Improved, user-friendly RF&MW calibration techniques for calibration laboratories and production environments.

Reducing calibration time & uncertainties by using known, characterized standards.

Harald Jaeger

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75 Years of Driving Innovation

ROHDE&SCHWARZ

Global Service Network

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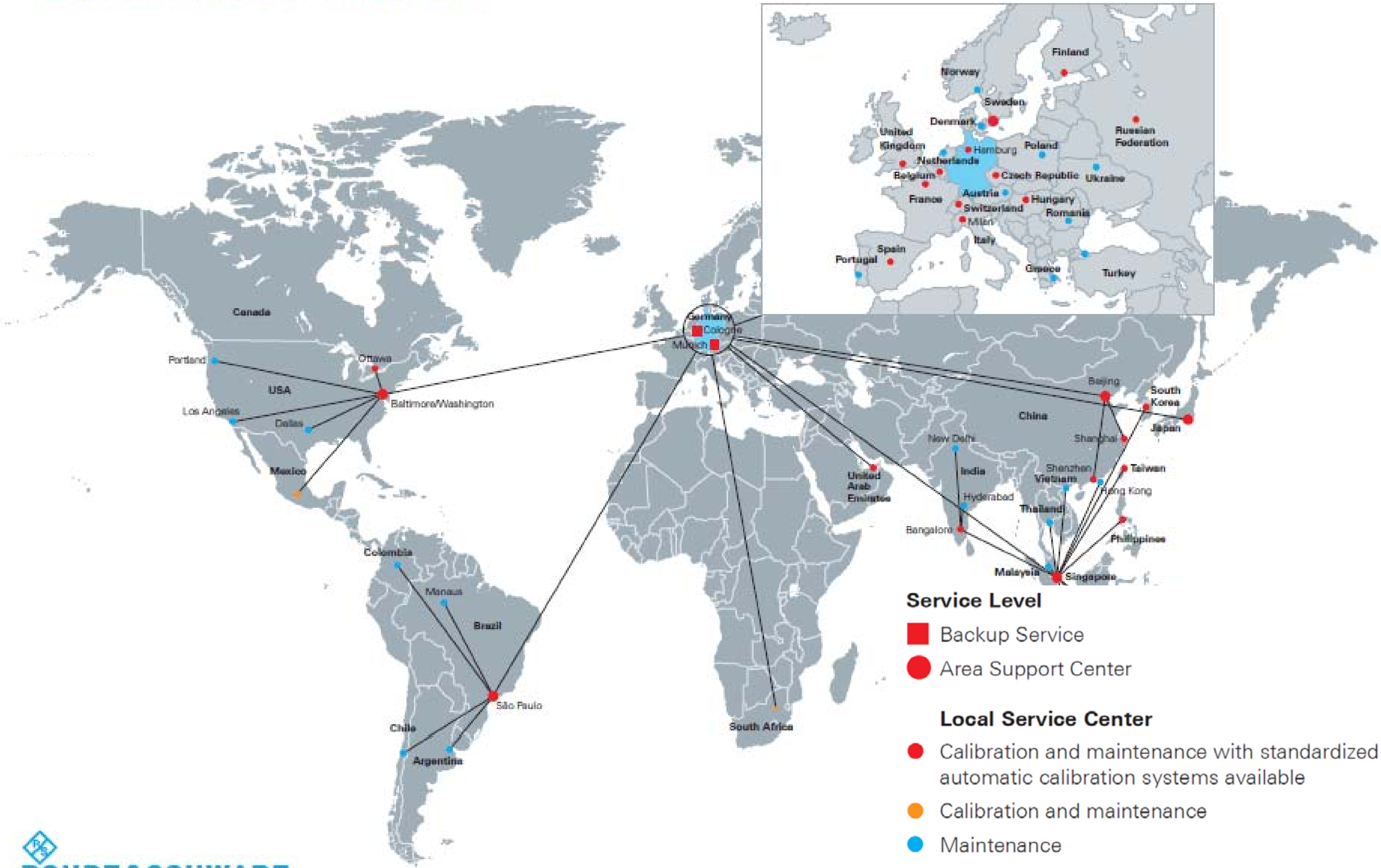
Global Service Network



Service Level

- Backup Service
- Area Support Center

Local Service Center

- Calibration and maintenance with standardized automatic calibration systems available
- Calibration and maintenance
- Maintenance

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India
United Arab Emirates
Hyderabad
Bangalore
Thailand
Malaysia
Vietna

Motivation

- **With frequencies getting higher - and specifications to be met getting tighter it's time to rethink some measurement procedures.**

- **When it comes to the MW frequency range circuit dimensions are getting smaller and smaller - and components very sensitive and expensive.**

- **Also, matching of the individual components involved (UUT as well as the standards used) is "very limited" - and there's usually not much choices ...**

Motivation

- **When it comes to calibration in the MW frequency range high levels of accuracy often go along with**
  - cumbersome, time consuming procedures
  - very sensitive calibration standards (e.g. air-lines)
  - very expensive equipment / calibration standards

- **These are some of the reasons why (too) often less accurate procedures are prefered**
  - to „save“ some money
  - to preserve the costly reference standards in the lab

Motivation

- **However, reducing measurement uncertainty directly improves the throughput in production and/or calibration labs.**

- **We‘re wasting valuable accuracy if appropriate measures are not taken. Or – in other words – we can gain margin for our UUT.**

- **The easier the handling of the instruments involved**
  - the less faults will occur
  - the higher the chance of a good repeatability.
  - the higher the chance nothing is damaged while performing the measurements.

Goals

- **Proposing calibration / measurement solutions, suitable for daily work in calibration laboratories and in production environments.**

- **Focus is on feasibility, accuracy and costs.**

Agenda

- **RF & MW Power Measurement**
  - Expanding the power measurement range of R&S NRP-Zxx power sensors
  - NRP-Z27/37 – Power Sensor modules for R&S FSMR Measurement Receiver
- **Vector Network Analysis**
  - Improving measurement accuracy by means of characterized calibration standards.
  - Using previous calibration results to improve accuracy.
  - User characterization of R&S ZV-Z5x automatic calibration units

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Expand your possibilites!
Power measurement

- **It's common practice to extend the measurement (i.e. level) range of power sensors using additional attenuators or directional couplers.**

- **It's also common practice to adapt "given" power sensors to different connector systems / genders or impedances using adapters and/or matching pads.**

- **These adapters / attenuators are usually either**
  - considered as "not significant"
  - considered as an additional uncertainty contributor only
  - considered "scalar" (insertion-loss) only
  - considered "scalar" (insertion-loss & mismatch error) only

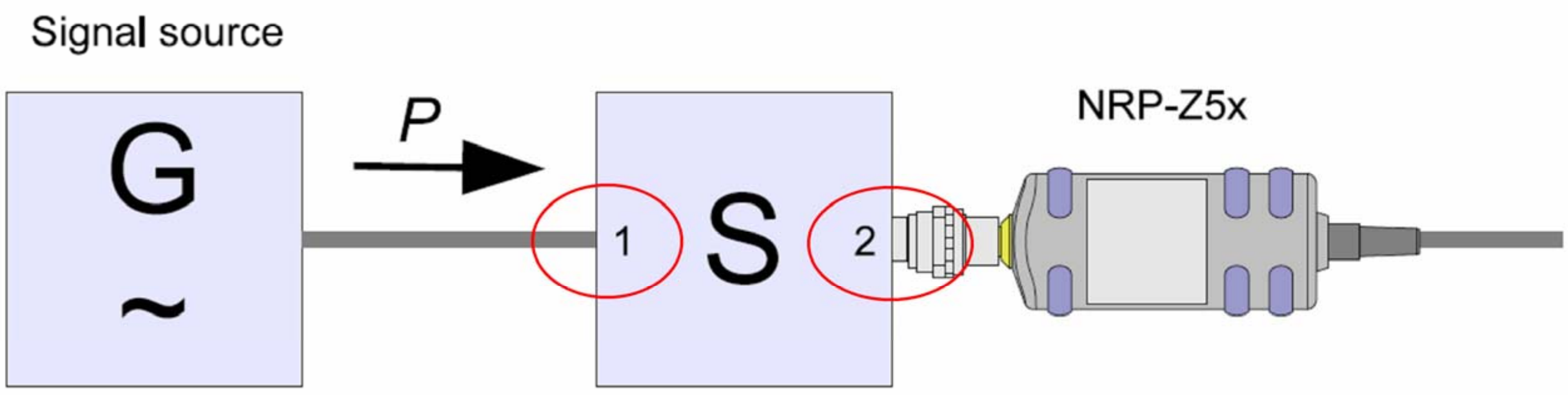
Expand your possibilites!
Power measurement

- **With frequencies getting higher e.g. the errors due to mismatch alone can easily reach orders of some % resp. some 0.1 dB.**

- **Modern Vector Network Analyzers also support measuring**
  - DUTs with different impedances (e.g. matching pads)
  - DUTs with different connectors systems (e.g. adapters)

- **However – it’s still a challenge to implement proper mathematical measures to correct for the systematic errors due to the “black box” between the power – sensor and the DUT.**

Expand your possibilites!
Error due to mismatch



Expand your possibilites!
Error due to mismatch

P_i	Incident power
P_{GZ0}	Power delivered to Z_0 load

The relationship between P_i and P_{GZ0} can be exactly described as:

$$P_i = \frac{P_{GZ0}}{\left|1 - \Gamma_G \Gamma_L\right|^2}$$

Consequently the limits of P_i are:

$$\frac{P_{GZ0}}{\left(1 + |\Gamma_G||\Gamma_L|\right)^2} \le P_i \le \frac{P_{GZ0}}{\left(1 - |\Gamma_G||\Gamma_L|\right)^2}$$

Expand your possibilites!
Error due to mismatch

- **The maximum relative error due to mismatch can be determined by way of approximation:**

$$\varepsilon_{\mathrm{m},\%} \approx 200\% \cdot r_G \cdot r_L \qquad \varepsilon_{\mathrm{m,dB}} \approx 8.7dB \cdot r_G \cdot r_L$$

- **Example $|\Gamma_G|$=0.1, $|\Gamma_L|$=0.1 :**

$$\varepsilon_{\mathrm{m},\%} \approx 200\% \cdot 0.1 \cdot 0.1 \approx 2\%$$

$$\varepsilon_{\mathrm{m,dB}} \approx 8.7dB \cdot 0.1 \cdot 0.1 \approx 0.087dB$$

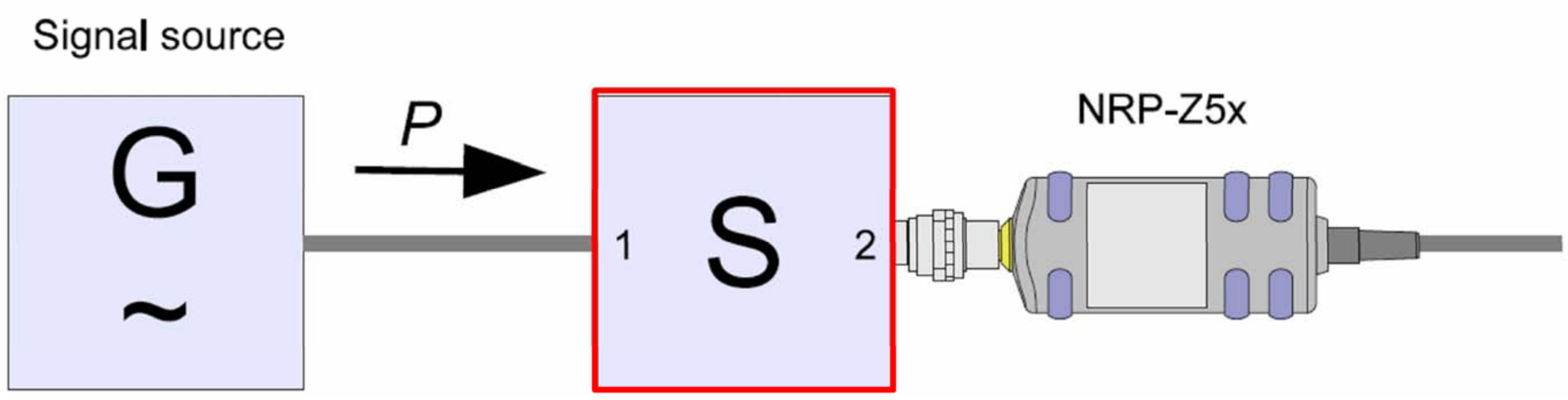
Expand your possibilites!
Power measurement

- **With the power sensor R&S NRP-Zxx, the influence of any twoport – e. g. an adapter – between the signal source and the sensor input can be considered, allowing the power P actually delivered by the signal source to be calculated.**

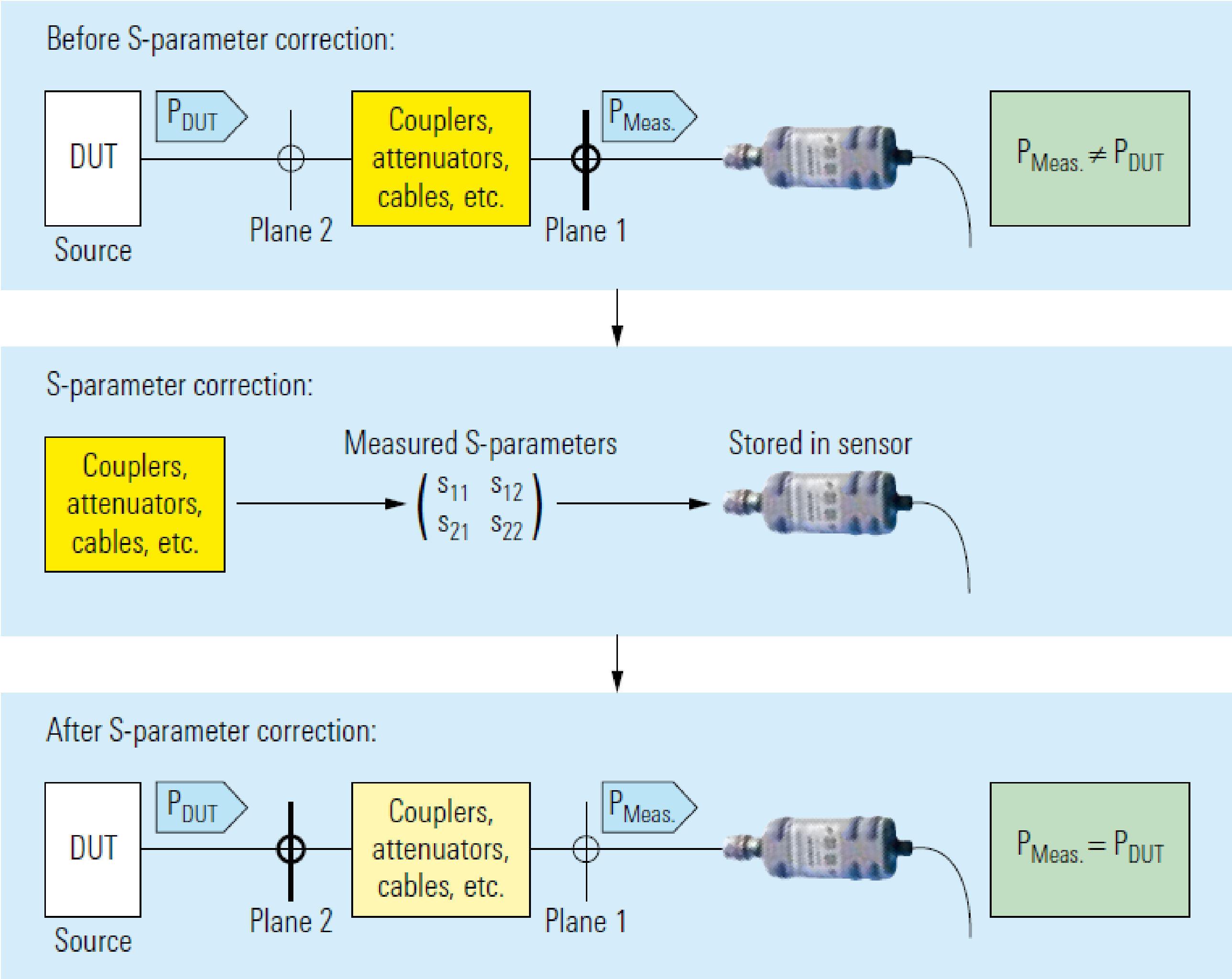
- **The twoport's S-parameters (in S2P / Touchstone format) can be uploaded onto the power sensor – and will be taken into consideration automatically.**

- **This feature does not only correct for the magnitude of the twoport's loss – but also corrects for the systematic error due to mismatch between the twoport and the power sensor.**

Expand your possibilites!
Power measurement

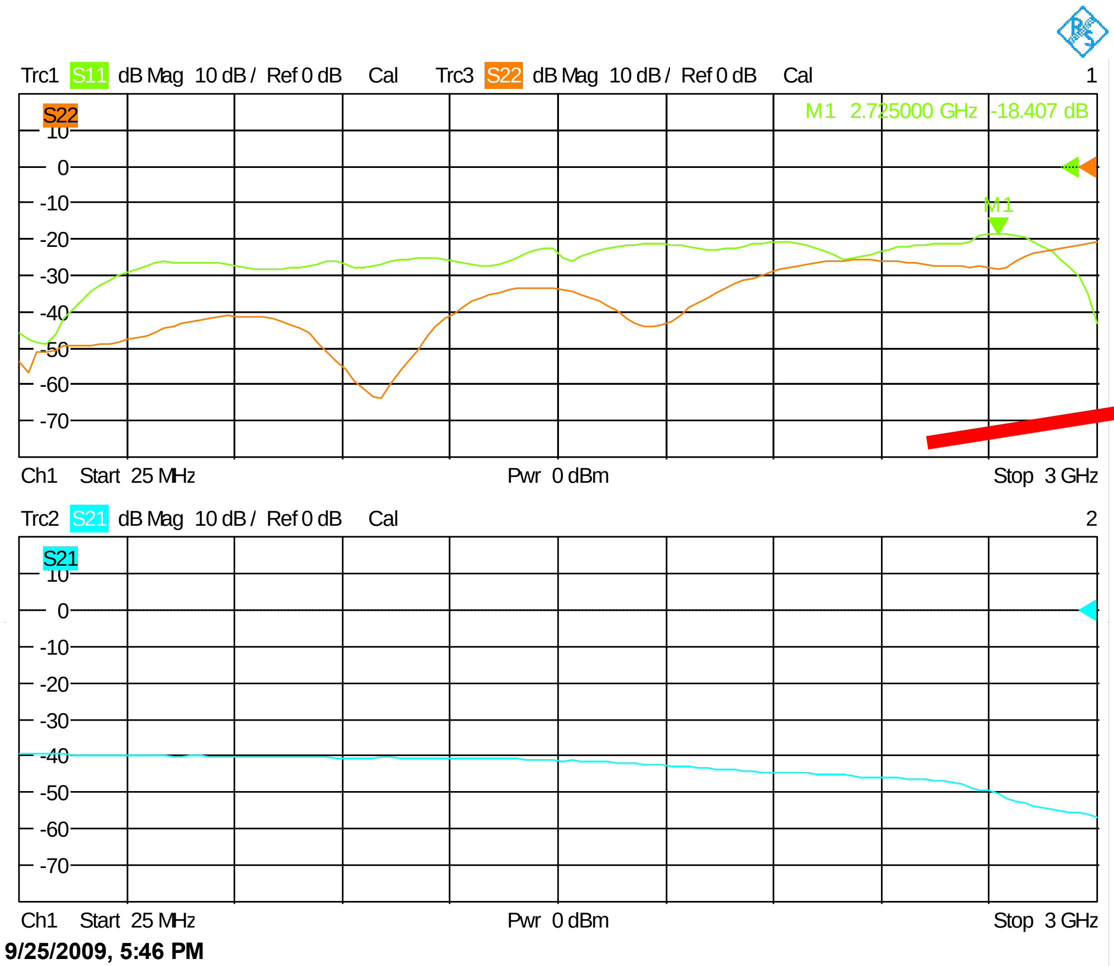


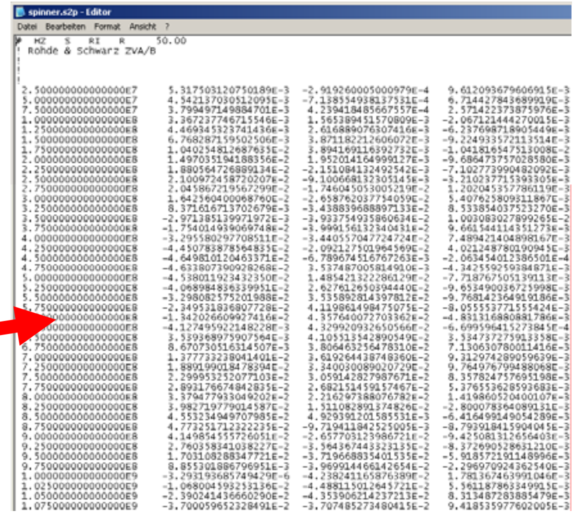
Expand your possibilites!



Expand your possibilites!

S-Parameters of adapter / attenuator …





spinner.s2p - Editor

Datei Bearbeiten Format Ansicht ?

HZ S RI R 50.00
! Rohde & Schwarz ZVA/B
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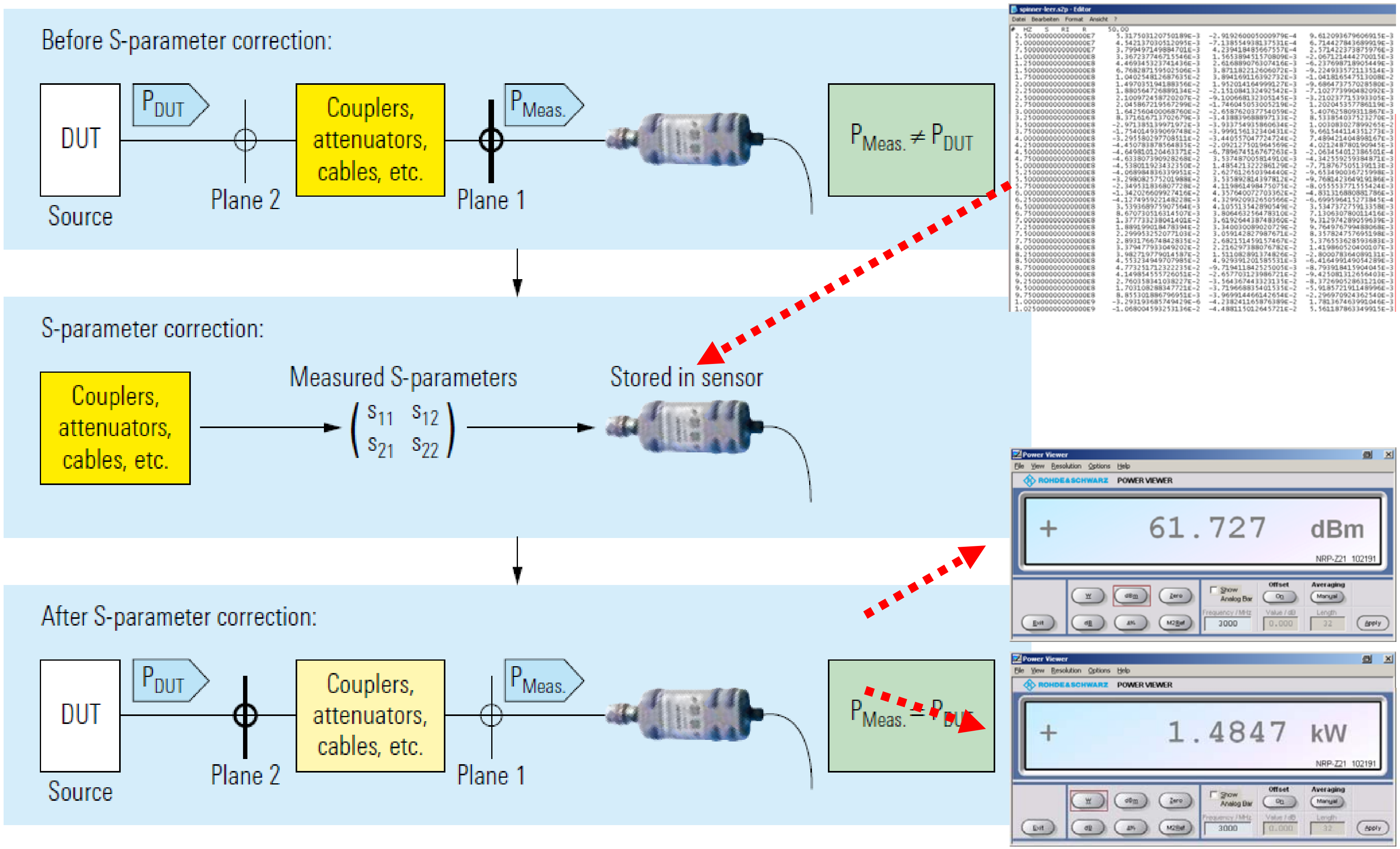
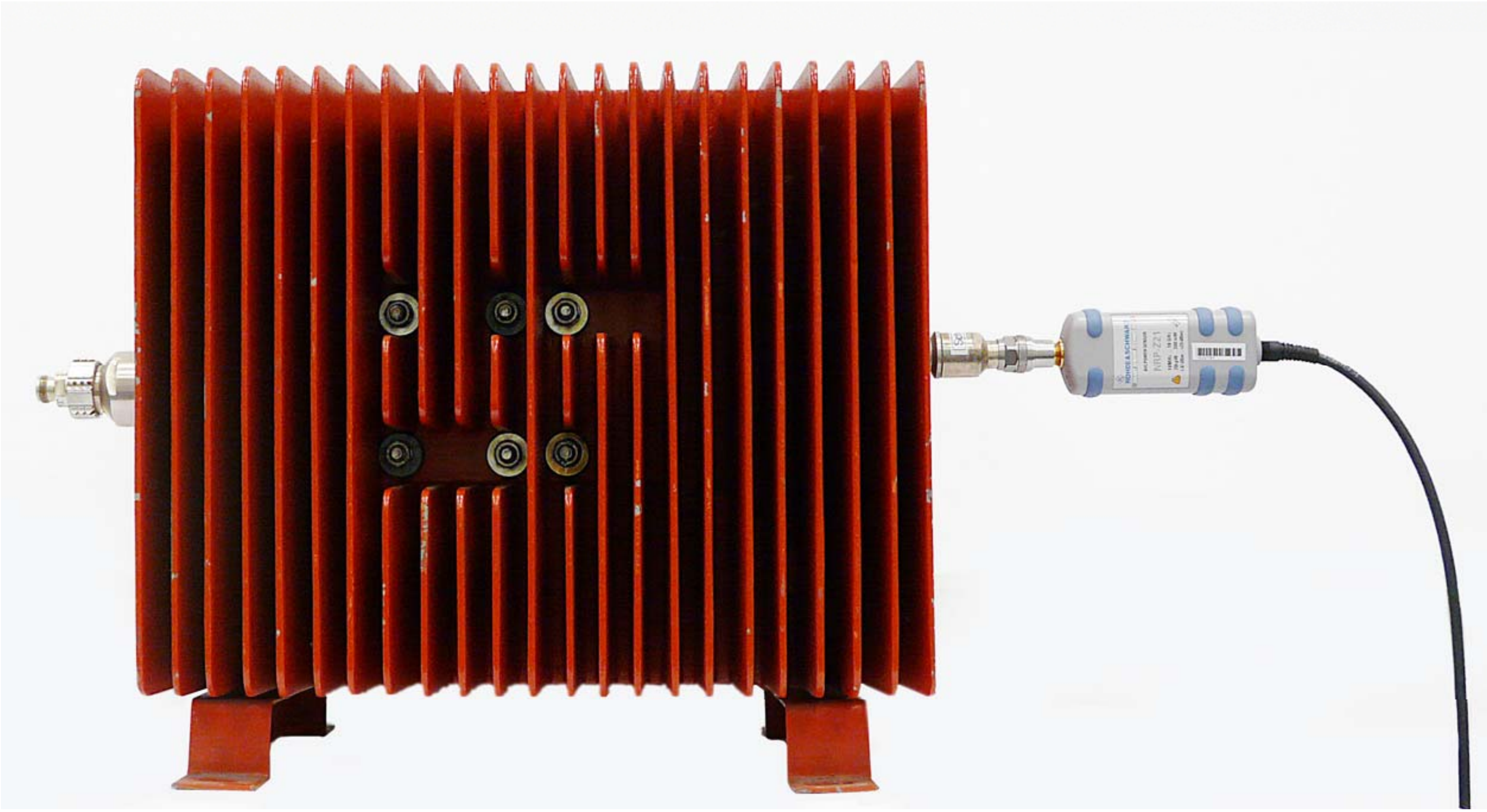
Expand your possibilites!

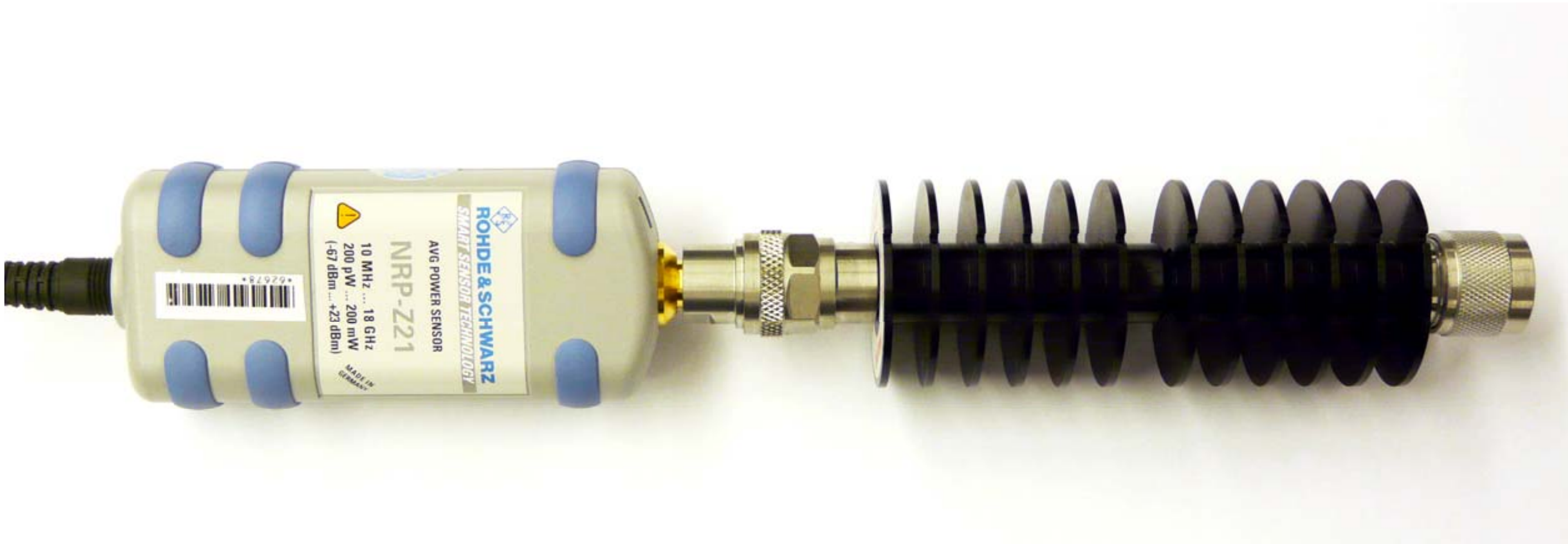


Expand your possibilites!

Power measurement up to 2 kW …



Expand your possibilites!
Power measurement up to 50 W …



Expand your possibilites!

Power measurement in 75 Ω systems …

Expand your possibilites!
R&S Sensors up to 23 dBm / 33dBm / 42 dBm / 45 dBm

Expand your possibilites!
Benefits in brief

- **Error due to mismatch between the twoport <> power sensor gets very small, i.e. is negligible in most cases.**
- **The power sensor itself takes care for the correction tables – and also for interpolation, if needed.**
- **If the (complex) reflection coefficient of the source (UUT) is known – the NRP-Zxx can also correct for this, purely systematic, error.**

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  - Improving measurement accuracy by means of characterized calibration standards.
  - Using previous calibration results to improve accuracy.
  - User characterization of R&S ZV-Z5x automatic calibration units

Expand your possibilites!

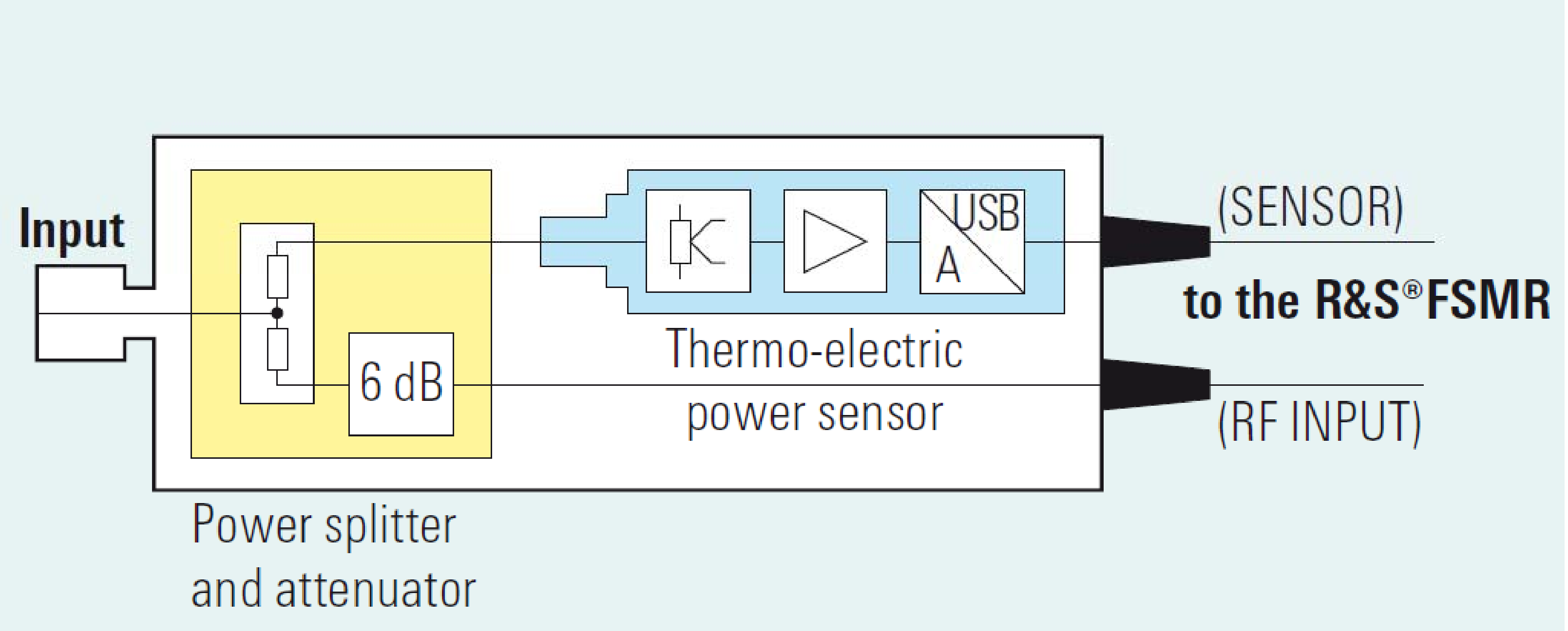
Power Sensors NRP-Z27 / 37 for R&S FSMR Measuring Receiver

Expand your possibilites!

Power Sensors NRP-Z27 / 37 for R&S FSMR Measuring Receiver

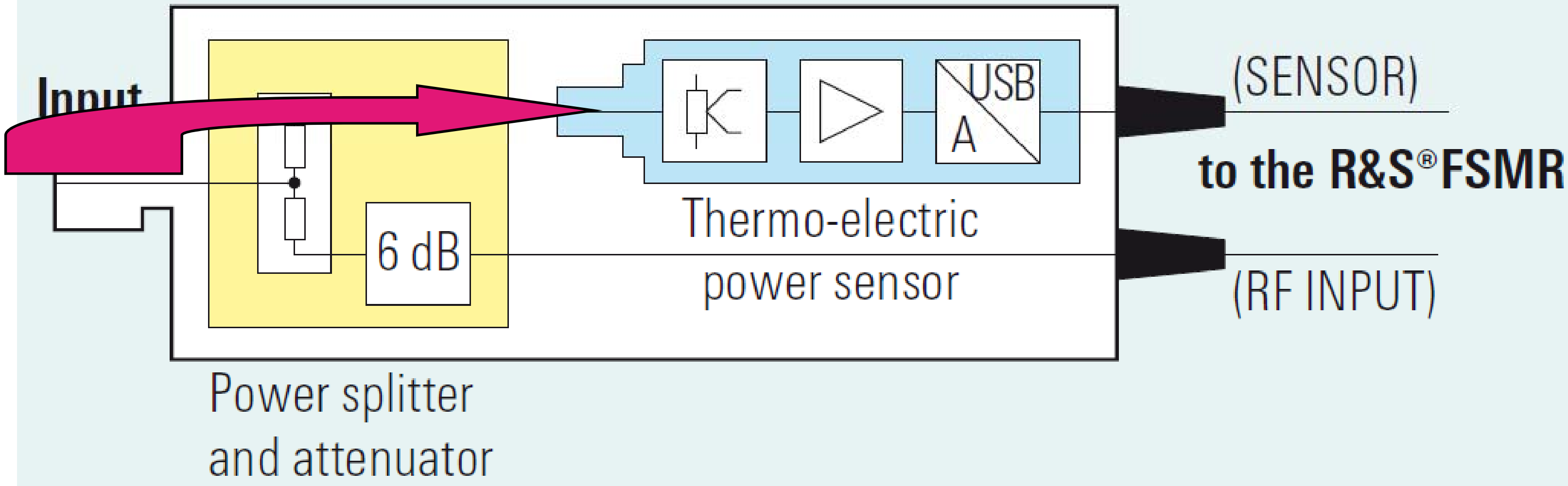
Expand your possibilites!

Power Sensors NRP-Z27 / 37 for R&S FSMR Measuring Receiver



Expand your possibilites!
Power Sensors NRP-Z27 / 37 for R&S FSMR Measuring Receiver

High levels („absolute“ reference)
Measured by means of a thermal power sensor

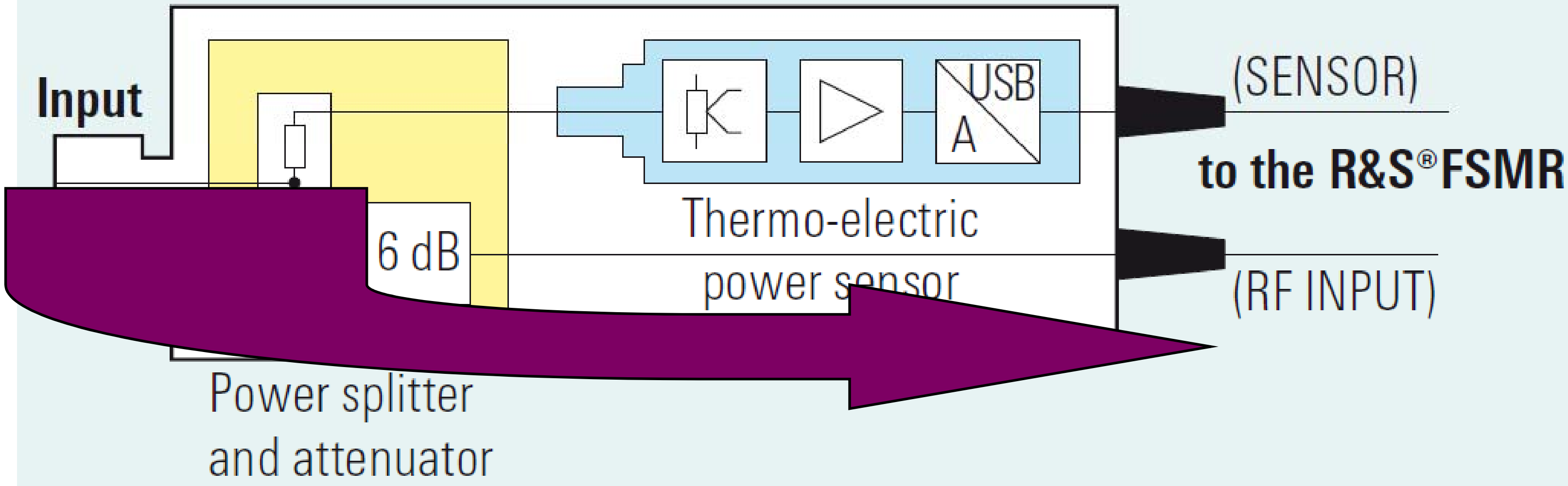


Expand your possibilites!

Power Sensors NRP-Z27 / 37 for R&S FSMR Measuring Receiver

Low levels

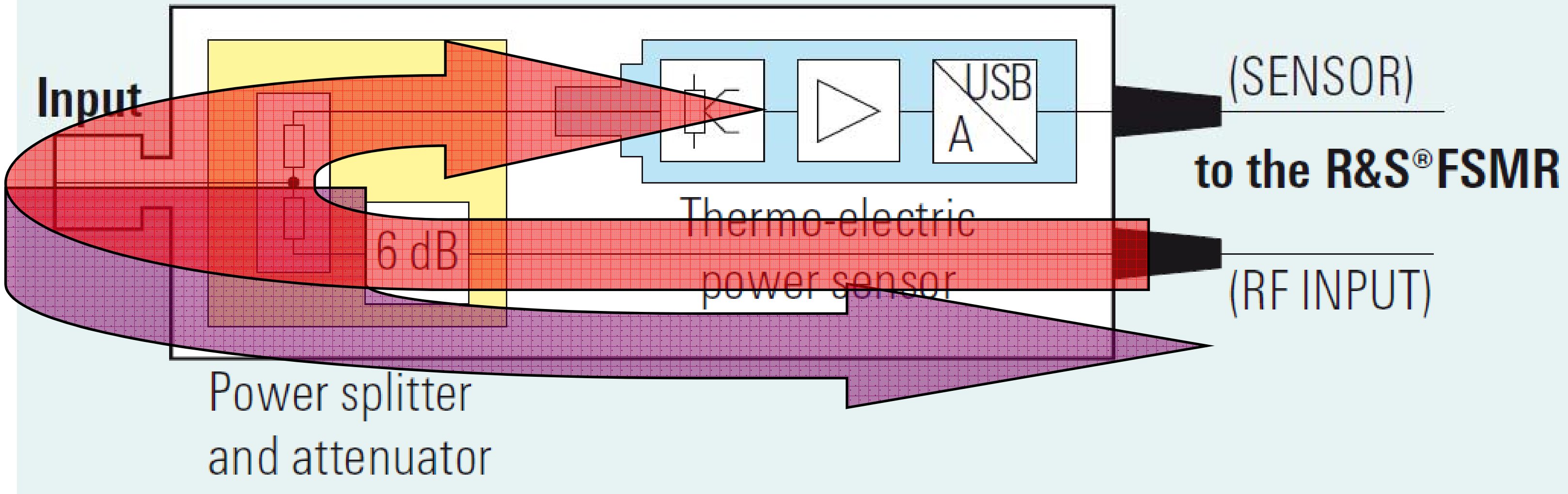
Measured by means of a narrowband receiver



Expand your possibilites!

Power Sensors NRP-Z27 / 37 for R&S FSMR Measuring Receiver

Residual reflected signal coming from SA
„Isolated“ from sensor – and further correction performed



NRP-Z27 / NRP-Z37 Power Sensor Modules

- **The built-in thermal power-sensor takes care for a high level of absolute accuracy (0.067 dB @ 100 MHz)**
- **By means of a 6 dB attenuator the isolation between the FSMR and the power-sensor is improved to > 24 dB nominal.**
- **The power-sensor module is fully characterized – as well as the (complex) input reflection coefficient of the FSMR is stored on the receiver.**
- **Compensation is performed by the intelligent power sensor itself: It corrects the effects of mismatch using the stored calibration data of the power splitter and the FSMR reflection coefficient.**

NRP-Z27 / NRP-Z37 Power Sensor Modules

		20°C to 25°C	15°C to 35°C	0°C to 50°C
Uncertainty for absolute power measurements on R&S FSMR26 [40)] From -10 dBm to +26 dBm	DC to < 100 MHz	*0.104 dB*	*0.109 dB*	*0.128 dB*
	100 MHz to 4.2 GHz	*0.116 dB*	*0.120 dB*	*0.138 dB*
	> 4.2 GHz to 8.0 GHz	*0.163 dB*	*0.166 dB*	*0.181 dB*
	> 8.0 GHz to 18.0 GHz	*0.183 dB*	*0.187 dB*	*0.207 dB*
	> 18.0 GHz to 26.5 GHz	*0.226 dB*	*0.235 dB*	*0.269 dB*
After numerical isolation correction	DC to < 100 MHz	*0.067 dB*	*0.074 dB*	*0.101 dB*
	100 MHz to 4.2 GHz	*0.077 dB*	*0.083 dB*	*0.107 dB*
	> 4.2 GHz to 8.0 GHz	*0.092 dB*	*0.099 dB*	*0.123 dB*
	> 8.0 GHz to 12.4 GHz	*0.099 dB*	*0.107 dB*	*0.135 dB*
	> 12.4 GHz to 18.0 GHz	*0.122 dB*	*0.130 dB*	*0.159 dB*
	> 18.0 GHz to 26.5 GHz	*0.154 dB*	*0.167 dB*	*0.212 dB*

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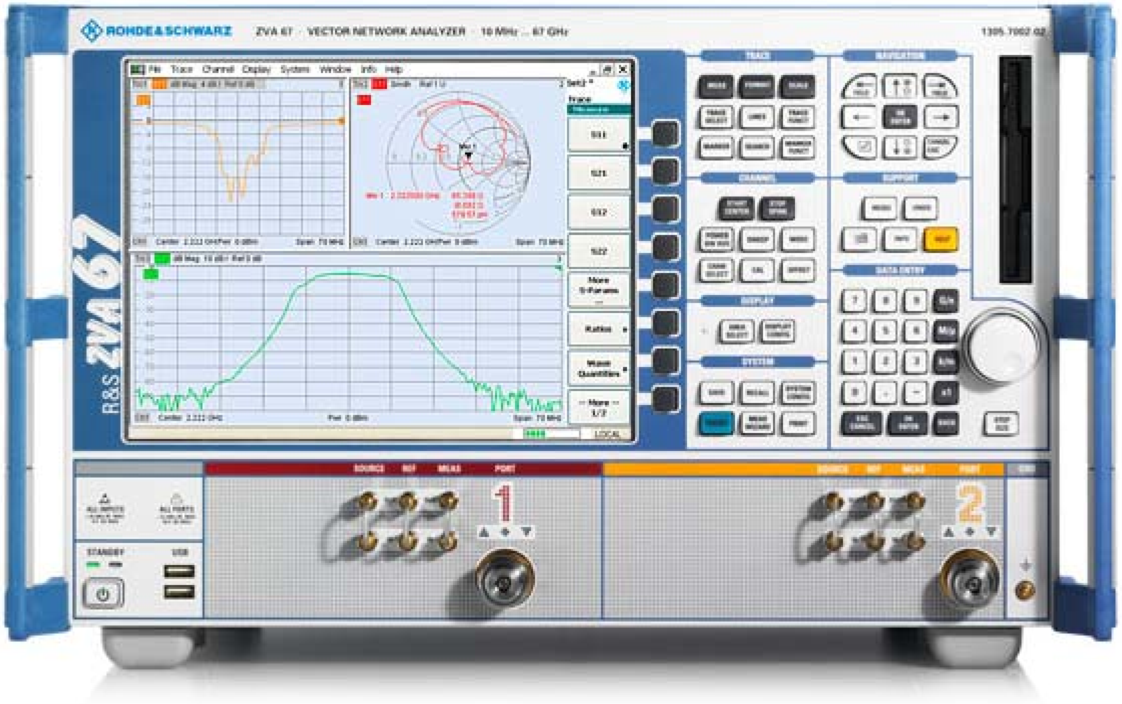
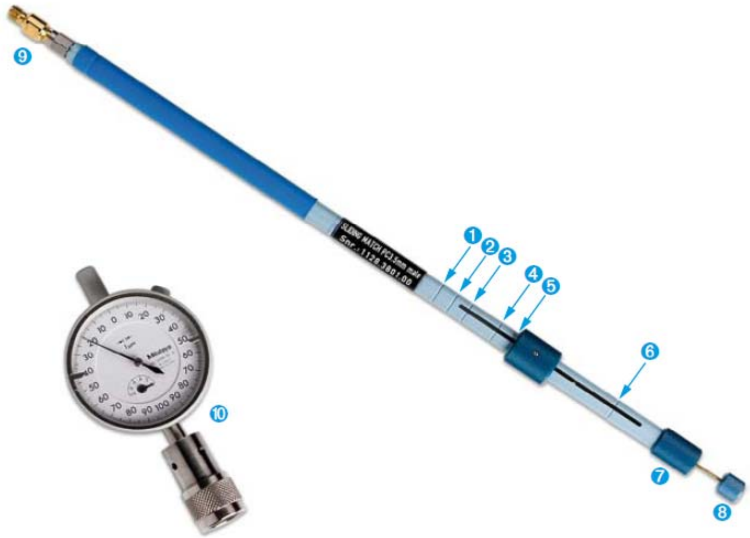
Vector Network Analyzer



Mechanical Calibration Kit in 3.5mm
Sliding Load



Calibration Standards of mechanical calibration kit

VNA w/ Electronic Calibration Unit

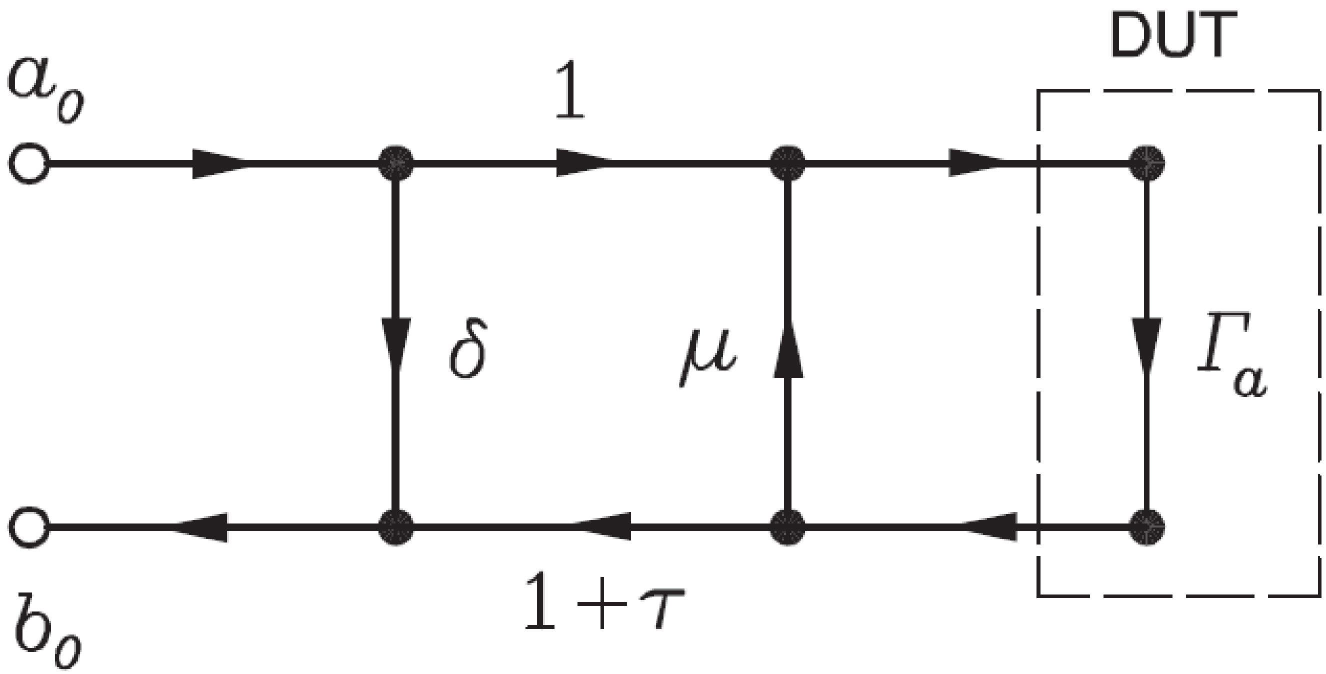
VNA Calibration

or better: Performing a system error correction

- **Vector Network Analyzers (VNAs) provide high measurement accuracy by means of sophisticated error corrections.**
- **While performing the, so called, calibration of the VNA, the systematic, time-invariant errors of the „system“ (i.e. including test cables, adapters, …) are determined and corrected for.**
- **In order to solve for the error parameters (e.g. directivity, matching, …) calibration standards have to be connected to the VNA.**

VNA Calibration

One port error model



One-port error model.

VNA Calibration
or better: Performing a system error correction

- **However – the quality of a VNA calibration can only be as good as the calibration standards used. Or – better – as good as the calibration standards used are known.**

- **For instance, the traditional model of the MATCH standard is usually simply „0“ reflection. I.e. every deviation from „0“ leeds to residual errors when determining the directivity parameter.**

- **The approach recommended is to „characterize“ the calibration standards (e.g. by means of a reference calibration kit OR calibration results from e.g. a NMI) and to use this characterized calibration kit as „transfer standard“.**

Creating a characterized, data based kit …

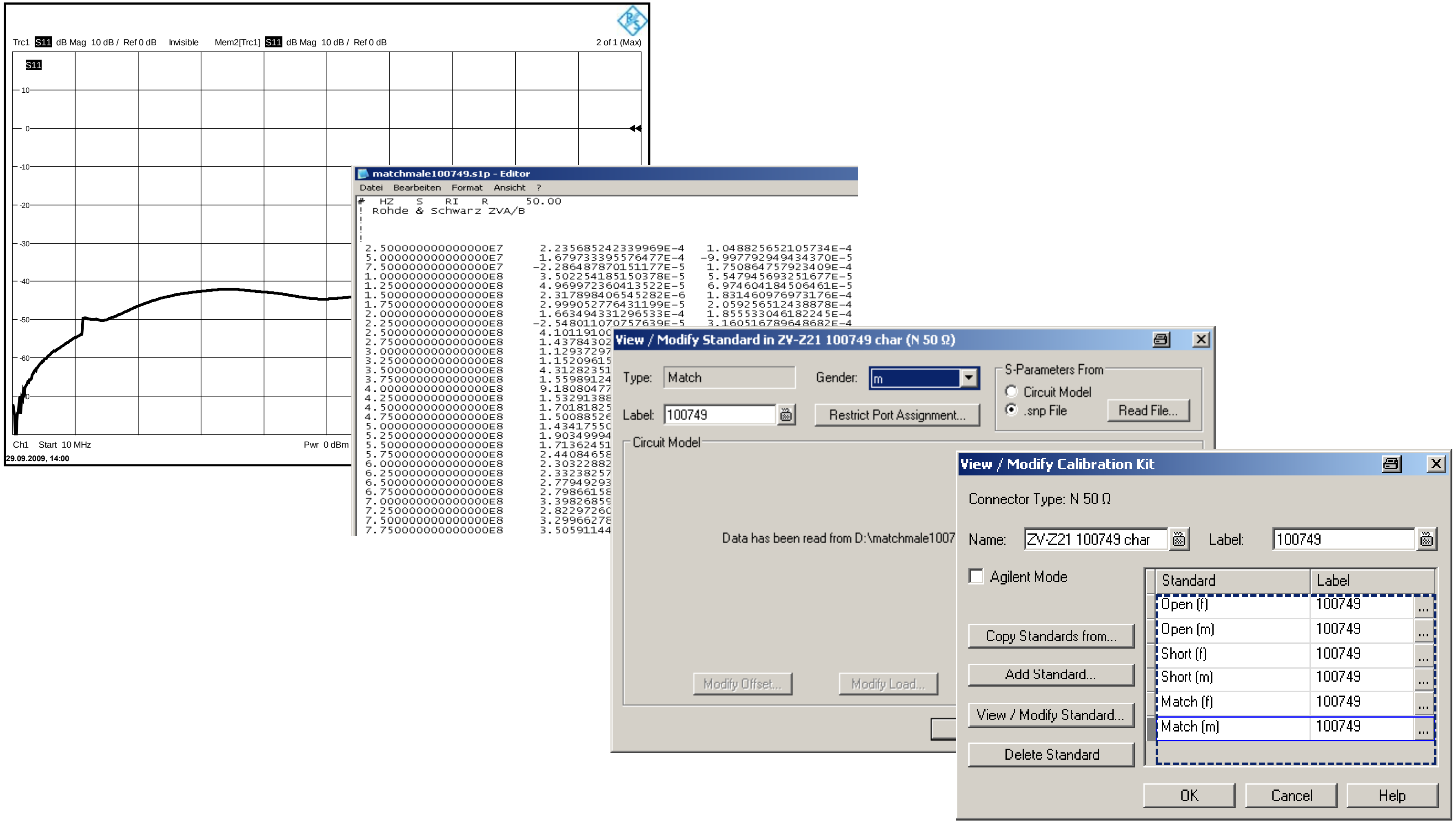
by means of a „reference“ calibration kit

- **Perform e.g. a „full one port“ calibration (using the most accurate calibration kit available in the lab)**
- **Measure the calibration standards from the kit to be characterized**
- **Export the trace data into S1P (Touchstone) format**
- **Import the trace data – and create a new, characterized kit.**

- **Optional:**
  - Use the (complex) mean value of repeated measurements.
  - Use the (complex) mean value of repeated calibrations – e.g. even with different calibration kits.
  - Use the (complex) mean value of different calibration procedures (OSM,TRL, …)

Creating a characterized, data based kit …

by measuring the kit with a reference kit



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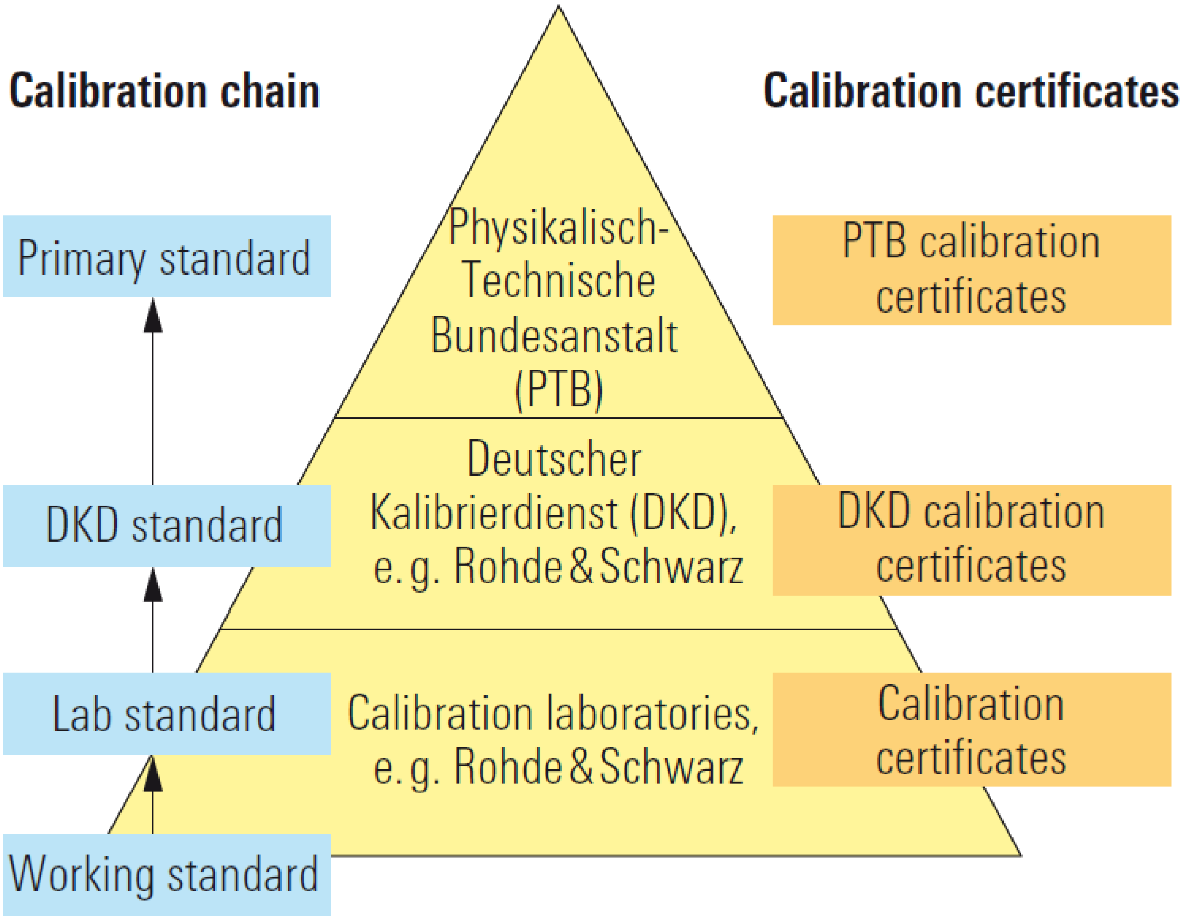
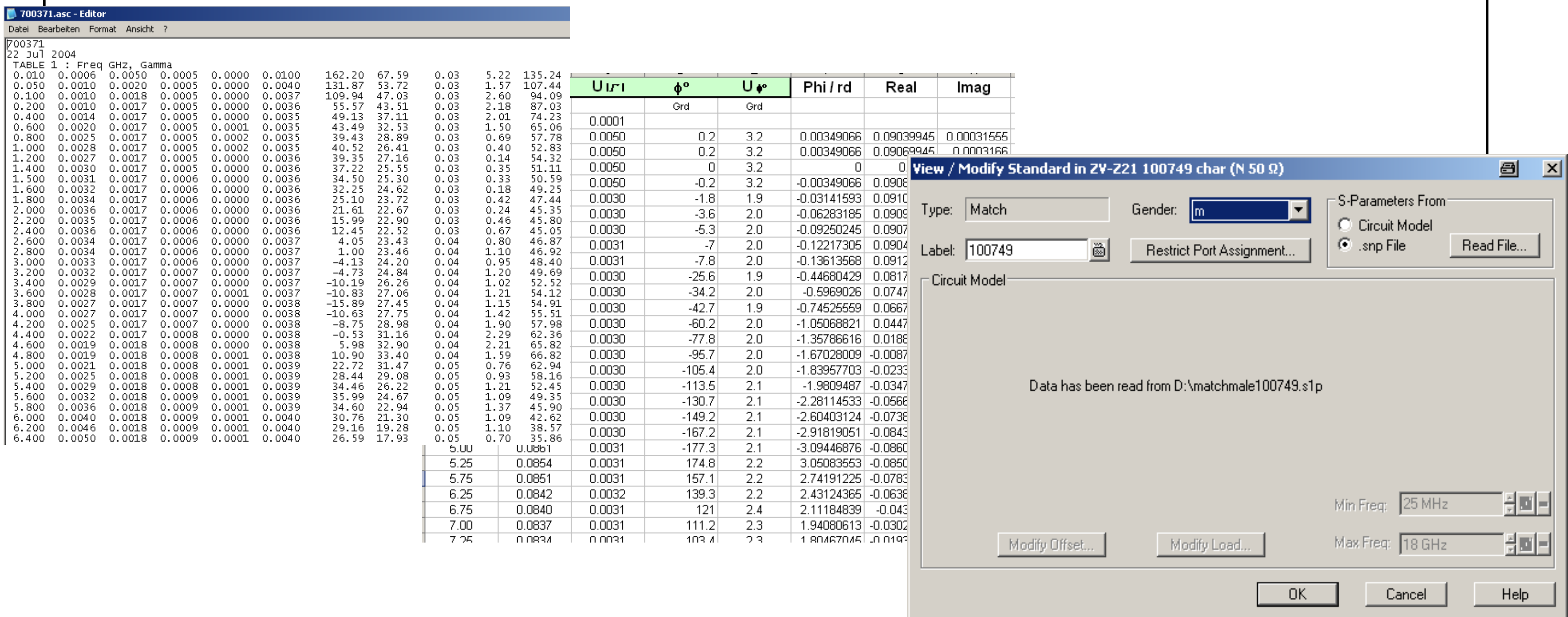
Calibration hierarchy



Creating a characterized, data based kit …

from calibration results, e.g. from a NMI or an accredited laboratory

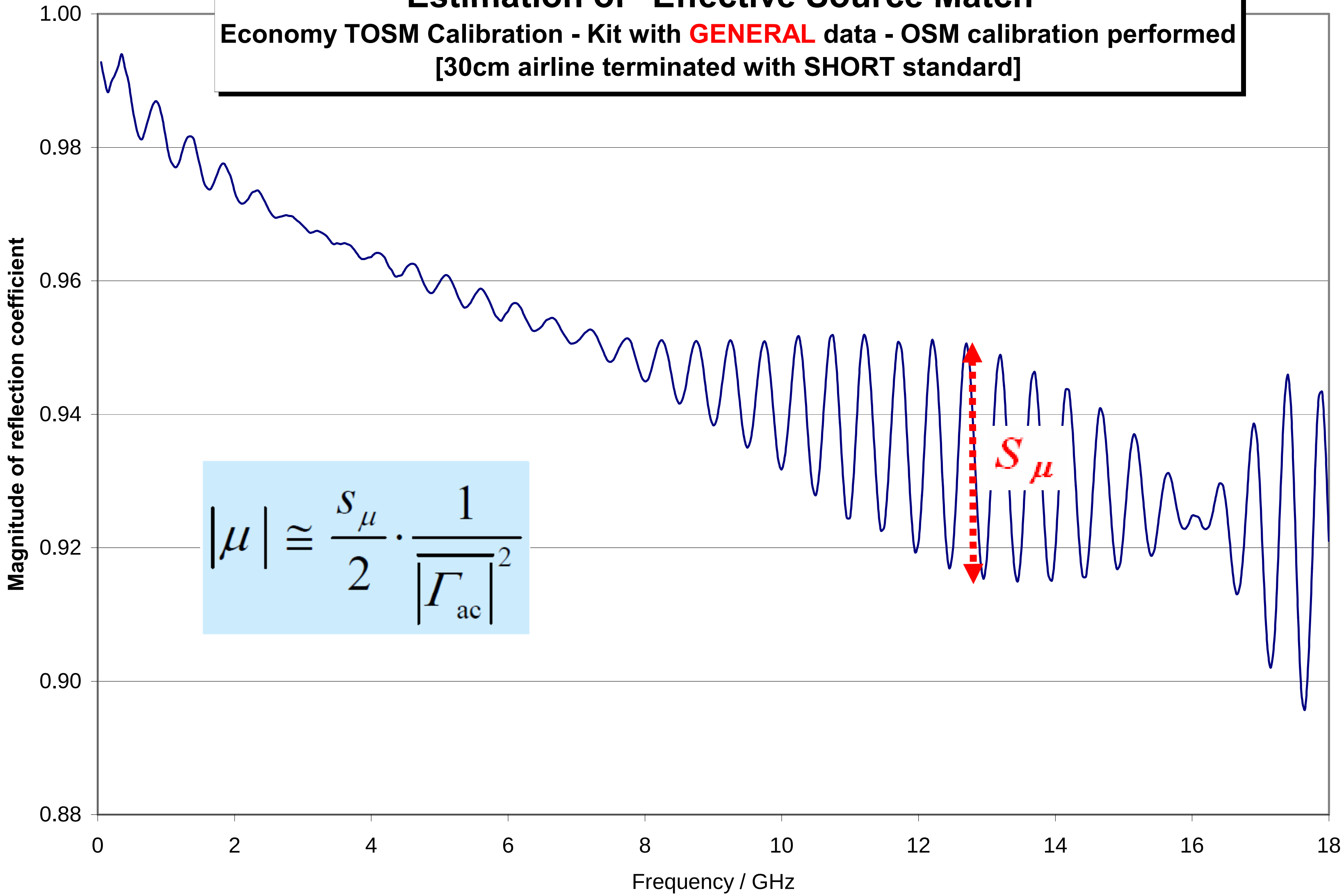
- **Calibration Data – provided by**
  - NMI (e.g. NIST, PTB, NPL, METAS, …)
  - Accredited Laboratory (e.g. A2LA, NVLAP, DKD, UKAS, …)



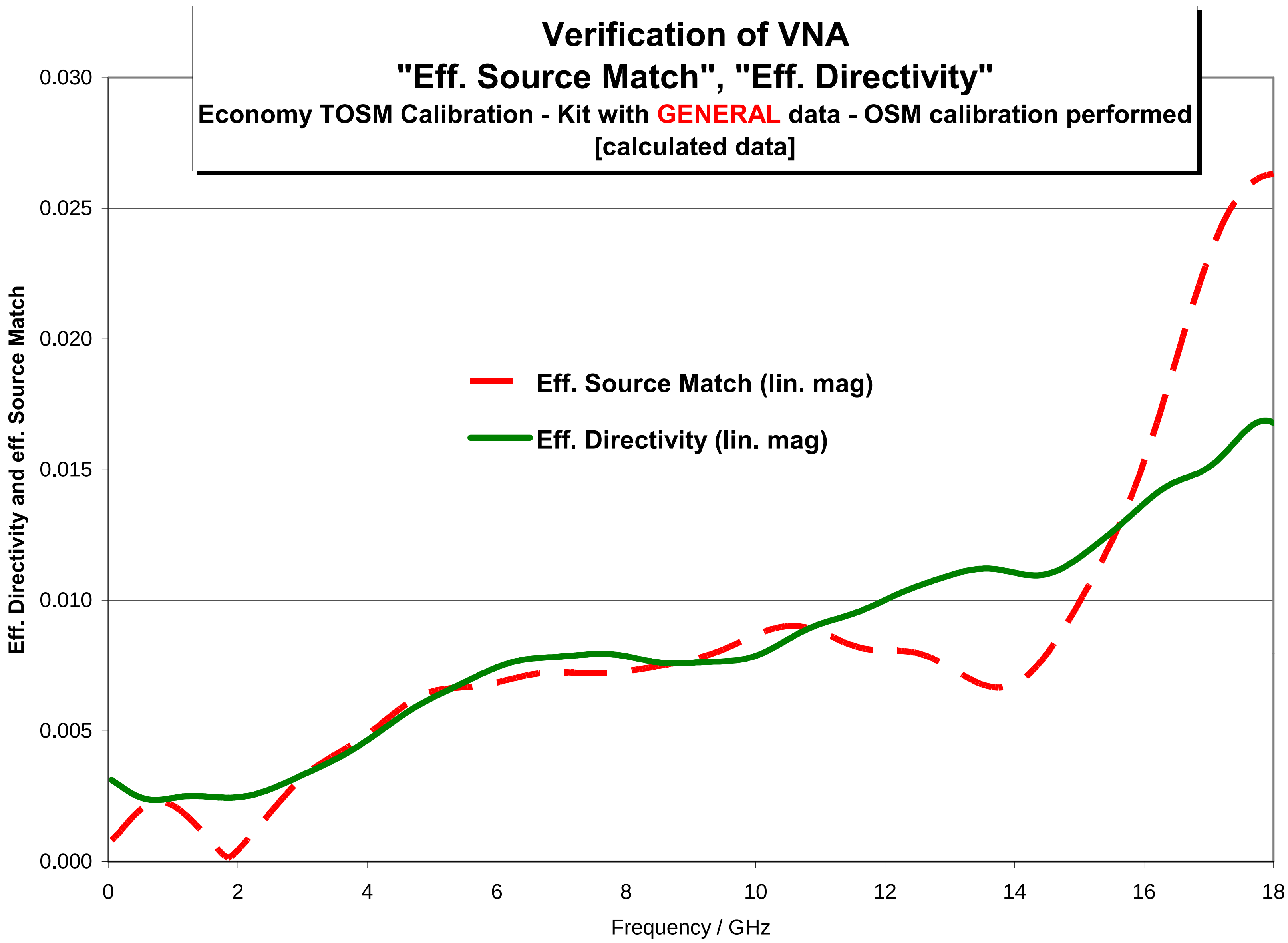
Example: Improving the accuracy of a N type calibration kit by means of characterization

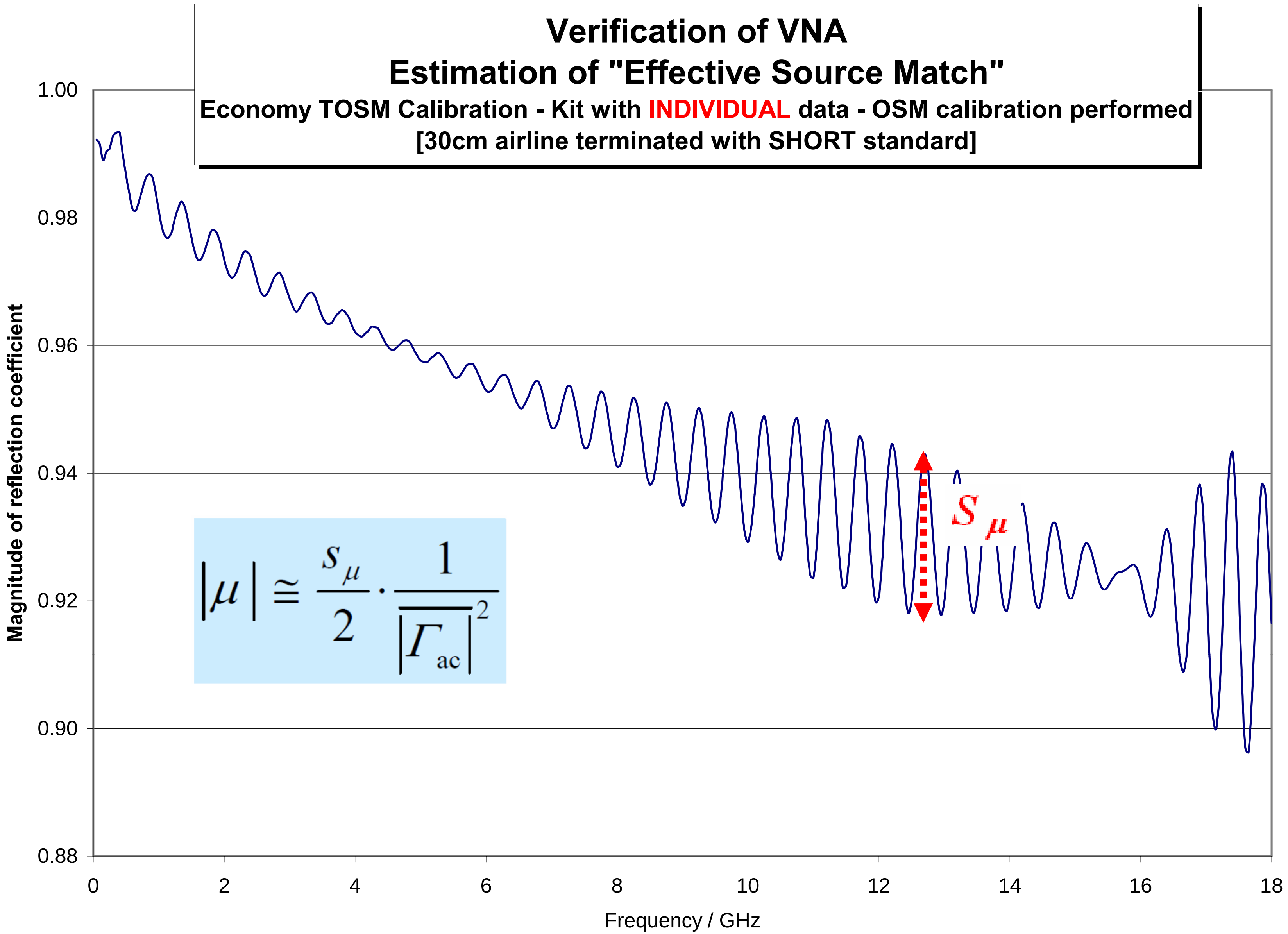
Verification of VNA
Estimation of "Effective Source Match"

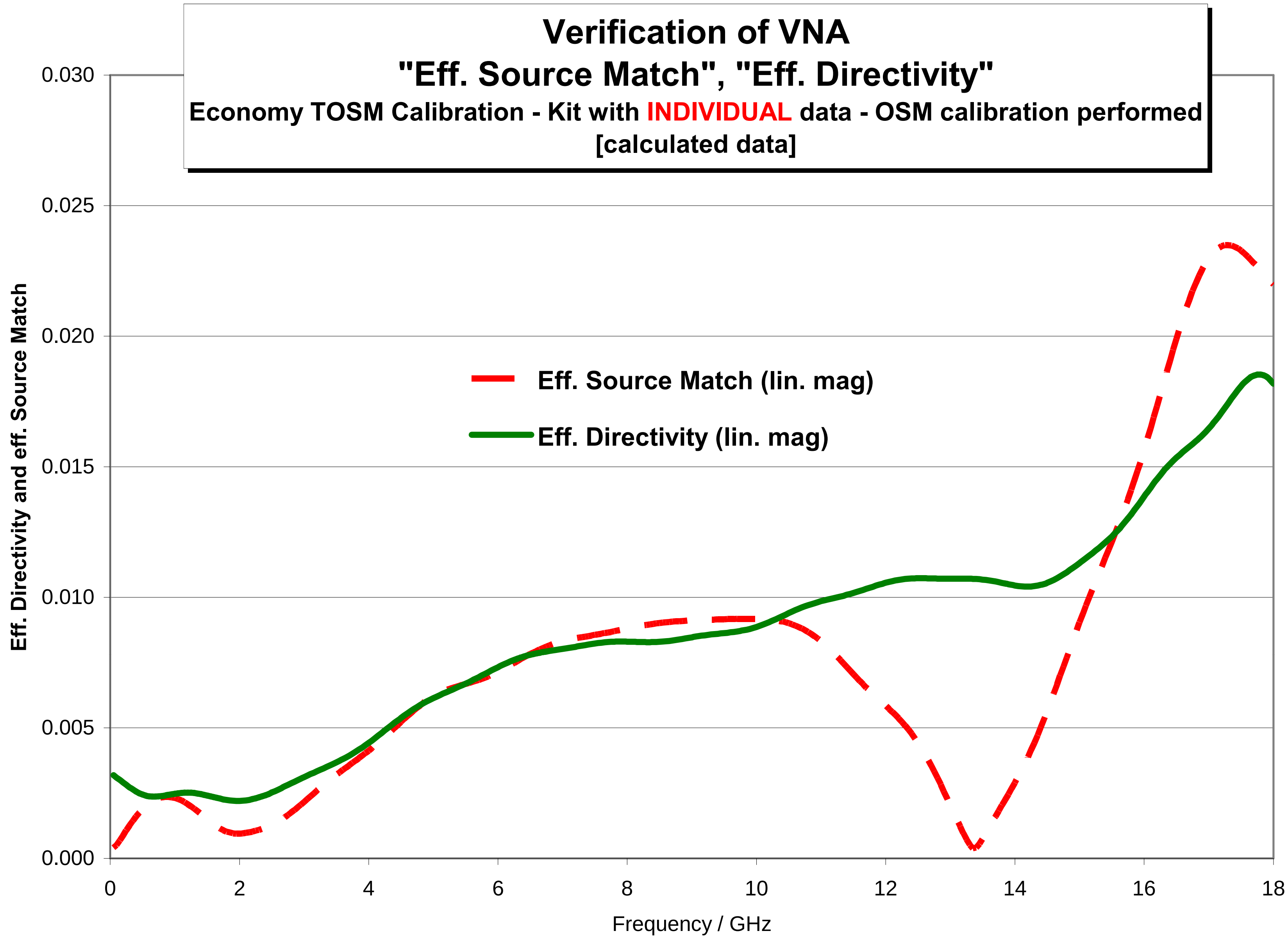
Economy TOSM Calibration - Kit with GENERAL data - OSM calibration performed
[30cm airline terminated with SHORT standard]



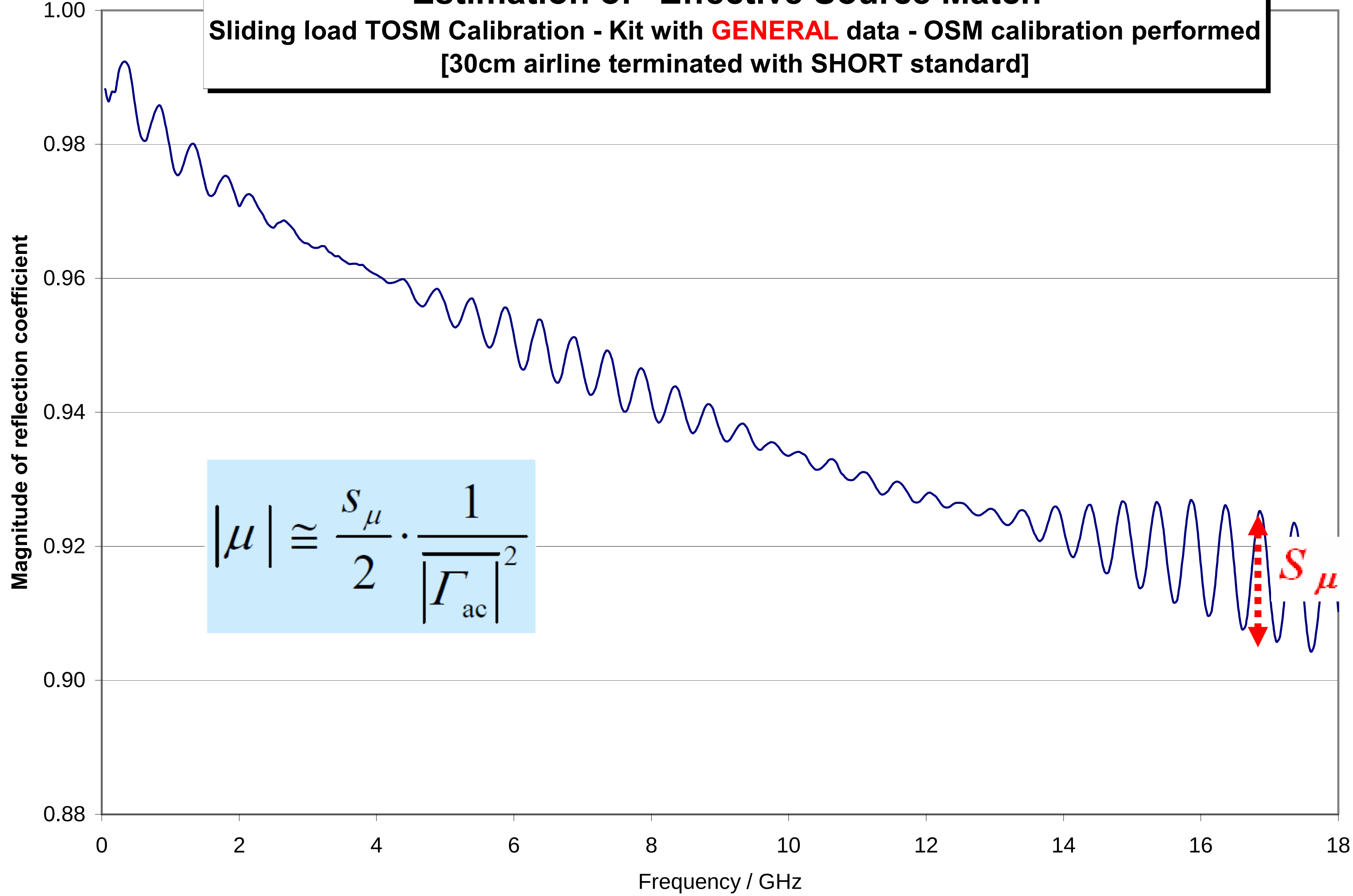
$$|\mu| \cong \frac{s_{\mu}}{2} \cdot \frac{1}{\overline{|\Gamma_{ac}|}^{2}}$$


Verification of VNA
"Eff. Source Match", "Eff. Directivity"
Economy TOSM Calibration - Kit with GENERAL data - OSM calibration performed
[calculated data]
Eff. Source Match (lin. mag)
Eff. Directivity (lin. mag)
Eff. Directivity and eff. Source Match
0.030
0.025
0.020
0.015
0.010
0.005
0.000
0
2
4
6
8
10
12
14
16
18
Frequency / GHz

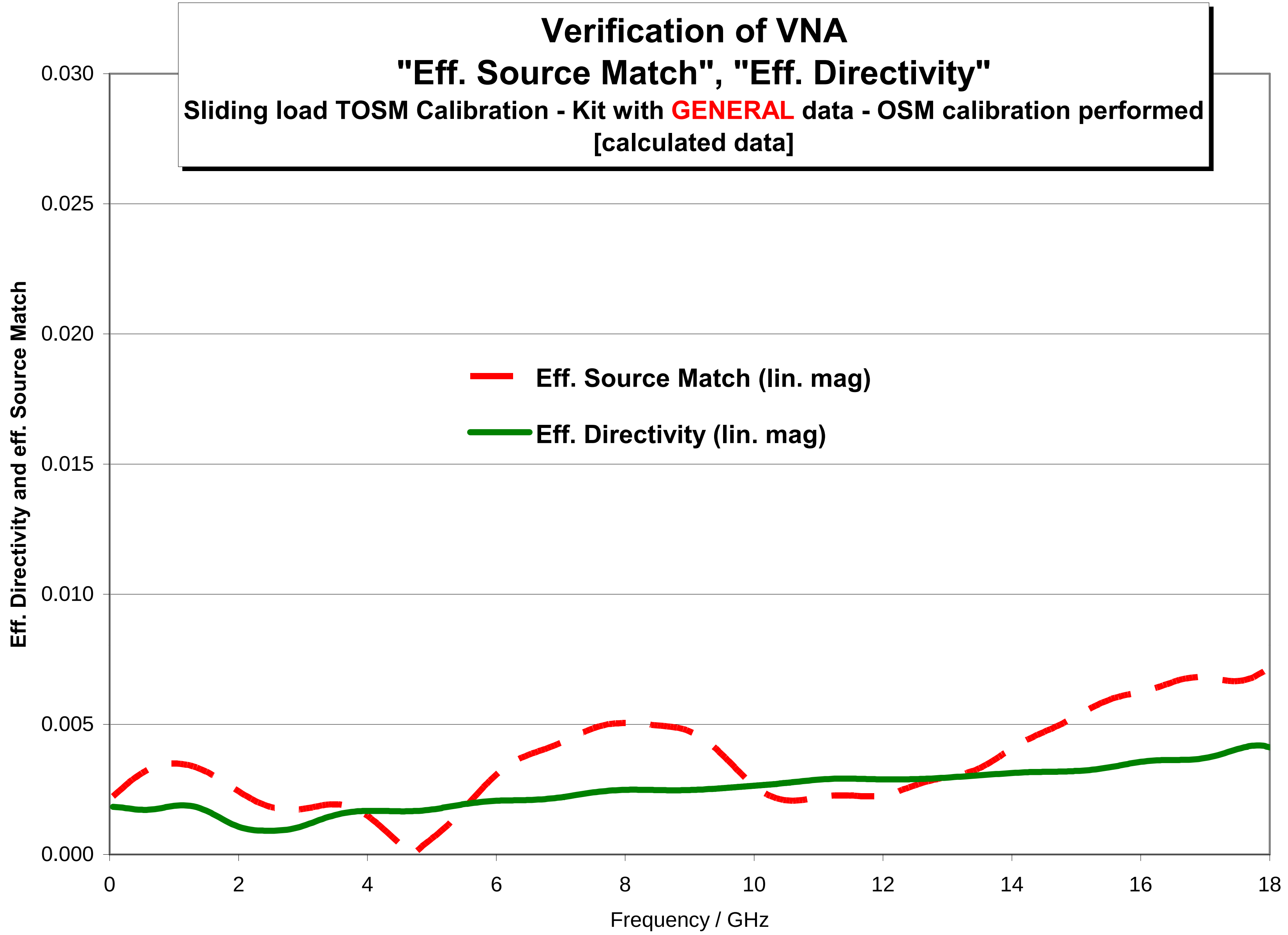

Verification of VNA
Estimation of "Effective Source Match"
Economy TOSM Calibration - Kit with INDIVIDUAL data - OSM calibration performed
[30cm airline terminated with SHORT standard]
Magnitude of reflection coefficient
1.00
0.98
0.96
0.94
0.92
0.90
0.88
0
2
4
6
8
10
12
14
16
18
Frequency / GHz
S_μ
$|\mu| \cong \frac{s_\mu}{2} \cdot \frac{1}{\overline{|\Gamma_{ac}|}^2}$

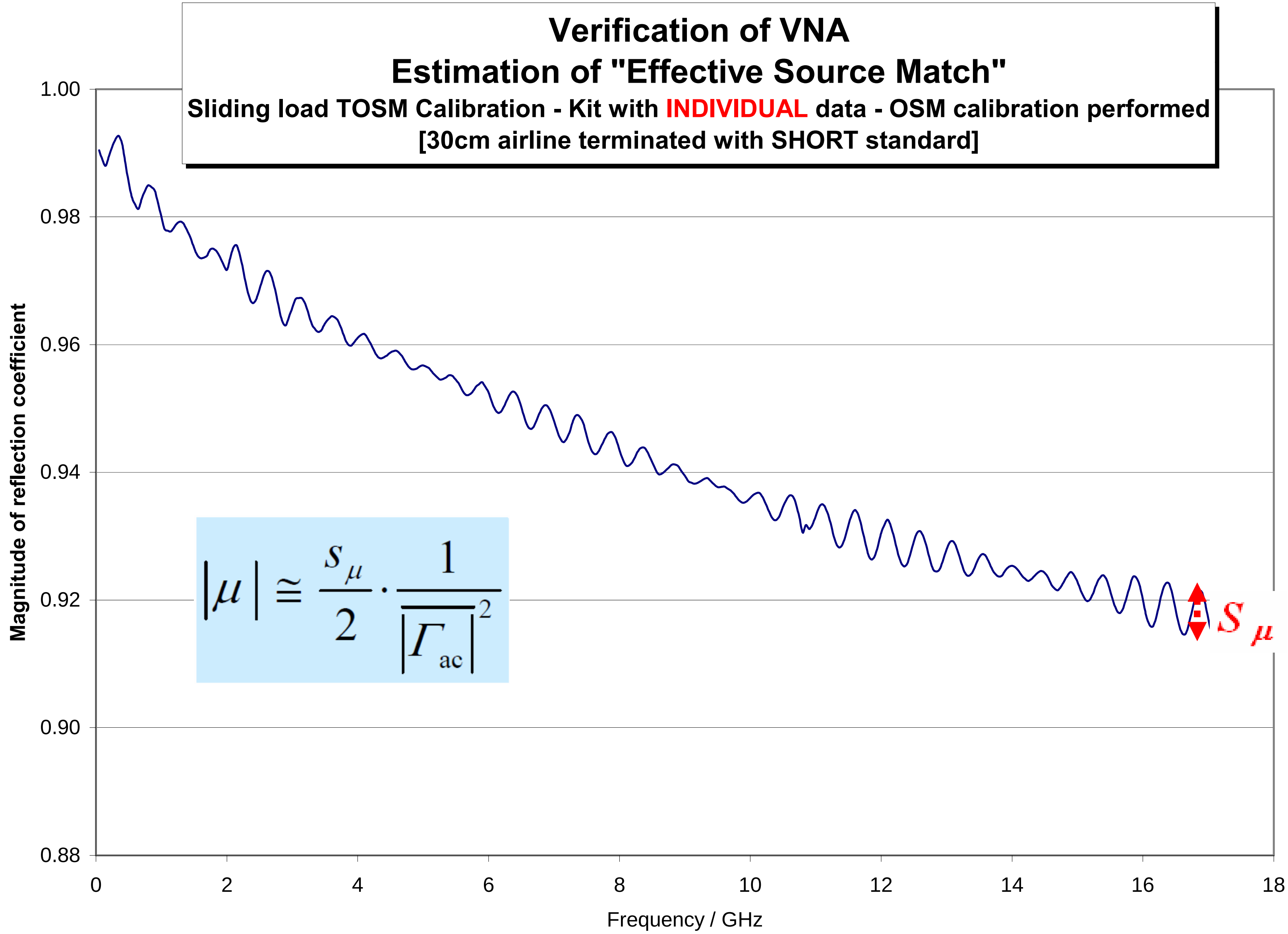

Verification of VNA
"Eff. Source Match", "Eff. Directivity"
Economy TOSM Calibration - Kit with INDIVIDUAL data - OSM calibration performed
[calculated data]
Eff. Source Match (lin. mag)
Eff. Directivity (lin. mag)
Eff. Directivity and eff. Source Match
0.030
0.025
0.020
0.015
0.010
0.005
0.000
0
2
4
6
8
10
12
14
16
18
Frequency / GHz

Verification of VNA
Estimation of "Effective Source Match"
Sliding load TOSM Calibration - Kit with GENERAL data - OSM calibration performed
[30cm airline terminated with SHORT standard]

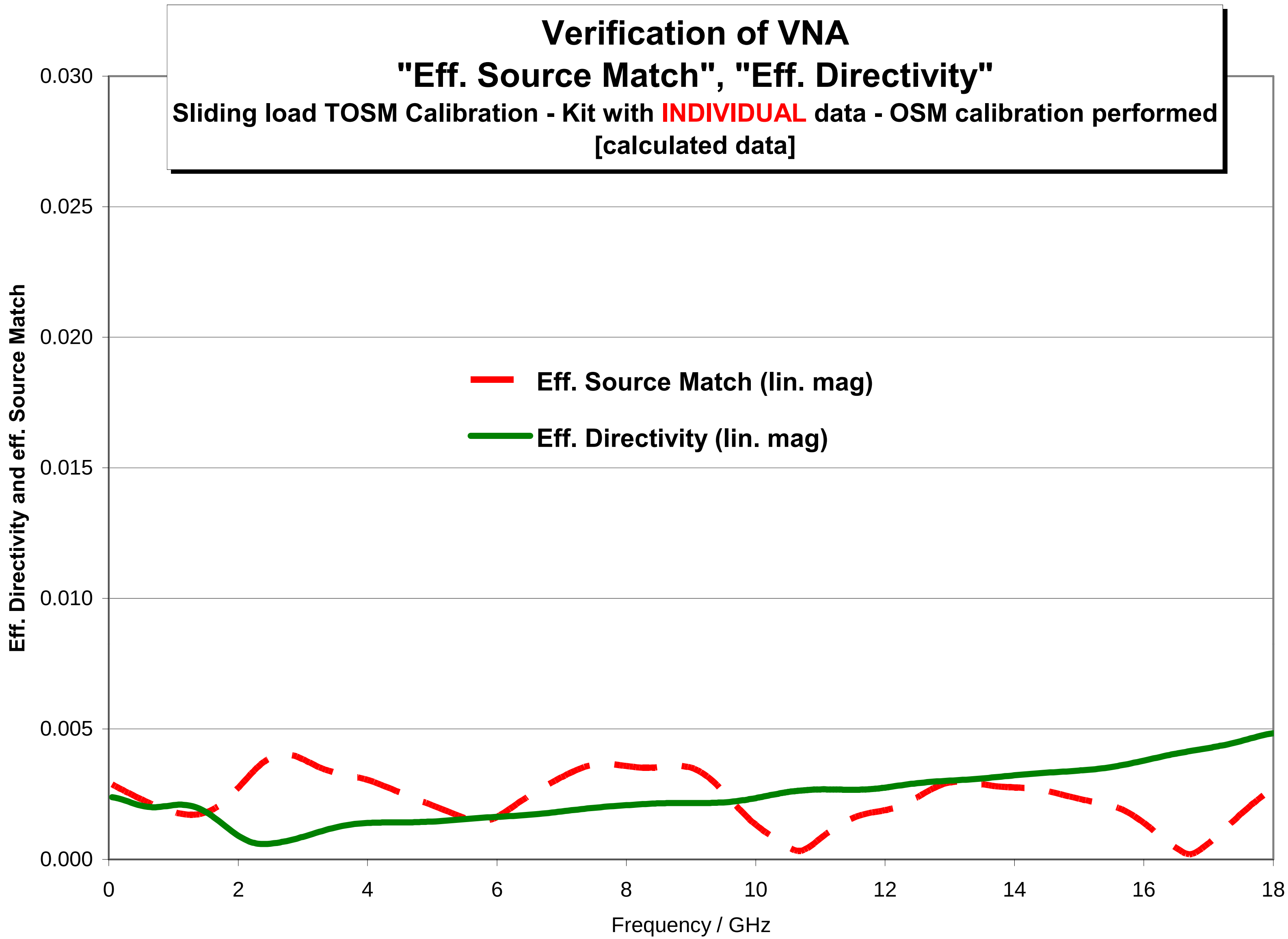


$$|\mu| \cong \frac{s_\mu}{2} \cdot \frac{1}{\overline{|\Gamma_{ac}|}^2}$$


Verification of VNA
"Eff. Source Match", "Eff. Directivity"
Sliding load TOSM Calibration - Kit with GENERAL data - OSM calibration performed
[calculated data]
0.030
0.025
0.020
0.015
0.010
0.005
0.000
Eff. Directivity and eff. Source Match
Eff. Source Match (lin. mag)
Eff. Directivity (lin. mag)
0
2
4
6
8
10
12
14
16
18
Frequency / GHz



$$|\mu| \cong \frac{s_\mu}{2} \cdot \frac{1}{\overline{|\Gamma_{ac}|}^2}$$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[calculated data]
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0.000
0
2
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12
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16
18
Frequency / GHz

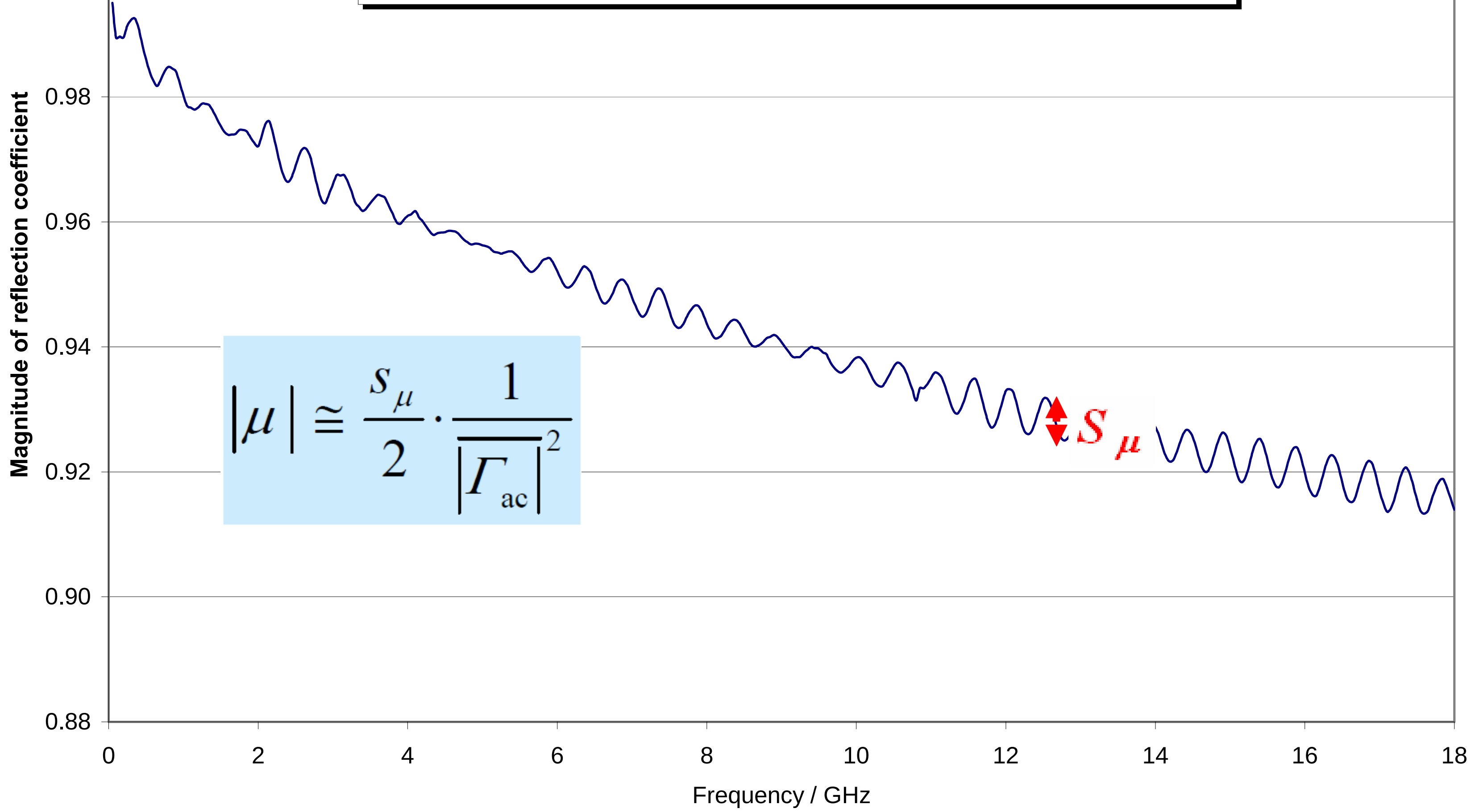
Verification of VNA
Estimation of "Effective Source Match"

Economy TOSM Calibration Kit

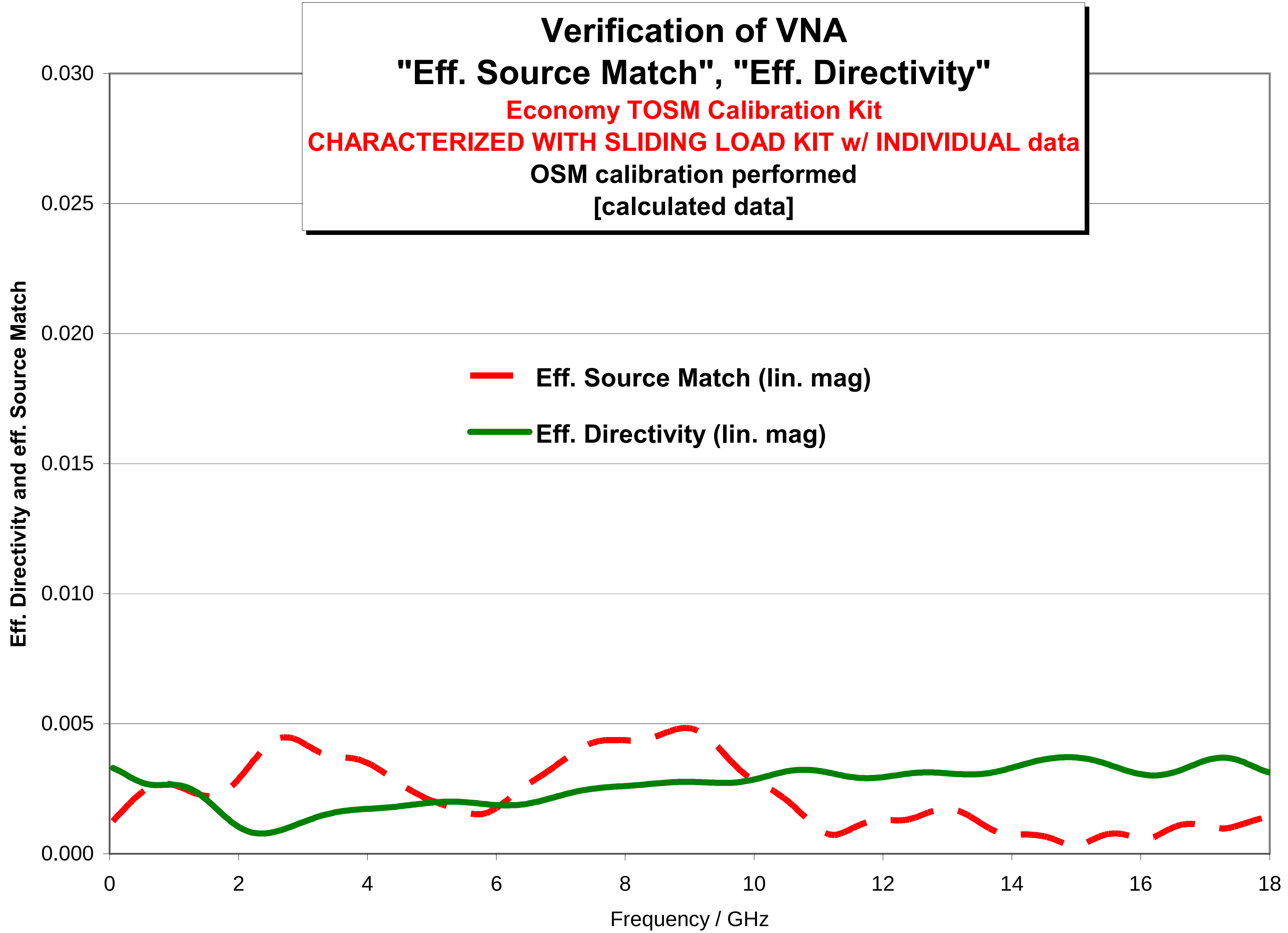
CHARACTERIZED WITH SLIDING LOAD KIT w/ INDIVIDUAL data

OSM calibration performed

[30cm airline terminated with SHORT standard]



$$|\mu| \cong \frac{s_\mu}{2} \cdot \frac{1}{\overline{|\Gamma_{ac}|}^2}$$


Verification of VNA
"Eff. Source Match", "Eff. Directivity"
Economy TOSM Calibration Kit
CHARACTERIZED WITH SLIDING LOAD KIT w/ INDIVIDUAL data
OSM calibration performed
[calculated data]
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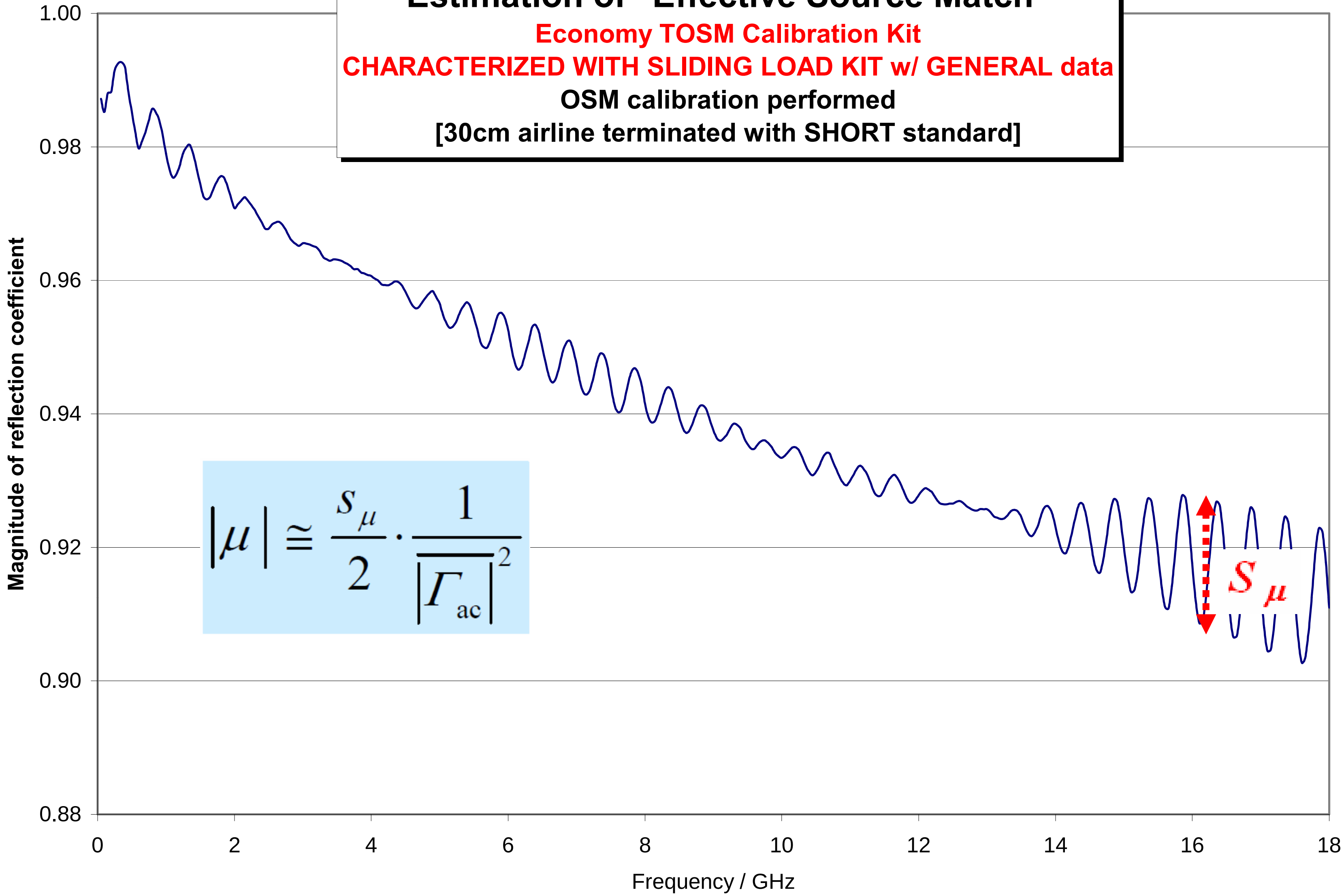
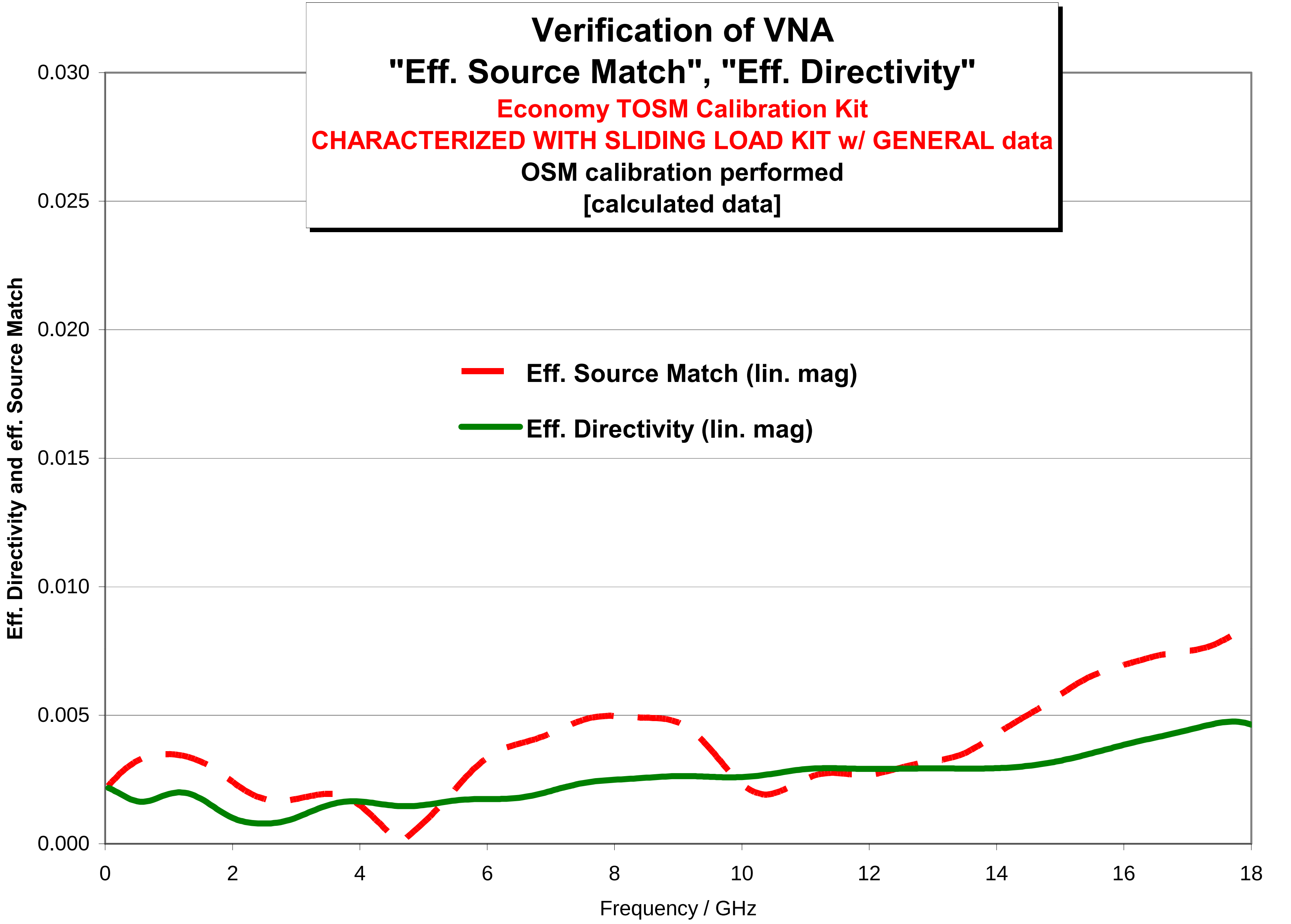
Frequency / GHz

Verification of VNA
Estimation of "Effective Source Match"

Economy TOSM Calibration Kit
CHARACTERIZED WITH SLIDING LOAD KIT w/ GENERAL data
OSM calibration performed
[30cm airline terminated with SHORT standard]



$$|\mu| \cong \frac{s_\mu}{2} \cdot \frac{1}{\overline{|\Gamma_{ac}|}^2}$$


Verification of VNA
"Eff. Source Match", "Eff. Directivity"
Economy TOSM Calibration Kit
CHARACTERIZED WITH SLIDING LOAD KIT w/ GENERAL data
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16
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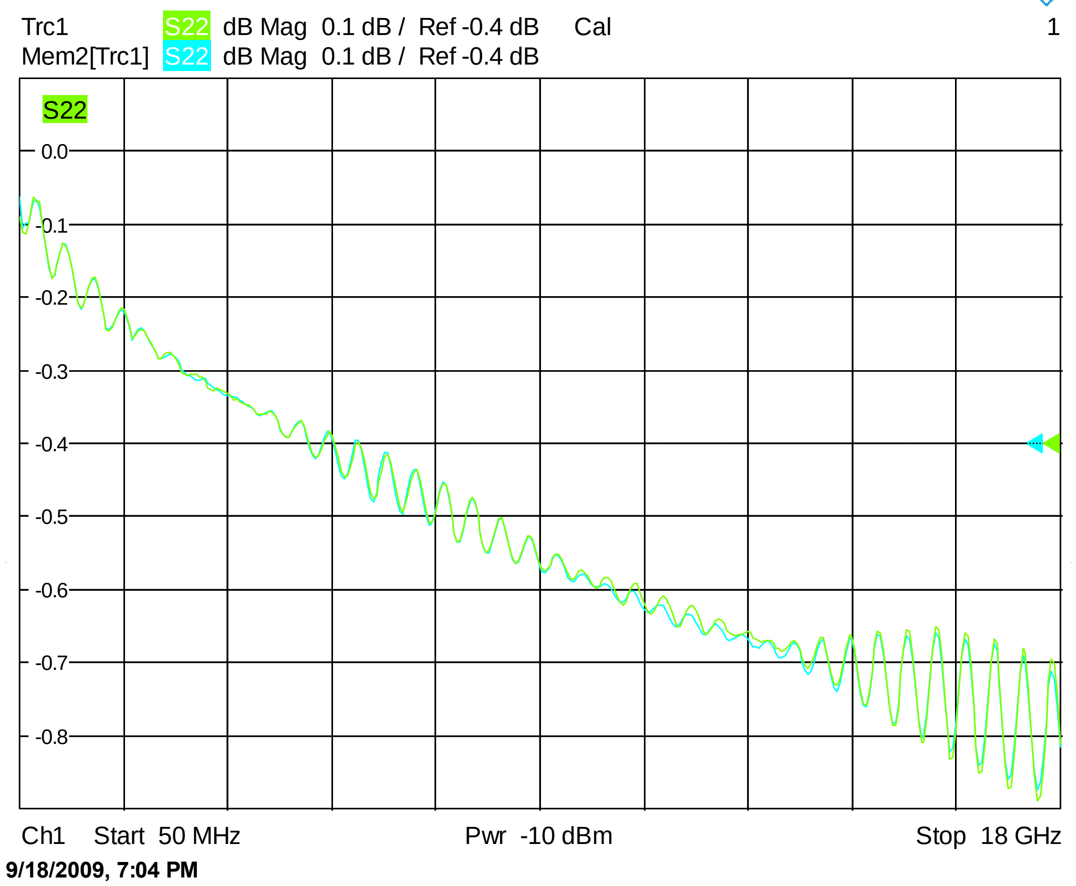
Frequency / GHz

Comparison I:

Performance of Economy – Kit

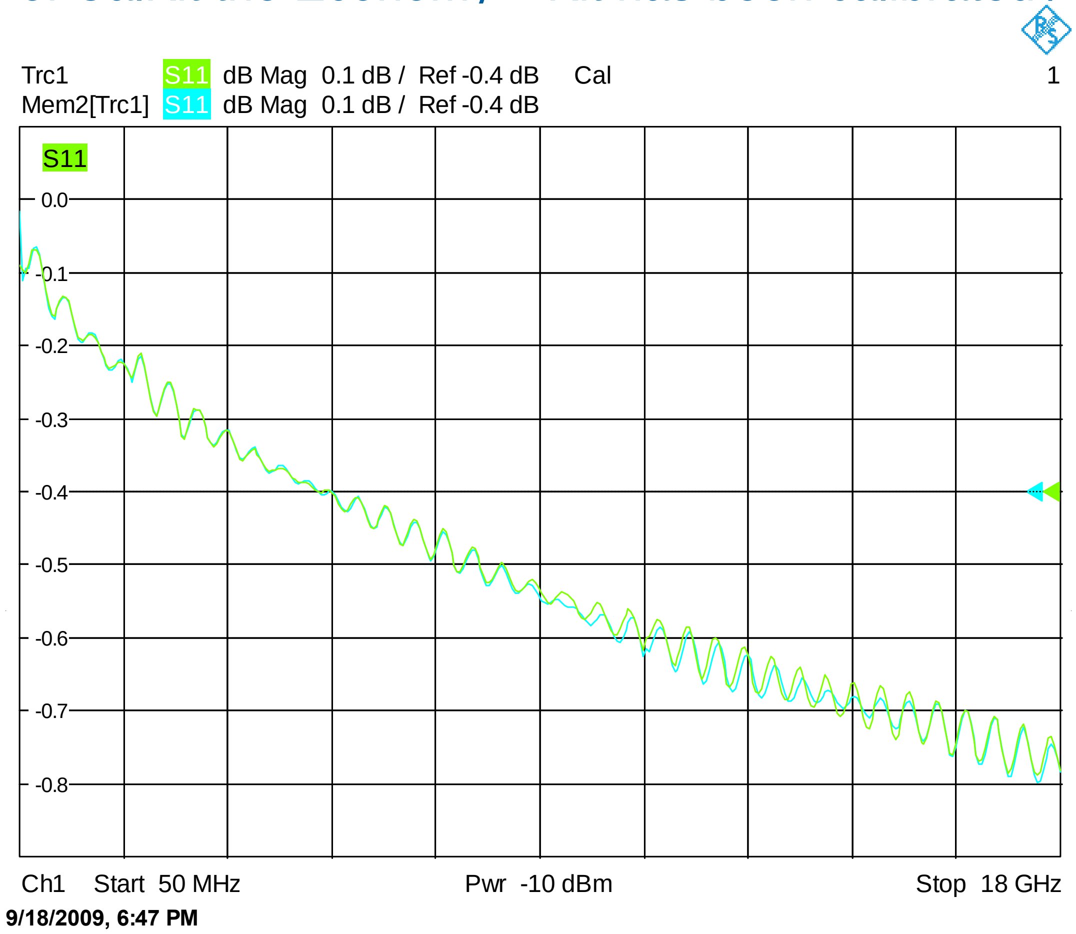
Performance of CalKit the Economy – Kit has been calibrated / characterized with!



Comparison II:

Performance of Economy – Kit

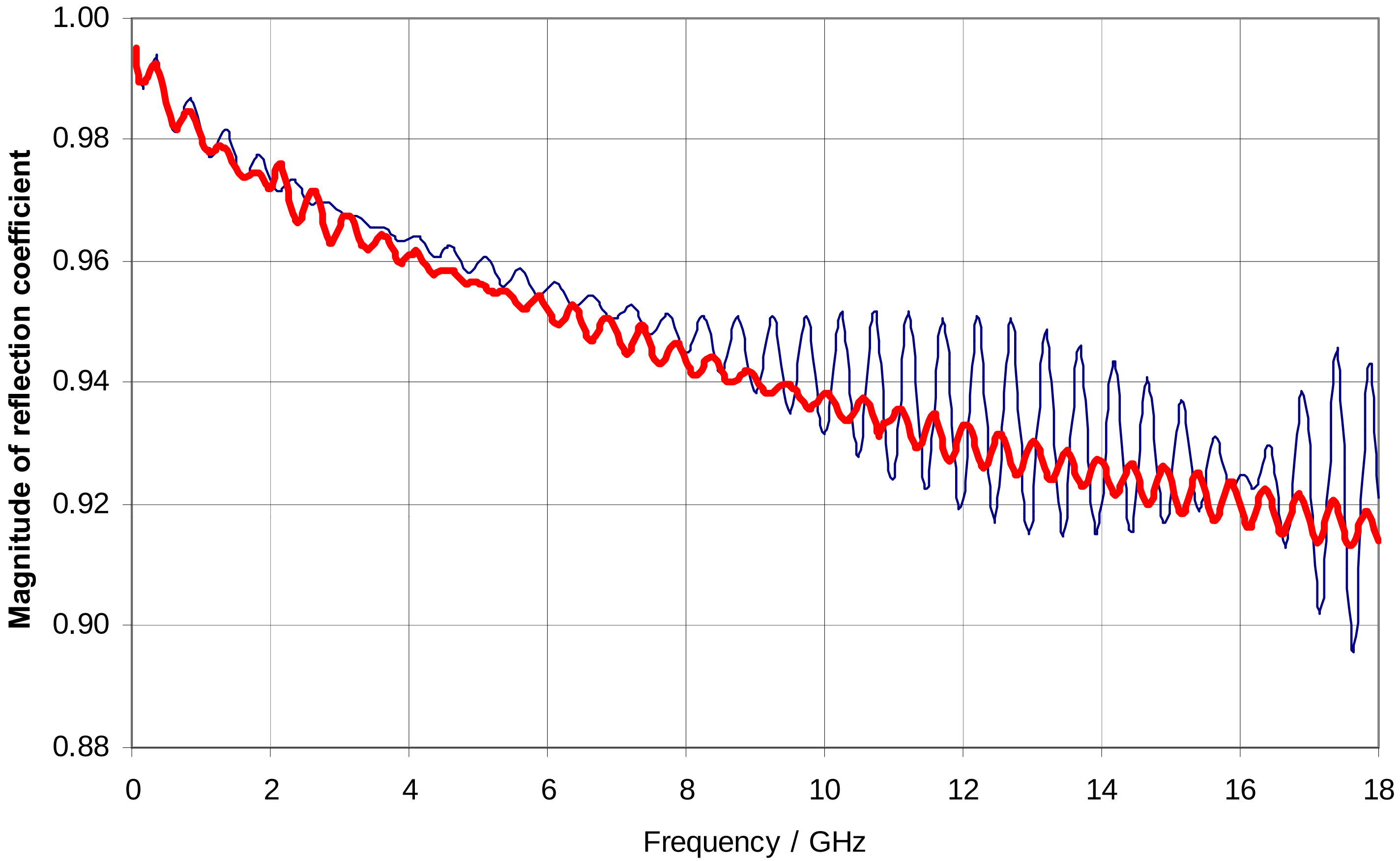
Performance of CalKit the Economy – Kit has been calibrated / characterized with!



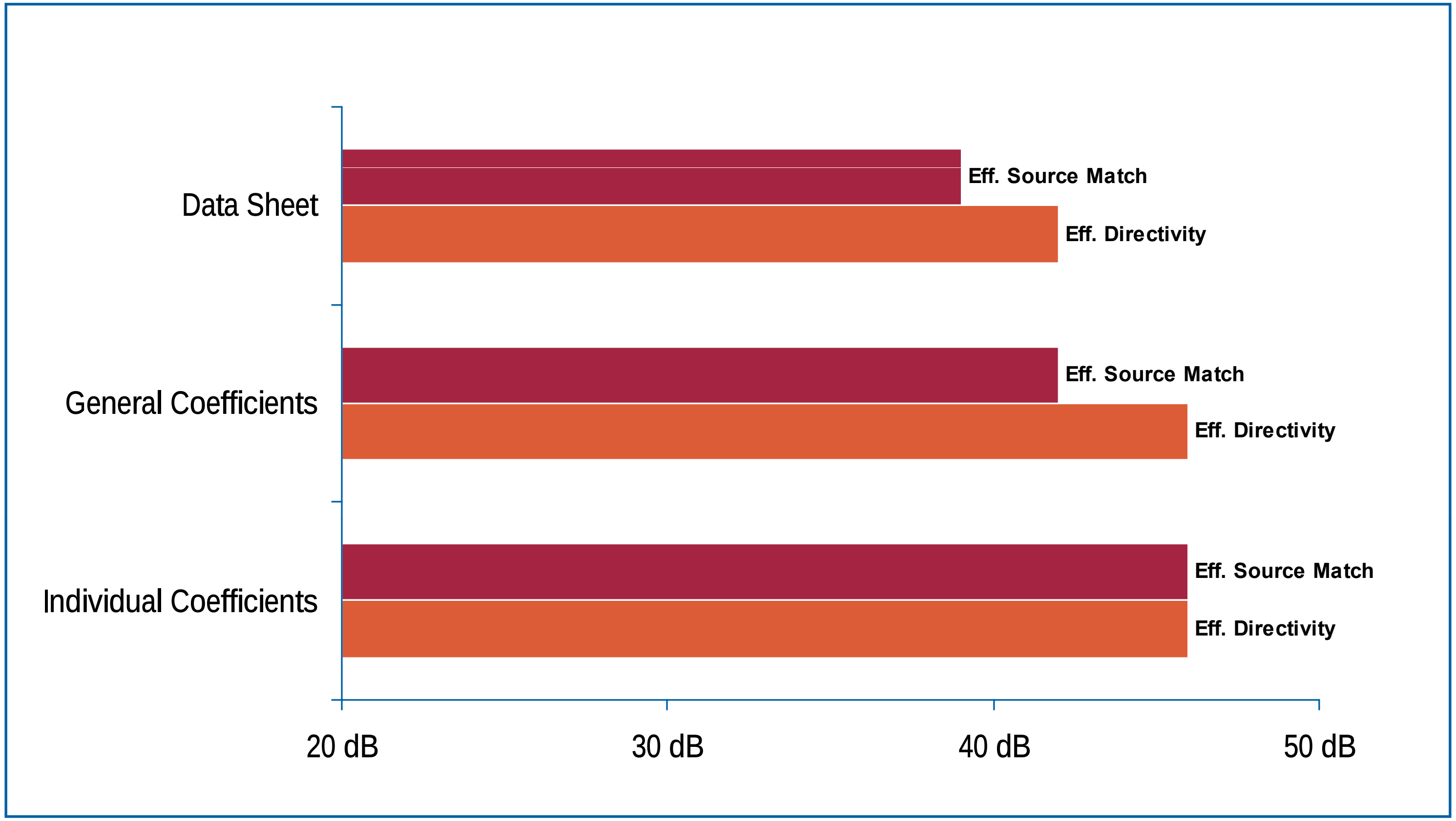
Comparison III:

Performance of Economy – Kit (initial, blue)

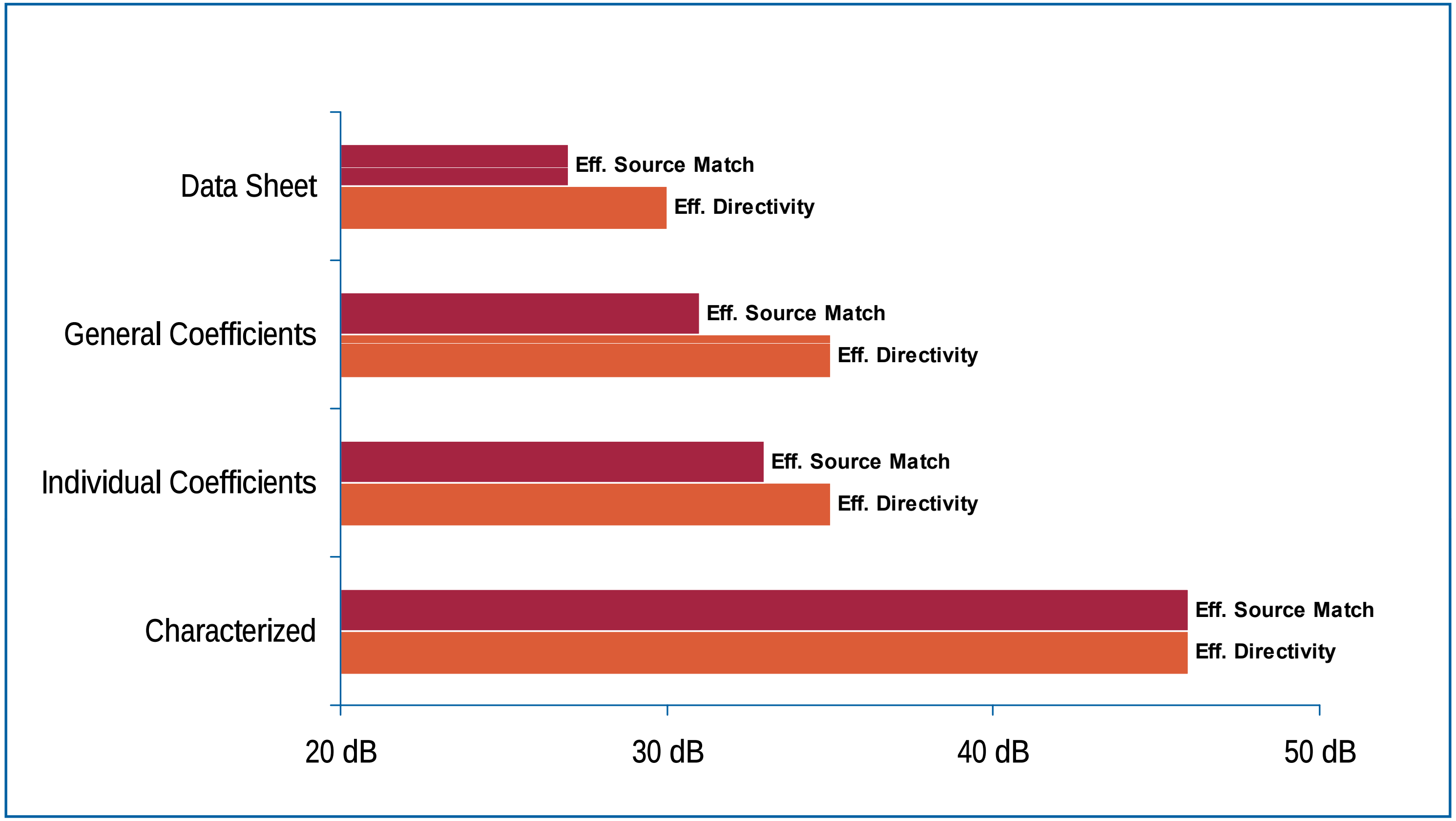
Performance of same Economy – Kit after characterization! (red)



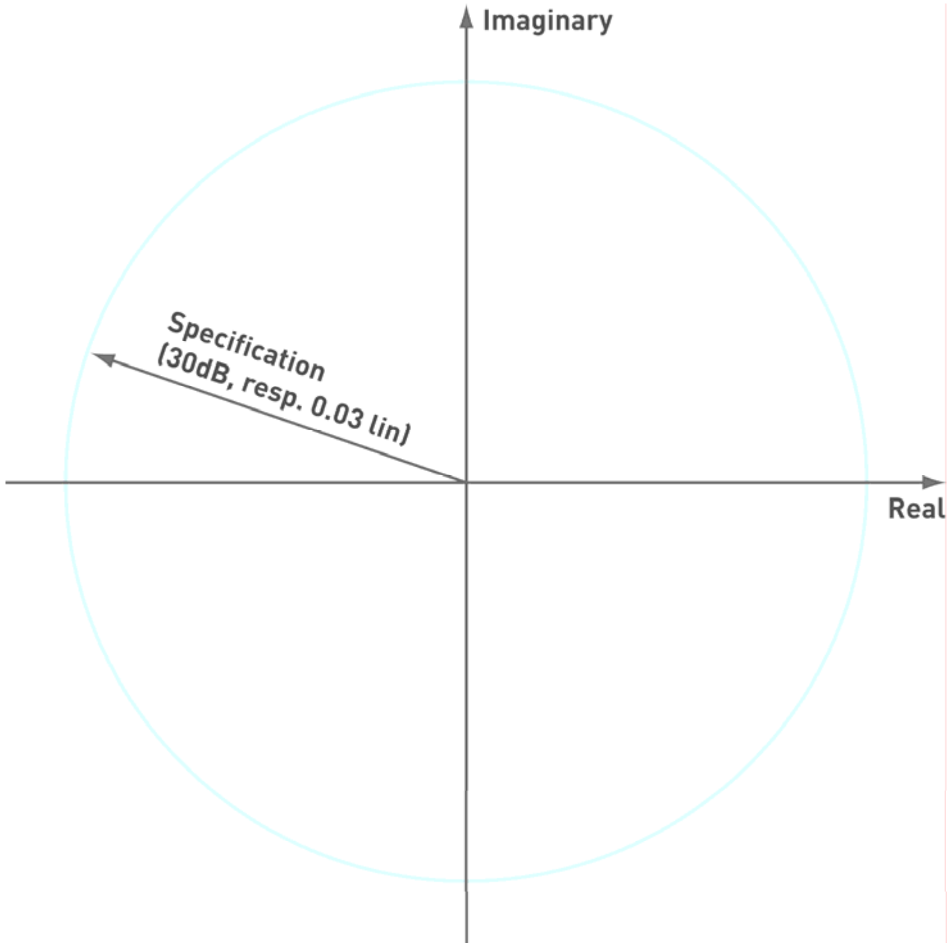
Performance of „Sliding Load Calibration Kit“



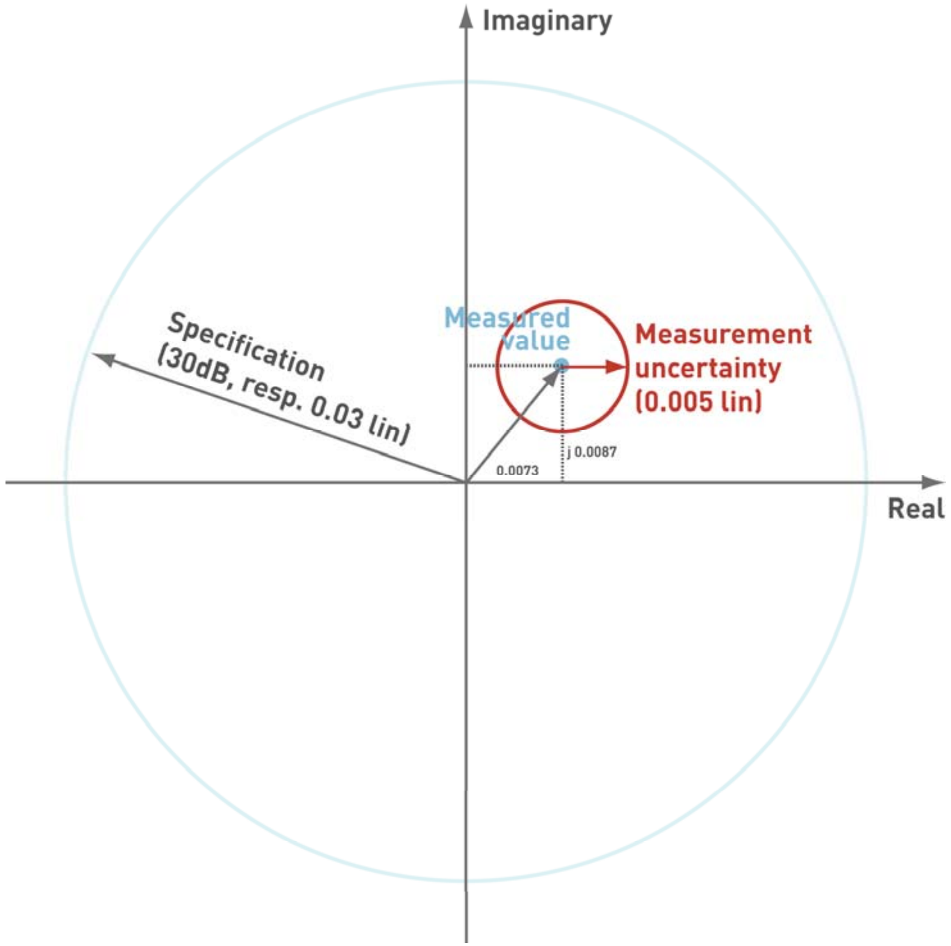
Performance of „Economy Calibration Kit“



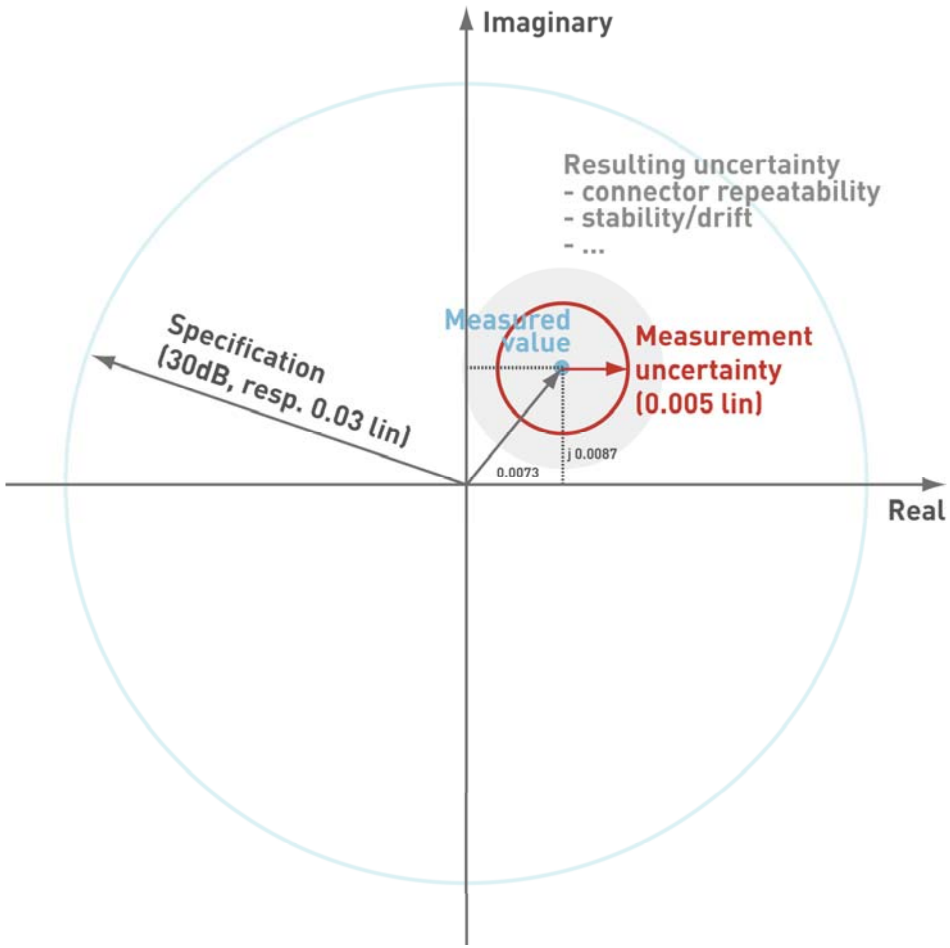
Performance of „Economy Calibration Kit“



Performance of „Economy Calibration Kit“



Performance of „Economy Calibration Kit“



Measurement uncertainties in brief

- **According EURAMET/cg-12/v.01 the uncertainty model for measuring S_{11}, S_{22} can be approximated as follows:**

$$U_{VRC} = D + T \cdot \Gamma + M \cdot \Gamma^2 + R_{VRC}$$

- where
  - **Γ is the Measured Voltage Reflection Coefficient**
  - **D is the Measured Effective Directivity**
  - **T is the Estimated Overall Effect of Tracking and Non-linearity**
  - **M is the Measured Effective Test Port Match**
  - **R_{VRC} represents all the Random contributions**

Measurement uncertainties in brief

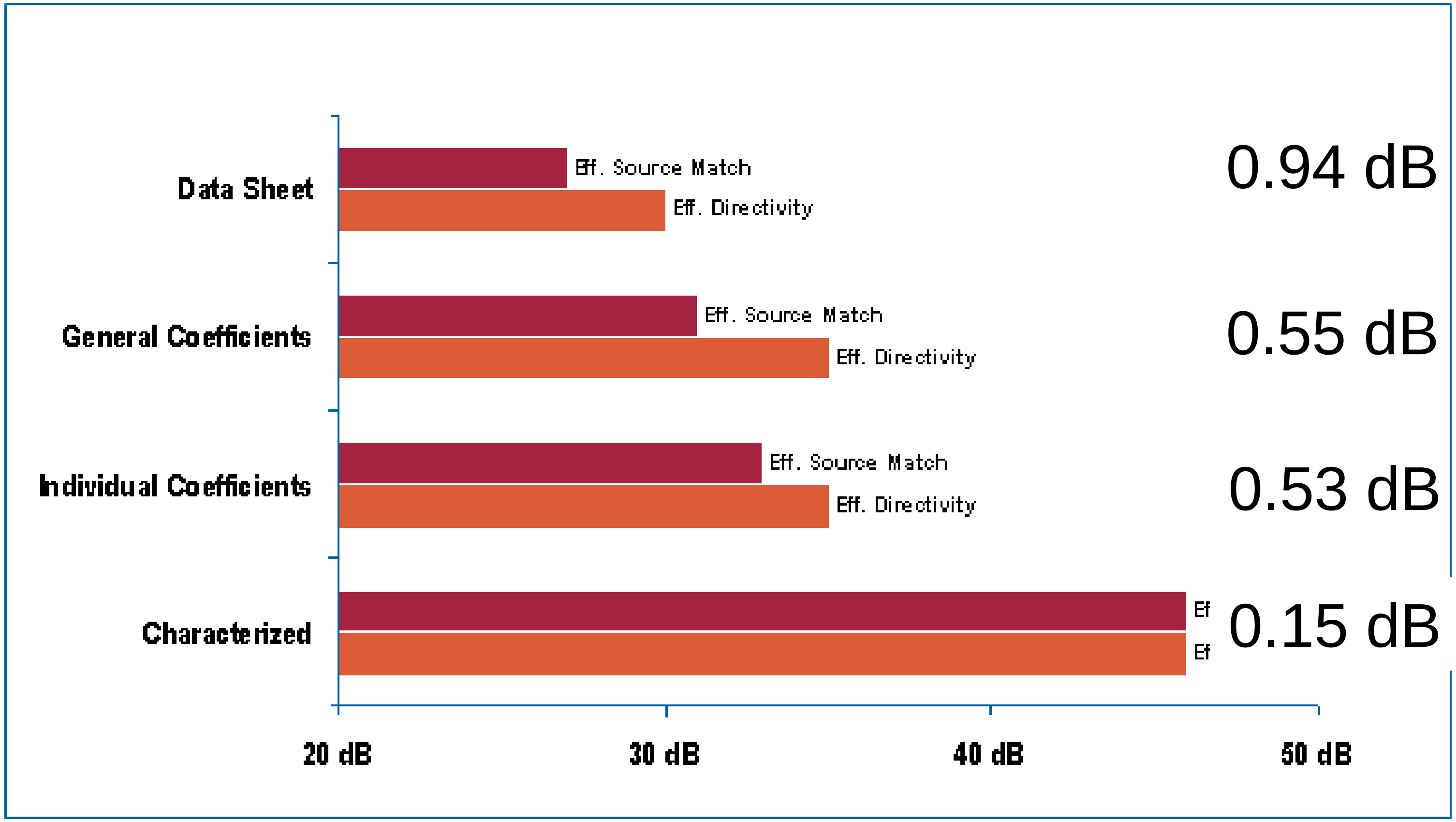
- **For demonstration reasons this model is furthermore simplified to the dominating terms :**

$$U_{VRC} \approx D + M \cdot \Gamma^2$$

- where
  - **Γ   is the Measured Voltage Reflection Coefficient**
  - **D   is the Measured Effective Directivity**
  - **M   is the Measured Effective Test Port Match**

Uncertainty using the „Economy Calibration Kit“
Return loss of DUT: 10 dB

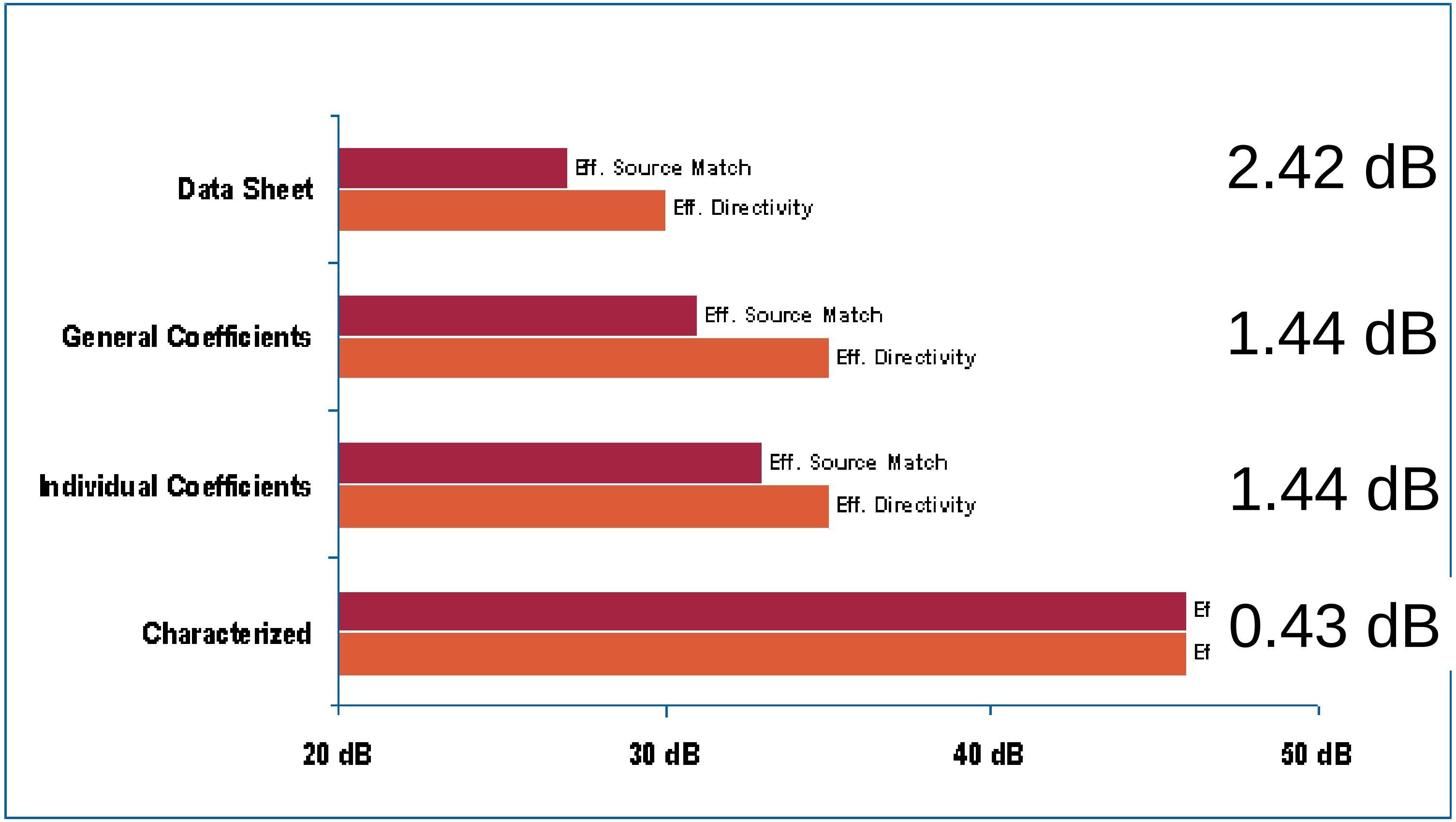
U_{VRC} (dB)



Uncertainty using the „Economy Calibration Kit“

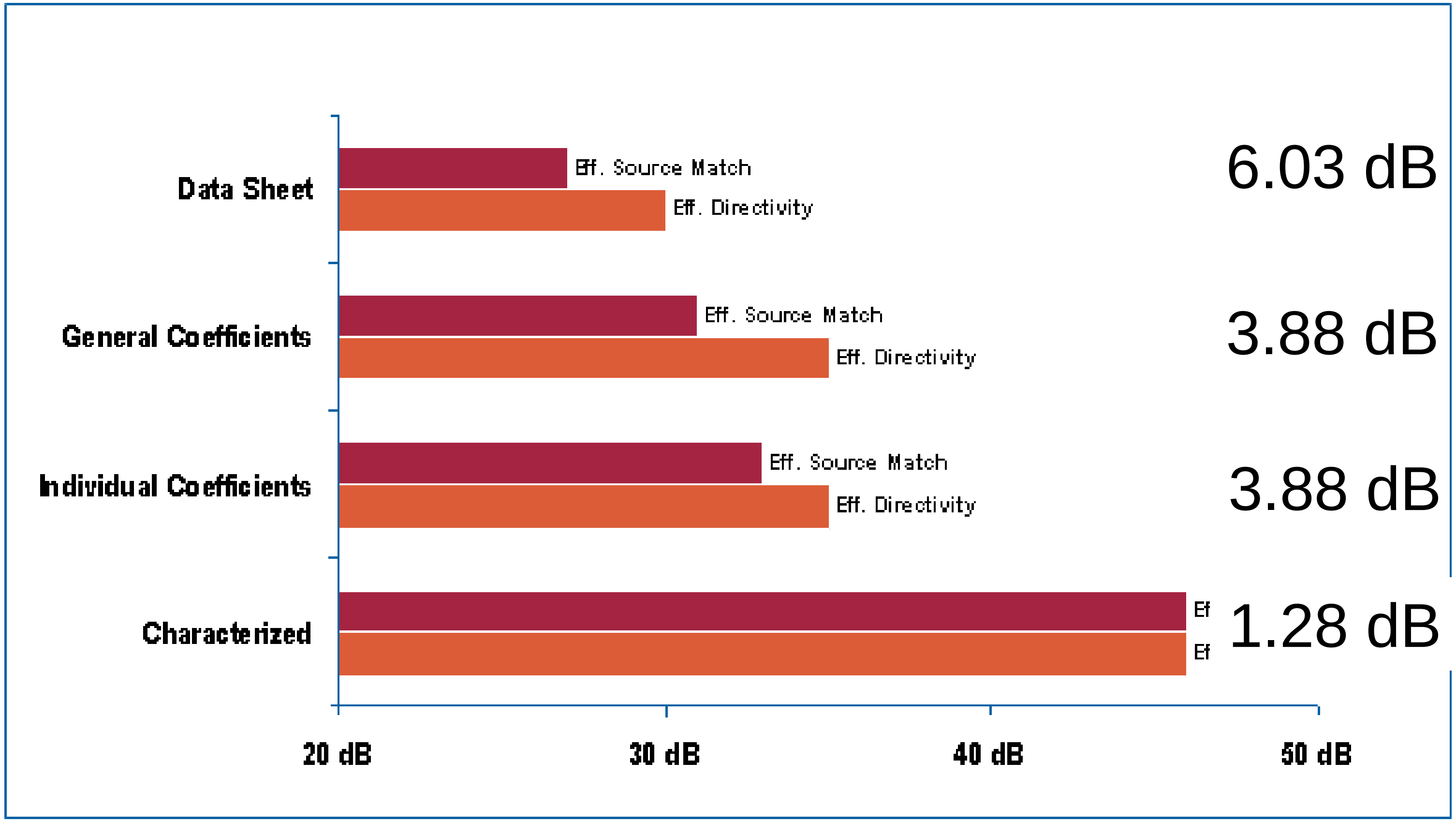
Return loss of DUT: 20 dB

U_{VRC} (dB)



Uncertainty using the „Economy Calibration Kit“
Return loss of DUT: 30 dB

U_{VRC} (dB)



Benefits of using characterized, data based standards

- **Improved accuracy**
  - as e.g. the mean value of several calibrations,
    e.g. even of several calibration kits
    and / or different calibration procedures (sliding load, TRL, …)
    can be transfered to a „fixed load“ calibration kit.

- **Improved precision in production lines**
  - as several calibration kits can be derived from one „reference“ source

- **Improved repeatability – as a significant error source (human errors) is minimized.**

- **Reducing the complexity of the calibration process saves time and helps keeping the numbers of errors low**

Benefits
- if calibration data are used

- **Increased accuracy @ no additional costs !**
  - If calibration results of the individual standards are available in electronic form (e.g. in touchstone S1P format) this major improvement in accuracy is „for free“.

- **„Improved traceability“ – result is shifted closer to the „true“ value (e.g. the reference values provided by a NMI)**

Benefits
- if calibration data are used

IT'S FREE!

- **Increased accuracy @ no additional costs !**
  - If calibration results of the individual standards are available in electronic form (e.g. in touchstone S1P format) this major improvement in accuracy is „for free“.
- **„Improved traceability“ – result is shifted closer to the „true“ value (e.g. the reference values provided by a NMI)**

Agenda

- **RF & MW Power Measurement**
  - Expanding the power measurement range of R&S NRP-Zxx power sensors
  - NRP-Z27/37 – Power Sensor modules for R&S FSMR Measurement Receiver
- **Vector Network Analysis**
  - Improving measurement accuracy by means of characterized calibration standards.
  - Using previous calibration results to improve accuracy.
  - User characterization of R&S ZV-Z5x automatic calibration units

USER – characterization of automatic calibration units ZV-Z5x

- **Automatic calibration units provide high levels of accuracy – and reduce the calibration time (especially when it comes to multiport calibrations) dramatically.**
- **Also, operation errors are reduced to a minimum. (e.g. there‘s an automatic detection of connectoed ports)**
- **However – even offering a high number of different types of such calibration units still does not solve all customer application problems.**

USER – characterization of electronic calibration units ZV-Z5x

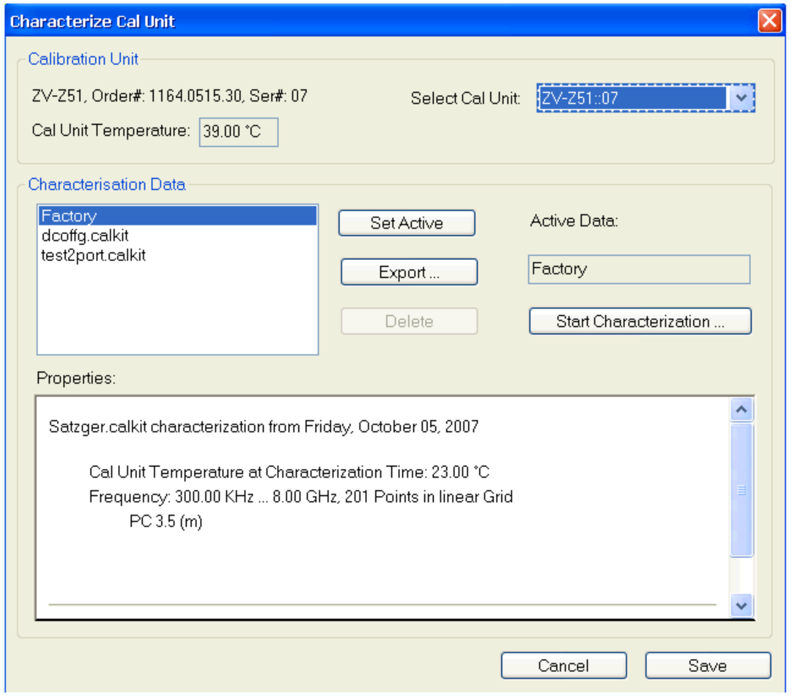
- **Simplified spoken a calibration unit can be considered as transfer standard only.**

- **I.e. if a VNA is calibrated (by means of a mechanical calibration kit or a suitable Calibration Unit) – this calibration can be used to characterize a Calibration Unit including e.g. adapters or matching pads etc. !**

- **This way a user can simply create the Cal Unit which is ideal for the application / purposes.**

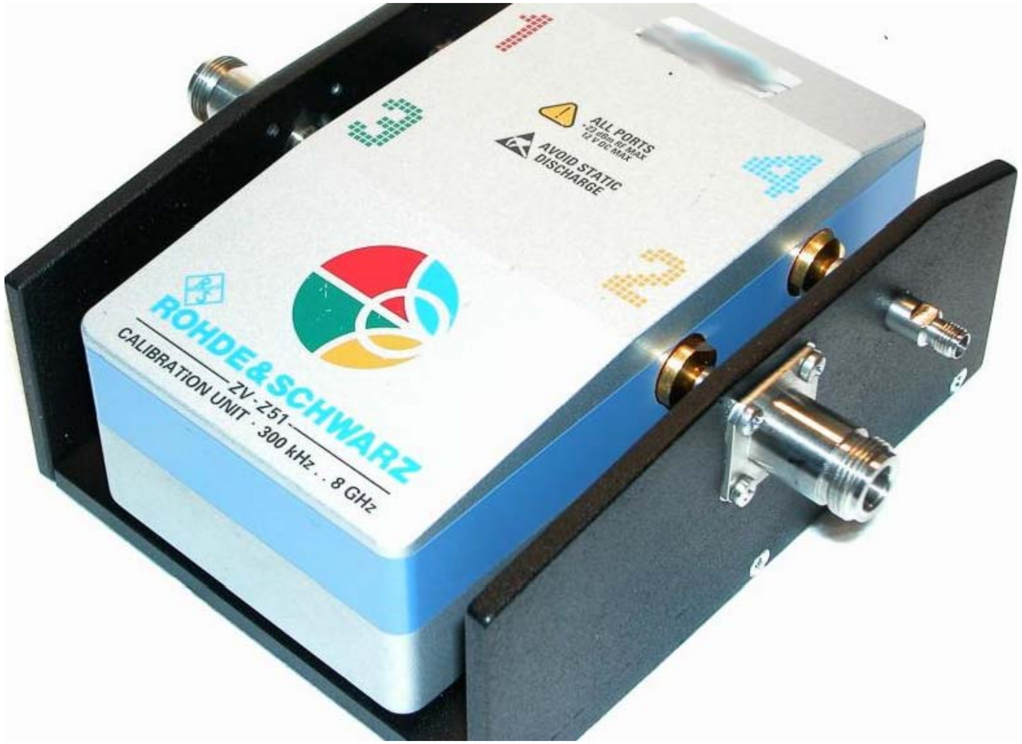
USER – characterization of electronic calibration units ZV-Z5x

- **The „USER – characterziation(s)“ is/are stored in addition to the (write - protected) factory – characterization and is fully supported by a wizard guiding the user.**



USER – characterization of electronic calibration units ZV-Z5x

- **Example: Customized Cal Unit serving a goals:**
  - support of N and 3.5mm in a „one box solution“
  - includes „port savers“



Summary

- When aiming for smaller measurement uncertainties identifying (and removing) systematic error sources should be one of the first steps to be performed.
- Using calibration data in mathematical corrections can help to significantly reducing measurement uncertainties in RF & MW measurements - while keeping associated costs low.
- If already integrated in the FW of smart T&M instruments even sophisticated mathematical corrections are very easy to be implemented.

End of presentation.

Muchas Gracias.

References – further reading

- EURAMET/cg-12/v.01:
  Guidelines on the Evaluation of Vector Network Analysers (VNA)
  July 2007
- EURAMET:
  Metrology in Short – 3rd Edition.
  July 2008
- R&S NRP Power Meter Family – Product Brochure
  V 3.00. July 2008
- Measuring Receiver R&S FSMR – Product Brochure
  V 2.00. April 2006
- R&S ZV-Z5x Calibration Units – Specifications
  Data Sheet. V 9.01

Contact

Dipl. Ing. [FH] Harald Jaeger

Rohde & Schwarz GmbH & Co. KG
Service Memmingen, Dept. 5SMM-T
Rohde-und-Schwarz-Str. 1
D-87700 Memmingen

harald.jaeger@rohde-schwarz.com
www.rohde-schwarz.com