Rohde & Schwarz Technology Seminar

Demystifying the Vector Network Analyser

Rohde & Schwarz Benelux B.V.

November 4th, 2015:
Hotel Mitland, Utrecht/NL

November 5th, 2015:
De Oude Kantien, Heverlee/B

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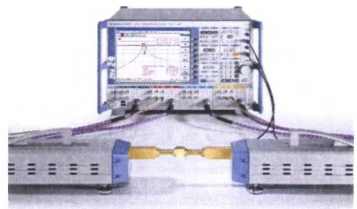
Seminar agenda



09.15 – 09.45
- Connector care and good practices – Jamie Lunn

09.45 – 10.45
- Network Analyser & S-Parameter basics – Jamie Lunn

10.45 – 11.15
- Coffee break & equipment hands-on

11.15 – 13.00
- Network Analyser calibration basics – Jamie Lunn

13.00 – 14.00
- Lunch & equipment hands-on

14.00 – 15.00
- Time Domain Reflectometry (TDR) – Mark Bailey

15.00 – 15.30
- Understanding measurements uncertainty and verification – Jamie Lunn

15.30– 16.00
- Coffee break & equipment hands-on

16.00 – 17.00
- Basic amplifier measurements with a Network Analyser – Mark Bailey

17.00
- Questions & finish

Demystifying the Network Analyser: Connector care and good practices

Jamie Lunn
Network Analyser Product Manager
(UK & Ireland)

R&S, November 2015

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Connector background: Why 50 Ohms?

Cable loss verses impedance

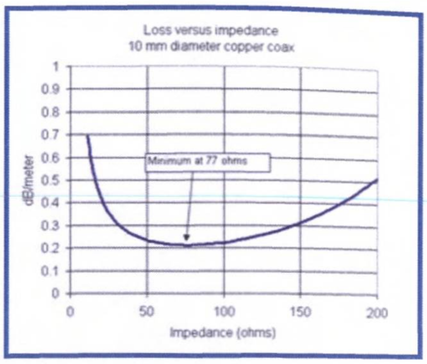
The impedance of coax is a function of the ratio of the inner/outer diameter and the dielectric material.
Minimum insertion loss is calculated out to be around **77 Ω.**

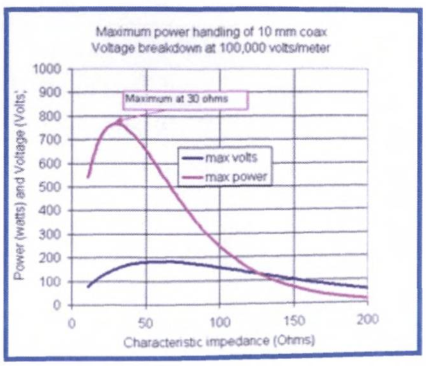
Peak Power Handling

The best peak power handling occurs at **30 Ω.**

The 50 ohm compromise

The mean between **77 Ω** and **30 Ω** is **53.5 Ω.**
50 Ω is the compromise between power handling capability and signal loss per unit length for an air dielectric.





Connector background: Why Different Connectors

Coaxial cables and connectors are designed to allow only one mode of propagation, TEM (Transverse ElectroMagnetic)

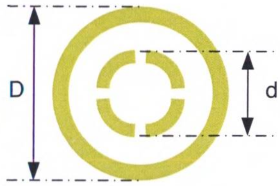
Above the cut-off frequency higher order modes can propagate interfering with the wanted mode (TE11).

Cut off Frequency is dependant on the connector dimensions.

$$f_c(GHz) = \frac{190.85}{(D+d)\sqrt{\varepsilon_R}}$$

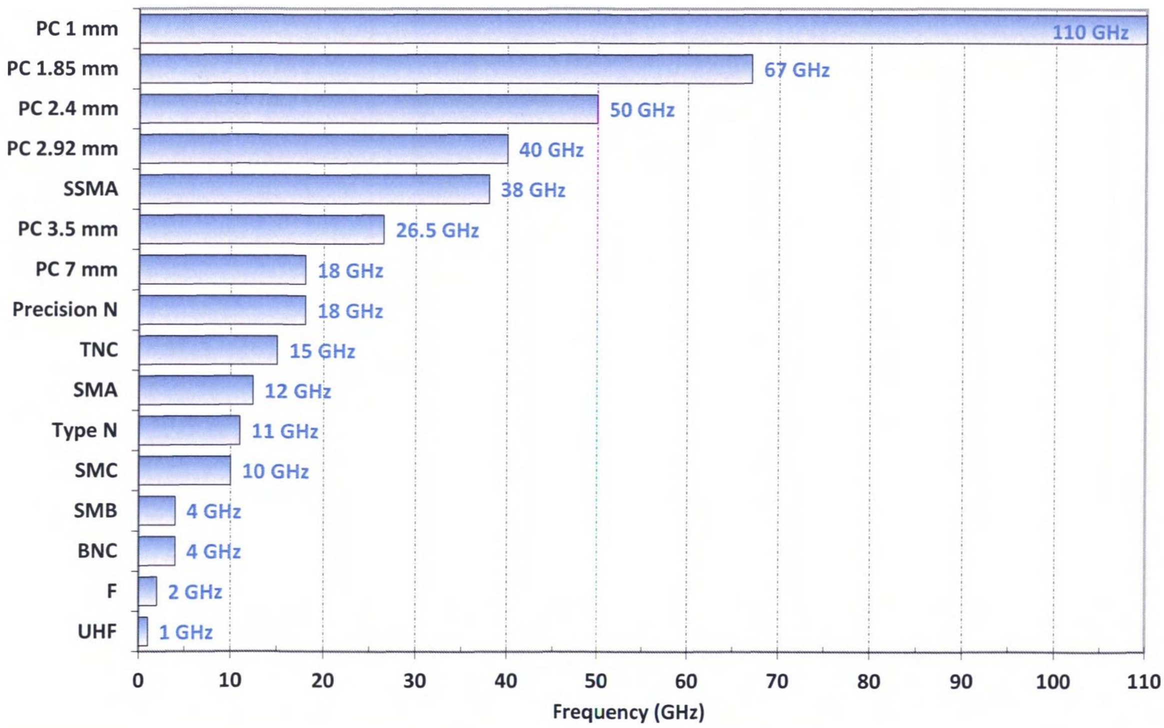
for D and d in millimeters

Coax Cross Section



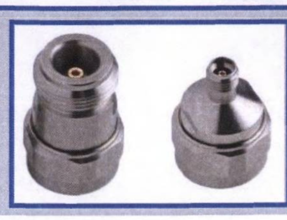
At higher frequencies the ratio D/d is reduced to increase the cut-off frequency. (example 3.5mm is 38GHz)

Coaxial Connector Frequency Overview



Common Test Equipment Connector Types

- Type N (18GHz)
- APC 7 mm (18GHz)
- SMA (18 GHz)
- PC 3.5 mm (26.5 GHz)
- PC 2.92 mm, K Connector (40 GHz)
- PC 2.4 mm (50 GHz)
- PC 1.85 mm, V Connector (67 GHz)



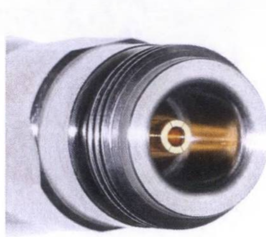
Type N & Precision 7 mm connector

Named after Paul Neill of Bell Labs after being developed in the 1940's. The Type N (Navy) connector was developed to satisfy the need for a durable, weatherproof, medium-size RF connector with consistent performance through 12 GHz. Precision Type N connectors are available up to 18GHz.

*Note: 75 ohm Type N designs have a smaller centre conductor and thus are not compatible with 50 ohm Type N connectors.

Max Frequency: **11 & 18 GHz**
Dielectric: **PTFE or Air**
Outer Conductor: **7.0 mm**
Recommended torque value:

12lb-inch (136N-cm)



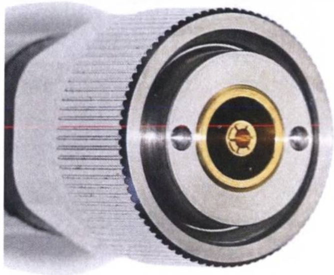
APC 7 or 7mm connector

APC-7 stands for "Amphenol precision connector", 7mm. Developed in the 60s jointly by Amphenal and HP, and is a sexless connector design. It provides the lowest VSWR and highest repeatability of any connector up to 18 GHz.

This connector has generally been replaced by Type N in most applications.

Max Frequency:	**18 GHz**
Dielectric:	**Air**
Outer Conductor:	**7.0 mm**
Recommended torque value:	

12lb-inch (136N-cm)



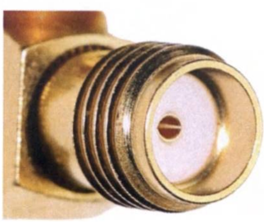
SMA connector

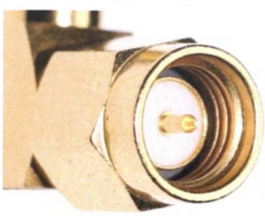
SMA (Sub Miniature version A) and was developed in the 1960's by Bendix Scintilla Corporation. 50 Ω SMA connectors are semi-precision, sub miniature units that provide good electrical performance from DC to 18 GHz.

These general purpose connectors are compact in size and mechanically have good durability. These are one of the most commonly used RF/Microwave connector.

Max Frequency:	**12 GHz (18 GHz)**
Dielectric:	**PTFE**
Outer Conductor:	**3.5 mm**
Recommended torque value:	

5lb-inch (56N-cm)





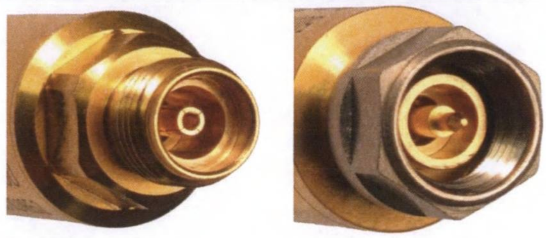
PC 3.5 mm connector

A precision (expensive) connector, based upon the original SMA connector. Its design strategy focused on highly-rugged physical interfaces that would mate with popular SMA dimensions, allowing thousands of repeatable connections.

This connector is fully compatible with cheaper SMA connectors but watch the tolerance of the centre pin of male SMAs

Max Frequency:	26.5GHz
Dielectric:	Air
Outer Conductor:	3.5 mm
Recommended torque value:	

8lb-inch (90N-cm)



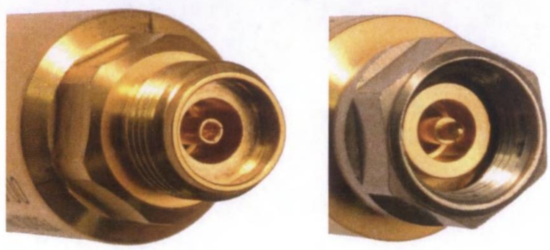
PC 2.92 mm or K connector

Precision connector, developed by Mario Maury in 1974. 2.92 mm will interface to cheaper SMA and PC 3.5 mm connectors. Often called "2.9 mm".

The original mass-marketed 2.92 mm connector, made by Wiltron (now Anritsu). Named the "K" connector, meaning it covers all of the K frequency bands.

Max Frequency:	40GHz
Dielectric:	Air
Outer Conductor:	2.92 mm
Recommended torque value:	

8lb-inch (90N-cm)

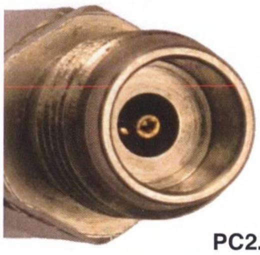


PC 2.4 & 1.85 mm Connectors

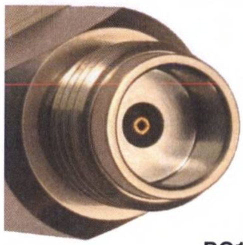
The 2.4 (50GHz) and 1.85 (67GHz) connectors are mechanically compatible with each other, but neither one will interface onto an SMA, 3.5 or 2.92 mm connector. This is intentional, so it's not possible to mix these expensive connectors in with less precise connectors such as SMA and cause irreparable damage.

Developed by Julius Botka and Paul Watson in 1986, along with the 1.85 mm connector.

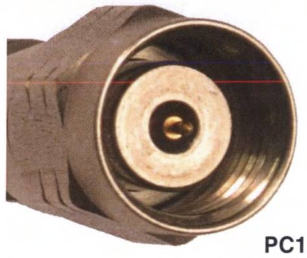
The 1.85 connector is often called the "V connector" as it covers the V frequency bands



PC2.4mm (f)



PC1.85mm (f)



PC1.85mm (m)

PC 1.00 mm Connector

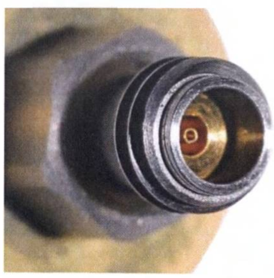
The coaxial cavity of this connector type has a smaller geometry to support the higher frequency.

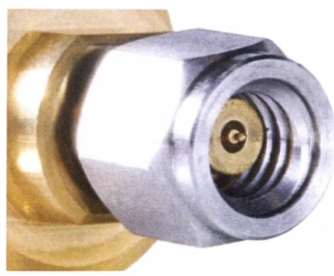
The mechanical coupling and thread sizes have been designed to maximize strength and to minimize damage to the inner conductor during the connecting process.

This connector is not compatible with any other connector design.

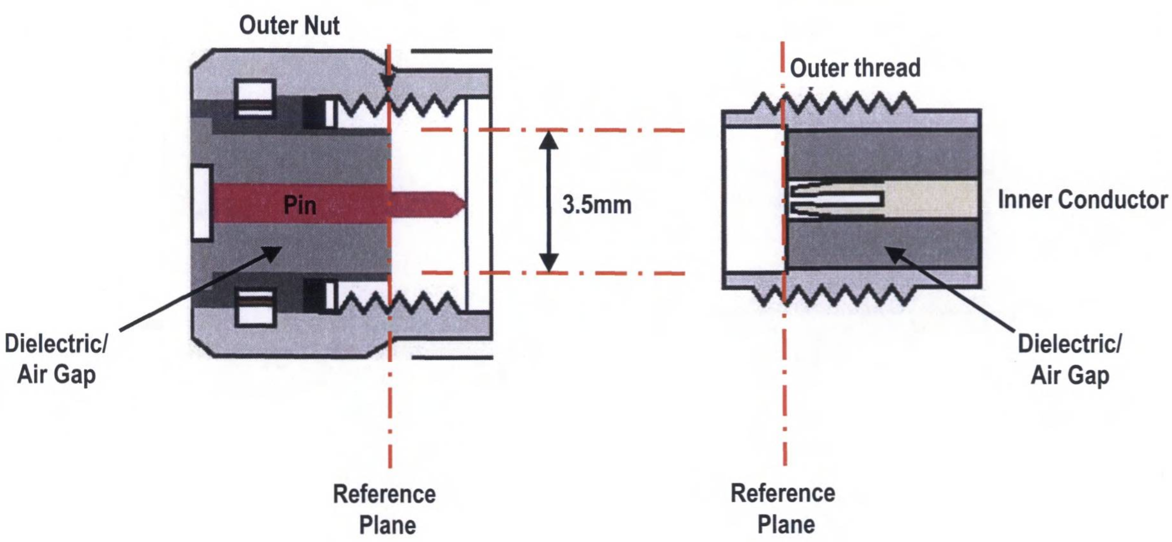
Max Frequency:	**110GHz**
Dielectric:	**Air**
Outer Conductor:	**1.00 mm**
Recommended torque value:	

3lb-inch (34N-cm)

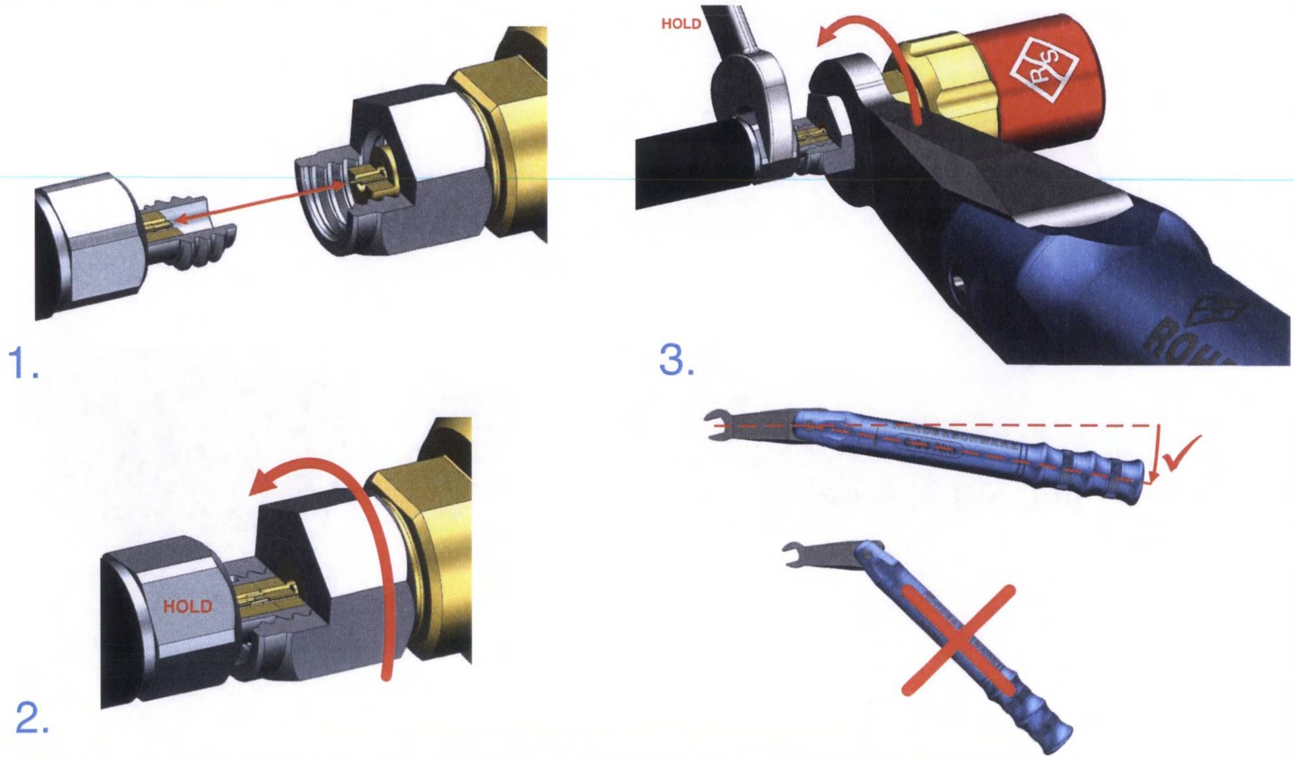




Construction of SMA/PC3.5mm connector



Alignment of coaxial connector



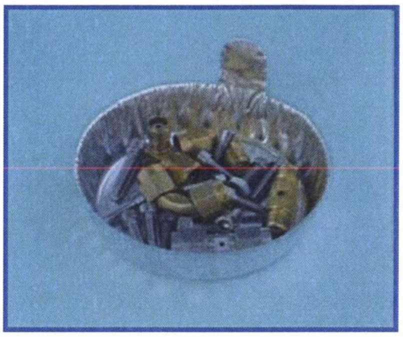
Handling and Storage

Do's

- ✓ Keep connectors clean
- ✓ Use plastic end caps during storage

Don'ts

- ✗ Do not store connectors loosely together
- ✗ Do not place connector face down on surfaces



Visual Inspection

Do's

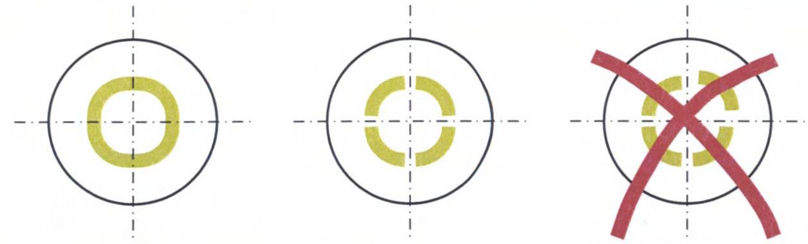
- ✓ Always Inspect all connectors carefully before each connection
- ✓ Look for metal particles/contaminants and defects

Don'ts

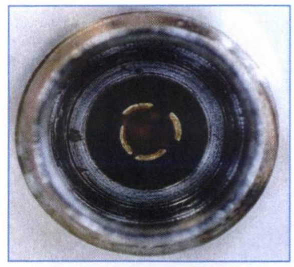
- ✗ Never use a damaged connector – Ever !!

Contact Integrity and Concentricity

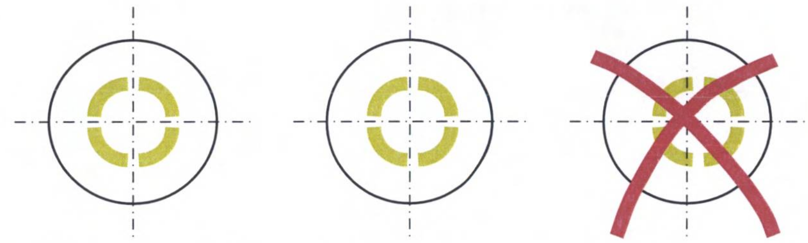
Contact Integrity



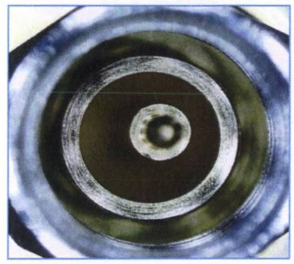
Perfectly formed contacts | Normal wear | Damaged contacts



Concentricity

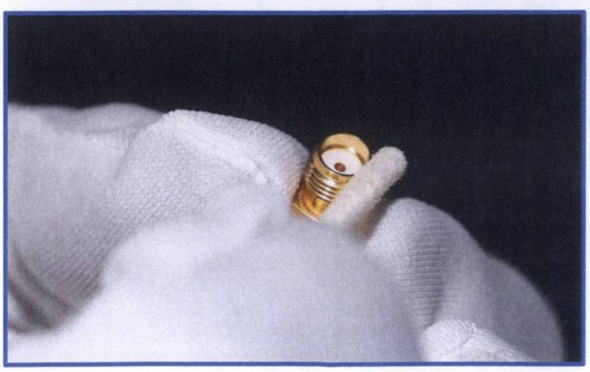


Perfectly Concentric | Slightly off centre | Excessively off centre



Connector Cleaning

- Use compressed air to dislodge any particles
- Use Isopropyl alcohol (do not use acetone)
- Use foam swabs, or lint free cloth
- Clean connector threads



Connector Gauging

Do's

- ✓ Clean and zero gauge before use
- ✓ Use correct gauge type for connector
- ✓ Use correct calibration block
- ✓ Gauge all connectors before use

Don'ts

- ✗ Use out of spec connector

Making Connections

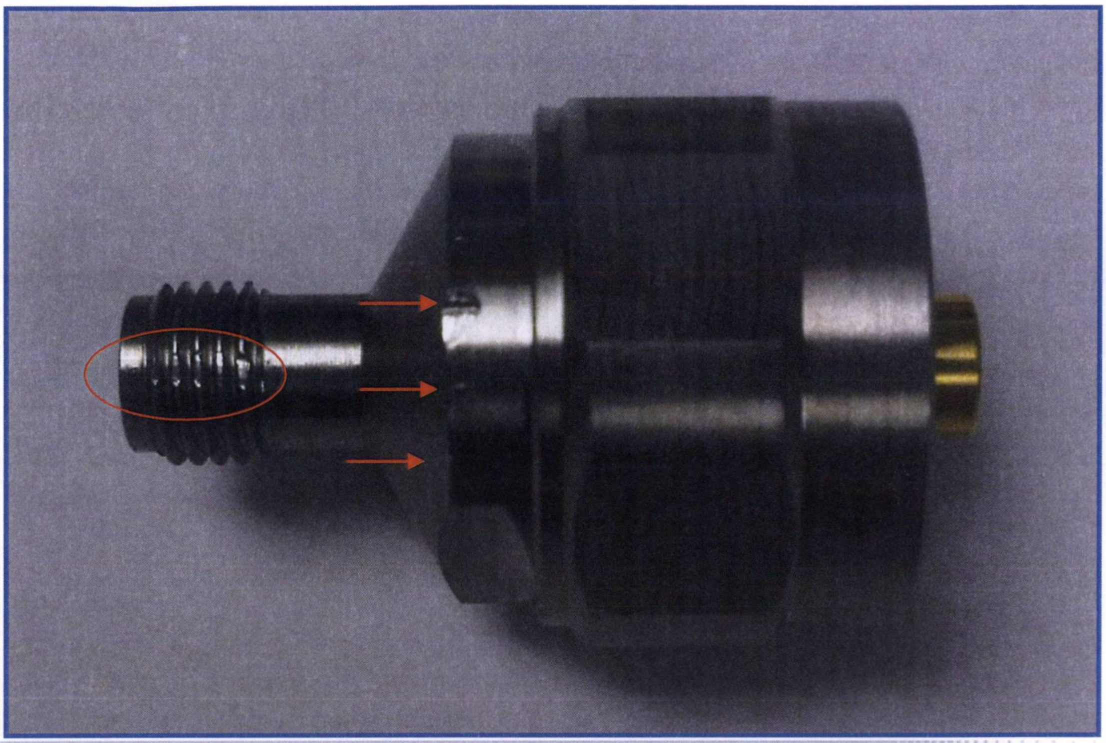
Do's

- ✓ Align connectors carefully
- ✓ Make preliminary connection carefully
  Do not use force!
- ✓ Only turn the outer connector nut…
- ✓ Use a torque wrench to tighten connector (check torque setting)

Don'ts

- ✗ Do not use pliers
- ✗ Do not tighten past torque wrench "break" point

Damaged connector by not using correct tools



Precision Calibration Kits and Cables

Precision Network Analyser calibration kits represent a substantial cost for replacement

Each standard must be stored with protective cover/dust cover

Ensure all standards are kept stored in the supplied box

Do not connect to low cost/cheap cables

Use connector savers where possible

Future considerations – Colour coordination*

■	Black	= 18 GHz	Type N connector
■	Brown	= 18 GHz	SMA connector
■	Red	= 20.0 GHz	Precision Type N connector
■	Orange	= 26.5 GHz	3.5mm connector
■	Yellow	= 40 GHz	2.92mm (K) connector
■	Green	= 50 GHz	2.4mm connector
■	Blue	= 67 GHz	1.85mm (V) connector
■	Violet	= 18 GHz	GPC-7 connector
■	Gray	= < Reserved for future use>	
□	White	= 110 GHz	1.0mm (W) connector

*IEEE Project Authorisation Request P1802 submitted for review January 2009 & approved May 2009.

Colour coded connector

Connector Adapter, 2.92mm(K) to 2.4mm
KEY: Yellow = 2.29mm K connector
Green = 2.4mm connector

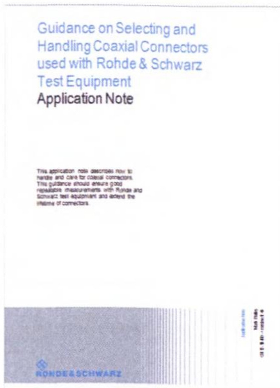
References

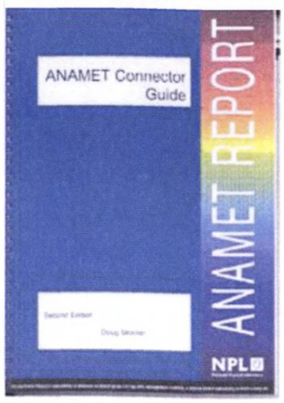
- **Guidance on Selecting and Handling Coaxial Connectors used with Rohde & Schwarz Test Equipment**
  Rohde & Schwarz Application note 1MA99_0e

- **Anamet connector guide**
  www.npl.co.uk/electromagnetic/clubs/anamet/connector_guide.pdf

- **Microwaves101.com**
  www.microwaves101.com/encyclopedia/connectors.cfm

- **Interchangeable Port Connector System, Test Port Adapter System**
  Rohde & Schwarz Application note 1MA100_3e





Questions?

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Rohde & Schwarz
Vector Network Analysis
Basics Training

Jamie Lunn
Vector Network Analyser Product Manager
UK & Ireland

R&S, November 2015

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Agenda

- S-Parameter Basics
- Formatting of complex data
- Sources of measurement errors
- Calibration techniques
- Enhanced calibration

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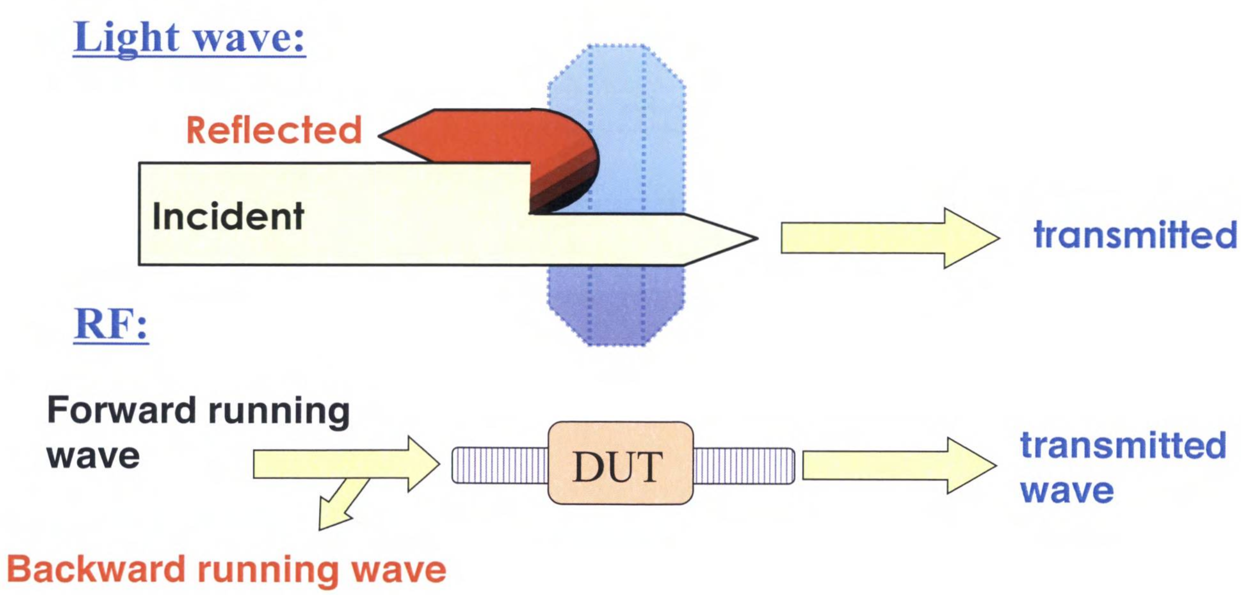
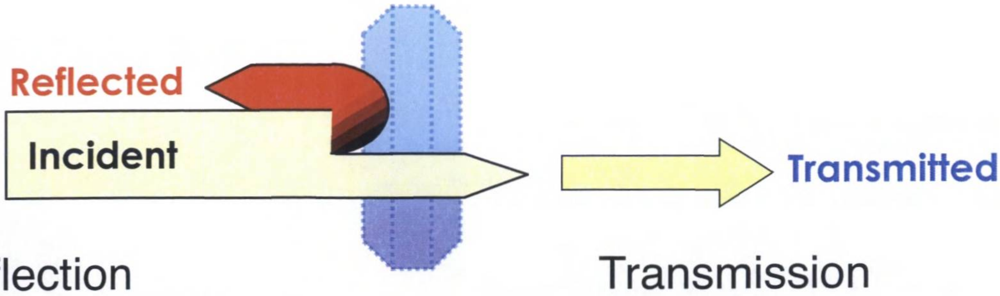
Reflection and transmission

Light wave analogy to RF-energy



RF Device Characterisation

Uni-Directional characterisation (one Path 2 port)



Reflection

$$\frac{\text{Reflection}}{\text{Incident}} = \frac{\text{Meas}_{\text{Port 1}}(\text{b1})}{\text{Ref}_{\text{Port 1}}(\text{a1})}$$

- SWR
- S-Parameters S11, S22
- Reflection Coefficient Γ, ρ
- Impedance (R+jX), Admittance (G+jB)
- Return loss

Transmission

$$\frac{\text{Transmitted}}{\text{Incident}} = \frac{\text{Meas}_{\text{Port 2}}(\text{b2})}{\text{Ref}_{\text{Port1}}(\text{a1})}$$

- Gain/Loss
- S-Parameters S21, S12
- Transmission Coefficient T, τ
- Phase Shift
- Group Delay

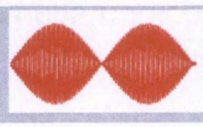
RF Device Characterisation

Reflection Parameters

$$\text{Reflection Coefficient } (\Gamma) = \frac{V_{reflected}}{V_{incident}} = \rho\angle\Phi = \frac{Z_L - Z_0}{Z_L + Z_0}$$

$$\text{Return Loss} = -20\log(\rho) \qquad \rho = |\Gamma|$$

$$\text{VSWR} = \frac{\text{Vmax}}{\text{Vmin}} = \frac{1+\rho}{1-\rho}$$



Reflection Measurements

No reflection ($Z_L = Z_0$)		*Full reflection (Z_L = open, short)*
0	***Reflection Coefficient Γ***	±1
∞ dB	***Return Loss***	0 dB
1	***VSWR***	∞

RF Device Characterisation

Transmission Parameters

$$\text{Transmission Coefficient } (\mathrm{T}) = \frac{V_{transmitted}}{V_{incident}} = \tau\angle\theta$$

$$\text{Insertion Loss (dB)} = -20\log\left|\frac{V_{transmitted}}{V_{incident}}\right| = -20\log\tau$$

$$\text{Gain (dB)} = 20\log\left|\frac{V_{transmitted}}{V_{incident}}\right| = 20\log\tau$$

Transmission Measurements

S-Parameter Basics

Characterising complex RF and Microwave Devices

- Low frequency techniques do not work for RF
  - The parameters H, Y and Z all require measurements to be made with the device terminated with open and short circuits
- Complex impedance computation is required
  - Matching devices over a wide frequency range is hard
- Scattering (S) parameters are used to characterise RF and Microwave devices

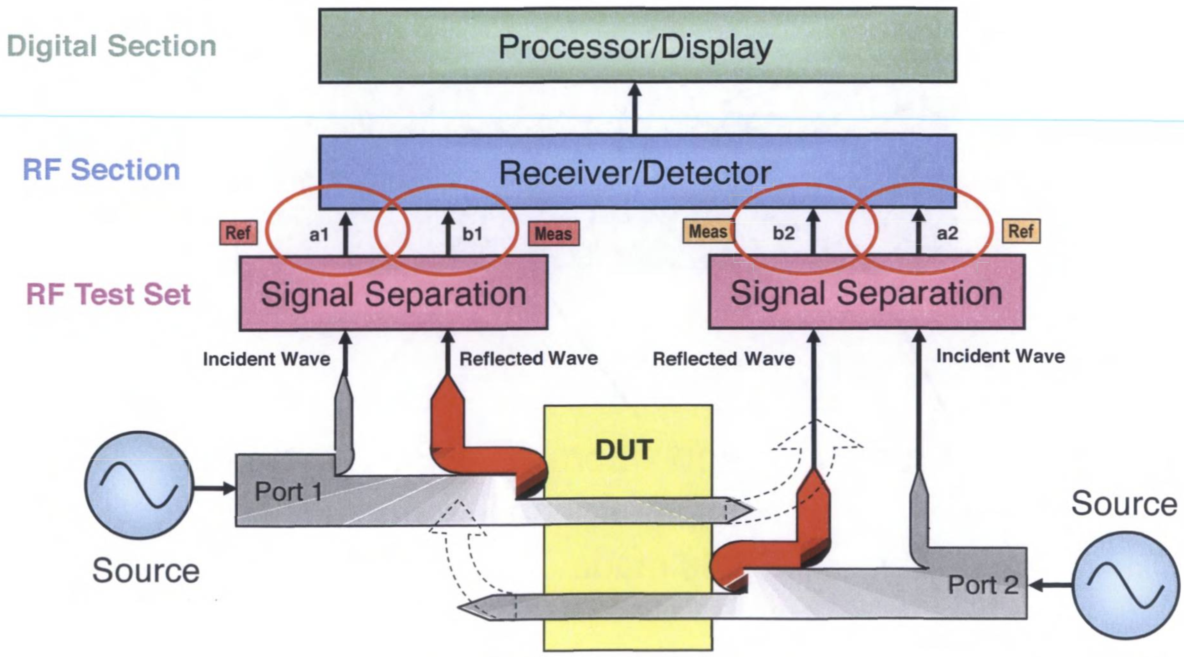
S-Parameter Basics

Benefits of S-Parameters

- Easy to characterise devices at high frequencies
- Avoidance of OPEN and SHORT measurements
- Measurements can be done in a matched (practical) state
- Avoidance of discrete current and voltage measurements
- Relate to familiar measurements (gain, loss, reflection coefficient etc)
- Easily cascaded to measure system performance
- In case of a defined measurement-system it doesn't make any difference to measure:
  - **Voltage**
  - **Current**
  - **Electrical field strength**
  - **Magnetic field strength**

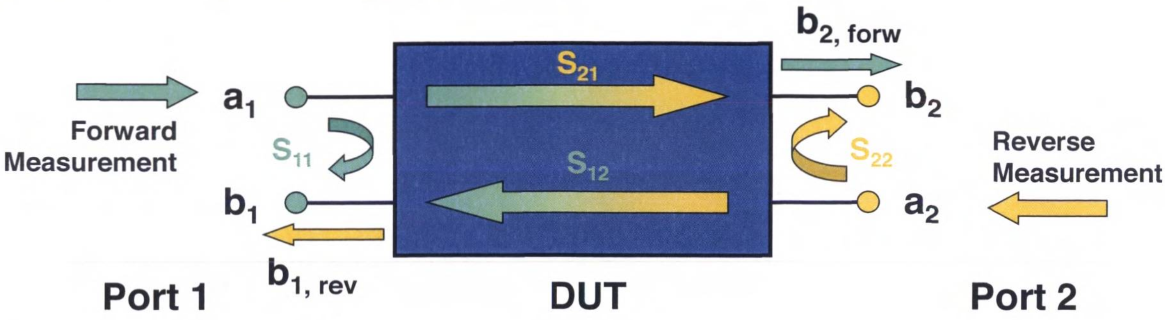
S-Parameter Basics

Realisation of Network Analyser Test set



S-Parameter Basics

Definition of S-Parameter Matrix



Scattering-Parameters (S-Parameters) represent the relationship between scattered waves (a, b)

- S-Parameters represent reflection and transmission coefficients
- S-Parameters are dimension free (units disappear when ratioed)
- These coefficients are based on a defined Line-system (usually 50 ohms)

S-Parameter Basics

Definition of S-Parameter Matrix

Reflected Waves

$$\begin{bmatrix} \underline{b}_1 \\ \underline{b}_2 \end{bmatrix} = \begin{bmatrix} \underline{S}_{11} & \underline{S}_{12} \\ \underline{S}_{21} & \underline{S}_{22} \end{bmatrix} \cdot \begin{bmatrix} \underline{a}_1 \\ \underline{a}_2 \end{bmatrix}$$

Incident Waves

Measured Port of wave quantity

Port where measurement is made

Port where stimulus is fed

S-Parameter terms (2 Port)

S_{11} = Forward reflection coefficient (input match)

S_{22} = Reverse reflection coefficient (output match)

S_{21} = Forward transmission coefficient (gain or loss)

S_{12} = Reverse transmission coefficient (isolation)

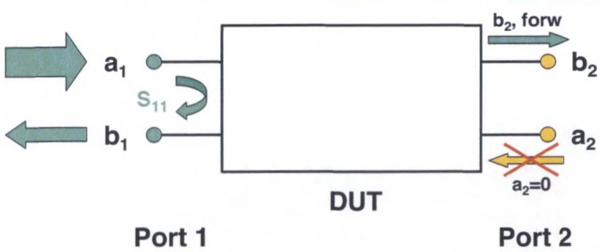
S-Parameters are complex linear power quantities. However we usually express them in a log-magnitude format

S-Parameter terms (2 Port)

$b_1 = S_{11} a_1 + S_{12} a_2$

$b_2 = S_{21} a_1 + S_{22} a_2$

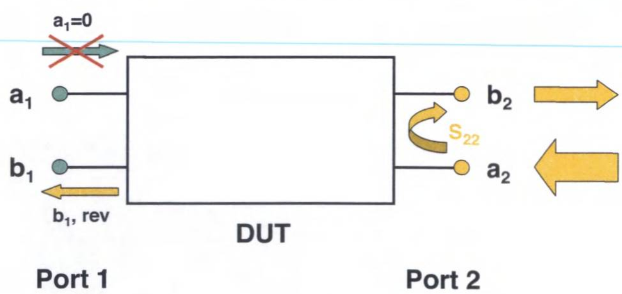
Input reflection coefficient S_{11}



Reflection Coefficient at Port 1 (Port 2 Matched)

$$\underline{S}_{11} = \left.\frac{\underline{b}_1}{\underline{a}_1}\right|_{\underline{a}_2=0}$$

Output reflection coefficient S_{22}



Reflection Coefficient at Port 2 (Port 1 Matched)

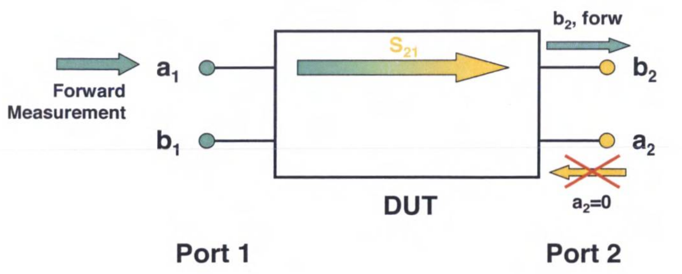
$$\underline{S}_{22} = \left.\frac{\underline{b}_2}{\underline{a}_2}\right|_{\underline{a}_1=0}$$

S-Parameter terms (2 Port)

$b_1 = S_{11} a_1 + S_{12} a_2$

$b_2 = S_{21} a_1 + S_{22} a_2$

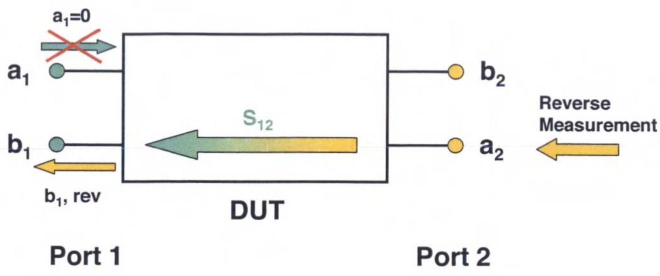
Forward transmission coefficient S_{21}



Forward transmission coefficient for Port 1 to Port 2

$$\underline{S}_{21} = \left.\frac{\underline{b}_2}{\underline{a}_1}\right|_{\underline{a}_2=0}$$

Reverse transmission coefficient S_{12}



Reverse transmission coefficient for Port 2 to Port 1

$$\underline{S}_{12} = \left.\frac{\underline{b}_1}{\underline{a}_2}\right|_{\underline{a}_1=0}$$

S-Parameter terms (2 Port)

Normally logarithmic values of S-parameters are used:

Return Loss:

$$\mathrm{RL} = -20\,log|\Gamma| = -20\,log|S_{11}|$$

Insertion Loss:

$$\mathrm{IL} = -20\,log|\tau| = -20\,log|S_{21}|$$

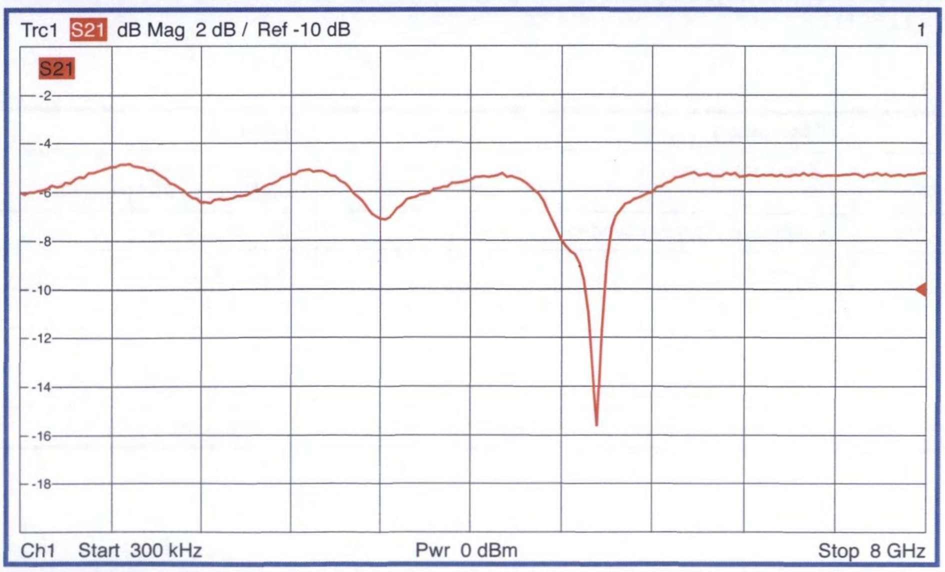
Agenda

- S-Parameter Basics
- Formatting of complex data
- Sources of measurement errors
- Calibration techniques
- Enhanced calibration

Display Formats and Diagram types

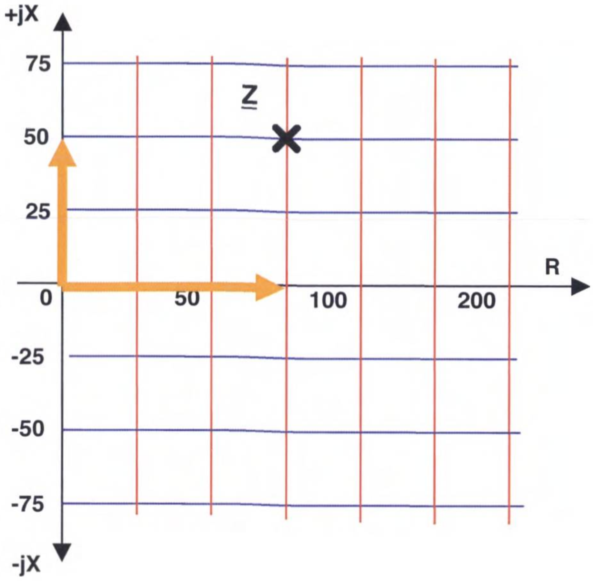
Cartesian format

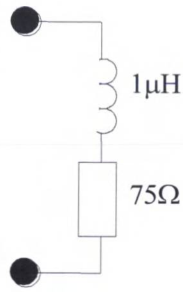
Cartesian diagrams are rectangular diagrams used to display a scalar quantity as a function of the stimulus variable (frequency).



Display Formats and Diagram types

Complex representation





$$f = 7{,}96\mathrm{MHz}$$

$$Z = 75\Omega + j2\pi \cdot 7{,}96\mathrm{MHz} \cdot 1\mu\mathrm{H}$$

$$Z = 75\Omega + j50\Omega$$

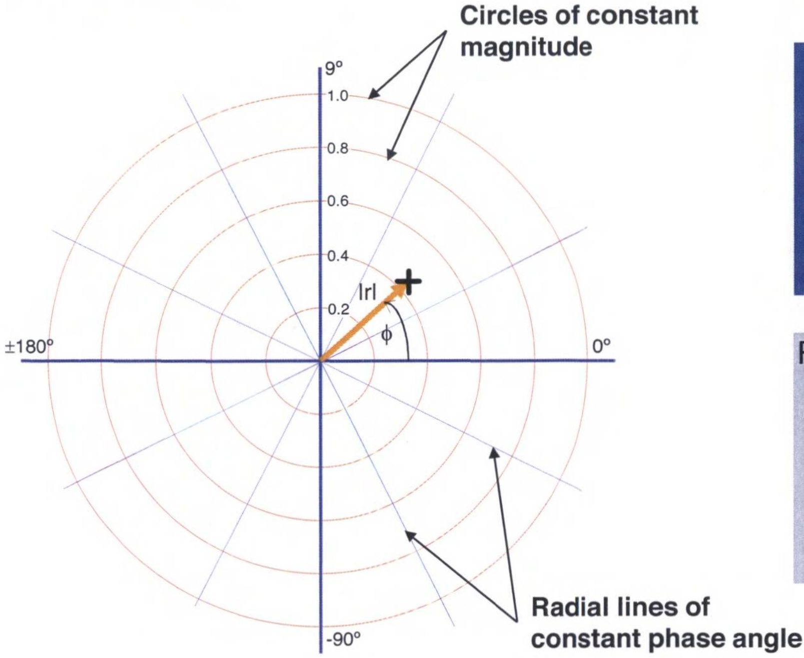
Conversion of Complex into Real Quantities

Conversion to different formats can be derived from the complex measurement value ($Z = X_{REAL} + jY_{IMAG}$)

Trace Format	Description	Formula
dB Mag	Magnitude of z in dB	$\lvert z\rvert = \mathrm{sqrt}\,(x^2 + y^2)$ dB Mag(z) = 20 * log|z| dB
Lin Mag	Magnitude of z, unconverted	$\lvert z\rvert = \mathrm{sqrt}\,(x^2 + y^2)$
Phase	Phase of z	$\phi(z) = \arctan(y/x)$
Real	Real part of z	Re(z) = x
Imag	Imaginary part of z	Im(z) = y
SWR	(Voltage) Standing Wave Ratio	SWR = (1 + |z|) / (1 – |z|)
Group Delay	Group delay, neg. derivative of the phase response	$-d\,\phi(z)/d\omega$ $(\omega = 2\pi * f)$

Display Formats and Diagram types

Polar format



Polar diagrams show data in the complex plane with a horizontal real axis and a vertical imaginary axis.

Reflection coefficient:

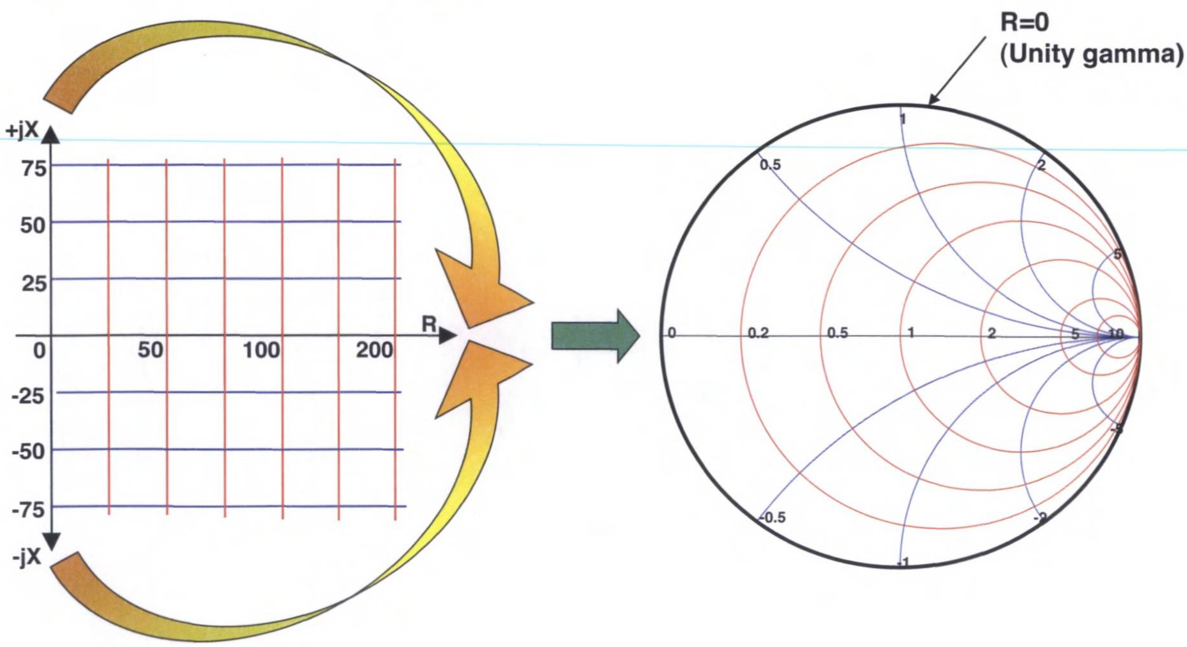
$$Z_0 = 50\Omega$$

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} = \frac{(75 + j50)\Omega - 50\Omega}{(75 + j50)\Omega + 50\Omega}$$

$$\Gamma = 0.415\angle 41.6°$$

Display Formats and Diagram types

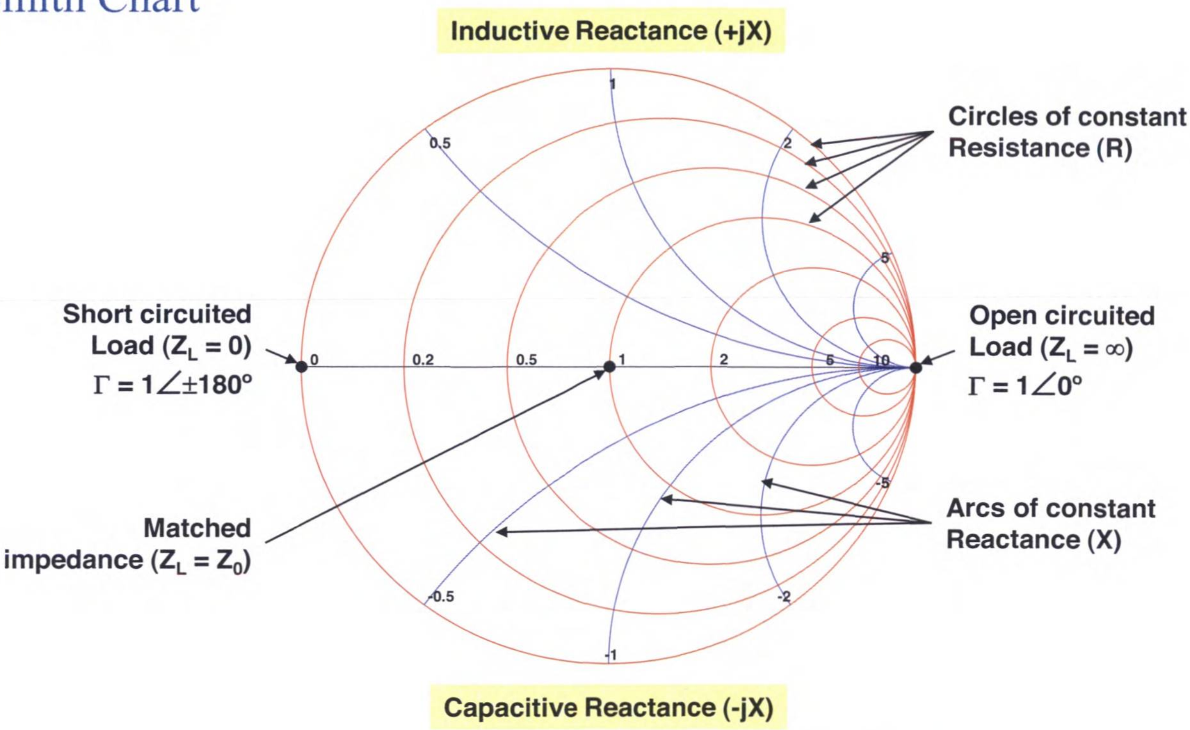
Construction of Smith Chart



Using a mathematical rule it is possible to transform the Cartesian format into a circle format (conforming image)

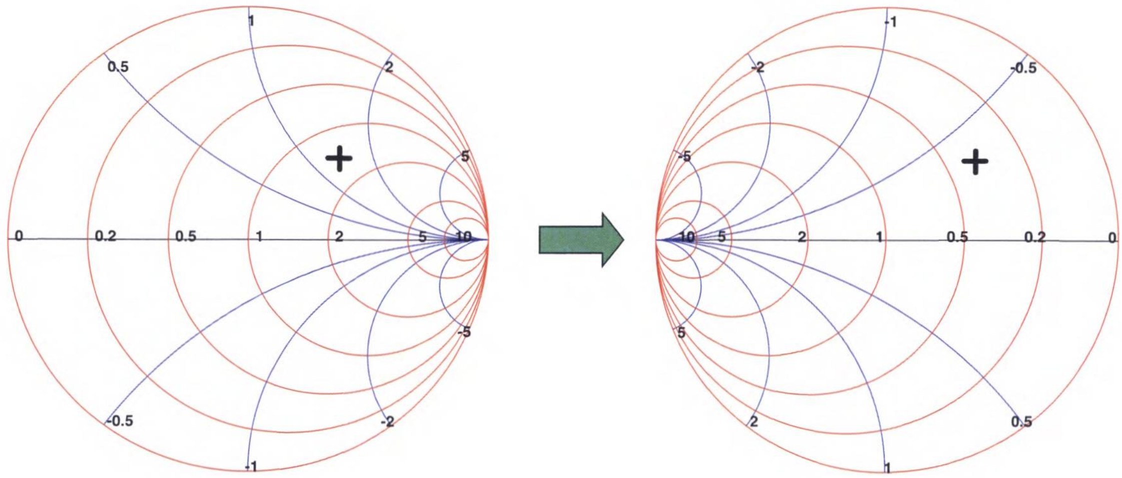
Display Formats and Diagram types

Smith Chart



Display Formats and Diagram types

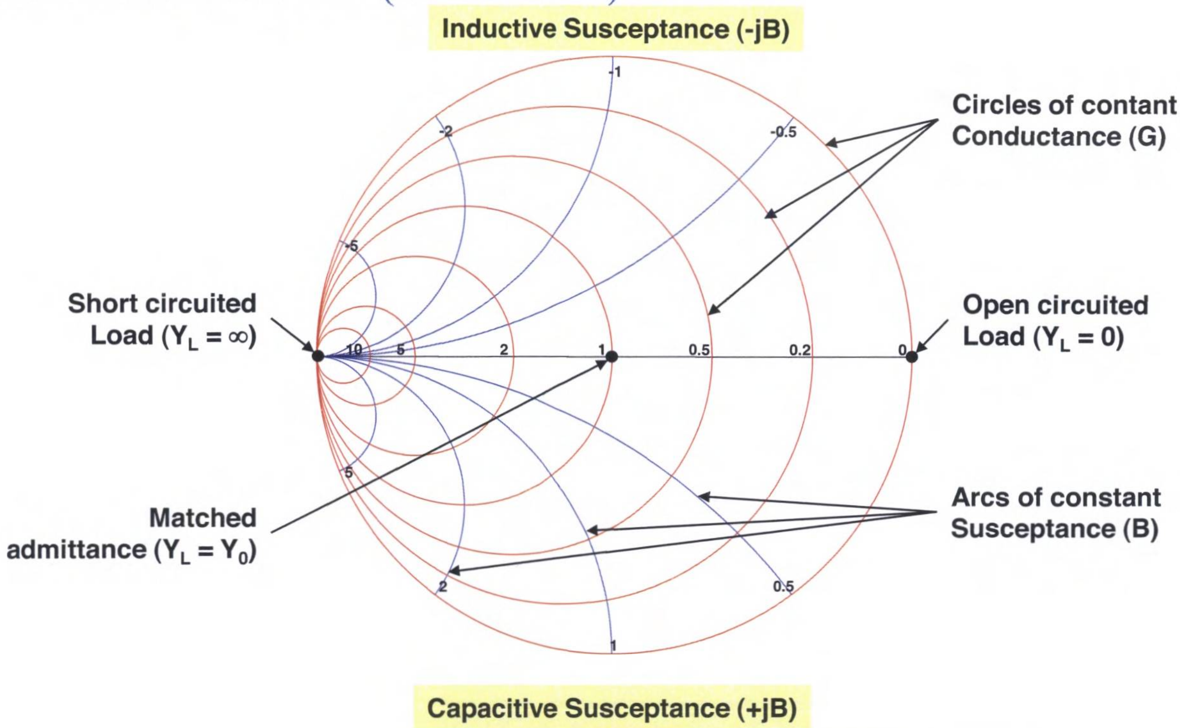
Inverted Smith Chart



The inverted Smith chart is point-symmetric to the Smith chart

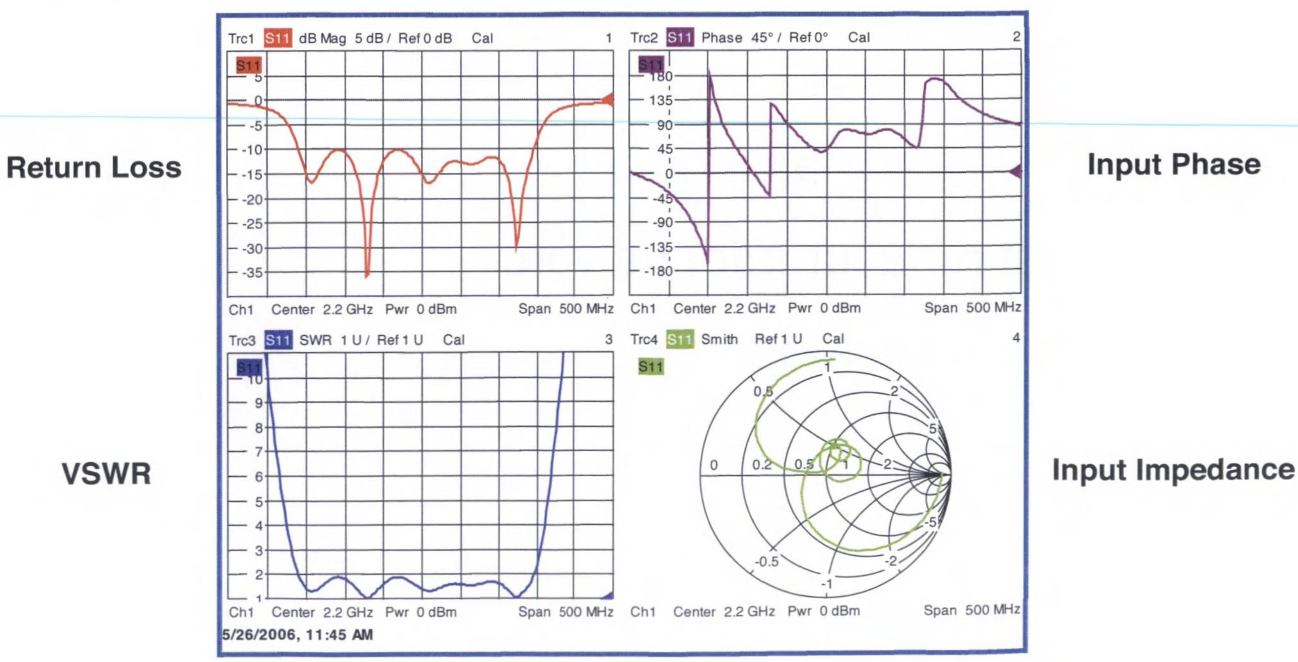
Display Formats and Diagram types

Inverted Smith Chart (Admittance)



Presentation of Results

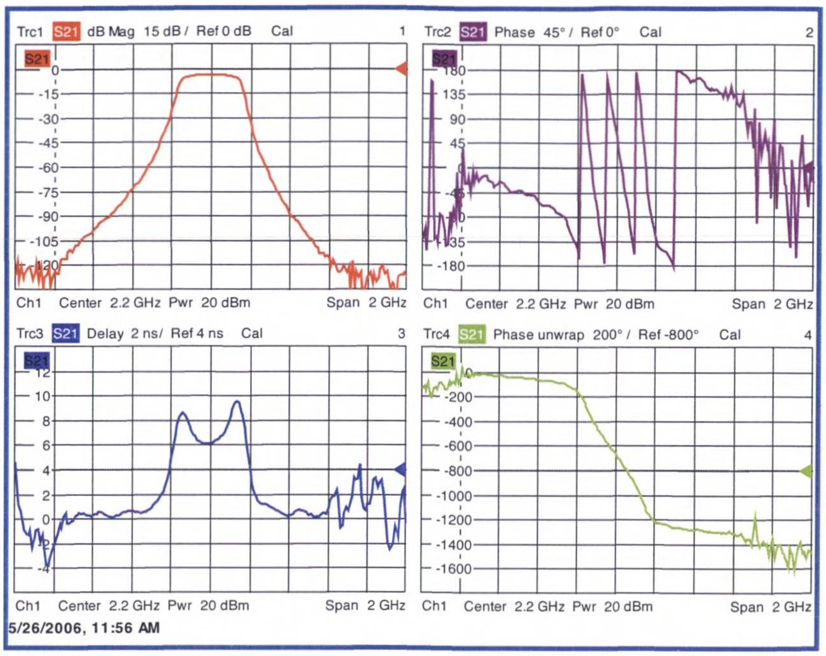
Reflection Measurements



Presentation of Results
Transmission Measurements

Gain/Loss

Group Delay



Transmission Phase

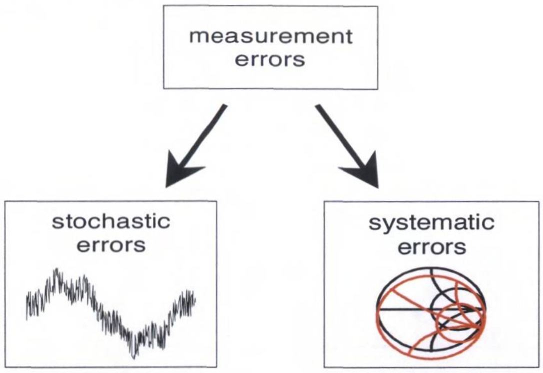
Transmission Phase Unwrapped

Agenda

- S-Parameter Basics
- Formatting of complex data
- Sources of measurement errors
- Calibration techniques
- Enhanced calibration

Measurement errors in network analysis

Types of Measurement Errors



No Error Correction

Corrected by Calibration

Error sources:
- Unpredictable
- Improvement, but no correction possible:
  - Signal to noise distance
  - Compression of the receiver
  - Stability of instrument
  - Stability of test setup

Error sources corrected by „system error correction":

- Systematic (constant) response of the external test set
- Systematic (constant) response of the internal test set
- [Drift corrected by re-calibration]

Background of System Error Correction

Typical error terms:

- Transmission loss (cables, adapters, couplers, etc,)
- Source match
- Load match
- Directivity (of coupler or bridge)
- Crosstalk

System error model

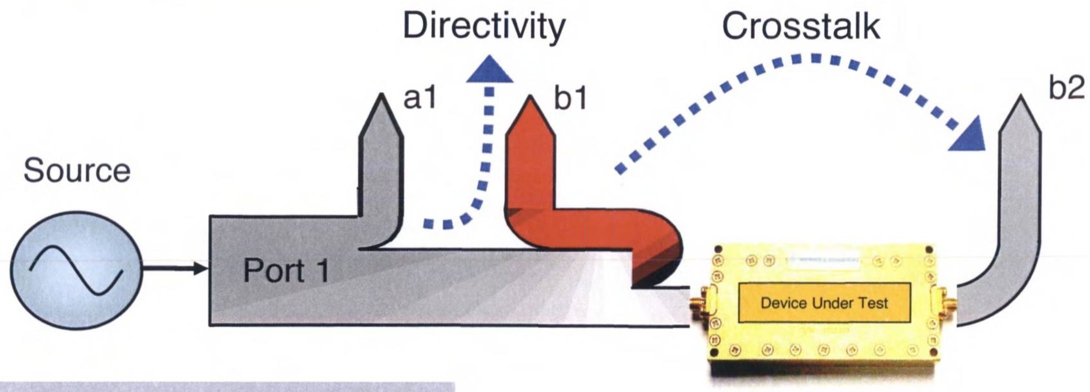
- Mathematical/physical description of error terms by error model
- Basis for correction procedure compensating for error terms

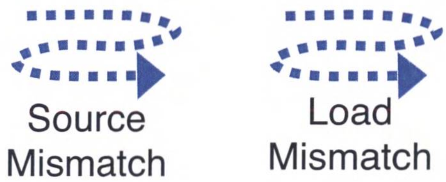
Task of System Error Correction

- Calculation of error terms for later correction of measurement data

Measurement errors in network analysis

Sources of systematic errors





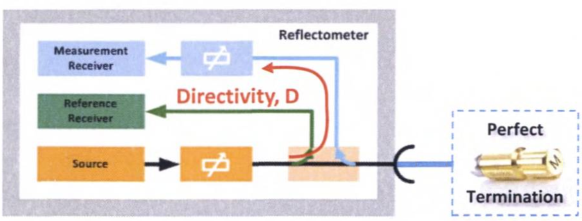
Error sources for transmission measurement:

- R_1 Reflection loss (tracking)
- T_1 Transmission loss (tracking)
- D_1 Directivity at port 1
- Γ_1 Source match at port 1
- Γ_2 Load match at port 2
- X_F Crosstalk

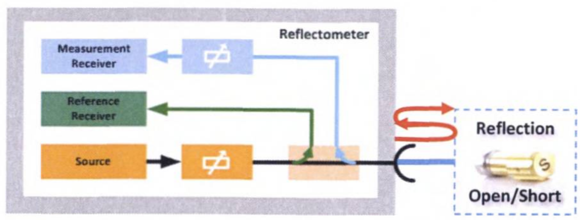
Reflection measurements errors

Sources of error

1. Error due to Directivity



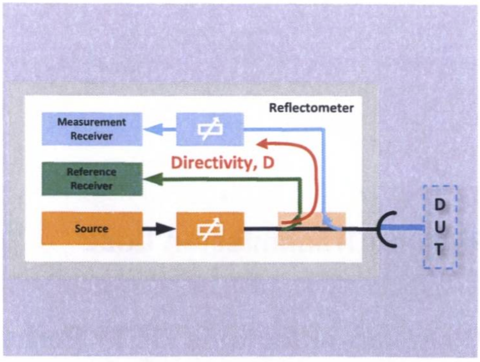
2. Error due to Test Port Match

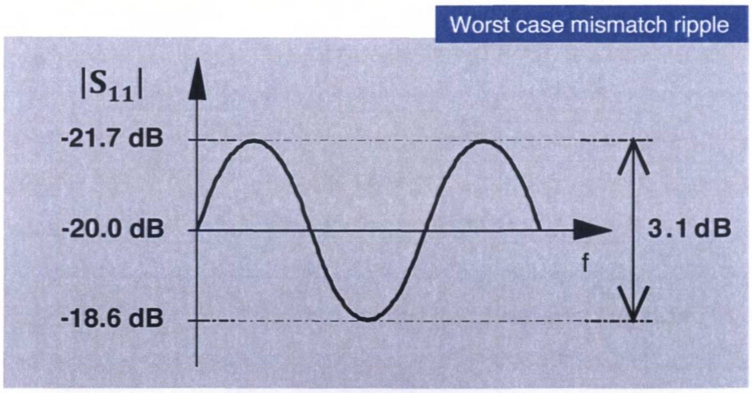


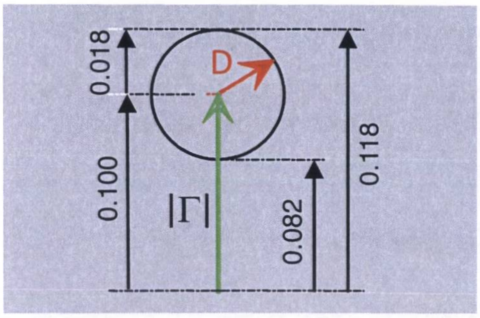
„Full One-Port“ calibration (OSM) 3 error terms:

D := Directivity
T := Reflection Tracking Loss
Γ := Port Match

Reflection measurement error example



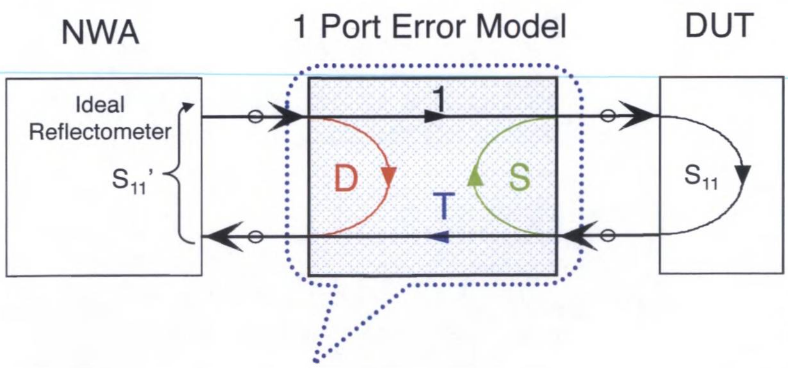




- DUT return loss: -20 dB (=0.100)
- Directivity of bridge: 35 dB (= 0.018)
- Min. value: 0.100 - 0.018 = 0.082 (-21.7 dB)
- Max. value: 0.100 + 0.018 = 0.118 (-18.6 dB)
- Measurement uncertainty: -1.4 dB to 1.7 dB

Reflection measurements errors

One Port error model: Error model



D = Directivity

S = Source Match (mismatch)

T = Reflection Tracking Loss

$S_{11'}$ = Measured return loss

S_{11} = Actual return loss

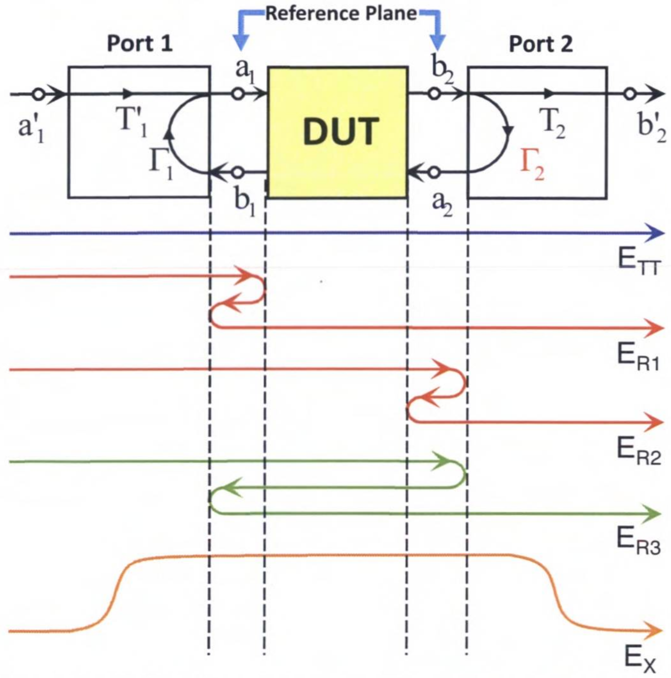
$$S_{11}' = D + T\left[\frac{S_{11}}{1 - S \cdot S_{11}}\right]$$

*Assumes good termination at port 2

To solve error terms, we measure 3 standards to generate 3 equations and 3 unknowns

Transmission measurements errors

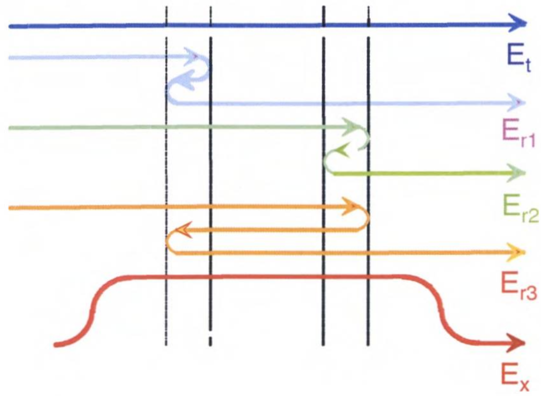
Sources of errors



1. Forward Transmission Loss
2. Mismatch-reflections DUT / Port 1
3. Mismatch-reflections DUT / Port 2
4. Multiport mismatch-reflections
5. Crosstalk

Error contribution just by mismatch (multiple reflections): ~ 0.1 to some dB !

Transmission measurement error example



Typical values:	
DUT return loss: $|S_{11}| = |S_{22}|$ =	**10 dB**
DUT trans. loss: $|S_{12}| = |S_{21}|$ =	**3 dB**
Port mismatch: $|\Gamma_1| = |\Gamma_2|$ =	**20 dB**

Wanted Signal:

$|E_t|$: 3dB	(0.70)

Error signals:

$|E_{r1}|$: - 10 dB - 20 dB - 3 dB = - 33 dB	(0.022)
$|E_{r2}|$: - 3 dB - 20 dB - 10 dB = - 33 dB	(0.022)
$|E_{r3}|$: - Neglegible	

Worst-case calculation:

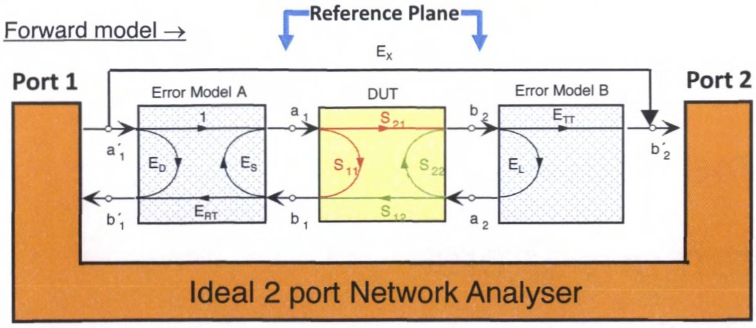
Min. value: 0.7 - 0.022 - 0.022 = 0.656	(-3.66 dB)
Max. value: 0.7 + 0.022 + 0.022 = 0.744	(-2.57 dB)

Measurement uncertainty: +0.66 dB to -0.43 dB

Full 2 Port Calibration models

Two Port error model – Complete description [TOSM]

Forward model →



E_D = directivity at error model A

E_S = fwd source match

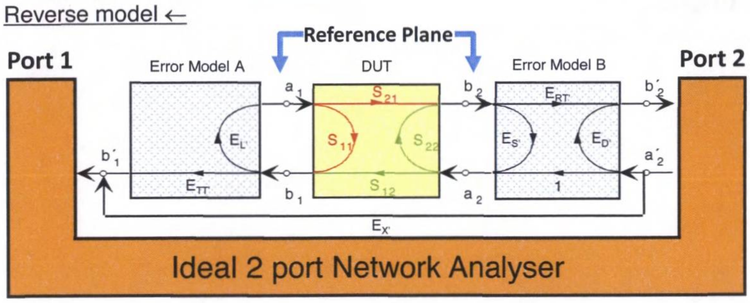
E_{RT} = fwd reflection tracking loss

E_L = fwd load match

E_{TT} = fwd transmission tracking loss

E_X = fwd crosstalk (port 1 to port 2)

Reverse model ←



$E_{D'}$ = directivity at error model B

$E_{S'}$ = rev source match

$E_{RT'}$ = rev reflection tracking loss

$E_{L'}$ = rev load match

$E_{TT'}$ = rev transmission tracking loss

$E_{X'}$ = rev crosstalk (port 2 to port 1)

Full 2 Port Calibration models

Two Port error model – Complete description [TOSM]

$$S_{11a} = \frac{\left(\frac{S_{11m}-E_D}{E_{RT}}\right)\left(1+\frac{S_{22m}-E_D'}{E_{RT}'}E_S'\right)-E_L\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(\frac{S_{12m}-E_X'}{E_{TT}'}\right)}{\left(1+\frac{S_{11m}-E_{D'}}{E_{RT}}E_S\right)\left(1+\frac{S_{22m}-E_D'}{E_{RT}'}E_S'\right)-E_L'E_L\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(\frac{S_{12m}-E_X'}{E_{TT}'}\right)}$$

$$S_{21a} = \frac{\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(1+\frac{S_{22m}-E_D'}{E_{RT}'}(E_S'-E_L)\right)}{\left(1+\frac{S_{11m}-E_D}{E_{RT}}E_S\right)\left(1+\frac{S_{22m}-E_D'}{E_{RT}'}E_S'\right)-E_L'E_L\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(\frac{S_{12m}-E_X'}{E_{TT}'}\right)}$$

$$S_{12a} = \frac{\left(\frac{S_{12m}-E_X'}{E_{TT}'}\right)\left(1+\frac{S_{11m}-E_D}{E_{RT}}(E_S-E_L')\right)}{\left(1+\frac{S_{11m}-E_D}{E_{RT}}E_S\right)\left(1+\frac{S_{22m}-E_D'}{E_{RT}'}E_S'\right)-E_L'E_L\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(\frac{S_{12m}-E_X'}{E_{TT}'}\right)}$$

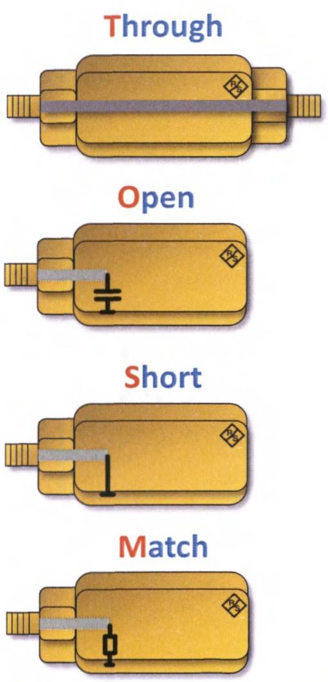
$$S_{22a} = \frac{\left(\frac{S_{22m}-E_D'}{E_{RT}'}\right)\left(1+\frac{S_{11m}-E_D}{E_{RT}}E_S\right)-E_L'\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(\frac{S_{12m}-E_X'}{E_{TT}'}\right)}{\left(1+\frac{S_{11m}-E_D}{E_{RT}}E_S\right)\left(1+\frac{S_{22m}-E_D'}{E_{RT}'}E_S'\right)-E_L'E_L\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(\frac{S_{12m}-E_X'}{E_{TT}'}\right)}$$

- Each actual S-parameter is a function of all four measured S-parameters
- Analyser must make forward *and reverse* sweep to update any one S-parameter

Agenda

- S-Parameter Basics
- Formatting of complex data
- Sources of measurement errors
- **Calibration techniques**
- Enhanced calibration

Definition of Calibration Standards



T = Through **(50 Ω, el. length)**
Well matched 50Ω through standard
Description of *electrical length, losses*

O = Open
Above approx. 100MHz different from ideal standard
Description of *electrical length, fringing capacitances, losses*

S = Short
In Coax-techniques good designs possible.
Description of *electrical length, inductance, losses*

M = Match
Broadband fixed match assumed to be ideal can use a model

Definition of Calibration Standards

Calibration Kit Parameters

- Derivation of the „ideal“ corrected S-parameters S_{xy}^{corr} from calibration kit parameters
  - Definition of the cal-kit parameters is an absolute requirement

- Accuracy strongly depends on the described cal-kit parameters
  - Resulting uncertainty after calibration strongly depends on ...

  ① **the accuracy of the cal-kit parameters**

  ② **the quality of the calibration standards**

Definition of Calibration Standards

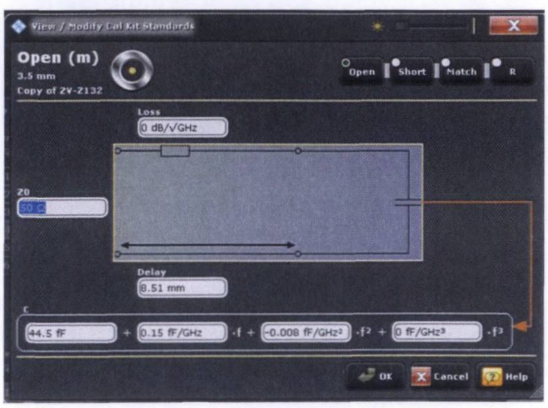
Calibration procedures requiring fully specified standards:

- Equivalent circuit model
  - Including (all) parameters affecting magnitude and phase
  - OPEN: Z_0 ,Loss, Delay, Fringing capacities
  - SHORT: Z_0, Loss, Delay, Inductance
  - MATCH: Z_0 , (or known $Z \approx Z_0$), (Delay)
  - LINE/THROUGH: Z_0, Loss, Delay

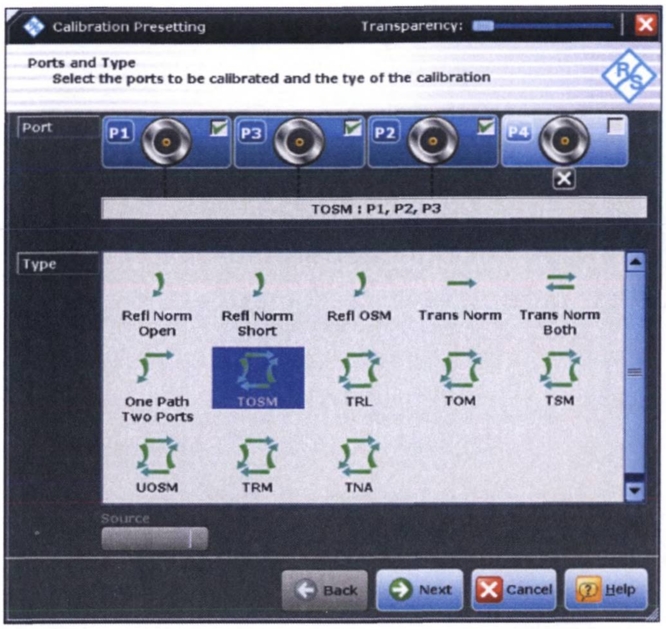
  → After calibration, the measurement trace corresponds to the response described by the parameters.

- S-parameter based description
  - Includes automatically all (parasitic) effects

  → After calibration, the measurement trace corresponds to the S-parameters



What calibration type should I choose???



???

Available Calibration Types:

Calibration Type	Standards	Parameters	Error Terms	General Accuracy	Application
Reflection Normalization	Open or Short	S_{11} (or S_{22}, ...)	Reflection tracking	Low to medium	Reflection measurements on any port.
Transmission Normalization	Through	S_{12}, S_{21} (or S_{13},...)	Transmission tracking	Medium	Transmission measurements in any direction and between any combination of ports.
Reflection OSM	Open, Short, Match[1]	S_{11} (or S_{22}, ...)	Reflection tracking, Source match Directivity,	High	Reflection measurements on any port.
One Path Two Ports	Open, Short, Match[1] (at source port), Through[2]	S_{11}, S_{21} (or S_{22},...)	Reflection tracking, Source match, Directivity, Transmission tracking	Medium to high	Unidirectional transmission measurements in any direction and between any combination of ports.
TOSM or UOSM (2-port, 3-port or 4-port)	Open, Short, Match[1] (at each port), Through[2](between all combinations of 2 ports)	All	Reflection tracking, Source match, Directivity, Load match, Transmission tracking,	High	Reflection and transmission measurements; classical 12-term error correction model.
TOM (2-port, 3-port or 4-port)	Open, Match (at both ports), Through	All	Reflection tracking, Source match, Directivity, Load match, Transmission tracking	High	Reflection and transmission measurements.
TSM (2-port, 3-port or 4-port)	Short, Match (at both ports), Through	All	Reflection tracking, Source match, Directivity, Load match, Transmission tracking	High	Reflection and transmission measurements.
TRM (2-port, 3-port or 4-port)	Reflect (equal at both ports), Match, Through	All	Reflection tracking, Source match, Directivity, Load match, Transmission tracking	High	Reflection and transmission measurements, especially in test fixtures.
TRL (2-port, 3-port or 4-port)	Reflect (at both ports), Through, Line1, Line2/3 (optional), combination with TRM (optional)	All	Reflection tracking, Source match, Directivity, Load match, Transmission tracking	High, high directivity	Reflection and transmission measurements, especially for planar circuits. Limited bandwidth.
TNA (2-port, 3-port or 4-port)	Through, Attenuation, Symmetric network	All	Reflection tracking, Source match, Directivity, Load match, Transmission tracking	High, lowest requirements on standards	Reflection and transmission measurements, especially for planar circuits.

Category of calibration styles

Standard Calibration

Default Calibration used for making a coaxial calibration with appropriate calibration kit.

Includes:
- Reflection Normalisation
- Transmission Normalisation
- Full One Port cal (OSM)
- One path Two Port calibration
- Full Two Port Calibration (TOSM)

All standards must be fully described and must be highly repeatable

Enhanced Calibration

Used where traditional Coaxial standards are not available or it is not possible to accurately describe the standards to be used.

Includes:
- Unknown Through Open Short Match (UOSM)
- Through Open Match (TOM)
- Through Short Match (TSM)
- Through Reflect Match (TRM)
- Through Reflect Line (TRL)
- Through Network Attenuation (TNA)

Only partial information needed to describe standards making them much more suited for, test fixtures, on wafer and freespace measurements.

Calibration Techniques

Differences between Standard Calibration Techniques

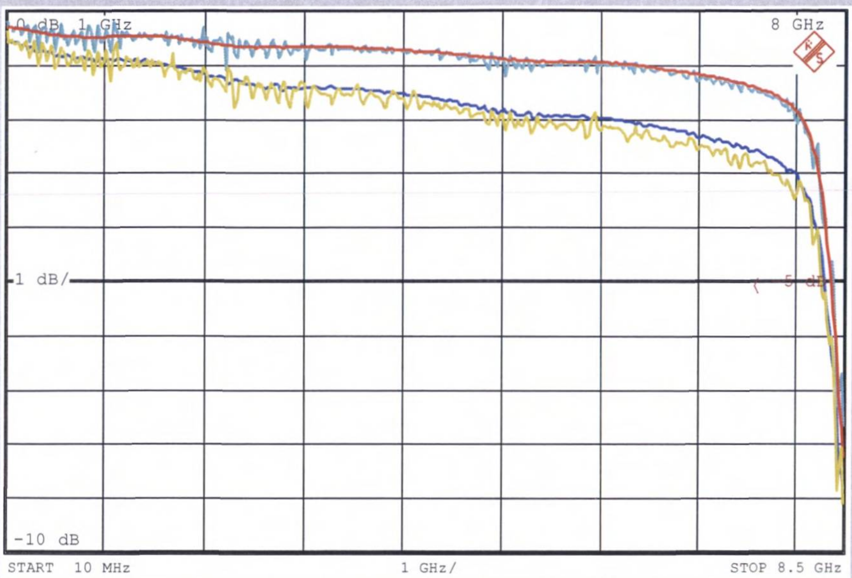
- 'Normalisation' (Response Cal)
  - Corrects for Loss and test port match by one term
  - Fast (unidirectional) but not highest accuracy
- 'One-path two-port' considerably more accurate
  - Corrects for mismatches between VNA output and DUT input
  - Measures DUT in forward direction only (S11 and S21)
  - Requires only one partial measurement

    => **Twice as fast as full two-port calibration**

    => **Important for Amplifier measurements**
  - If port 2 of VNA is perfectly matched, similar accuracy compared to full two port calibration (Can be improved further with matching attenuators)
- 'Full two-port' calibration has highest accuracy
  - Corrects for mismatches of VNA's test ports
  - Measures the DUT in forward and reverse direction
  - Requires two partial measurements

Network Analyser Calibration

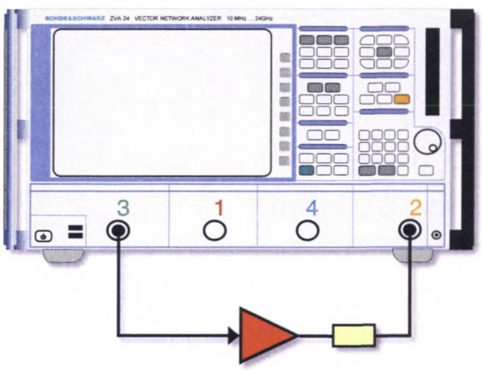
Measurement with Different Calibration Methods



- Channel 1(blue): Measurement of S_{21} using the factory calibration
- Channel 2(green): Measurement of S_{21} using a normalization
- Channel 3(red): Measurement of S_{21} using a full two-port calibration
- Channel 4(yellow): Measurement of b_2/a_1 of the filter

Network Analyser Calibration

Special case for measuring amplifiers in compression



$$S_{11a}=\frac{(\frac{S_{11m}-E_D}{E_{RT}})(1+\frac{S_{22m}-E_D'}{E_{RT}'}E_S')-E_L(\frac{S_{21m}-E_X}{E_{TT}})(\frac{S_{12m}-E_X'}{E_{TT}'})}{(1+\frac{S_{11m}-E_D'}{E_{RT}}E_S)(1+\frac{S_{22m}-E_D'}{E_{RT}'}E_S')-E_L'E_L(\frac{S_{21m}-E_X}{E_{TT}})(\frac{S_{12m}-E_X'}{E_{TT}'})}$$

$$S_{21a}=\frac{(\frac{S_{21m}-E_X}{E_{TT}})(1+\frac{S_{22m}-E_D'}{E_{RT}'}(E_S'-E_L))}{(1+\frac{S_{11m}-E_D}{E_{RT}}E_S)(1+\frac{S_{22m}-E_D'}{E_{RT}'}E_S')-E_L'E_L(\frac{S_{21m}-E_X}{E_{TT}})(\frac{S_{12m}-E_X'}{E_{TT}'})}$$

$$S_{12a}=\frac{(\frac{S_{12m}-E_X'}{E_{TT}'})(1+\frac{S_{11m}-E_D}{E_{RT}}(E_S-E_L'))}{(1+\frac{S_{11m}-E_D}{E_{RT}}E_S)(1+\frac{S_{22m}-E_D'}{E_{RT}'}E_S')-E_L'E_L(\frac{S_{21m}-E_X}{E_{TT}})(\frac{S_{12m}-E_X'}{E_{TT}'})}$$

$$S_{22a}=\frac{(\frac{S_{22m}-E_D'}{E_{RT}'})(1+\frac{S_{11m}-E_D}{E_{RT}}E_S)-E_L'(\frac{S_{21m}-E_X}{E_{TT}})(\frac{S_{12m}-E_X'}{E_{TT}'})}{(1+\frac{S_{11m}-E_D}{E_{RT}}E_S)(1+\frac{S_{22m}-E_D'}{E_{RT}'}E_S')-E_L'E_L(\frac{S_{21m}-E_X}{E_{TT}})(\frac{S_{12m}-E_X'}{E_{TT}'})}$$

Error terms for 12 term model used in full 2-Port correction cannot be measured correctly due to partial measurements.

Solution – Uni-directional "one path two port" calibration, but we must remove errors due to load match of the VNA

Agenda

- S-Parameter Basics
- Formatting of complex data
- Sources of measurement errors
- Calibration techniques
- Enhanced calibration

Enhanced Calibration Techniques

Motivation

- Coaxial connectors, commercial cal-kits - No Problem with TOSM ☺
  - 4 standards required
  - Complete description of parameters (capacitance, length, loss etc.)
  - But no information on quality of calibration without further check

- Calibration in test fixtures, on wafers - Problems ☹
  - Individual standards required
  - Cal-kit parameters from individual TOSM standards needed???

Solution

- Calibration techniques with a reduced number of standards
- Use of calibration standards which do not need accurate & full parameter descriptions.

Enhanced Calibration Techniques

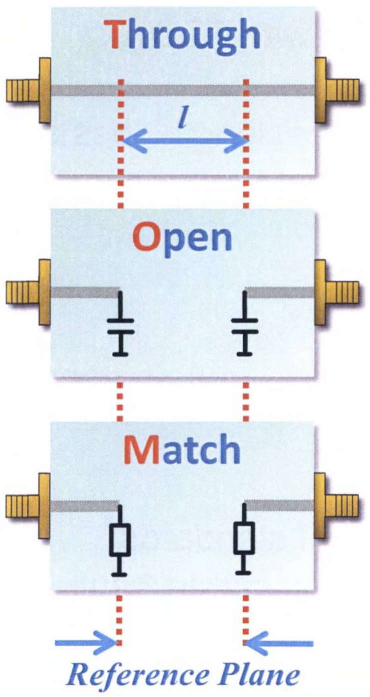
Techniques of Full Two-Port Calibration

Calibration procedure	Number of Calibration steps	Special feature
TOSM	7	classical procedure
TOM (TSM)	5	inherent verification
TRM	5	Designed for test fixtures
TRL	4	High Directivity
TNA	3	Designed for test fixtures
UOSM	7	Similar to TOSM Allows unknown THROUGH Includes „Adapter Removal“

- TOM, TRM, TNA patented for R&S.

Enhanced Calibration Techniques

TOM - Calibration Technique



T = Through (50 Ω, el. length)

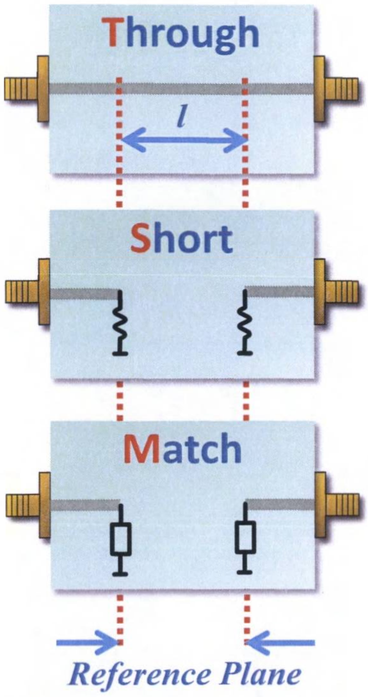
O = Open (el. Length, Capacitance & loss)

M = Match (50 Ω, assumed to be ideal)

- Calibration with known calibration standards
- Requires a well matched, low loss Through standard with electrical length that may be different from zero.
- The characteristics of all standards must be fully known; the Match may have non-ideal characteristics.
- Implicit verification with Short standard can be made if using standard coaxial calibration kit.

Enhanced Calibration Techniques

TSM - Calibration Technique

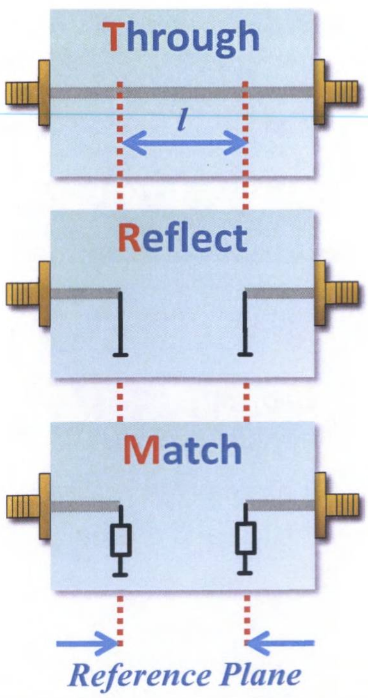


T = Through	**(50 Ω, el. length)**
S = Short	**(el. Length, inductance & loss)**
M = Match	**(50 Ω, assumed to be ideal)**

- Calibration with known calibration standards
- The characteristics of all standards must be fully known; the Match may have non-ideal characteristics.
- TSM calibration can replace TOM calibration if no appropriate "Open" standard is available, especially in the high frequency domain.
- Short is easier to realise in the higher frequencies

Enhanced Calibration Techniques

TRM/LRM - Calibration Technique

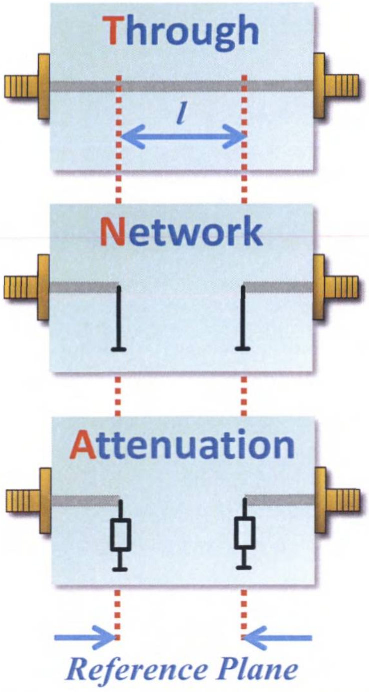


T = Through	**(50 Ω, el. length)**
R = Reflect	**(Reflecting two port standard)**
M = Match	**(50 Ω, assumed to be ideal)**

- Calibration with unknown calibration standard Reflect is allowed. No information about electrical length and capacitance is required.
- Reflect standard may be unknown (open or short), but must be identical for both ports („reflection symmetry")
- Especially suitable for test fixtures with a fixed spacing (e.g. SMD components)

Enhanced Calibration Techniques

TNA: a Generalisation of TRM-Technique



T = Through (50 Ω, el. length)

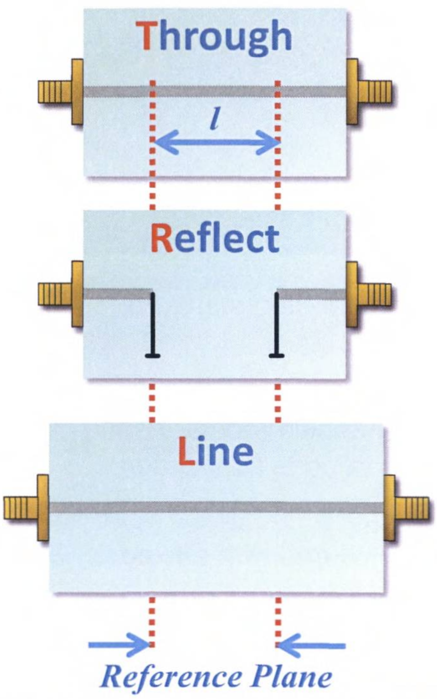
N = Network (Reflecting two port standard)

A = Attenuator (50 Ω, >10dB attenuation)

- Calibration with 3 *two-port calibration standards*
- The cal-standard *Network* may be unknown, *just approximately OPEN or SHORT characteristics.* No electrical lengths or capacitance required. Must be symmetrical.
- The attenuation of the cal standard *Attenuator* may be unknown, a good match is assumed
- Especially suited for test fixtures with a fixed spacing and on wafer measurements

Enhanced Calibration Techniques

TRL/LRL: Narrow band High Directivity calibration



T = Through (50 Ω, el. length)

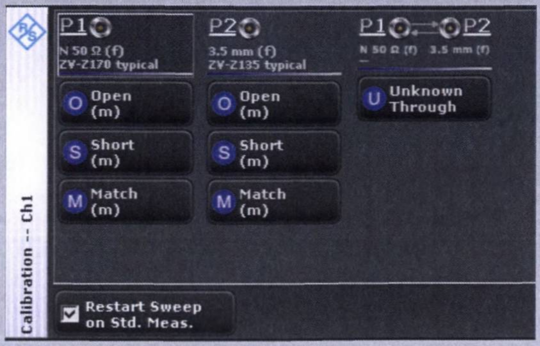
R = Reflect (Reflecting two port standard)

L = Line (50 Ω, ¼ Wavelength longer)

- Useful for DUT‘s in test fixtures or on wafer calibration
- Cal Kit: TOSM Kit + TRL supplementry Kit, or customer designed calibration fixture
- ☺ High Directivity and standards are easy to realise
- ☹ Limitations for wideband calibration and coaxial standards are difficult to handle

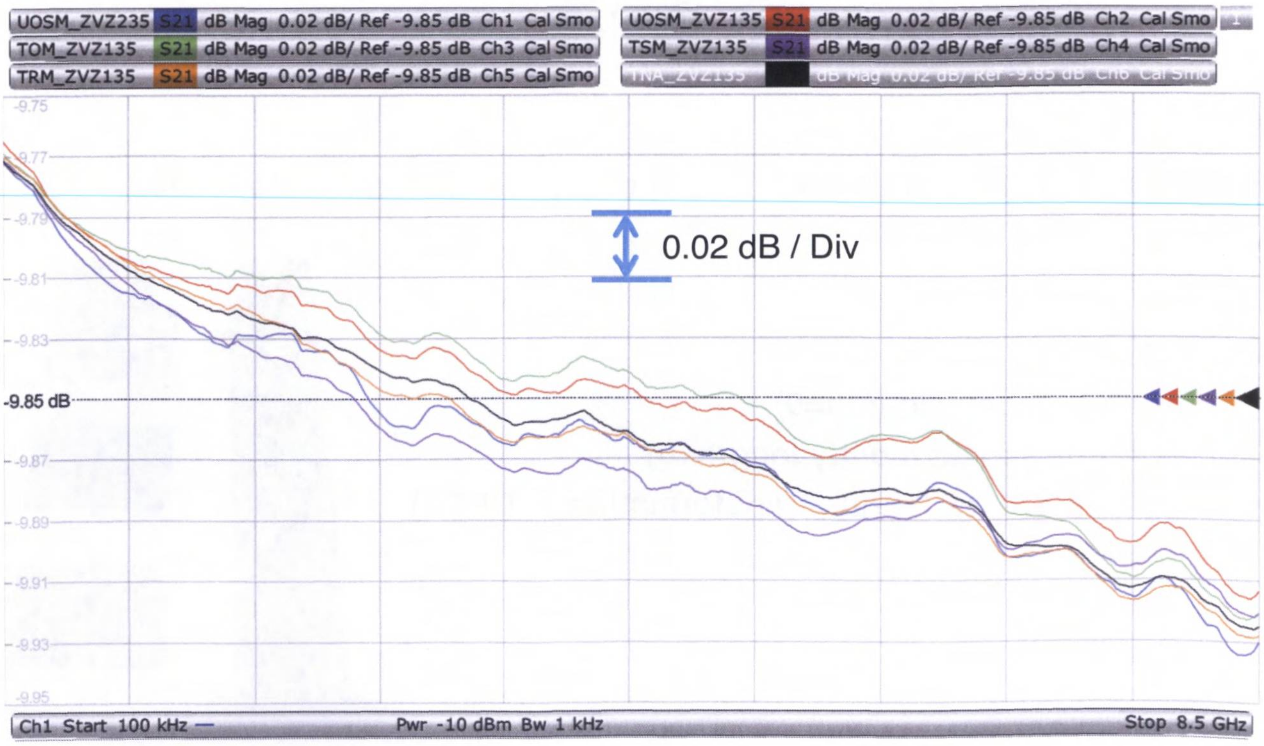
Enhanced Calibration Techniques - UOSM

- 7 term calibration method, derived from TOSM. Allows "Unknown Through"
  - Developed by R&S* and first introduced with the ZVB (2004)
  - No characterisation data for THROUGH required
- Uses 4 standards for 2-port calibration (Unknown Through, Open, Short, Match)
  - Suitable for multiport calibrations
- Overcomes the non-idealistic effects of the THROUGH (even male-female)
  - Unknown Through is characterized by full S-parameter matrix
  - Matching of THROUGH is taken into account!
- Suitable for DUTs with different In/Out connector types and even different impedances.
- UOSM requires well described Open, Short & Match calibration standards



*) First described by Ferrero & Pisani in 1992 in IEEE Mwave

Comparison of calibration styles



Selecting a Suited Calibration Technique

- Crucial questions:

  Regarding the test setup, which standards can be designed the easiest way ?
  For which standard can I get the parameters with best accuracy ?

- Examples

  Cables:

  Coaxial cal-standards applicable, minimization of calibration time expected.
  ⇒ TOSM/UOSM, TSM (verification), TRM

  Wafer and PCB-boards:

  Easy design of lines with different length. Often symmetric test ports.
  ⇒ TRL/LRL, TRM/LRM, TNA

  Test fixture with fixed gap for DUT (no variation of length possible):

  Cal-technique with standards of different length (TRL/LRL) not applicable.
  ⇒ TNA

Waveguide Calibration Techniques
12 Term and 7 Term error models

- Calibration Techniques

  TOSM ⇒ T-OS-S-M (OS:= Offset Short, OPEN not realisable in WG)
  TRM ⇒ TSM
  TRL, etc

- Standards

  Through (mostly length=0)
  Short (or Reflect mostly length=0)
  Offset Short (el. length, transformation to OPEN)
  Match
  Line(s)

Special types of calibration

Automatic Calibration Units

Automatically performs a full calibration on all ports using a series of electronic switches.

Highest level of accuracy

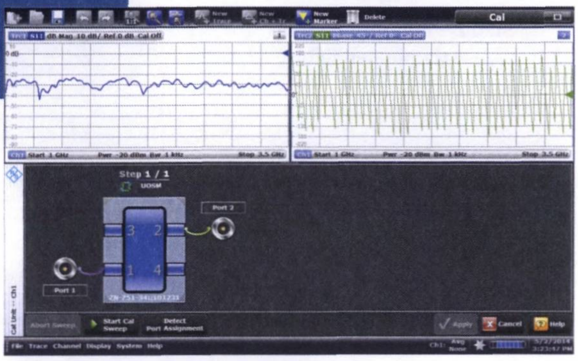
Versions available up to 50GHz

Available in 2, 4, 6 and 8 Port versions

User definable port configurations

Connects to VNA via USB interface

R&S®ZN-Z51 calibration unit.

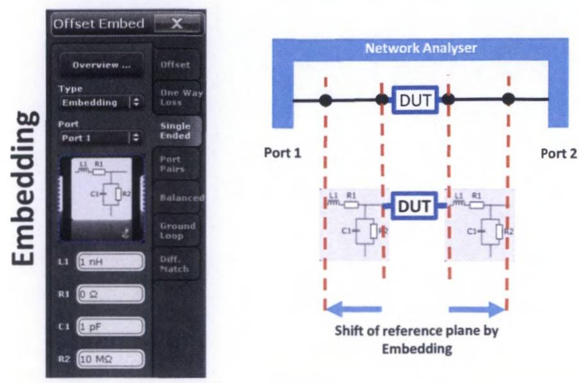


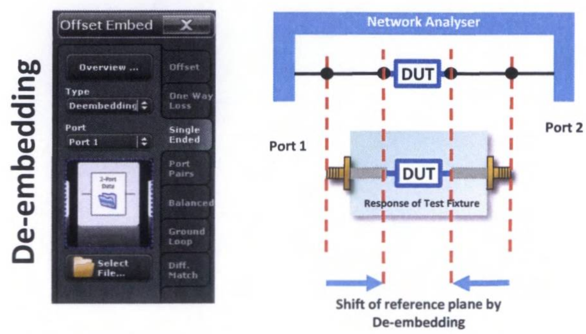
R&S®ZN-Z152 calibration unit.

Reference plane offset

Embedding / De-embedding

- Where calibration standards are not physically practical
- Importing of S-Parameter file or network to offset the physical reference plane:
  - Embedding – Add additional mathematical networks to each reference plane (matching networks)
  - De-embedding – Removal of unwanted mathematical networks to each reference plane (test fixture removal)

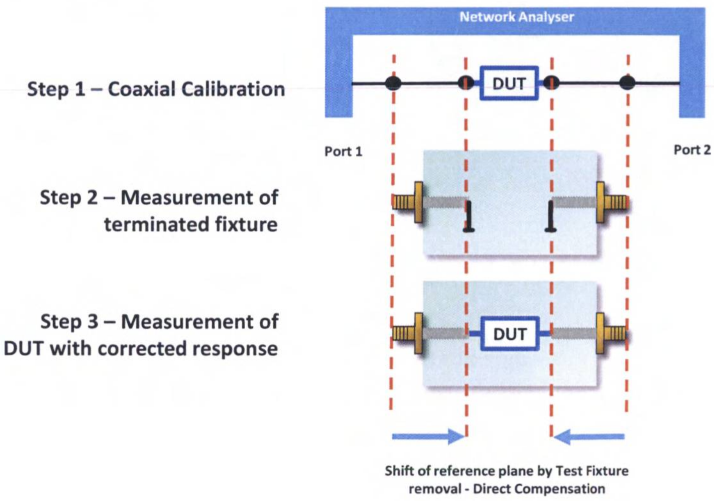




Reference plane Offset

Test Fixture Removal with 'Direct Compensation'

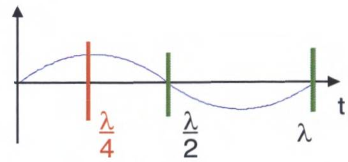
- Shifting of physical reference plane with an undefined Short/Open circuit.
- Using 'Direct Compensation' a frequency dependant transmission factor is calculated.



Any Questions??

Appendix
TRL: Definition of Line

- Phase shift caused by a LINE must not be equal to $n \times \lambda/2$ or 180°
- Length must ONLY be known for phase information of ± 180°
  - Limitations of frequency ranges
  - Calibration just in frequency bands
  - Frequency band depend on length of the LINE(s
- Praxis:



$$\Delta\varphi(l) = 20° \ldots 160°$$

$$f_{START} = \frac{1}{360°} * \frac{c}{l_{(LINE)}} (20° + n * 180°)$$

$$f_{STOP} = \frac{1}{360°} * \frac{c}{l_{(LINE)}} (160° + n * 180°)$$

Extension of frequency range by adding calibration standards:
MATCH & LINE 2
= T-R-L_1-L_2-M

Appendix
TRL: Standards & Frequency range

Step 1: Frequency, Wavelength of interest $\Rightarrow$ $l_{(LINE1)} = \frac{\lambda(f)}{4}$

Step 2: With known l_{line}, frequency band(s) Δf:

$$f_{START} = \frac{1}{360°} * \frac{c}{l_{(LINE)}} (20° + n * 180°)$$

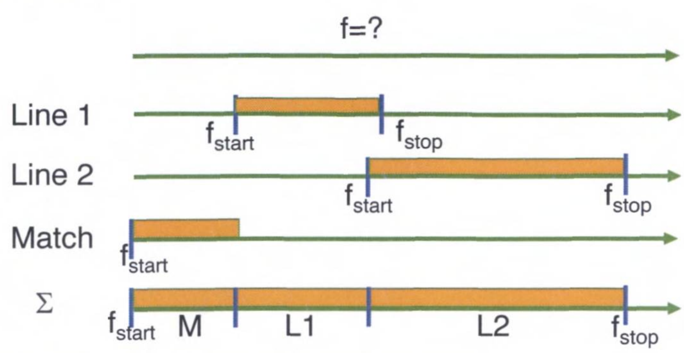
$$f_{STOP} = \frac{1}{360°} * \frac{c}{l_{(LINE)}} (160° + n * 180°)$$

Frequency bands with n=0,1,2...

Step 3: Extension of frequency range

To higher frequency range:
e.g. $L_{(LINE\ 2)} = L_{(LINE1)} / 2(4)$

To lower frequency range:
Broadband Match



Demystifying the network analyser. Time Domain Reflectometry (TDR)

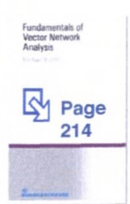
Mark Bailey, CEng
RF & Microwave Application Engineer

R&S, November 2015

ROHDE&SCHWARZ

Agenda – Time Domain Reflectometry (TDR)

- Introduction to TDR:
  - What is TDR?
  - What is TDR used for?
- Measurement considerations:
  - Impulse and step responses
  - Unambiguous range
  - Resolution in time (and distance)
- Entering "Time Domain" on the R&S®ZNB VNA:
  - Band pass and low pass transformation modes
  - Filter profiles or "Windows"
  - Rise-time
  - Time domain gating
  - Export file formats



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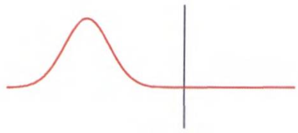
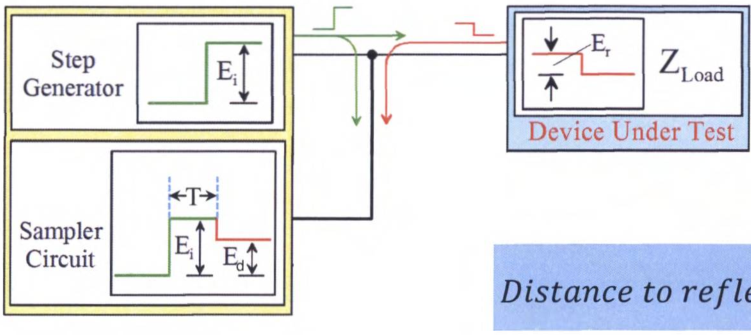
What is Time Domain Reflectometry (TDR)?

- Measurement technique that observes the behaviour of reflected electrical waveforms propagating in a homogenous medium, from a known stimulus.



Wikipedia

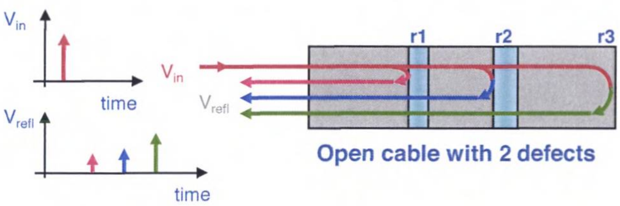
- Performed in the time domain, hence for most applications this directly relates to distance.



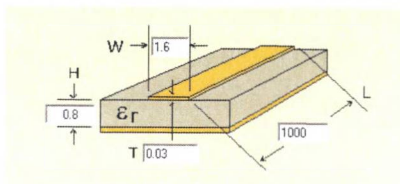
$$Distance\ to\ reflection = v_p.\frac{T}{2}$$

What is TDR used for?

- Cable fault location / distance to fault.

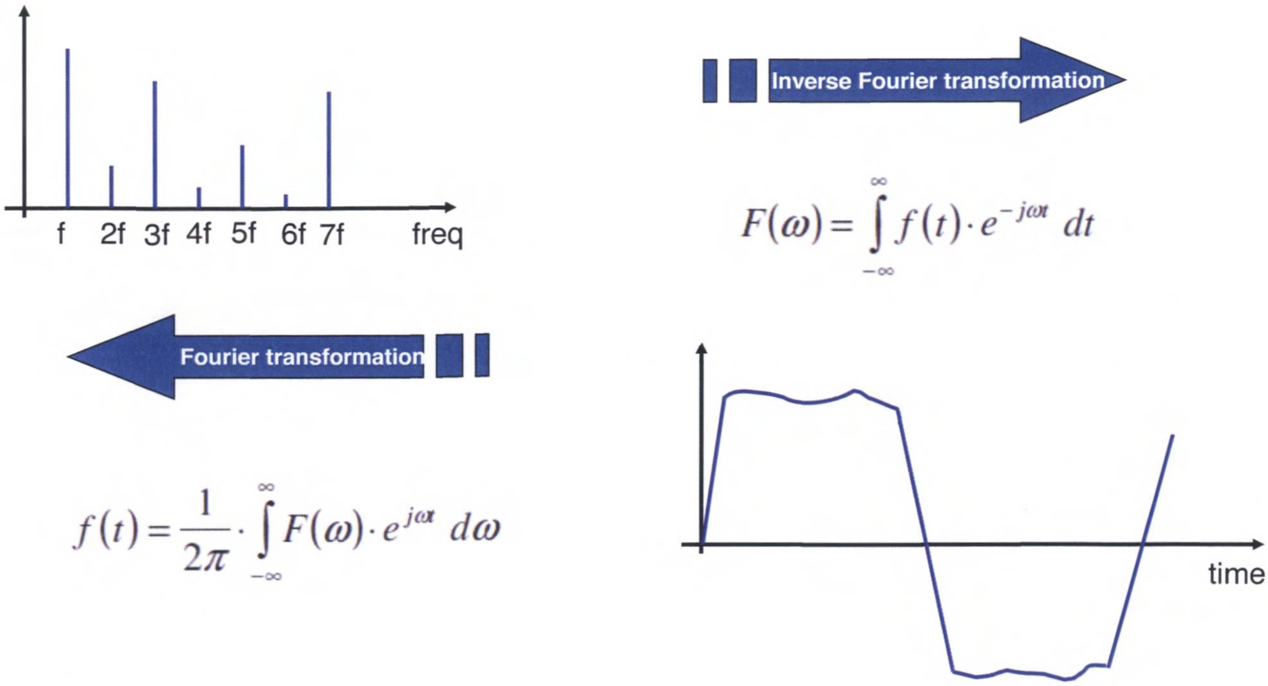


- Impedance measurement and mismatch, e.g. stripline/microstrip structures or test fixtures.
- Rise time.
- Balanced line performance, e.g. intrapair and interpair skews.



- Moving the reference plane across sources of mismatch, e.g. connectors.

TDR – Time & frequency domain relationships

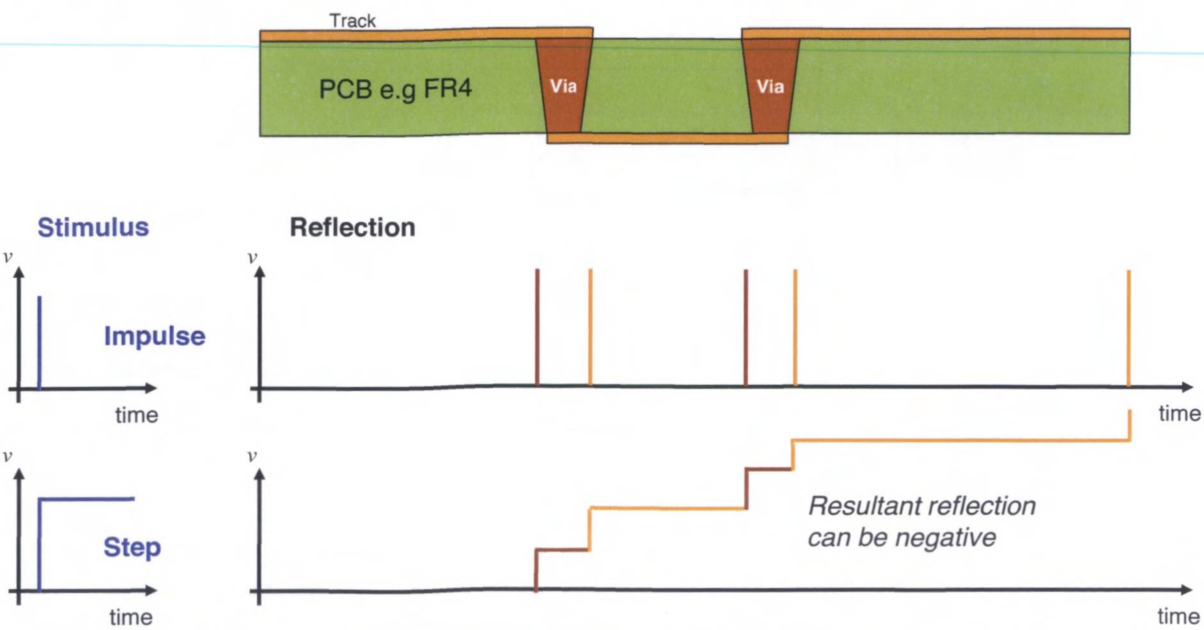


$$F(\omega) = \int_{-\infty}^{\infty} f(t) \cdot e^{-j\omega t}\, dt$$

$$f(t) = \frac{1}{2\pi} \cdot \int_{-\infty}^{\infty} F(\omega) \cdot e^{j\omega t}\, d\omega$$

Impulse and step responses

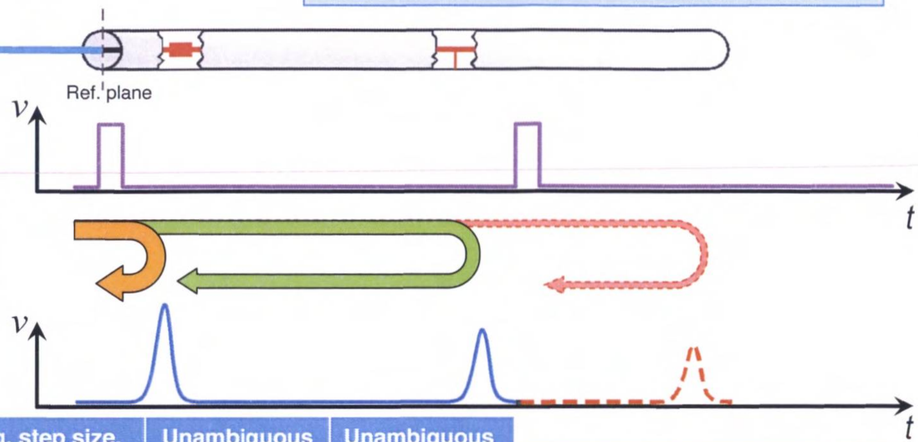
- **The step response is the integrated impulse response**



Unambiguous range (Unique range)

$$\Delta t\ (unambiguous\ range) = {}^{1}/_{\Delta f} = \frac{(No.of\ points - 1)}{Sweep\ span}$$

- *Δf spacing between adjacent sweep points.*
- *Δt slightly reduced for low pass transformation.*

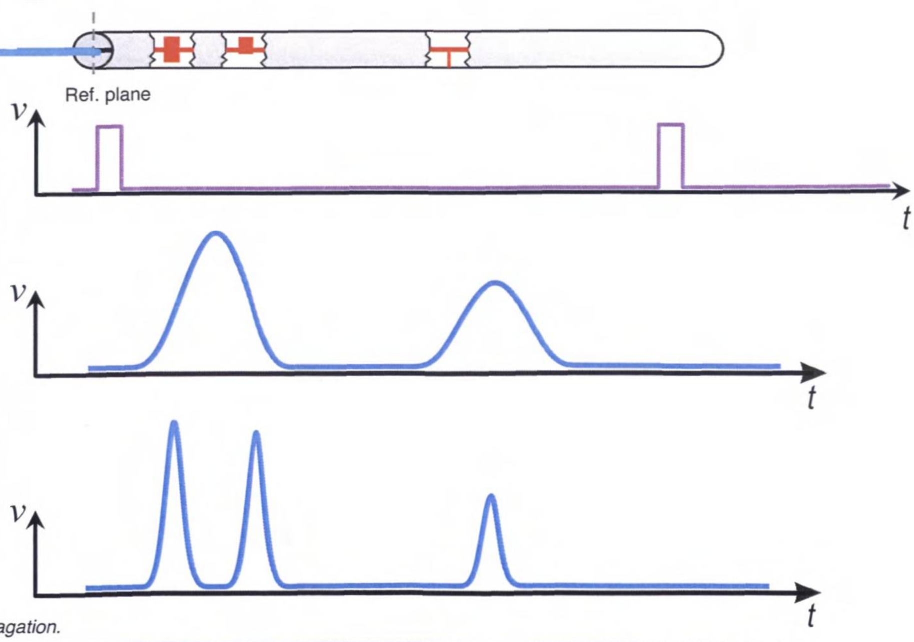


Increase unique range:
- Increase number of points (*increases sweep time*)
- *Reduce frequency span.*

Frequency span (GHz)	No. of points	Freq. step size, Δf (MHz)	Unambiguous time, Δt (ns)	Unambiguous distance, (m)*
8	101	80	12.5	1.87
8	201	40	25	3.74
2	201	10	100	14.98
20	10001	2	500	74.9

* The distances assume speed of light propagation and are automatically calculated by the R&S®ZNB.
The unambiguous range accounts for the sum of the propagation times for the incident and reflected waves.

Resolution in time (and distance)



Increase resolution:
- Requires shorter pulse:
  - Increase frequency span (*doubling the frequency span, doubles the resolution*).

Frequency span (GHz)	Time (ps)	Distance (mm)
1	500	150
4	125	37.5
8	63	19
20	25	7.5

Examples of typical resolution.
***Note:** Distance refers to speed of light propagation.*

Entering "Time Domain" on the R&S®ZNB VNA

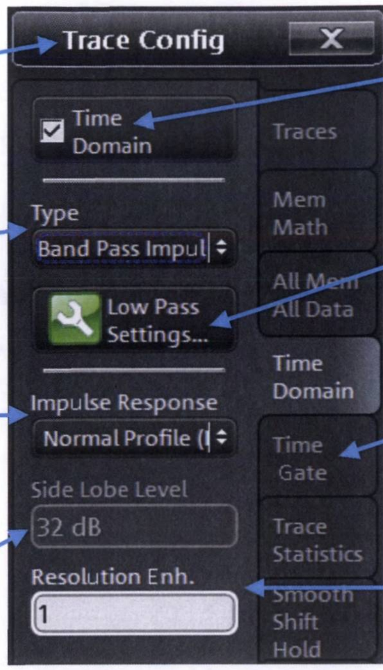
Option R&S ZNB-K2, Time domain

Accessed through the Trace Configuration menu

Select type of time domain mode

Select desired "profile" (filter) from a list

For a User defined filter, "*Arbitrary Sidelobes*"



Activate/deactivate Time Domain function on the active trace

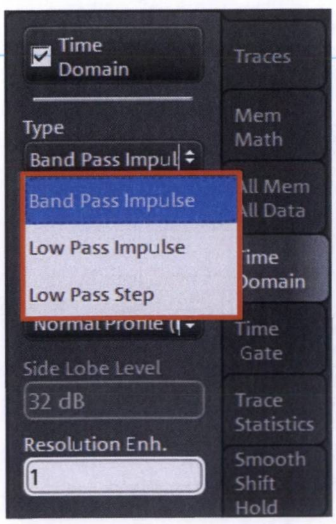
Additional settings for "Low pass" modes

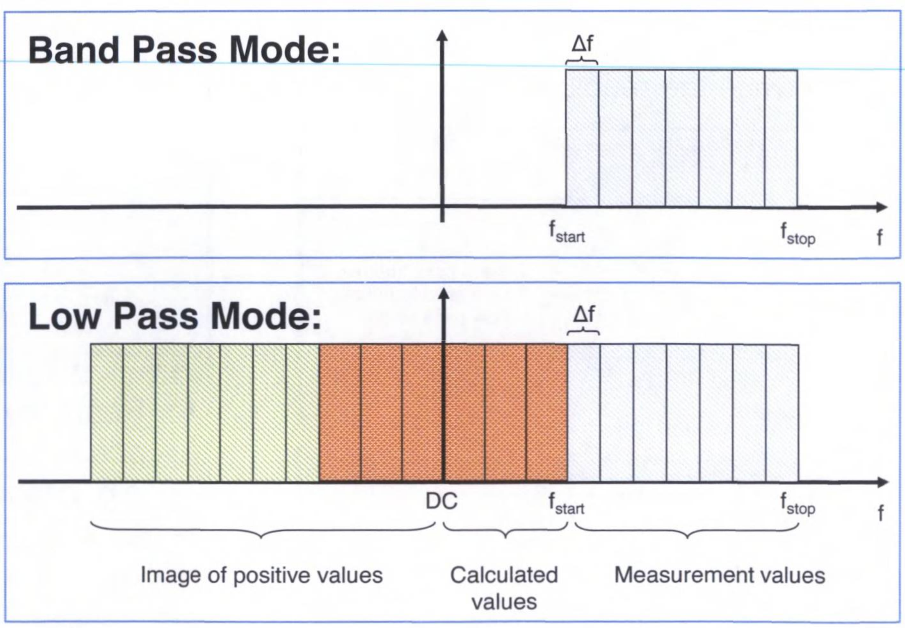
Tab to access "Time Gate" function

Set "Resolution Enhancement"

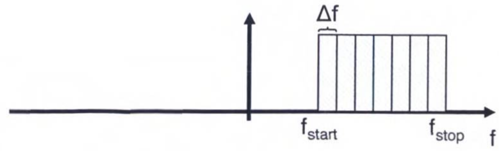
Band pass and low pass transformation modes

The VNA supports three types of time domain mode:



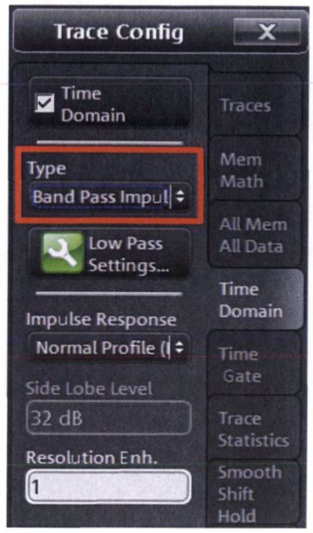


Band pass mode



"Band pass impulse" - default TDR mode on the R&S®ZNB.

- **Useful for detecting impedance mismatches.**
- **Works with any set of equidistant sweep points.**

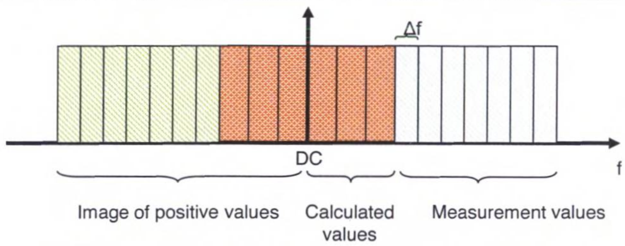


Typical applications:

- **Scalar measurement (*phase is undetermined*).**
- **Devices that do not operate down to DC, e.g., band pass or high pass filters.**

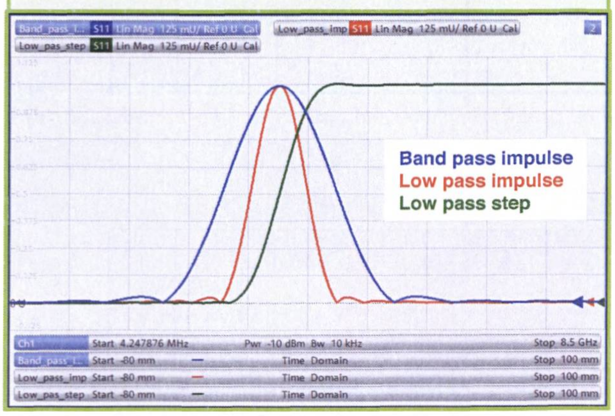
No band pass step mode.

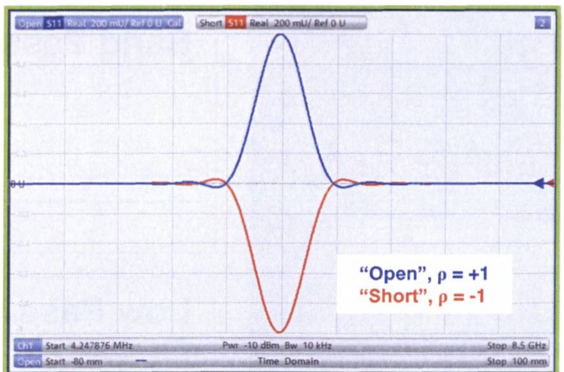
Low pass mode



Advantages (*compared with band pass*):

- Twice the frequency range ⇒ twice the resolution.





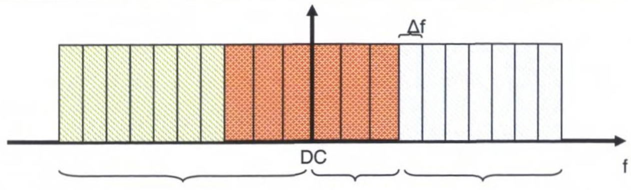
- Real time response giving phase information, *e.g. capacitive or inductive.*

Requires:

- DC value
- Harmonic frequency grid

Note: No DC content when measuring band pass or high pass filters

Low pass mode



"Harmonic grid"

- **Measured points set at Δf intervals.**
- **Creates calculated frequency values from DC to first measured point at Δf intervals.**
- **DC value required**

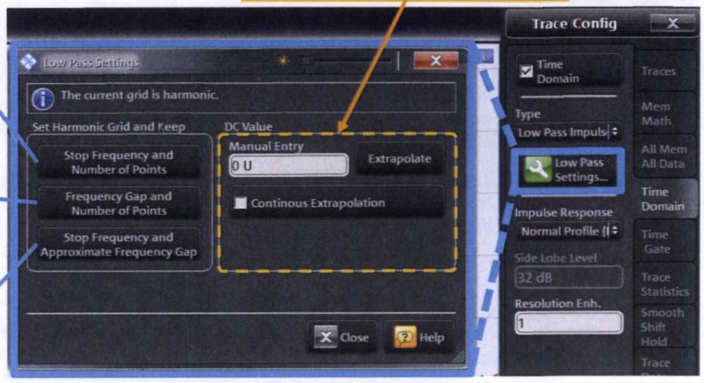
Reflection coefficient value at DC for the system characteristic impedance:

$\Gamma_{Open} = +1$
$\Gamma_{short} = -1$
$\Gamma_{match} = 0$

VNA adjusts the frequency step size:
- Time domain resolution remains constant
- Slight change to unambiguous range

VNA adjusts the stop frequency:
- Slight change to time domain resolution
- Unambiguous range remains constant

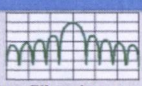
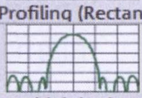
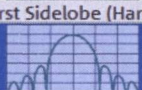
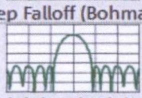
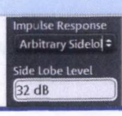
VNA adjusts the no. of points (*sweep time*)
- Time domain resolution remains constant
- Unambiguous range approx. constant.



Profiles or "Windows"

The finite sweep range of the frequency domain causes side lobes in the time domain.

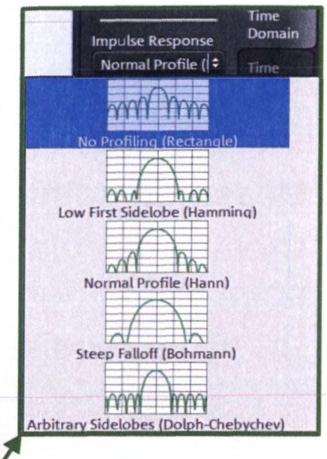
Using suitable filtering, the time domain response can be optimised.

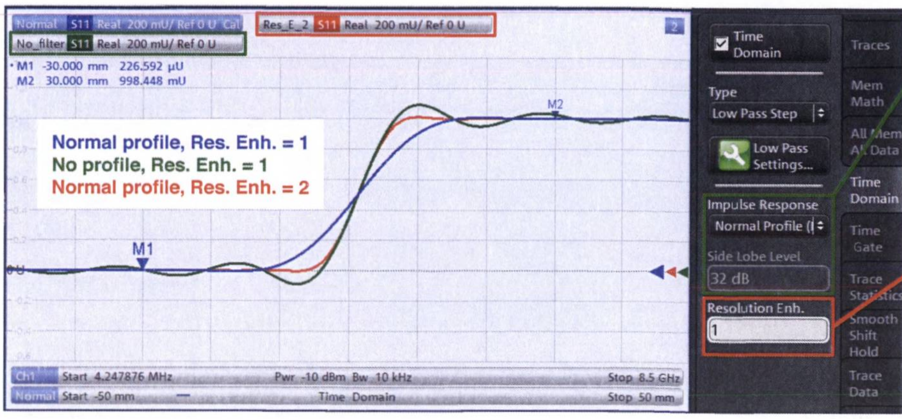
Window	Side lobe suppression	Relative Impulse width	Best for…
 No Profiling (Rectangle)	13 dB	1	…
 Low First Sidelobe (Hamming)	43 dB	1.4	Response resolution: closely spaced responses of similar amplitude.
 Normal Profile (Hann)	32 dB	1.6	Compromise of pulse width and side lobe suppression.
 Steep Falloff (Bohmann)	46 dB	1.9	Dynamic range: Separation of distant responses with different amplitudes.
 Arbitrary Sidelobes (Dolph-Chebychev)	User defined 	1.2 (*@ 32 dB side lobe suppression*)	User defined: trade-off between side lobe suppression and impulse width.

Rise Time

Rise time is affected by:

- Frequency span
- Bandpass/lowpass mode ($Rt_{Bpm} = 2 \times Rt_{Lpm}$)
- Impulse response profile ($Rt_{Normal\ profile} = 2 \times Rt_{No\ profile}$)
  - Increased side-lobe suppression ⇒ increased rise time.



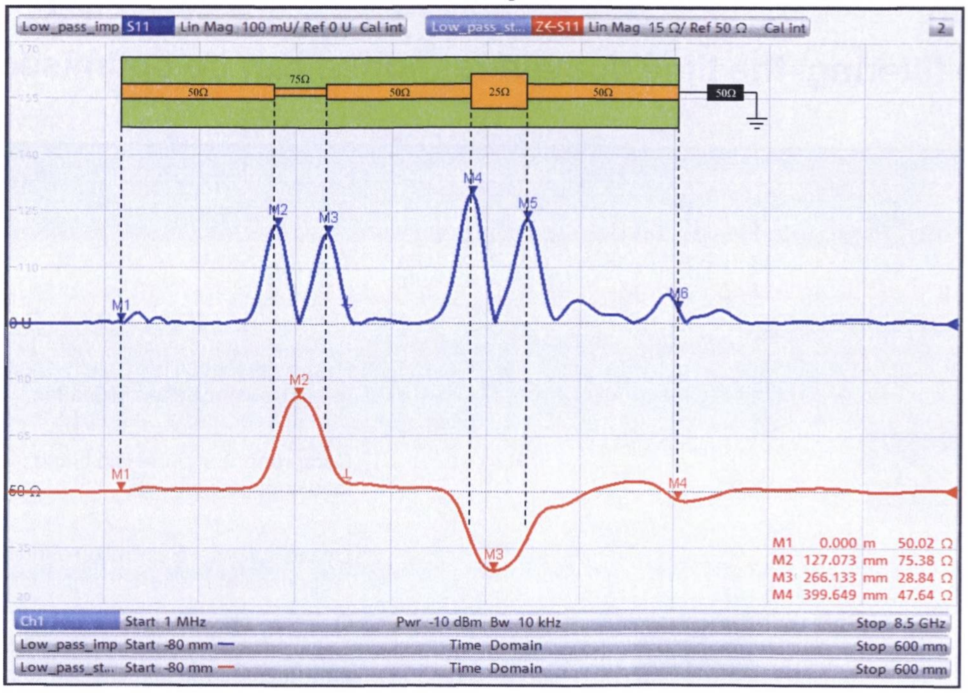


Open circuit response

Resolution Enhancement:
Mathematical linear prediction of the frequency range ⇒ improved time domain resolution.
(*Example: Res. Enh = 2*)

System impedance mismatch and measurement

- **Measurement of a microstrip structure**

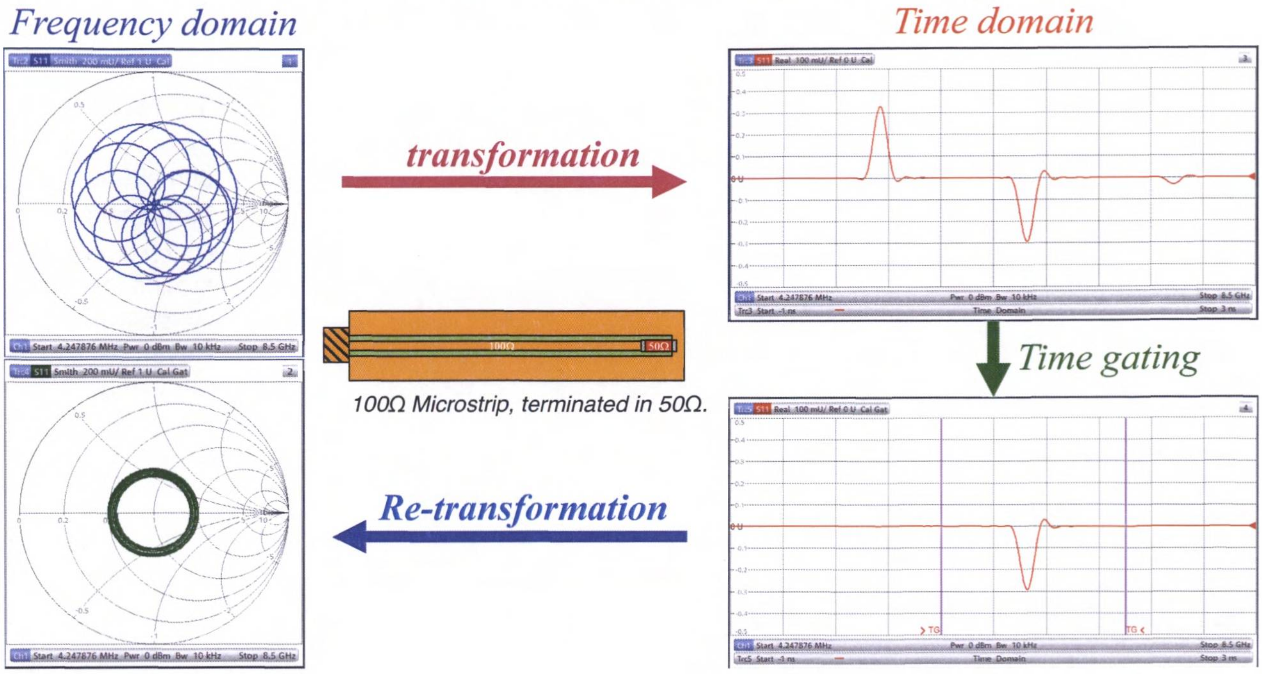


Low pass impulse:
- showing impedance mismatch

Low pass step:
- measure impedance

Time domain gating

Provides a method of viewing the frequency response of a discrete part of the time domain, thus removing unwanted responses.



“Time Gate” on the ZNB VNA

Accessed through the Trace Configuration menu

Defines the start and stop (*centre and span*) times for the gate.

Lines on the time domain display show the gate range

Select desired gate filter response

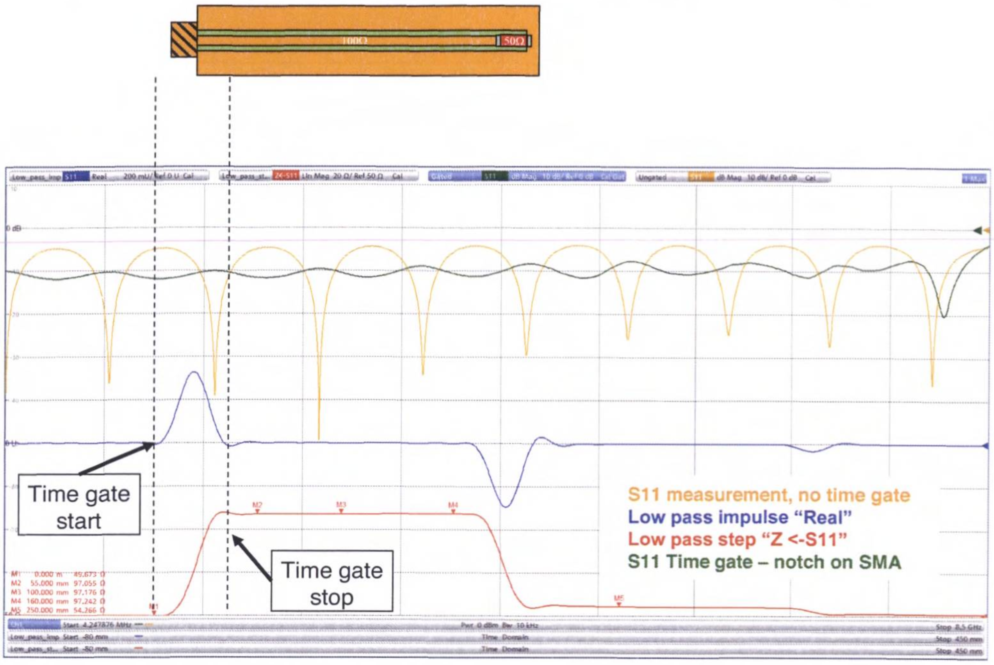
Select the filter used on the time domain trace

Applications:

- Removing the effects of:
  - Test fixtures/jigs.
  - Connectors.
- Antenna measurements, removing:
  - Unwanted reflections.
  - Effects of adjacent antennas (*cross-talk*).
- Also use to assess RF performance of connectors or soldered joints, etc.

Time domain gating - continued

100Ω Microstrip terminated with on-board 50Ω load



S11 measurement:

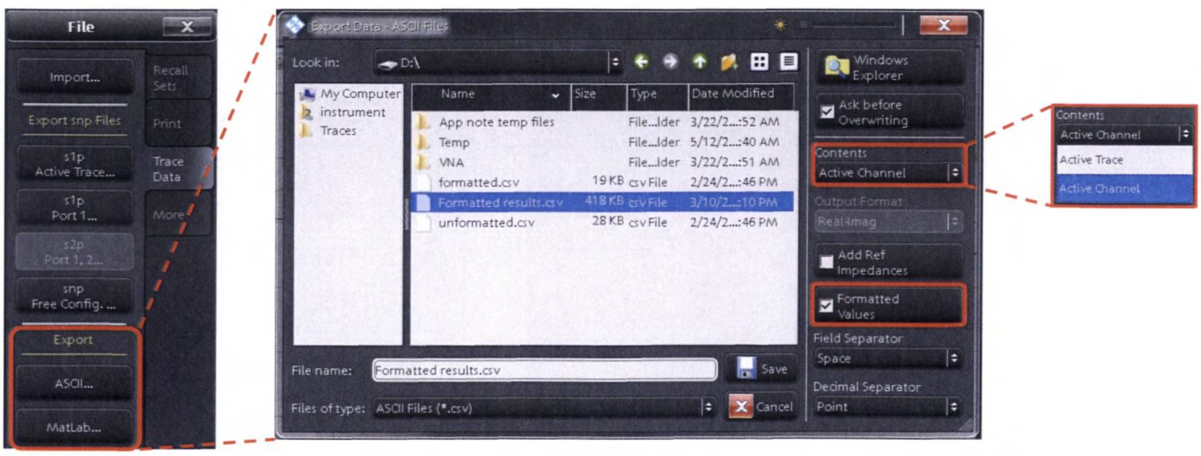
- Set up in the time domain
- Turn on time gate.
- Notch time gate set around the input connector.
- Revert back to the frequency domain.
- Result is the time domain gated frequency response.

File formats

Note: Saving an ".snp" file saves a normal <u>frequency domain</u> s-parameter file (*no time gating*).

Time domain is a formatted function applied to each trace.

To export the time domain and/or time domain gated results as seen on the R&S®ZNB screen:



Summary

Test requirements:

- Increase unambiguous range – Increase number of points.
- Increase resolution – Increase frequency span (bandwidth), or use "*Resolution Enhancement*".

Time domain modes:

- Band pass impulse – Scalar indication of the magnitude of the reflection coefficient; use when DUT doesn't operate to DC; no phase.
- Low pass modes – Higher resolution; complex result; requires harmonic grid.
  - Impulse: good for resolving discontinuities.
  - Step: recommended for impedance measurements.

Time domain gating:

- Useful for gating out unwanted effects in the frequency domain.

Questions

References

R&S Publications:

- App. Note, "*Time Domain Measurements using Vector Network Analyzer R&S®ZVR*", 1EZ44.
- "*Fundamentals of Vector Network Analysis*", Michael Hiebel, ISBN 978-3-939837-06-0
- R&S®ZNB/ZNBT Vector Network Analyzers, User Manual.
- R&S®ZNB/ZNBT Vector Network Analyzers, On-instrument "Help".

R&S Application Videos:

- "*Signal integrity of differential structures measured in the time domain using the R&S ZNB*" - https://www.youtube.com/watch?v=jhnAEhGnp5w
- "*Signal integrity - measuring rise time using R&S®ZVA with a true differential signal (part 2 of 4)*" - https://www.youtube.com/watch?v=YGHASkVQtwI
- "*Signal integrity - measuring differential impedance vs. distance using R&S®ZVA (part 3 of 4)*" - https://www.youtube.com/watch?v=5sJjd9SvVQw
- "*Signal integrity - time domain skew between two differential lines using R&S®ZVA (part 4 of 4)*" - https://www.youtube.com/watch?v=Yq64ZQlzQSc

Demystifying the Network Analyser: Measurement Uncertainty and Verification

Jamie Lunn
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UK & Ireland

R&S, November 2015

ROHDE&SCHWARZ

Agenda

- Measurement accuracy and uncertainty using the data sheet
- Calculation of measurement uncertainty using the VNAMUC tool
- Measurement uncertainty using verification standards
- Measurement uncertainty using R&S T-Check
- Summary

Agenda

- **Measurement accuracy and uncertainty using the data sheet**
- Calculation of measurement uncertainty using the VNAMUC tool
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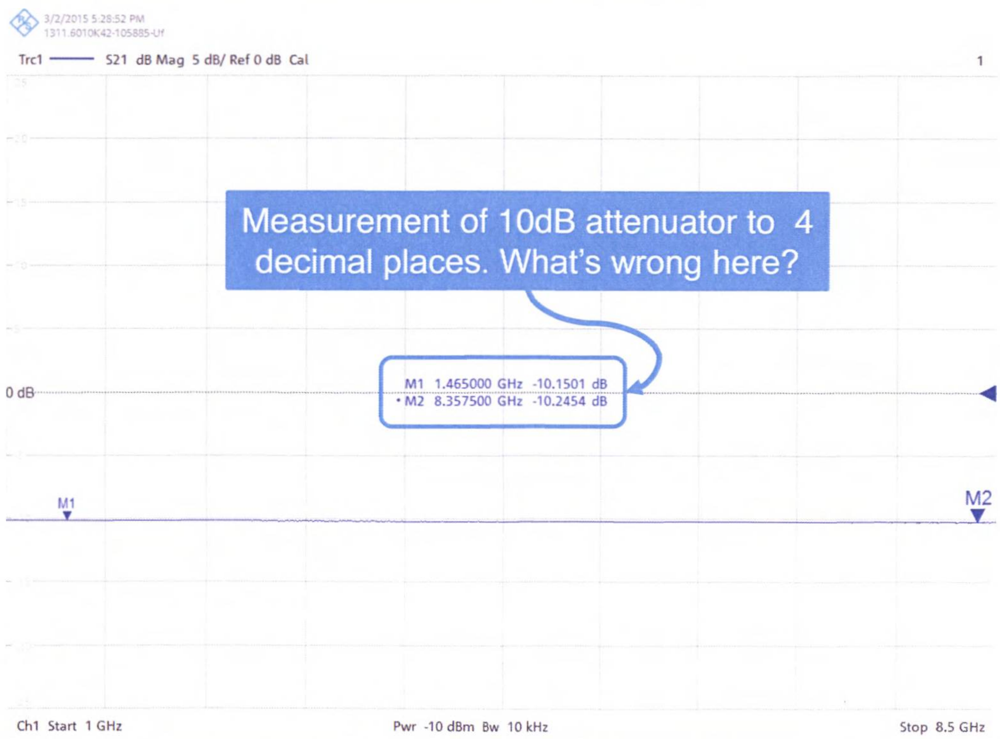
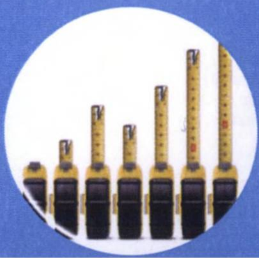
The problem with measurements…



What defines the quality of the measurement?

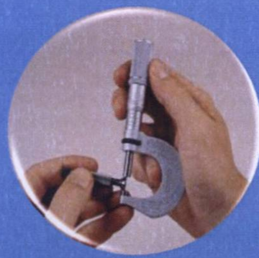


Validity

A measurement is 'valid' if it returns what it is expected from a legitimate instrument setup. What is measured must also be relevant to the parameter being investigated.

Accuracy

This describes how closely a measurement comes to the true value of a physical quantity. The 'true' value is the value that would be obtained by a perfect measurement. (for example, an ideal instrument without errors)



Precision

The number of significant digits to which a value has been reliably measured.

Repeatability refers to the spread of data under the same test conditions.

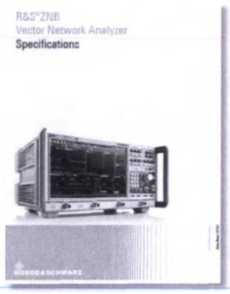
Reproducibility refers to the spread of data under different test conditions (instrumentation, climate, operator etc)

Uncertainty

The uncertainty of a measurement is the doubt that exists about its value. For any measurement – there is always a margin of error which is a measure of the possible deviation from the true value.

The Quality of Measurements – The Key Terms

What can you see from the data sheet?



- **Measurement accuracy**
  - Conditional guidance based upon specific criteria such as instrument type, test conditions and calibration kit
- **Factory calibrated system data**
  - Default effective system data and absolute power values at the test ports available from a "preset" state of the instrument
- **Effective system data**
  - Instrument characteristics (such as directivity, port matching, tracking), resulting from the raw (uncorrected) data following the application of the system error correction.
  - Conditional on the instrument, it's settings and the calibration kit used during the user calibration.
- **Raw performance of the test ports**
  - The uncorrected hardware properties, which effect the physical power waves
  - E.g. real match the DUT sees when looking back into the network analyser

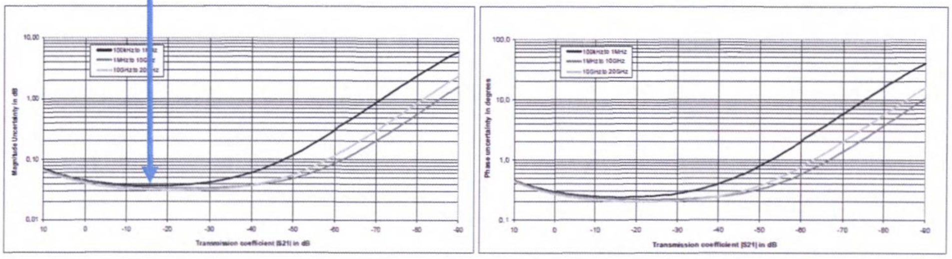
Data Sheet Measurement accuracy:

Transmission measurements

Measurement accuracy of the R&S®ZNB20

This data is valid between +18 °C and +28 °C, provided the temperature has not varied by more than 1 °C since calibration. Validity of the data is conditional on the use of an R&S®ZV-Z235 calibration kit. This calibration kit is used to achieve the effective system data specified below. Frequency points, measurement bandwidth and sweep time have to be identical for measurement and calibration (no interpolation allowed).

Accuracy of transmission measurements		
100 kHz to 1 MHz	+5 dB to –35 dB	< 0.05 dB or < 0.5°
	–35 dB to –50 dB	< 0.1 dB or < 1°
	–50 dB to –60 dB	< 0.3 dB or < 5°
1 MHz to 10 GHz	+5 dB to –35 dB	< 0.05 dB or < 0.5°
	–35 dB to –50 dB	< 0.06 dB or < 0.6°
	–50 dB to –60 dB	< 0.1 dB or < 1°
10 GHz to 20 GHz	+5 dB to –35 dB	< 0.05 dB or < 0.5°
	–35 dB to –50 dB	< 0.08 dB or < 0.8°
	–50 dB to –60 dB	< 0.15 dB or < 1.5°
Specifications are based on a matched DUT, a measurement bandwidth of 10 Hz and a nominal source power of –10 dBm.		



Typical accuracy of transmission magnitude and transmission phase measurements for the R&S®ZNB20 in the frequency range from 100 kHz to 20 GHz. Analysis conditions: $S_{11} = S_{22} = 0$, cal. power –10 dBm, meas. power –10 dBm.

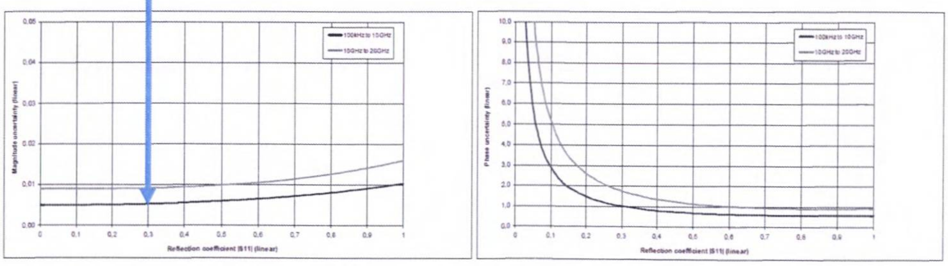
Data Sheet Measurement accuracy:

Reflection measurements

Measurement accuracy of the R&S®ZNB20

This data is valid between +18 °C and +28 °C, provided the temperature has not varied by more than 1 °C since calibration. Validity of the data is conditional on the use of an R&S®ZV-Z235 calibration kit. This calibration kit is used to achieve the effective system data specified below. Frequency points, measurement bandwidth and sweep time have to be identical for measurement and calibration (no interpolation allowed).

Accuracy of reflection measurements		
100 kHz to 10 GHz	0 dB to –15 dB	< 0.3 dB or < 2°
	–15 dB to –25 dB	< 1.0 dB or < 6°
	–25 dB to –35 dB	< 3.0 dB or < 20°
10 GHz to 20 GHz	0 dB to –15 dB	< 0.5 dB or < 4°
	–15 dB to –25 dB	< 1.6 dB or < 10°
	–25 dB to –35 dB	< 7.5 dB or < 35°
Specifications are based on an isolating DUT, a measurement bandwidth of 10 Hz and a nominal source power of –10 dBm.		



Typical accuracy of reflection magnitude and reflection phase measurements for the R&S®ZNB20 in the frequency range from 100 kHz to 20 GHz. Analysis conditions: $S_{12} = S_{21} = 0$, cal. power –10 dBm, meas. power –10 dBm.

Data Sheet factory calibrated system data:

Factory-calibrated system data

This data is valid between +18 °C and +28 °C. It is based on a source power of –10 dBm and a measurement bandwidth of 1 kHz.

Directivity	9 kHz to 50 kHz	> 20 dB, typ. 35 dB
	50 kHz to 4.5 GHz	> 30 dB, typ. 50 dB
	4.5 GHz to 10 GHz	> 30 dB, typ. 50 dB
	10 GHz to 20 GHz	> 25 dB, typ. 35 dB
	20 GHz to 35 GHz	> 20 dB, typ. 20 dB
	35 GHz to 40 GHz	> 15 dB, typ. 20 dB
Source match	9 kHz to 50 kHz	> 20 dB, typ. 35 dB
	50 kHz to 4.5 GHz	> 30 dB, typ. 50 dB
	4.5 GHz to 10 GHz	> 30 dB, typ. 50 dB
	10 GHz to 20 GHz	> 25 dB, typ. 35 dB
	20 GHz to 35 GHz	> 20 dB, typ. 20 dB
	35 GHz to 40 GHz	> 15 dB, typ. 20 dB
Reflection tracking	9 kHz to 20 GHz	< 0.5 dB, typ. 0.1 dB
	20 GHz to 40 GHz	< 0.5 dB, typ. 0.1 dB
Transmission tracking	9 kHz to 20 GHz	< 0.5 dB, typ. 0.1 dB
	20 GHz to 40 GHz	< 0.5 dB, typ. 0.1 dB
Load match of the R&S®ZNB4 and the R&S®ZNB8	9 kHz to 50 kHz	> 10 dB, typ. 15 dB
	50 kHz to 8.5 GHz	> 20 dB, typ. 25 dB
Load match of the R&S®ZNB20	100 kHz to 1 MHz	> 16 dB, typ. 20 dB
	1 MHz to 2 GHz	> 20 dB, typ. 23 dB
	2 GHz to 20 GHz	> 16 dB, typ. 19 dB
Load match of the R&S®ZNB40	10 MHz to 50 MHz	> 15 dB, typ. 18 dB
	50 MHz to 2 GHz	> 20 dB, typ. 22 dB
	2 GHz to 6 GHz	> 16 dB, typ. 18 dB
	6 GHz to 10 GHz	> 12 dB, typ. 14 dB
	10 GHz to 20 GHz	> 10 dB, typ. 12 dB
	20 GHz to 40 GHz	> 8 dB, typ. 10 dB

Data Sheet effective system data:

⇨Performance defined by the quality of the calibration kit used

Effective system data

This data is valid between +18 °C and +28 °C, provided the temperature has not varied by more than 1 °C since calibration. Frequency points, measurement bandwidth and sweep time have to be identical for measurement and calibration (no interpolation allowed).

The data is based on a measurement bandwidth of 10 Hz and system error calibration with an R&S®ZV-Z235 calibration kit.

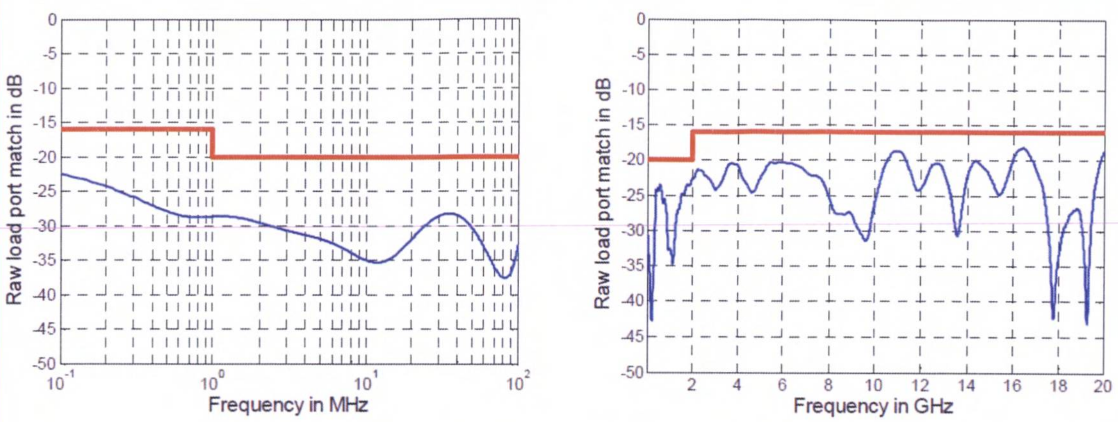
R&S®ZNB20	100 kHz to 10 GHz	10 GHz to 20 GHz
Directivity	46 dB	41 dB
Source match	43 dB	38 dB
Load match	44 dB	40 dB
Reflection tracking	0.05 dB	0.05 dB
Transmission tracking	0.025 dB	0.035 dB

Effective system data of R&S®ZV-Z235

The specified effective system data are established after performing a suitable system error calibration, e.g. TOSM, at a R&S®ZVA, R&S®ZVB, or R&S®ZVT vector network analyzer, using the characteristic data of the calibration kit, which are stored on a provided USB stick. This data is valid between +18 °C and +28 °C, at a measurement bandwidth of 10 Hz, and a nominal power of –10 dBm at the calibration ports. The calibration kit is fully functional down to 0 Hz, with effective system data as specified below, although the data is only verified for frequencies as stated.

Directivity	10 MHz to 700 MHz	> 36 dB, typ. 46 dB
	700 MHz to 24 GHz	> 40 dB, typ. 46 dB
Source match	10 MHz to 700 MHz	> 30 dB, typ. 43 dB
	700 MHz to 24 GHz	> 36 dB, typ. 43 dB
Reflection tracking	10 MHz to 700 MHz	< 0.2 dB, typ. 0.04 dB
	700 MHz to 24 GHz	< 0.1 dB, typ. 0.02 dB
Load match	10 MHz to 700 MHz	> 36 dB, typ. 46 dB
	700 MHz to 24 GHz	> 40 dB, typ. 46 dB
Transmission tracking	10 MHz to 700 MHz	< 0.2 dB, typ. 0.04 dB
	700 MHz to 24 GHz	< 0.1 dB, typ. 0.02 dB

Data Sheet raw test port performance:

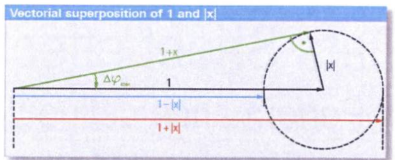


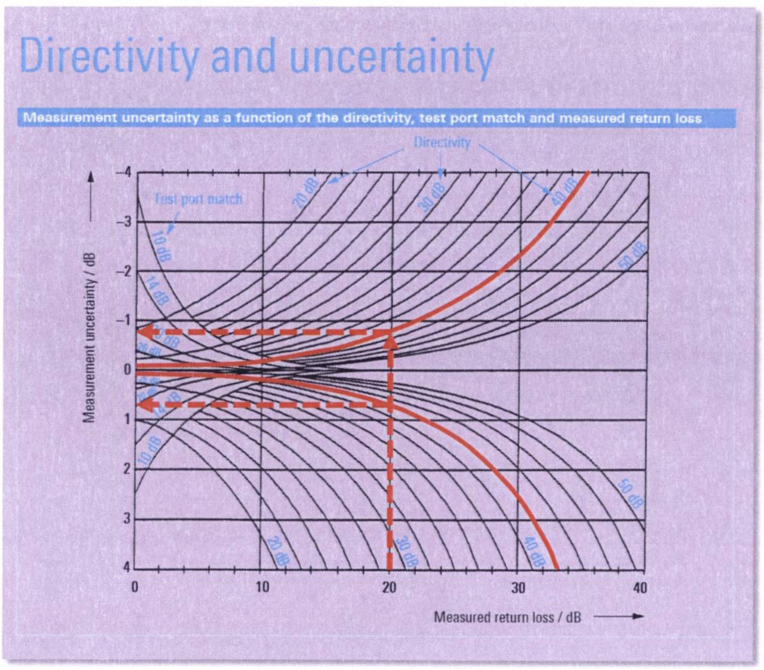
Raw load port match versus frequency for the R&S®ZNB20.

This is important as it describes the REAL test port match that your device will see when connected to the network analyser

Example using the poster

Directivity = 40dB, $|S_{11}|$ = 20dB





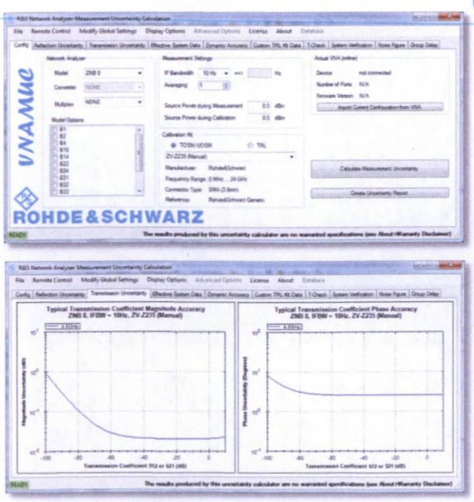
Signal to error signal	Measurement uncertainty	
|x| in dB	1 + |x| in dB	1 − |x| in dB
0	6.021	∞
1	5.535	−19.271
2	5.078	−13.737
3	4.649	−10.691
4	4.249	−8.658
5	3.876	−7.177
6	3.529	−6.041
7	3.207	−5.141
8	2.911	−4.410
9	2.638	−3.806
10	2.387	−3.302
11	2.157	−2.876
12	1.946	−2.513
13	1.755	−2.201
14	1.580	−1.933
15	1.422	−1.701
16	1.278	−1.499
17	1.148	−1.323
18	1.030	−1.169
19	0.924	−1.034
20	0.828	−0.915
21	0.742	−0.811
22	0.664	−0.719

Agenda

- Measurement accuracy and uncertainty using the data sheet
- **Calculation of measurement uncertainty using the VNAMUC tool**
- Measurement uncertainty using verification standards
- Measurement uncertainty using R&S T-Check
- Summary

Calculation of Measurement Uncertainty – VNAMUC

When specific criteria is to be provided to understand the uncertainty



(Vector Network Analyzer Measurement Uncertainty Calculator)

Theoretical calculation of VNA uncertainty
- Based upon user selection of VNA type, measurement parameters, options, calibration kit and DUT properties

Communication directly with VNA
- Transfer of settings and measurement data

Performing VNA verification measurement
- Definition and handling of verification kits
- Performing VNA verification

Performing VNA T-Check
- Definition and handling of T-Check devices
- Performing T-Check verification

Documentation of results
(zooming, marker readout etc)

Agenda

- Measurement accuracy and uncertainty using the data sheet
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- Summary

Verification standards…

>VERIFICATION<

When you wish to check the measurement accuracy of your "real life" VNA test system after user calibration (system error correction)

Performs evaluation of system properties of the VNA

Requires measurements on several Verification Standards (VS)

"Verification" means:

Comparison of the measurement results S_{xx} with the values specified for the defined verification standards

Verification standards: specified with tighter limits than the calibration standards

Traceable!

Standards that are not used during the normal calibration of the VNA

For example: Stepped line/through, attenuator, mismatch, offset short

Evaluation of uncertainty

(under given conditions)

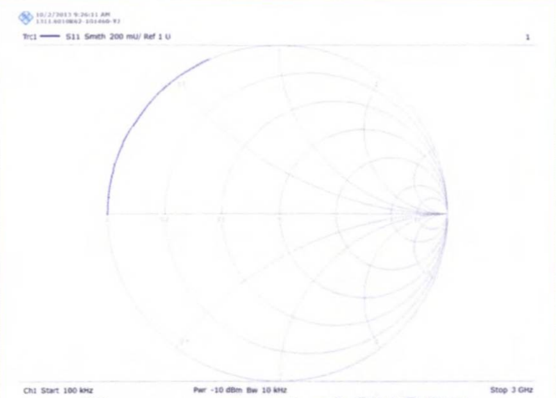
Information on effective directivity, port matching, transmission/reflection tracking

Definition of Verification

Plausibility of test results from a device different to the device under test

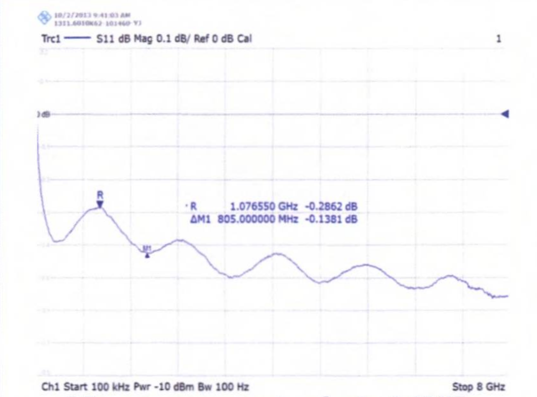
- Known device, air-line or DUT supplied with characterisation data
- Calibration standard not used for calibration (SHORT after TRM)

Provides a check not full verification



Measurement of SHORT:

Electrical length
Phase measurement
Attenuation



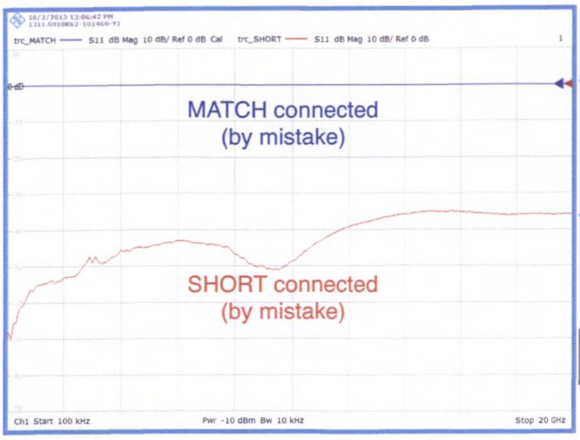
Measurement of air LINE:

Ripple:
measure for effective directivity and port match
Uncertainty of reflection measurement
E.g.: peak-peak: 0.14 dB: 36 dB port match

Reproducibility **verses** Verification

Why must a verification standard be different from the calibration standard?

- Calibration referred to the <u>description data</u> of the calibration standards (length, attenuation, impedance etc)
- Measurement trace of a calibration standard <u>corresponds to the definition data.</u>



Calibration step: **SHORT** but incorrectly applying the **MATCH** standard
Trace corresponds = definition data of the **SHORT**

Calibration step: **MATCH** but incorrectly applying the **SHORT** standard
Trace corresponds = definition data of the **MATCH**

No information on system performance gained by reconnecting a calibration standard used during calibration

Types of verification standards: R&S Verification kits

Verification standards defined by

- *.s1p and *.s2p files
- Uncertainty data

Supported connector types (male-female connection):

- N
- 3.5mm
- 2.92mm
- 2.4mm
- 1.8mm

Offset Short

- Length ~15 mm

Attenuator

- -40 dB
- Length ~30 mm

Mismatch

- 20 dB (Z_0=60 Ohm)
- Length ~ 15 mm

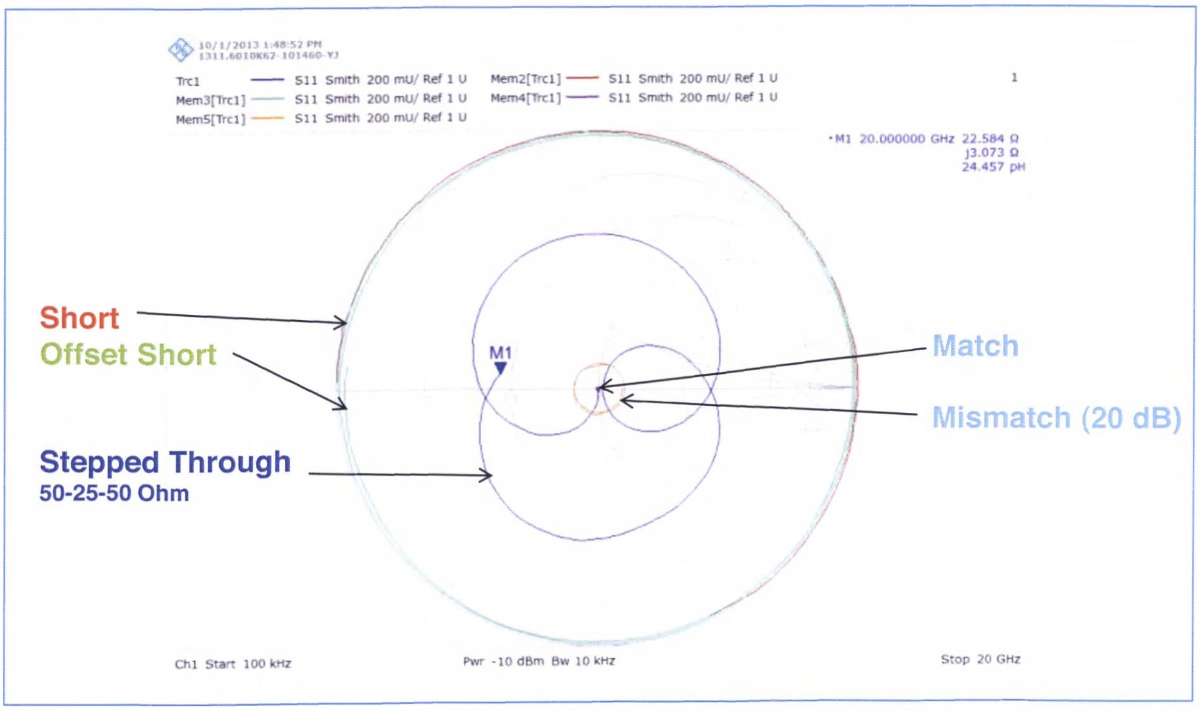
Stepped Through

- 50Ω - 25Ω - 50Ω
- Length ~ 30mm

All RF measurement quantities traced to National Metrology Institutes. e.g. PTB (Germany), NPL (UK) etc

Typical Impedance (S_{11}) of verification standards

Comparison with Short and Match calibration standards



Verification Software Tool VNAMUC

Performing & Analysis of verification

Handling of the verification kits

- Import of verification kit data
- Automatic setup of VNA
- Selection of standard and measurement

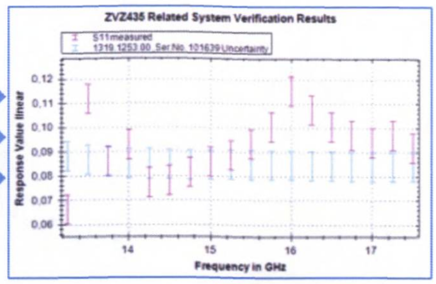
Verification

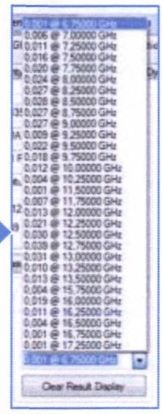
Transfer of measurement data from VNA to VNAMUC tool

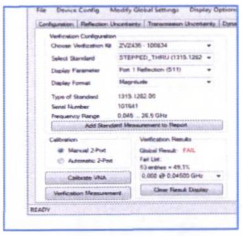
Comparison

Data of verification standard measured on VNA including error bars.

Data specified for verification standard plus error bar specified by PTB







Criterion for pass/fail decision

$|X_{meas}-X_{VS}| < U_{meas}+U_{VS,}$

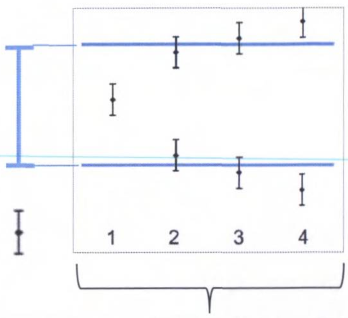
(where X := measured / specified, U := uncertainty)

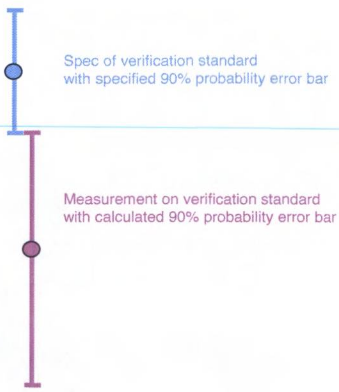
Listing of all failing values

R&S®VNAMUC Pass/Fail criterion

Error bar of verification standard

Measurement value taken on verification standard by VNA



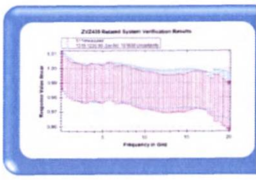


Pass/Fail distinction of cases:

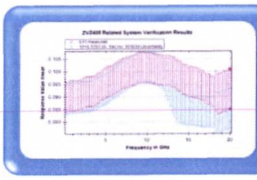
1. Pass
2. Pass with low probability for fail
3. Pass with increased probability for fail
4. Fail

Uses the uncertainty data from VNAMUC to overlay the error bars on the verification measurement from the VNA. If the measurement passes then the calculated uncertainty data can be applied to the current setup.

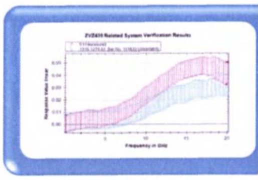
Verification Measurements and Interpretation



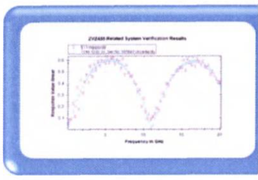
Offset Short
- Verification of **high reflecting** measurements
- Verification of measurements with similar parameters: given by error bars



Mismatch
- Verification of **low reflecting** measurements
- Verification of measurements with similar parameters: given by error bars



Attenuator
- Verification of **low reflecting** measurements
- Verification of measurements with similar parameters: given by error bars
- Check for linearity



Stepped Through
- Verification **mid range** reflecting measurements
- Verification of measurements with similar parameters: given by error bars
- Check for linearity

Verification Summary: Info from R&S®VNAMUC

Pass/Fail Information
- Can be read directly from R&S®VNAMUC tool
- If all results are passed: Uncertainty graphs from R&S®VNAMUC are met

Information on accuracy:
- Can be derived directly from the VS's error bar constellation
- Accuracy can be estimated for a DUT similar to the connected VS

Information on effective system data:
- (Mis)Match: Directivity
- (Offset)Short: Mismatch, Directivity, Reflection Tracking
- Stepped Through: Transmission Tracking, Linearity
- Attenuator: Linearity

Case	Result of Offset Short	Result of Mismatch	Directivity	Source Match
1	✓	✓	OK	OK
2	✓	×	OK	Not OK
3	×	×	Not OK	No conclusion
4	×	✓	Not OK	No conclusion

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R&S T-Check

The golden medium between investment, effort, and validity of verification

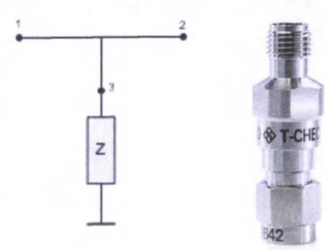
What is it?

- Gives a check of the system performance after a calibration
- Provides an indication that the specifications provided in the data sheet of the VNA can be met

How does it work?

- Uses the symmetry of the S-Parameters for a 3-port device
- The deviation from symmetry (or reciprocity) gives a measure for the measurement uncertainty
- Calculated from what's known as the C_T factor (ideal device $C_T = 1$)

$$c_T = \frac{|S_{11}S_{21}^* + S_{12}S_{22}^*|}{\sqrt{(1-|S_{11}|^2-|S_{12}|^2)(1-|S_{21}|^2-|S_{22}|^2)}}$$



R&S T-Check

The golden medium between investment, effort, and validity of verification

What are the benefits over a full verification kit?

- Only one device is required to be measured - Simple to use
- Lower cost than purchasing a full verification kit

Are there any limitations?

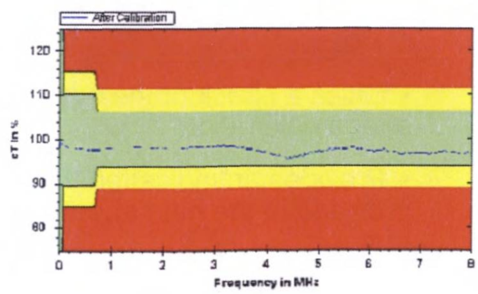
- Gives an indication as to whether the specification in the data sheet of the VNA is met
- Uses magnitude information, no information about the phase is provided
- Only provides a measurement for a given part of the Smith chart. T-Check has around 8dB return loss
- As all four S-Parameters contribute to the C_T factor is not possible to ascertain what errors can contribute to a fail

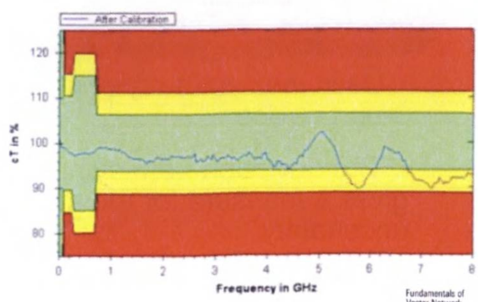
T-Check

The results screen

- c_T gives the deviation in % from the specification
- **Green range:** Uncertainty as stated in the network analyser data sheet is met
- **Yellow range:** >acceptable<

  (The phase can be constructive or destructive giving the unknown yellow region on the graph)
- **Pass/fail interpretation not possible because T-Check only uses the magnitude information.**
- Gives indication that the accuracy curves from the data sheet are met for the given conditions.





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Agenda

- Measurement accuracy and uncertainty using the data sheet
- Calculation of measurement uncertainty using the VNAMUC tool
- Measurement uncertainty using verification standards
- Measurement uncertainty using R&S T-Check
- **Summary**

Summary:

- Network analyser accuracy after system error correction strongly related to the description and quality of the calibration standards
- Re-connection of the standards used during calibration offers no indication to the accuracy of the measurement
- The data sheet only gives an indication of accuracy under specific conditions

- Calculation of measurement uncertainty for given user conditions can be made with the R&S VNAMUC tool.
- Verification standards can be used to derive a real life indication of accuracy
  - Comparison of real verses desired values (compared to national standards)
  - Direct information on measurement uncertainty (for specific conditions)
  - Check for effective system data
  - Connection of all verification standards for a full system verification
- Use of the T-Check for a quick, low cost verification of measurement accuracy

Questions?

ROHDE&SCHWARZ

Demystifying the network analyser. Basic Amplifier Measurements with a VNA

Mark Bailey, CEng
RF & Microwave Application Engineer

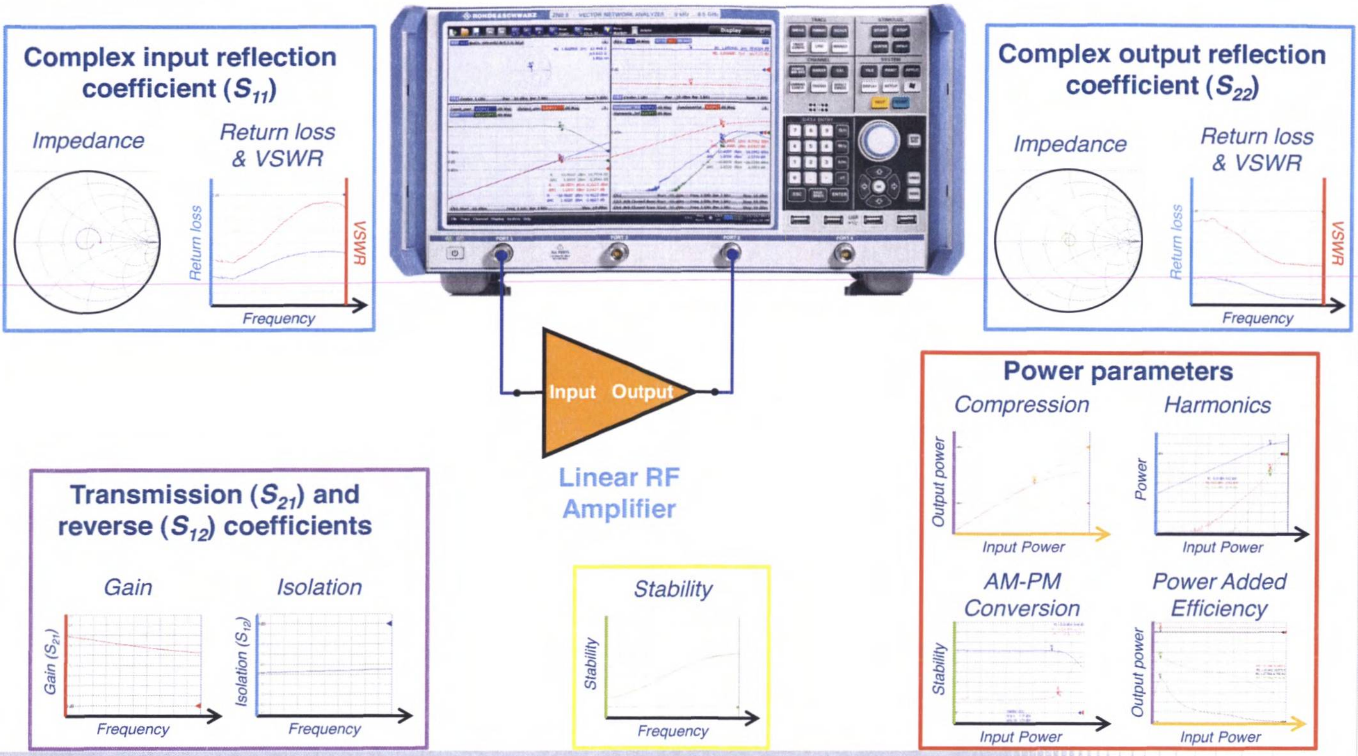
R&S, November 2015

ROHDE&SCHWARZ

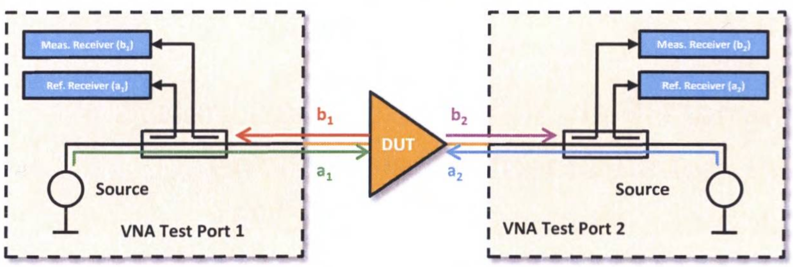
Agenda – Basic amplifier measurements

- **Small signal RF amplifiers – key parameters**
- **Practical measurement considerations**
- **Example measurements with the ZNB**
  - Step 1 – Configuring the ZNB
  - Step 2 – Calibration
    - System error correction
    - Power calibration
    - Introducing "SMARTerCal"
    - Scalar power calibration
    - Check the calibrations
  - Step 3 – Amplifier measurements
    - S-parameters
    - Stability
    - Compression point / power sweep
    - Harmonics
    - AM to PM conversion
    - Power Added Efficiency

Small signal RF amplifiers – key parameters



Capabilities of a vector network analyser (VNA)



A modern VNA is the most effective way to characterise a linear RF amplifier.

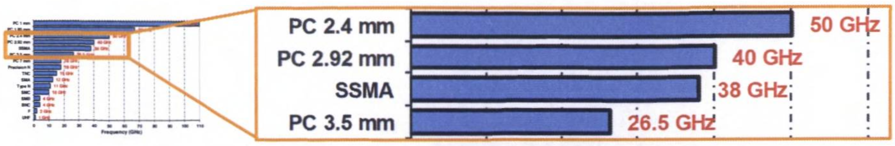
- Multiple VNA measurement channels allow configurations with swept frequency and power, all within one measurement setup.
- The amplifier need only be connected to the VNA once for all tests, reducing connector wear and minimising errors.

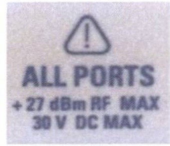
Two calibrations are required:

- System error correction – *requires calibration standards.*
- Test port reference receiver and source power levels – *requires a power sensor.*

Practical measurement considerations

Frequency range?	• VNA – *e.g. min/max frequencies. Harmonic measurements?* • Connector types and calibration standards





Power levels?	• DUT input power – maximise the signal to noise ratio. Stay below the compression level of the DUT (*pre-amp/attenuation may be needed*). • DUT output power – must be significantly below the damage level of the VNA ports (*attenuation may be needed*).
What sweep resolution? **Fast measurements?** **Minimised impact of noise?**	**Compromise of:** • No. of measurement points or frequency steps per sweep – *More points/steps increases the time per sweep.* • Intermediate Frequency (IF) bandwidth – highly selective and smaller filter bandwidths help to reject noise around the measurement frequency. Impact -> increased measurement time.

Example measurements with the ZNB

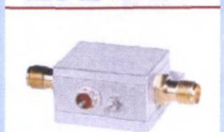
Aims of the exercise:

1. Configure the ZNB with two channels:
   1. frequency sweep
   2. power sweep
2. Efficiently calibrate for system error correction and power levels.
3. Measure the amplifier performance:
   - full 2-port S-parameters
   - stability
   - 1 dB compression point
   - harmonics

Device under test (DUT):

FREQUENCY (MHz)		GAIN (dB)			MAXIMUM POWER (dBm)			DYNAMIC RANGE		VSWR (:1) Typ.	
					Output (1 dB Compr.)		Input	NF (dB)	IP3 (dBm)		
f_L	f_U	Typ.	Min.	Flatness[1] Typ.	L	U	(no damage)	Typ.	Typ.	In	Out
20	3000	19	14	±2.2	+8	+8	+13	3.8	+22	1.4	1.6

ZJL-3G+



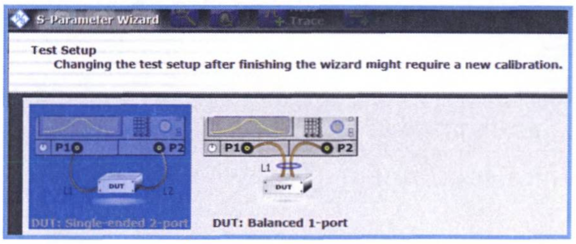
Mini-Circuits RF amplifier

Step 1 – Configuring the ZNB

For this example, minimum settings required on the ZNB network analyser are:

PRESET			
Channel 1		Channel 2	
Start frequency	1 GHz	Start power	-25 dBm
Stop frequency	3.5 GHz	Stop power	0 dBm
Source power level	-20 dBm	CW frequency	2 GHz
Number of points	201	Number of points	201
IF measurement bandwidth	1 kHz	IF measurement bandwidth	1 kHz

Quickly configure for S-parameter measurements using the "S-parameter Wizard"



Step 2 - Calibration

Purpose:

To define measurement reference planes at the interface of the VNA test cables to the DUT, providing:

- Full system error correction
- Corrected power levels

Required:

R&S ZNB SMARTerCal – *software tool that manages the calibration process. Couples system error correction with scalar power calibration:*

- Calibration kit – *manual or auto calibration unit and torque spanner.*
- Power sensor – *power alignment of reference receivers.*
- "Flatness calibration" of the RF power source - *requires 50 Ω or DUT.*

Step 2 – Calibration. "R&S ZNB SMARTerCal"

The R&S ZNB supports the SMARTerCal calibration tool…

Enhanced wave correction
Combines system error correction with scalar power calibration to provide vector corrected wave-quantities (enhanced wave quantities)

All encompassing routine
Scans all configured traces and channels to provide an all encompassing calibration technique in one easy connection. Particularly suited to frequency converting setups

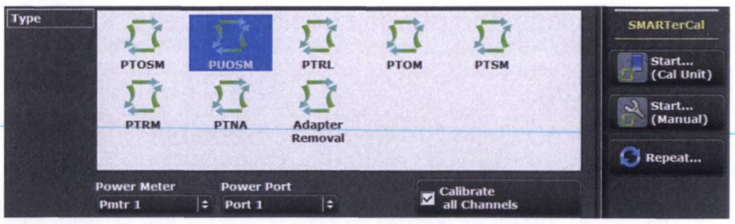
Minimal connection of power sensor
Power sensor connected to a nominated test port. Power reference is transferred to all test ports via the system error correction.

Correction for power sensor reflection coefficient
System error correction is used to measure the gamma of the power sensor to correct for absolute power mismatch.

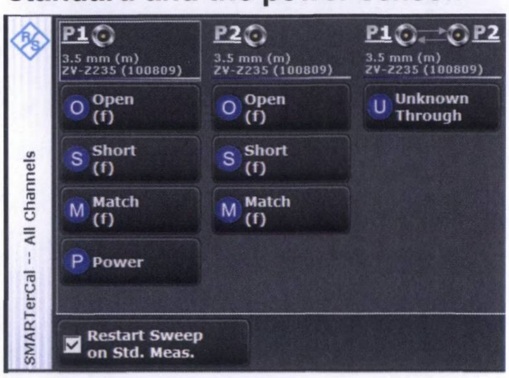
Step 2 – Calibration. Example

SMARTerCal - Using a manual calibration kit and power sensor:

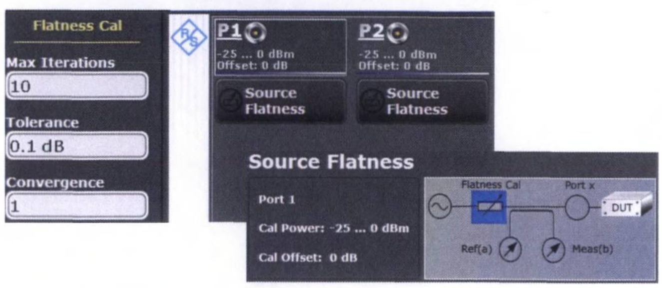
1. **Calibration Type:** PUOSM (Power, Unknown through, Open, Short, Match)
2. **Select connector type and calibration kit** (*defines the cal standards*)



3. **Step through calibration, applying each standard and the power sensor.**

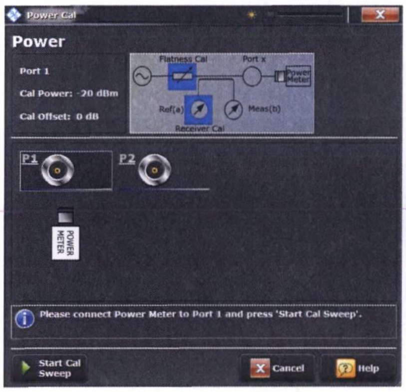


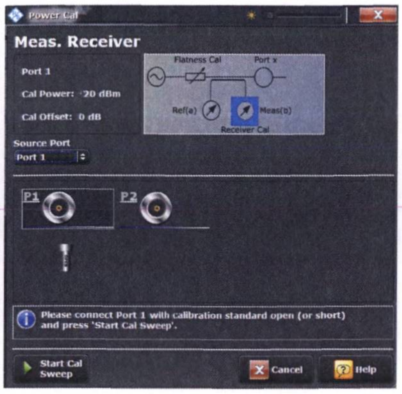
4. **Apply the SMARTerCal calibration.**
5. **Perform source power flatness calibration.**

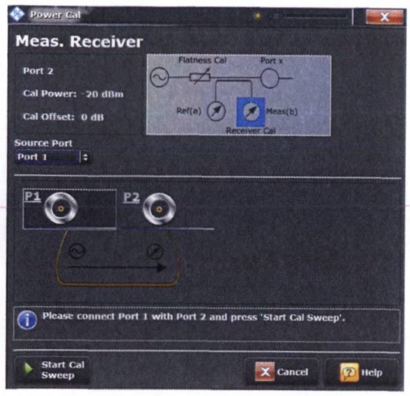


Step 2 – Calibration. Scalar power calibration

A scalar power calibration can be performed without using SMARTerCal.







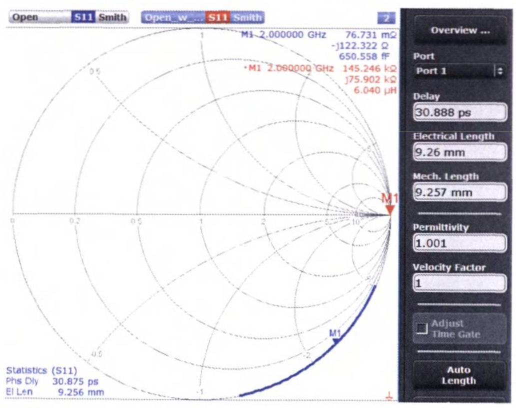
A power sensor is used to perform the scalar power calibration:

- Source level and reference receiver on source test port – *power sensor*
- Measurement receiver on source test port – *Port 1 reference receiver*
- Measurement receiver on receiving test port - *Port 1 reference receiver*

Good practice – Check systematic error calibration

1. **Known through**
   - S21 - Are loss and phase sensible values? *Use "Trace Statistics" to measure delay/length.*
   - S11/S22 - 50 Ω on Smith chart? Sensible return loss?
2. **Match (50 Ω)**
   - S11/S22 – 50 Ω on Smith chart.
   - S11/S22 – Compare return loss measurement with the match data (.s1p).

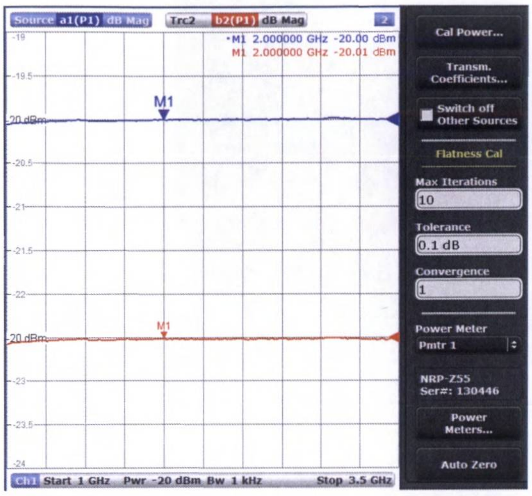
3. **Reflection (open/short)**
   - S11/S22 – Smith chart. Note the applied offset to get back to the reference plain.

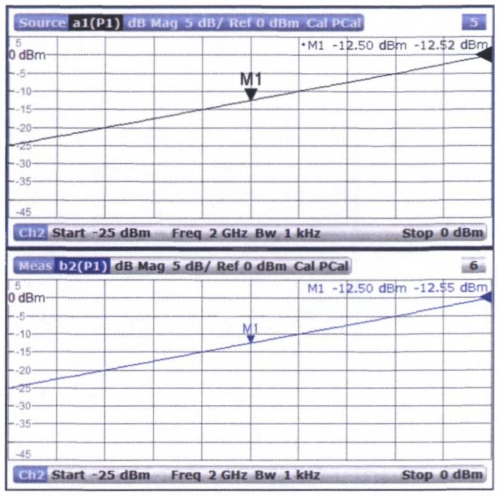


Good practice – Check power calibration

Connect a known through. Observe the wave quantities in the frequency and power domains:

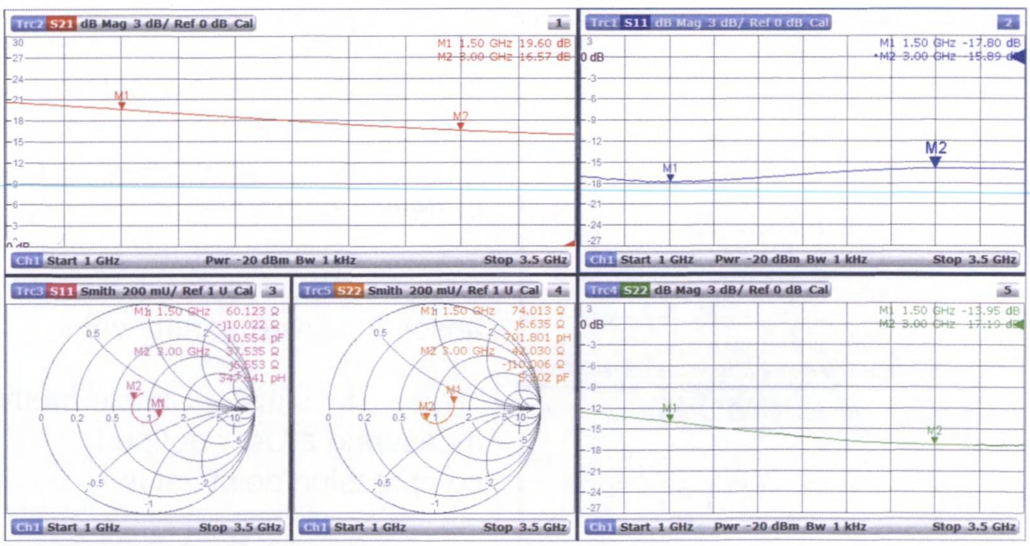
- 'a1' source Port 1
- 'b2' source Port 1





Ready for measuring? Turn off the RF sources and connect the DUT.

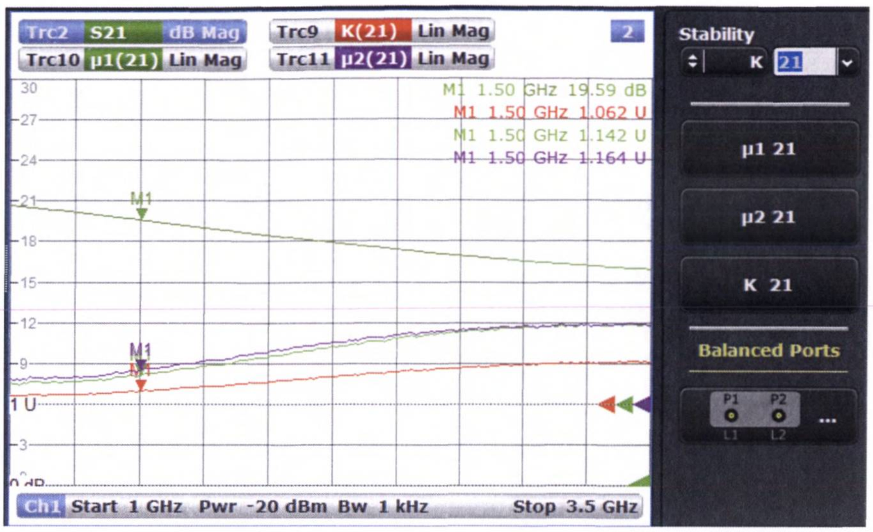
Measurements: S-parameters



Characterisation of linear parameters:

- Gain
- Gain flatness
- Reverse gain or Isolation
- Return Loss
- Voltage Standing Wave Ratio (VSWR)
- Complex impedance

Measurements: S-parameters, Stability

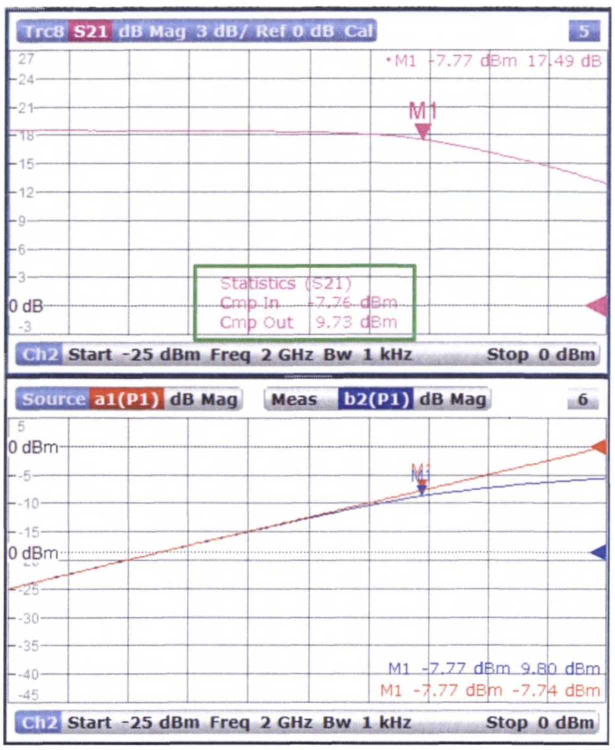


Uses the complex S-parameters to calculate stability factors:

- *K*, Rollett stability factor
- μ_1, input stability factor
- μ_2, output stability factor

Device is unconditional stable when $K > 1$ and $\mu_1 > 1$ or $\mu_2 > 1$

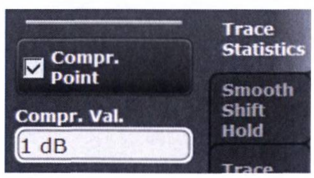
Measurements: Compression point / power sweep



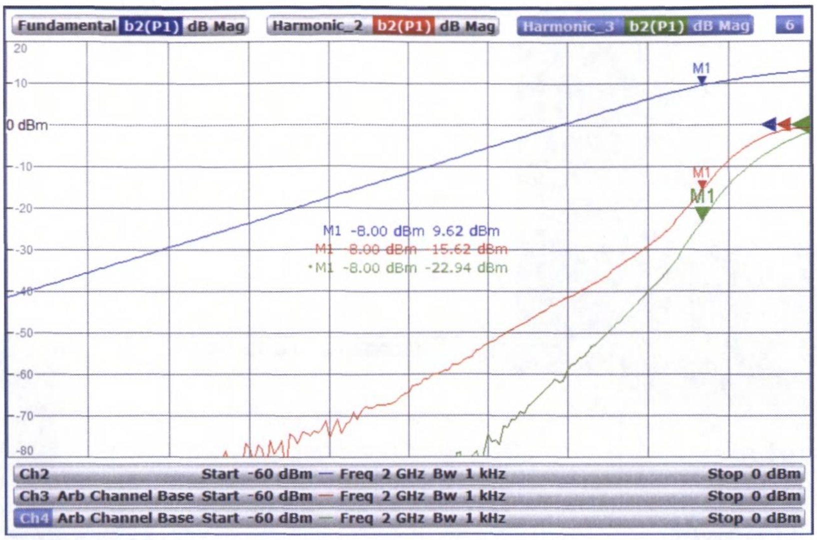
Linear power sweep to measure DUT's linearity over a wide power range (*>100 dB with extended power range option*). Allows measurement of device compression point.

Power calibration needed to measure absolute wave-quantity value.

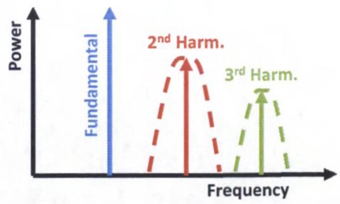
"Trace Statistics" – Simple method of measuring a User defined compression point value.



Measurements: Harmonics



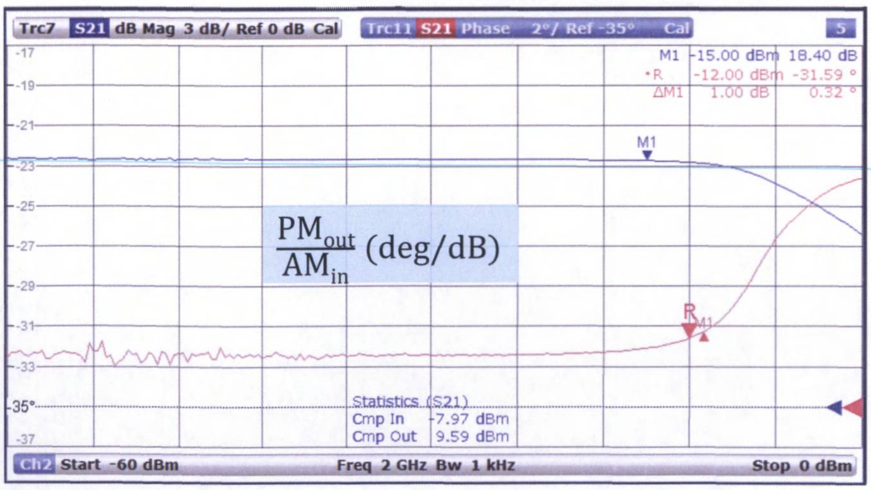
ZNB option:
- *ZNB K4 Freq Conversion*



Modern VNAs allow the source and receiver frequencies to be offset, allowing measurement of harmonics.

With the source providing a fundamental frequency, the receivers can be set to measure 2nd and 3rd harmonics. Requires power calibration.

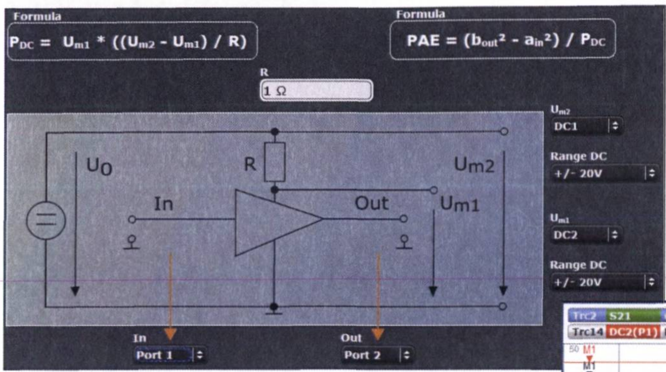
Measurements: AM to PM conversion



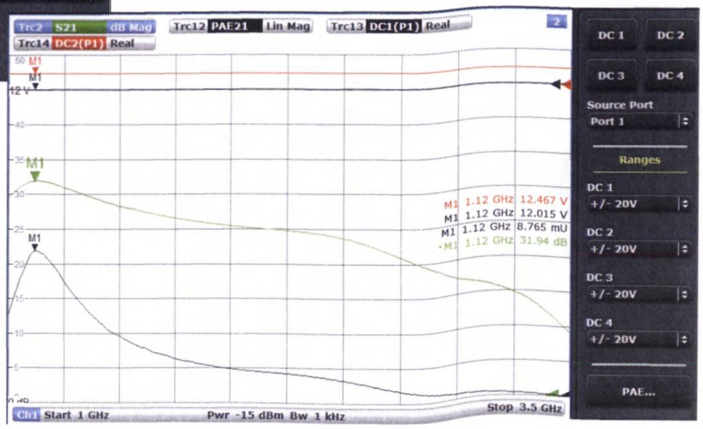
Amplitude Modulation (AM) to Phase Modulation (PM)
- Measure of phase deviation caused by amplitude change.
- Important in systems using QAM, and/or pre-distortion.
- Stimulus = Power sweep.
- System error correction & power cal => Vector corrected wave quantities.

Measurements: Power Added Efficiency

ZNB option:
- *ZNB B81 DC Inputs*



$$PAE = \frac{\left(\left|P_{OUT}\right| - \left|P_{IN}\right|\right)}{P_{DC}}$$



DC measuring inputs and a small value precision resistor provide a measure of DC power.

Requires RF power calibration.

Questions

References

R&S Publications:

- App. Note: "*Basic RF Amplifier Measurements using the R&S ZNB Vector Network Analyzer and 'SMARTerCal'*", 1EZ65
- App. Note: "*Power Added Efficiency Measurement with R&S®ZNB/R&S®ZVA*", 1EZ64
- "*Fundamentals of Vector Network Analysis*", Michael Hiebel, ISBN 978-3-939837-06-0
- R&S®ZNB/ZNBT Vector Network Analyzers, User Manual.
- R&S®ZNB/ZNBT Vector Network Analyzers, On-instrument "Help".

R&S Application Videos:

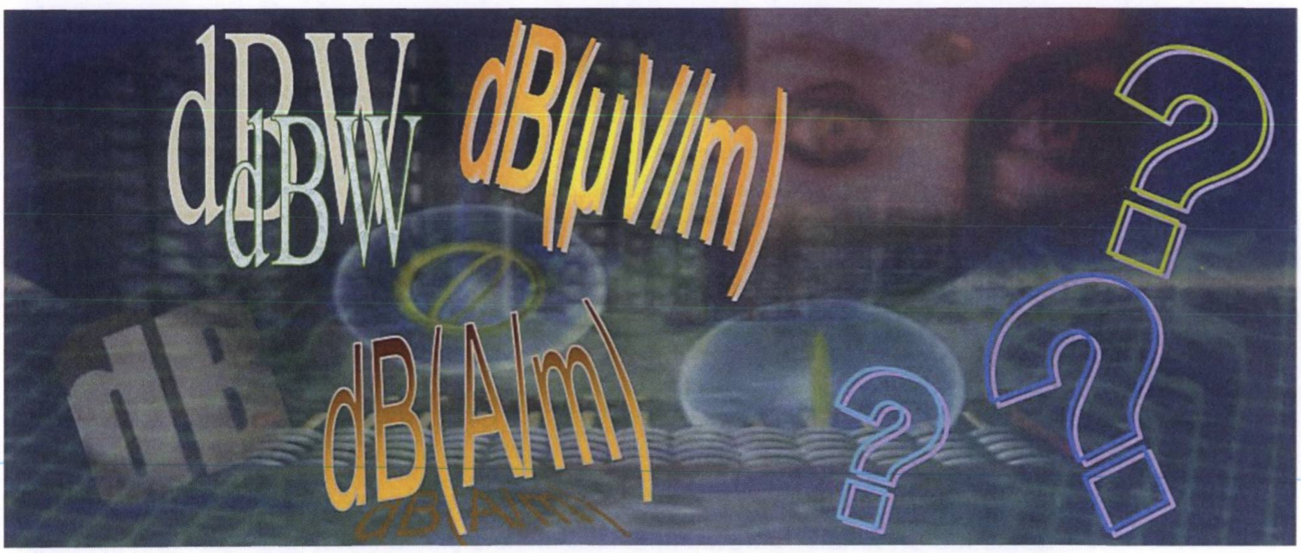
- "*Power calibration for Amplifier Measurements using the R&S®ZVA Network Analyser*" - http://tinyurl.com/npy6whe
- "*Guidance on performing network analyzer coaxial calibration*" - http://tinyurl.com/oyyzwxa

dB or not dB?
Everything you ever wanted to know about decibels but were afraid to ask…
Application Note

Products:

- Signal Generators
- Spectrum Analyzers
- Test Receivers
- Network Analyzers
- Power Meters
- Audio Analyzers

True or false: 30 dBm + 30 dBm = 60 dBm? Why does 1% work out to be -40 dB one time but then 0.1 dB or 0.05 dB the next time? These questions sometimes leave even experienced engineers scratching their heads. Decibels are found everywhere, including power levels, voltages, reflection coefficients, noise figures, field strengths and more. What is a decibel and how should we use it in our calculations? This Application Note is intended as a refresher on the subject of decibels.



Note:

Please find up to date document on our homepage

http://www.rohde-schwarz.com/appnote/1MA98

Application Note
A. Winter
4.2015 – 1MA98_12e

ROHDE&SCHWARZ

Table of Contents

1 Introduction

%, dB, dBm and dB (µV/m) are important concepts that every engineer should understand in his (or her) sleep. Because if he does not, he is bound to be at a disadvantage in his work. When these terms come up in discussions with customers or colleagues, he will have trouble focusing on the real issue if he is busy wondering whether 3 dB means a factor of 2 or 4 (or something else). It is well worth the effort to review these concepts from time to time and keep familiar with them.

While this Application Note is not intended as a textbook, it will help to refresh your knowledge of this topic if you studied it before or provide a decent introduction if it is new to you.

When it comes to writing formulas and units, we have followed the international standards specified in ISO 31 and IEC 27 (or else we have indicated where it is common practice to deviate from the standard).

2 Why use decibels in our calculations?

Engineers have to deal with numbers on an everyday basis, and some of these numbers can be very large or very small. In most cases, what is most important is the ratio of two quantities. For example, a mobile radio base station might transmit approx. 80 W of power (antenna gain included). The mobile phone receives only about 0.000 000 002 W, which is 0.000 000 002 5 % of the transmitted power.

Whenever we must deal with large numerical ranges, it is convenient to use the logarithm of the numbers. For example, the base station in our example transmits at +49 dBm while the mobile phone receives -57 dBm, producing a level difference of +49 dBm - (-57 dBm) = 106 dB.

Another example: If we cascade two amplifiers with power gains of 12 and 16, respectively, we obtain a total gain of 12 times 16 = 192 (which you can hopefully calculate in your head – do you?). In logarithmic terms, the two amplifiers have gains of 10.8 dB and 12 dB, respectively, producing a total gain of 22.8 dB, which is definitely easier to calculate.

When expressed in decibels, we can see that the values are a lot easier to manipulate. It is a lot easier to add and subtract decibel values in your head than it is to multiply or divide linear values. This is the main reason we like to make our computations in decibels.

2.1 Definition of dB

Although the base 10 logarithm of the ratio of two power values is a dimensionless quantity, it has units of "Bel" in honor of the inventor of the telephone (Alexander Graham Bell). In order to obtain more manageable numbers, we use the dB (decibel, where "deci" stands for one tenth) instead of the Bel for computation purposes. We have to multiply the Bel values by 10 (just as we need to multiply a distance by 1000 if we want to use millimeters instead of meters).

$$a = 10 \cdot \log_{10}\left(\frac{P_1}{P_2}\right) \mathrm{dB}$$

As mentioned above, the advantage of using decibels is that the huge range of the signals commonly encountered in telecommunications and radio frequency engineering can be represented with more manageable numbers.

Example:

P_1 is equal to 200 W and P_2 is equal to 100 mW. What is their ratio a in dB?

$$a = 10 \cdot \log_{10}\left(\frac{P_1}{P_2}\right) \mathrm{dB} = 10 \cdot \log_{10}(2000)\,\mathrm{dB} = 33.01\,\mathrm{dB}$$

Of course, before dividing these power levels, we have to convert them to the same unit, i.e. W or mW. We will not obtain the correct result if we just divide 200 by 100.

Nowadays, we use base 10 logarithms almost exclusively. The abbreviation for a base 10 logarithm is **lg**. In older textbooks, you will sometimes see the natural logarithm used, which is the base e logarithm (e = approx. 2.718). In this Application Note, we use only the base 10 logarithm, which we abbreviate with lg without indicating the base further on.

Of course, it is also possible to convert decibels back to linear values. We must first convert from dB to Bel by dividing the value by 10. Then, we must raise the number 10 (since we are using a base 10 logarithm) to this power:

$$\frac{P_1}{P_2} = 10^{\frac{a/\mathrm{dB}}{10}}$$

Example:

a = 33.01 dB, what is P_1 / P_2?
After first computing 33.01 / 10 = 3.301, we obtain:

$$\frac{P_1}{P_2} = 10^{3.301} = 1999.9$$

2.2 What does dBm mean?

If we refer an arbitrary power value to a fixed reference quantity, the logarithmic ratio of the two values yields a new absolute quantity. This quantity is defined as a level.

The reference quantity most commonly used in telecommunications and radio frequency engineering is a power of 1 mW (one thousandth of one Watt) into 50 Ohm.

The general power ratio P_1 to P_2 now becomes a ratio of P_1 to 1 mW. The logarithmic ratio provides the level L. According to IEC 27 the reference value had to be indicated in the level index:

$$L_{P(\mathrm{re\,1\,mW})} = 10 \cdot \lg\left(\frac{P_1}{1\,mW}\right)\ \mathrm{dB}$$

or the short form:

$$L_{P/1\,\mathrm{mW}} = 10 \cdot \lg\left(\frac{P_1}{1\,mW}\right)\ \mathrm{dB}$$

For example 5 mW corresponds to a level of $L_{P/1mW}$ = 6.99 dB.

To denote the reference of 1 mW, the ITU introduced the unit **dBm**. This unit is more common than the IEC 27 terminology, and will be used throughout this paper. With this, our example reads as follows:

$$L_p = 10 \cdot \lg\left(\frac{5mW}{1\,mW}\right) \text{ dBm} = 6.99 \text{ dBm}$$

To give you a feeling for the orders of magnitude which tend to occur, here are some examples: The output power range of signal generators extends typically from -140 dBm to +20 dBm or 0.01 fW (femto Watt) to 0.1 W. Mobile radio base stations transmit at +43 dBm or 20 W. Mobile phones transmit at +10 dBm to +33 dBm or 10 mW to 2 W. Broadcast transmitters operate at +70 dBm to +90 dBm or 10 kW to 1 MW.

2.3 What is the difference between voltage decibels and power decibels?

First, please forget everything you have ever heard about voltage and power decibels. There is only one type of decibel, and it represents a ratio of two power levels P_1 and P_2. Of course, any power level can be expressed as a voltage if we know the resistance.

$$P_1 = \frac{U_1^2}{R_1} \quad \text{and} \quad P_2 = \frac{U_2^2}{R_2}$$

We can compute the logarithmic ratio as follows:

$$a = 10 \cdot \lg\left(\frac{P_1}{P_2}\right) \text{dB} = 10 \cdot \lg\left(\frac{U_1^2}{U_2^2} \cdot \frac{R_2}{R_1}\right) \text{dB}$$

Using the following 3 familiar identities,

$$\log\left(\frac{1}{x}\right) = -\log(x)$$

$$\log(x^y) = y \cdot \log(x)$$

$$\log(xy) = \log(x) + \log(y)$$

We obtain (again using lg to mean the base 10 logarithm):

$$a = 10 \cdot \lg\left(\frac{P_1}{P_2}\right) \text{dB} = 10 \cdot \lg\left(\frac{U_1^2}{U_2^2} \cdot \frac{R_2}{R_1}\right) \text{dB} = 20 \cdot \lg\left(\frac{U_1}{U_2}\right) \text{dB} - 10 \cdot \lg\left(\frac{R_1}{R_2}\right) \text{dB}$$

Note the minus sign in front of the resistance term.

In most cases, the reference resistance is equal for both power levels, i.e. $R_1 = R_2$.

Since

$$10 \cdot \lg(1) = 0$$

we can simplify as follows:

$$a = 10 \cdot \lg\left(\frac{P_1}{P_2}\right)\mathrm{dB} = 20 \cdot \lg\left(\frac{U_1}{U_2}\right)\mathrm{dB}$$ **(simplified for $R_1 = R_2$!)**

This also explains why we use 10·lg for power ratios and 20·lg for voltage ratios.

Caution: (Very important!) This formula is valid only if $R_1 = R_2$. If, as sometimes occurs in television engineering, we need to take into account a conversion from 75 Ohm to 50 Ohm, we need to consider the ratio of the resistances.

Conversion back to linear values is the same as before. For voltage ratios, we must divide the value a by 20 since we use U^2 and **deci**bels (20 = 2·10, 2 from U^2, 10 from deci).

$$\frac{P_1}{P_2} = 10^{\frac{a/\mathrm{dB}}{10}}$$

$$\frac{U_1}{U_2} = 10^{\frac{a/\mathrm{dB}}{20}}$$

2.4 What is a level?

As we saw above, dBm involves a reference to a power level of 1 mW. Other frequently used reference quantities include 1 W, 1 V, 1 µV and also 1 A or 1 µA. According to IEC 27, they are designated as dB (W), dB (V), dB (µV), dB (A) and dB (µA), respectively, or in field strength measurements, dB (W/m2), dB (V/m), dB (µV/m), dB (A/m) and dB (µA/m). As was the case for dBm, the conventional way of writing these units according to ITU is dBW, dBV, dBµV, dBA, dBµA, dBW/m2, dBV/m, dBµV/m, dBA/m and dBµA/m. These units will be used in this paper.

From the relative values for power level P_1 (voltage U_1) referred to power level P_2 (voltage U_2), we obtain absolute values using the reference values above.

These absolute values are also known as **levels**. A level of 10 dBm means a value which is 10 dB above 1 mW, and a level of -17 dB(µV) means a value which is 17 dB below 1 µV.

When computing these quantities, it is important to keep in mind whether they are power quantities or voltage quantities.

Some examples of power quantities include power, energy, resistance, noise figure and power flux density.

Voltage quantities (also known as field quantities) include voltage, current, electric field strength, magnetic field strength and reflection coefficient.

Examples:

A power flux density of 5 W/m2 has the following level:

$$L_{P/1W/m^2} = 10 \cdot \lg\left(\frac{5\ \mathrm{W/m^2}}{1\ \mathrm{W/m^2}}\right) = 7\ \mathrm{dB\ (W/m^2)}$$

A voltage of 7 µV can also be expressed as a level in dB(µV):

$$L_{U/1\mu V} = 20 \cdot \lg\left(\frac{7\ \mu\mathrm{V}}{1\ \mu\mathrm{V}}\right) = 16.9\ \mathrm{dB}\ (\mu\mathrm{V})$$

Conversion from levels to linear values requires the following formulas:

$$P = 10^{\frac{a/\mathrm{dB}}{10}} \cdot P_{ref}$$

or

$$U = 10^{\frac{u/\mathrm{dB}}{20}} \cdot U_{ref}$$

Examples:

A power level of -3 dB(W) has the following power:

$$P = 10^{\frac{-3}{10}} \cdot 1\ \mathrm{W} = 0.5 \cdot 1\ \mathrm{W} = 500\ \mathrm{mW}$$

A voltage level of 120 dB(µV) has a voltage of:

$$U = 10^{\frac{120}{20}} \cdot 1\ \mu\mathrm{V} = 1000000 \cdot 1\ \mu\mathrm{V} = 1\ \mathrm{V}$$

2.5 Attenuation and gain

The linear transfer function a_{lin} of a two-port circuit represents the ratio of the output power to the input power:

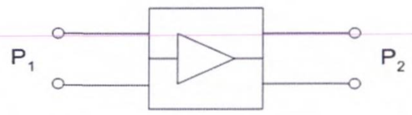


Fig. 2-1: Two-port circuit

$$a_{lin} = \frac{P_2}{P_1}$$

The transfer function is normally specified in dB:

$$a = 10 \cdot \lg \frac{P_2}{P_1} \text{dB}$$

If the output power P_2 of a two-port circuit is greater than the input power P_1, then the logarithmic ratio of P_2 to P_1 is positive. This is known as **amplification** or **gain**.

If the output power P_2 of a two-port circuit is less than the input power P_1, then the logarithmic ratio of P_2 to P_1 is negative. This is known as **attenuation** or **loss** (the minus sign is omitted).

Computation of the power ratio or the voltage ratio from the decibel value uses the following formulas:

$$\frac{P_2}{P_1} = 10^{\frac{a/\text{dB}}{10}}$$

or

$$\frac{U_2}{U_1} = 10^{\frac{a/\text{dB}}{20}}$$

(for $R_{out} = R_{in}$)

Conventional amplifiers realize gains of up to 40 dB in a single stage, which corresponds to voltage ratios up to 100 and power ratios up to 10000. With higher values, there is a risk of oscillation in the amplifier. However, higher gain can be obtained by connecting multiple stages in series. The oscillation problem can be avoided through suitable shielding.

The most common attenuators have values of 3 dB, 6 dB, 10 dB and 20 dB. This corresponds to voltage ratios of 0.7, 0.5, 0.3 and 0.1 or power ratios of 0.5, 0.25, 0.1 and 0.01. Here too, we must cascade multiple attenuators to obtain higher values. If we attempt to obtain higher attenuation in a single stage, there is a risk of crosstalk.

2.5.1 Series connection of two-port circuits:

In the case of series connection (cascading) of two-port circuits, we can easily compute the total gain (or total attenuation) by adding the decibel values.

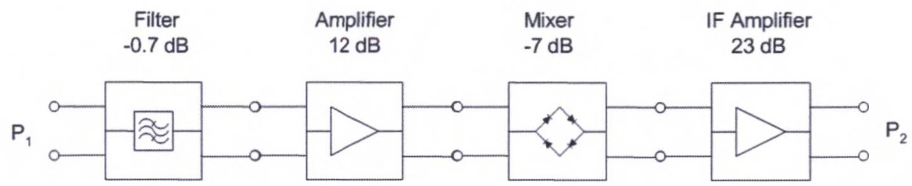


Fig. 2-2: Cascading two-port circuits

The total gain is computed as follows:

$$a = a_1 + a_2 + \ldots + a_n$$

Example:

Fig. 2-2 shows the input stages of a receiver. The total gain a is computed as follows:

a = -0.7 dB + 12 dB - 7 dB + 23 dB = 27.3 dB.

3 Conversion from decibels to percentage and vice versa

The term "percent" comes from the Latin and literally means "per hundred". 1% means one hundredth of a value.

$1\,\%\,\text{of}\ x = 0.01\cdot \text{x}$

When using percentages, we need to ask two questions:

- Are we calculating voltage quantities or power quantities?
- Are we interested in x% of a quantity or x% more or less of a quantity?

As mentioned above, voltage quantities are voltage, current, field strength and reflection coefficient, for example.

Power quantities include power, resistance, noise figure and power flux density.

3.1 Converting % voltage to decibels and vice versa

x% of a voltage quantity is converted to decibels as follows:

$$a = 20\cdot \lg \frac{x}{100}\ \text{dB}$$

In other words: To obtain a value of x% in decibels, we must first convert the percentage value x to a rational number by dividing x by 100. To convert to decibels, we multiply the logarithm of this rational number by 20 (voltage quantity: 20) as shown above.

Example:

Assume the output voltage of a two-port circuit is equal to 3% of the input voltage. What is the attenuation a in dB?

$$a = 20\cdot \lg \frac{3}{100}\ \text{dB} = -30.46\ \text{dB}$$

We can convert a decibel value a to a percentage as follows:

$$x = 100\,\%\cdot 10^{\frac{a/\text{dB}}{20}}$$

Example:

Calculate the output voltage of a 3 dB attenuator as a percentage of the input voltage.

$$x = 100\,\%\cdot 10^{\frac{-3}{20}} = 70.8\,\%$$

The output voltage of a 3 dB attenuator is equal to 71% of the input voltage.
Note: Attenuation means negative decibel values!

3.2 Converting % power to decibels and vice versa

x% of a power quantity is converted to decibels as follows:

$$a = 10 \cdot \lg \frac{x}{100} \text{ dB}$$

To obtain a value in decibels, we first convert the percentage value x to a rational number (as shown above) by dividing the number by 100. To convert to decibels (as described in section 2), we multiply the logarithm of this rational number by 10 (power quantity: 10).

Example:

Assume the output power of a two-port circuit is equal to 3% of the input power. What is the attenuation a in dB?

3 %·P = 0.03·P

$$a = 10 \cdot \lg \frac{3}{100} \text{ dB} = -15.23 \text{ dB}$$

We can convert a decibel value a to a percentage as follows:

$$x = 100\,\% \cdot 10^{\frac{a/\text{dB}}{10}}$$

Example:

Calculate the output power of a 3 dB attenuator as a percentage of the input power.

$$x = 100\,\% \cdot 10^{\frac{-3}{10}} = 50.1\,\%$$

The power at the output of a 3 dB attenuator is half as large (50%) as the input power. Note: As above, attenuation means negative decibel values!

3.3 Converting % voltage more or less to decibels

x% more (or less) of a value means that we add (or subtract) the given percentage to (or from) the starting value. For example, if the output voltage U_2 of an amplifier is supposed to be x% greater than the input voltage U_1, we calculate as follows:

$$U_2 = U_1 + x\,\% \cdot U_1 = U_1\left(1 + \frac{x}{100}\right)$$

If the output voltage is less than the input voltage, then x should be a negative value.

Conversion to a decibel value requires the following formula:

$$a = 20 \cdot \lg\left(1 + \frac{x}{100}\right) \mathrm{dB}$$

Note: Use a factor of 20 for voltage quantities.

Example:

The output voltage of an amplifier is 12.2% greater than the input voltage. What is the gain in decibels?

$$a = 20 \cdot \lg\left(1 + \frac{12.2}{100}\right) \mathrm{dB} = 1\,\mathrm{dB}$$

Note that starting with even relatively small percentage values, a given plus percentage will result in a different decibel value than its corresponding minus percentage.

20% more results in	+1.58 dB
20% less results in	-1.94 dB

3.4 Converting % power more or less to decibels

Analogous to the voltage formula, we have the following for power:

$$P_2 = P_1 + x\,\% \cdot P_1 = P_1\left(1 + \frac{x}{100}\right)$$

Conversion to a decibel value requires the following formula:

$$a = 10 \cdot \lg\left(1 + \frac{x}{100}\right) \mathrm{dB}$$

Note: Use a factor of 10 for power quantities.

Example:

The output power of an attenuator is 20% less than the input power. What is the attenuation in decibels?

$$a = 10 \cdot \lg\left(1 + \frac{-20}{100}\right) \mathrm{dB} = -0.97\,\mathrm{dB} \approx -1\,\mathrm{dB}$$

As before, we can expect asymmetry in the decibel values starting with even small percentage values.

4 Using dB values in computations

This section demonstrates how to add power levels and voltages in logarithmic form, i.e. in decibels.

4.1 Adding power levels

30 dBm + 30 dBm = 60 dBm? Of course not! If we convert these power levels to linear values, it is obvious that 1 W + 1 W = 2 W. This is 33 dBm and not 60 dBm. However, this is true only if the power levels to be added are uncorrelated. Uncorrelated means that the instantaneous values of the power levels do not have a fixed phase relationship with one another.

Note: Power levels in logarithmic units need to be converted prior to addition so that we can add linear values. If it is more practical to work with decibel values after the addition, we have to convert the sum back to dBm.

Example:

We want to add three signals P_1, P_2 and P_3 with levels of 0 dBm, +3 dBm and -6 dBm. What is the total power level?

$$P_1 = 10^{\frac{0}{10}} = 1\,\text{mW}$$

$$P_2 = 10^{\frac{3}{10}} = 2\,\text{mW}$$

$$P_3 = 10^{\frac{-6}{10}} = 0.25\,\text{mW}$$

$$P = P_1 + P_2 + P_3 = 3.25\,\text{mW}$$

Converting back to decibels we get

$$L_{P/1mW} = 10 \cdot \lg\left(\frac{3.25\,\text{mW}}{1\,\text{mW}}\right)\text{dBm} = 5.12\,\text{dBm}$$

The total power level is 5.12 dBm.

4.2 Measuring signals at the noise limit

One common task involves measurement of weak signals close to the noise limit of a test instrument such as a receiver or a spectrum analyzer. The test instrument displays the sum total of the inherent noise and signal power, but it should ideally display only the signal power. The prerequisite for the following calculation is that the test instrument must display the RMS power of the signals. This is usually the case with power meters, but with spectrum analyzers, it is necessary to switch on the RMS detector.

First, we determine the inherent noise L_r of the test instrument by turning off the signal. Then, we measure the signal with noise L_{tot}. We can obtain the power P of the signal alone by subtracting the linear power values.

Example:

The displayed noise L_r of a power meter is equal to -70 dBm. When a signal is applied, the displayed value increases to L_{tot} = -65 dBm. What is the power level of the signal in dBm?

$$P_r = 10^{\frac{-70}{10}}\ \mathrm{mW} = 0.000\,000\,1\ \mathrm{mW}$$

$$P_{tot} = 10^{\frac{-65}{10}}\ \mathrm{mW} = 0.000\,000\,316\ \mathrm{mW}$$

$$P = P_{tot} - P_r\ P = 0.000\,000\,316\ \mathrm{mW} - 0.000\,000\,1\ \mathrm{mW} = 0.000\,000\,216\ \mathrm{mW}$$

$$L_{P/1mW} = 10 \cdot \lg \frac{0.000\,000\,216\ \mathrm{mW}}{1\ \mathrm{mW}}\ \mathrm{dBm} = -66.6\ \mathrm{dBm}$$

The signal power level is -66.6 dBm.

We can see that without any compensation, the noise of the test instrument will cause a display error of 1.6 dB, which is relatively large for a precision test instrument.

4.3 Adding voltages

Likewise, we can add decibel values for voltage quantities only if we convert them from logarithmic units beforehand. We must also know if the voltages are correlated or uncorrelated. If the voltages are correlated, we must also know the phase relationship of the voltages.

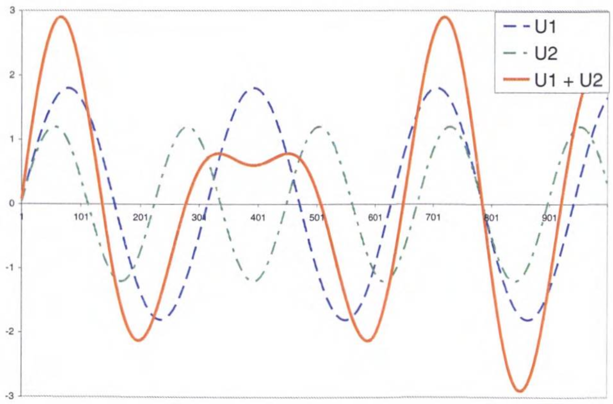


Fig. 4-1: Addition of two uncorrelated voltages

We add uncorrelated voltages quadratically, i.e. we actually add the associated power levels. Since the resistance to which the voltages are applied is the same for all of the signals, the resistance will disappear from the formula:

$$U = \sqrt{U_1^{\,2} + U_2^{\,2} + \ldots + U_n^{\,2}}$$

If the individual voltages are specified as levels, e.g. in dB (V), we must first convert them to linear values.

Example:

We add three uncorrelated voltages $L_1 = 0$ dB (V),
$L_2 = -6$ dB(V) and $L_3 = +3$ dB(V) as follows to obtain the total voltage U:

$$U_1 = 10^{\frac{U_1/\mathrm{dB(V)}}{20}} \cdot U_{ref} = 10^{\frac{0}{20}} \cdot 1\,\mathrm{V} = 1\,\mathrm{V}$$

$$U_2 = 10^{\frac{U_2/\mathrm{dB(V)}}{20}} \cdot U_{ref} = 10^{\frac{-6}{20}} \cdot 1\,\mathrm{V} = 0.5\,\mathrm{V}$$

$$U_3 = 10^{\frac{U_3/\mathrm{dB(V)}}{20}} \cdot U_{ref} = 10^{\frac{3}{20}} \cdot 1\,\mathrm{V} = 1.41\,\mathrm{V}$$

$$U = \sqrt{U_1^{\,2} + U_1^{\,2} + U_1^{\,2}} = \sqrt{1^2 + 0.5^2 + 1.41^2}\,\mathrm{V} = 1.75\,\mathrm{V}$$

After converting U to dB(V), we obtain:

$$L_{U/1\mathrm{V}} = 20\log\frac{1.75\,\mathrm{V}}{1\,\mathrm{V}}\,\mathrm{dB(V)} = 4.86\,\mathrm{dB(V)}$$

If the voltages are correlated, the computation becomes significantly more complicated. As we can see from the following figures, the phase angle of the voltages determines the total voltage, which is produced.

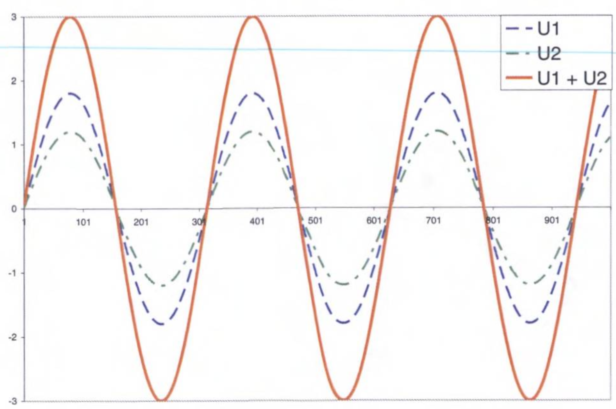


Fig. 4-2: Addition of two correlated voltages, 0° phase angle

Blue represents voltage U_1, green represents voltage U_2 and red represents the total voltage U.

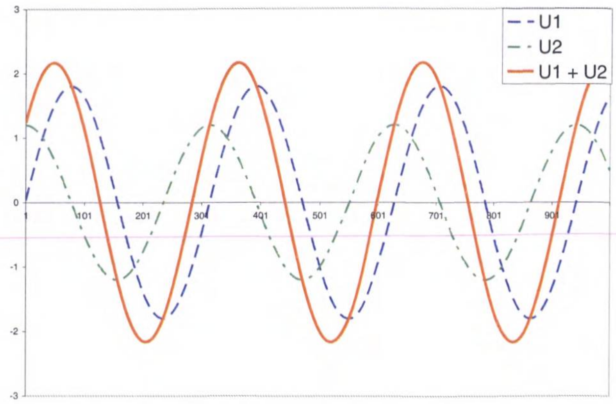


Fig. 4-3: Addition of two correlated voltages, 90° phase angle

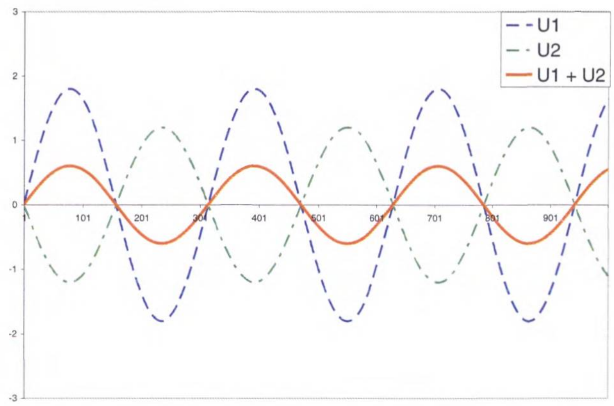


Fig. 4-4: Addition of two correlated voltages, 180° phase angle

The total voltage U ranges from $U_{max} = U_1 + U_2$ for phase angle 0° (in-phase) to $U_{min} = U_1 - U_2$ for phase angle 180° (opposite phase). For phase angles in between, we must form the vector sum of the voltages (see elsewhere for more details).

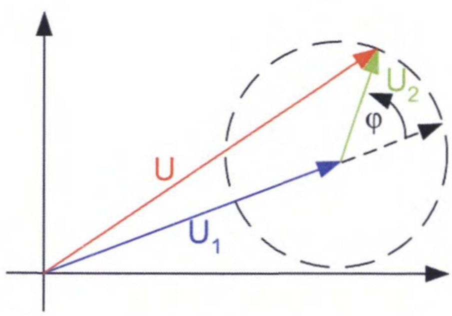


Fig. 4-5: Vector addition of two voltages

In actual practice, we normally only need to know the extreme values of the voltages, i.e. U_{max} and U_{min}.

If the voltages U_1 and U_2 are in the form of level values in dB (V) or dB (µV), we must first convert them to linear values just as we did with uncorrelated voltages. However, the addition is linear instead of quadratic (see the next section about peak voltages).

4.4 Peak voltages

If we apply a composite signal consisting of different voltages to the input of an amplifier, receiver or spectrum analyzer, we need to know the peak voltage. If the peak voltage exceeds a certain value, limiting effects will occur which can result in undesired mixing products or poor adjacent channel power. The peak voltage U is equal to:

$$U = U_1 + U_2 + ... + U_n$$

The maximum drive level for amplifiers and analyzers is usually indicated in dBm. In a 50 Ω system, conversion based on the peak voltage (in V) is possible with the following formula:

$$L_{P/1mW} = 10 \cdot \lg\left(\frac{U^2}{50\Omega} \cdot 10^3\right) \text{dBm}$$

The factor 10^3 comes from the conversion from Watts to milli Watts

Note that this power level represents the instantaneous peak power and not the RMS value of the power.

5 What do we measure in decibels?

This section summarizes some of the terms and measurement quantities, which are typically specified in decibels. This is not an exhaustive list and we suggest you consult the bibliography if you would like more information about this subject. The following sections are structured to be independent of one another so you can consult just the information you need.

5.1 Signal-to-noise ratio (S/N)

One of the most important quantities when measuring signals is the signal-to-noise ratio (S/N). Measured values will fluctuate more if the S/N degrades. To determine the signal-to-noise ratio, we first measure the signal S and then the noise power N with the signal switched off or suppressed using a filter. Of course, it is not possible to measure the signal without any noise at all, meaning that we will obtain correct results only if we have a good S/N.

$$SN = \frac{S}{N}$$

or in dB:

$$SN = 10 \cdot \lg \frac{S}{N}\ \mathrm{dB}$$

Sometimes, distortion is also present in addition to noise. In such cases, it is conventional to determine the signal to noise and distortion (SINAD) as opposed to just the signal-to-noise ratio.

$$SINAD = \frac{S}{N + D}$$

or in dB:

$$SINAD = 10 \lg \frac{S}{N + D}\ \mathrm{dB}$$

Example:

We would like to measure the S/N ratio for an FM radio receiver. Our signal generator is modulated at 1 kHz with a suitable FM deviation. At the loudspeaker output of the receiver, we measure a power level of 100 mW, which represents both the signal and noise power. The noise power, which is measured next, must be subtracted from this quantity to determine the signal power.

We now turn off the modulation on the signal generator and measure a noise power of 0.1 µW at the receiver output. The S/N is computed as follows:

$$SN = 10 \cdot \lg \frac{100\,\text{mW} - 0.1\,\mu\text{W}}{0.1\,\mu\text{W}} = 59.99\,\text{dB}$$

To determine the SINAD value, we again modulate the signal generator at 1 kHz and measure (as before) a receiver power level of 100 mW. Now, we suppress the 1 kHz signal using a narrow notch filter in the test instrument. At the receiver output, all we now measure is the noise and the harmonic distortion. If the measured value is equal to, say, 0.5 µW, we obtain the SINAD as follows:

$$SINAD = 10 \cdot \lg \frac{100\,\text{mW} - 0.5\,\mu\text{W}}{0.5\,\mu\text{W}} = 53.01\,\text{dB}$$

5.2 Noise

Noise is caused by thermal agitation of electrons in electrical conductors. The power P which can be consumed by a sink (e.g. receiver input, amplifier input) is dependent on the temperature T and on the measurement bandwidth B (please do not confuse bandwidth B with B = Bel!).

$$P = kTB$$

Here, k is Boltzmann's constant 1.38 x 10^{-23} JK^{-1} (Joules per Kelvin, 1 Joule = 1 Watt-Second), T is the temperature in K (Kelvin, 0 K corresponds to -273.15°C or –459.67°F) and B is the measurement bandwidth in Hz.

At room temperature (20°C, 68°F), we obtain per Hertz bandwidth a power of:

$$P = kT \cdot 1\,\text{Hz} = 1.38 \cdot 10^{-23}\,\text{WsK}^{-1} \cdot 293.15\,\text{K} \cdot 1\,\text{Hz} = 4.047 \cdot 10^{-21}\,\text{W}$$

If we convert this power level to dBm, we obtain the following:

$$L_{P/1mW/1\text{Hz}} = 10 \cdot \lg \left(\frac{4.047 * 10^{-18}\,\text{mW}}{1\,\text{mW}} \right) \text{dBm} = -173.93\,\text{dBm/Hz}$$

The thermal noise power at a receiver input is equal to -174 dBm per Hertz bandwidth. Note that this power level is not a function of the input impedance, i.e. it is the same for 50 Ω, 60 Ω and 75 Ω systems.

The power level is proportional to bandwidth B. Using the bandwidth factor b in dB, we can compute the total power as follows:

$$b = 10 \cdot \lg \left(\frac{B}{1\,\text{Hz}} \right) \text{dB}$$

$$L_{P/1mW} = -174\,\text{dBm} + b$$

Example:

An imaginary spectrum analyzer that produces no intrinsic noise is set to a bandwidth of 1 MHz. What noise power will it display?

$$b = 10 \cdot \lg\left(\frac{1\,\text{MHz}}{1\,\text{Hz}}\right)\text{dB} = 10 \cdot \lg\left(\frac{1000000\,\text{Hz}}{1\,\text{Hz}}\right)\text{dB} = 60\,\text{dB}$$

$$L_{P/1mW} = -174\,\text{dBm} + 60\,\text{dB} = -114\,\text{dBm}$$

The noise power level, which is displayed at room temperature at a 1 MHz bandwidth, is equal to -114 dBm.

A receiver / spectrum analyzer produces 60 dB more noise with a 1 MHz bandwidth than with a 1 Hz bandwidth. A noise level of -114 dBm is displayed. If we want to measure lower amplitude signals, we need to reduce the bandwidth. However, this is possible only until we reach the bandwidth of the signal. To a certain extent, it is possible to measure signals even if they lie below the noise limit since each additional signal increases the total power, which is displayed (see the section on measuring signals at the noise limit above). However, we will quickly reach the resolution limit of the test instrument we are using.

Certain special applications such as deep-space research and astronomy necessitate measurement of very low-amplitude signals from space probes and stars, for example. Here, the only possible solution involves cooling down the receiver input stages to levels close to absolute zero (-273.15°C or –459.67 F).

5.3 Averaging noise signals

To display noise signals in a more stable fashion, it is conventional to switch on the averaging function provided in spectrum analyzers. Most spectrum analyzers evaluate signals using what is known as a sample detector and average the logarithmic values displayed on the screen. This results in a systematic measurement error since lower measured values have an excessive influence on the displayed measurement result. The following figure illustrates this effect using the example of a signal with sinusoidal amplitude modulation.

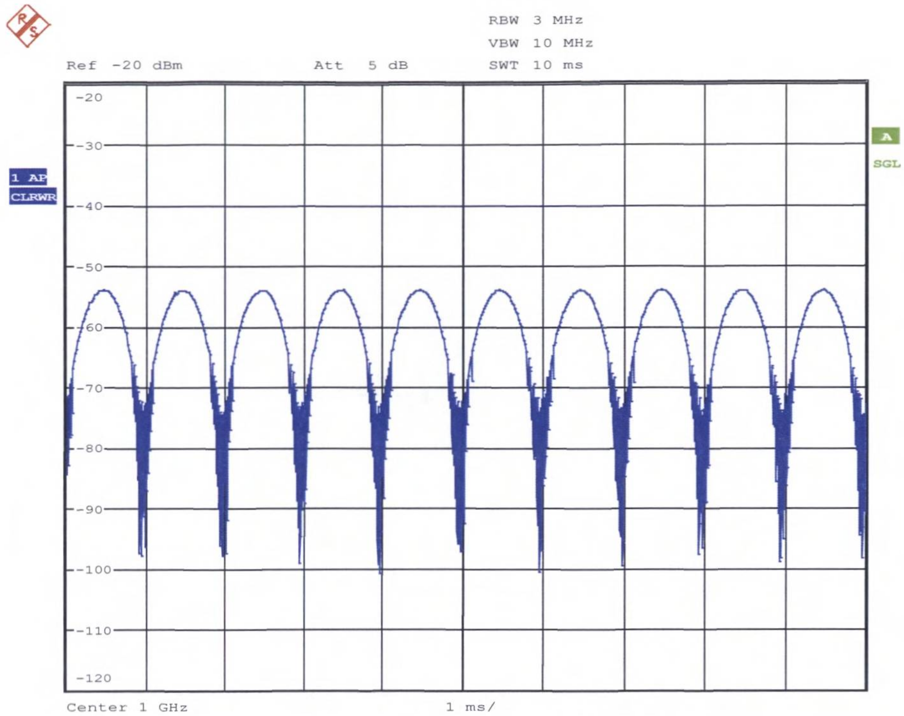


Fig. 5-1: Amplitude-modulated signal with logarithmic amplitude values as a function of time

As we can see here, the sinewave is distorted to produce a sort of heart-shaped curve with an average value, which is too low, by 2.5 dB. R&S spectrum analyzers use an RMS detector to avoid this measurement error (see [4]).

5.4 Noise factor, noise figure

The noise factor F of a two-port circuit is defined as the ratio of the input signal-to-noise ratio SN_{in} to the output signal-to-noise ratio SN_{out}.

$$F = \frac{SN_{in}}{SN_{out}}$$

The signal-to-noise ratio S/N is determined as described above.

If the noise factor is specified in a logarithmic unit, we use the term noise figure (NF).

$$NF = 10 \cdot \lg \frac{SN_{in}}{SN_{out}} \text{ dB}$$

When determining the noise figure, which results from cascading two-port circuits, it is necessary to consider certain details, which are beyond the scope of this Application Note. Details can be found in the relevant technical literature or on the Internet (see [3] and [4]).

5.5 Phase noise

An ideal oscillator has an infinitely narrow spectrum. Due to the different physical effects of noise, however, the phase angle of the signal varies slightly which results in a broadening of the spectrum. This is known as **phase noise**.

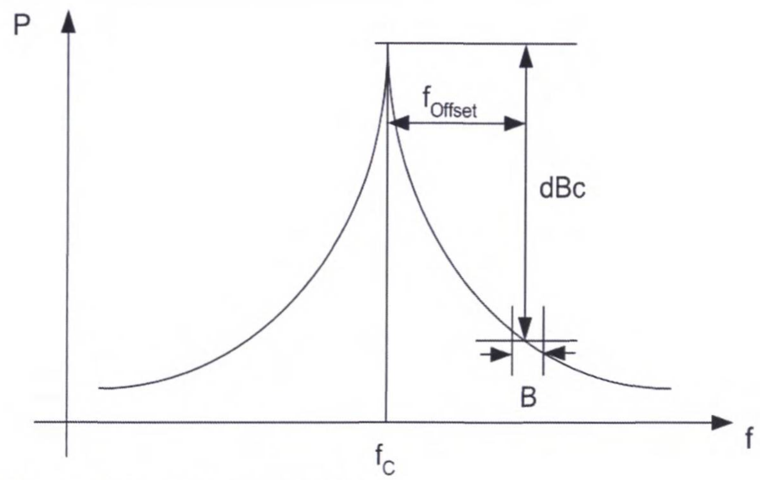


Fig. 5-2: Phase noise of an oscillator

To measure this phase noise, we must determine the noise power of the oscillator PR as a function of the offset from the carrier frequency f_c (known as the offset frequency f_{Offset}) using a narrowband receiver or a spectrum analyzer in a bandwidth B. We then reduce the measurement bandwidth B computationally to 1 Hz. Now, we reference this power to the power of the carrier Pc to produce a result in dBc (1 Hz bandwidth). The c in dBc stands for "carrier".

We thus obtain the phase noise, or more precisely, the single sideband (SSB) phase noise L:

$$P = 10 \cdot \lg\left(\frac{P_R}{P_c} \cdot \frac{1}{B/1\,\mathrm{Hz}}\right) \mathrm{dBc}$$

dBc is also a violation of the standard, but it is used everywhere. Conversion to linear power units is possible, but is not conventional.

Data sheets for oscillators signal generators and spectrum analyzers typically contain a table with phase noise values at different offset frequencies. The values for the upper and lower sidebands are assumed equal.

Offset	SSB Phase Noise
10 Hz	- 86 dBc (1 Hz)
100 Hz	- 100 dBc (1 Hz)
1 kHz	- 116 dBc (1 Hz)
10 kHz	-123 dBc (1 Hz)
100 kHz	-123 dBc (1 Hz)
1 MHz	-144 dBc (1 Hz)
10 MHz	-160 dBc (1 Hz)

Table 5-1: SSB phase noise at 640 MHz

Most data sheets contain curves for the single sideband phase noise ratio, which do not drop off so monotonically as the curve in Fig. 5-2. This is because the phase locked loops (PLLs) used in modern instruments to keep oscillators locked to a reference crystal oscillator result in an improvement but also a degradation of the phase noise as a function of the offset frequency due to certain design problems.

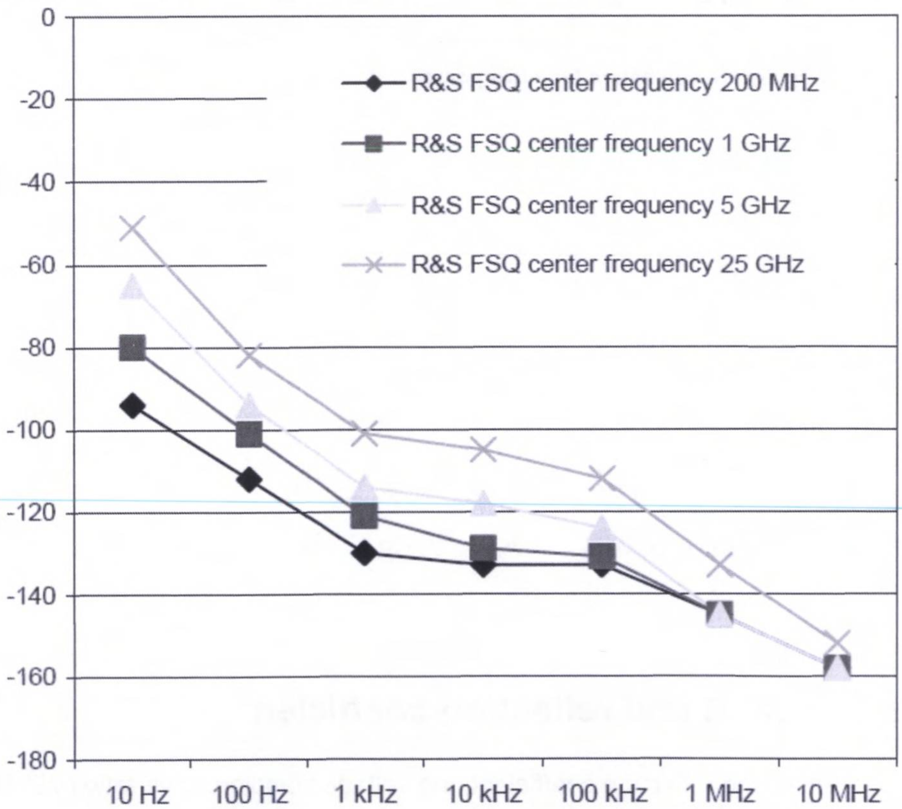


Fig. 5-3: Phase noise curves for the Signal Analyzer R&S®FSQ

When comparing oscillators, it is also necessary to consider the value of the carrier frequency. If we multiply the frequency of an oscillator using a zero-noise multiplier (possible only in theory), the phase noise ratio will degrade proportionally to the voltage, i.e. if we multiply the frequency by 10, the phase noise will increase by 20 dB at the same offset frequency. Accordingly, microwave oscillators are always worse than RF oscillators as a general rule. When mixing two signals, the noise power levels of the two signals add up at each offset frequency.

5.6 S parameters

Two-port circuits are characterized by four parameters: S_{11} (input reflection coefficient), S_{21} (forward transmission coefficient), S_{12} (reverse transmission coefficient) and S_{22} (output reflection coefficient).

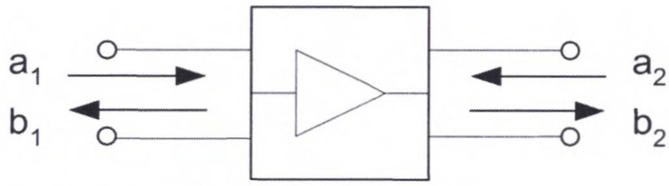


Fig. 5-4: S parameters for a two-port circuit

The S parameters can be computed from the wave quantities a_1, b_1 and a_2, b_2 as follows:

$$S_{11} = \frac{b_1}{a_1} \quad S_{21} = \frac{b_2}{a_1} \quad S_{12} = \frac{b_1}{a_2} \quad S_{22} = \frac{b_2}{a_2}$$

Wave quantities a and b are voltage quantities.

If we have the S parameters in the form of decibel values, the following formulas apply:

$$s_{11} = 20 \cdot \lg S_{11}\ \text{dB} \qquad s_{21} = 20 \cdot \lg S_{21}\ \text{dB}$$

$$s_{12} = 20 \cdot \lg S_{12}\ \text{dB} \qquad s_{22} = 20 \cdot \lg S_{22}\ \text{dB}$$

5.7 VSWR and reflection coefficient

Like the reflection coefficient, the voltage standing wave ratio (VSWR) or standing wave ratio (SWR) is a measure of how well a signal source or sink is matched to a reference impedance. VSWR has a range from 1 to infinity and is not specified in decibels. However, the reflection coefficient r is.

The relationship between r and VSWR is as follows:

$$r = \left| \frac{1-VSWR}{1+VSWR} \right|$$

$$VSWR = \left| \frac{1+r}{1-r} \right|$$

For VSWR = 1 (very good matching), r = 0. For a very high VSWR, r approaches 1 (mismatch or total reflection).

r represents the ratio of two voltage quantities. For r in decibels, we have a_r:

$$a_r = 20 \cdot \lg\left(\frac{r}{1}\right) \text{dB}$$

(or the other way around:)

$$r = 10^{\frac{a_r / dB}{20}}$$

a_r is called return loss.

For computation of the VSWR from the reflection coefficient, r is inserted as a linear value.

The following table shows the relationship between VSWR, r and a_r/dB. If you just need a rough approximation of r from the VSWR, simply divide the decimal part of the VSWR in half. This works well for VSWR values up to 1.2.

VSWR	r	a_r [dB]
1.002	0.001	60
1.004	0.002	54
1.006	0.003	50
1.008	0.004	48
1.01	0.005	46
1.02	0.01	40
1.04	0.02	34
1.1	0.05	26
1.2	0.1	20
1.3	0.13	18
1.4	0.16	15
1.5	0.2	14

Table 5-2: Conversion from VSWR to reflection coefficient r and return loss a_r

Note that for two-port circuits, r corresponds to the input reflection coefficient S11 or the output reflection coefficient S22.

Attenuators have the smallest reflection coefficients. Good attenuators have reflection coefficients <5% all the way up to 18 GHz. This corresponds to a return loss of > 26 dB or a VSWR < 1.1. Inputs to test instruments and outputs from signal sources generally have VSWR specifications <1.5, which corresponds to r < 0.2 or r > 14 dB.

5.8 Field strength

For field strength measurements, we commonly see the terms power flux density, electric field strength and magnetic field strength.

Power flux density S is measured in W/m2 or mW/m2. The corresponding logarithmic units are dB (W/m2) and dB (mW/m2).

$$L_{S/1W/m^2} = 10 \cdot \lg\left(\frac{S}{1\,\mathrm{W/m}^2}\right) \mathrm{dB(W/m^2)}$$

$$L_{S/1mW/m^2} = 10 \cdot \lg\left(\frac{S}{1\,\mathrm{mW/m}^2}\right) \mathrm{dB(mW/m^2)}$$

Electric field strength E is measured in V/m or µV/m. The corresponding logarithmic units are dB (V/m) and dB (µV/m).

$$L_{E/1V/m^2} = 20 \cdot \lg\left(\frac{E/(\mathrm{V/m})}{1/(\mathrm{V/m})}\right) \mathrm{dB(V/m)}$$

$$L_{E/1\mu V/m^2} = 20 \cdot \lg\left(\frac{E/(\mu\mathrm{V/m})}{1/(\mu\mathrm{V/m})}\right) \mathrm{dB(\mu V/m)}$$

Conversion from dB (V/m) to dB (µV/m) requires the following formula:

$$L_{E/1\mu V/m^2} = L_{E/1V/m^2} + 120\,\mathrm{dB}$$

Addition of 120 dB corresponds to multiplication by 10^6 in linear units.
1 V = 10^6 µV.

Example:

-80 dB (V/m) = -80 dB(µV/m) + 120 dB = 40 dB(µV/m)

Magnetic field strength H is measured in A/m or µA/m. The corresponding logarithmic units are dB (A/m) and dB (µA/m).

$$L_{H/1A/m} = 20 \cdot \lg\left(\frac{H/(\mathrm{A/m})}{1(\mathrm{A/m})}\right) \mathrm{dB(A/m)}$$

$$L_{H/1\mu A/m} = 20 \cdot \lg\left(\frac{H/(\mu\mathrm{A/m})}{1(\mu\mathrm{A/m})}\right) \mathrm{dB(\mu A/m)}$$

Conversion from dB (A/m) to dB (µA/m) requires the following formula:

$$L_{H/1\mu A/m} = L_{H/1A/m} + 120\,\mathrm{dB}$$

Example:

20 dB(µA/m) = 20 dB(A/m) – 120 dB = -100 dB(A/m)

For additional information on the topic of field strength, see [1].

5.9 Antenna gain

Antennas generally direct electromagnetic radiation into a certain direction. The power gain G that results from this at the receiver is specified in decibels with respect to a reference antenna. The most common reference antennas are the isotropic radiator and the λ/2 dipole. The gain is specified in dBi or dBD. If the power gain is needed in linear units, the following formula can be used for conversion:

$$G_{lin} = 10^{\frac{G/dB_i}{10}} \quad \text{or} \quad G_{lin} = 10^{\frac{G/dB_D}{10}}$$

For more details about antenna gain and the term antenna factor, see [1].

5.10 Crest factor

The ratio of the peak power to the average thermal power (RMS value) of a signal is known as the crest factor. A sinusoidal signal has a peak value, which is 2 times greater than the RMS value, meaning the crest factor is 2, which equals 3 dB.

For modulated RF signals, the crest factor is referred to the peak value of the modulation envelope instead of the peak value of the RF carrier signal. A frequency-modulated (FM) signal has a constant envelope and thus a crest factor of 1 (0 dB).

If we add up many sinusoidal signals, the peak value can theoretically increase up to the sum of the individual voltages. The peak power Ps would then equal:

$$P_s = \frac{(U_1 + U_2 + \ldots + U_n)^2}{R}$$

The RMS power P is obtained by adding up the individual power values:

$$P = \frac{U^2}{R} = \frac{U_1{}^2}{R} + \frac{U_2{}^2}{R} + \ldots + \frac{U_n{}^2}{R}$$

We thus obtain a crest factor CF equal to:

$$C_F = \frac{P_s}{P}$$

$$C_F = 10 \cdot \lg \frac{P_s}{P} \text{ dB}$$

The more (uncorrelated) signals we add up, the less probable it becomes that the total of the individual voltages will be reached due to the different phase angles. The crest factor fluctuates around a level of about 11 dB. The signal has a noise-like appearance.

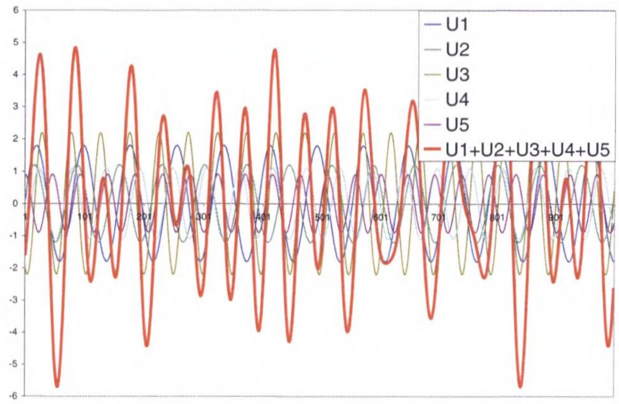


Fig. 5-5: A noise-like signal with a crest factor of 11 dB

Examples: The crest factor of noise is equal to approx. 11 dB. OFDM signals as are used in DAB, DVB-T and WLAN also have crest factors of approx. 11 dB. The CDMA signals stipulated by the CDMA2000 and UMTS mobile radio standards have crest factors ranging up to 15 dB, but they can be reduced to 7 dB to 9 dB using special techniques involving the modulation data. Except for bursts, GSM signals have a constant envelope due to the MSK modulation and thus a crest factor of 0 dB. EDGE signals have a crest factor of 3.2 dB due to the filter function of the 8PSK modulation (also excluding bursts).

Fig. 5-6 shows the so-called Complementary Cumulative Distribution Function (CCDF) of a noise like signal. The Crest Factor is that point of the measurement curve, where it reaches the x-axis. In the picture, this is at appr. 10.5 dB.

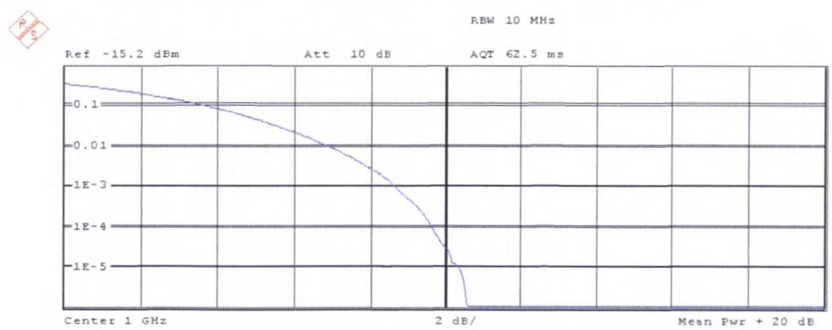


Fig. 5-6: Crest factor measured with the Signal Analyzer R&S®FSQ

5.11 Channel power and adjacent channel power

Modern communications systems such as GSM, CDMA2000 and UMTS manage a huge volume of calls. To avoid potential disruptions and the associated loss of revenue, it is important to make sure that exactly the permissible channel power P_{ch} (where ch stands for channel) is available in the useful channel and no more. The power in the useful channel is most commonly indicated as the level L_{ch} in dBm.

$$L_{ch/1mW} = 10 \cdot \lg\left(\frac{P_{ch}}{1\,\mathrm{mW}}\right)\mathrm{dBm}$$

This is normally 20 W or 43 dBm.

In the adjacent channels, the power may not exceed the value P_{adj}. This value ACPR (Adjacent Channel Power Ratio) is measured as a ratio to the power in the useful channel and is specified in dB.

$$ACPR = 10 \cdot \lg\left(\frac{P_{adj}}{P_{ch}}\right)\mathrm{dB}$$

Here, values of -40 dB (for mobile radio devices) down to -70 dB (for UMTS base stations) are required in the immediately adjacent channel and correspondingly higher values in the alternate channels.

When measuring the power levels, it is important to consider the bandwidth of the channels. It can be different for the useful channel and the adjacent channel. Example (CDMA2000): Useful channel 1.2288 MHz, adjacent channel 30 kHz. Sometimes, it is also necessary to select a particular type of modulation filtering, e.g. square-root-cosine-roll-off.

Modern spectrum analyzers have built-in measurement functions, which automatically take into account the bandwidth of the useful channel and adjacent channel as well as the filtering. For more information, see also [4].

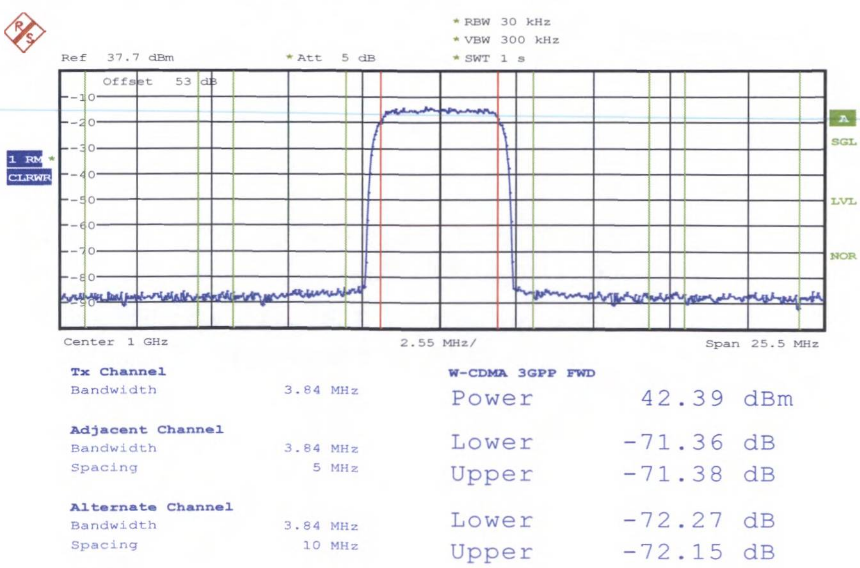


Fig. 5-7: Adjacent channel power for a UMTS signal, measured with the Signal Analyzer R&S®FSQ

5.12 Modulation quality EVM

Ideally, we would like to be able to decode signals from digitally modulated transmitters with as few errors as possible in the receiver. Over the course of the transmission path, noise and interference are superimposed in an unavoidable process. This makes it all the more important for the signal from the transmitter to exhibit good quality. One measure of this quality is the deviation from the ideal constellation point. The figure below illustrates this based on the example of QPSK modulation.

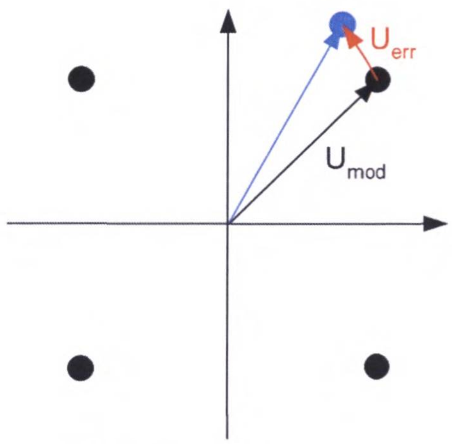


Fig. 5-8: Modulation error

To determine the modulation quality, the magnitude of the error vector U_{err} is referenced to the nominal value of the modulation vector U_{mod}. This quotient is known as the vector error or the error vector magnitude (EVM) and is specified as a percentage or in decibels.

$$EVM_{lin} = \frac{|U_{err}|}{|U_{mod}|} \cdot 100\,\%$$

$$EVM = 20 \cdot \lg\left(\frac{|U_{err}|}{|U_{mod}|}\right) \mathrm{dB}$$

We distinguish between the peak value EVM_{peak} occurring over a certain time interval and the RMS value of the error EVM_{RMS}.

Note that these vectors are voltages. This means we must use 20·lg in our calculations. An EVM of 0.3% thus corresponds to -50 dB.

5.13 Dynamic range of A/D and D/A converters

Important properties of analog to digital (A/D) and digital to analog (D/A) converters include the clock frequency f_{clock} and the number of data bits n. For each bit, we can represent twice (or half, depending on our point of view) the voltage. We thus obtain a dynamic range D of 6 dB per bit (as we have already seen, 6 dB corresponds to a factor of 2 for a voltage quantity). There is also a system gain of 1.76 dB for measurement of sine shaped signals.

$$D = 20 \cdot \lg\left(2^n\right) + 1.76\,\mathrm{dB}$$

Example:

A 16-bit D/A converter has a dynamic range of 96.3 dB + 1.76 dB = 98 dB.

In practice, A/D and D/A converters exhibit certain nonlinearities, which make it impossible to achieve their full theoretical values. In addition, clock jitter and dynamic effects mean that converters have a reduced dynamic range particularly at high clock frequencies. A converter is then specified using what is known as the spurious-free dynamic range or the number of effective bits.

Example:

An 8-bit A/D converter is specified as having 6.3 effective bits at a clock frequency of 1 GHz. It thus produces a dynamic range of 37.9 dB +1.76 dB = 40 dB.

For a 1 GHz clock frequency, an A/D converter can handle signals up to 500 MHz (Nyquist frequency). If we use only a fraction of this bandwidth, we can actually gain dynamic range by using decimation filters. For example, an 8-bit converter can achieve 60 dB or more dynamic range instead of only 50 dB (= 8 · 6 + 1.76 dB).

Based on the dynamic range, we can compute the number of effective bits as follows:

$$2^n = 10^{\frac{D/dB - 1.76}{20}}$$

With $n = \log_2\left(2^n\right)$ (log2 is the base 2 logarithm) and

$$\log_2(x) = \frac{\log_{10}(x)}{\log_{10}(2)} \quad \text{or} \quad \log_{10}\left(10^x\right) = x$$

We obtain:

$$n/Bit = \frac{\log_{10}\left(10^{\frac{D/dB - 1.76}{20}}\right)}{\log_{10}(2)} = \frac{\frac{D/dB - 1.76}{20}}{\log_{10}(2)} = \frac{D/dB - 1.76}{20\log_{10}(2)}$$

Example:

How many effective bits does an A/D converter have with a dynamic range of 70 dB?
We compute as follows:
70 dB – 1.76 dB = 68.2 dB and 20log₁₀(2) = 6.02

68.2 / 6.02 = 11.3
We thus obtain a result of 11.3 effective bits.

5.14 dB (FS) (Full Scale)

Analog to digital converters and digital to analog converters have a maximum dynamic range, which is determined by the range of numbers they can process. For example, an 8-bit A/D converter can handle numbers from 0 to a maximum of 2^8 - 1= 255. This number is also known as the full-scale value (n_{FS}). We can specify the drive level n of such converters with respect to this full-scale value and represent this ratio logarithmically.

$$a = 20 \cdot \lg\left(\frac{n}{n_{FS}}\right) \mathrm{dB(FS)}$$

Example:

A 16-bit A/D converter has a range of values from 0 to 2^{16} - 1 = 65535. If we drive this converter with the voltage which is represented by a numerical value of 32767, we have:

$$a = 20 \cdot \lg\left(\frac{32737}{65535}\right) \mathrm{dB(FS)} = \text{-}6.02\,\mathrm{dB(FS)}$$

If the converter is expected to represent positive and negative voltages, we must divide the range of values by two and take into account a suitable offset for the zero point.

5.15 Sound pressure level

In the field of acoustic measurements, the sound pressure level L_p is measured in decibels. L_p is the logarithmic ratio of sound pressure p referred to a sound pressure p_0 = 20 µPa (micro pascals). Sound pressure p0 is the lower limit of the pressure, which the human ear can perceive in its most sensitive frequency range (around 3 kHz). This pressure level is known as the threshold of hearing.

$$L_p = 20 \cdot \lg\left(\frac{p}{p_0}\right) \mathrm{dB}$$

$$p = 10^{\frac{L_p}{20}} \cdot p_0$$

5.16 Weighted sound pressure level dB(A)

The human ear has a rather pronounced frequency response, which also depends on the sound pressure level. When measuring sound pressure, weighting filters are used to simulate this frequency response. This provides us with level values, which come closer to simulating human loudness perception compared to unweighted levels. The different types of weighting filters are known as A, B, C and D.

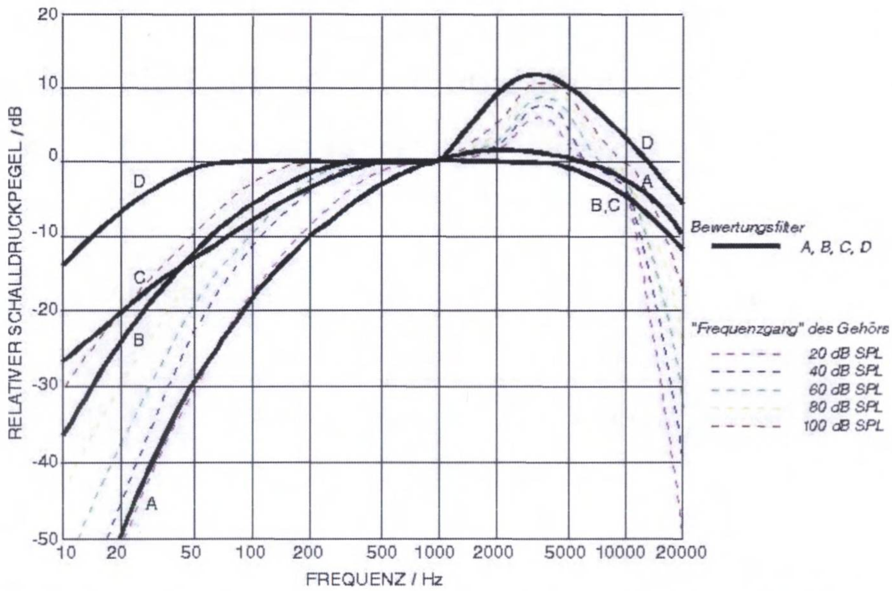


Fig. 5-9: Weighting filters A, B, C and D and the frequency response of human hearing

The A filter is used the most. The level measured in this manner is known as L_{pA} and is specified in units of **dB(A)** to designate the weighting filter.

A difference in sound pressure level of 10 dB(A) is perceived as roughly a doubling of the volume. Differences of 3 dB(A) are clearly audible. Smaller differences in sound level can usually be recognized only through direct comparison.

Example:

Our hearing range extends from 0 dB(A) (threshold of hearing) up to the threshold of pain at about 120 dB(A) to 134 dB(A). The sound pressure level in a very quiet room is approximately 20 dB(A) to 30 dB(A). Using 16 data bits, the dynamic range of a music CD can reach 98 dB, sufficient to satisfy the dynamic range of the human ear.

6 A few numbers worth knowing

Working with decibel values is a lot easier if you memorize a few key values. From just a few simple values, you can easily derive other values when needed. We can further simplify the problem by rounding exact values up or down to some easy to remember numbers. All we have to do is remember the simplified values, e.g. a power ratio of 2 corresponds to 3 dB (instead of the exact value of 3.02 dB which is rarely needed).

The following table lists some of the most useful numbers to remember.

6.1 Table for conversion between decibels and linear values

	Power ratio		Voltage ratio	
dB value	Rough	Exact	Rough	Exact
0.1 dB	±2 %	+2.3 % -2.3%	±1 %	+1.16 % -1.15 %
0.2 dB	±4 %	+4.7 % -4.5 %	±2%	+2.33 % -2.23 %
0.5 dB	±10 %	+12.2 % -10.9 %	±5 %	+5.9 % -5.5 %
1 dB	± 20 %	+25.9 % -20.5 %	±10 %	+12.2 % -11.9 %
3 dB	2 0.5	1.995 0.501	1.4 0.7	1.412 0.798
3.02 dB	2 0.5	2.0 0.5	1.414 0.707	$\sqrt{2}$ $1/\sqrt{2}$
5 dB	3 0.33	3.16 0.316	1.8 0.6	1.778 0.562
6 dB	4 0.25	3.98 0.25	2 0.5	1.995 0.501
10 dB	10 0.1	10 0.1	3 0.3	3.162 0.316
20 dB	100 0.01	100 0.01	10 0.1	10 0.1
40 dB	10000 0.0001	10000 0.0001	100 0.01	100 0.01
60 dB	1000000 0.000001	1000000 0.000001	1000 0.001	1000 0.001

Table 6-1: Conversion between decibels and linear values

From this table, you should probably know at least the rough values for 3 dB, 6 dB, 10 dB and 20 dB by heart.

Note: 3 dB is not an exact power ratio of 2 and 6 dB is not exactly 4! For everyday usage, however, these simplifications provide sufficient accuracy and as such are commonly used.

Intermediate values, which are not found in the table, can often be derived easily:

4 dB = 3 dB + 1 dB, corresponding to a factor of 2 + 20% of the power, i.e. approx. 2.4 times the power.

7 dB = 10 dB – 3 dB, corresponding to 10 times the power and then half, i.e. 5 times the power.

6.2 Table for adding decibel values

If you need to compute the sum of two values specified in decibels precisely, you must convert them to linear form, add them and then convert them back to logarithmic form. However, the following table is useful for quick calculations. Column 1 specifies under Delta dB the difference between the two dB values. Column 2 specifies a correction factor for power quantities. Column 3 specifies a correction factor for voltage quantities. Add the correction factor to the higher of the two dB values to obtain the total.

Delta dB	Power	Voltage
0	3.01	6.02
1	2.54	5.53
2	2.12	5.08
3	1.76	4.65
4	1.46	4.25
5	1.19	3.88
6	0.97	3.53
7	0.79	3.21
8	0.64	2.91
9	0.51	2.64
10	0.41	2.39
11	0.33	2.16
12	0.27	1.95
13	0.21	1.75
14	0.17	1.58
15	0.14	1.42
16	0.11	1.28
17	0.09	1.15
18	0.07	1.03
19	0.05	0.92
20	0.04	0.83

Table 6-2: Correction factors for adding decibel values

Example:

1. *Suppose we would like to add power levels of -60 dBm and -66 dBm. We subtract the decibel values to obtain a difference of 6 dB. From the table, we read off a correction factor of 0.97 dB. We add this value to the higher of the two values, i.e. -60 dBm (-60 dBm is greater than -65 dBm!) and obtain a total power of -59 dBm.*

2. *When we switch on a signal, the noise displayed by a spectrum analyzer increases by 0.04 dB. From the table, we can see that the level of this signal lies about 20 dB below the noise level of the spectrum analyzer.*

3. *We would like to add two equal voltages. This means that the level difference is 0 dB. The total voltage lies 6 dB (value from the table) above the value of one voltage (= twice the voltage).*

6.3 Some more useful values

The following values are also useful under many circumstances:

- 13 dBm corresponds to URMS = 1 V into 50 Ω
- 0 dBm corresponds to URMS = 0.224 V into 50 Ω
- 107 dB (µV) corresponds to 0 dBm into 50 Ω
- 120 dB (µV) corresponds to 1 V
- -174 dBm is the thermal noise power in 1 Hz bandwidth at a temperature of approx. 20 °C (68 °F).

6.4 Other reference quantities

So far, we have used 1 mW and 50 Ω as our reference quantities. However, there are other reference systems, including most importantly the 75 Ω system in television engineering and the 600 Ω system in acoustic measurement technology. The 60 Ω system formerly used in RF technology and the 600 Ω system in the United States with a reference value of 1.66 mW are now rather rare. However, it is easy to adapt the formulas given above to these reference systems.

R	P_0	U_0	Note
50 Ω	1 mW	0.224 V	RF engineering
60 Ω	1 mW	0.245 V	RF engineering (old)
75 Ω	1 mW	0.274 V	TV engineering
600 Ω	1 mW	0.775 V	Acoustics
600 Ω	1.66 mW	1.000 V	US standard

Table 6-3: Additional reference systems

6.5 Accuracy, number of decimal places

How many decimal places should be used when we specify decibel values?

If we increase a value x, which is a power quantity, specified in decibels by 0.01 dB, the related linear value will change as follows:

$$x\,\mathrm{dB} + 0.01\,\mathrm{dB} \equiv 10^{\frac{x+0{,}01}{10}} = 10^{\frac{x}{10}} \cdot 10^{\frac{0{,}01}{10}} = 10^{\frac{x}{10}} \cdot 1.0023$$

This is equivalent to a 0.23% change in the power. Voltage quantities change by only 0.11%. These minor changes cannot be distinguished from normal fluctuations of the measurement result.

Accordingly, it does not make sense to specify decibel values with, say, five or more decimal places, except in a few rare cases.

7 Smartphone Apps

To ease calculations as the ones done in the preceding chapters, Rohde & Schwarz provides a range of apps for tablets and smartphones.

At present, versions for Android, iOS und Windows Phone are provided for you free of charge on the respective app portals. To find them easily, please use search terms “Rohde“, “Schwarz“, and “dB“, “Calculator“ or "Field Strength" and "Estimator". If you are reading this application note on a smart device, simply click on the following link for direct access into the Rohde & Schwarz app landing page.

1. dB Calculator

The dB Calculator App comprises five independent calculation tools. dBm Calculator, Voltage Calculator, Unit Converter, dB Converter and VSWR Converter.

- **Android:**
  https://play.google.com/store/apps/details?id=com.rohdeschwarz.dbcalculator
- **iOS:**
  https://itunes.apple.com/app/id489100786
- **Windows Phone:**
  https://www.microsoft.com/store/apps/9nblggh0fwcd

2. Pulsed RF Calculator

Modern spectrum analyzers as the R&S®FSW offer high sophisticated personalities for this measurement task. If such an analyzer is not available, the App Pulsed RF Calculator might help you to find appropriate spectrum analyzer settings and to calculate the so-called pulse desensitization for correct measurement of the pulse signal amplitudes.

- **Android:**
  https://play.google.com/store/apps/details?id=com.rohdeschwarz.pulsedrfcalculator
- **iOS:**
  https://itunes.apple.com/app/id969034080
- **Windows Phone:**
  https://www.microsoft.com/store/apps/9nblggh5xn5c

3. Field Strength & Power Estimator

The App calculates power flux density, electric and magnetic field strength from the transmitted power, associated frequency and gain of the transmitting antenna.

Additionally the input power into a receiver with 50 Ohm input impedance is calculated from the gain of the receiving antenna.

The App automatically converts power flux density into electric and magnetic field strength.

Depending on the transmitted frequency, various parameters influence the received power and field strength like non-line-of-sight propagation, polarization change, reflection, and multi-path propagation. Additionally antenna VSWR and cable losses have to be considered.

The Field Strength and Power Estimator does not consider these impairments. It assumes conditions that are close to the best possible theoretical values. This is why we say the program is an Estimator, not a Calculator.

- **Android:**
  https://play.google.com/store/apps/details?id=com.rohdeschwarz.android.powerestimator
  iOS:
  https://itunes.apple.com/app/id364229792
- **Windows Phone:**
  https://www.microsoft.com/store/apps/9nblggh0fwb1

4. Power Viewer Mobile

With Power Viewer Mobile, you are able to use Rohde&Schwarz®NRP-Z Power Sensors with your Android smartphone or tablet.

- **Android:**
  https://play.google.com/store/apps/details?id=com.rohdeschwarz.android.nrpdriver

5. Wireless Communication Calculator

The Rohde & Schwarz Wireless Communications Calculator App is an essential part of any wireless engineer's toolkit. Featuring all of today's most important and popular cellular and non-cellular standards, we cover them all from A to Zigbee. Just enter the technology and band of interest, and we do the rest. Enter a channel number and we'll provide the correct downlink and uplink frequencies in both numeric and graphic format. Low, mid, and high channels are also shown for a quick reference. In the "power" mode, we give you the maximum UE power allowed for that class device, or, in the case of GSM, power versus PCL/Gamma.

- **Android:**
  https://play.google.com/store/apps/details?id=elcom.wccandroid
- **iOS: (currently not available)**

- **Windows Phone**:
  https://www.microsoft.com/store/apps/9nblggh5xmzf

6. Aviation RF Link

The App Aviation RF Link allows quick calculation of the forward link from a ground station to an aircraft. Based on the RF power of the ground station, the tool calculates the distance with a given field strength to be achieved at the aircraft antenna or calculates the field strength at a given power and distance to the aircraft.

The tool calculates the path loss based on line-of-sight (LOS) conditions and does not take into account multipath propagation on the ground.
In addition to the RF path, the tool calculates the radio horizon based on the given height of the aircraft and the ground station. If the calculated LOS is lower than the distance that can be achieved with the given radio conditions, this is indicated by a red dot on the LOS tab. In this case, the radio horizon is the limiting factor and not the RF link budget.
The line of sight is calculated in accordance with ICAO Annex 10 Vol. V.
The default for the antenna gain of 2.14 dBi corresponds to an Omni-directional antenna.
The default for the field strength of 75 uV/m corresponds to the ICAO recommendation for minimum reception at the aircraft antenna.

- **Android:**
  https://play.google.com/store/apps/details?id=eu.tarienna.android.aviationlink
- **iOS:**
  https://itunes.apple.com/app/id421145880

To check out all other available Apps from Rohde & Schwarz on different App portals, just click on the following links depending on the device you are using.

- **Android:**
  https://play.google.com/store/apps/developer?id=Rohde+%26+Schwarz+GmbH+%26+Co.+KG
- **iOS:**
  https://itunes.apple.com/developer/id364229795
- **Windows Phone:**
  https://www.microsoft.com/de-de/store/search/apps?q=Rohde+%26+Schwarz

8 Bibliography

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2. R&S dB Calculator, Application Note 1GP77, Rohde & Schwarz GmbH &Co. KG 1GP77
3. For further explanation of the terminology used in this Application Note, see also www.wikipedia.org.
4. Christoph Rauscher, Fundamentals of Spectrum Analysis, Rohde & Schwarz GmbH&Co. KG, PW 0002.6629.00
5. Correct usage of quantities, units and equations, Brochure, Rohde & Schwarz GmbH &Co. KG, 2012

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