Final Report
SIM.EM.RF-S17

Supplementary Comparison INTI-PTB
Scattering Coefficients - PC-3.5 connector

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Contents

1 Introduction

1.1 Motivations

The purpose of this comparison is to demonstrate the competence of the NMI (National Metrology Institute) from Argentina (INTI) in S-parameter measurements up to 32 GHz in 3.5 mm coaxial connector. For this purpose, the Physikalisch-Technische Bundesanstalt (PTB) from Germany has participated as the reference NMI, being INTI the pilot laboratory.

In addition, this comparison shows how digitalization during the measurement process and data analysis can improve a comparison outcome, being this comparison, to the best of this author's knowledge, one of the first comparison under BIPM scope in which exchanged data between participants consisted of digital uncertainty objects [1], [2].

1.2 Measured Quantities

3.5 mm devices were measured from 1 GHz to 32 GHz (inclusive) in 1 GHz steps.
For one-port devices, the measurand was the complex-valued reflection coefficient S_{11}. The matched load (VSWR=1.0) and mismatched load (VSWR=2.0) were chosen to perform reflection measurements at low and high magnitude values respectively.

For two-port devices (10 dB and 30 dB attenuators) the measurands were the four complex-valued S-parameters (S_{11}, S_{21}, S_{12} and S_{22}). Male port was referred as port number 1 for the purpose of this report.

S-parameters results were informed by participants as uncertainty objects generated with the software METAS VNA Tools [3]. These data structures contain all the data required to fulfill a comprehensive comparison. An example of part of the data included within such an object can be seen in Figure 1:

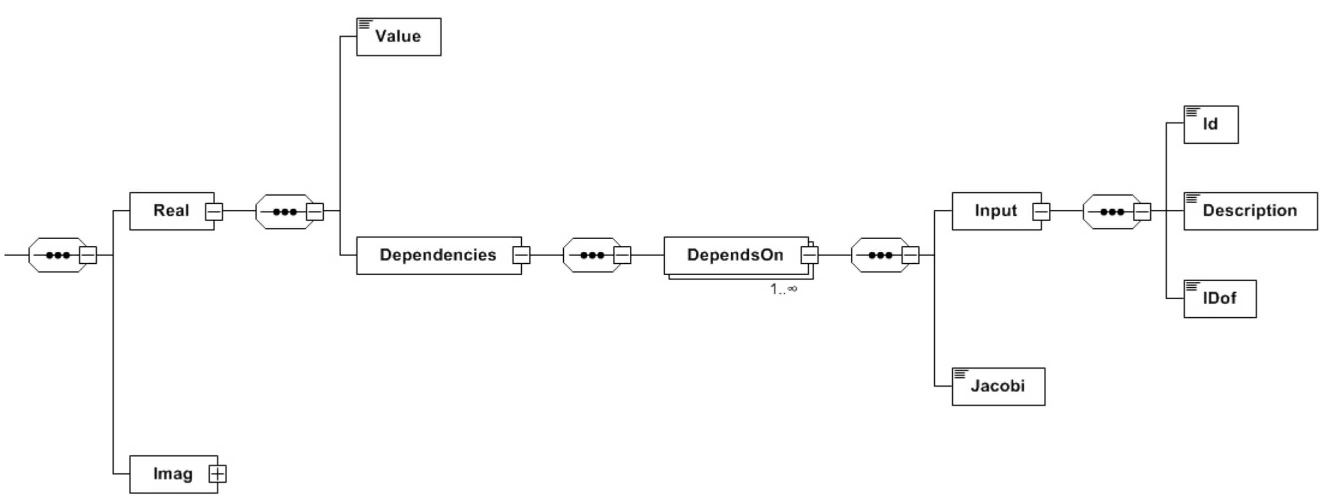

Figure 1: *Uncertainty object. XML tree structure*

2 Traveling Standards

2.1 Description

The selected standards detailed in Table 1 are commercially available devices covering low and high reflection and transmission coefficients.

Type	Nominal Value	Model	Serial Number	Connector Gender
Attenuator	10 dB	Agilent 8493C	77986	Male/Female
Attenuator	30 dB	Keysight 8493C	86234	Male/Female
Matched Load	50 Ω (VSWR=1.0)	Agilent 909D opt 040	50840	Male
Mismatched Load	VSWR=2.0	Maury 8033B2.00	9873	Male

Table 1: *Traveling standards description*

2.2 Images of Traveling Standards

Figure 2: *One-port devices*

Figure 3: *Two-port devices*

3 Participants and Organization

3.1 Participants

Guillermo Monasterios

Instituto Nacional de tecnología Industrial (**INTI)**

RF & Microwaves Laboratory

San Martín - Buenos Aires

ARGENTINA

Karsten Kuhlmann

Physikalisch-Technische Bundesanstalt (**PTB)**

High-Frequency Base Quantities (2.22)

Braunschweig

GERMANY

3.2 Schedule

Table 2 depicts the date on which each laboratory has measured. Despite the fact of being a bilateral comparison, it takes 2 years to complete it because of the COVID-19 pandemic, which hit just in the middle of the time schedule. Firstly, INTI has taken the first set of measurements and then, after the traveling standards returned back to Argentina, a second round of measurements were performed in order to check standards stability.

Laboratory	Measurement date
INTI (Argentina). 1st set of measurements	October 2019
PTB (Germany)	March 2021
INTI (Argentina) 2nd set of measurements	August 2021

Table 2: *Participant measurement dates*

4 Measurement Methods

All participants performed their measurements with a VNA (Vector Network Analyzer) based system. In this comparison, the 2-port devices were defined with the male port as port 1 and the female port as port 2 as was stated in the technical protocol [4].

Laboratory	Hardware	Calibration method
INTI (Argentina)	VNA Rohde & Schwarz ZVK	OSM/TRL
PTB (Germany)	Agilent PNA N5227A	SOLT

Table 3: *Participant measurement methods*

The complete report from each laboratory is included in Annex C.

5 Standards Stability

In order to check the mechanical stability of the traveling standards, pin-depth measurements of each device were taken at both laboratories.

Annex D shows pin-depth measurements of each participant. It shows that pin depth values remain practically constant during all the way between Europe and South America.

At the end of the comparison, the pilot laboratory neither find any damage to the connectors.

To ensure electrical stability of the traveling standards, the pilot laboratory performed a control measurement of each standard.
During this step, a drift on the mismatched load (Maury 8033B2.00 s/n 9873) was detected. This stability issue was corroborated by PTB, so it seems that the fault arose at some point during the trip to Europe. Because of that, INTI and PTB agreed not to inform results belonging to this non-repeatable standard.

A comparison of both measurements corresponding to that standard made by the pilot laboratory can be seen in Annex E.

6 Treatment of Measurement Data

6.1 Integrity of Data Files

The checksum of each measurement file was provided to the pilot, so data integrity was verified upon receiving the measurement results.

6.2 Evaluation of Results

The analysis of results has been done for S_{11} (one-port devices) and S_{21} (two-port devices) at frequencies of 2 GHz, 9 GHz, 18 GHz, 26 GHz and 32 GHz.

As stated in section 1.2, each measured complex S-parameter was reported. Given that uncertainty objects were used throughout this comparison exercise, each complex parameter already has its associated covariance matrix V_i:

$$V_i = \begin{pmatrix} u^2(x) & u(x,y) \\ u(y,x) & u^2(y) \end{pmatrix} \tag{1}$$

To attain confidence in the results, a consistency analysis is proposed using the verification criteria presented in [5] for the multivariate case. The matrix equations are the following:

$$\epsilon = \frac{1}{k}\sqrt{\hat{d}\,(V(\hat{d}))^{-1}\hat{d}'} \tag{2}$$

$$\hat{d} = [\,\mathrm{Re}[\hat{S}^r_{ab} - \hat{S}^c_{ab}]\;\; \mathrm{Im}[\hat{S}^r_{ab} - \hat{S}^c_{ab}]\,] \tag{3}$$

being $\hat{S}^c_{ab}$ INTI's measurement, $\hat{S}^r_{ab}$, PTB's measurement (reference data) and V representing a covariance matrix. The coverage factor for approximately 95% confidence level in the two-dimensional case is k=2.45.
If no correlation between PTB and INTI is assumed, then:

$$V(\hat{d}) = V(\hat{S}^r_{ab}) + V(\hat{S}^c_{ab}) \tag{4}$$

The pass criterion requires that $\epsilon \leq 1$. The fact that this criterion is applied to all four s-parameters is represented with generic letters a and b as in S_{ab}.

7 Report of Results

Each measured S-parameter is reported in Annex A by Cartesian coordinates with its combined standard uncertainty plus the correlation coefficient $u(x, y)$ between both real and imaginary parts of S_{ab} .

Additionally, a graph per each analized frequency is presented, displaying the expanded uncertainty as 95% confidence regions. For that purpose, a bivariate normal distribution is assumed for the measurand [6].

Results in cartesian planes were plotted with METAS VNA Tools version 2.5.3.
In Annex B the uncertainty budget for the corresponding combined uncertainty is shown.

8 Conclusions

Comparison of results between both participants has shown good consistency as can be seen on the pass criterion in Annex A, which was significantly less than one in all cases.

Different VNA calibration methods have been tested and a high level of agreement among reflection coefficient measurement was achievable.

Confidence regions were provided graphically, which led to a more realistic notion of the measurement process given it is the mathematical nature of uncertainty in the complex plane. The information needed to make this possible was available thanks to the fact that data exchanged between participants consisted of data objects as a pioneering approach for this type of metrological exercise.

References

[1] M Zeier et al 2012 Metrologia 49 809, Metas.UncLib-a measurement uncertainty calculator for advanced problems.

[2] Hall, Blair & White, David. (2020). Digital representation of measurement uncertainty for metrological traceability.

[3] METAS VNA Tools, Online: http://www.metas.ch/vnatools.

[4] Technical Protocol. Supplementary Comparison INTI-PTB. Scattering Coefficients - PC-3.5 connector. Available online: https://www.bipm.org/kcdb/comparison?id=1651.

[5] EURAMET Calibration Guide No. 12, "Guidelines on the Evaluation of Vector Network Analysers (VNA)", Version 3.0 (03/2018).

[6] M.Zeier, "On the analysis of multidimensional quantities in measurement comparison", CPEM 2006 Conference Digest, Torino, July 2006, pp 458-459.

[7] G. Monasterios and L. Corach, "Mixed Uncertainty Propagation Method in S-Parameter Measurements," 2018 Conference on Precision Electromagnetic Measurements (CPEM 2018), 2018, pp. 1-2, doi: 10.1109/CPEM.2018.8500970.

Annex A: Results

A.1 Matched Load

NMI	Measurement and combined standard uncertainty S_{11} - Matched load @2 GHz				
	$Re(S_{11})$	$u(Re(S_{11}))$ combined 1-sigma	$Im(S_{11})$	$u(Im(S_{11}))$ combined 1-sigma	$r(x,y)$
INTI	-0.0019	0.0026	0.0017	0.0026	0.00056
PTB	-0.0013	0.0018	0.0004	0.0018	0.00050
	Verification factor ϵ= 0.016				

Table 4

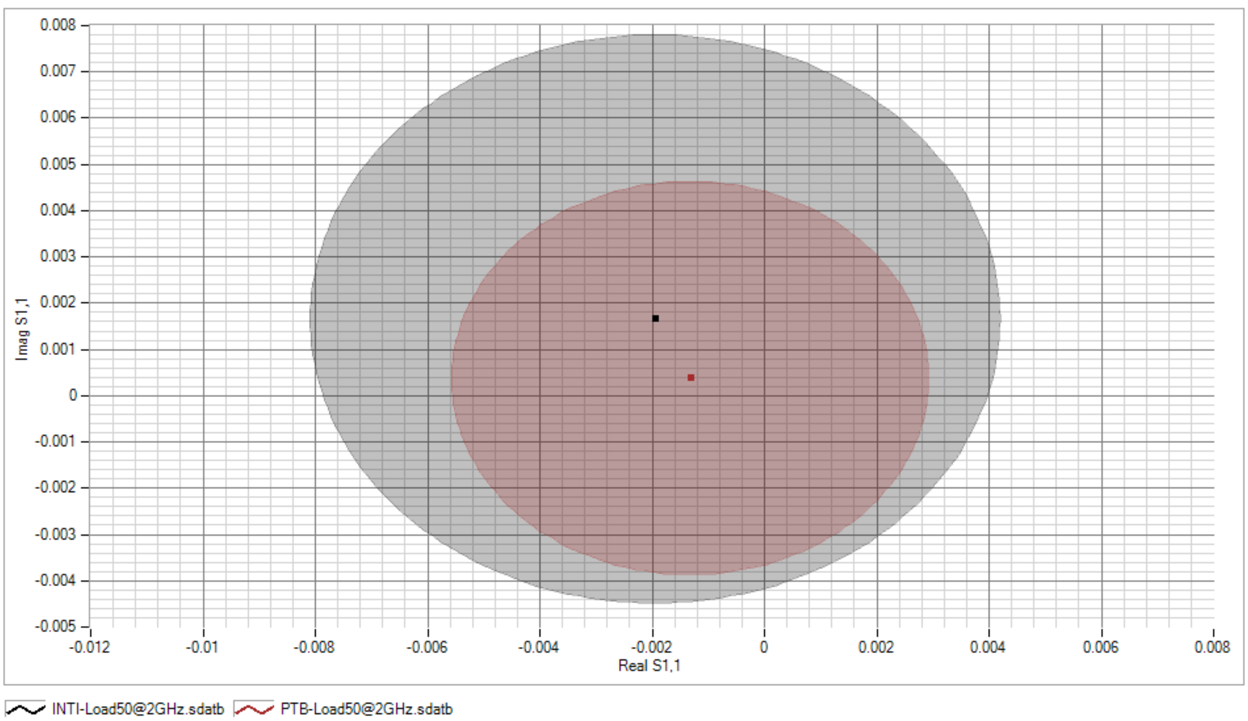

Figure 4: 95% confidence uncertainty region - Matched load @2 GHz

NMI	Measurement and combined standard uncertainty S_{11} - Matched Load @9 GHz				
	$Re(S_{11})$	$u(Re(S_{11}))$ combined 1-sigma	$Im(S_{11})$	$u(Im(S_{11}))$ combined 1-sigma	$r(x,y)$
INTI	0.0019	0.0032	-0.0027	0.0032	0.0019
PTB	0.0022	0.0018	-0.0023	0.0018	0.0048
	Verification factor ϵ= 0.0023				

Table 5

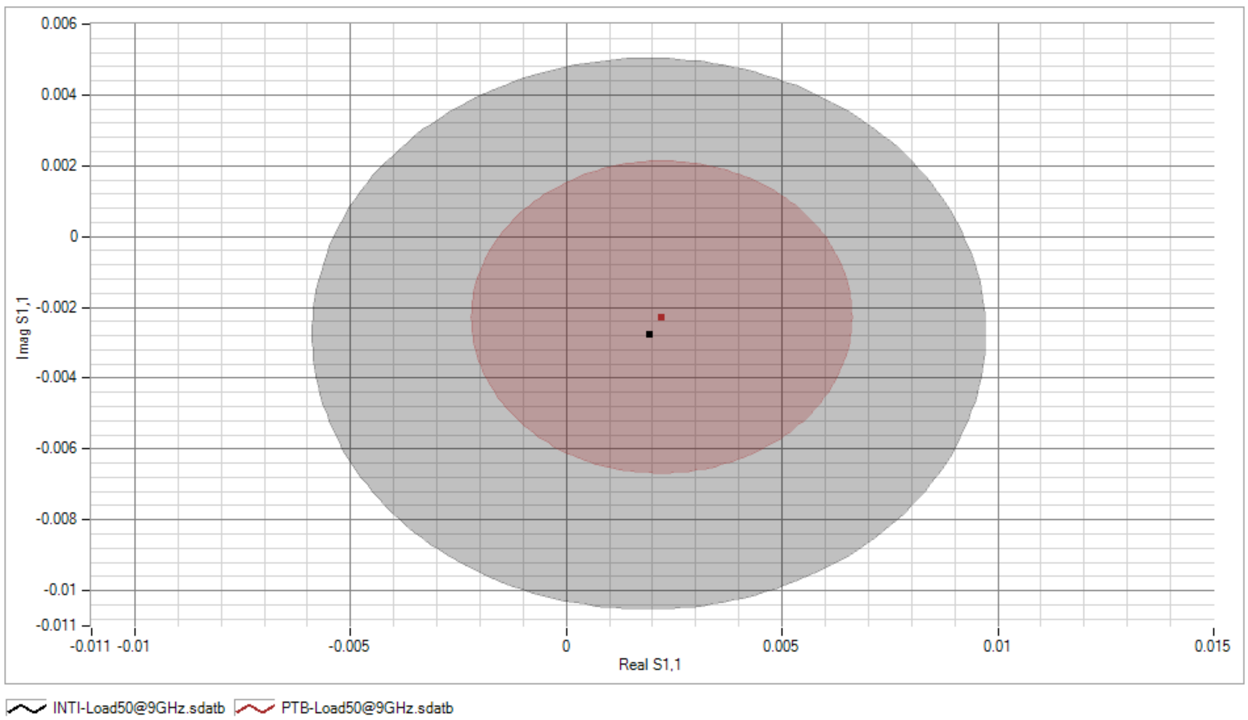

Figure 5: 95% confidence uncertainty region - Matched load @9 GHz

NMI	Measurement and combined standard uncertainty S_{11} - Matched Load @18 GHz				
	$Re(S_{11})$	$u(Re(S_{11}))$ combined 1-sigma	$Im(S_{11})$	$u(Im(S_{11}))$ combined 1-sigma	$r(x,y)$
INTI	0.0016	0.0032	-0.0123	0.0032	-0.0011
PTB	0.0025	0.0025	-0.0134	0.0024	0.018
	Verification factor ϵ= 0.0039				

Table 6

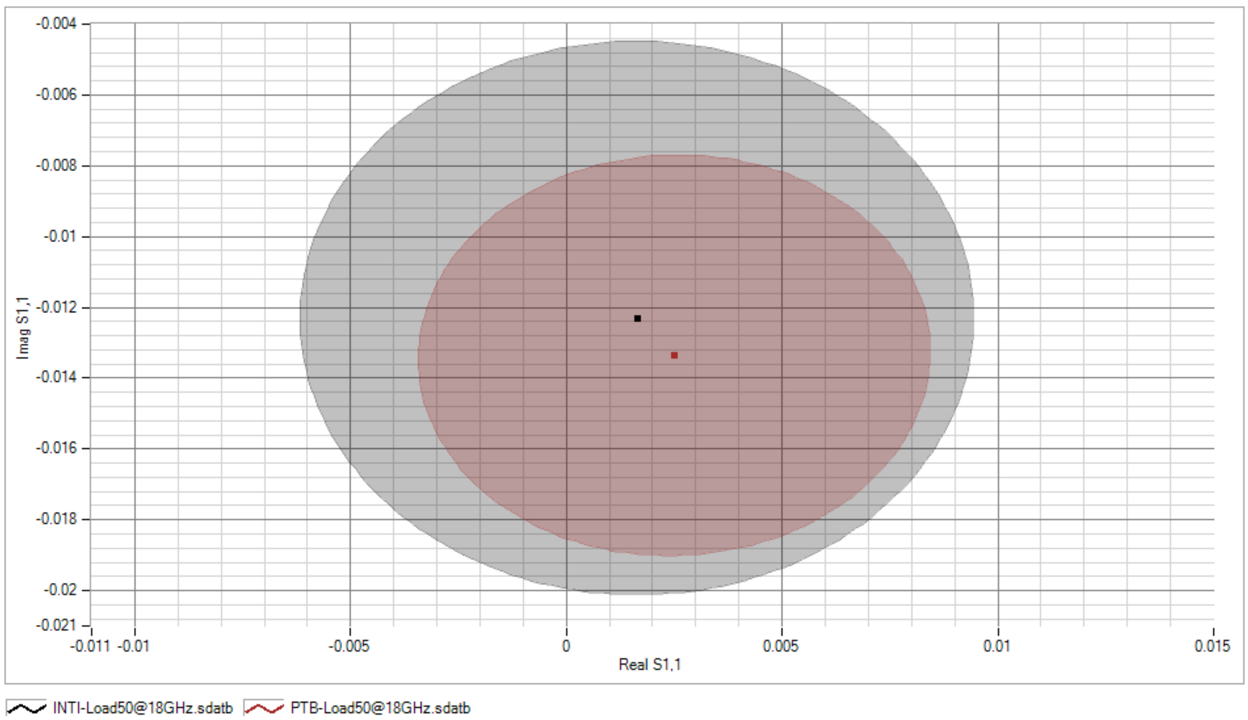

Figure 6: 95% confidence uncertainty region - Matched load @18 GHz

NMI	Measurement and combined standard uncertainty S_{11} - Matched Load @26 GHz				
	$Re(S_{11})$	$u(Re(S_{11}))$ combined 1-sigma	$Im(S_{11})$	$u(Im(S_{11}))$ combined 1-sigma	$r(x,y)$
INTI	0.0024	0.0033	0.0352	0.0033	-0.0074
PTB	0.0055	0.0031	0.0350	0.0025	-0.078
	Verification factor ϵ= 0.0017				

Table 7

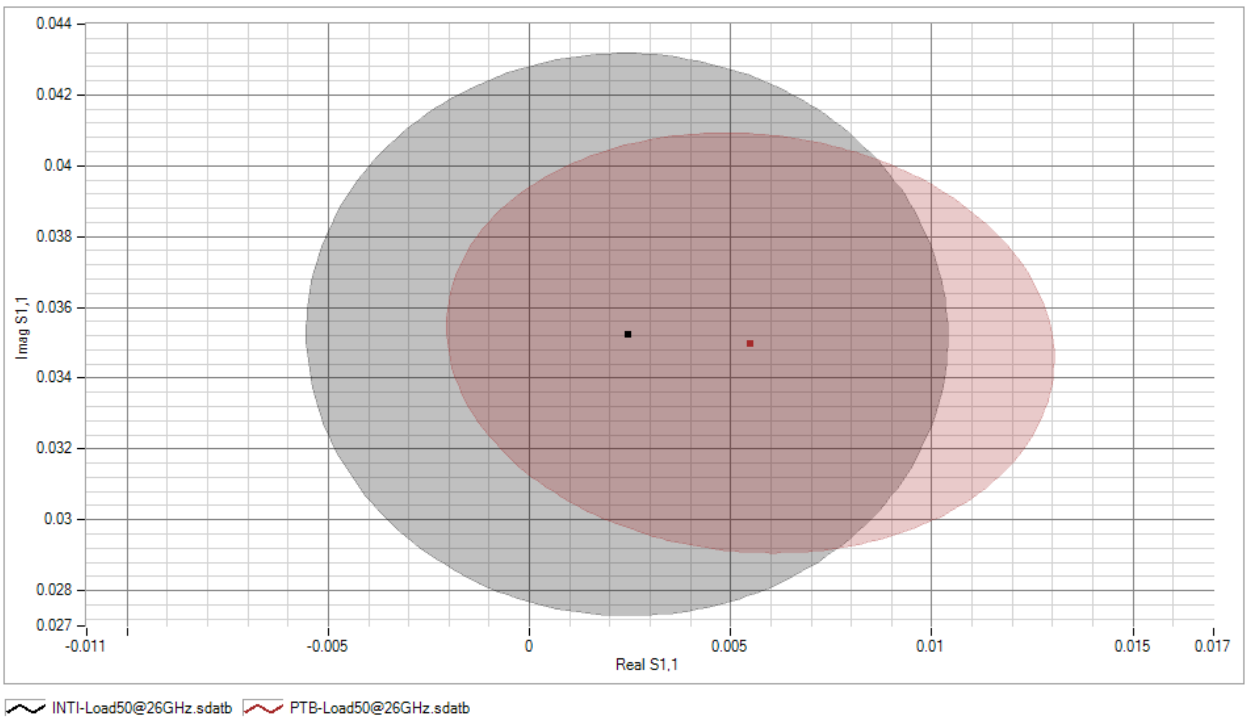

Figure 7: 95% confidence uncertainty region - Matched load @26 GHz

NMI	Measurement and combined standard uncertainty S_{11} - Matched Load @32 GHz				
	$Re(S_{11})$	$u(Re(S_{11}))$ combined 1-sigma	$Im(S_{11})$	$u(Im(S_{11}))$ combined 1-sigma	$r(x,y)$
INTI	-0.0190	0.0052	-0.0716	0.0052	0.0011
PTB	-0.0202	0.0049	-0.0713	0.0030	-0.30
	Verification factor ϵ= 0.0006				

Table 8

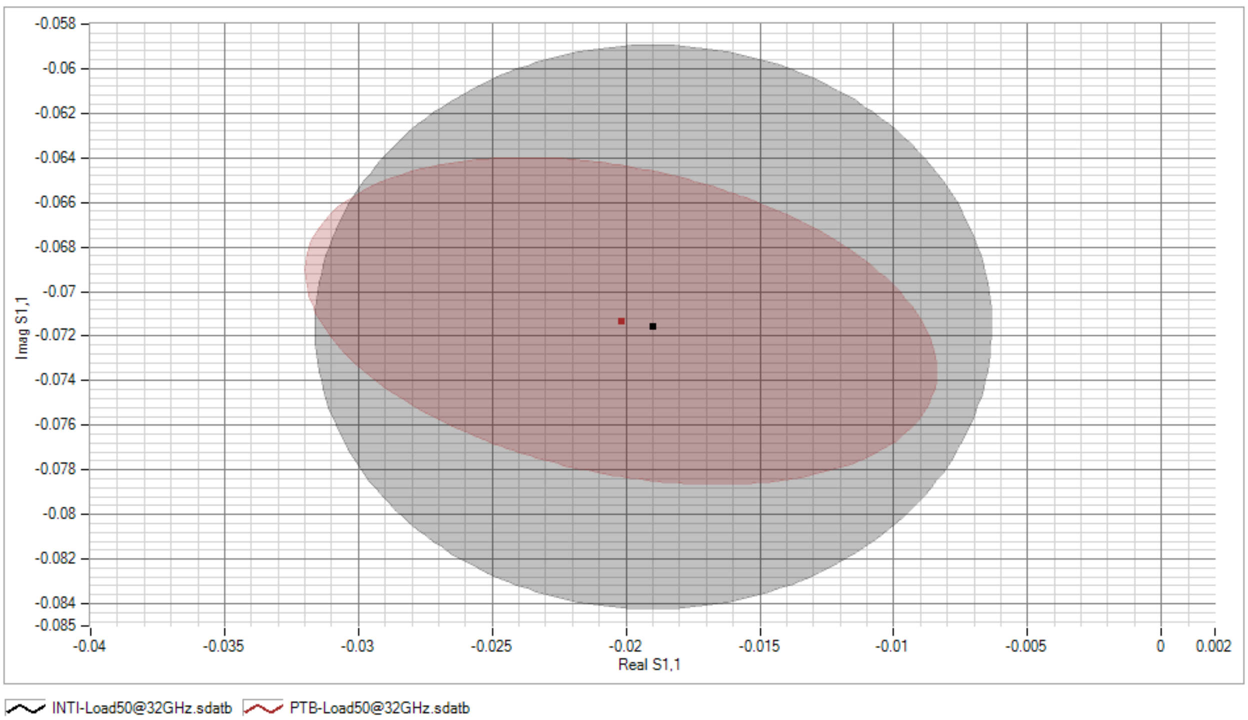

Figure 8: 95% confidence uncertainty region - Matched load @32 GHz

A.2 10 dB Attenuator

NMI	Measurement and combined standard uncertainty S_{21} - 10 dB Attenuator @2 GHz				
	$Re(S_{21})$	$u(Re(S_{21}))$ combined 1-sigma	$Im(S_{21})$	$u(Im(S_{21}))$ combined 1-sigma	$r(x,y)$
INTI	0.02981	0.00010	-0.31626	0.00052	-0.59
PTB	0.0297	0.0088	-0.3166	0.0014	0.60
	Verification factor ϵ= 0.0005				

Table 9

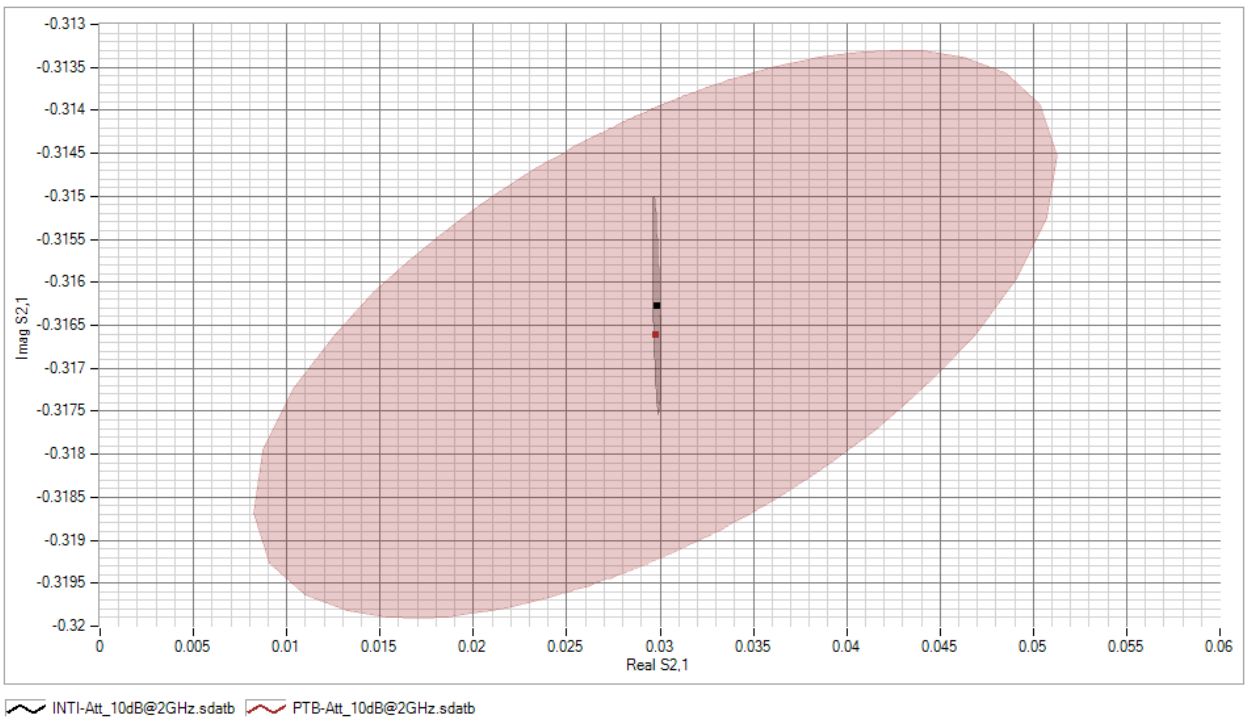

Figure 9: 95% confidence uncertainty region - 10 dB attenuator @2GHz

NMI	Measurement and combined standard uncertainty S_{21} - 10 dB Attenuator @9 GHz				
	$Re(S_{21})$	$u(Re(S_{21}))$ combined 1-sigma	$Im(S_{21})$	$u(Im(S_{21}))$ combined 1-sigma	$r(x, y)$
INTI	0.29383	0.00048	-0.10943	0.00025	-0.76
PTB	0.2942	0.0032	-0.1087	0.0082	0.94
	Verification factor ϵ= 0.0004				

Table 10

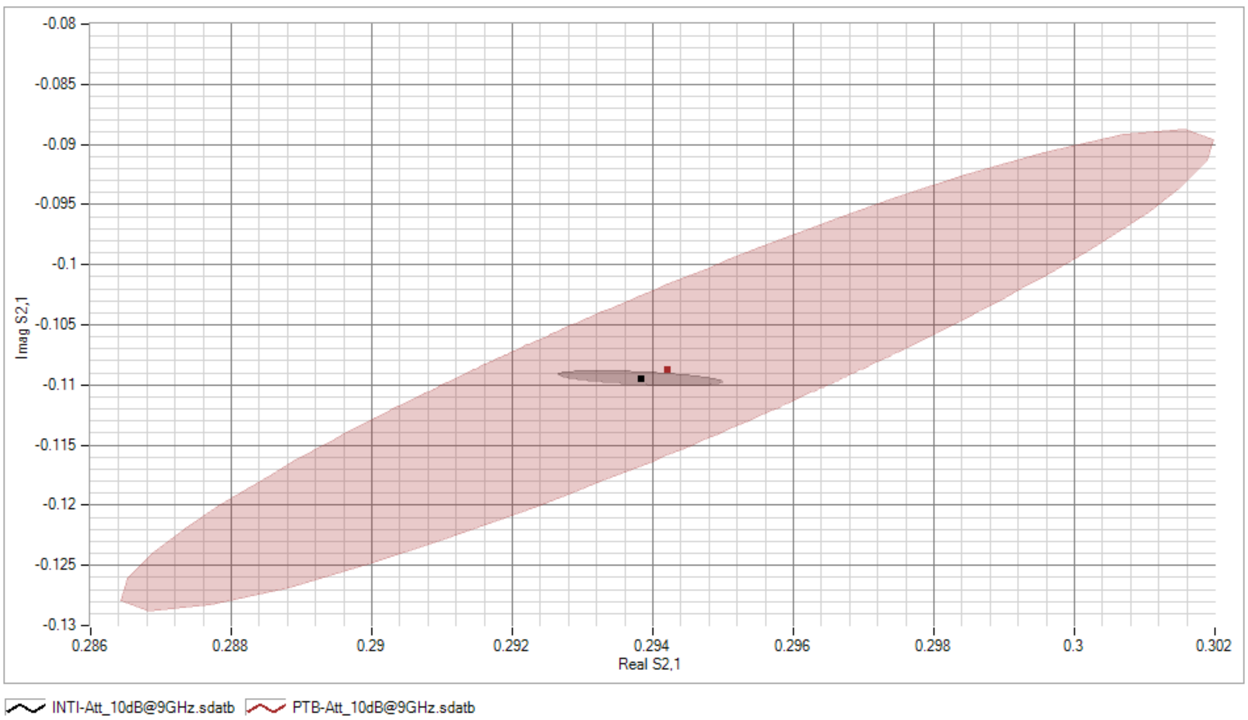

Figure 10: 95% confidence uncertainty region - 10 dB attenuator @9GHz

NMI	Measurement and combined standard uncertainty S_{21} - 10 dB Attenuator @18 GHz				
	$Re(S_{21})$	$u(Re(S_{21}))$ combined 1-sigma	$Im(S_{21})$	$u(Im(S_{21}))$ combined 1-sigma	$r(x,y)$
INTI	0.22695	0.00057	-0.20957	0.00051	-0.46
PTB	0.2284	0.0059	-0.2085	0.0064	0.97
	Verification factor ϵ= 0.0009				

Table 11

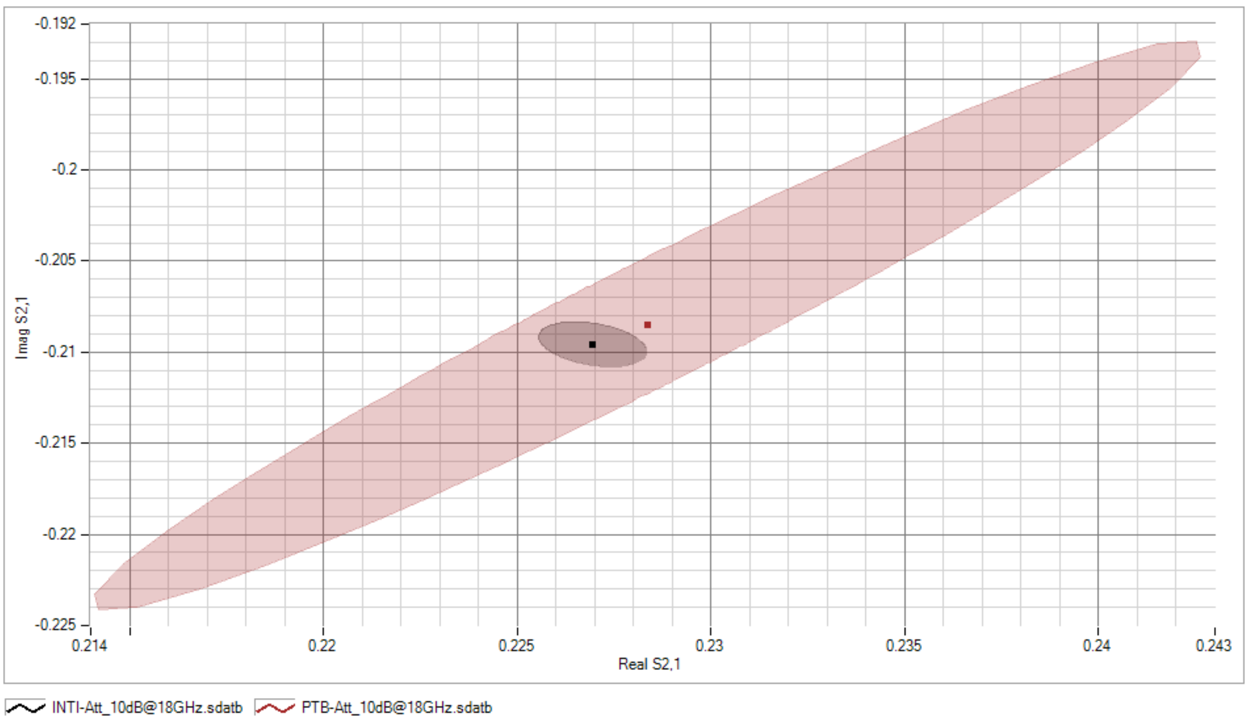

Figure 11: 95% confidence uncertainty region - 10 dB attenuator @18GHz

NMI	Measurement and combined standard uncertainty S_{21} - 10 dB Attenuator @26 GHz				
	$Re(S_{21})$	$u(Re(S_{21}))$ combined 1-sigma	$Im(S_{21})$	$u(Im(S_{21}))$ combined 1-sigma	$r(x, y)$
INTI	0.27406	0.00079	-0.15099	0.00065	-0.32
PTB	0.2753	0.0042	-0.1488	0.0077	0.96
	Verification factor ϵ= 0.0010				

Table 12

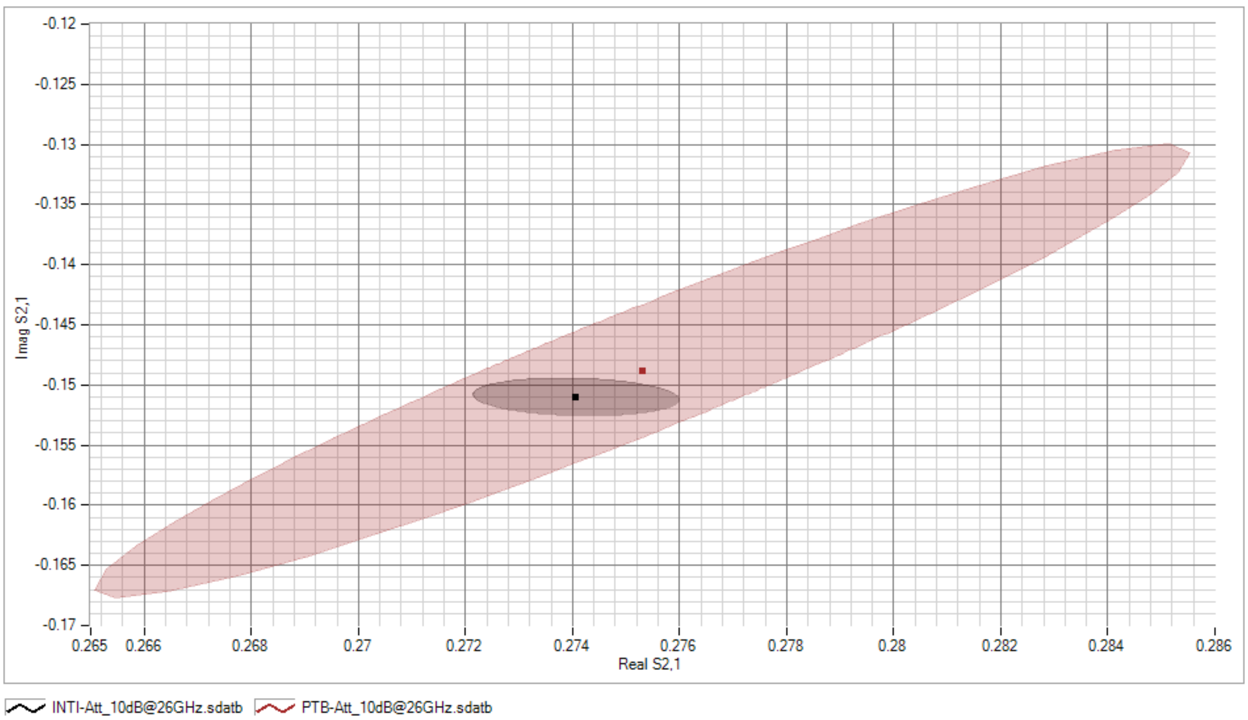

Figure 12: 95% confidence uncertainty region - 10 dB attenuator @26GHz

NMI	Measurement and combined standard uncertainty S_{21} - 10 dB Attenuator @32 GHz				
	$Re(S_{21})$	$u(Re(S_{21}))$ combined 1-sigma	$Im(S_{21})$	$u(Im(S_{21}))$ combined 1-sigma	$r(x,y)$
INTI	0.15715	0.00095	0.2817	0.0015	0.47
PTB	0.1561	0.0079	0.2827	0.0045	-0.96
	Verification factor ϵ= 0.0009				

Table 13

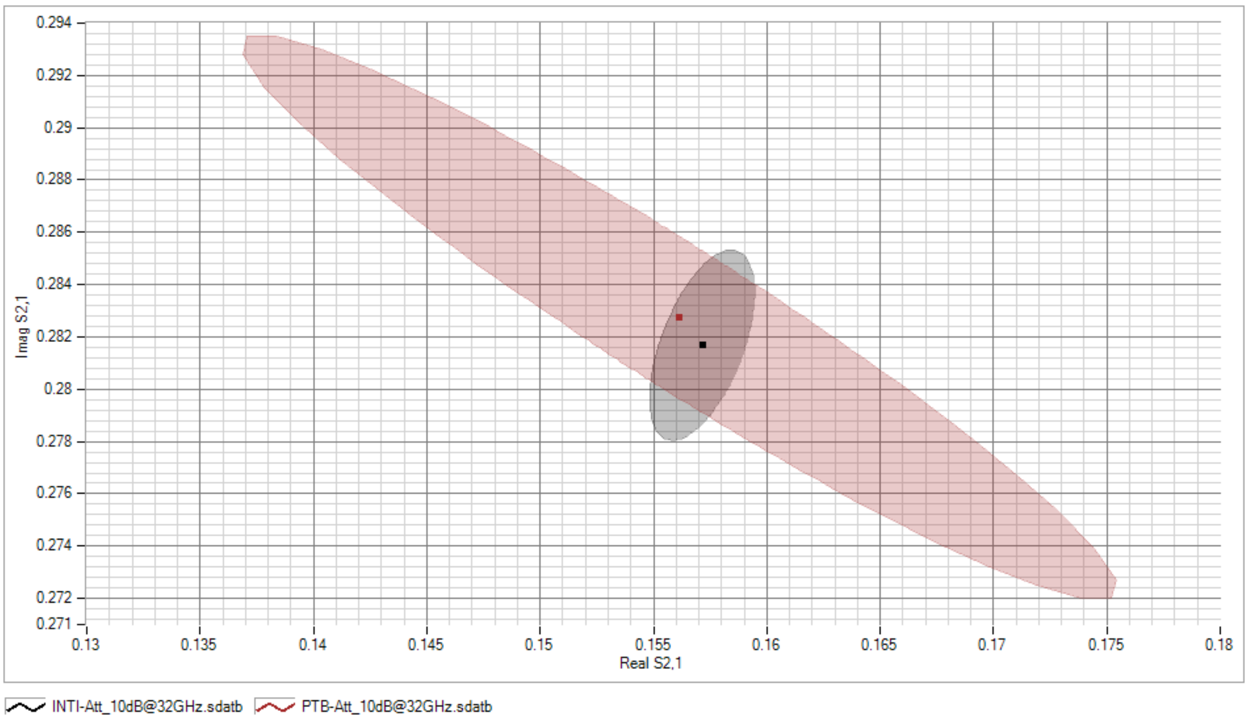

Figure 13: 95% confidence uncertainty region - 10 dB attenuator @32GHz

A.3 30 dB Attenuator

NMI	Measurement and combined standard uncertainty S_{21} - 30 dB Attenuator @2 GHz				
	$Re(S_{21})$	$u(Re(S_{21}))$ combined 1-sigma	$Im(S_{21})$	$u(Im(S_{21}))$ combined 1-sigma	$r(x, y)$
INTI	0.0000822	0.0000092	-0.031335	0.000056	-0.078
PTB	0.00008	0.00088	-0.03139	0.00011	0.018
	Verification factor ϵ= 0.00004				

Table 14

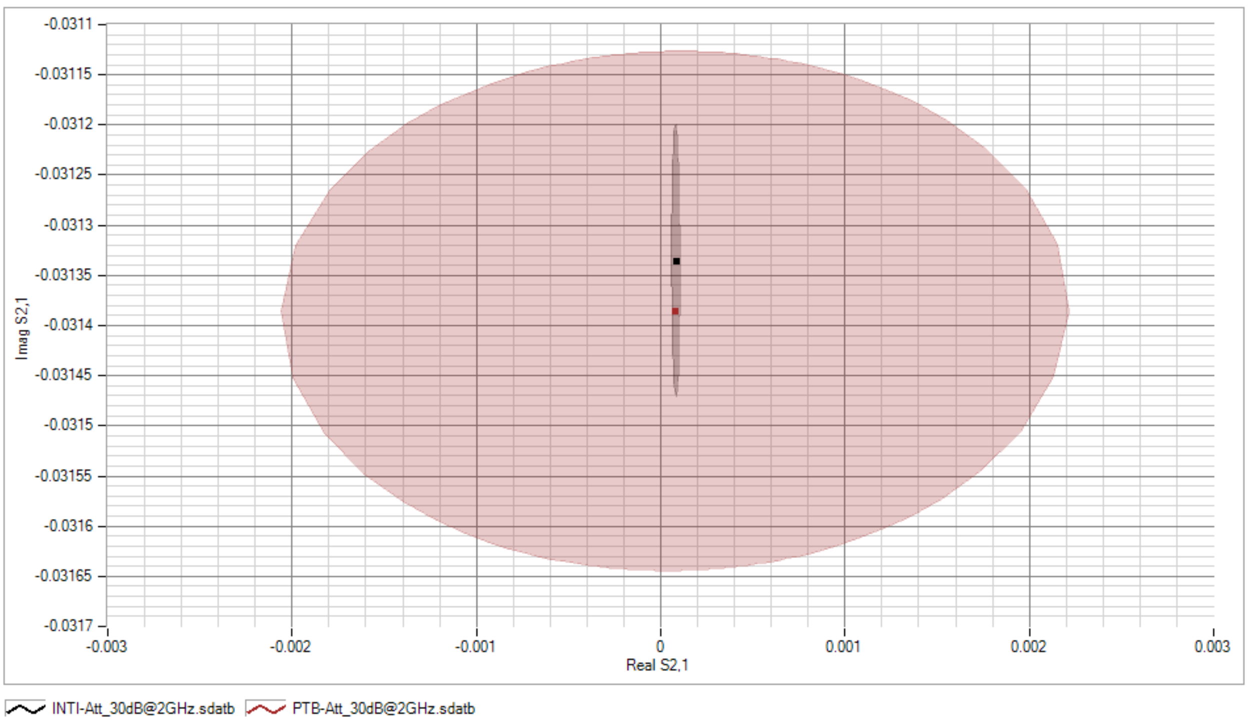

Figure 14: 95% confidence uncertainty region - 30 dB attenuator @2GHz

NMI	Measurement and combined standard uncertainty S_{21} - 30 dB Attenuator @9 GHz				
	$Re(S_{21})$	$u(Re(S_{21}))$ combined 1-sigma	$Im(S_{21})$	$u(Im(S_{21}))$ combined 1-sigma	$r(x,y)$
INTI	0.022104	0.000049	-0.021397	0.000044	-0.68
PTB	0.02220	0.00060	-0.02134	0.00063	0.97
	Verification factor ϵ= 0.00008				

Table 15

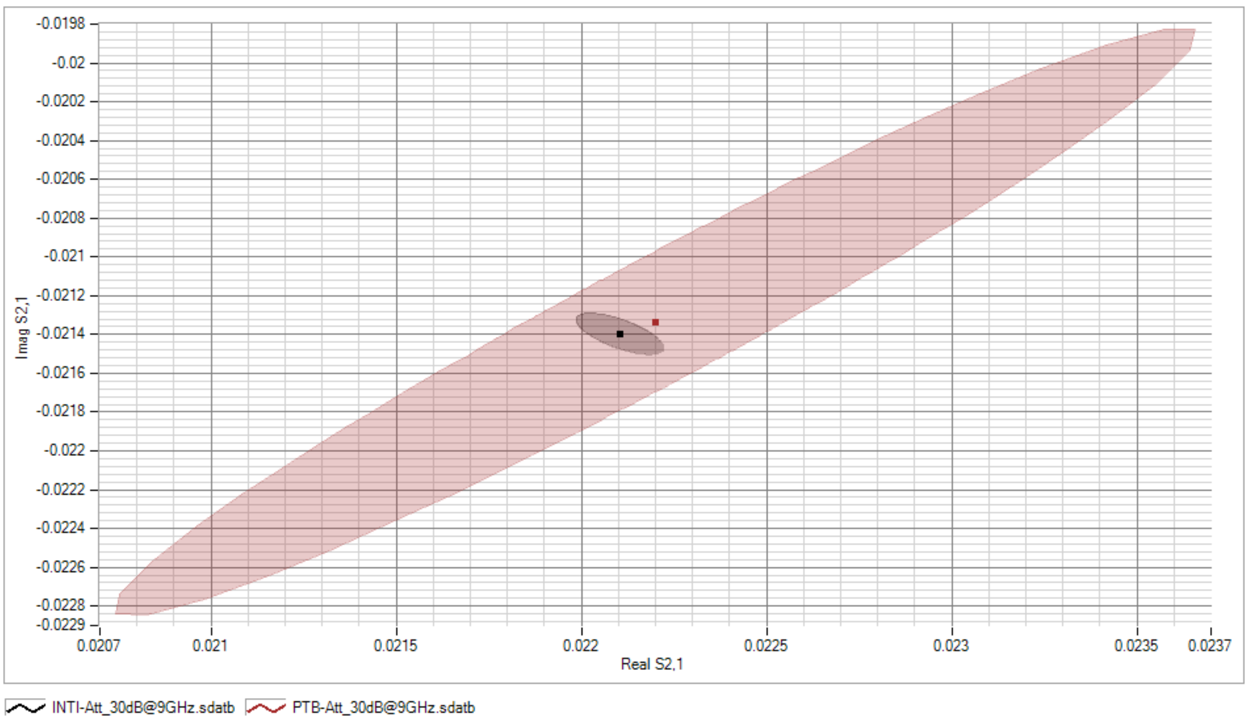

Figure 15: 95% confidence uncertainty region - 30 dB attenuator @9GHz

NMI	Measurement and combined standard uncertainty S_{21} - 30 dB Attenuator @18 GHz				
	$Re(S_{21})$	$u(Re(S_{21}))$ combined 1-sigma	$Im(S_{21})$	$u(Im(S_{21}))$ combined 1-sigma	$r(x,y)$
INTI	-0.000023	0.000059	-0.029861	0.000069	-0.14
PTB	0.00024	0.00084	-0.02989	0.00011	0.07
	Verification factor ϵ= 0.0002				

Table 16

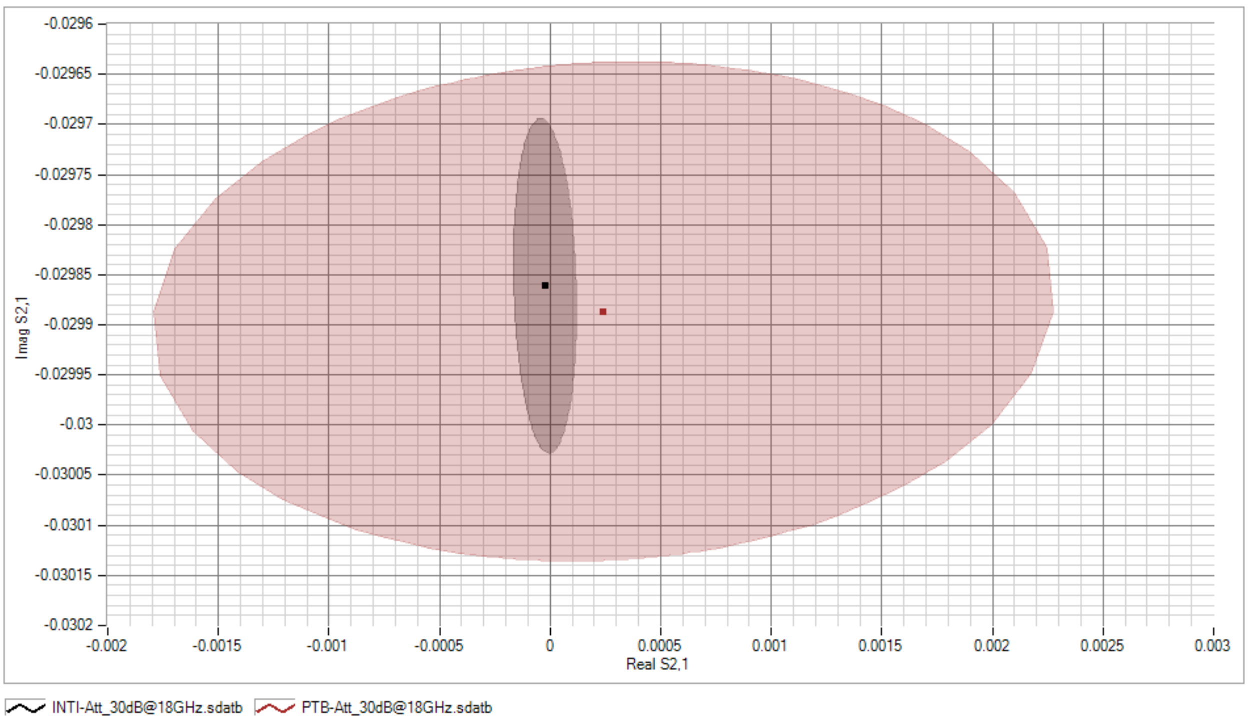

Figure 16: 95% confidence uncertainty region - 30 dB attenuator @18GHz

NMI	Measurement and combined standard uncertainty S_{21} - 30 dB Attenuator @26 GHz				
	$Re(S_{21})$	$u(Re(S_{21}))$ combined 1-sigma	$Im(S_{21})$	$u(Im(S_{21}))$ combined 1-sigma	$r(x,y)$
INTI	-0.004496	0.000094	-0.030499	0.000093	0.072
PTB	-0.00408	0.00086	-0.03054	0.00016	-0.68
	Verification factor ϵ= 0.0001				

Table 17

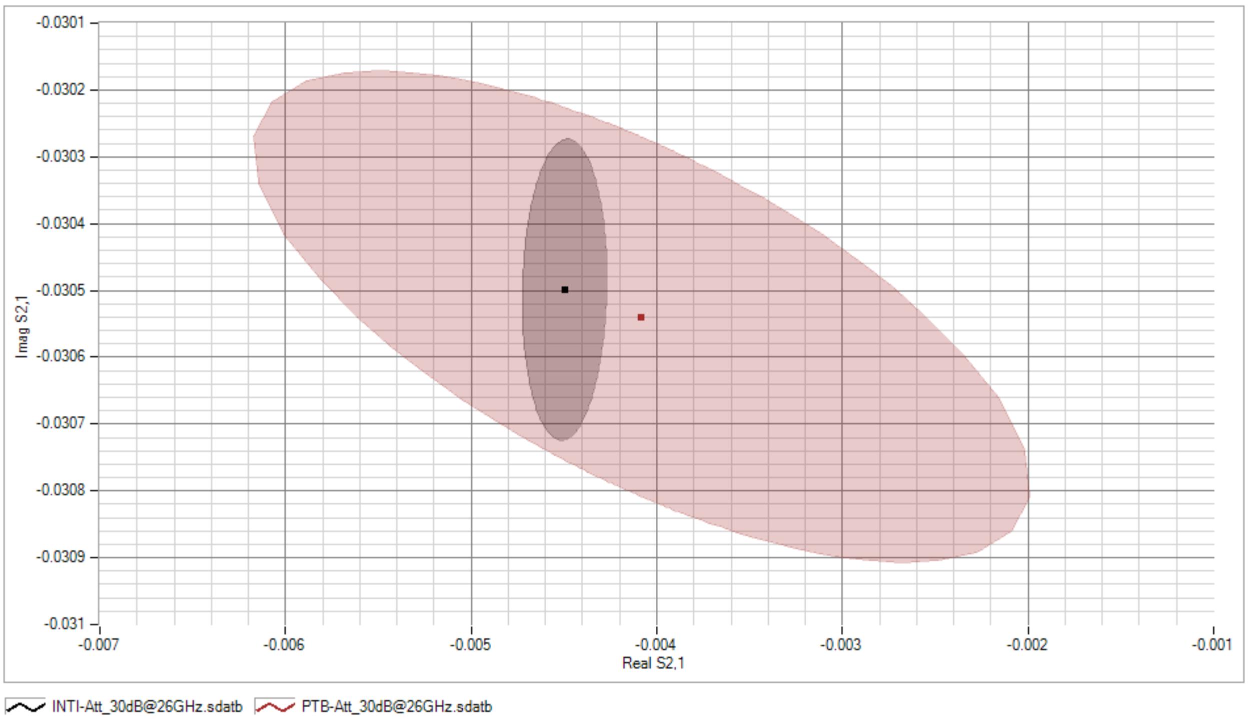

Figure 17: 95% confidence uncertainty region - 30 dB attenuator @26GHz

NMI	Measurement and combined standard uncertainty S_{21} - 30 dB Attenuator @32 GHz				
	$Re(S_{21})$	$u(Re(S_{21}))$ combined 1-sigma	$Im(S_{21})$	$u(Im(S_{21}))$ combined 1-sigma	$r(x,y)$
INTI	0.02968	0.00017	-0.01764	0.00015	-0.57
PTB	0.02988	0.00050	-0.01734	0.00084	0.96
	Verification factor ϵ= 0.22				

Table 18

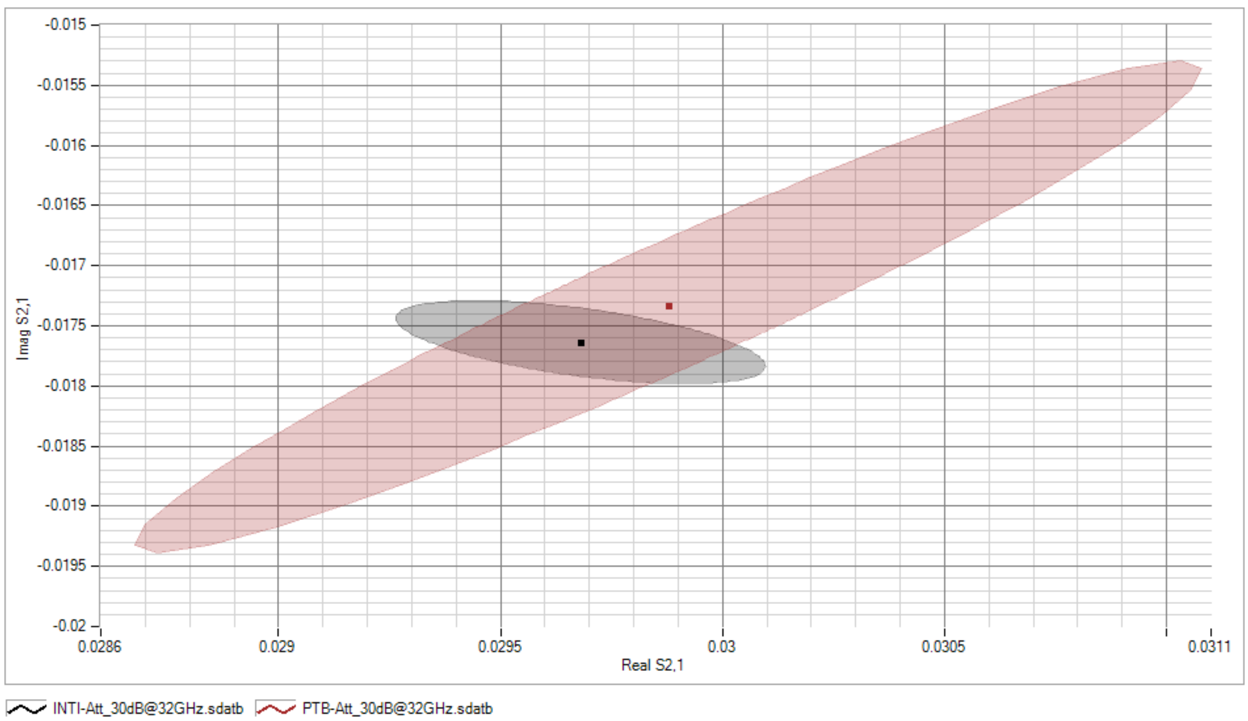

Figure 18: 95% confidence uncertainty region - 30 dB attenuator @32GHz

Annex B: Uncertainty Budgets

Following are the uncertainty budgets including only the relevant sources of uncertainty for each particular measurement.

B.1 INTI Uncertainty Budgets

B.1.1 Reflection Measurements

Quantity	Uncertainty contribution	Percentage %
Calibration Standards	0.0025	99.9
	u_{total}	0.0026

Uncertainty budget INTI. Matched load $Re(S_{11})$ @2 GHz

Quantity	Uncertainty contribution	Percentage %
Calibration Standards	0.0025	99.9
	u_{total}	0.0026

Uncertainty budget INTI. Matched load $Im(S_{11})$ @2 GHz

Quantity	Uncertainty contribution	Percentage %
Calibration Standards	0.0032	98
Connector Repeatability	0.00032	1
Type-A Repeatability	0.00024	1
	u_{total}	0.0032

Uncertainty budget INTI. Matched load $Re(S_{11})$ @9 GHz

Quantity	Uncertainty contribution	Percentage %
Calibration Standards	0.0032	99
Connector Repeatability	0.0020	1
	u_{total}	0.0032

Uncertainty budget INTI. Matched load $Im(S_{11})$ @9 GHz

Quantity	Uncertainty contribution	Percentage %
Calibration Standards	0.0032	98
Connector Repeatability	0.00032	1
	u_{total}	0.0032

Uncertainty budget INTI. Matched load $Re(S_{11})$ @18 GHz

Quantity	Uncertainty contribution	Percentage %
Calibration Standards	0.0032	98
Connector Repeatability	0.00032	1
Type-A Repeatability	0.00027	1
	u_{total}	0.0032

Uncertainty budget INTI. Matched load $Im(S_{11})$ @18 GHz

Quantity	Uncertainty contribution	Percentage %
Calibration Standards	0.0032	94
Connector Repeatability	0.00050	2
VNA Linearity	0.00049	2
VNA Drift	0.00032	1
	u_{total}	0.0033

Uncertainty budget INTI. Matched load $Re(S_{11})$ @26 GHz

Quantity	Uncertainty contribution	Percentage %
Calibration Standards	0.0032	94
Connector Repeatability	0.00050	2
Type-A Repeatability	0.00037	1
VNA Drift	0.00032	1
VNA Noise	0.00025	1
	u_{total}	0.0033

Uncertainty budget INTI. Matched load $Im(S_{11})$ @26 GHz

Quantity	Uncertainty contribution	Percentage %
Calibration Standards	0.0050	95
Connector Repeatability	0.0010	4
VNA Drift	0.00058	1
	u_{total}	0.0052

Uncertainty budget INTI. Matched load $Re(S_{11})$ @32 GHz

Quantity	Uncertainty contribution	Percentage %
Calibration Standards	0.0050	95
Connector Repeatability	0.0010	4
VNA Drift	0.00058	1
	u_{total}	0.0052

Uncertainty budget INTI. Matched load $Im(S_{11})$ @32 GHz

B.1.2 Transmission Measurements

B.1.2.1 10 dB Attenuator

Quantity	Uncertainty contribution	Percentage %
VNA Noise	0.000062	47
Type-A Repeatability	0.000046	25
VNA Linearity	0.000043	22
VNA Drift	0.000019	5
	u_{total}	0.00010

Uncertainty budget INTI. 10 dB attenuator $Re(S_{21})$ @2 GHz

Quantity	Uncertainty contribution	Percentage %
VNA Linearity	0.00043	70
VNA Drift	0.00021	16
VNA Noise	0.00016	9
Cable Stability	0.000091	3
	u_{total}	0.00052

Uncertainty budget INTI. 10 dB attenuator $Im(S_{21})$ @2 GHz

Quantity	Uncertainty contribution	Percentage %
VNA Linearity	0.00035	55
VNA Drift	0.00019	16
Cable Stability	0.00017	13
VNA Noise	0.00015	9
Type-A Repeatability	0.00013	7
	u_{total}	0.00048

Uncertainty budget INTI. 10 dB attenuator $Re(S_{21})$ @9 GHz

Quantity	Uncertainty contribution	Percentage %
Type-A Repeatability	0.00017	50
VNA Linearity	0.00013	28
VNA Drift	0.000072	8
VNA Noise	0.000065	7
Cable Stability	0.000063	7
	u_{total}	0.00025

Uncertainty budget INTI. 10 dB attenuator $Im(S_{21})$ @9 GHz

Quantity	Uncertainty contribution	Percentage %
Type-A Repeatability	0.00034	35
VNA Linearity	0.00032	32
VNA Drift	0.00022	15
VNA Noise	0.00018	10
Cable Stability	0.00016	8
	u_{total}	0.00057

Uncertainty budget INTI. 10 dB attenuator $Re(S_{21})$ @18 GHz

Quantity	Uncertainty contribution	Percentage %
VNA Linearity	0.00030	35
Type-A Repeatability	0.00027	28
VNA Drift	0.00021	17
VNA Noise	0.00017	11
Cable Stability	0.00015	9
	u_{total}	0.00051

Uncertainty budget INTI. 10 dB attenuator $Im(S_{21})$ @18 GHz

Quantity	Uncertainty contribution	Percentage %
VNA Linearity	0.00038	24
Type-A Repeatability	0.00038	24
VNA Noise	0.00037	22
VNA Drift	0.00036	21
Cable Stability	0.00024	9
	u_{total}	0.00079

Uncertainty budget INTI. 10 dB attenuator $Re(S_{21})$ @26 GHz

Quantity	Uncertainty contribution	Percentage %
Type-A Repeatability	0.00050	61
VNA Noise	0.00024	14
VNA Linearity	0.00021	11
VNA Drift	0.00020	10
Cable Stability	0.00013	4
	u_{total}	0.00065

Uncertainty budget INTI. 10 dB attenuator $Im(S_{21})$ @26 GHz

Quantity	Uncertainty contribution	Percentage %
Cable Stability	0.00064	46
Type-A Repeatability	0.00048	26
VNA Noise	0.00036	15
VNA Drift	0.00026	8
VNA Linearity	0.00022	5
	u_{total}	0.00095

Uncertainty budget INTI. 10 dB attenuator $Re(S_{21})$ @32 GHz

Quantity	Uncertainty contribution	Percentage %
Cable Stability	0.0011	58
Type-A Repeatability	0.00054	13
VNA Noise	0.00051	12
VNA Drift	0.00046	10
VNA Linearity	0.00041	7
	u_{total}	0.0015

Uncertainty budget INTI. 10 dB attenuator $Im(S_{21})$ @32 GHz

B.1.2.2 30 dB Attenuator

Quantity	Uncertainty contribution	Percentage %
Type-A Repeatability	0.0000069	56
VNA Noise	0.0000060	42
VNA Linearity	0.0000010	1
	u_{total}	0.0000092

Uncertainty budget INTI. 30 dB attenuator $Re(S_{21})$ @2 GHz

Quantity	Uncertainty contribution	Percentage %
VNA Linearity	0.000042	58
VNA Drift	0.000030	30
VNA Noise	0.000016	8
Cable Stability	0.0000091	3
Type-A Repeatability	0.0000069	1
	u_{total}	0.000056

Uncertainty budget INTI. 30 dB attenuator $Im(S_{21})$ @2 GHz

Quantity	Uncertainty contribution	Percentage %
VNA Linearity	0.000032	45
Type-A Repeatability	0.000023	23
VNA Drift	0.000021	20
Cable Stability	0.000013	7
VNA Noise	0.000011	5
	u_{total}	0.000049

Uncertainty budget INTI. 30 dB attenuator $Re(S_{21})$ @9 GHz

Quantity	Uncertainty contribution	Percentage %
VNA Linearity	0.000031	52
VNA Drift	0.000021	23
Type-A Repeatability	0.000014	11
Cable Stability	0.000012	8
VNA Noise	0.000011	6
	u_{total}	0.000044

Uncertainty budget INTI. 30 dB attenuator $Im(S_{21})$ @9 GHz

Quantity	Uncertainty contribution	Percentage %
Type-A Repeatability	0.000057	96
VNA Noise	0.000012	4
	u_{total}	0.000059

Uncertainty budget INTI. 30 dB attenuator $Re(S_{21})$ @18 GHz

Quantity	Uncertainty contribution	Percentage %
VNA Drift	0.000043	41
VNA Linearity	0.000040	34
Cable Stability	0.000022	10
VNA Noise	0.000021	9
Type-A Repeatability	0.000016	6
	u_{total}	0.000069

Uncertainty budget INTI. 30 dB attenuator $Im(S_{21})$ @18 GHz

Quantity	Uncertainty contribution	Percentage %
Type-A Repeatability	0.000091	95
VNA Noise	0.000017	3
VNA Drift	0.0000090	1
	u_{total}	0.000094

Uncertainty budget INTI. 30 dB attenuator $Re(S_{21})$ @26 GHz

Quantity	Uncertainty contribution	Percentage %
VNA Drift	0.000059	41
VNA Noise	0.000040	19
VNA Linearity	0.000039	18
Type-A Repeatability	0.000034	13
Cable Stability	0.000026	8
	u_{total}	0.000093

Uncertainty budget INTI. 30 dB attenuator $Im(S_{21})$ @26 GHz

Quantity	Uncertainty contribution	Percentage %
Cable Stability	0.00012	49
VNA Drift	0.000072	18
Type-A Repeatability	0.000072	18
VNA Noise	0.000054	10
VNA Linearity	0.000037	5
	u_{total}	0.00017

Uncertainty budget INTI. 30 dB attenuator $Re(S_{21})$ @32 GHz

Quantity	Uncertainty contribution	Percentage %
Cable Stability	0.000071	26
Type-A Repeatability	0.00010	55
VNA Drift	0.000043	9
VNA Noise	0.000039	8
VNA Linearity	0.000022	2
	u_{total}	0.00015

Uncertainty budget INTI. 30 dB attenuator $Im(S_{21})$ @32 GHz

B.2 PTB Uncertainty Budgets

B.2.1 Reflection Measurements

Quantity	Uncertainty contribution	Percentage %
Cable Stability	0.0014	66
Calibration Standards	0.0010	33
	u_{total}	0.0018

Uncertainty budget PTB. Matched load $Re(S_{11})$ @2 GHz

Quantity	Uncertainty contribution	Percentage %
Cable Stability	0.0014	66
Calibration Standards	0.0010	33
	u_{total}	0.0018

Uncertainty budget PTB. Matched load $Im(S_{11})$ @2 GHz

Quantity	Uncertainty contribution	Percentage %
Cable Stability	0.0014	62
Calibration Standards	0.0010	31
Connector Repeatability	0.00047	7
	u_{total}	0.0018

Uncertainty budget PTB. Matched load $Re(S_{11})$ @9 GHz

Quantity	Uncertainty contribution	Percentage %
Cable Stability	0.0014	62
Calibration Standards	0.0010	31
Connector Repeatability	0.00047	7
	u_{total}	0.0018

Uncertainty budget PTB. Matched load $Im(S_{11})$ @9 GHz

Quantity	Uncertainty contribution	Percentage %
Calibration Standards	0.0018	52
Cable Stability	0.0016	43
Connector Repeatability	0.00047	4
	u_{total}	0.0025

Uncertainty budget PTB. Matched load $Re(S_{11})$ @18 GHz

Quantity	Uncertainty contribution	Percentage %
Calibration Standards	0.0018	57
Cable Stability	0.0014	38
Connector Repeatability	0.00047	4
	u_{total}	0.0024

Uncertainty budget PTB. Matched load $Im(S_{11})$ @18 GHz

Quantity	Uncertainty contribution	Percentage %
Cable Stability	0.0024	61
Calibration Standards	0.0018	32
Connector Repeatability	0.00075	6
VNA Drift	0.00029	1
	u_{total}	0.0031

Uncertainty budget PTB. Matched load $Re(S_{11})$ @26 GHz

Quantity	Uncertainty contribution	Percentage %
Calibration Standards	0.0018	52
Cable Stability	0.0015	36
Connector Repeatability	0.00075	10
VNA Drift	0.00029	1
	u_{total}	0.0025

Uncertainty budget PTB. Matched load $Im(S_{11})$ @26 GHz

Quantity	Uncertainty contribution	Percentage %
Cable Stability	0.0042	76
Calibration Standards	0.0018	13
Connector Repeatability	0.0015	10
	u_{total}	0.0049

Uncertainty budget PTB. Matched load $Re(S_{11})$ @32 GHz

Quantity	Uncertainty contribution	Percentage %
Cable Stability	0.0019	39
Calibration Standards	0.0018	35
Connector Repeatability	0.0015	25
VNA Drift	0.00030	1
	u_{total}	0.0030

Uncertainty budget PTB. Matched load $Im(S_{11})$ @32 GHz

B.2.2 Transmission Measurements

B.2.2.1 10 dB Attenuator

Quantity	Uncertainty contribution	Percentage %
Cable Stability	0.0088	99.9
	u_{total}	0.0088

Uncertainty budget PTB. 10 dB attenuator $Re(S_{21})$ @2 GHz

Quantity	Uncertainty contribution	Percentage %
Cable Stability	0.0013	96
VNA Linearity	0.00026	4
	u_{total}	0.0014

Uncertainty budget PTB. 10 dB attenuator $Im(S_{21})$ @2 GHz

Quantity	Uncertainty contribution	Percentage %
Cable Stability	0.0032	99
VNA Linearity	0.00025	1
	u_{total}	0.0032

Uncertainty budget PTB. 10 dB attenuator $Re(S_{21})$ @9 GHz

Quantity	Uncertainty contribution	Percentage %
Cable Stability	0.0082	99.9
	u_{total}	0.0082

Uncertainty budget PTB. 10 dB attenuator $Im(S_{21})$ @9 GHz

Quantity	Uncertainty contribution	Percentage %
Cable Stability	0.0059	99.8
	u_{total}	0.0059

Uncertainty budget PTB. 10 dB attenuator $Re(S_{21})$ @18 GHz

Quantity	Uncertainty contribution	Percentage %
Cable Stability	0.0064	99.8
	u_{total}	0.0064

Uncertainty budget PTB. 10 dB attenuator $Im(S_{21})$ @18 GHz

Quantity	Uncertainty contribution	Percentage %
Cable Stability	0.0042	99.4
	u_{total}	0.0042

Uncertainty budget PTB. 10 dB attenuator $Re(S_{21})$ @26 GHz

Quantity	Uncertainty contribution	Percentage %
Cable Stability	0.0064	99.8
	u_{total}	0.00065

Uncertainty budget PTB. 10 dB attenuator $Im(S_{21})$ @26 GHz

Quantity	Uncertainty contribution	Percentage %
Cable Stability	0.0079	99.8
	u_{total}	0.0079

Uncertainty budget PTB. 10 dB attenuator $Re(S_{21})$ @32 GHz

Quantity	Uncertainty contribution	Percentage %
Cable Stability	0.0044	99.4
	u_{total}	0.0045

Uncertainty budget PTB. 10 dB attenuator $Im(S_{21})$ @32 GHz

B.2.2.2 30 dB Attenuator

Quantity	Uncertainty contribution	Percentage %
Cable Stability	0.00087	99.9
	u_{total}	0.00088

Uncertainty budget PTB. 30 dB attenuator $Re(S_{21})$ @2 GHz

Quantity	Uncertainty contribution	Percentage %
Cable Stability	0.00010	94
VNA Linearity	0.000026	6
	u_{total}	0.00011

Uncertainty budget PTB. 30 dB attenuator $Im(S_{21})$ @2 GHz

Quantity	Uncertainty contribution	Percentage %
Cable Stability	0.00060	99.8
	u_{total}	0.00060

Uncertainty budget PTB. 30 dB attenuator $Re(S_{21})$ @9 GHz

Quantity	Uncertainty contribution	Percentage %
Cable Stability	0.00062	99.8
	u_{total}	0.00063

Uncertainty budget PTB. 30 dB attenuator $Im(S_{21})$ @9 GHz

Quantity	Uncertainty contribution	Percentage %
Cable Stability	0.00083	99.9
	u_{total}	0.00084

Uncertainty budget PTB. 30 dB attenuator $Re(S_{21})$ @18 GHz

Quantity	Uncertainty contribution	Percentage %
Cable Stability	0.000098	93
VNA Linearity	0.000024	6
Calibration Standards	0.000010	1
	u_{total}	0.00011

Uncertainty budget PTB. 30 dB attenuator $Im(S_{21})$ @18 GHz

Quantity	Uncertainty contribution	Percentage %
Cable Stability	0.00085	99.8
	u_{total}	0.00086

Uncertainty budget PTB. 30 dB attenuator $Re(S_{21})$ @26 GHz

Quantity	Uncertainty contribution	Percentage %
Cable Stability	0.00015	94
Calibration Standards	0.000022	2
VNA Linearity	0.000025	3
	u_{total}	0.00016

Uncertainty budget PTB. 30 dB attenuator $Im(S_{21})$ @26 GHz

Quantity	Uncertainty contribution	Percentage %
Cable Stability	0.00049	99.4
	u_{total}	0.00050

Uncertainty budget PTB. 30 dB attenuator $Re(S_{21})$ @32 GHz

Quantity	Uncertainty contribution	Percentage %
Cable Stability	0.00083	99.8
	u_{total}	0.00084

Uncertainty budget PTB. 30 dB attenuator $Im(S_{21})$ @32 GHz

Annex C: Participants Reports

C.1 INTI Report

Description of the measurement method

The measurements were performed using a Vector Network Analyzer calibrated with a 3.5 mm connector calibration kit Agilent 85052C.

Two-port devices were measured using a TRL method and its variants depending on the frequency range. Reported results are obtained as the mean of twelve measurements.

One-port devices were measured using an OSM method using databased defined standards and four mesurements for each 90° spaced connector position. The OSM traceability approach was implemented according to [7], which is based on the ripple method over a TRL calibration for the standards definition and on a rigourous method thereafter.

Uncertainty and traceability

Both methods have traceability to dimensional quantities by means of 50 ohm coaxial air-dielectric lines.

C.2 PTB Report

Description of the measurement method

To determine the S-parameters, the device under test (DUT) was connected to a vector network analyser (VNA), calibrated with national standards traceable to characterised beadless air-dielectric lines.

The uncertainty is calculated with the Metas VNA Tools II.

Annex D: Mechanical Pin Depth Measurements

The following tables shows reported values of pin depth in the order they were measured.

10 dB Attenuator	Pin depth [µm] Male port	Pin depth [µm] Female port
INTI (1st measurement)	10.2	40.6
PTB	10	41
INTI (2nd measurement)	10.2	40.6

Table 19: *Pin depth measurements - 10 dB attenuator*

30 dB Attenuator	Pin depth [µm] Male port	Pin depth [µm] Female port
INTI (1st measurement)	50	39
PTB	51	38
INTI (2nd measurement)	50	39

Table 20: *Pin depth measurements - 30 dB attenuator*

Matched Load	Pin depth [µm]
INTI (1st measurement)	11
PTB	10
INTI (2nd measurement)	11

Table 21: *Pin depth measurements - Matched load*

Mismatched Load	Pin depth [µm]
INTI (1st measurement)	8
PTB	10
INTI (2nd measurement)	8

Table 22: *Pin depth measurements - Mismatched load*

Annex E: Electrical Stability of Standards

The following figure show the measurement of the mismatched load made by the pilot laboratory, normalized to the mean value of the measurements obtained at the beginning and at the final control measurement across the entire frequency band.

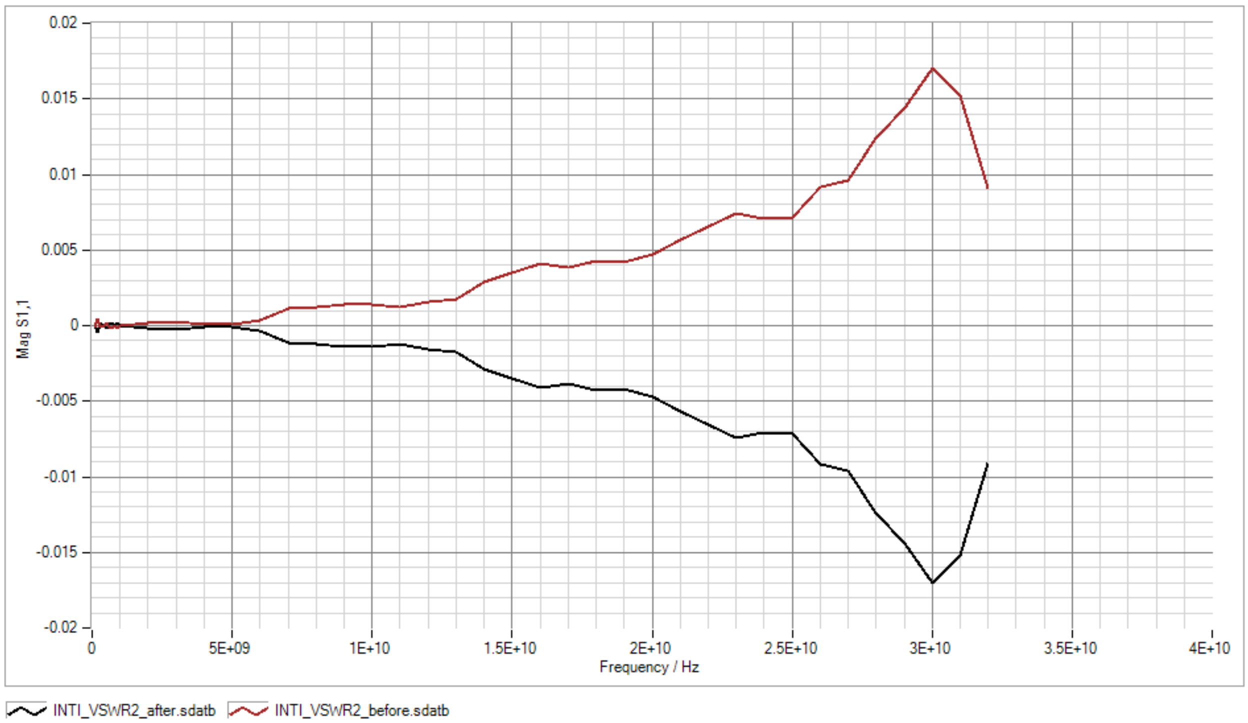

Figure 19: *Mismatched load drift. Magnitude normalized to its mean value with 100 MHz steps*