EURAMET Project 1188:
2.4 mm 50 GHz Thermocouple Power Sensor
v01

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Abstract

This report summarizes the results of an interlaboratory measurement comparison on a commercial thermocouple power sensor up to 50 GHz (2.4mm connector). Two national metrology institutes participated in this exercise. The measurand was the calibration factor as well as the complex input reflection coefficient at a nominal power level of 1 mW.

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1. Introduction

The first international comparison on RF power in the 2.4mm coaxial line system (CCEM.RF-S1.CL / GTRF/02-03) was organized in 2002 and conducted between 2002 to 2004. At that time the travelling standards were AC coupled thermocouple power sensors (HP8487A). Today, a new generation of thermocouple power sensors is available on the market which are DC coupled. They offer lower input reflection coefficient, and include internal metering as well as an USB interface. Therefore, the calibration factor can be defined in a different way with lower uncertainties compared to AC coupled sensors. For the participants, this bilateral comparison offers the possibility to verify their measurement procedures, and it provides the possibility to identify and eliminate errors.

2. Participants and Schedule

Table 1 lists the participants in this bilateral interlaboratory comparison. METAS provided the travelling
standard, coordinated the measurements, performed control measurements to monitor the stability of the device, analysed the data, acted as coordinator of the Euramet project and wrote this report.

Acronym	Laboratory
METAS	Federal Office of Metrology Bern-Wabern, Switzerland contact: Jürg Furrer e-mail: juerg.furrer@metas.ch
PTB	Physikalisch-Technische Bundesanstalt, Braunschweig, Germany contact: Dr. Rolf Judaschke e-mail: rolf.judaschke@ptb.de

Table 1: Participants and contacts of the comparison.

Table 2~~Table 2~~ shows the sequence of measurements performed by the participants. The last column is the time delay in days with respect to the first measurement done by METAS 09/2009. Initially, the comparison was intended to start in 4Q/2009. Due to other duties, PTB finalized the work on their 50 GHz direct comparison system in winter 2010. In February 2011, PTB informed that their complex input reflection coefficient measurements were incorrect due to problems with the VNA and requested to repeat the reflection measurements.

Feldfunktion geändert

Laboratory	Type of Work	Result	Code	End of measurement	Time line (days)
METAS	Measurement 1	Metas Protocol 1	MET1	03.09.2009	0
METAS	Measurement 2	Certificate of calibration	MET2	19.08.2010	350
PTB	Measurement 1	PTB Protocol 1	PTB1	26.01.2011	510
PTB	Measurement 2	Updated PTB Protocol 1	PTB2	16.02.2011	531
PTB	Measurement 3	PTB new S11	PTB3	23.02.2011	538
METAS	Cross Check	Metas Protocol 2	MET3	23.05.2011	627

Table 2: Sequence of measurements performed by participants.

3. Travelling Standard and Measurements

The measurement standard was a 2.4 mm thermocouple power sensor type NRP-Z56, SN101446 (R&S) covering the frequency range DC to 50 GHz (2.4 mm (male) - connector) and specified with a dynamic range from -35 dBm to +20 dBm. This sensor type incorporates a power meter and an USB interface which enables data readout without using an additional power meter. The sensor was provided by Metas.

The measurands of this comparison were:

- Calibration factor (relative to the calibration factor at 100 kHz) at the nominal power level of 1 mW (0 dBm), expressed in W/W at 55 test frequencies: 100 kHz, 50 MHz, 100 MHz, 200 MHz, 500 MHz, 1 GHz, 2 GHz, 3 GHz, …, 48 GHz, 49 GHz, and 50 GHz.

  The calibration factor CF (relative to the calibration factor at 100 kHz) is defined as:

  $$CF(f)_{100\,kHz}\ \ \text{(W/W)} = \left.\frac{P_{\text{incident}}(f = 100\text{ kHz})}{P_{\text{incident}}(f)}\right|_{P_{\text{ind}}=\text{const.}}$$ (same instrument indication)

- Complex input reflection coefficient at the same measurement frequencies, expressed in real and imaginary part.

Documentation of the results:

The participants were asked to document their results in the form of a calibration certificate and with a GUM [1] compliant measurement uncertainty budget.

Tables and figures of the electronic data submitted by the participants can be found in appendix A. Additional information of the participants, as uncertainty budgets, are shown in appendix B.

3.1 Behaviour of the Travelling Standard

Control and cross check measurements to monitor the stability of the travelling standard were performed two times by Metas as listed in Table 2~~Table 2~~. The results didn't show any drift of the device under test (DUT), and therefore no corrections were necessary. Cross check results can be found in appendix C.

Feldfunktion geändert

4. Data Analysis

The data analysis in this report is restricted to the results submitted by the participants in the form of certificates of calibration. These values are listed in appendix A.

The normalized Error (E_n) is calculated as a measure of the agreement between the results of the participants. It is defined as the difference between the results normalized with respect to the difference of expanded uncertainties of both participants.

$|E_n| < 1$ indicates an agreement between the participants at the 95 % level.

4.1 Results

4.1.1 Normalized Calibration Factor

The results for the calibration factor are shown for the nominal power level ($P_{Cal\ nom}$ = 1 mW) in three graphs as well as in Table 3. The following quantities are plotted:

CF_{ME}: Calibration Factor from METAS
CF_{PTB}: Calibration Factor from PTB
$u(CF_{ME})$: Standard uncertainty in CF_{ME}
$u(CF_{PTB})$: Standard uncertainty in CF_{PTB}
Error = $CF_{PTB} - CF_{ME}$

$$U(\text{Error}) = 2 \cdot \sqrt{u(CF_{PTB})^2 + u(CF_{ME})^2}$$

E_n = Error / U(Error)

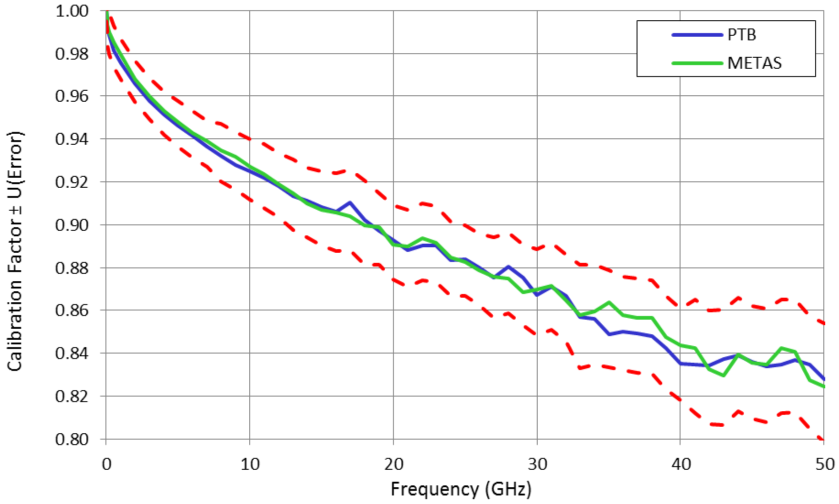

Figure 1: Calibration factor $CF(f)_{100kHz} \pm U$(Error), linear frequency range.

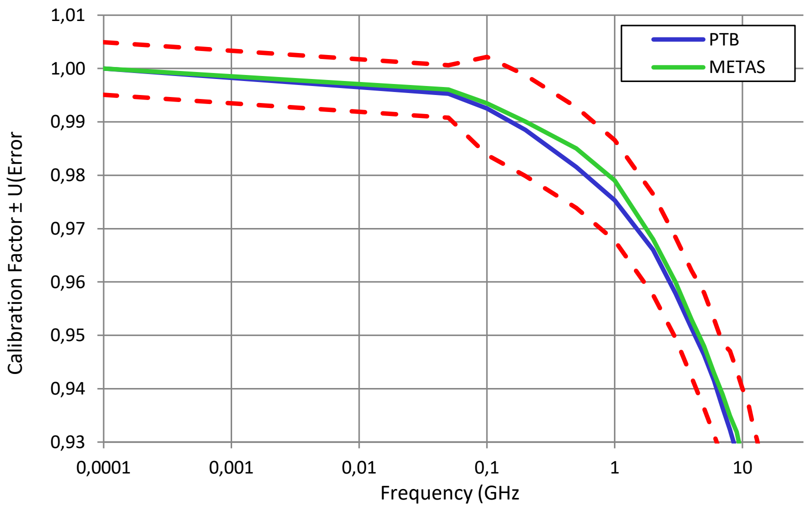

Figure 2: Calibration factor $CF(f)_{100kHz}$ ± U(Error), logarithmic frequency range.

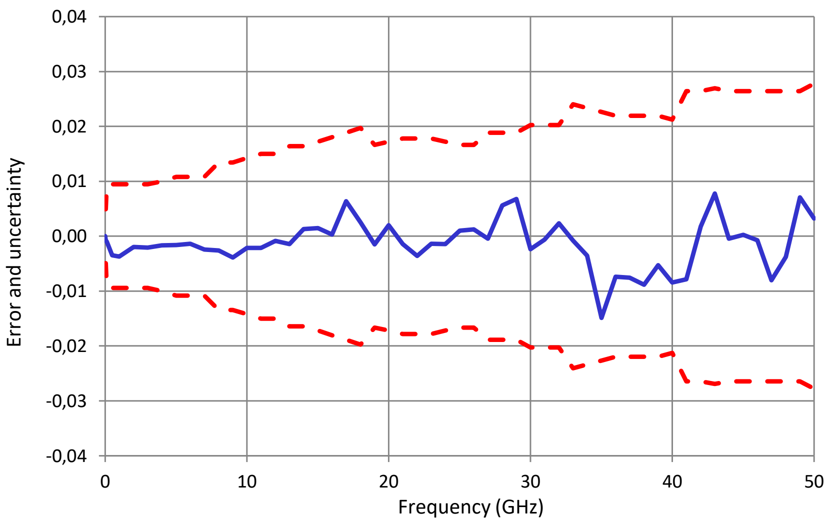

Figure 3: Error ± U(Error).

Table 3: Normalized Calibration Factor $CF(f)_{100kHz}$

Frequency MHz	E_n	Error	U(Error)	CF_{PTB}	CF_{ME}	$u(CF_{PTB})$	$u(CF_{ME})$
0.1	0.000	0.0000	0.0049	1.0000	1.0000	0.0010	0.0023
50	-0.160	-0.0008	0.0049	0.9953	0.9961	0.0010	0.0023
100	-0.105	-0.0010	0.0092	0.9925	0.9935	0.0040	0.0023
200	-0.163	-0.0015	0.0094	0.9885	0.9901	0.0040	0.0025
500	-0.370	-0.0035	0.0094	0.9816	0.9851	0.0040	0.0025
1000	-0.396	-0.0037	0.0094	0.9753	0.9790	0.0040	0.0025
2000	-0.208	-0.0020	0.0094	0.9660	0.9680	0.0040	0.0025
3000	-0.223	-0.0021	0.0094	0.9579	0.9600	0.0040	0.0025
4000	-0.165	-0.0016	0.0100	0.9513	0.9530	0.0040	0.0030
5000	-0.149	-0.0016	0.0108	0.9463	0.9479	0.0045	0.0030
6000	-0.127	-0.0014	0.0108	0.9416	0.9429	0.0045	0.0030
7000	-0.225	-0.0024	0.0108	0.9365	0.9389	0.0045	0.0030
8000	-0.193	-0.0026	0.0135	0.9323	0.9349	0.0050	0.0045
9000	-0.288	-0.0039	0.0135	0.9280	0.9319	0.0050	0.0045
10000	-0.151	-0.0021	0.0142	0.9247	0.9269	0.0055	0.0045
11000	-0.141	-0.0021	0.0150	0.9217	0.9239	0.0060	0.0045
12000	-0.059	-0.0009	0.0150	0.9180	0.9188	0.0060	0.0045
13000	-0.088	-0.0014	0.0164	0.9134	0.9148	0.0065	0.0050
14000	0.078	0.0013	0.0164	0.9111	0.9098	0.0065	0.0050
15000	0.087	0.0015	0.0172	0.9083	0.9068	0.0070	0.0050
16000	0.017	0.0003	0.0180	0.9061	0.9058	0.0075	0.0050
17000	0.339	0.0064	0.0189	0.9102	0.9038	0.0080	0.0050
18000	0.129	0.0025	0.0197	0.9023	0.8998	0.0085	0.0050
19000	-0.092	-0.0015	0.0166	0.8973	0.8988	0.0045	0.0070
20000	0.118	0.0020	0.0172	0.8928	0.8908	0.0050	0.0070
21000	-0.082	-0.0015	0.0178	0.8883	0.8898	0.0055	0.0070
22000	-0.201	-0.0036	0.0178	0.8902	0.8938	0.0055	0.0070
23000	-0.077	-0.0014	0.0178	0.8904	0.8918	0.0055	0.0070
24000	-0.082	-0.0014	0.0172	0.8833	0.8847	0.0050	0.0070
25000	0.060	0.0010	0.0166	0.8837	0.8827	0.0045	0.0070
26000	0.073	0.0012	0.0166	0.8799	0.8787	0.0045	0.0070
27000	-0.024	-0.0004	0.0189	0.8753	0.8757	0.0050	0.0080
28000	0.298	0.0056	0.0189	0.8803	0.8747	0.0050	0.0080
29000	0.359	0.0068	0.0189	0.8755	0.8687	0.0050	0.0080
30000	-0.118	-0.0024	0.0202	0.8673	0.8697	0.0055	0.0085
31000	-0.030	-0.0006	0.0202	0.8711	0.8717	0.0055	0.0085
32000	0.115	0.0023	0.0202	0.8670	0.8647	0.0055	0.0085
33000	-0.033	-0.0008	0.0240	0.8569	0.8577	0.0085	0.0085
34000	-0.150	-0.0035	0.0233	0.8562	0.8597	0.0085	0.0080
35000	-0.658	-0.0149	0.0226	0.8488	0.8637	0.0080	0.0080
36000	-0.336	-0.0074	0.0219	0.8503	0.8577	0.0075	0.0080
37000	-0.345	-0.0076	0.0219	0.8491	0.8567	0.0075	0.0080
38000	-0.404	-0.0089	0.0219	0.8478	0.8567	0.0075	0.0080
39000	-0.242	-0.0053	0.0219	0.8423	0.8476	0.0075	0.0080
40000	-0.398	-0.0085	0.0213	0.8352	0.8436	0.0070	0.0080
41000	-0.297	-0.0079	0.0264	0.8348	0.8426	0.0065	0.0115
42000	0.067	0.0018	0.0264	0.8344	0.8326	0.0065	0.0115
43000	0.289	0.0078	0.0269	0.8373	0.8296	0.0070	0.0115
44000	-0.018	-0.0005	0.0264	0.8391	0.8396	0.0065	0.0115
45000	0.010	0.0003	0.0264	0.8359	0.8356	0.0065	0.0115
46000	-0.027	-0.0007	0.0264	0.8339	0.8346	0.0065	0.0115
47000	-0.305	-0.0081	0.0264	0.8346	0.8426	0.0065	0.0115
48000	-0.142	-0.0038	0.0264	0.8368	0.8406	0.0065	0.0115
49000	0.268	0.0071	0.0264	0.8347	0.8276	0.0065	0.0115
50000	0.116	0.0032	0.0278	0.8278	0.8246	0.0070	0.0120

4.1.2 Complex Input Reflection Coefficient

The reflection coefficient Γ was measured with a vector network analyzer (VNA) as complex quantity with real and imaginary components (Γ_{real}, Γ_{imag}) at a nominal calibration power of 1 mW.

The applied VNA uncertainty calculation results in an uncertainty that is equal for both components, and the correlation between real and imaginary parts is assumed to be zero. Therefore, the uncertainty $U(|\Gamma|)$ for the magnitude $|\Gamma|$ is equal to those of the real and imaginary part (Γ_{real}, Γ_{imag}).

$$|\Gamma| = \sqrt{\Gamma_{real}^2 + \Gamma_{imag}^2} \qquad U(|\Gamma|) = U(\Gamma_{real}) = U(\Gamma_{imag})$$

The following quantities are plotted:

Γ_{Re_PTB}, Γ_{Im_PTB}, $|\Gamma_{PTB}|$: complex input reflection coefficient from PTB
Γ_{Re_MET}, Γ_{Im_MET}, $|\Gamma_{MET}|$: complex input reflection coefficient from METAS
$u(|\Gamma_{PTB}|)$: standard uncertainty of $|\Gamma|$ from PTB
$u(|\Gamma_{MET}|)$: standard uncertainty of $|\Gamma|$ from METAS
Error = $|\Gamma_{PTB} - \Gamma_{MET}|$
$U(\text{Error}) = 2 \cdot \sqrt{u(\Gamma_{PTB})^2 + u(\Gamma_{MET})^2}$
E_n = Error / U(Error)

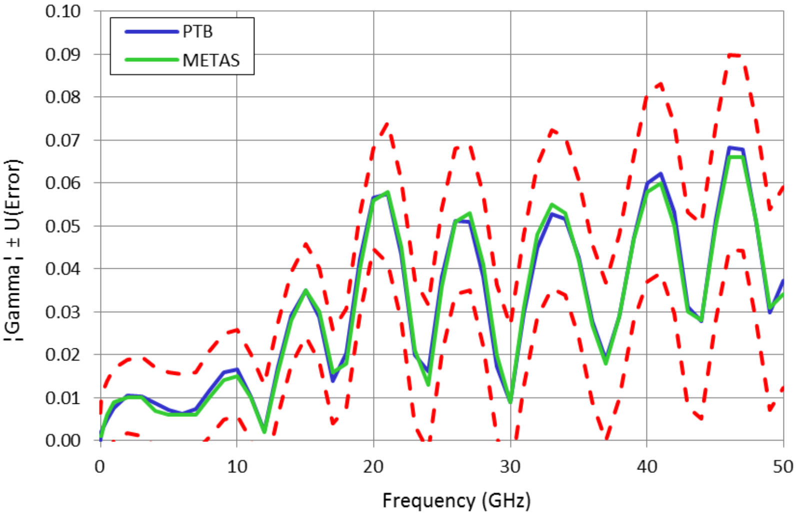

Figure 4: Magnitude $|\Gamma|$ ± U(Error) of input reflection coefficient.

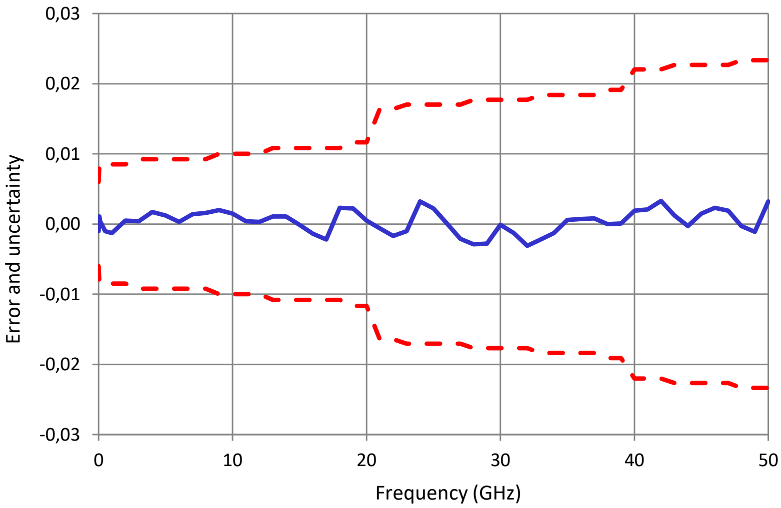

Figure 5: Error and uncertainty of magnitude $|\Gamma|$ of input reflection coefficient.

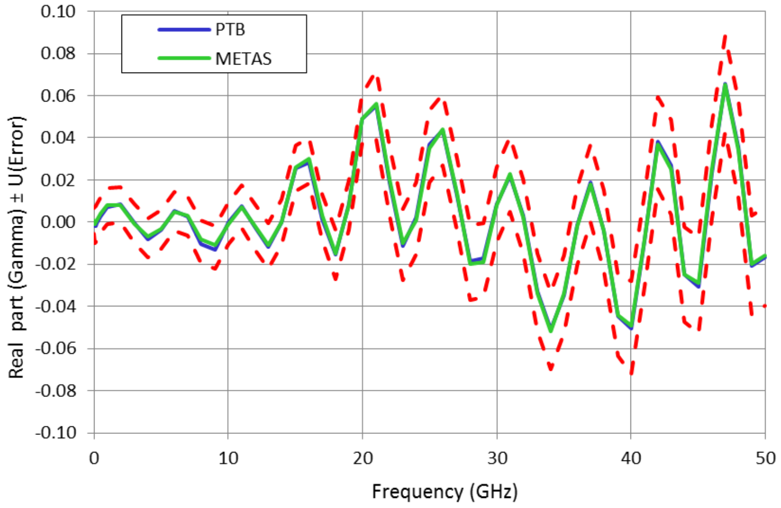

Figure 6: Real part Γ_{Re} ± U(Error) of input reflection coefficient.

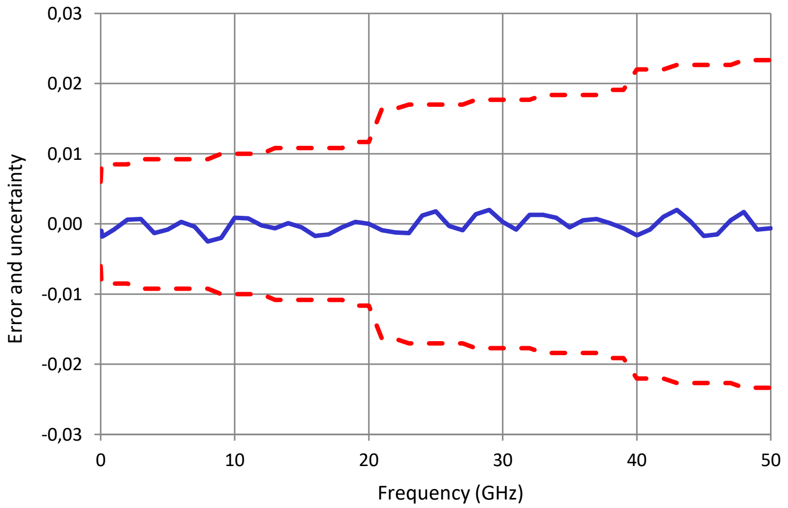

Figure 7: Error and uncertainty of real part Γ_{Re} of input reflection coefficient.

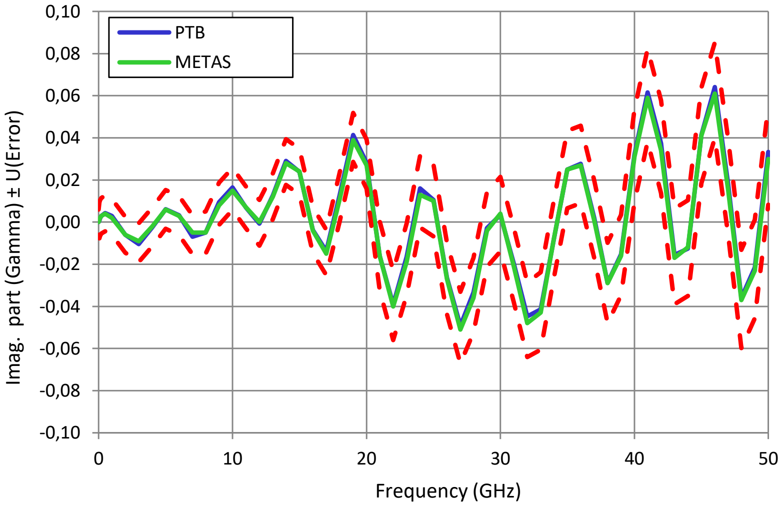

Figure 8: Imaginary part Γ_{Im} ± *U*(Error) of input reflection coefficient.

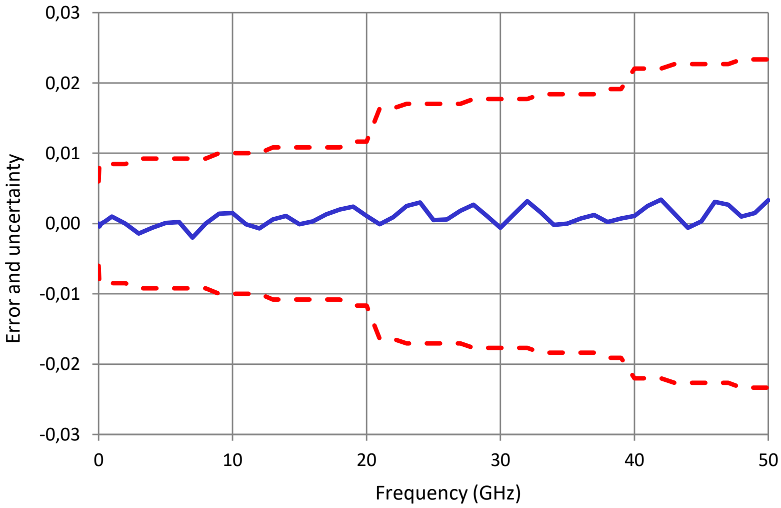

Figure 9: Error and uncertainty of imaginary part Γ_{Im} of input reflection coefficient.

Table 4: Complex input reflection coefficient Γ

Freq. MHz	E_n $\|\Gamma\|$	Error $\|\Gamma\|$	U(Error)	Γ_{Re_PTB}	Γ_{Im_PTB}	Γ_{Re_MET}	Γ_{Im_MET}	$u(\Gamma_{PTB})$	$u(\Gamma_{MET})$
0.1	-0.167	-0.001	0.006			0.001	0.000		0.003
50	0.130	0.001	0.008	-0.0020	0.0006	-0.001	0.001	0.003	0.003
100	0.047	0.000	0.008	-0.0018	0.0017	0.000	0.002	0.003	0.003
200	0.012	0.000	0.008	-0.0007	0.0030	0.001	0.003	0.003	0.003
500	-0.118	-0.001	0.008	0.0026	0.0043	0.004	0.004	0.003	0.003
1000	-0.153	-0.001	0.008	0.0072	0.0030	0.008	0.002	0.003	0.003
2000	0.059	0.001	0.008	0.0086	-0.0060	0.008	-0.006	0.003	0.003
3000	0.043	0.000	0.009	-0.0003	-0.0104	-0.001	-0.009	0.0035	0.003
4000	0.184	0.002	0.009	-0.0083	-0.0026	-0.007	-0.002	0.0035	0.003
5000	0.130	0.001	0.009	-0.0038	0.0061	-0.003	0.006	0.0035	0.003
6000	0.033	0.000	0.009	0.0053	0.0032	0.005	0.003	0.0035	0.003
7000	0.152	0.001	0.009	0.0026	-0.0070	0.003	-0.005	0.0035	0.003
8000	0.160	0.002	0.010	-0.0105	-0.0050	-0.008	-0.005	0.004	0.003
9000	0.200	0.002	0.010	-0.0130	0.0094	-0.011	0.008	0.004	0.003
10000	0.150	0.002	0.010	-0.0001	0.0165	-0.001	0.015	0.004	0.003
11000	0.040	0.000	0.010	0.0078	0.0069	0.007	0.007	0.004	0.003
12000	0.028	0.000	0.011	-0.0022	-0.0007	-0.002	0.000	0.0045	0.003
13000	0.102	0.001	0.011	-0.0116	0.0126	-0.011	0.012	0.0045	0.003
14000	0.102	0.001	0.011	0.0001	0.0291	0.000	0.028	0.0045	0.003
15000	-0.009	0.000	0.011	0.0255	0.0239	0.026	0.024	0.0045	0.003
16000	-0.129	-0.001	0.011	0.0283	-0.0037	0.030	-0.004	0.0045	0.003
17000	-0.203	-0.002	0.011	0.0015	-0.0137	0.003	-0.015	0.0045	0.003
18000	0.197	0.002	0.012	-0.0155	0.0130	-0.015	0.011	0.005	0.003
19000	0.189	0.002	0.012	0.0083	0.0414	0.008	0.039	0.005	0.003
20000	0.043	0.001	0.012	0.0490	0.0281	0.049	0.027	0.005	0.003
21000	-0.037	-0.001	0.016	0.0551	-0.0161	0.056	-0.016	0.005	0.0065
22000	-0.104	-0.002	0.016	0.0188	-0.0391	0.020	-0.040	0.005	0.0065
23000	-0.059	-0.001	0.017	-0.0133	-0.0165	-0.010	-0.019	0.0055	0.0065
24000	0.188	0.003	0.017	0.0022	0.0160	0.001	0.013	0.0055	0.0065
25000	0.129	0.002	0.017	0.0368	0.0105	0.035	0.010	0.0055	0.0065
26000	0.006	0.000	0.017	0.0437	-0.0264	0.044	-0.027	0.0055	0.0065
27000	-0.123	-0.002	0.017	0.0131	-0.0492	0.014	-0.051	0.0055	0.0065
28000	-0.164	-0.003	0.018	-0.0186	-0.0333	-0.020	-0.036	0.006	0.0065
29000	-0.158	-0.003	0.018	-0.0170	-0.0029	-0.019	-0.004	0.006	0.0065
30000	-0.006	0.000	0.018	0.0083	0.0034	0.008	0.004	0.006	0.0065
31000	-0.073	-0.001	0.018	0.0222	-0.0197	0.023	-0.021	0.006	0.0065
32000	-0.175	-0.003	0.018	0.0033	-0.0448	0.002	-0.048	0.006	0.0065
33000	-0.120	-0.002	0.018	-0.0327	-0.0414	-0.034	-0.043	0.0065	0.0065
34000	-0.071	-0.001	0.018	-0.0511	-0.0082	-0.052	-0.008	0.0065	0.0065
35000	0.033	0.001	0.018	-0.0345	0.0250	-0.034	0.025	0.0065	0.0065
36000	0.038	0.001	0.018	-0.0015	0.0277	-0.002	0.027	0.0065	0.0065
37000	0.044	0.001	0.018	0.0187	0.0022	0.018	0.001	0.0065	0.0065
38000	0.000	0.000	0.019	-0.0039	-0.0288	-0.004	-0.029	0.007	0.0065
39000	0.005	0.000	0.019	-0.0446	-0.0153	-0.044	-0.016	0.007	0.0065
40000	0.086	0.002	0.022	-0.0506	0.0321	-0.049	0.031	0.007	0.0085
41000	0.095	0.002	0.022	-0.0088	0.0615	-0.008	0.059	0.007	0.0085
42000	0.150	0.003	0.022	0.0380	0.0374	0.037	0.034	0.007	0.0085
43000	0.053	0.001	0.023	0.0270	-0.0156	0.025	-0.017	0.0075	0.0085
44000	-0.013	0.000	0.023	-0.0246	-0.0126	-0.025	-0.012	0.0075	0.0085
45000	0.066	0.001	0.023	-0.0307	0.0413	-0.029	0.041	0.0075	0.0085
46000	0.101	0.002	0.023	0.0235	0.0641	0.025	0.061	0.0075	0.0085
47000	0.084	0.002	0.023	0.0655	0.0177	0.065	0.015	0.0075	0.0085
48000	-0.013	0.000	0.023	0.0357	-0.0360	0.034	-0.037	0.008	0.0085
49000	-0.047	-0.001	0.023	-0.0208	-0.0215	-0.020	-0.023	0.008	0.0085
50000	0.137	0.003	0.023	-0.0166	0.0333	-0.016	0.030	0.008	0.0085

4.2 Summarizing Results

The analysis of all measured quantities at each individual test frequency and each test level resulted in $|E_n| < 1$, which indicates an overall agreement between the participants at the 95 % level.

Control measurements to investigate the behaviour of the travelling standard during the whole measurement period showed no drift or stability problems and therefore no corrections were necessary.

5. Conclusions

A bilateral comparison for the calibration factor (normalised frequency response) of a commercial thermocouple power sensor was carried out. Both participants used a direct comparison setup with different types of power standards which were traced to different NMIs. While PTB used a set of thermistor power sensors as standards, Metas employed a thermocouple reference standard. Overall, good agreement was achieved over the entire frequency range.

6. Acknowledgement

METAS would like to thank PTB for the very cooperative and fruitful collaboration in this comparison.

A. Data submitted by participants

A.1 Data submitted by PTB

Table 5: Data submitted (PTB2, January 26th, 2011)

Normalized Calibration Factor $CF(f)_{100kHz}$ at 0 dBm		
Frequency MHz	CF_{PTB} (W/W)	$U(CF_{PTB})$ (W/W)
0.1	1.0000	0.002
50	0.9953	0.002
100	0.9925	0.008
200	0.9885	0.008
500	0.9816	0.008
1000	0.9753	0.008
2000	0.9660	0.008
3000	0.9579	0.008
4000	0.9513	0.008
5000	0.9463	0.009
6000	0.9416	0.009
7000	0.9365	0.009
8000	0.9323	0.010
9000	0.9280	0.010
10000	0.9247	0.011
11000	0.9217	0.012
12000	0.9180	0.012
13000	0.9134	0.013
14000	0.9111	0.013
15000	0.9083	0.014
16000	0.9061	0.015
17000	0.9102	0.016
18000	0.9023	0.017
19000	0.8973	0.009
20000	0.8928	0.011
21000	0.8883	0.011
22000	0.8902	0.011
23000	0.8904	0.011
24000	0.8833	0.010
25000	0.8837	0.009
26000	0.8799	0.009
27000	0.8753	0.010
28000	0.8803	0.010
29000	0.8755	0.010
30000	0.8673	0.011
31000	0.8711	0.011
32000	0.8670	0.011
33000	0.8569	0.017
34000	0.8562	0.017
35000	0.8488	0.016
36000	0.8503	0.015
37000	0.8491	0.015
38000	0.8478	0.015
39000	0.8423	0.015
40000	0.8352	0.013
41000	0.8348	0.013
42000	0.8344	0.013
43000	0.8373	0.014
44000	0.8391	0.013
45000	0.8359	0.013

Normalized Calibration Factor $CF(f)_{100kHz}$ at 0 dBm		
Frequency MHz	CF_{PTB} (W/W)	$U(CF_{PTB})$ (W/W)
46000	0.8339	0.013
47000	0.8346	0.013
48000	0.8368	0.013
49000	0.8347	0.013
50000	0.8278	0.014

Table 6: Data submitted (PTB3, February, 23th, 2011)

Voltage Reflection Coefficient at 0 dBm (1 mW)			
Freq. MHz	Γ_{Re_PTB}	Γ_{Im_PTB}	$U(\Gamma_{PTB})$
0.1	---	---	---
50	-0.0020	0.0006	0.006
100	-0.0018	0.0017	0.006
200	-0.0007	0.0030	0.006
500	0.0026	0.0043	0.006
1000	0.0072	0.0030	0.006
2000	0.0086	-0.0060	0.006
3000	-0.0003	-0.0104	0.007
4000	-0.0083	-0.0026	0.007
5000	-0.0038	0.0061	0.007
6000	0.0053	0.0032	0.007
7000	0.0026	-0.0070	0.007
8000	-0.0105	-0.0050	0.008
9000	-0.0130	0.0094	0.008
10000	-0.0001	0.0165	0.008
11000	0.0078	0.0069	0.008
12000	-0.0022	-0.0007	0.009
13000	-0.0116	0.0126	0.009
14000	0.0001	0.0291	0.009
15000	0.0255	0.0239	0.009
16000	0.0283	-0.0037	0.009
17000	0.0015	-0.0137	0.009
18000	-0.0155	0.0130	0.010
19000	0.0083	0.0414	0.010
20000	0.0490	0.0281	0.010
21000	0.0551	-0.0161	0.010
22000	0.0188	-0.0391	0.010
23000	-0.0133	-0.0165	0.011
24000	0.0022	0.0160	0.011
25000	0.0368	0.0105	0.011
26000	0.0437	-0.0264	0.011
27000	0.0131	-0.0492	0.011
28000	-0.0186	-0.0333	0.012
29000	-0.0170	-0.0029	0.012
30000	0.0083	0.0034	0.012
31000	0.0222	-0.0197	0.012
32000	0.0033	-0.0448	0.012
33000	-0.0327	-0.0414	0.013
34000	-0.0511	-0.0082	0.013
35000	-0.0345	0.0250	0.013
36000	-0.0015	0.0277	0.013
37000	0.0187	0.0022	0.013

Voltage Reflection Coefficient at 0 dBm (1 mW)			
Freq. MHz	Γ_{Re_PTB}	Γ_{Im_PTB}	$U(\Gamma_{PTB})$
38000	-0.0039	-0.0288	0.014
39000	-0.0446	-0.0153	0.014
40000	-0.0506	0.0321	0.014
41000	-0.0088	0.0615	0.014
42000	0.0380	0.0374	0.014
43000	0.0270	-0.0156	0.015
44000	-0.0246	-0.0126	0.015
45000	-0.0307	0.0413	0.015
46000	0.0235	0.0641	0.015
47000	0.0655	0.0177	0.015
48000	0.0357	-0.0360	0.016
49000	-0.0208	-0.0215	0.016
50000	-0.0166	0.0333	0.016

A.2 Data submitted by METAS

Metas certificate of calibration 217-01237 issued 19 August 2010

Table 7: Data submitted by METAS (measured 3rd September 2009)

Normalized Calibration Factor $CF(f)_{100kHz}$ at 0 dBm		
Frequency MHz	CF_{MET} (W/W)	$U(CF_{MET})$ (W/W)
0.1	1.0000	0.0045
50	0.9961	0.0045
100	0.9935	0.0045
200	0.9901	0.005
500	0.9851	0.005
1000	0.9790	0.005
2000	0.9680	0.005
3000	0.9600	0.005
4000	0.9530	0.006
5000	0.9479	0.006
6000	0.9429	0.006
7000	0.9389	0.006
8000	0.9349	0.009
9000	0.9319	0.009
10000	0.9269	0.009
11000	0.9239	0.009
12000	0.9188	0.009
13000	0.9148	0.010
14000	0.9098	0.010
15000	0.9068	0.010
16000	0.9058	0.010
17000	0.9038	0.010
18000	0.8998	0.010
19000	0.8988	0.014
20000	0.8908	0.014
21000	0.8898	0.014
22000	0.8938	0.014
23000	0.8918	0.014
24000	0.8847	0.014

Normalized Calibration Factor $CF(f)_{100kHz}$ at 0 dBm		
Frequency MHz	CF_{MET} (W/W)	$U(CF_{MET})$ (W/W)
25000	0.8827	0.014
26000	0.8787	0.014
27000	0.8757	0.016
28000	0.8747	0.016
29000	0.8687	0.016
30000	0.8697	0.017
31000	0.8717	0.017
32000	0.8647	0.017
33000	0.8577	0.017
34000	0.8597	0.016
35000	0.8637	0.016
36000	0.8577	0.016
37000	0.8567	0.016
38000	0.8567	0.016
39000	0.8476	0.016
40000	0.8436	0.016
41000	0.8426	0.023
42000	0.8326	0.023
43000	0.8296	0.023
44000	0.8396	0.023
45000	0.8356	0.023
46000	0.8346	0.023
47000	0.8426	0.023
48000	0.8406	0.023
49000	0.8276	0.023
50000	0.8246	0.024

Table 8: Data submitted by METAS (measured 3rd September 2009)

Voltage Reflection Coefficient at 0 dBm (1 mW)			
Freq. MHz	Γ_{Re_MET}	Γ_{Im_MET}	$U(\Gamma_{MET})$
0.1	0.001	0.000	0.006
50	-0.001	0.001	0.006
100	0.000	0.002	0.006
200	0.001	0.003	0.006
500	0.004	0.004	0.006
1000	0.008	0.002	0.006
2000	0.008	-0.006	0.006
3000	-0.001	-0.009	0.006
4000	-0.007	-0.002	0.006
5000	-0.003	0.006	0.006
6000	0.005	0.003	0.006
7000	0.003	-0.005	0.006
8000	-0.008	-0.005	0.006
9000	-0.011	0.008	0.006
10000	-0.001	0.015	0.006
11000	0.007	0.007	0.006
12000	-0.002	0.000	0.006
13000	-0.011	0.012	0.006
14000	0.000	0.028	0.006
15000	0.026	0.024	0.006
16000	0.030	-0.004	0.006

Voltage Reflection Coefficient at 0 dBm (1 mW)			
Freq. MHz	Γ_{Re_MET}	Γ_{Im_MET}	$U(\Gamma_{MET})$
17000	0.003	-0.015	0.006
18000	-0.015	0.011	0.006
19000	0.008	0.039	0.006
20000	0.049	0.027	0.006
21000	0.056	-0.016	0.013
22000	0.020	-0.040	0.013
23000	-0.010	-0.019	0.013
24000	0.001	0.013	0.013
25000	0.035	0.010	0.013
26000	0.044	-0.027	0.013
27000	0.014	-0.051	0.013
28000	-0.020	-0.036	0.013
29000	-0.019	-0.004	0.013
30000	0.008	0.004	0.013
31000	0.023	-0.021	0.013
32000	0.002	-0.048	0.013
33000	-0.034	-0.043	0.013
34000	-0.052	-0.008	0.013
35000	-0.034	0.025	0.013
36000	-0.002	0.027	0.013
37000	0.018	0.001	0.013
38000	-0.004	-0.029	0.013
39000	-0.044	-0.016	0.013
40000	-0.049	0.031	0.017
41000	-0.008	0.059	0.017
42000	0.037	0.034	0.017
43000	0.025	-0.017	0.017
44000	-0.025	-0.012	0.017
45000	-0.029	0.041	0.017
46000	0.025	0.061	0.017
47000	0.065	0.015	0.017
48000	0.034	-0.037	0.017
49000	-0.020	-0.023	0.017
50000	-0.016	0.030	0.017

B. Additional Information by the Participants

B.1 PTB

PTB provided two data sets resulting from different reflection measurements. The calibration factor resulting from the first measurement (26th January 2011) are based on the ill-behaved reflection coefficient measurement as described in Annex B.2, while the second (issued 23 February 2011) uses the reflection measurement values listed in table 6.

B.1.1 Method of Calibration

Calibration Factor:

Fig. 7 shows the direct comparison measurement setup of PTB. Four thermistor standards covering the frequency ranges 50 MHz to 18 GHz, 18 GHz to 26.5 GHz, 26.5 GHz to 40 GHz, and 33 GHz to 50 GHz as well as the DUT were alternately connected to one of the output ports of a power splitter. Simultaneously with the DUT/standard power measurement (indicated power $P_{\mathrm{ind,X}}$ and $P_{\mathrm{ind,N}}$, respectively), the incident power level is monitored by a reference power sensor (indicated power $P_{\mathrm{ind,G}}$) via the second output port of the power splitter. In the frequency band 33 GHz to 50 GHz, a directional coupler was used instead of the power splitter to eliminate the error induced by the significant effective source reflection coefficient of the splitter in combination with the also significantly mismatched thermistor standard.

The calibration factor $\eta_{\mathrm{cal,N}}$ of the thermistor standards was determined by long-term microcalorimeter measurements at PTB resulting in low uncertainties. While the standard for the lowest frequency range has an N-male connector, the three thermistors are equipped with waveguide connectors.

To mate the standards with the reference plane 2,4mm connector, coax-to-coax and waveguide-to-coax adapters, respectively, are used. The S-parameters of the adapters are measured separately by VNA measurements. From the calibration factor $\eta_{\mathrm{cal,N}}$ of the thermistors, their complex input reflection coefficient and S-parameters of the adapters, the calibration factor $\eta'_{\mathrm{cal,N}}$ and the input reflection coefficient Γ'_{N} of the combined adapter-thermistor standard is calculated. A cross-check between the calculated input reflection coefficient Γ'_{N} of the combined standard and its directly measured value gives an indication of the validity of the adapter measurement.

The equivalent source reflection coefficient Γ_{G} of the power splitter/directional coupler was determined by applying the Juroshek-Method [3].

Knowing the complex-valued source reflection coefficient and the DUT/standard input reflection coefficient, a correction of the mismatch error was performed.

Since the overall frequency range was subdivided into the four subsets, two measurement results were obtained at each turnover frequency at 18 GHz, 26.5 GHz as well as for the range between 33 GHz and 40 GHz. A maximum difference of 0.8% indicates consistency of the reference calorimeter calibration.

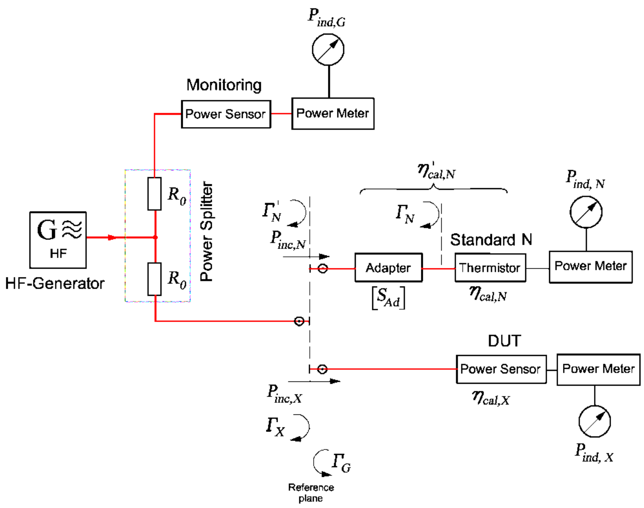

Figure 10: The calibration setup used at PTB.

Reflection Coefficient: The reflection coefficient was measured using a R&S ZVA-50 vector network analyzer using short-open- load standards which are traced to airline standards.

B.1.2 Uncertainty Budget

Table 9Table 9 shows the uncertainty contributions and an example uncertainty budget for the frequency dependent calibration factor. All uncertainty contributions are relative. Therefore all sensitivity coefficients are unity and are left out.

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Table 9: Example uncertainty budget for frequency dependent calibration factor at 0 dBm

Source of relative uncertainty contribution	**Probab. distrib.**	**Standard uncertainty contribution at frequency [GHz]**					
		2	8	20	30	40	50
Calibration factor of standard sensor	normal	0.00246	0.00353	0.00405	0.00429	0.00577	0.00575
Drift of standard sensor	uniform	0.00071	0.00102	0.00117	0.00124	0.00167	0.00166
Calibration factor of standard sensor at f_{ref}	normal	0.00277	0.00267	0.00253	0.00241	0.00173	0.00180
Drift of standard sensor at f_{ref}	uniform	0.00080	0.00077	0.00073	0.00070	0.00050	0.00052
Mismatch factor	U-shaped	0.00026	0.00043	0.00143	0.00189	0.00095	0.00136
Mismatch factor at f_{ref}	U-shaped	0.00083	0.00080	0.00076	0.00073	0.00052	0.00054
Power ratio DUT	normal	0.00016	0.00002	0.00002	0.00003	0.00083	0.00213
Power ratio standard	normal	0.00007	0.00022	0.00024	0.00024	0.00006	0.00021
Power ratio DUT: nonlinearity, drift, resolution of DUT power meter	uniform	0.00029	0.00028	0.00026	0.00025	0.00018	0.00019
Power ratio standard: nonlinearity, drift, resolution of std. power meter	uniform	0.00048	0.00046	0.00044	0.00042	0.00030	0.00031
Power ratio DUT: nonlinearity, drift, resolution of monitor power meter	uniform	0.00029	0.00028	0.00026	0.00025	0.00018	0.00019
Power ratio standard: nonlinearity, drift, resolution of monitor power meter	uniform	0.00029	0.00028	0.00026	0.00025	0.00018	0.00019
Combined relative standard uncertainty		0.0040	0.00473	0.00525	0.00554	0.00063	0.00068
Expanded uncertainty		0.0080	0.0095	0.0105	0.0111	0.0129	0.0136
Calibration factor	$\eta_{cal,100kHz}$	**0.9660**	**0.9323**	**0.8928**	**0.8673**	**0.8352**	**0.8278**

B.2 PTB Results first measurement of Complex Input Reflection Coefficient

In the frequency range 18 GHz to 33 GHz, the first data set (Jan 2011) showed irregular results for the phase of the reflection coefficient since the algebraic sign of both real and imaginary part has been measured opposite to their physically correct value. Since the magnitude of the result was not affected, the error kept undiscovered und could not reproduced by a later performed repeated measurement using the same VNA settings.

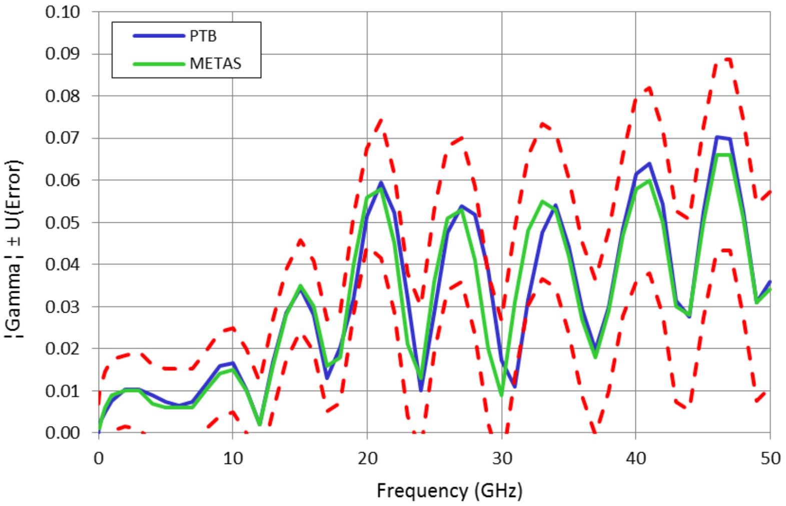

Figure 11: Magnitude $|\Gamma| \pm U$(Error) of input reflection coefficient (1st measurement).
(Reference value $|\Gamma|$ = Metas)

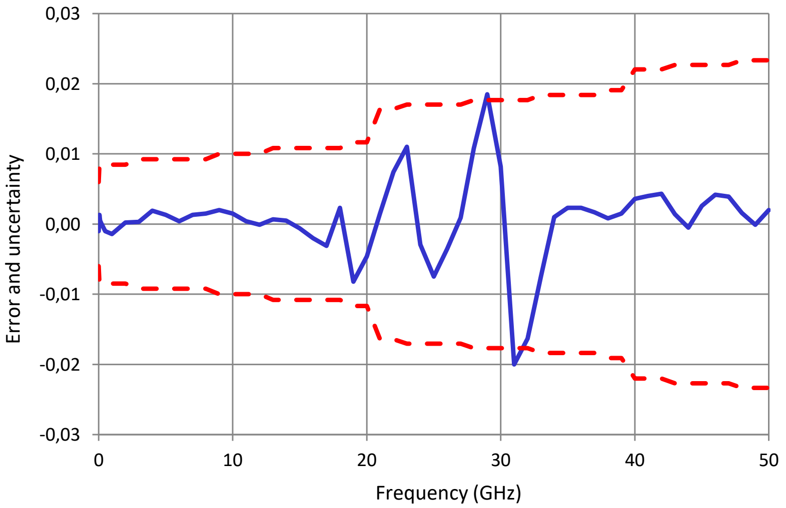

Figure 12: Error and uncertainty of magnitude $|\Gamma|$ of input reflection coefficient.

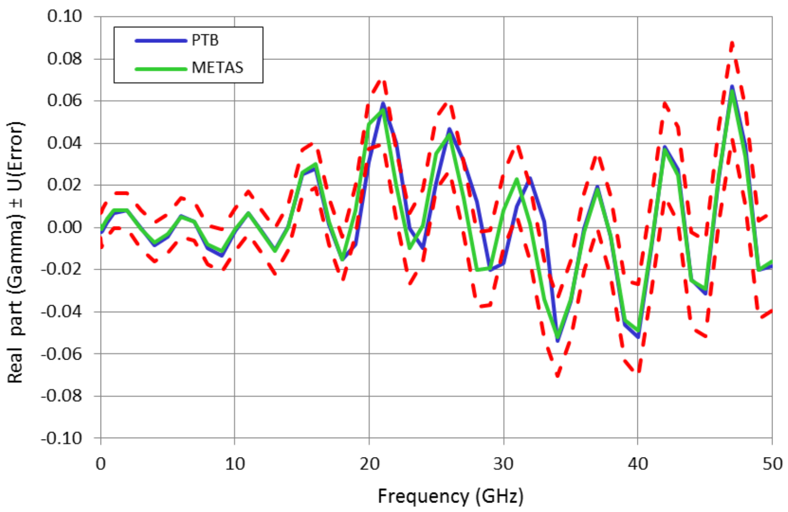

Figure 13: Real part Γ_{Re} ± U(Error) of input reflection coefficient (1st measurement).
(Reference value $|\Gamma|$ = Metas)

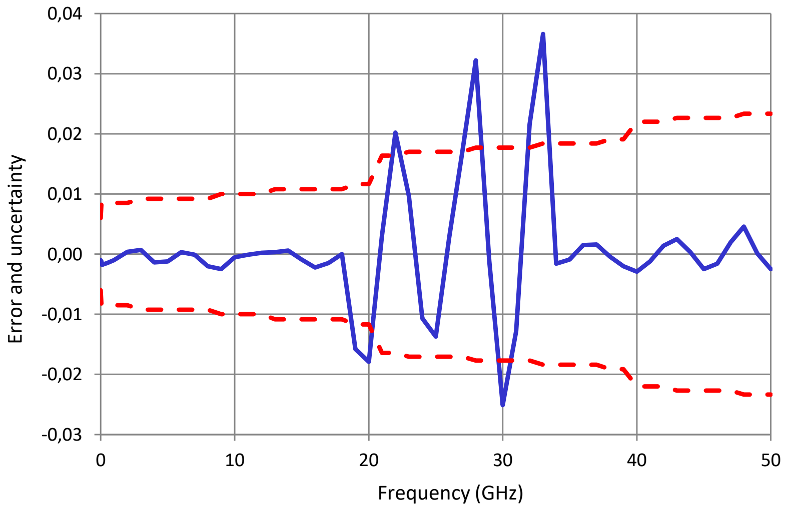

Figure 14: Error and uncertainty of real part Γ_{Re} of input reflection coefficient (1st measurement).

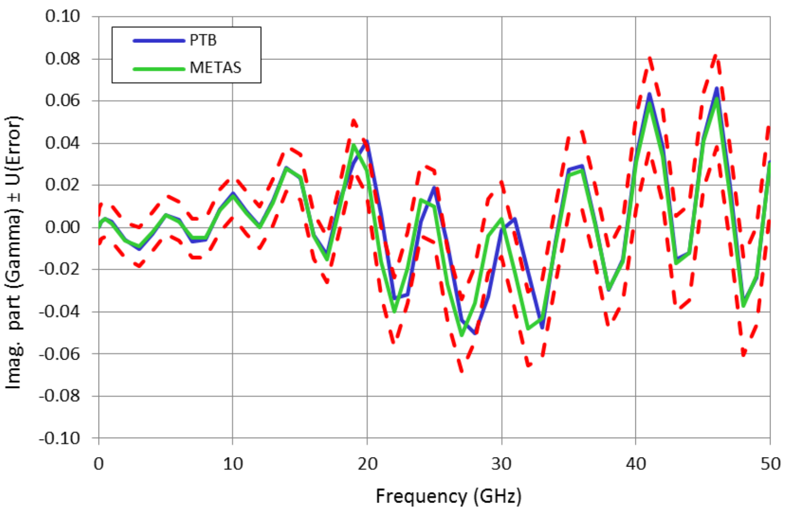

Figure 15: Imaginary part Γ_{im} ± U(Error) of input reflection coefficient (1st measurement).
(Reference value $|\Gamma|$ = Metas)

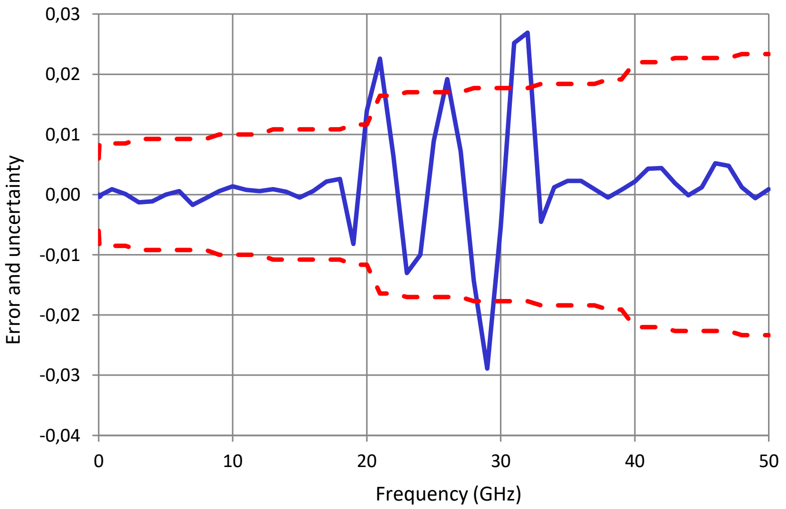

Figure 16: Error and uncertainty of imaginary part Γ_{im} of input reflection coefficient (1st measurement).

B.3 METAS

Metas provided a certificate of calibration 217-01237 issued August, 19th, 2010.

B.3.1 Method of Calibration

Calibration Factor: Metas uses the well known direct comparison setup [2], [3] according to Figure 17Figure 17. The frequency-.dependent calibration factor of the DUT is traced to the power standard.

The standard power sensor REF and the DUT (device under test) are alternately connected to the power splitter. Their readout is taken simultaneously with the monitoring power sensor MON.

A mismatch factor correction was applied by knowing the equivalent source reflection coefficient Γ_G of the splitter as well as the input reflection coefficient of DUT and power standard. Γ_G of the power splitter was determined by using the Juroshek-Method [3].

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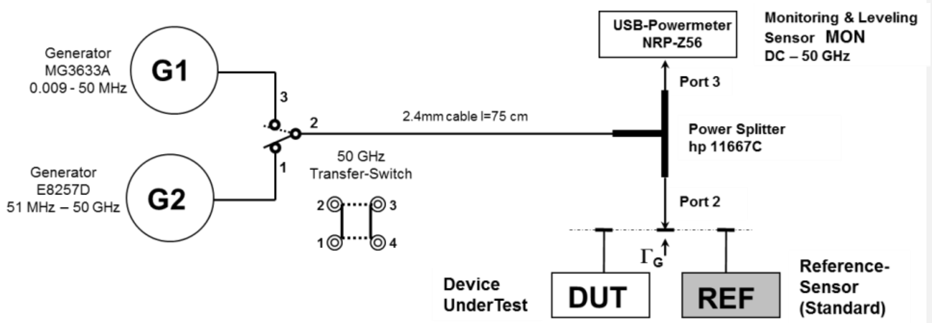

Figure 17: Setup used at Metas to determine the calibration factor vs. frequency.

Reflection coefficient: The reflection coefficient was measured by means of Agilent E8361C and hp8751A vector network analyzers. Calibration method E8361C: open-short-sliding load; hp8751A: open-short-load.

B.3.2 Uncertainty Budget

Calibration Factor:

Table 10: Example uncertainty budget for frequency dependent calibration factor (4 GHz / 1 mW)

Uncertainty Budget f = 4 GHz Calibration power = 1 mW (0 dBm)									
xi	Mesurand Xi	Description	Prob. Distrib	di	Estimate xi	Unit Estimate	Standard-Uncertainty u(xi) [lin]	Sensitivity Coefficient ci	Std-Unc contribution u(xi) [lin]
x1	R_{DUT}	$R = P_{DUT\_Read}$ / P_{MON_Read}	norm.	1	1.00017	[lin]	0.00011	0.960	0.00010
x2	R_{REF}	$R = P_{REF\_Read}$ / P_{MON_Read}	norm.	1	1.03055	[lin]	0.00015	-0.932	-0.00014
x3	K_{eREF}	Calibration Factor Ke_REF	norm.	0.5	0.9895	[lin]	0.0025	0.971	0.00243
x4	δKe	δKe: Drift & Aging Ke_REF	rect.	0.577	0	[lin]	0.0005	0.960	0.00048
x5	D_{MON}	Linearity MON	norm.	0.5	1	[lin]	0.0005	-0.960	-0.00048
x6	D_{REF}	Linearity REF	norm.	0.5	1	[lin]	0.0005	0.960	0.00048
x8	MF	Mismatch-Factor	norm.	1	1.0001	[lin]	0.00018	0.960	0.00018
x11	U_{transf_50MHz}	Unc transfer from $f_{normalizing}$ (50MHz)	-	1	1	[lin]	0.00150	0.960	0.00144
x15	SRREF	Resolution (Meter) REF	rect.	0.577	1	[lin]	0.00100	-0.960	-0.00096
x16	SRDUT	Resolution (Meter) DUT	rect.	0.577	1	[lin]	0.00100	0.960	0.00096
x17	ZS	Zero Set	rect.	0.577	0	[W]	0.00001	0.960	0.00000
x18	ZD	Zero Drift	rect.	0.577	0	[W]	0.00003	0.960	0.00003
x19	TC	Temperatur Coeff. (System)	rect.	0.577	1	[lin]	0.00100	0.960	0.00096
x20	N	Noise	rect.	0.577	0	[W]	0.00004	0.960	0.00004
x22	H_{REF}	Harmonics, REF (thermal sensor)	U	0.707	1	[dB]	1.00E-03	-0.960	-9.60E-04
x23	H_{DUT}	Harmonics, DUT (diode sensor)	U	0.707	1	[dB]	1.00E-03	0.960	9.60E-04
		Calibration Factor					**K_{e_DUT} (W/W) =**		**0.9604**
		Combined Standard Uncertainty					$u(K_{eDUT})$ (W/W) =		0.00365
		Expanded Standard Uncertainty					$U(K_{eDUT})$ (W/W) =		**0.0073**
		Expanded Std Unc (rounded)					**$U(K_{eDUT})$ (W/W) =**		**0.008**

Table 11: Example uncertainty budget for frequency dependent calibration factor (50 GHz / 1 mW)

Uncertainty Budget f = 50 GHz Calibration power = 1 mW (0 dBm)									
xi	Mesurand Xi	Description	Prob. Distrib	di	Estimate xi	Unit Estimate	Standard-Uncertainty u(xi) [lin]	Sensitivity Coefficient ci	Std-Unc contribution u(xi) [lin]
x1	R_{DUT}	$R = P_{DUT\_Read}$ / P_{MON_Read}	norm.	1	1.01958	[lin]	0.00099	0.815	0.00081
x2	R_{REF}	$R = P_{REF\_Read}$ / P_{MON_Read}	norm.	1	1.08690	[lin]	0.00095	-0.764	-0.00072
x3	K_{eREF}	Calibration Factor Ke_REF	norm.	0.5	0.8814	[lin]	0.011	0.942	0.01037
x4	δKe	δKe: Drift & Aging Ke_REF	rect.	0.577	0	[lin]	0.0005	0.831	0.00042
x5	D_{MON}	Linearity MON	norm.	0.5	1	[lin]	0.0005	-0.831	-0.00042
x6	D_{REF}	Linearity REF	norm.	0.5	1	[lin]	0.0005	0.831	0.00042
x8	MF	Mismatch-Factor	norm.	1	1.0046	[lin]	0.00467	0.831	0.00388
x11	U_{transf_50MHz}	Unc transfer from $f_{normalizing}$ (50MHz)	-	1	1	[lin]	0.00150	0.831	0.00125
x15	SRREF	Resolution (Meter) REF	rect.	0.577	1	[lin]	0.00100	-0.831	-0.00083
x16	SRDUT	Resolution (Meter) DUT	rect.	0.577	1	[lin]	0.00100	0.831	0.00083
x17	ZS	Zero Set	rect.	0.577	0	[W]	0.00001	0.831	0.00000
x18	ZD	Zero Drift	rect.	0.577	0	[W]	0.00003	0.831	0.00002
x19	TC	Temperatur Coeff. (System)	rect.	0.577	1	[lin]	0.00100	0.831	0.00083
x20	N	Noise	rect.	0.577	0	[W]	0.00004	0.831	0.00004
x22	H_{REF}	Harmonics, REF (thermal sensor)	U	0.707	1	[dB]	1.00E-03	-0.831	-8.31E-04
x23	H_{DUT}	Harmonics, DUT (diode sensor)	U	0.707	1	[dB]	1.00E-03	0.831	8.31E-04
		Calibration Factor					**K_{e_DUT} (W/W) =**		**0.8246**
		Combined Standard Uncertainty					$u(K_{eDUT})$ (W/W) =		0.01137
		Expanded Standard Uncertainty					$U(K_{eDUT})$ (W/W) =		0.02273
		Expanded Std Unc (rounded)					**$U(K_{eDUT})$ (W/W) =**		**0.023**

C. Control and Cross Check Measurements of the Travelling Standard

Control and cross check measurements to investigate drift and stability of the travelling standard during the whole measurement period were performed by Metas two times (03.09.2009, Day 1, MET1 and 23.05.2011, Day 627, MET3), according to Table 2Table 2.

The results showed no significant drift of the device under test (DUT) and therefore no corrections were necessary.

The results for the calibration factor are shown for the nominal power level ($P_{\text{Cal nom}}$ = 1 mW) in three graphs as well as in Table 3. The following quantities are plotted:

CF_{MET1}: Calibration Factor measured at METAS 03.09.2009, Day 1
CF_{MET3}: Calibration Factor measured at METAS 23.05.2011, Day 627
$u(CF_{\text{MET1}})$: Standard uncertainty in CF_{MET1}
$u(CF_{\text{MET3}})$: Standard uncertainty in CF_{MET2}
Error = $CF_{\text{MET1}} - CF_{\text{MET3}}$

$$U(\text{Error}) = 2 \cdot \sqrt{u(CF_{\text{MET1}})^2 + u(CF_{\text{MET3}})^2}$$

E_n = Error / U(Error)

If E_n < 0.1 the measured drift is regarded as insignificant, i.e. no corrections are made.

C.1 Crosscheck of Normalized Frequency Response, Metas 9/2009 – 5/2011

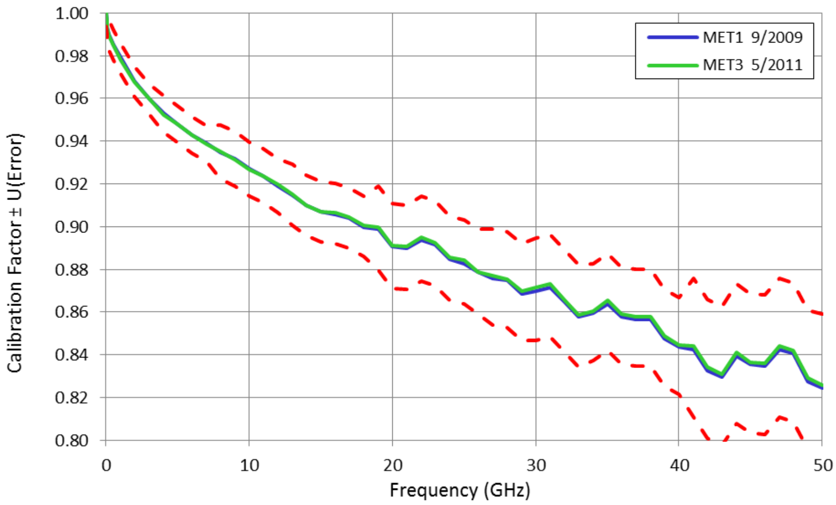

Figure 18: Calibration factor $CF(f)_{100\text{kHz}} \pm U$(Error), linear frequency range.

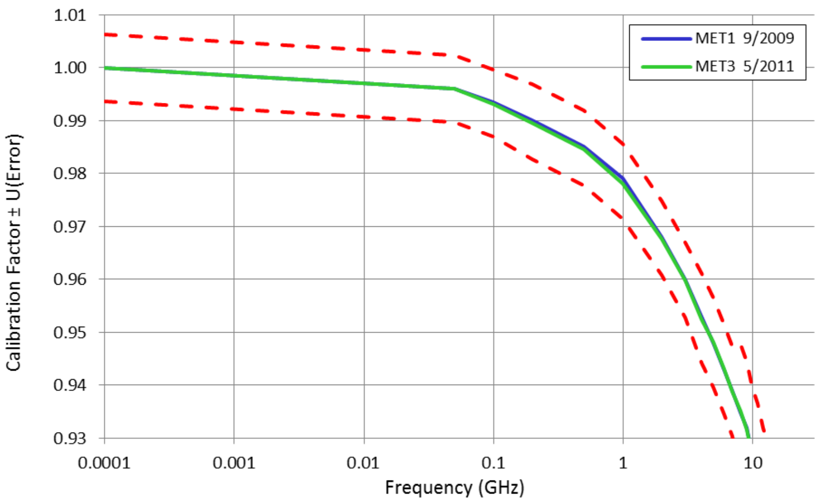

Figure 19: Calibration factor $CF(f)_{100kHz}$ ± U(Error), logarithmic frequency range.

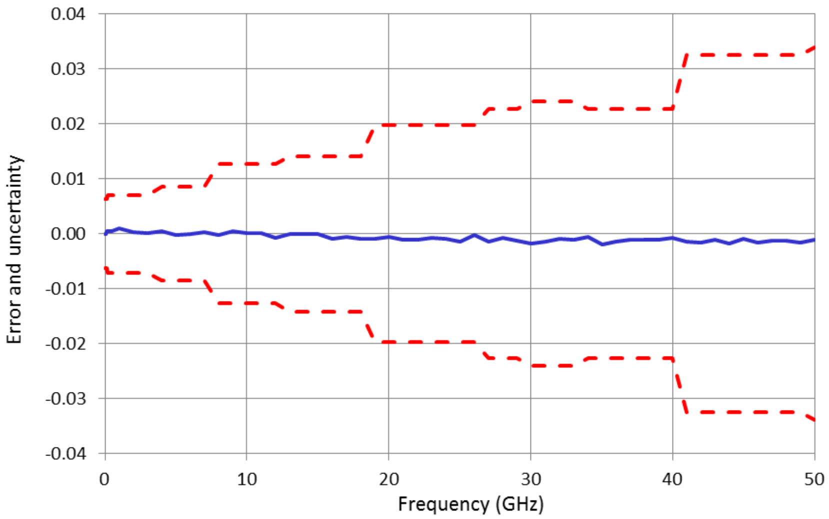

Figure 20: Error ± U(Error).

Table 12: Crosscheck of normalized frequency response at 0 dBm, Metas 9/2009 – 5/2011.

Frequency MHz	En	Error	U(Error)	CF_{MET1}	u(CF_{MET1})	CF_{MET3}	u(CF_{MET3})
0.1	0.000	0.0000	0.0064	1.0000	1.0000	0.0023	0.0023
50	-0.002	0.0000	0.0064	0.9961	0.9961	0.0023	0.0023
100	0.058	0.0004	0.0064	0.9935	0.9931	0.0023	0.0023
200	0.064	0.0005	0.0071	0.9901	0.9896	0.0025	0.0025
500	0.064	0.0005	0.0071	0.9851	0.9846	0.0025	0.0025
1000	0.140	0.0010	0.0071	0.9790	0.9780	0.0025	0.0025
2000	0.043	0.0003	0.0071	0.9680	0.9677	0.0025	0.0025
3000	0.025	0.0002	0.0071	0.9600	0.9598	0.0025	0.0025
4000	0.058	0.0005	0.0085	0.9530	0.9525	0.0030	0.0030
5000	-0.022	-0.0002	0.0085	0.9479	0.9481	0.0030	0.0030
6000	-0.017	-0.0001	0.0085	0.9429	0.9431	0.0030	0.0030
7000	0.022	0.0002	0.0085	0.9389	0.9387	0.0030	0.0030
8000	-0.018	-0.0002	0.0127	0.9349	0.9351	0.0045	0.0045
9000	0.031	0.0004	0.0127	0.9319	0.9315	0.0045	0.0045
10000	0.007	0.0001	0.0127	0.9269	0.9268	0.0045	0.0045
11000	0.003	0.0000	0.0127	0.9239	0.9238	0.0045	0.0045
12000	-0.060	-0.0008	0.0127	0.9188	0.9196	0.0045	0.0045
13000	-0.011	-0.0002	0.0141	0.9148	0.9150	0.0050	0.0050
14000	-0.005	-0.0001	0.0141	0.9098	0.9099	0.0050	0.0050
15000	-0.010	-0.0001	0.0141	0.9068	0.9070	0.0050	0.0050
16000	-0.060	-0.0008	0.0141	0.9058	0.9067	0.0050	0.0050
17000	-0.045	-0.0006	0.0141	0.9038	0.9044	0.0050	0.0050
18000	-0.069	-0.0010	0.0141	0.8998	0.9008	0.0050	0.0050
19000	-0.050	-0.0010	0.0198	0.8988	0.8998	0.0070	0.0070
20000	-0.028	-0.0006	0.0198	0.8908	0.8913	0.0070	0.0070
21000	-0.058	-0.0012	0.0198	0.8898	0.8909	0.0070	0.0070
22000	-0.054	-0.0011	0.0198	0.8938	0.8948	0.0070	0.0070
23000	-0.040	-0.0008	0.0198	0.8918	0.8926	0.0070	0.0070
24000	-0.048	-0.0009	0.0198	0.8847	0.8857	0.0070	0.0070
25000	-0.070	-0.0014	0.0198	0.8827	0.8841	0.0070	0.0070
26000	-0.013	-0.0003	0.0198	0.8787	0.8790	0.0070	0.0070
27000	-0.063	-0.0014	0.0226	0.8757	0.8771	0.0080	0.0080
28000	-0.035	-0.0008	0.0226	0.8747	0.8755	0.0080	0.0080
29000	-0.054	-0.0012	0.0226	0.8687	0.8699	0.0080	0.0080
30000	-0.073	-0.0017	0.0240	0.8697	0.8714	0.0085	0.0085
31000	-0.057	-0.0014	0.0240	0.8717	0.8731	0.0085	0.0085
32000	-0.038	-0.0009	0.0240	0.8647	0.8656	0.0085	0.0085
33000	-0.049	-0.0012	0.0240	0.8577	0.8588	0.0085	0.0085
34000	-0.028	-0.0006	0.0226	0.8597	0.8603	0.0080	0.0080
35000	-0.085	-0.0019	0.0226	0.8637	0.8656	0.0080	0.0080
36000	-0.061	-0.0014	0.0226	0.8577	0.8590	0.0080	0.0080
37000	-0.051	-0.0011	0.0226	0.8567	0.8578	0.0080	0.0080
38000	-0.050	-0.0011	0.0226	0.8567	0.8578	0.0080	0.0080
39000	-0.045	-0.0010	0.0226	0.8476	0.8487	0.0080	0.0080
40000	-0.035	-0.0008	0.0226	0.8436	0.8444	0.0080	0.0080
41000	-0.045	-0.0015	0.0325	0.8426	0.8441	0.0115	0.0115
42000	-0.048	-0.0016	0.0325	0.8326	0.8341	0.0115	0.0115
43000	-0.034	-0.0011	0.0325	0.8296	0.8307	0.0115	0.0115
44000	-0.054	-0.0017	0.0325	0.8396	0.8413	0.0115	0.0115
45000	-0.026	-0.0009	0.0325	0.8356	0.8364	0.0115	0.0115
46000	-0.049	-0.0016	0.0325	0.8346	0.8362	0.0115	0.0115
47000	-0.042	-0.0014	0.0325	0.8426	0.8440	0.0115	0.0115
48000	-0.038	-0.0012	0.0325	0.8406	0.8418	0.0115	0.0115
49000	-0.050	-0.0016	0.0325	0.8276	0.8292	0.0115	0.0115
50000	-0.034	-0.0012	0.0339	0.8246	0.8257	0.0120	0.0120

D. Technical Protocol

Measurement Comparison:
2.4 mm 50 GHz Thermocouple Power Sensor
Technical Protocol

Foreword
PTB and METAS have agreed on a bilateral inter laboratory comparison of a radio frequency (RF) 2.4 mm thermocouple power sensor.
The main goal of the comparison is the determination of the calibration factor in the frequency range of 100 kHz to 50 GHz as well as the complex input reflection coefficient of the sensor. This comparison offers the participants the possibility to verify their measurement procedures including the evaluation of measurement uncertainty and it provides a possibility to find and fix errors.

Participants
- Physikalisch-Technische Bundesanstalt PTB, Bundesallee 100, D-38116 Braunschweig, Germany
- Federal Office of Metrology METAS, CH-3003 Bern-Wabern, Switzerland

Pilot laboratory
Metas acts as the pilot lab, acts as a coordinator of the Euramet project and writes the reports.

Device under calibration
The measurement standard is a 2.4 mm thermocouple power sensor type NRP-Z56, SN101446 (R&S) with a frequency range DC to 50 GHz (2.4 mm (male) - connector) and a dynamic range from -35 dBm to + 20 dBm.

The device is provided by Metas.

Measurands
The measurands of this comparison are:

- Calibration factor (relative to the calibration factor at 100 kHz) at the nominal power level of 1 mW (0 dBm), expressed in W/W at total 56 test frequencies: 100 kHz, 50 MHz, 100, 200, 500 MHz, 1 GHz, 2, 3 … 25, 26, 26.5, 27, 28 … 49, 50 GHz.
- Complex input reflection coefficient at the same frequencies, expressed in real and imaginary parts.

Documentation of the results
The participants are asked to document their results in the form of a calibration certificate and a GUM compliant measurement uncertainty budget.

Analysis and report
The analysis of the comparison will be confidential and the initial report will only be available to the participants. After approval by all participants the final report with the results of the comparison will be published in the Euramet database.

Time table

Date	***Participant***	***transfer to***
March 2010	METAS measurements	-
August 2010	METAS	PTB
January 2011	PTB measurements	
March 2011	PTB	METAS
April 2011	METAS control measurements	
May 2011	Metas draft report	
June 2011	discussion of the results and corrections	
July 2011	Final report to EURAMET	

E. References

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[2] Juroshek, J. R. NIST: 0.05 - 50 GHz Direct Comparison Power Calibration System; Conference on Precision Electromagnetic Measurements , May 14-19, 2000, Syndey, Australia - May 01, 2000.

[3] John R. Juroschek: „A Direct Calibration Method For Measuring Equivalent Source Mismatch“; Microwave Journal, October 1997.

[4] G. Wübbeler, C. Elster, T. Reichel, R. Judaschke, "Determination of Complex Residual Error Parameters of a Calibrated Vector Network Analyzer," 69^{th} ARFTG Conference, Honolulu, USA, June 2007.

[5] G. Wübbeler, C. Elster, T. Reichel, R. Judaschke, "Determination of the Complex Residual Error Parameters of a Calibrated One-Port Vector Network Analyzer," IEEE Trans. Instrum. Meas., vol. 58, no. 9, pp. 3238-3244, 2009.