| \leq 1$ .

## 6. DISCUSSION OF THE RESULTS

The comparison was organised in a single loop of five laboratories.

The results were reported to the pilot laboratory in linear Effective Efficiency value format. The chosen frequencies are 50 MHz, 500 MHz, 1 GHz, 2 GHz, 4 GHz, 6 GHz, 8 GHz, 10 GHz, 12 GHz, 14 GHz, 16 GHz, and 18 GHz for the comparison.

The measurement uncertainties were calculated according to the JCGM 100 “Guide to the Expression of Uncertainty in Measurement” [2] for the coverage probability of approximately 95%.

All contributions to the measurement uncertainty listed in the report submitted by each participant. Participants were also requested to provide detailed uncertainty budgets and the combined standard uncertainties for the aforementioned measurand.

The EE measurement results and combined uncertainties of STD1 and STD2 with the reference values and combined uncertainties can be found in Table 4 and Table 7, respectively. Comparison reference values and combined uncertainties were calculated according to the Chapter 5.

Degree of equivalence values with respect to the reference value of EE and between each of the measurements can be found in Table 5 and Table 8.

The  $E_n$  value stated at ISO / IEC 17043 “Conformity assessment — General requirements for proficiency testing” [4] Standard for each EE measurement and frequencies can be found in Table 6 and Table 9.

We became aware of the systematic differences in the measurement results between the participants after the first draft of the report (Draft-A) was completed. This difference is attributed to the possible errors produced by the traveling standard which might not be the best for this particular comparison as well as the minor differences in the measurement procedures followed by the participants. Figures 2 to 5 gives the first analysis of the comparison results.

The first version of the report (draft A) which was prepared using the measurement results provided by the participants has been shared with all participants in the online and in person meetings. The systematic errors among the results were emphasized in these meetings and possible sources of these errors were discussed. As a result, it was decided that the comparison results cannot be used to update existing CMC entities or add new CMC entities in the current CMCs.

Comparison evaluation was performed for EE values. DoE values with uncertainties and EE values (included  $U(x_i)$ ) with uncertainties were given in Figure 6-53.

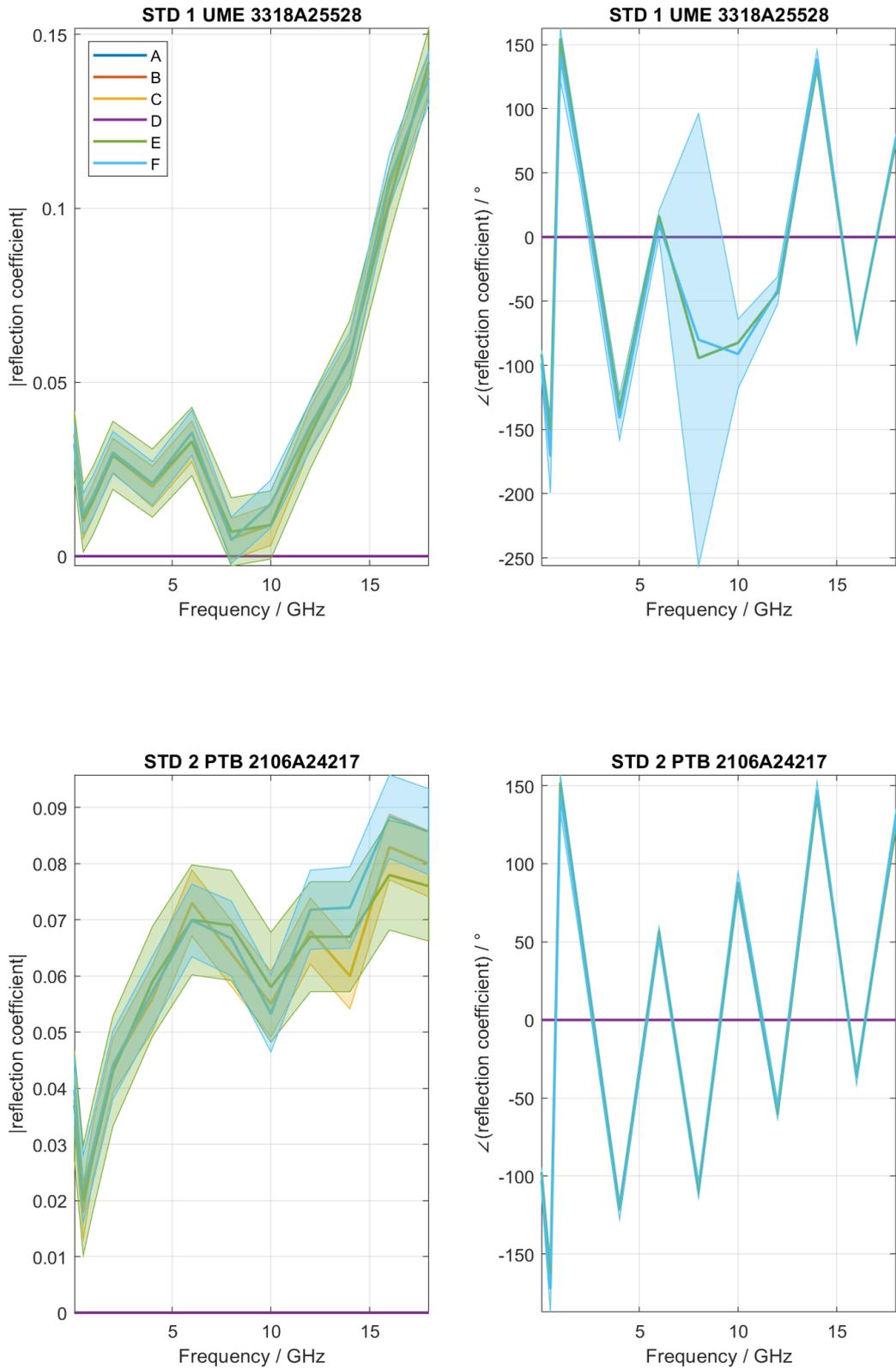


Figure 2. Reflection coefficients of travelling standards

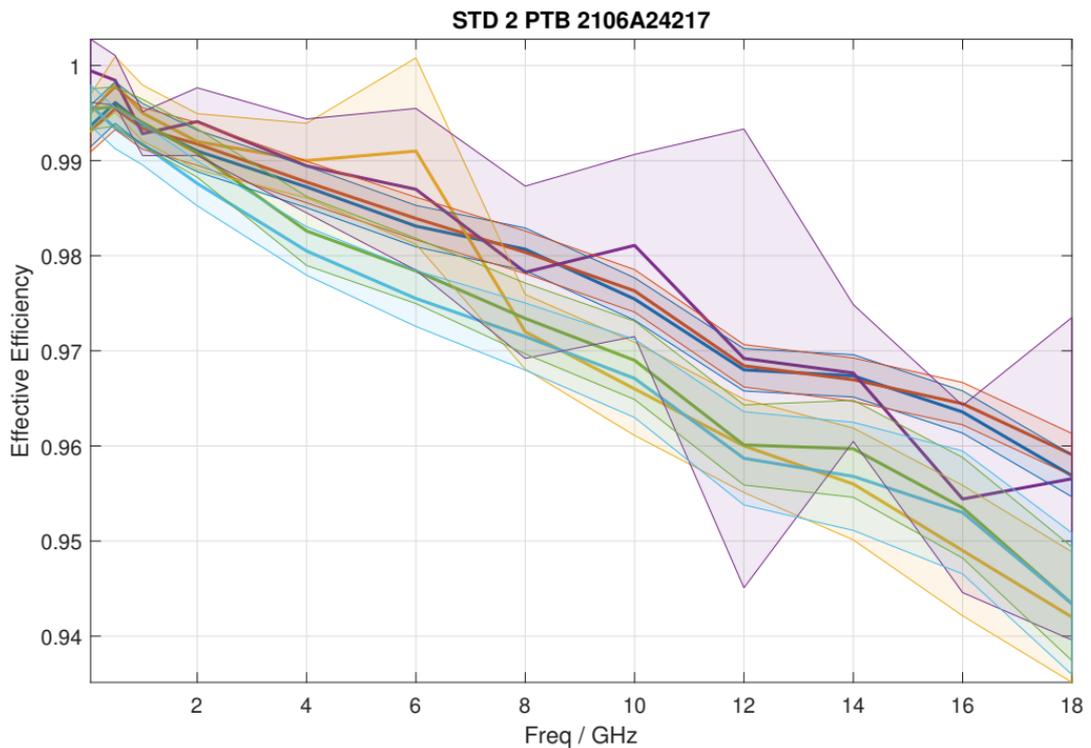
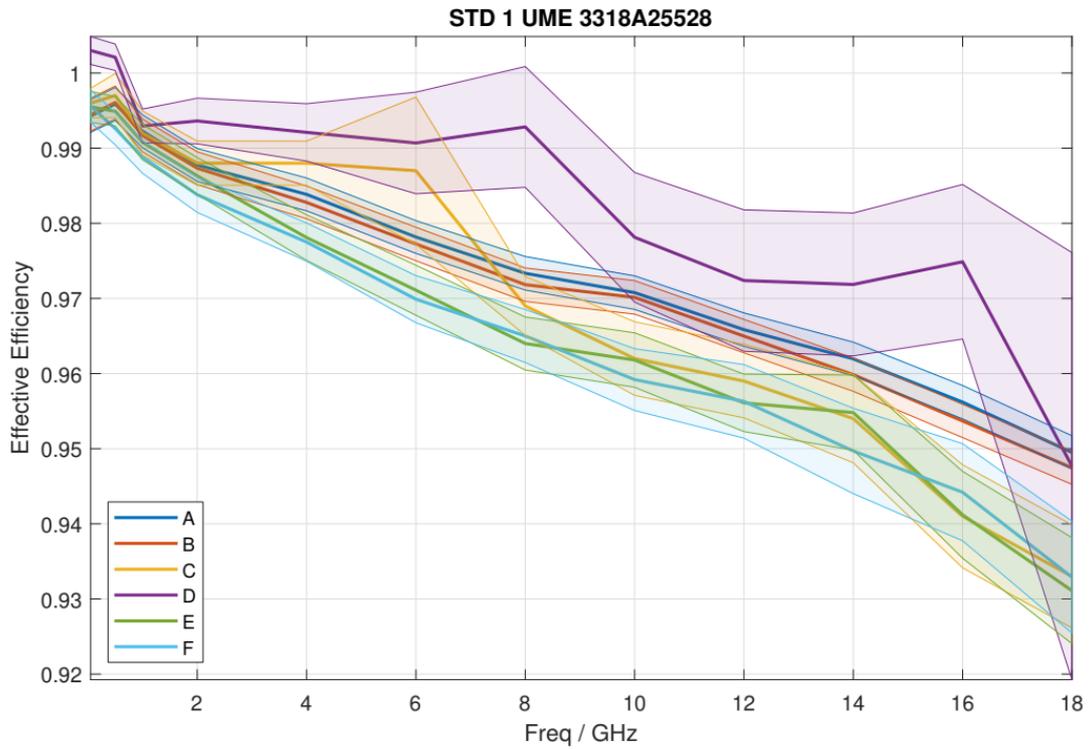


Figure 3. Effective efficiencies of travelling standards

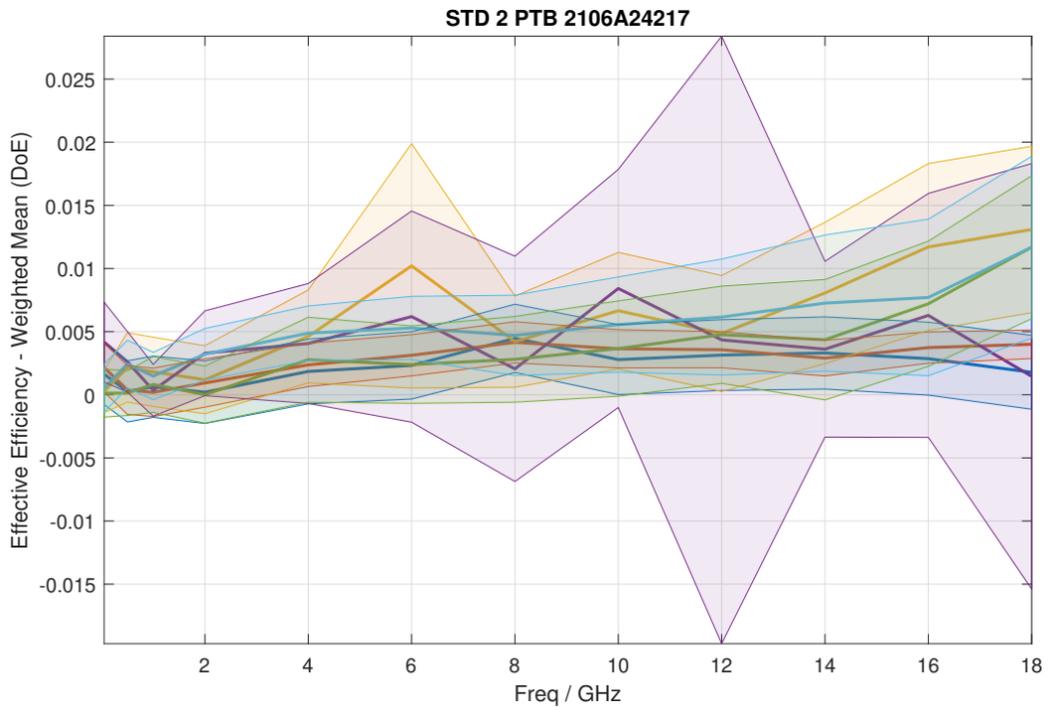
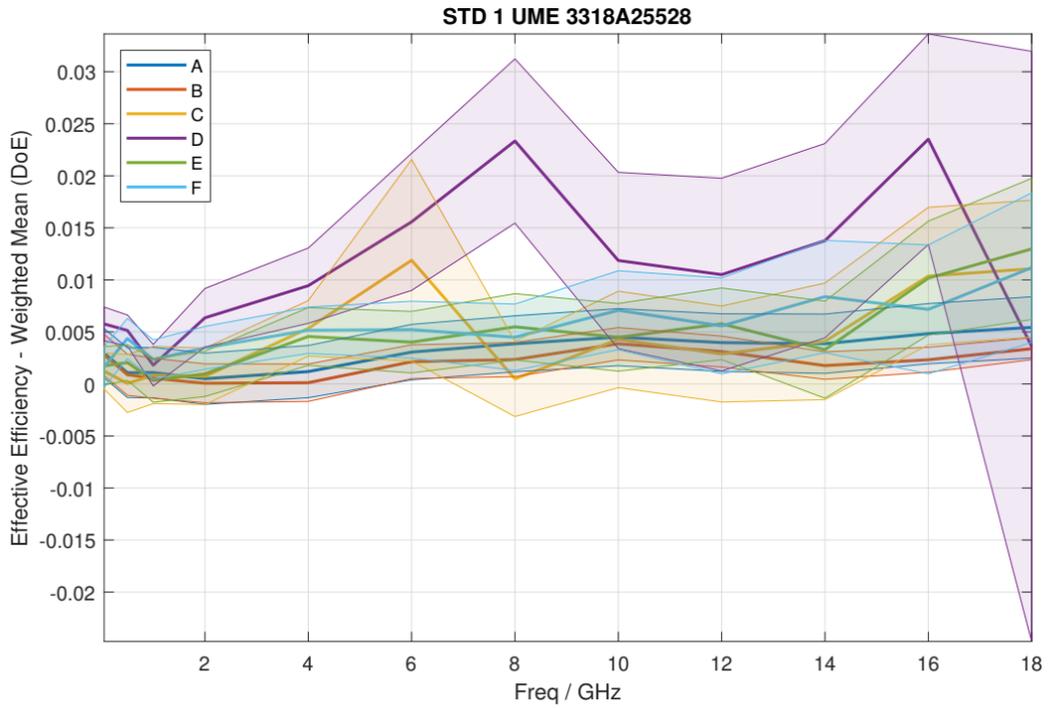


Figure 4. DoE of effective efficiency of travelling standards

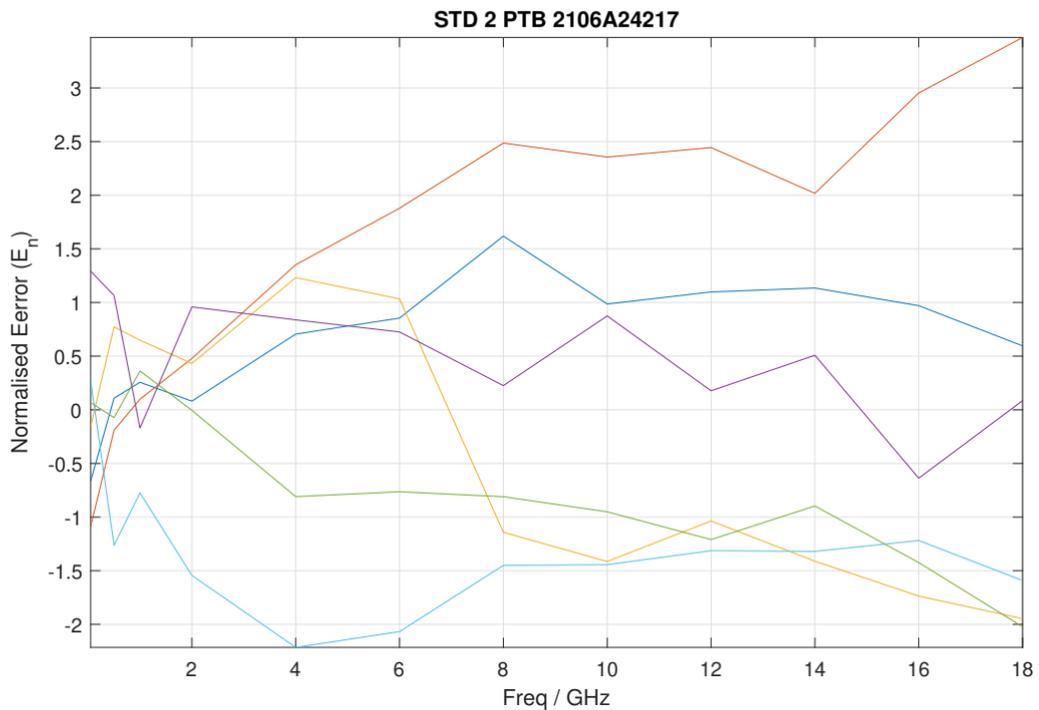
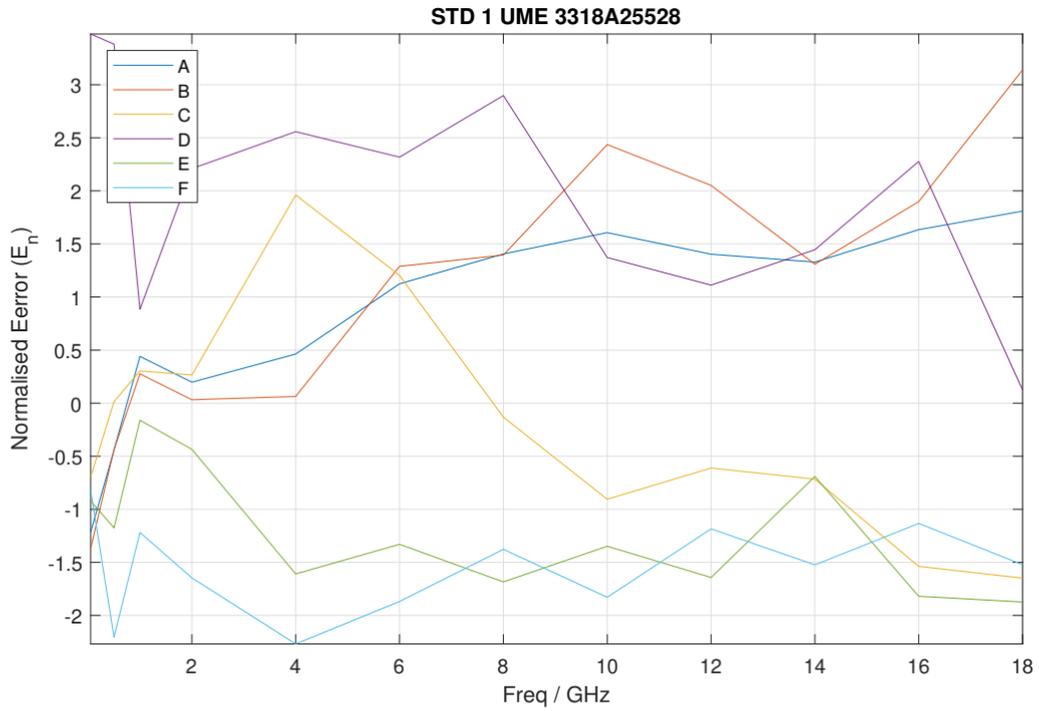


Figure 5.  $E_n$  Values of participants

Table 4. Effective Efficiency and uncertainty of STD1 (3318A25528)

Laboratory	UME		NMISA		NIS		NPL		PTB		Reference Value	
	EE	Unc.	EE	Unc.	EE	Unc.	EE	Unc.	EE	Unc.	$x_{ref}$	$U_{ref}$
<b>50 MHz</b>	0.9943	0.0045	0.9960	0.0020	1.0030	0.0019	0.9955	0.0021	0.9956	0.0022	0.9976	0.0022
<b>500 MHz</b>	0.9959	0.0045	0.9970	0.0030	1.0021	0.0018	0.9949	0.002	0.9926	0.0022	0.9971	0.0023
<b>1 GHz</b>	0.9922	0.0045	0.9920	0.0030	0.9930	0.0023	0.9908	0.0024	0.9888	0.0022	0.9911	0.0023
<b>2 GHz</b>	0.9878	0.0045	0.9880	0.0030	0.9936	0.0031	0.9863	0.0025	0.9838	0.0024	0.9873	0.0026
<b>4 GHz</b>	0.9838	0.0045	0.9880	0.0030	0.9921	0.0039	0.9781	0.0031	0.9775	0.0026	0.9827	0.0031
<b>6 GHz</b>	0.9782	0.0044	0.9870	0.0100	0.9907	0.0069	0.9711	0.0034	0.9699	0.0032	0.9742	0.0036
<b>8 GHz</b>	0.9733	0.0046	0.9690	0.0040	0.9928	0.0082	0.9640	0.0036	0.9650	0.0036	0.9685	0.0036
<b>10 GHz</b>	0.9708	0.0046	0.9620	0.0050	0.9781	0.0088	0.9618	0.0037	0.9592	0.0042	0.9640	0.0040
<b>12 GHz</b>	0.9658	0.0045	0.9590	0.0050	0.9724	0.0096	0.9561	0.0039	0.9563	0.0050	0.9599	0.0042
<b>14 GHz</b>	0.9620	0.0045	0.9540	0.0060	0.9719	0.0097	0.9548	0.0051	0.9497	0.0058	0.9571	0.0044
<b>16 GHz</b>	0.9562	0.0045	0.9410	0.0070	0.9749	0.0105	0.9412	0.0059	0.9442	0.0066	0.9497	0.0047
<b>18 GHz</b>	0.9495	0.0045	0.9330	0.0070	0.9477	0.0290	0.9311	0.0072	0.9329	0.0076	0.9403	0.0050

Table 5. Degrees of Equivalence and uncertainty of STD1 (3318A25528)

Labs	UME		NMISA		NIS		NPL		PTB	
	<i>D</i>	<i>U<sub>D</sub></i>	<i>D</i>	<i>U<sub>D</sub></i>	<i>D</i>	<i>U<sub>D</sub></i>	<i>D</i>	<i>U<sub>D</sub></i>	<i>D</i>	<i>U<sub>D</sub></i>
<b>50 MHz</b>	0.0033	0.0050	-0.0016	0.0030	0.0054	0.0029	-0.0021	0.0030	-0.0020	0.0031
<b>500 MHz</b>	0.0012	0.0050	-0.0001	0.0038	0.0050	0.0029	-0.0022	0.0030	-0.0045	0.0032
<b>1 GHz</b>	-0.0012	0.0050	0.0009	0.0038	0.0019	0.0033	-0.0003	0.0033	-0.0023	0.0032
<b>2 GHz</b>	-0.0005	0.0052	0.0007	0.0040	0.0063	0.0040	-0.0010	0.0036	-0.0035	0.0035
<b>4 GHz</b>	-0.0011	0.0054	0.0053	0.0043	0.0094	0.0050	-0.0046	0.0044	-0.0052	0.0041
<b>6 GHz</b>	-0.0040	0.0057	0.0128	0.0106	0.0165	0.0078	-0.0031	0.0050	-0.0043	0.0048
<b>8 GHz</b>	-0.0048	0.0058	0.0005	0.0054	0.0243	0.0089	-0.0045	0.0051	-0.0035	0.0051
<b>10 GHz</b>	-0.0068	0.0060	-0.0020	0.0064	0.0142	0.0096	-0.0022	0.0054	-0.0048	0.0058
<b>12 GHz</b>	-0.0060	0.0062	-0.0009	0.0065	0.0125	0.0105	-0.0038	0.0057	-0.0036	0.0065
<b>14 GHz</b>	-0.0049	0.0063	-0.0031	0.0075	0.0148	0.0107	-0.0023	0.0067	-0.0074	0.0073
<b>16 GHz</b>	-0.0065	0.0065	-0.0087	0.0084	0.0252	0.0115	-0.0085	0.0076	-0.0055	0.0081
<b>18 GHz</b>	-0.0092	0.0067	-0.0073	0.0086	0.0073	0.0294	-0.0092	0.0088	-0.0074	0.0091

Table 6.  $E_n$  values of the comparison of STD1 (3318A25528)

Labs	$ E_n $				
Frequencies	UME	NMISA	NIS	NPL	PTB
50 MHz	0.67	0.55	<b>1.85</b>	0.71	0.66
500 MHz	0.24	0.02	<b>1.73</b>	0.72	<b>1.42</b>
1 GHz	0.23	0.25	0.58	0.08	0.71
2 GHz	0.09	0.18	<b>1.57</b>	0.27	0.99
4 GHz	0.20	<b>1.22</b>	<b>1.88</b>	<b>1.06</b>	<b>1.29</b>
6 GHz	0.70	<b>1.21</b>	<b>2.12</b>	0.62	0.88
8 GHz	0.83	0.09	<b>2.72</b>	0.89	0.70
10 GHz	<b>1.13</b>	0.31	<b>1.47</b>	0.40	0.83
12 GHz	0.97	0.13	<b>1.19</b>	0.66	0.55
14 GHz	0.77	0.41	<b>1.39</b>	0.34	<b>1.01</b>
16 GHz	<b>1.00</b>	<b>1.03</b>	<b>2.19</b>	<b>1.12</b>	0.67
18 GHz	<b>1.36</b>	0.85	0.25	<b>1.05</b>	0.82

Table 7. Effective Efficiency and uncertainty of STD2 (2106A24217)

Laboratory	UME		NMISA		NIS		NPL		PTB		Reference Value	
Frequencies	EE	Unc.	EE	Unc.	EE	Unc.	EE	Unc.	EE	Unc.	$x_{ref}$	$U_{ref}$
<b>50 MHz</b>	0.9936	0.0045	0.9950	0.0020	0.9994	0.0034	0.9954	0.0022	0.9958	0.0022	0.9957	0.0022
<b>500 MHz</b>	0.9961	0.0045	0.9980	0.0030	0.9984	0.0027	0.9957	0.0021	0.9934	0.0022	0.9960	0.0023
<b>1 GHz</b>	0.9938	0.0045	0.9950	0.0030	0.9928	0.0024	0.9940	0.0025	0.9917	0.0022	0.9932	0.0024
<b>2 GHz</b>	0.9910	0.0045	0.9920	0.0030	0.9941	0.0036	0.9908	0.0026	0.9876	0.0024	0.9905	0.0027
<b>4 GHz</b>	0.9872	0.0045	0.9900	0.0040	0.9894	0.0050	0.9826	0.0037	0.9805	0.0026	0.9844	0.0033
<b>6 GHz</b>	0.9831	0.0044	0.9910	0.0100	0.9870	0.0087	0.9784	0.0035	0.9755	0.0030	0.9790	0.0039
<b>8 GHz</b>	0.9807	0.0046	0.9720	0.0040	0.9783	0.0092	0.9734	0.0038	0.9715	0.0036	0.9740	0.0039
<b>10 GHz</b>	0.9754	0.0046	0.9660	0.0050	0.9811	0.0098	0.9690	0.0042	0.9671	0.0042	0.9700	0.0043
<b>12 GHz</b>	0.9680	0.0045	0.9600	0.0050	0.969	0.025	0.9601	0.0043	0.9587	0.0050	0.9619	0.0047
<b>14 GHz</b>	0.9674	0.0045	0.9560	0.0060	0.9677	0.0073	0.9597	0.0052	0.9568	0.0058	0.9618	0.0050
<b>16 GHz</b>	0.9636	0.0045	0.9490	0.0070	0.954	0.010	0.9535	0.0054	0.9530	0.0066	0.9564	0.0054
<b>18 GHz</b>	0.9569	0.0045	0.9420	0.0070	0.957	0.017	0.9434	0.0061	0.9434	0.0076	0.9492	0.0058

Table 8. Degrees of Equivalence and uncertainty of STD2 (2106A24217)

Labs	UME		NMISA		NIS		NPL		PTB	
	<i>D</i>	<i>U<sub>D</sub></i>	<i>D</i>	<i>U<sub>D</sub></i>	<i>D</i>	<i>U<sub>D</sub></i>	<i>D</i>	<i>U<sub>D</sub></i>	<i>D</i>	<i>U<sub>D</sub></i>
<b>50 MHz</b>	0.0021	0.0050	-0.0007	0.0030	0.0037	0.0041	-0.0003	0.0031	0.0001	0.0031
<b>500 MHz</b>	-0.0001	0.0050	0.0020	0.0038	0.0025	0.0035	-0.0003	0.0031	-0.0026	0.0032
<b>1 GHz</b>	-0.0006	0.0051	0.0018	0.0038	-0.0003	0.0033	0.0008	0.0034	-0.0015	0.0032
<b>2 GHz</b>	-0.0005	0.0052	0.0015	0.0040	0.0036	0.0045	0.0003	0.0037	-0.0029	0.0036
<b>4 GHz</b>	-0.0029	0.0055	0.0056	0.0052	0.0051	0.0060	-0.0018	0.0049	-0.0039	0.0042
<b>6 GHz</b>	-0.0041	0.0059	0.0120	0.0107	0.0080	0.0095	-0.0006	0.0052	-0.0035	0.0049
<b>8 GHz</b>	-0.0066	0.0060	-0.0020	0.0056	0.0042	0.0100	-0.0006	0.0054	-0.0025	0.0053
<b>10 GHz</b>	-0.0055	0.0063	-0.0040	0.0066	0.0111	0.0107	-0.0010	0.0060	-0.0029	0.0060
<b>12 GHz</b>	-0.0061	0.0065	-0.0019	0.0068	0.0073	0.0251	-0.0018	0.0063	-0.0032	0.0068
<b>14 GHz</b>	-0.0056	0.0067	-0.0058	0.0078	0.0059	0.0089	-0.0021	0.0072	-0.0050	0.0076
<b>16 GHz</b>	-0.0072	0.0071	-0.0074	0.0089	-0.0020	0.0114	-0.0029	0.0076	-0.0034	0.0085
<b>18 GHz</b>	-0.0077	0.0074	-0.0072	0.0091	0.0074	0.0183	-0.0058	0.0085	-0.0058	0.0096

Table 9. En values of the comparison of STD2 (2106A24217)

Labs	$ E_n $				
Frequencies	UME	NMISA	NIS	NPL	PTB
<b>50 MHz</b>	0.41	0.24	0.92	0.10	0.03
<b>500 MHz</b>	0.03	0.54	0.70	0.08	0.80
<b>1 GHz</b>	0.13	0.48	0.10	0.24	0.46
<b>2 GHz</b>	0.10	0.37	0.80	0.08	0.81
<b>4 GHz</b>	0.52	<b>1.09</b>	0.85	0.35	0.92
<b>6 GHz</b>	0.70	<b>1.12</b>	0.84	0.11	0.71
<b>8 GHz</b>	<b>1.11</b>	0.37	0.42	0.12	0.48
<b>10 GHz</b>	0.87	0.60	<b>1.04</b>	0.16	0.48
<b>12 GHz</b>	0.93	0.28	0.29	0.29	0.47
<b>14 GHz</b>	0.83	0.74	0.67	0.29	0.65
<b>16 GHz</b>	<b>1.01</b>	0.84	0.17	0.38	0.40
<b>18 GHz</b>	<b>1.04</b>	0.79	0.40	0.68	0.60

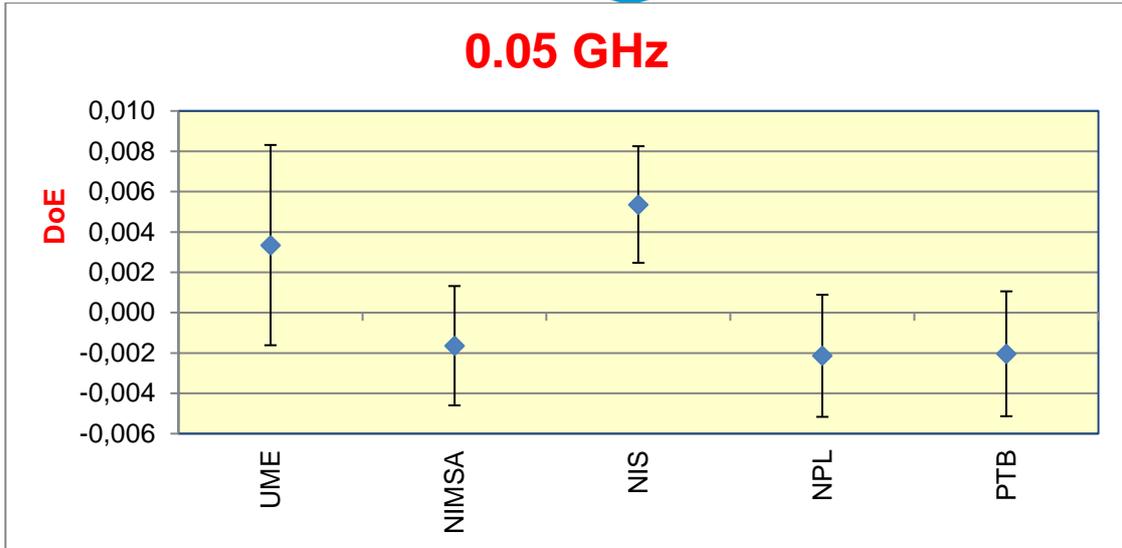


Figure 6. DoE at 50 MHz for STD1 (3318A25528) @EE

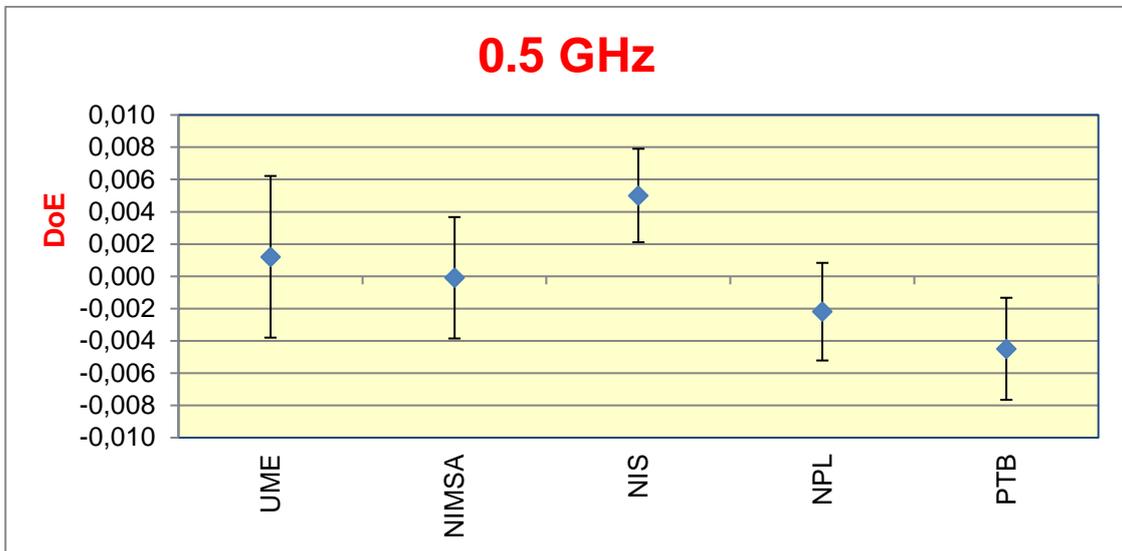


Figure 7. DoE at 500 MHz for STD1 (3318A25528) @EE

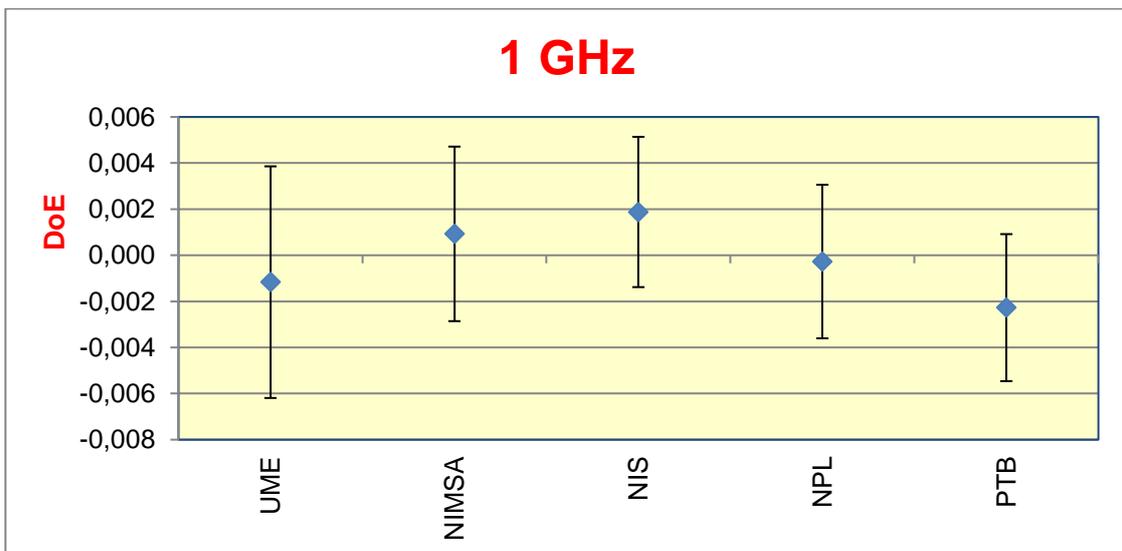


Figure 8. DoE at 1 GHz for STD1 (3318A25528) @EE

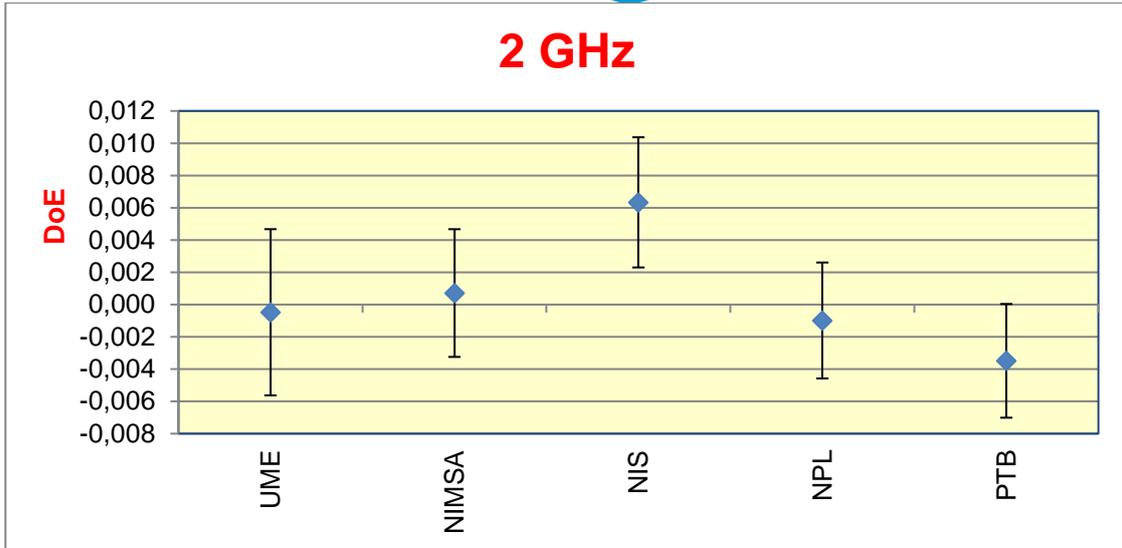


Figure 9. DoE at 2 GHz for STD1 (3318A25528) @EE

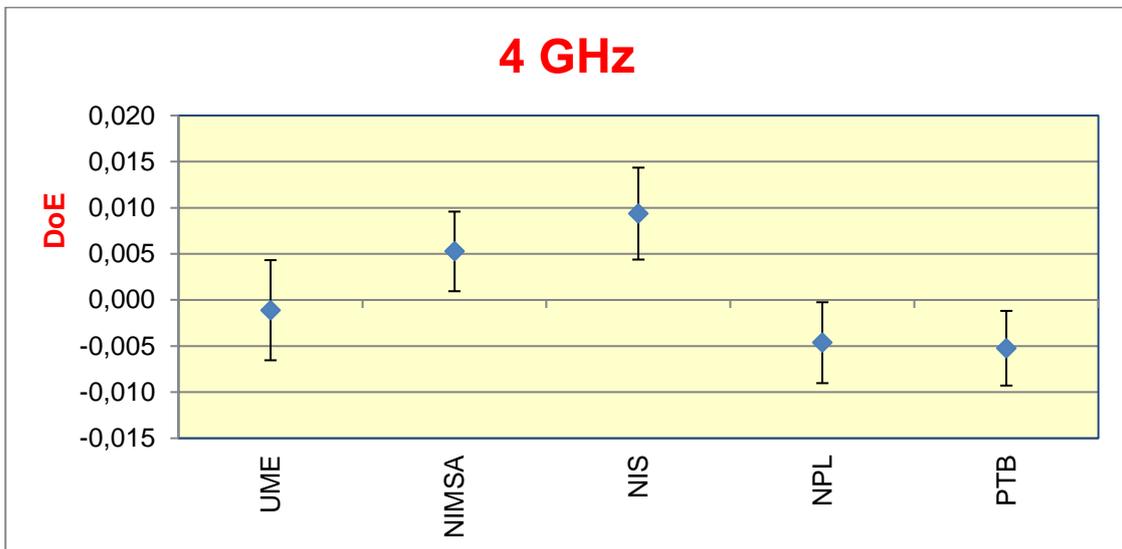


Figure 10. DoE at 4 GHz for STD1 (3318A25528) @EE

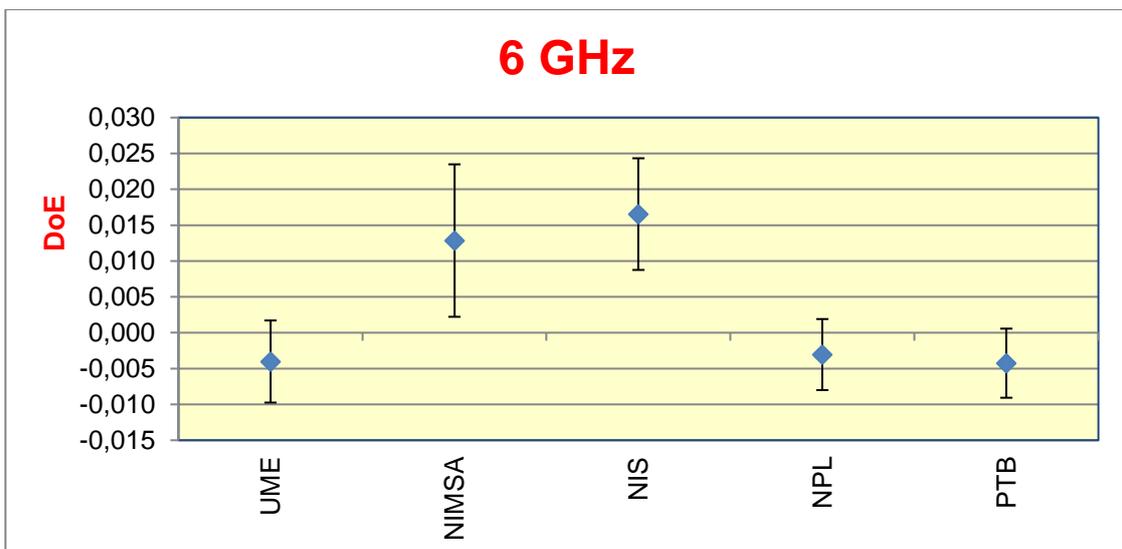


Figure 11. DoE at 6 GHz for STD1 (3318A25528) @EE

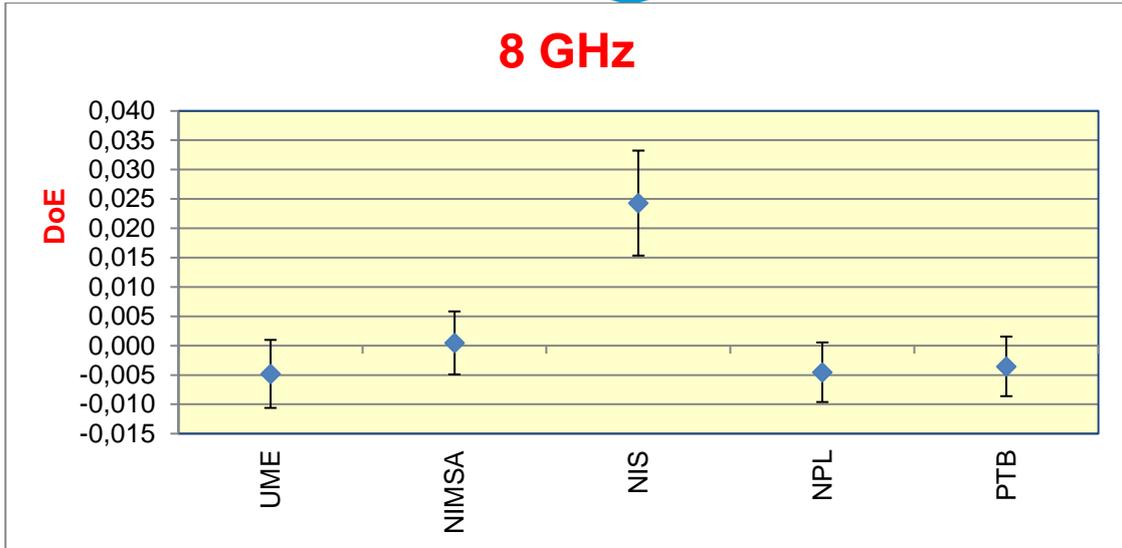


Figure 12. DoE at 8 GHz for STD1 (3318A25528) @EE

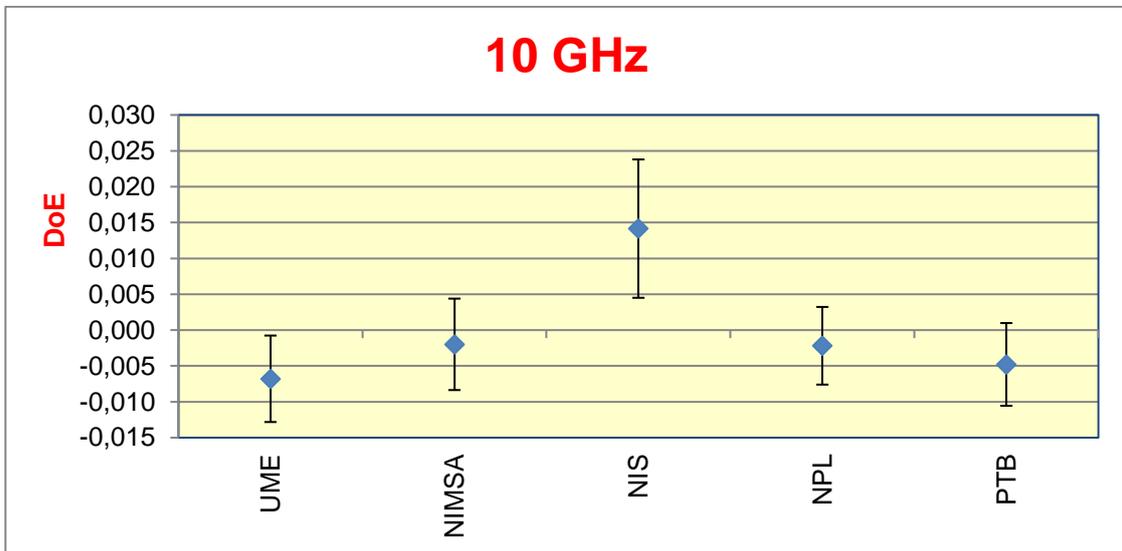


Figure 13. DoE at 10 GHz for STD1 (3318A25528) @EE

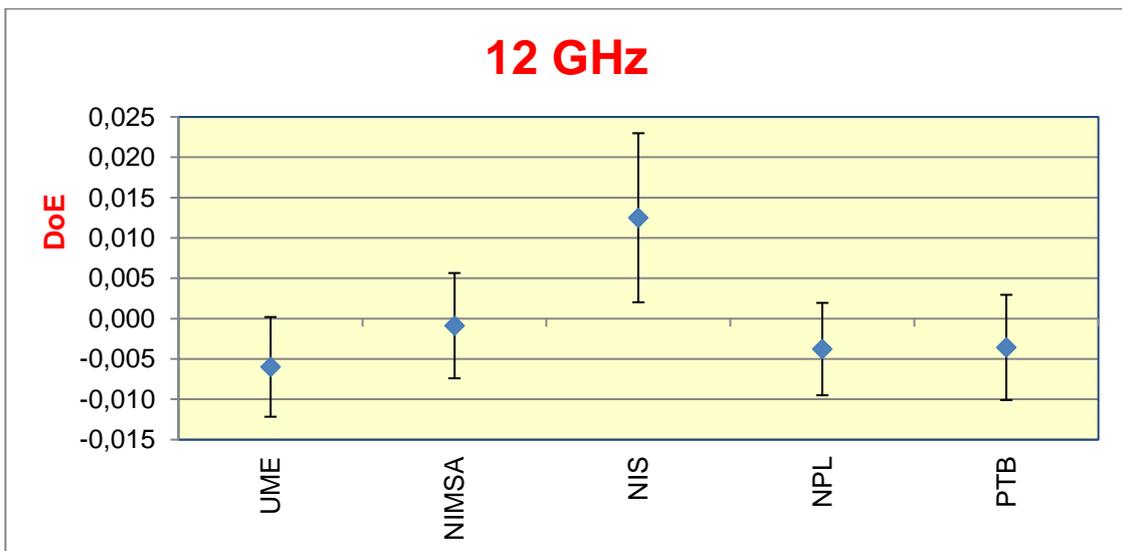


Figure 14. DoE at 12 GHz for STD1 (3318A25528) @EE

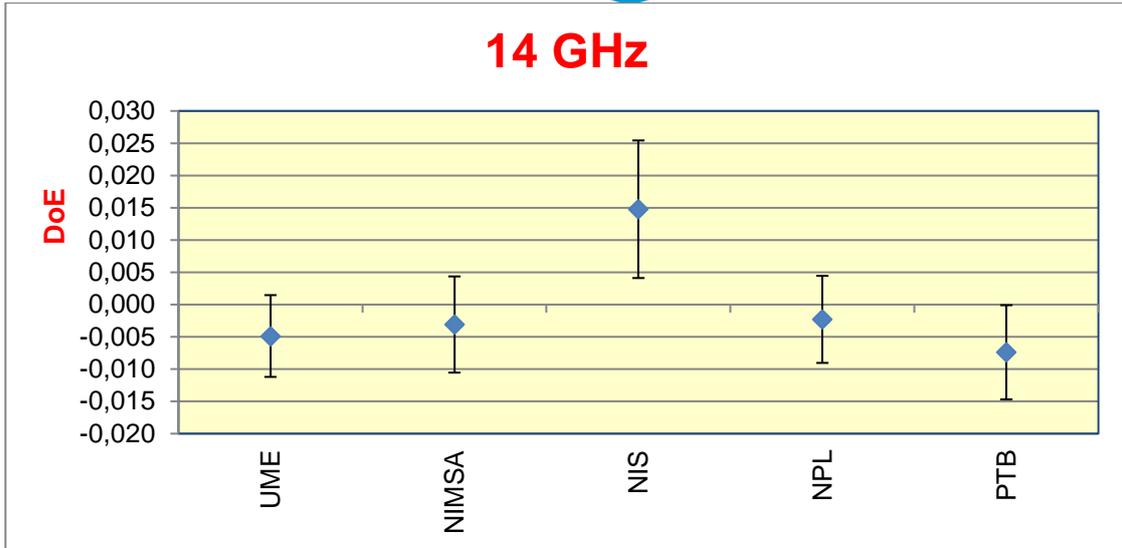


Figure 15. DoE at 14 GHz for STD1 (3318A25528) @EE

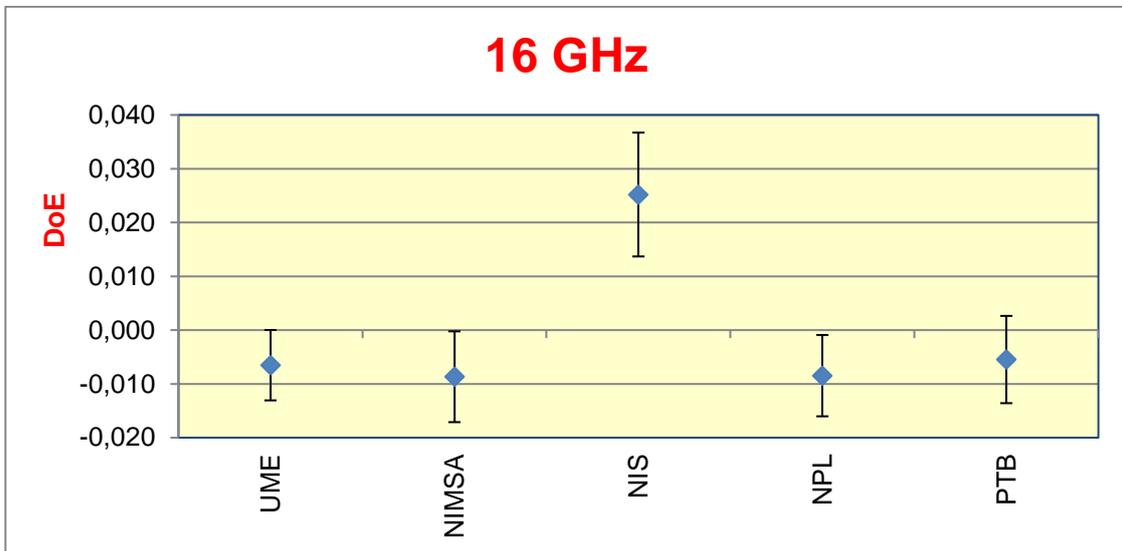


Figure 16. DoE at 16 GHz for STD1 (3318A25528) @EE

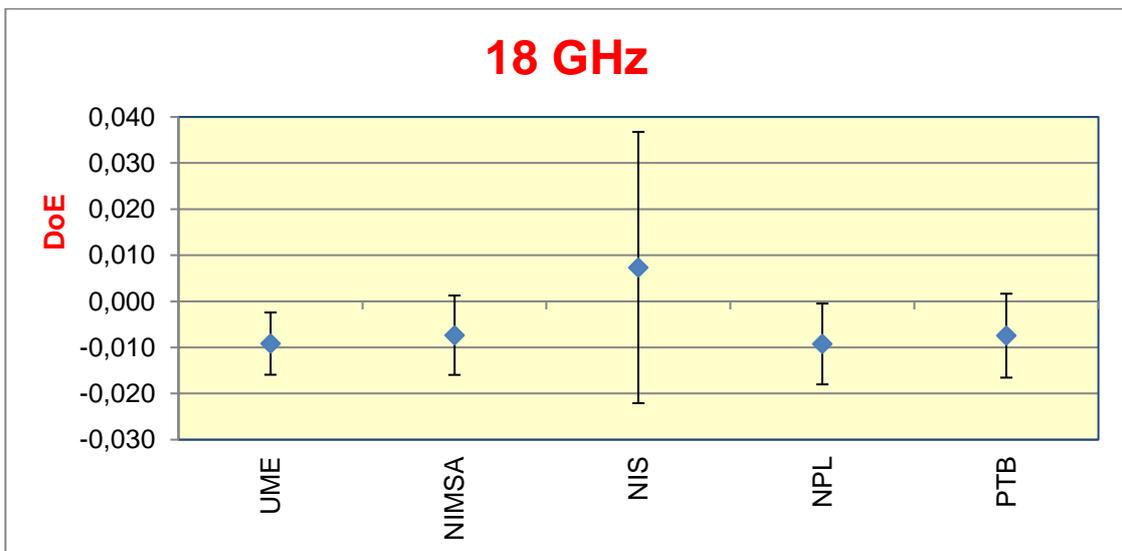


Figure 17. DoE at 18 GHz for STD1 (3318A25528) @EE

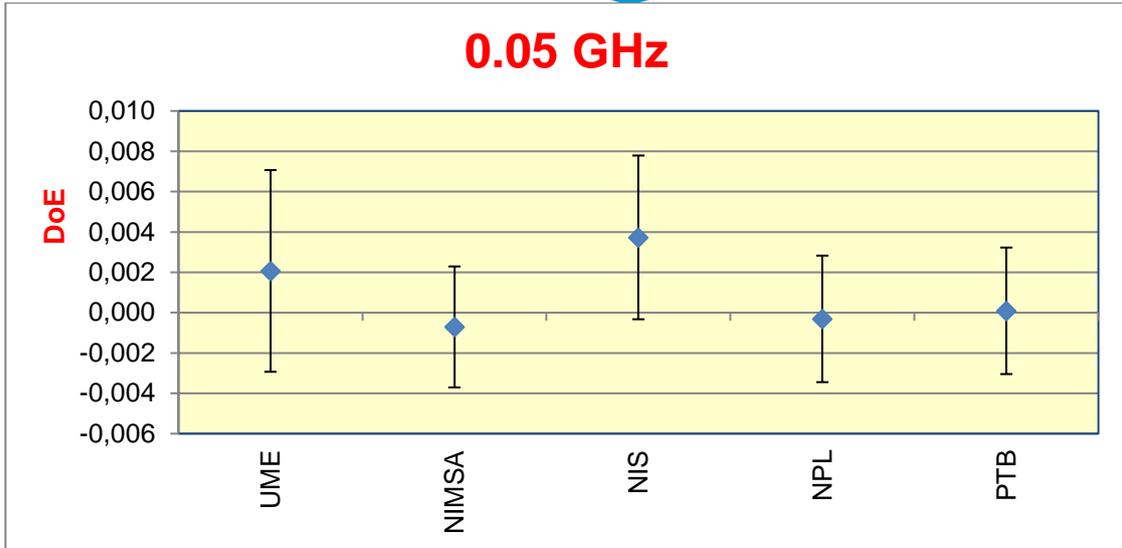


Figure 18. DoE at 50 MHz for STD2 (2106A24217) @EE

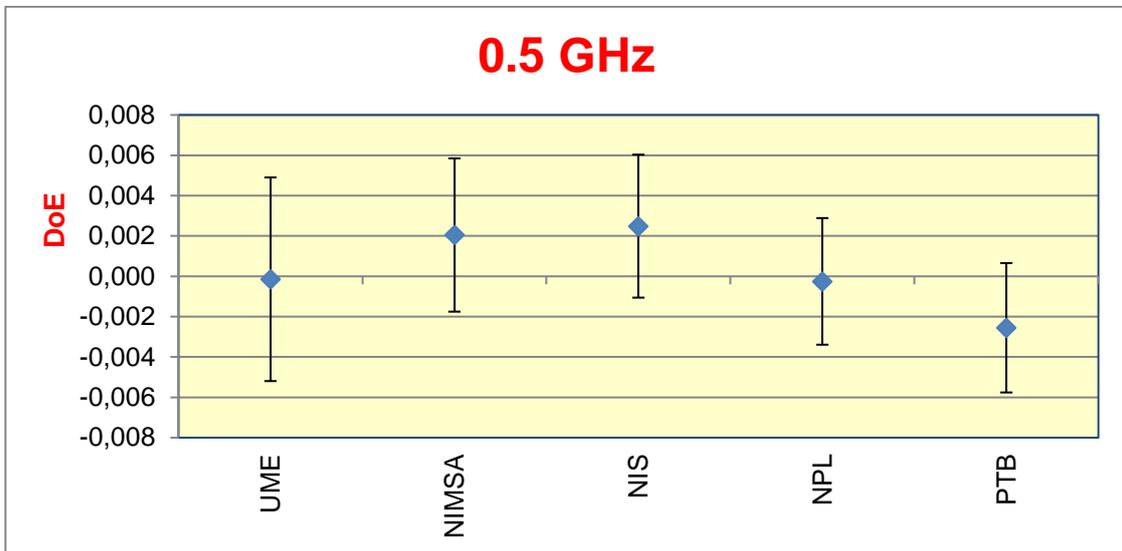


Figure 19. DoE at 500 MHz for STD2 (2106A24217) @EE

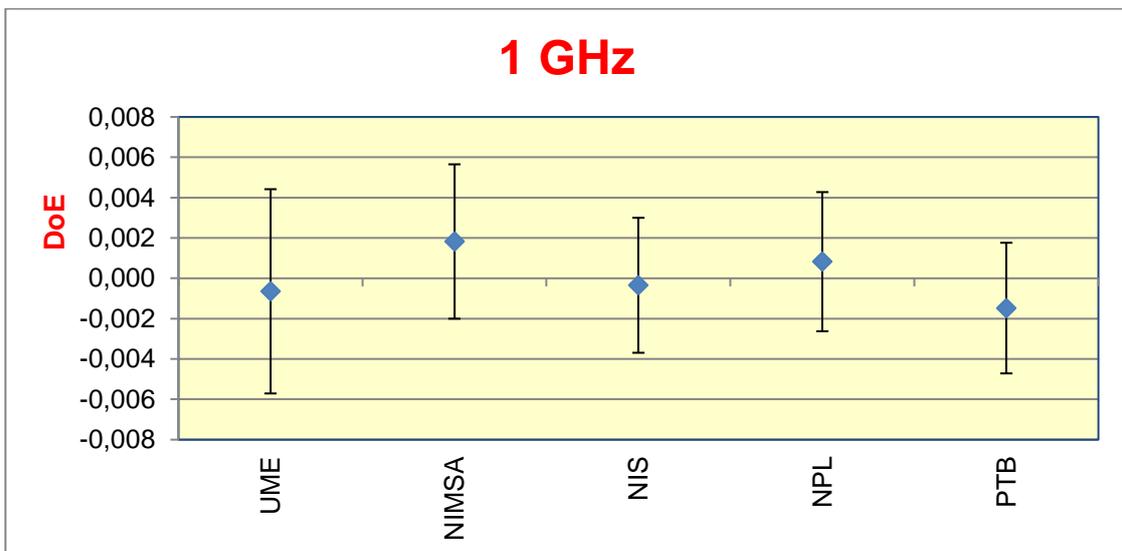


Figure 20. DoE at 1 GHz for STD2 (2106A24217) @EE

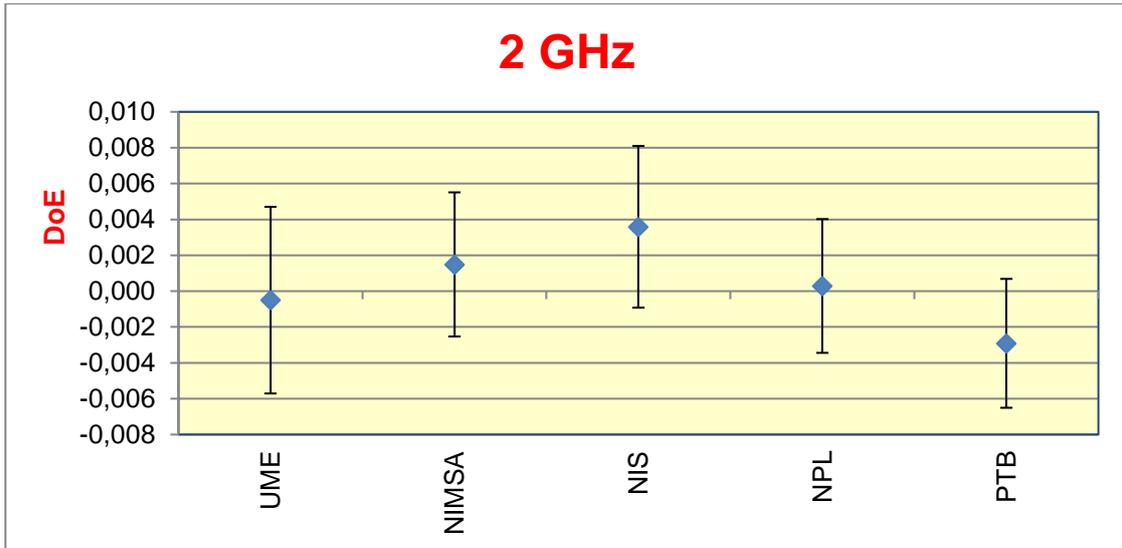


Figure 21. DoE at 2 GHz for STD2 (2106A24217) @EE

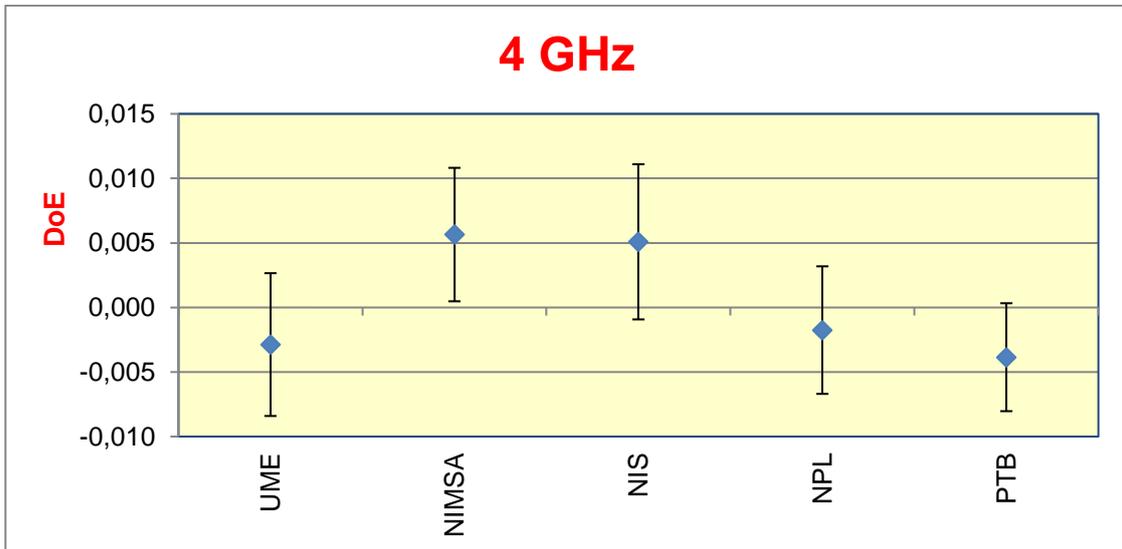


Figure 22. DoE at 4 GHz for STD2 (2106A24217) @EE

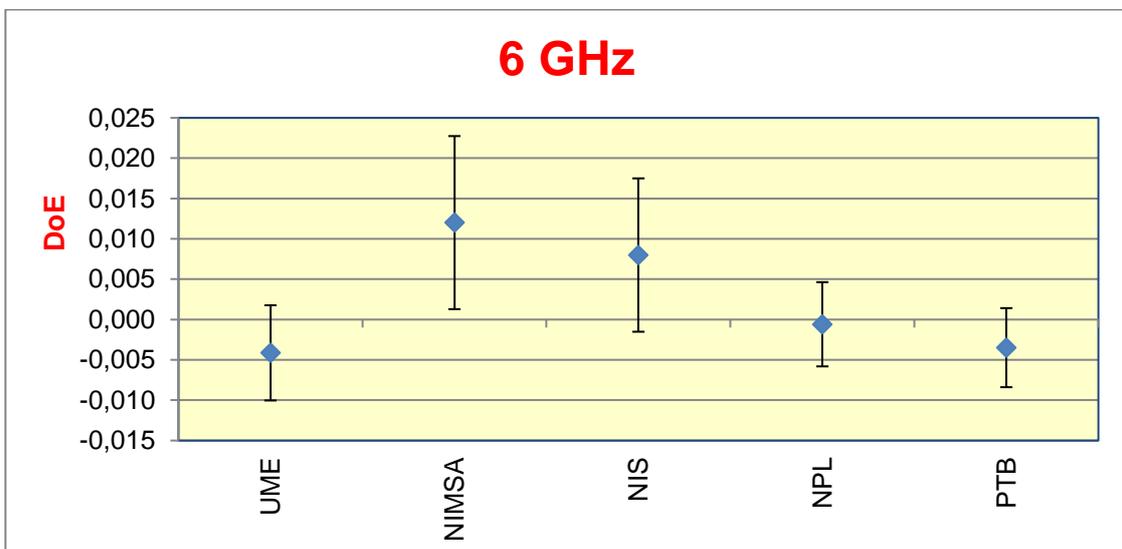


Figure 23. DoE at 6 GHz for STD2 (2106A24217) @EE

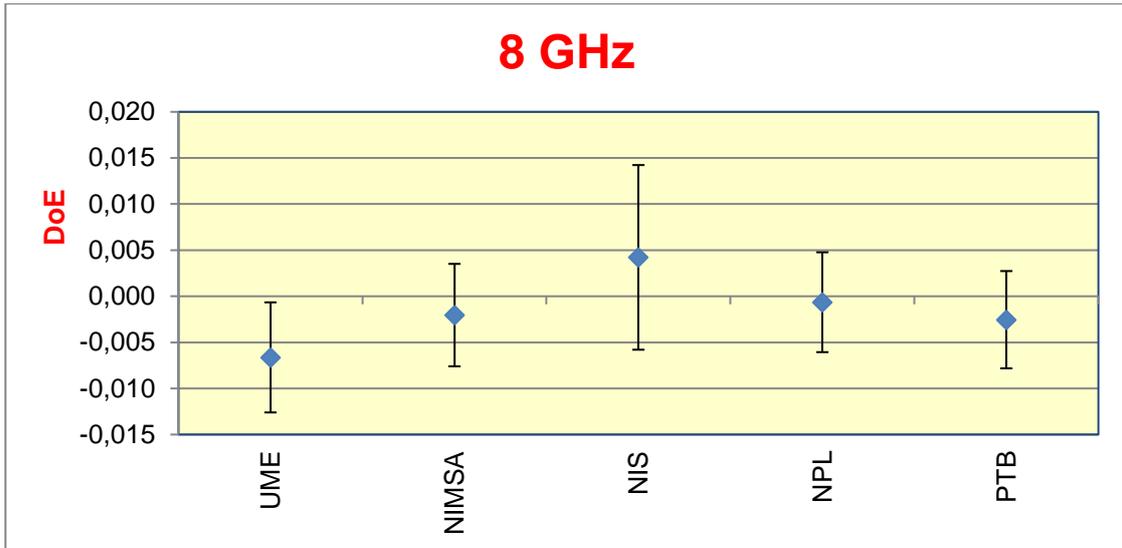


Figure 24. DoE at 8 GHz for STD2 (2106A24217) @EE

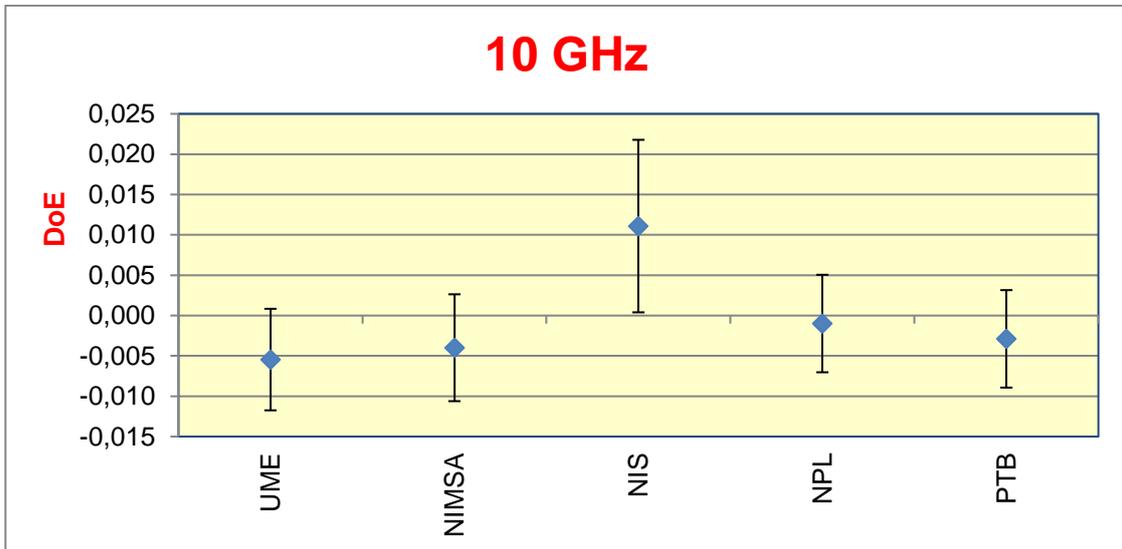


Figure 25. DoE at 10 GHz for STD2 (2106A24217) @EE

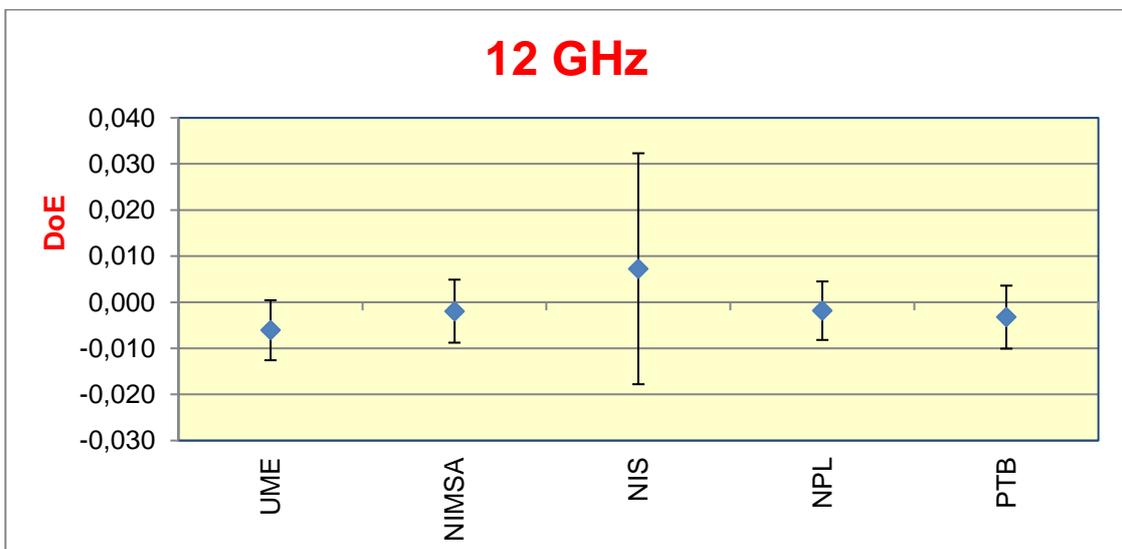


Figure 26. DoE at 12 GHz for STD2 (2106A24217) @EE

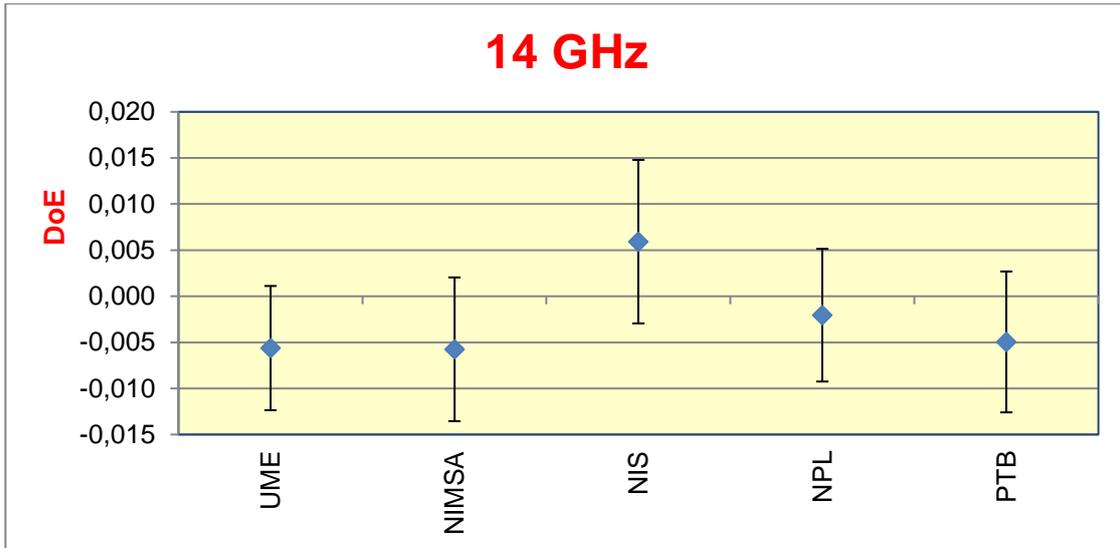


Figure 27. DoE at 14 GHz for STD2 (2106A24217) @EE

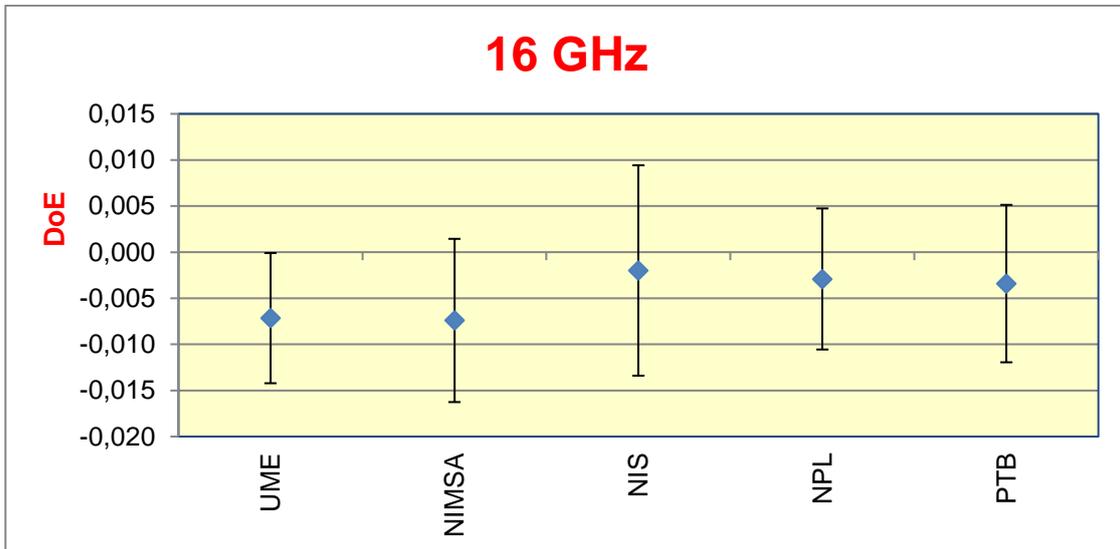


Figure 28. DoE at 16 GHz for STD2 (2106A24217) @EE

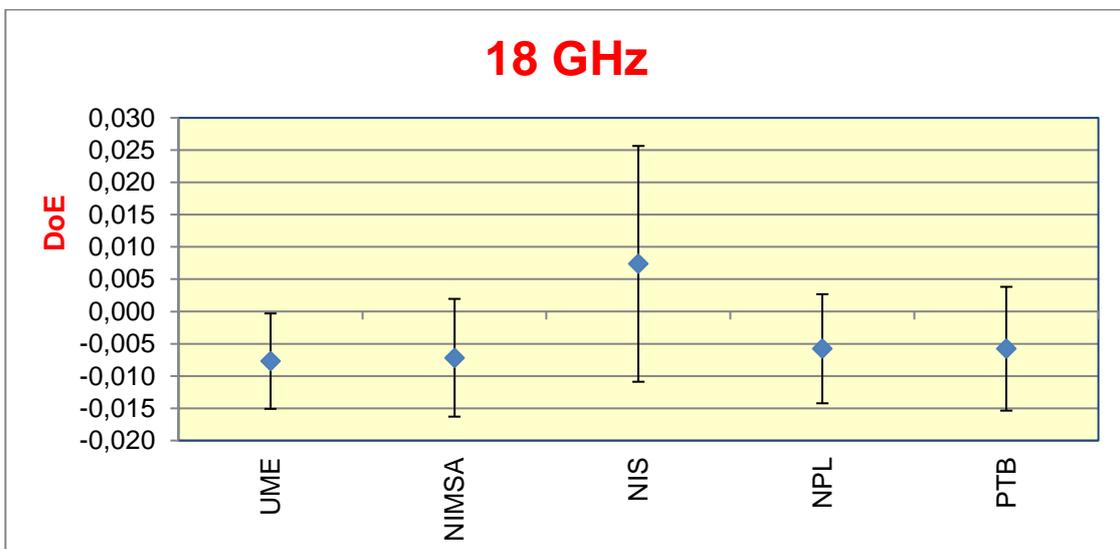


Figure 29. DoE at 18 GHz for STD2 (2106A24217) @EE

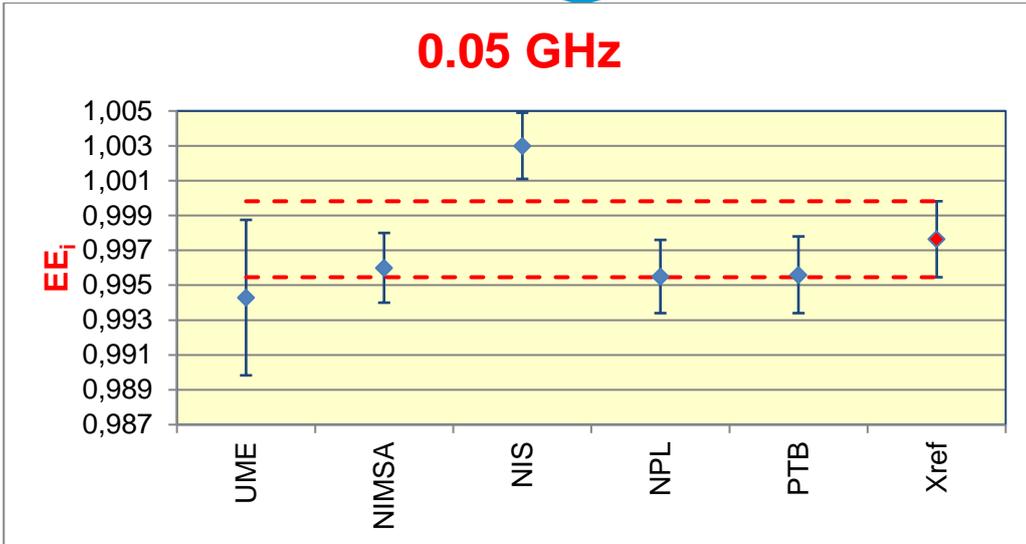


Figure 30. EE at 50 MHz for STD1 (3318A25528)

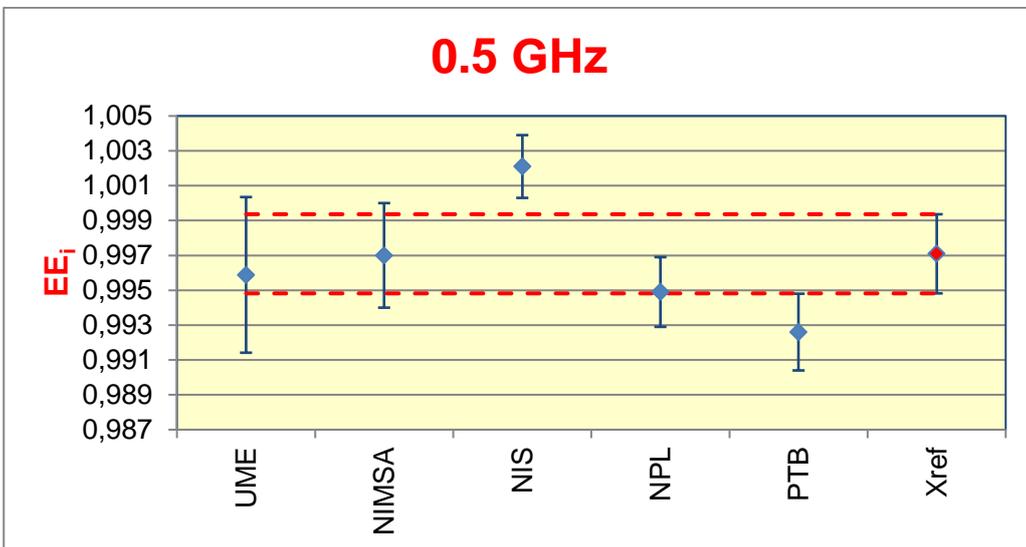


Figure 31. EE at 500 MHz for STD1 (3318A25528)

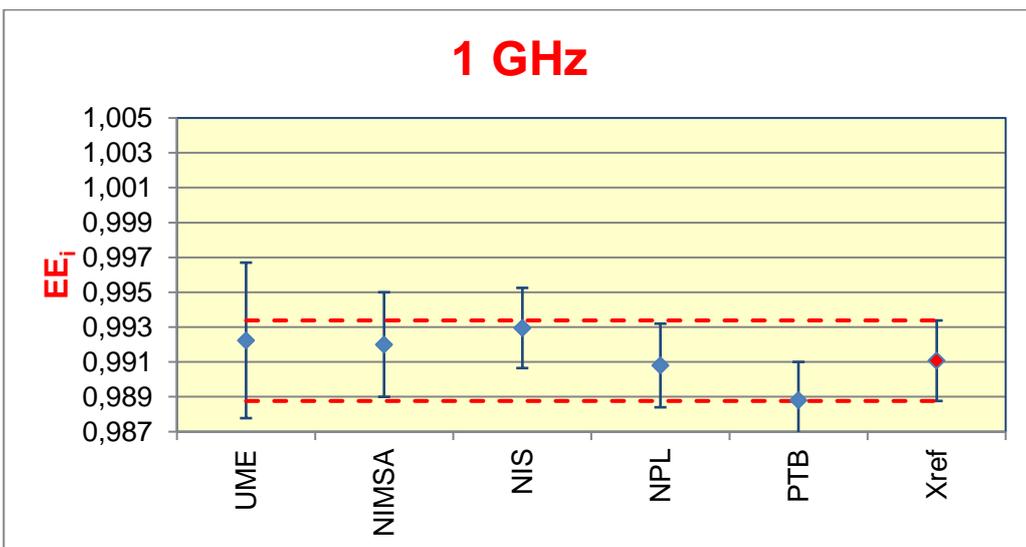


Figure 32. EE at 1 GHz for STD1 (3318A25528)

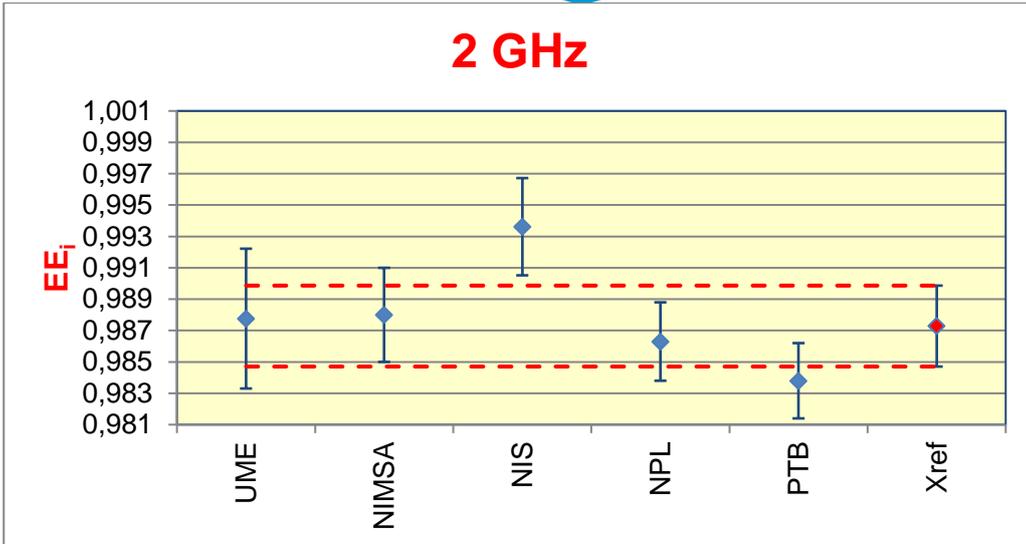


Figure 33. EE at 2 GHz for STD1 (3318A25528)

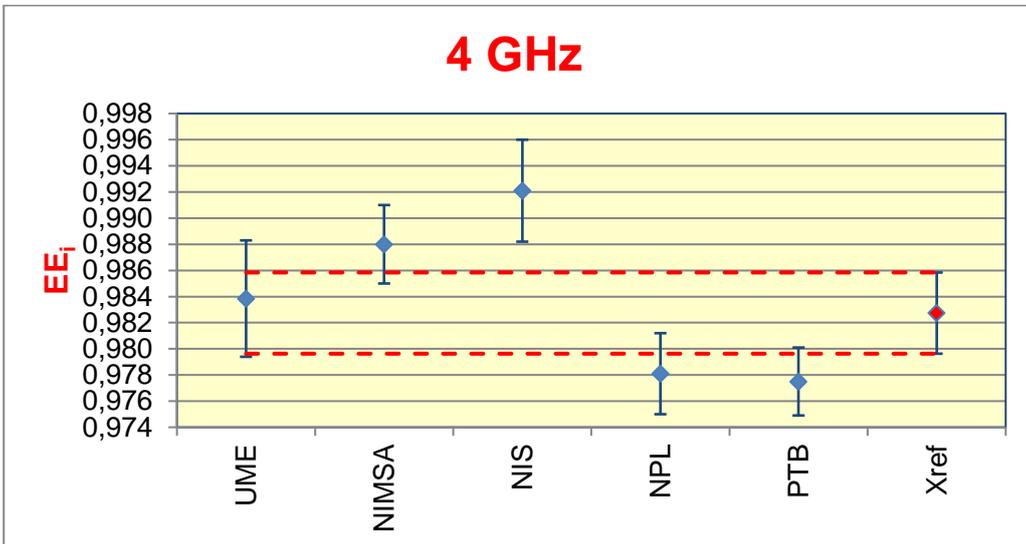


Figure 34. EE at 4 GHz for STD1 (3318A25528)

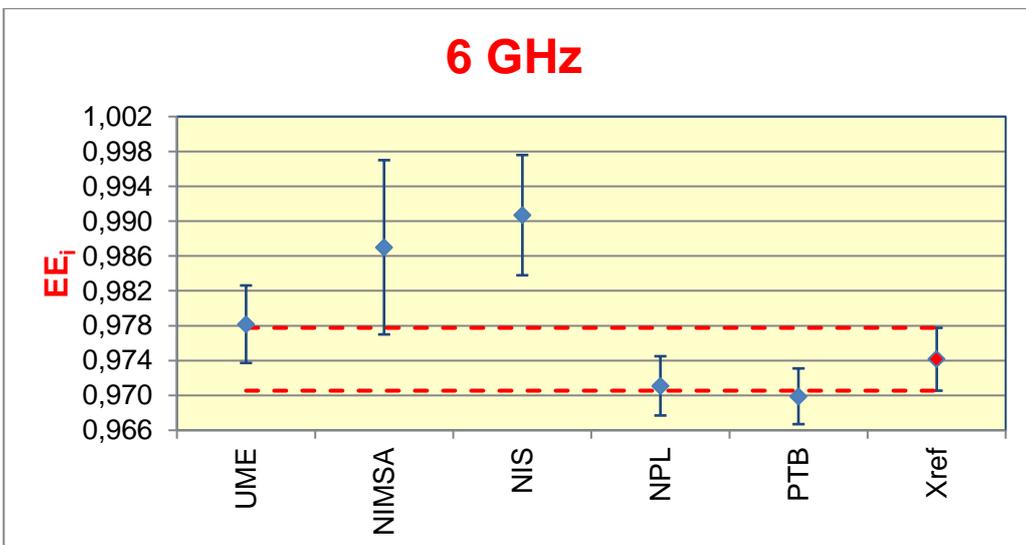


Figure 35. EE at 6 GHz for STD1 (3318A25528)

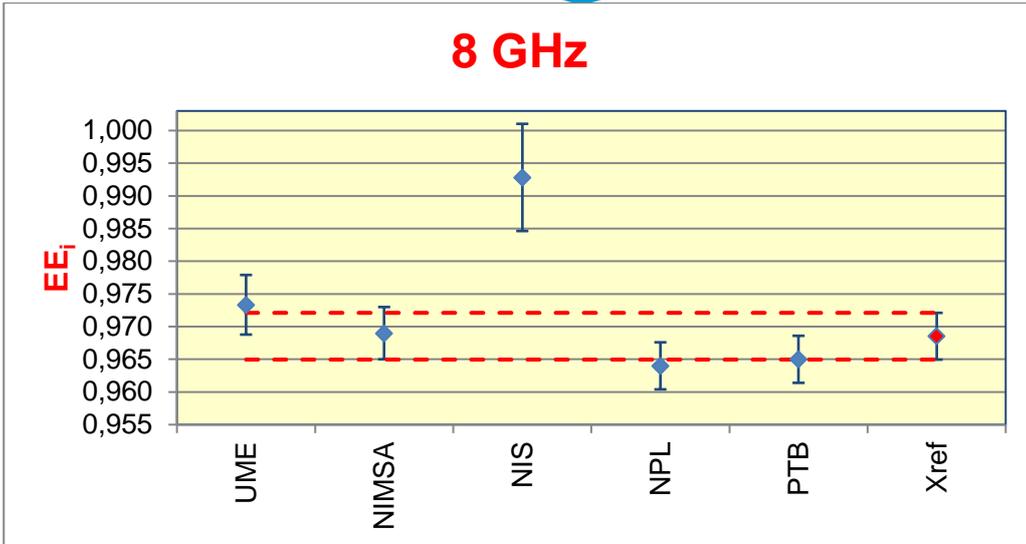


Figure 36. EE at 8 GHz for STD1 (3318A25528)

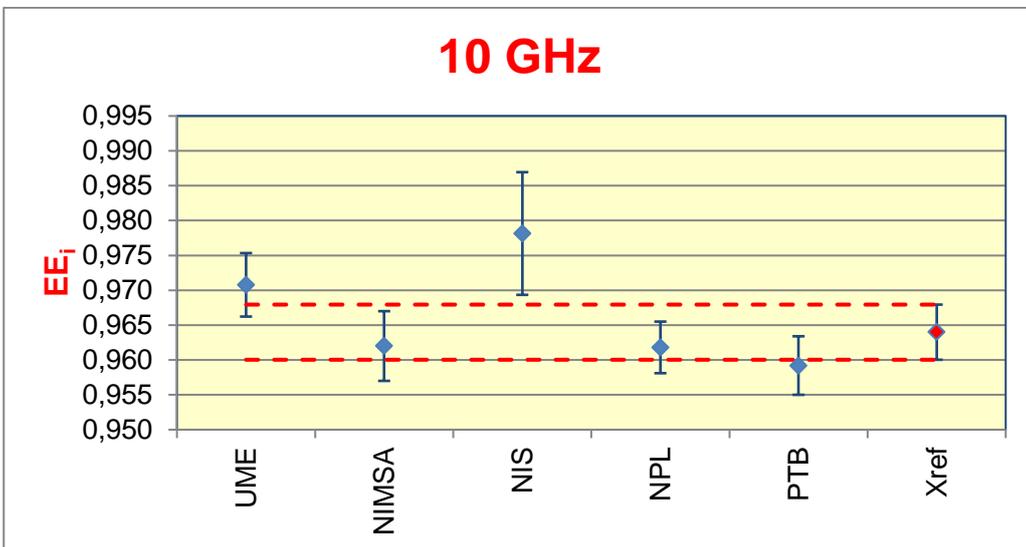


Figure 37. EE at 10 GHz for STD1 (3318A25528)

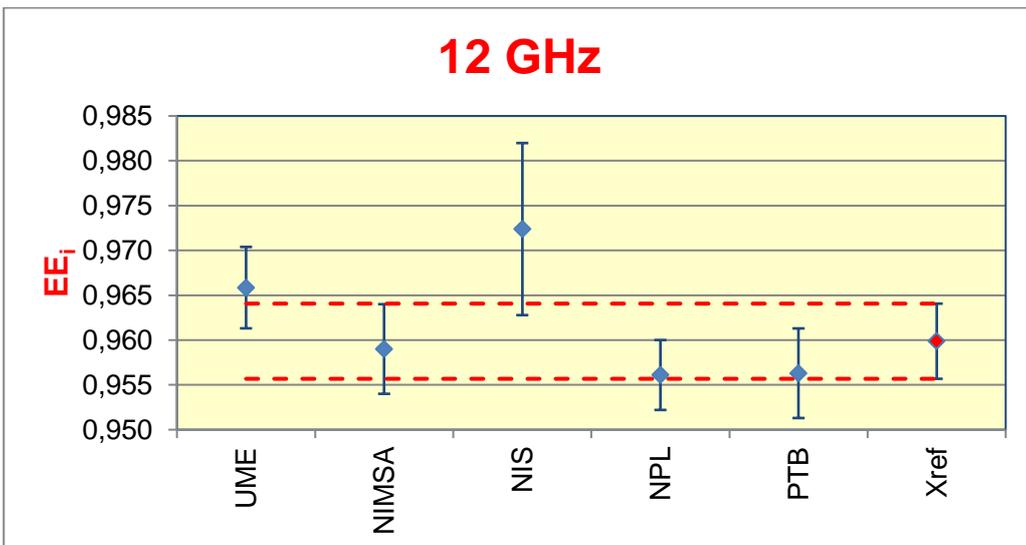


Figure 38. EE at 12 GHz for STD1 (3318A25528)

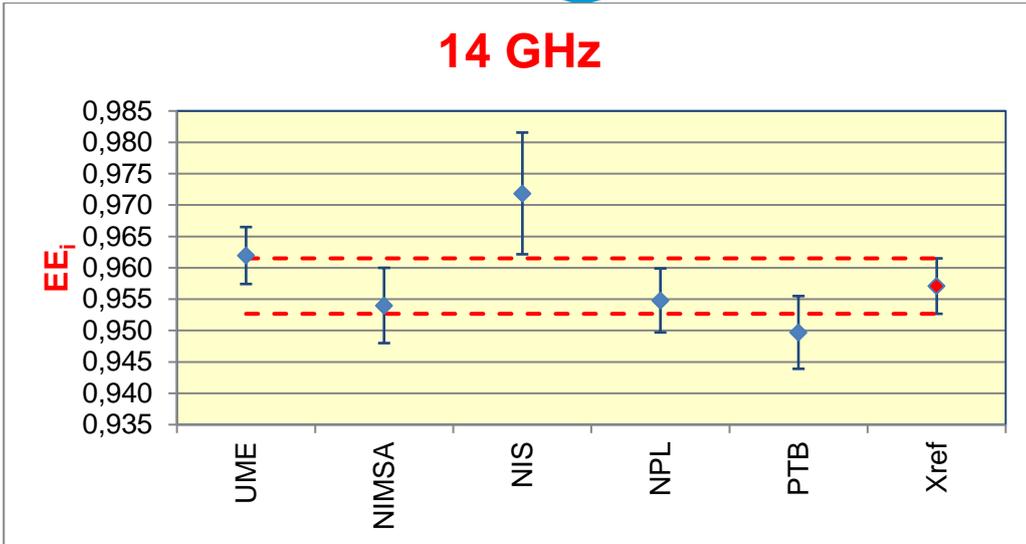


Figure 39. EE at 14 GHz for STD1 (3318A25528)

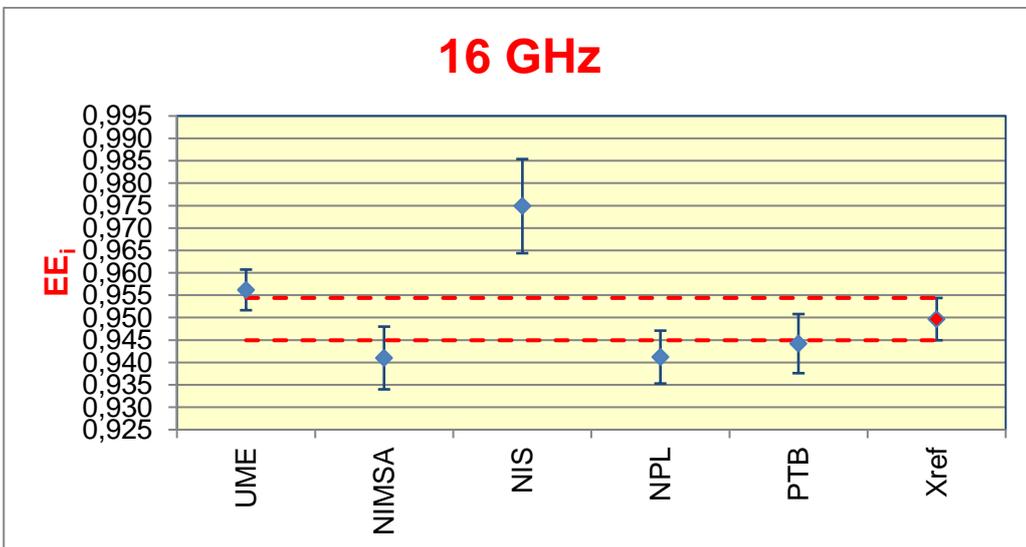


Figure 40. EE at 16 GHz for STD1 (3318A25528)

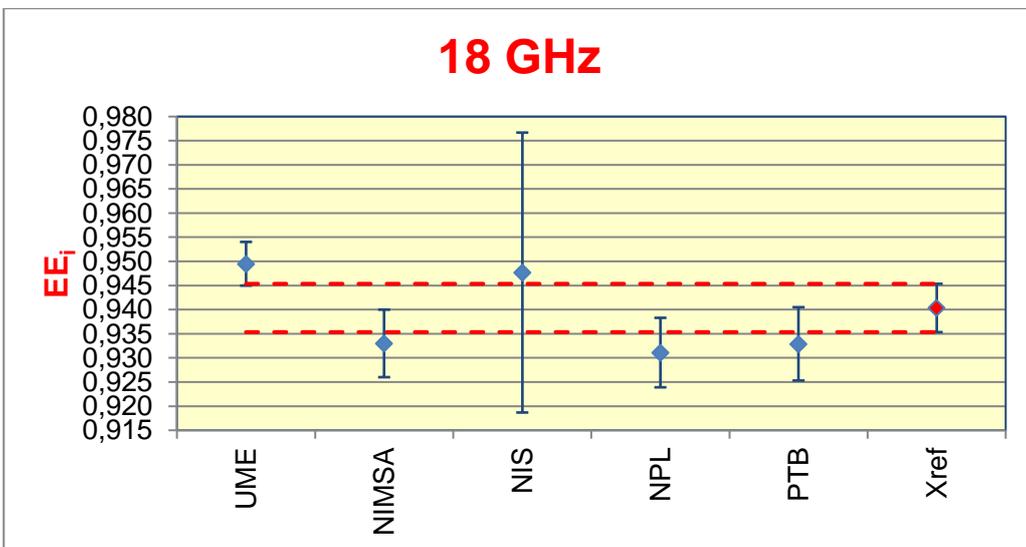


Figure 41. EE at 18 GHz for STD1 (3318A25528)

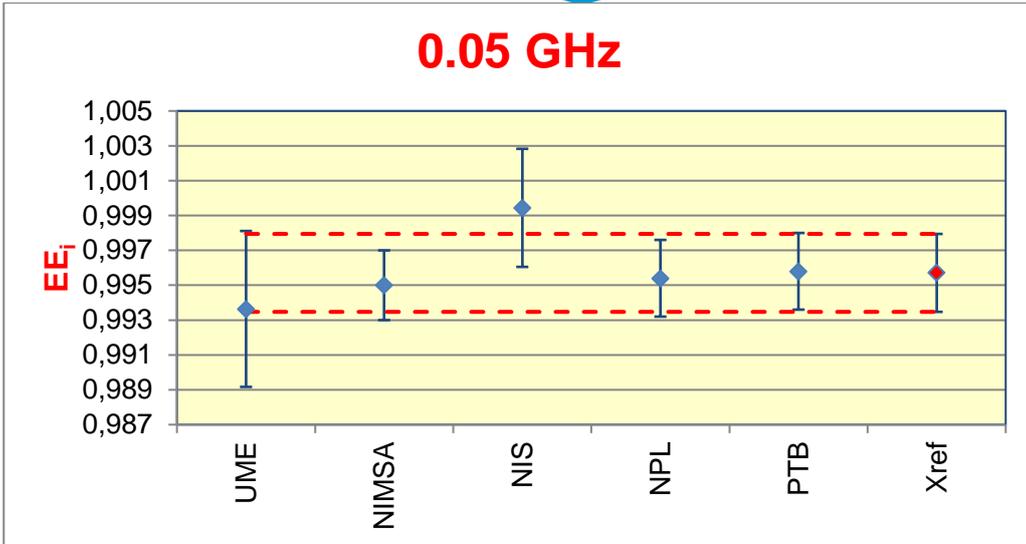


Figure 42. EE at 50 MHz for STD2 (2106A24217)

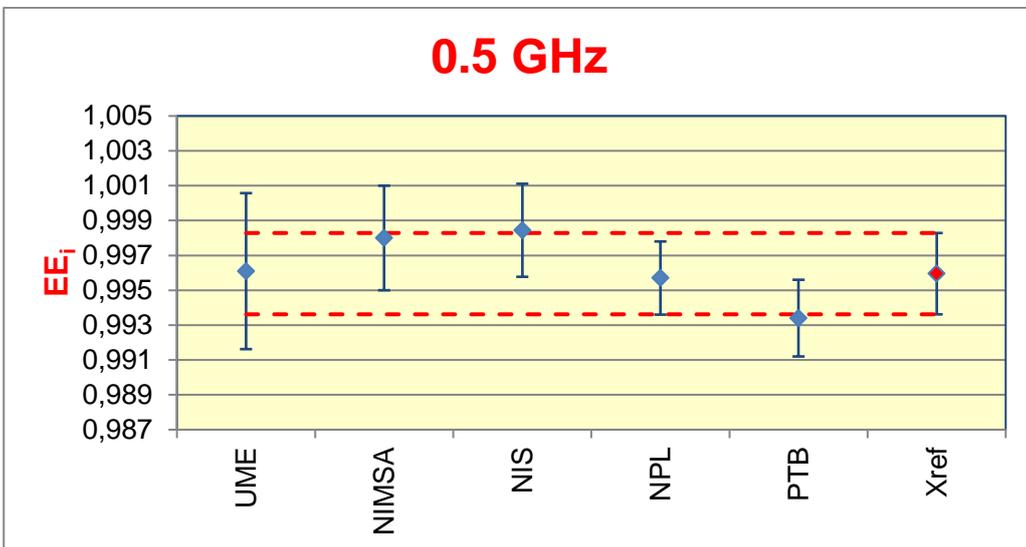


Figure 43. EE at 500 MHz for STD2 (2106A24217)

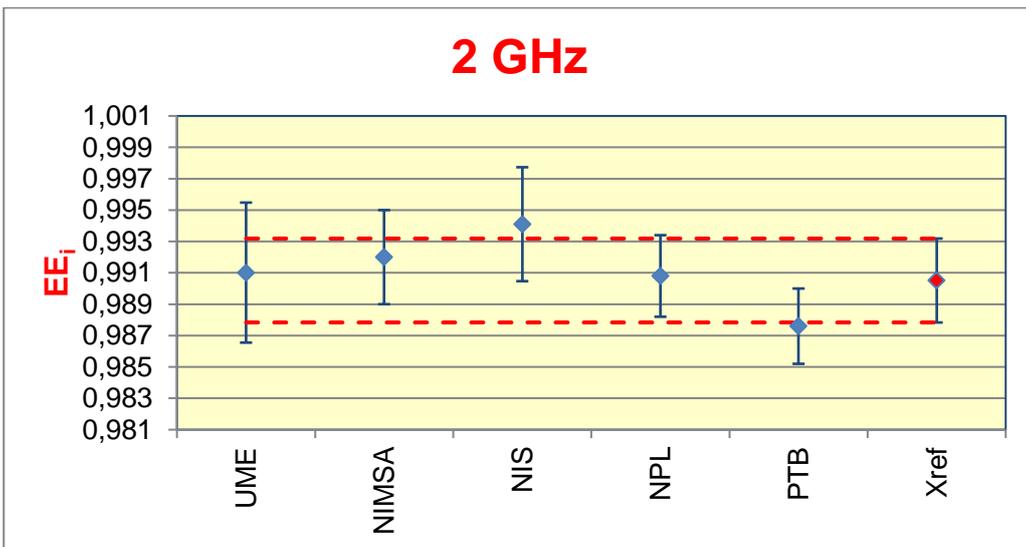


Figure 44. EE at 1 GHz for STD2 (2106A24217)

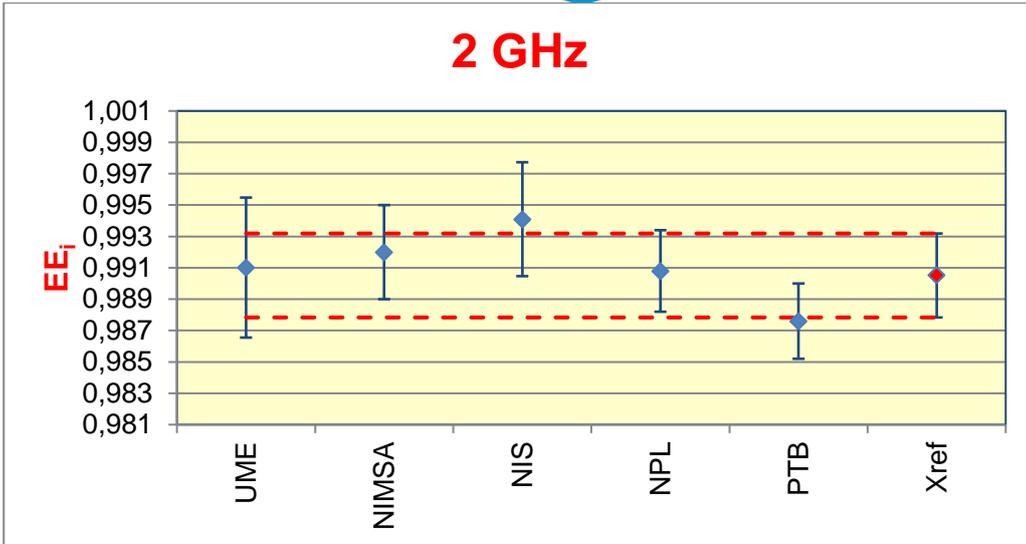


Figure 45. EE at 2 GHz for STD2 (2106A24217)

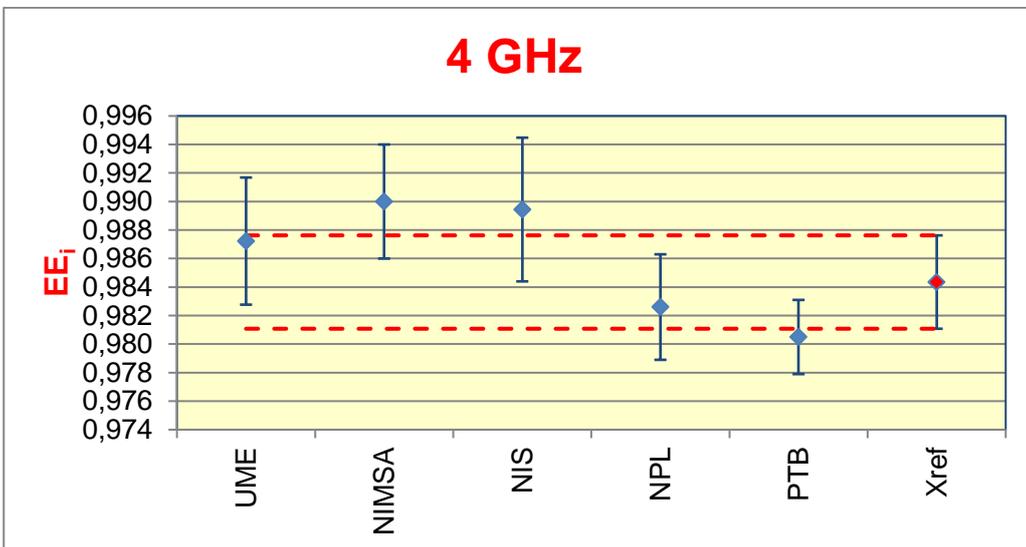


Figure 46. EE at 4 GHz for STD2 (2106A24217)

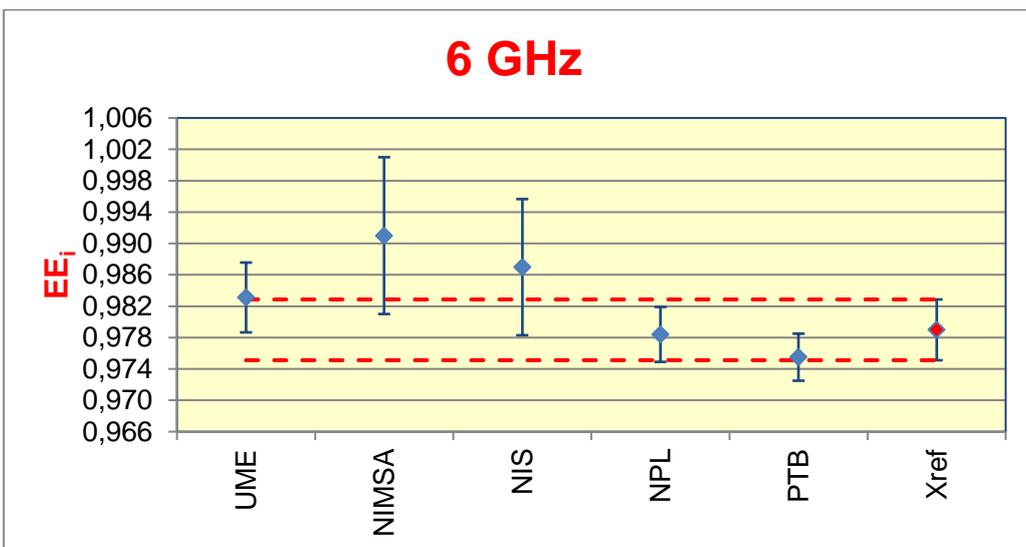


Figure 47. EE at 6 GHz for STD2 (2106A24217)

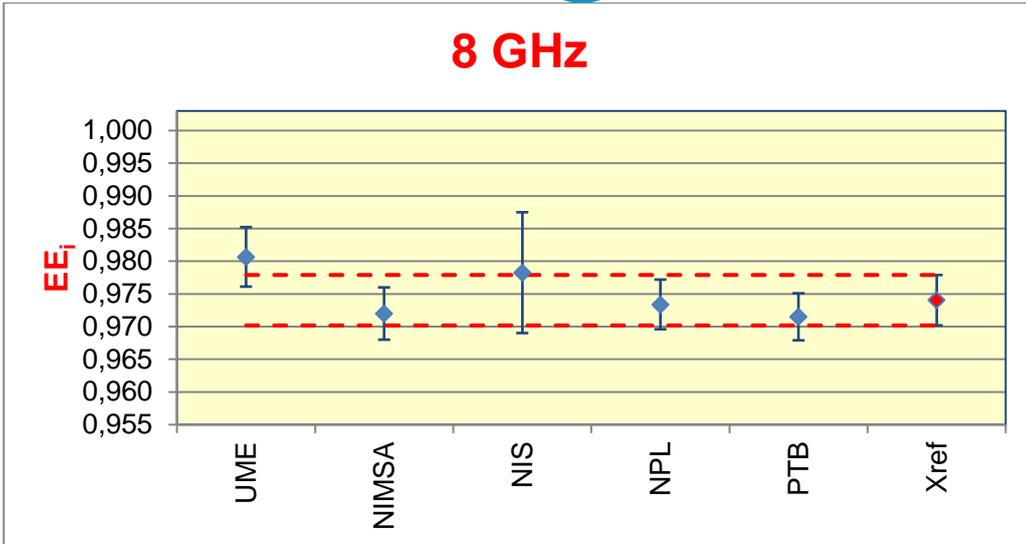


Figure 48. EE at 8 GHz for STD2 (2106A24217)

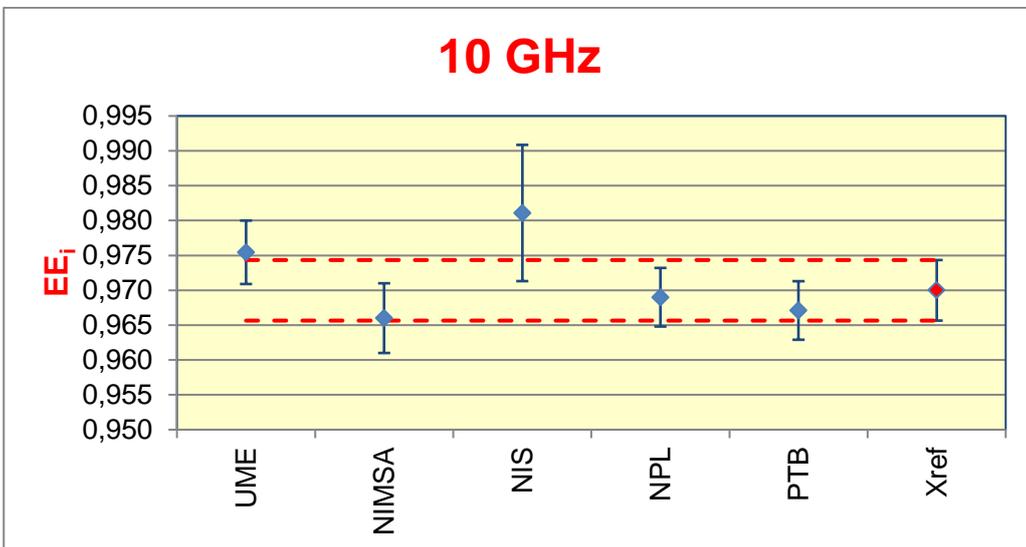


Figure 49. EE at 10 GHz for STD2 (2106A24217)

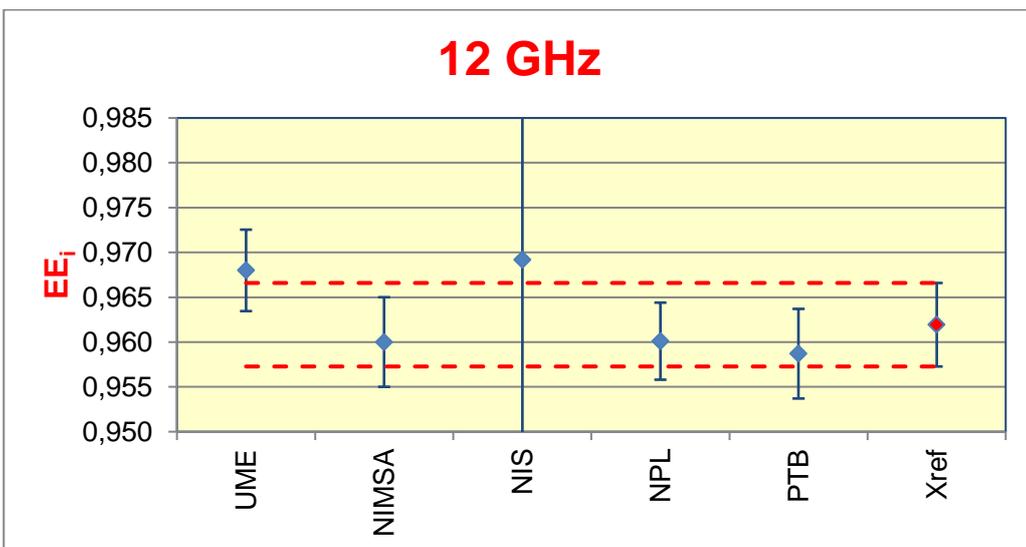


Figure 50. EE at 12 GHz for STD2 (2106A24217)

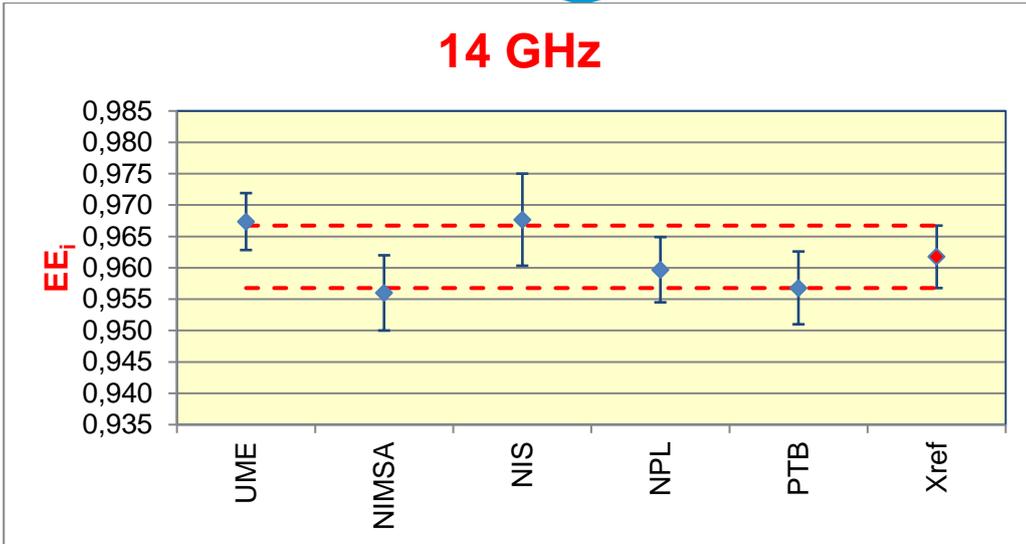


Figure 51. EE at 14 GHz for STD2 (2106A24217)

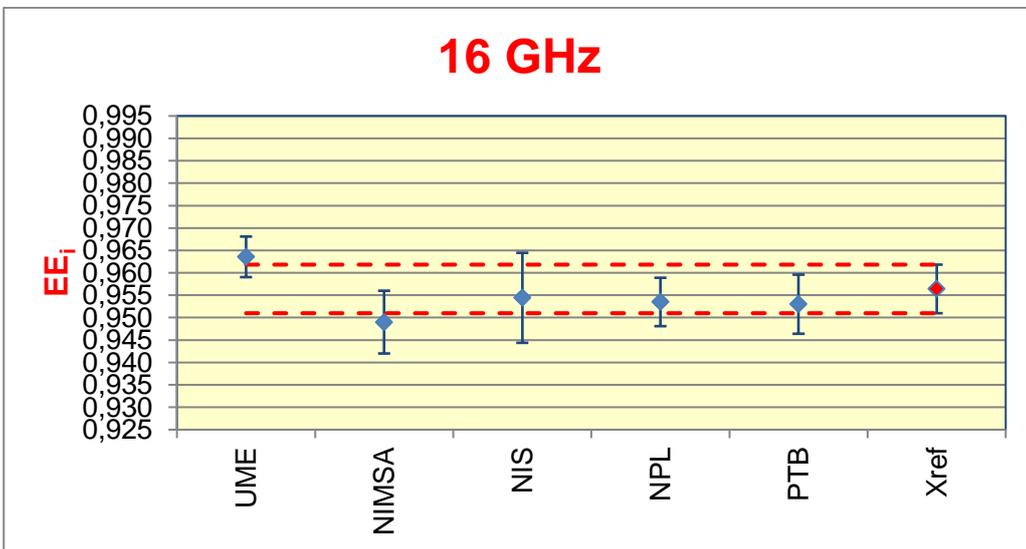


Figure 52. EE at 16 GHz for STD2 (2106A24217)

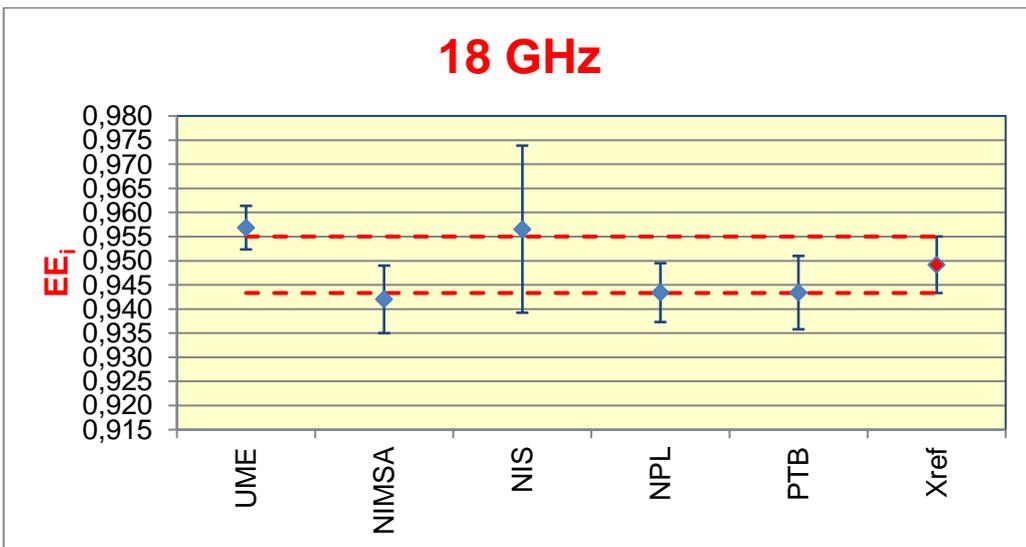


Figure 53. EE at 18 GHz for STD2 (2106A24217)

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- [2] IEEE 287-2007, IEEE Standard for Precision Coaxial Connectors (DC to 110 GHz), 2007.
- [3] Evaluation of measurement data - Guide to the Expression of Uncertainty in Measurement (GUM). JCGM 100. First edition. September 2008 (available on the BIPM website: [http://www.bipm.org/utis/common/documents/jcgm/JCGM\\_100\\_2008\\_E.pdf](http://www.bipm.org/utis/common/documents/jcgm/JCGM_100_2008_E.pdf))
- [4] ISO / IEC 17043 "Conformity assessment — General requirements for proficiency testing". International Standardization Organization". 2010

## ANNEX A. COMPARISON MEASUREMENTS REPORT of TÜBİTAK UME

### 1. PARTICIPANT INFORMATION

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### 2. MEASUREMENT DATE

Comparison : 18.09.2018 - 24.09.2018

Check up : June 2020.

### 3. ENVIRONMENTAL CONDITION

Temperature : 23±1 °C

Relative Humidity : 45±15 rh%

### 4. REFERENCES USED IN MEASUREMENT

Instrument Name	Manufacturer	Type / Model	Serial No	Traceability
Thin-line	TÜBİTAK UME	PCN	PCN-52	TÜBİTAK UME
Voltmeter	Agilent	34420A	MY42000160	TÜBİTAK UME
Nanovoltmeter	Agilent	34420A	MY42000160	TÜBİTAK UME
Signal Generator	Agilent	E8257C	US42340118	TÜBİTAK UME
Power Meter	HP	432A	3303U00514	TÜBİTAK UME
Thin-line	TÜBİTAK UME	PCN	PCN-51	TÜBİTAK UME
VNA	R&S	ZVA50	100147	TÜBİTAK UME
Calibration Kit	Agilent	85054B	MY39200345	TÜBİTAK UME

## 5. MEASUREMENT METHOD

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

TÜBİTAK UME's micro-calorimeter system illustration is given in Figure A1.

Effective efficiency ( $\eta$ ) is the ratio of a substituted DC power to a real microwave power (Eq. A1). The Effective efficiency was calculated by using Eq. A2 at TÜBİTAK UME.

$$\eta = \frac{\text{Substitute d DC power}}{\text{Micwowave power}} \quad (\text{A1})$$

$$\eta = \frac{1}{1 + \frac{V_1^2}{V_1^2 - V_2^2} \frac{e_2 - e_1 L_n}{e_1 L_n}} \quad (\text{A2})$$

Where

$V_1$  Wheatstone bridge output voltage while RF off

$V_2$  Wheatstone bridge output voltage while RF on

$e_1$  Thermopile output voltage while RF off

$e_2$  Thermopile output voltage while RF on

Thermopile linearity;

$$L_T = 1 + \frac{\Delta k}{k_1} \quad (\text{A3})$$

Where;

$\Delta k$  Thermopile nonlinearity coefficient

$k_1$  Thermopile conversion coefficient

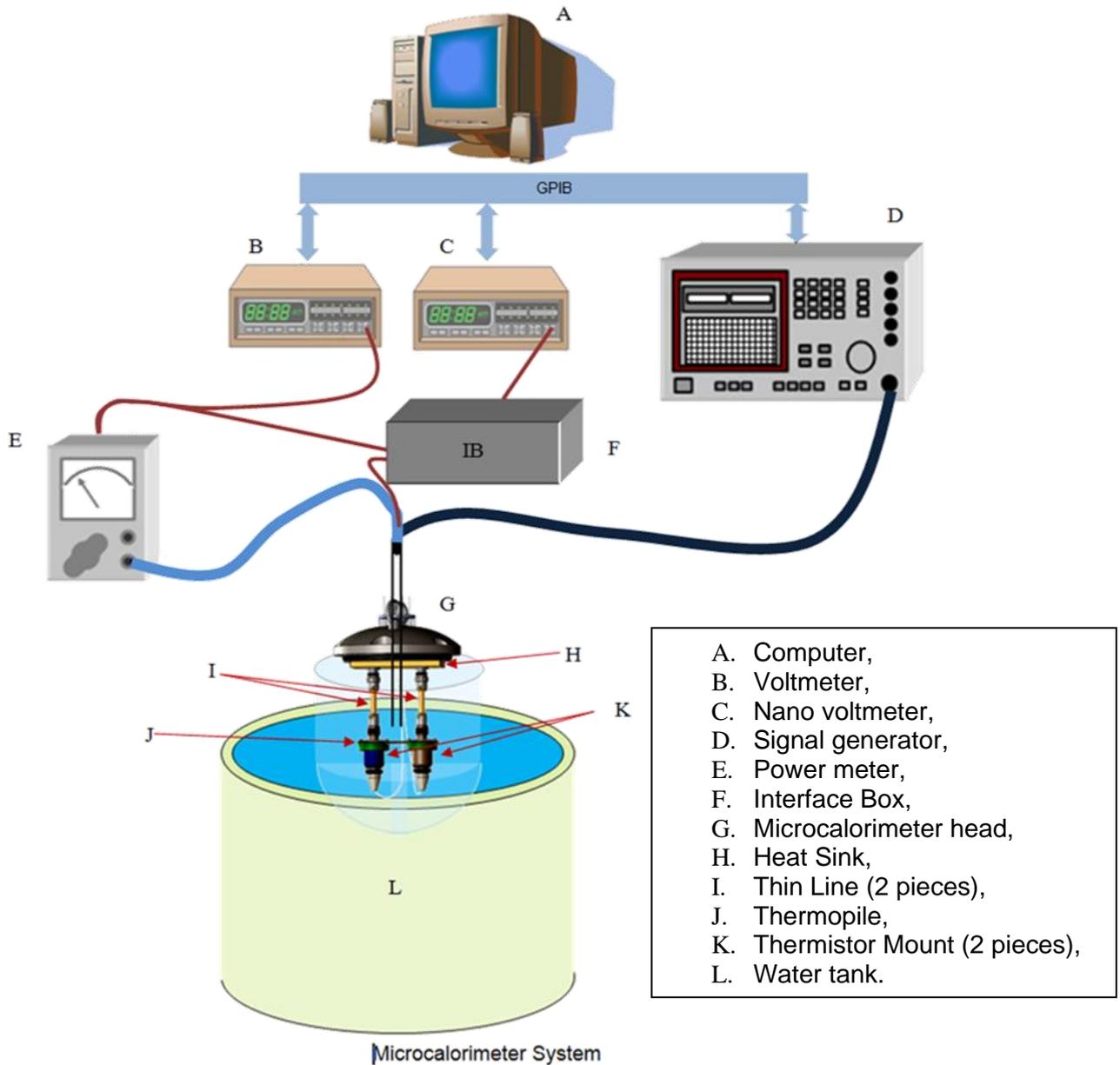


Figure A1. Illustration of TÜBİTAK UME's Micro-calorimeter

Travelling standards' reflection coefficients were measured by VNA.

## 6. MEASUREMENT RESULT

**Table A.1.** Reflection coefficient of the travelling STD1

Frequency	Reflection Coefficient ( $(S_{11} = x + jy)$ ) of STD Power Sensor			
	Real Component x	Real Component Uncertainty (k=2)	Imaginary Component y	Imaginary Component Uncertainty (k=2)
<b>50 MHz</b>	-0.0042	0.0040	-0.0322	0.0040
<b>500 MHz</b>	-0.0115	0.0040	-0.0023	0.0040
<b>1 GHz</b>	-0.0135	0.0040	0.0106	0.0040
<b>2 GHz</b>	0.0190	0.0040	0.0265	0.0040
<b>4 GHz</b>	-0.0184	0.0040	-0.0123	0.0040
<b>6 GHz</b>	0.0378	0.0040	0.0084	0.0040
<b>8 GHz</b>	0.0007	0.0040	-0.0010	0.0040
<b>10 GHz</b>	0.0037	0.0040	-0.0140	0.0040
<b>12 GHz</b>	0.0279	0.0080	-0.0217	0.0080
<b>14 GHz</b>	-0.0388	0.0080	0.0418	0.0080
<b>16 GHz</b>	0.0253	0.0082	-0.1028	0.0082
<b>18 GHz</b>	0.0402	0.0084	0.1343	0.0084

**Table A.2.** Effective efficiency of the travelling STD1

Frequency	Effective Efficiency	Uncertainty (k=2)
<b>50 MHz</b>	0.9943	0.0045
<b>500 MHz</b>	0.9959	0.0045
<b>1 GHz</b>	0.9922	0.0045
<b>2 GHz</b>	0.9878	0.0045
<b>4 GHz</b>	0.9838	0.0045
<b>6 GHz</b>	0.9782	0.0044
<b>8 GHz</b>	0.9733	0.0046
<b>10 GHz</b>	0.9708	0.0046
<b>12 GHz</b>	0.9658	0.0045
<b>14 GHz</b>	0.9620	0.0045
<b>16 GHz</b>	0.9562	0.0045
<b>18 GHz</b>	0.9495	0.0045

**Table A.3.** Reflection coefficient of the travelling STD2

Frequency	Reflection Coefficient ( $(S_{11} = x + jy)$ ) of STD2 Power Sensor			
	Real Component x	Real Component Uncertainty (k=2)	Imaginary Component y	Imaginary Component Uncertainty (k=2)
50 MHz	-0.0084	0.0040	-0.0368	0.0040
500 MHz	-0.0217	0.0040	-0.0029	0.0040
1 GHz	-0.0243	0.0040	0.0167	0.0040
2 GHz	0.0241	0.0040	0.0390	0.0040
4 GHz	-0.0319	0.0040	-0.0493	0.0040
6 GHz	0.0406	0.0041	0.0572	0.0041
8 GHz	-0.0236	0.0041	-0.0616	0.0041
10 GHz	0.0015	0.0041	0.0552	0.0041
12 GHz	0.0360	0.0081	-0.0565	0.0081
14 GHz	-0.0595	0.0081	0.0448	0.0081
16 GHz	0.0739	0.0081	-0.0459	0.0081
18 GHz	-0.0439	0.0081	0.0693	0.0081

**Table A.4.** Effective efficiency of the travelling STD2

Frequency	Effective Efficiency	Uncertainty (k=2)
50 MHz	0.9936	0.0045
500 MHz	0.9961	0.0045
1 GHz	0.9938	0.0045
2 GHz	0.9910	0.0045
4 GHz	0.9872	0.0045
6 GHz	0.9831	0.0044
8 GHz	0.9807	0.0046
10 GHz	0.9754	0.0046
12 GHz	0.9680	0.0045
14 GHz	0.9674	0.0045
16 GHz	0.9636	0.0045
18 GHz	0.9569	0.0045

## ANNEX B. COMPARISON MEASUREMENTS REPORT of NMISA

### 1. PARTICIPANT INFORMATION

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### 2. MEASUREMENT DATE

December 2019 – January 2020

### 3. ENVIRONMENTAL CONDITION

Temperature :  $23 \pm 3$  °C

Relative Humidity:  $45 \pm 15$  %rh

### 4. REFERENCES USED IN MEASUREMENT

Instrument Name	Manufacturer	Type / Model	Serial No	Traceability
Std. resistor	Cropico	RS3-50 $\Omega$	28H-0432	NMISA
Multiplexer module (voltmeter)	Keysight	34901A	MY41233441	NMISA
Calibration kit	Keysight	85054B	MY39200487	METAS
Transfer standard	Rohde & Schwarz and Weinschel	NRP-Z51 and 1870A	..105071 and 11443	NMISA
Power meter	HP	432B	2130A02640	NMISA

## 5. MEASUREMENT METHOD

The Effective Efficiency of the travelling standards (DUTs) was determined by employing a calibrated transfer standard consisting of a power splitter (Weinschel model 1870A) and a Rohde & Schwarz thermal power sensor (model NRP-Z51) where the power sensor is permanently connected to one output port of the power splitter. The transfer standard was calibrated against the national RF power primary standard (7 mm dual line dry load calorimeter), which operates by equating the heat dissipated by applied RF power with the heat dissipated by a known applied DC power. The calorimeter was then replaced with a DUT (thermistor mount), to determine the effective efficiency. A block diagram of the setup for calibrating the transfer standard against the calorimeter as well as calibrating the DUT against the transfer standard is shown in the Figure below.

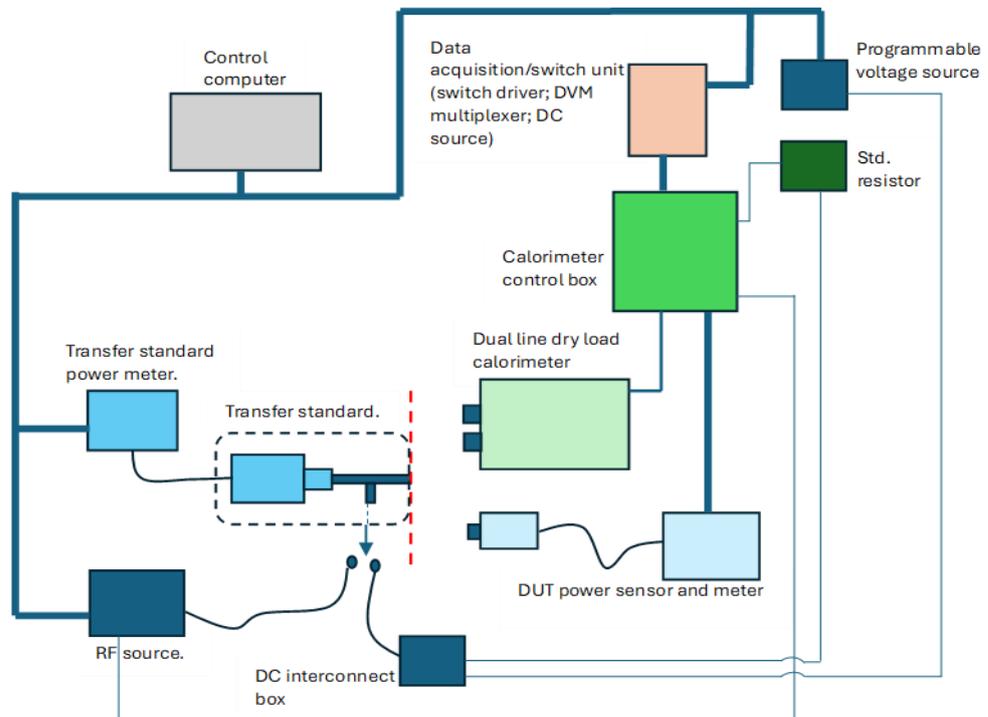


Figure A2. Block diagram of setup for measuring the transfer standard against the calorimeter as well as the DUT against the transfer standard

The voltage reflection coefficients (VRC) of the travelling standards were determined by direct measurement against a PNA vector network analyser employing VNA TOOLS II software. The PNA vector network analyser was calibrated using an HP 85054B kit, which was calibrated at METAS (Switzerland).

The calibration factor of the DUT,  $K(\text{DUT})$ , was determined by using the following formula (B1):

$$K(DUT) = \frac{P(DUT)(1-|r|^2)}{P(TS)MF} * K(sys) \tag{B1}$$

from which the effective efficiency ( $\eta$ ) is determined using the formula (B2)

$$\eta = \frac{K(DUT)}{(1-|r|^2)} \tag{B2}$$

Where

P(DUT) - power reading of the DUT power meter

P(TS) - power reading of the transfer standard power meter when attached to DUT.

r - reflection coefficient of the DUT

MF - mismatch factor between the DUT and the transfer standard.

K(sys) - transfer standard calibration coefficient/constant, which is the product of the power indicated on the transfer standard when connected to the calorimeter and mismatch factor of the transfer standard/the calorimeter, divided by the power absorbed by the calorimeter.

The calibration coefficients are determined periodically according to the maintenance schedule of the national RF power primary standard measurement system. The national RF power standard is a coaxial dual line dry load calorimeter with type N input connectors. It measures RF power by using DC-RF substitution techniques. The national RF power primary standard traceability is through DC voltage, resistance and 50  $\Omega$  RF impedance standards.

## 6. MEASUREMENT RESULT

**Table B.1.** Reflection coefficient of travelling STD1

Frequency	Reflection Coefficient of STD1 Power Sensor	
	VRC (Magnitude)	VRC Uncertainty (k=2)
50 MHz	0.0350	0.0050
500 MHz	0.0100	0.0050
1 GHz	0.0160	0.0050
2 GHz	0.0290	0.0050
4 GHz	0.0200	0.0060
6 GHz	0.0330	0.0060
8 GHz	0.0050	0.0060
10 GHz	0.0090	0.0060
12 GHz	0.0370	0.0060
14 GHz	0.0570	0.0060
16 GHz	0.1060	0.0060
18 GHz	0.1390	0.0060

**Table B.2.** Effective efficiency of the travelling STD1

Frequency	Effective Efficiency	Uncertainty (k=2)
50 MHz	0.9960	0.0020
500 MHz	0.9970	0.0030
1 GHz	0.9920	0.0030
2 GHz	0.9880	0.0030
4 GHz	0.9880	0.0030
6 GHz	0.9870	0.0100
8 GHz	0.9690	0.0040
10 GHz	0.9620	0.0050
12 GHz	0.9590	0.0050
14 GHz	0.9540	0.0060
16 GHz	0.9410	0.0070
18 GHz	0.9330	0.0070

**Table B.3.** Reflection coefficient of the travelling STD2

Frequency	Reflection Coefficient of STD2 Power Sensor	
	VRC (Magnitude)	VRC Uncertainty (k=2)
50 MHz	0.0380	0.0050
500 MHz	0.0180	0.0050
1 GHz	0.0290	0.0050
2 GHz	0.0440	0.0050
4 GHz	0.0560	0.0060
6 GHz	0.0730	0.0060
8 GHz	0.0640	0.0060
10 GHz	0.0550	0.0060
12 GHz	0.0680	0.0060
14 GHz	0.0600	0.0060
16 GHz	0.0830	0.0060
18 GHz	0.0800	0.0060

**Table B.4.** Effective efficiency of the travelling STD2

<b>Frequency</b>	<b>Effective Efficiency</b>	<b>Uncertainty (k=2)</b>
<b>50 MHz</b>	0.9950	0.0020
<b>500 MHz</b>	0.9980	0.0030
<b>1 GHz</b>	0.9950	0.0030
<b>2 GHz</b>	0.9920	0.0030
<b>4 GHz</b>	0.9900	0.0040
<b>6 GHz</b>	0.9910	0.0100
<b>8 GHz</b>	0.9720	0.0040
<b>10 GHz</b>	0.9660	0.0050
<b>12 GHz</b>	0.9600	0.0050
<b>14 GHz</b>	0.9560	0.0060
<b>16 GHz</b>	0.9490	0.0070
<b>18 GHz</b>	0.9420	0.0070



## ANNEX C. COMPARISON MEASUREMENTS REPORT of NIS

### 1. PARTICIPANT INFORMATION

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### 2. MEASUREMENT DATE

27.06.2019 - 04.07.2019

### 3. ENVIRONMENTAL CONDITION

Temperature :  $23 \pm 1$  °C

Relative Humidity:  $40\% \pm 10$  %rh

### 4. REFERENCES USED IN MEASUREMENT

Instrument Name	Manufacturer	Type / Model	Serial No	Traceability
Vector Network Analyzer	Rohde & Schwartz	ZVA40	1145.1110.4 0	PTB
Calibration Kit	Agilent	85054B	3106A02127	UME
Signal generator	Rohde & Schwartz	SMB-100A	175957	PTB
Power meter	Hewlett Packard	432A	1848A17444	NIST
Multimeter	Hewlett Packard	3457A	B13965	NIST
Power Splitter	Keysight	11667A	MY51357035	NIST
Thermistor mount	Hewlett Packard	8478B	3318A25071	NIST



## 5. MEASUREMENT METHOD

A type N resistive power splitter was used to deliver power from R&S signal generator SMB 100A (100 KHz-40 GHz) to its two measurement arms. The nominal power delivered to each arm was 1 mW. The output of the microwave source was connected to port 1 of the power splitter; the traveling standard and the reference standard were connected to port 2 and port 3 of the splitter. The measurements were carried out in a temperature controlled environment: @ (23±1) °C and RH: 40%± 10 %.

Measurement of the voltage reflection coefficients (VRC) for both traveling and reference mounts were performed using R&S ZVA 40 (10 MHz-40 GHz) VNA with METAS software version II. The measurement of effective source match for the resistive power splitter was made using same VNA and the 'direct method' of Juroshek. The effective efficiency of the traveling standard is given as (Eq. C1):

$$\eta_{eT} = \eta_{efR} \frac{1 - |\Gamma_R|^2}{1 - |\Gamma_T|^2} \frac{P_{mT}}{P_{mR}} \frac{|S_{31}|^2}{|S_{21}|^2} \frac{\left| 1 - \left( S_{22} - \frac{S_{21}}{S_{31}} S_{23} \right) \Gamma_T \right|^2}{\left| 1 - \left( S_{33} - \frac{S_{31}}{S_{21}} S_{23} \right) \Gamma_R \right|^2} \quad (C1)$$

where

$\eta$ : Effective efficiency of traveling standard

$\eta_e$ : Effective efficiency of reference standard

$\Gamma_R$ : Reflection coefficient of reference standard

$\Gamma_T$ : Reflection coefficient of traveling standard

$P_{mT}$ : Power measured by power meter connected to traveling standard

$P_{mR}$ : Power measured by power meter connected to reference standard

$S$ : Scattering parameters of power splitter

The ratio  $S_{31}/S_{21}$  of the resistive splitter has been measured using ten repeated connections.

The thermistor mounts were operated with a pair of HP power meters, connected to a digital voltmeter. The reference thermistor mount (manufacture: HP, model: 8474B, Serial No.: MY54250009) was calibrated using NIS micro-calorimeter. Right hand side of equation C1, contains five parts of uncertainty sources, reference effective efficiency, loss ratio, power ratio, square of splitter output tracking, and mismatch correction factor; numerical weights were estimated and RSS method was used to calculate traveling standard's effective efficiency uncertainty.

The expanded uncertainties are for a level of confidence of approximately 95%. They were calculated using a coverage factor  $k = 2$ .



## 6. MEASUREMENT RESULT

Measured pin depth of STD1: 0.0036 inches,  $U(k=2) = 0.0002$  inches

Measured pin depth of STD2: 0.0005 inches,  $U(k=2) = 0.0002$  inches

**Table C.1.** Reflection coefficient of travelling STD1

Frequency	Reflection Coefficient of STD1 Power Sensor	
	VRC (Lin Magnitude)	VRC Uncertainty (k=2)
50 MHz	0.0320	0.0020
500 MHz	0.0110	0.0020
1 GHz	0.0170	0.0020
2 GHz	0.0310	0.0060
4 GHz	0.021	0.011
6 GHz	0.037	0.011
8 GHz	0.013	0.011
10 GHz	0.012	0.011
12 GHz	0.056	0.032
14 GHz	0.063	0.032
16 GHz	0.084	0.032
18 GHz	0.086	0.050

**Table C.2.** Effective efficiency of the travelling STD1

Frequency	Effective Efficiency	Uncertainty (k=2)
50 MHz	1.0030	0.0019
500 MHz	1.0021	0.0018
1 GHz	0.9930	0.0023
2 GHz	0.9936	0.0031
4 GHz	0.9921	0.0039
6 GHz	0.9907	0.0069
8 GHz	0.9928	0.0082
10 GHz	0.9781	0.0088
12 GHz	0.9724	0.0096
14 GHz	0.9719	0.0097
16 GHz	0.975	0.011
18 GHz	0.948	0.029



**Table C.3.** Reflection coefficient of the travelling STD2

Frequency	Reflection Coefficient of STD2 Power Sensor	
	VRC (Magnitude)	VRC Uncertainty (k=2)
50 MHz	0.0380	0.0010
500 MHz	0.0210	0.0010
1 GHz	0.0290	0.0020
2 GHz	0.0460	0.0060
4 GHz	0.059	0.011
6 GHz	0.071	0.011
8 GHz	0.066	0.011
10 GHz	0.056	0.011
12 GHz	0.08	0.032
14 GHz	0.083	0.032
16 GHz	0.082	0.032
18 GHz	0.069	0.051

**Table C.4.** Effective efficiency of the travelling STD2

Frequency	Effective Efficiency	Uncertainty (k=2)
50 MHz	0.9994	0.0034
500 MHz	0.9984	0.0027
1 GHz	0.9928	0.0024
2 GHz	0.9941	0.0036
4 GHz	0.9894	0.0050
6 GHz	0.9870	0.0087
8 GHz	0.9783	0.0092
10 GHz	0.9811	0.0098
12 GHz	0.969	0.025
14 GHz	0.9677	0.0073
16 GHz	0.954	0.010
18 GHz	0.957	0.017

## ANNEX D. COMPARISON MEASUREMENTS REPORT of NPL

### 1. PARTICIPANT INFORMATION

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### 2. MEASUREMENT DATE

18 February 2019 - 26 March 2019

### 3. ENVIRONMENTAL CONDITION

Temperature :  $23 \pm 1$  °C

Relative Humidity:  $45 \pm 15$  %rh

### 4. REFERENCES USED IN MEASUREMENT

Instrument Name	Manufacturer	Type / Model	Serial No	Traceability
Coaxial Transfer standard	NPL	NRVZ51-1870A	100492-6693	NPL
DMM	Keysight	43870A	168520	NPL
Power meter	HP	432A	---	NPL
Vector Network Analyser	Keysight	N5222B	MY57181306	NPL
Type-N coaxial calibration kit	HP	85054	CIS/C/008	NPL

## 5. MEASUREMENT METHOD

The Effective Efficiency ( $EE$ ) of the sensors were measured at a nominal power level of 1 mW, with the sensors connected to a 432A power meter and biased to 200 Ohm. The sensors were measured using the NPL power transfer system traceable to the NPL Dual Line Calorimeter.

The Effective Efficiency is defined as follows (Eq. D1):

$$EE = \frac{P_{o,f}}{P_{a,f}} \quad (D1)$$

Where  $P_{o,f}$  is the indicated power and  $P_{a,f}$  is the absorbed power at the measured frequency.

The Voltage Reflection Coefficient ( $VRC$ ) measurement was performed using a calibrated Vector Network Analyser. The performance of the Vector Network Analyser was verified using impedance check standards calibrated using the NPL primary impedance measurement facility.

The measured values relate to the performance of the device under test when connected into a transmission line system having a characteristic impedance of 50  $\Omega$ .

## 6. MEASUREMENT RESULT

Measured pin depth of STD1: 0.004 inches,  $U(k=2) = 0.0002$  inches

Measured pin depth of STD2: 0.0010 inches,  $U(k=2) = 0.0002$  inches

**Table D.1.** Reflection coefficient of travelling STD1

Frequency	Reflection Coefficient of STD1 Power Sensor	
	VRC (Lin Magnitude)	VRC Uncertainty (k=2)
50 MHz	0.032	0.010
500 MHz	0.011	0.010
1 GHz	0.016	0.010
2 GHz	0.029	0.010
4 GHz	0.021	0.010
6 GHz	0.033	0.010
8 GHz	0.007	0.010
10 GHz	0.009	0.010
12 GHz	0.035	0.010
14 GHz	0.058	0.010
16 GHz	0.102	0.010
18 GHz	0.142	0.010

**Table D.2.** Effective efficiency of the travelling STD1

Frequency	Effective Efficiency	Uncertainty (k=2)
50 MHz	0.9955	0.0021
500 MHz	0.9949	0.002
1 GHz	0.9908	0.0024
2 GHz	0.9863	0.0025
4 GHz	0.9781	0.0031
6 GHz	0.9711	0.0034
8 GHz	0.9640	0.0036
10 GHz	0.9618	0.0037
12 GHz	0.9561	0.0039
14 GHz	0.9548	0.0051
16 GHz	0.9412	0.0059
18 GHz	0.9311	0.0072

**Table D.3.** Reflection coefficient of the travelling STD2

Frequency	Reflection Coefficient of STD2 Power Sensor	
	VRC (Magnitude)	VRC Uncertainty (k=2)
50 MHz	0.037	0.010
500 MHz	0.020	0.010
1 GHz	0.028	0.010
2 GHz	0.043	0.010
4 GHz	0.059	0.010
6 GHz	0.070	0.010
8 GHz	0.069	0.010
10 GHz	0.058	0.010
12 GHz	0.067	0.010
14 GHz	0.067	0.010
16 GHz	0.078	0.010
18 GHz	0.076	0.010

**Table D.4.** Effective efficiency of the travelling STD2

Frequency	Effective Efficiency	Uncertainty (k=2)
50 MHz	0.9954	0.0022
500 MHz	0.9957	0.0021
1 GHz	0.9940	0.0025
2 GHz	0.9908	0.0026
4 GHz	0.9826	0.0037
6 GHz	0.9784	0.0035
8 GHz	0.9734	0.0038
10 GHz	0.9690	0.0042
12 GHz	0.9601	0.0043
14 GHz	0.9597	0.0052
16 GHz	0.9535	0.0054
18 GHz	0.9434	0.0061

## ANNEX E. COMPARISON MEASUREMENTS REPORT of PTB

### 1. PARTICIPANT INFORMATION

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### 2. MEASUREMENT DATE

December 2018 to January 2019

### 3. ENVIRONMENTAL CONDITION

Temperature :  $(23 \pm 1) ^\circ\text{C}$

Relative Humidity:  $(50 \pm 10) \%$

### 4. REFERENCES USED IN MEASUREMENT

Instrument Name	Manufacturer	Type / Model	Serial No	Traceability
Digital Voltmeter	Hewlett Packard	3457A	3114A17754	PTB
Nanovoltmeter	Keithley	182	529330	PTB

### 5. MEASUREMENT METHOD

The calibration covered the determination of the effective efficiency  $\eta_{\text{eff}}$ .

To determine  $\eta_{\text{eff}}$ , the bolometer sensor was placed in a coaxial microcalorimeter of the same connector type. The bolometer element was d.c.-connected to an automatically balancing bridge circuit to determine the d.c. substitution power  $P_s$ , that corresponds to the RF power absorbed by the bolometer element. The high frequency power incident to the sensor input was stabilized. Inside the microcalorimeter there was a thermal connection between the connector of the device under

test and the measurement plane in which the thermopile for the calorimetric determination of the RF power absorbed in the sensor was located. The effective efficiency was determined according to the following Eq. E1:

$$\eta_{\text{eff}} = \frac{1 - \left(\frac{U_2}{U_1}\right)^2}{\frac{e_2 - \left(\frac{U_2}{U_1}\right)}{e_1}} \cdot \prod \Delta k_i \quad (\text{E1})$$

with

$U_1$  bolometer bridge voltage with the RF power switched off,

$U_2$  bolometer bridge voltage with the RF power switched on,

$e_1$  value of the thermopile output voltage with the RF power switched off,

$e_2$  value of the thermopile output voltage with the RF power switched on,

$\prod \Delta k_i$  correction factor to eliminate various error influences.

## 6. MEASUREMENT RESULT

Measured pin depth of STD1: 0.004 inches,  $U (k=2) = 0.0002$  inches

Measured pin depth of STD2: 0.0008 inches,  $U (k=2) = 0.0002$  inches

**Table E.1.** Reflection coefficient of travelling STD1

Frequency	Reflection Coefficient of STD1 Power Sensor	
	VRC (Lin Magnitude)	VRC Uncertainty (k=2)
50 MHz	0.0324	0.0060
500 MHz	0.0122	0.0061
1 GHz	0.0172	0.0061
2 GHz	0.0298	0.0062
4 GHz	0.0209	0.0064
6 GHz	0.0355	0.0066
8 GHz	0.0046	0.0068
10 GHz	0.0151	0.0070
12 GHz	0.0376	0.0072
14 GHz	0.0571	0.0074
16 GHz	0.1082	0.0076
18 GHz	0.1375	0.0078

**Table E.2.** Effective efficiency of the travelling STD1

Frequency	Effective Efficiency	Uncertainty (k=2)
50 MHz	0.9956	0.0022
500 MHz	0.9926	0.0022
1 GHz	0.9888	0.0022
2 GHz	0.9838	0.0024
4 GHz	0.9775	0.0026
6 GHz	0.9699	0.0032
8 GHz	0.9650	0.0036
10 GHz	0.9592	0.0042
12 GHz	0.9563	0.0050
14 GHz	0.9497	0.0058
16 GHz	0.9442	0.0066
18 GHz	0.9329	0.0076

**Table E.3.** Reflection coefficient of the travelling STD2

Frequency	Reflection Coefficient of STD2 Power Sensor	
	VRC (Magnitude)	VRC Uncertainty (k=2)
50 MHz	0.0397	0.0060
500 MHz	0.0221	0.0061
1 GHz	0.0292	0.0061
2 GHz	0.0441	0.0062
4 GHz	0.0572	0.0064
6 GHz	0.0699	0.0066
8 GHz	0.0667	0.0068
10 GHz	0.0533	0.0070
12 GHz	0.0718	0.0072
14 GHz	0.0722	0.0074
16 GHz	0.0884	0.0076
18 GHz	0.0857	0.0078

**Table E.4.** Effective efficiency of the travelling STD2

Frequency	Effective Efficiency	Uncertainty (k=2)
50 MHz	0.9958	0.0022
500 MHz	0.9934	0.0022
1 GHz	0.9917	0.0022
2 GHz	0.9876	0.0024
4 GHz	0.9805	0.0026
6 GHz	0.9755	0.0030
8 GHz	0.9715	0.0036
10 GHz	0.9671	0.0042
12 GHz	0.9587	0.0050
14 GHz	0.9568	0.0058
16 GHz	0.9530	0.0066
18 GHz	0.9434	0.0076