HAM RADIO 2013

Measurement and Application of Scattering Parameters in RF-Design

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Program

- **Scattering (S-) parameters**
- **Break**
- **Measuring S-parameters with a VNA**
- **Applications**

Many thanks to:
- *Eric Hecker*
- *Kurt Poulsen*
- *Gerfried Palme*
- *Alan Rowe*
- *Jan Verduyn*
- *Jim Tonne*

Hochschule Ulm

What are Scattering Parameters?

1. A different angle to dc
2. a and b instead of voltage and current
3. Complex reflection coefficient
4. S-parameters

Hochschule Ulm

Who is afraid of S-parameters!

$$U = R \cdot I$$ Ohm

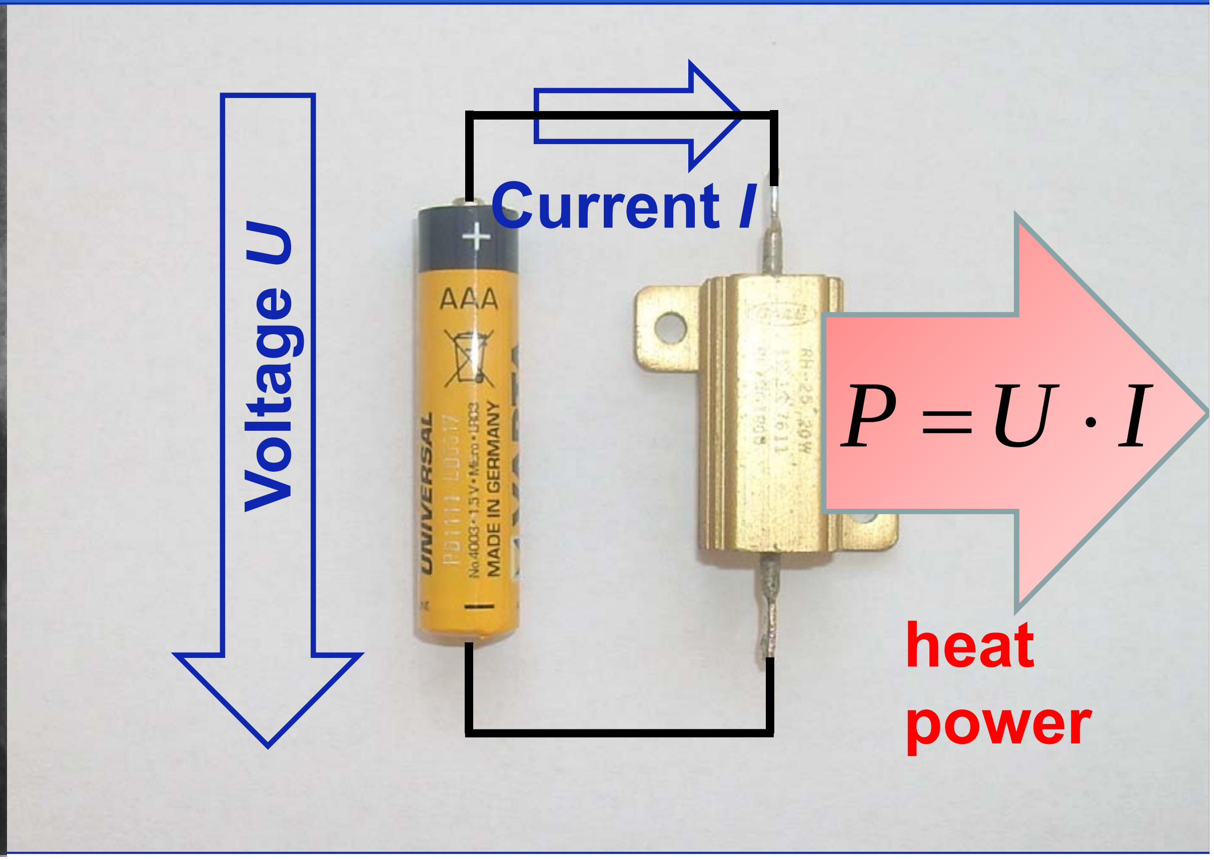
$$b = S \cdot a$$ S-Par.

Response | System | Excitation

equivalent description

Hochschule Ulm

A different angle to dc
Ohms‘ Law (1)

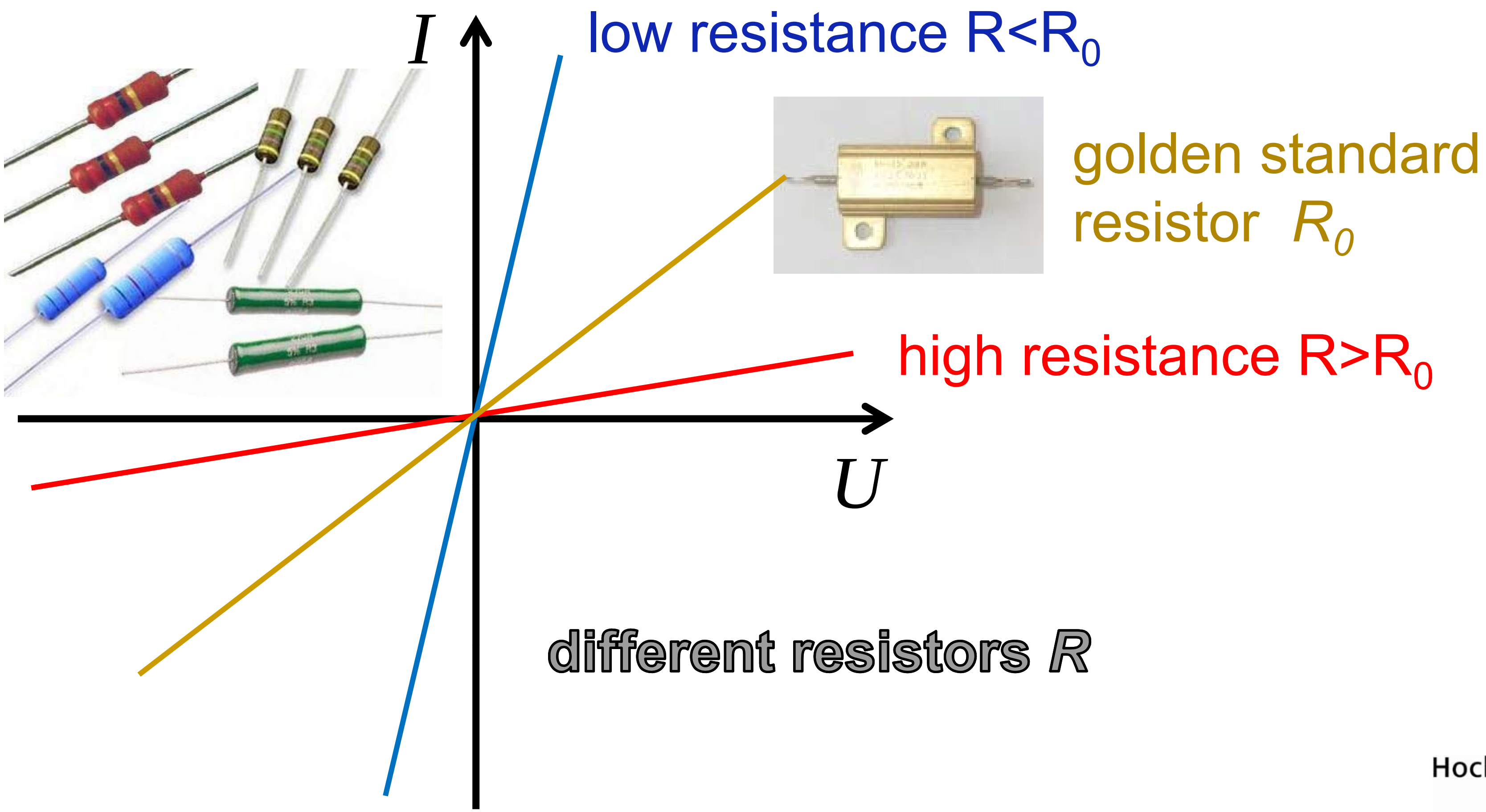


Georg Simon Ohm
(1789-1854)

$$\boxed{U = R \cdot I}$$

Hochschule Ulm

Ohms‘ Law (2)

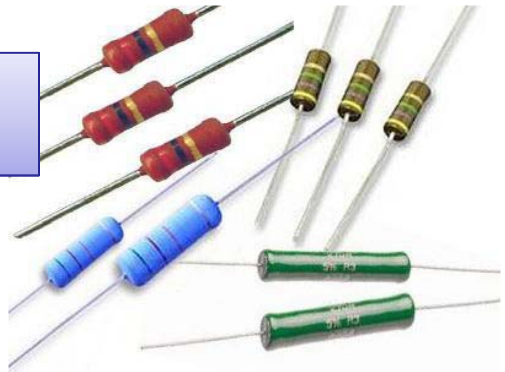


Hochschule Ulm

Normalizing Resistor *R to* Reference Resistor R_0

We scale arbitrary resistors in multiples of our reference resistance R_0 :

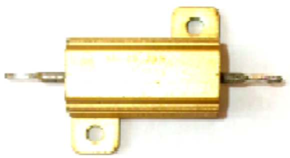
Resistor R



$$r = \frac{R}{R_0}$$

normalized r

Resistor R_0



$$r_0 = \frac{R_0}{R_0} = 1$$

normalized *1*

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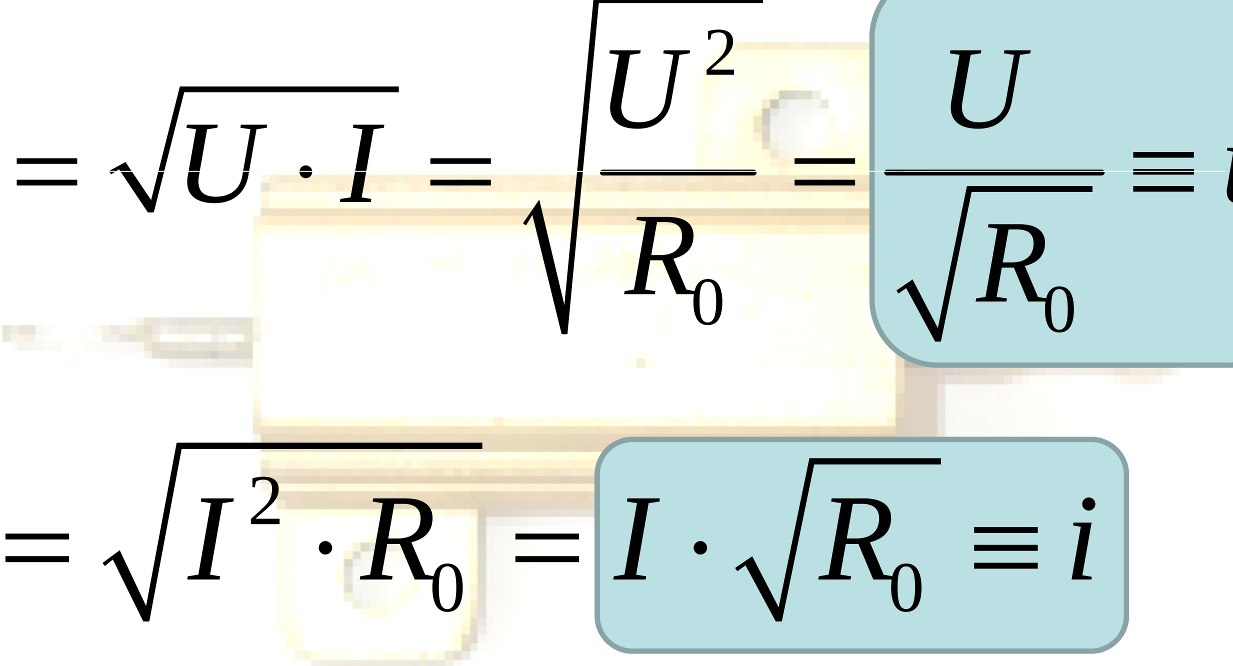
New Units for Voltage and Current: Normalization of U und I via R_0

Focus on power P dissipated in R_0:

$$\sqrt{P} = \sqrt{U \cdot I} = \sqrt{\frac{U^2}{R_0}} = \boxed{\frac{U}{\sqrt{R_0}} \equiv u}$$

$$= \sqrt{I^2 \cdot R_0} = \boxed{I \cdot \sqrt{R_0} \equiv i}$$



Resistor R_0 in circuit

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New Units for Voltage and Current:

$I \rightarrow i$ $\qquad\qquad$ $U \rightarrow u$

Focus on power *P* dissipated in R_0:

$$\boxed{i \equiv I \cdot \sqrt{R_0}} = \sqrt{P} = \boxed{\frac{U}{\sqrt{R_0}} \equiv u}$$

u and *i* are still voltage and current, but units have changed.

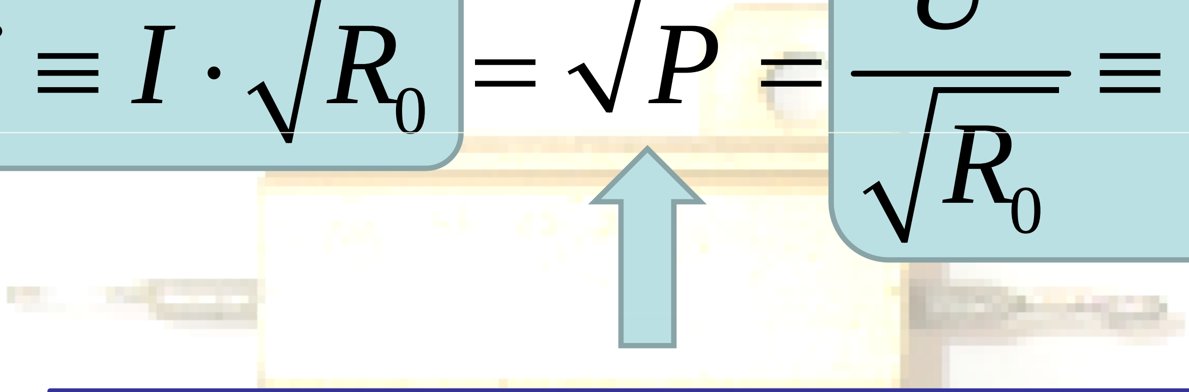
u and *i* have identical units, namely $\sqrt{Watt}$

Resistor R_0 in circuit

New Units for Voltage and Current:
$I \rightarrow i$ $\qquad\qquad$ $U \rightarrow u$

Focus on power *P* dissipated in R_0:

$$\boxed{i \equiv I \cdot \sqrt{R_0}} = \sqrt{P} = \boxed{\frac{U}{\sqrt{R_0}} \equiv u}$$



Here special case $u = i = \sqrt{P}$
Reason: $R = R_0$
i.e. $U = R_0 \cdot I$

Resistor R_0 in circuit

Hochschule Ulm

Now arbitrary Resistor *R* instead of R_0

Ohm's Law still applies:

$$u = r \cdot i$$

because:

Normalized resistance!

$$\frac{u}{i} = \frac{\dfrac{U}{\sqrt{R_0}}}{I \cdot \sqrt{R_0}} = \frac{U}{I \cdot R_0} = \frac{R}{R_0} \equiv r$$

Now arbitrary resistor *R!!!*

Hochschule Ulm

Dissipated Power in arbitrary Resistor

$$\boxed{P = u \cdot i}$$

still applies

because:

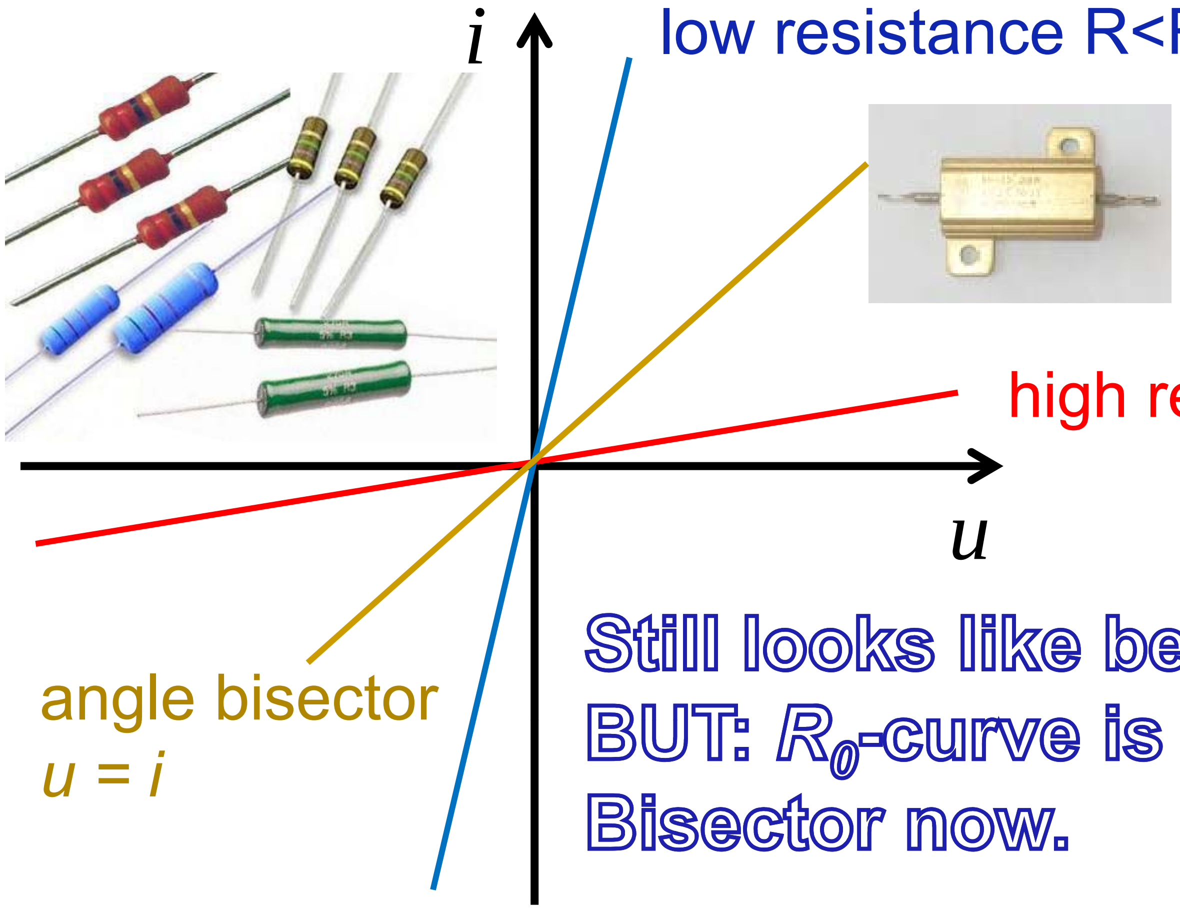
$$u \cdot i = \frac{U}{\cancel{\sqrt{R_0}}} \cdot I \cdot \cancel{\sqrt{R_0}} = U \cdot I = P$$

reduce!

Now arbitrary resistor *R!!!*

Hochschule Ulm

Ohm‘s Law with new Voltage and Current Units



Still looks like before.
BUT: R_0-curve is angle Bisector now.

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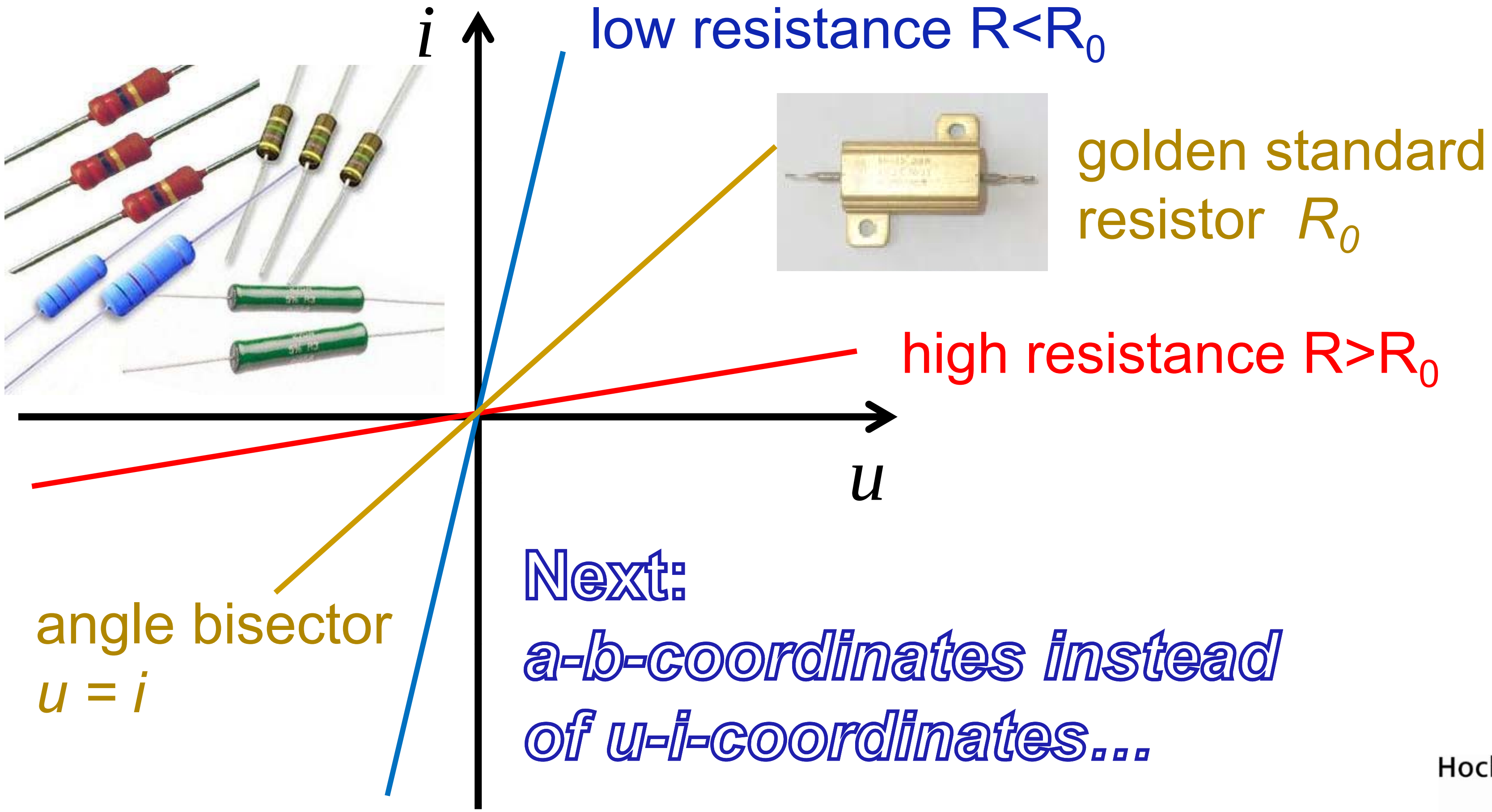
Now we get down to business:
A different angle to dc…



Next:

a-b-coordinates instead of u-i-coordinates...

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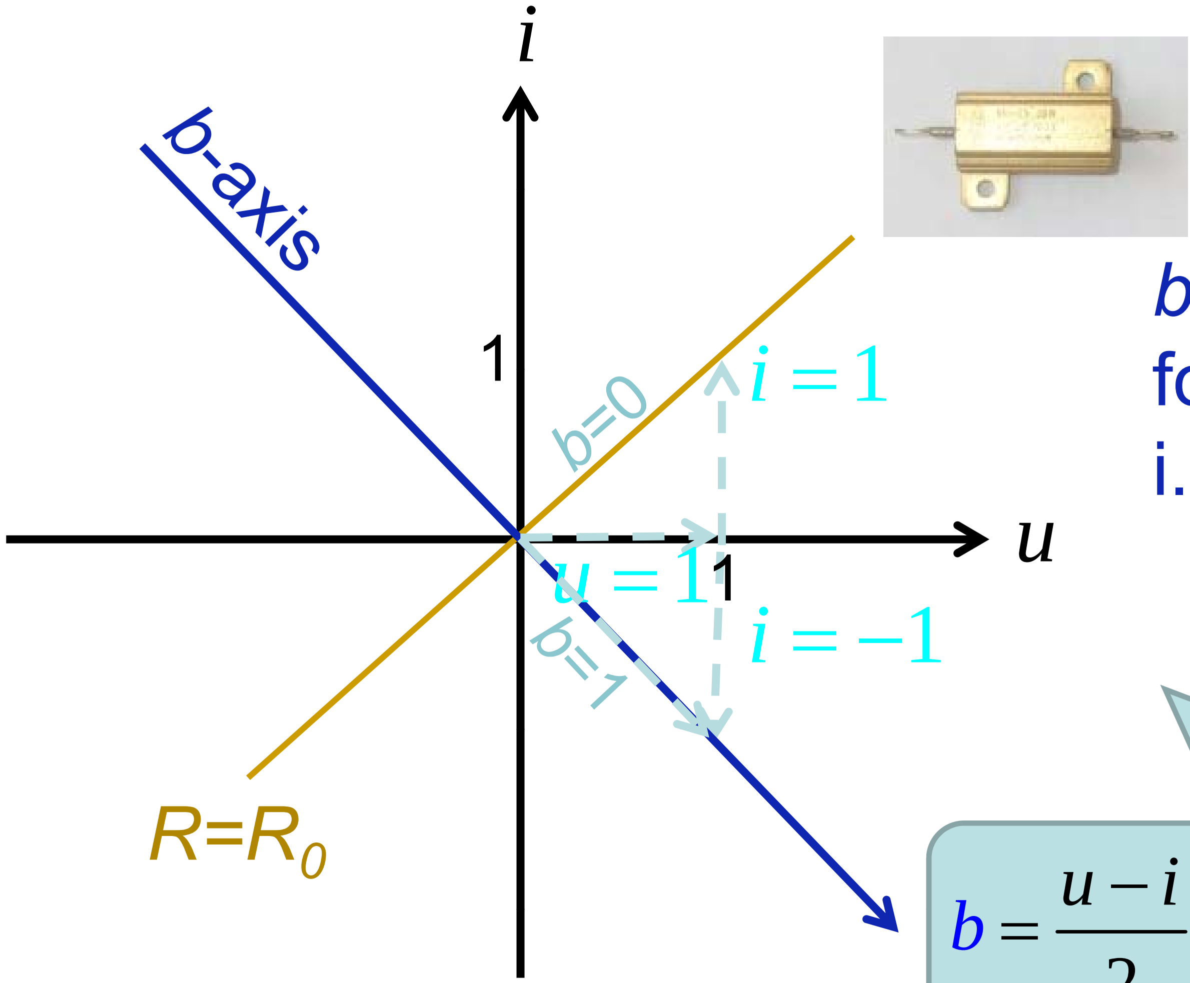
From Voltage and Current…
…to *b*…

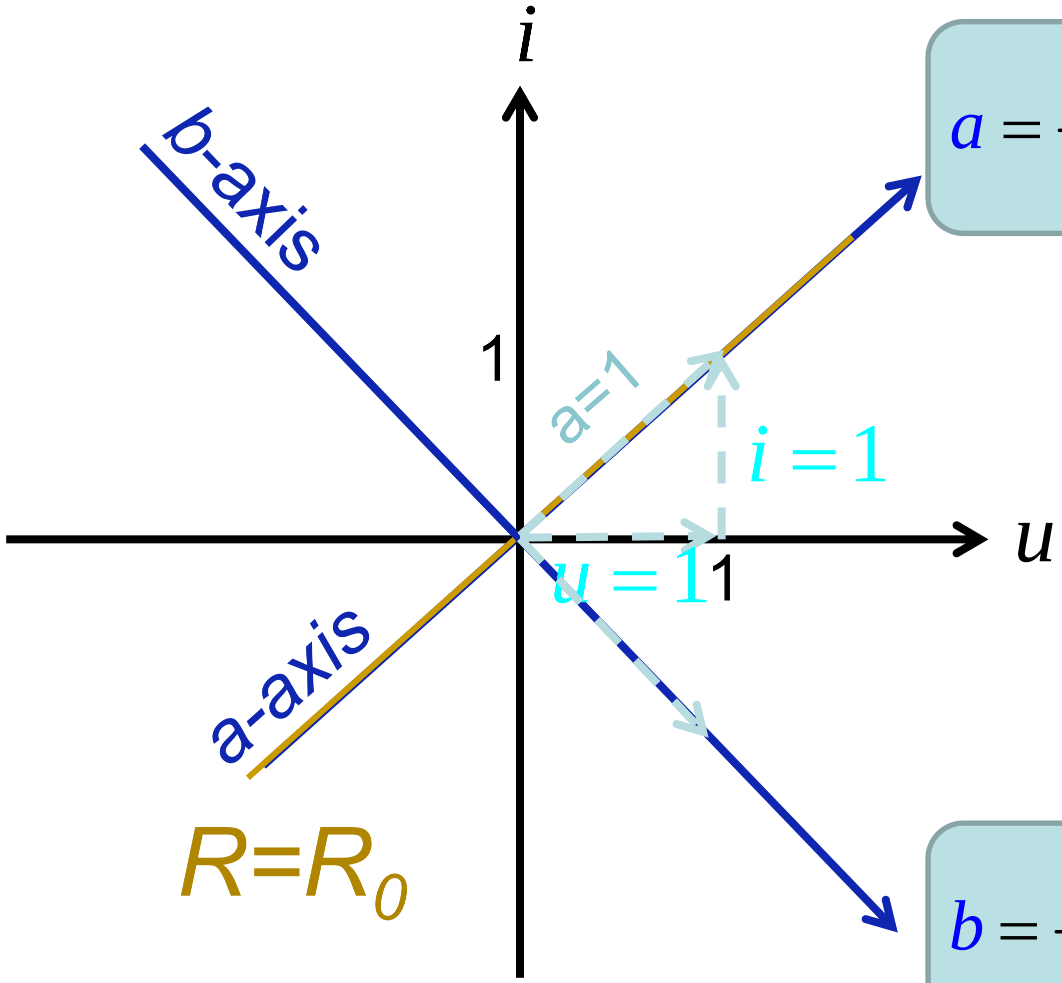


b shall yield zero
for $R=R_0$,
i.e. for $u = i$

$$b = \frac{u-i}{2}$$

Hochschule Ulm

From Voltage and Current…
…to *b*…and *a* !



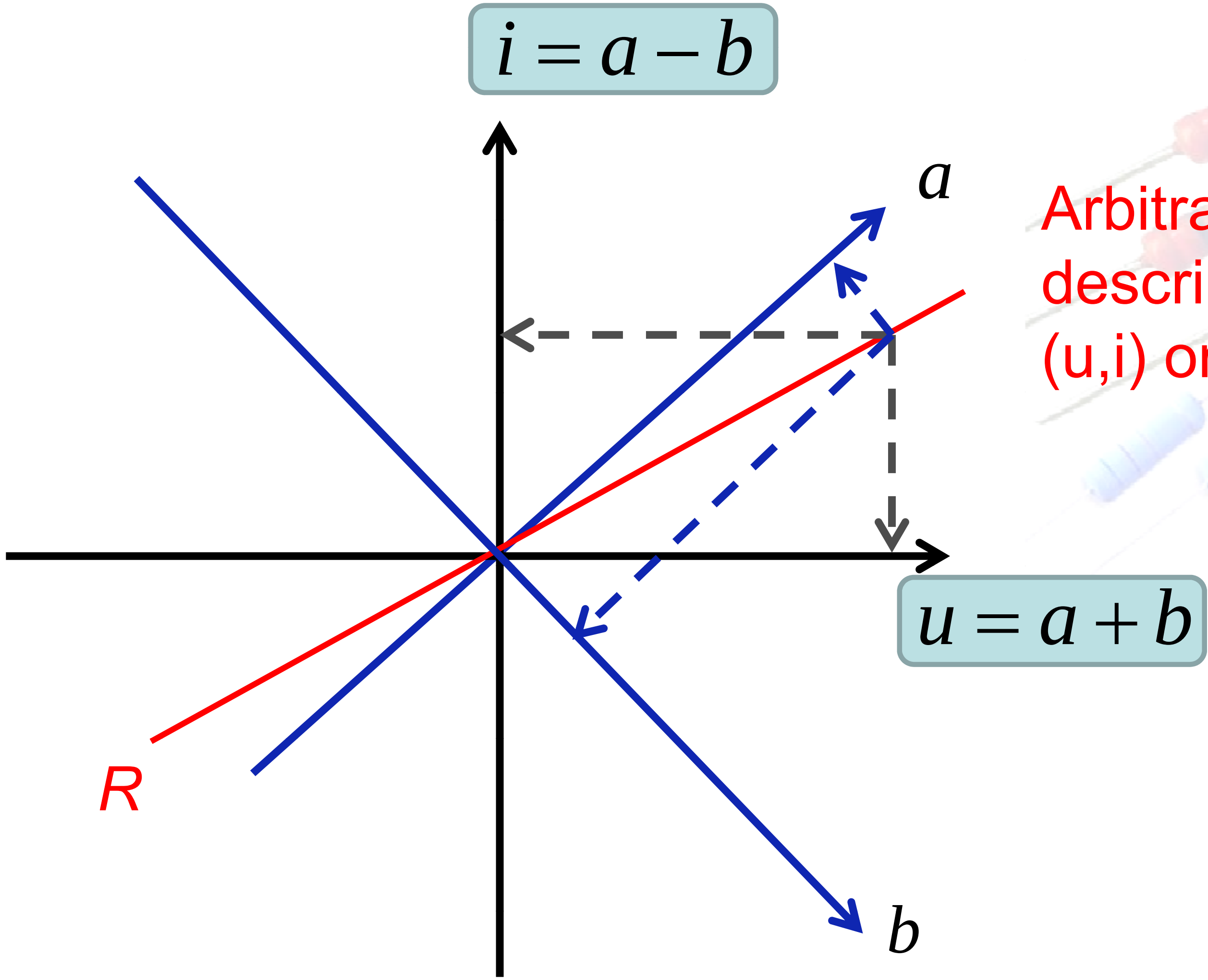
$$a=\frac{u+i}{2}$$

$$b=\frac{u-i}{2}$$

a-axis shall be perpendicular to *b*-axis

Hochschule Ulm

This works the other way round, too: Voltage and Current from *a* and *b*



Arbitrary resistor *R* can be described equivalently in (u,i) or (a,b)-coordinates.

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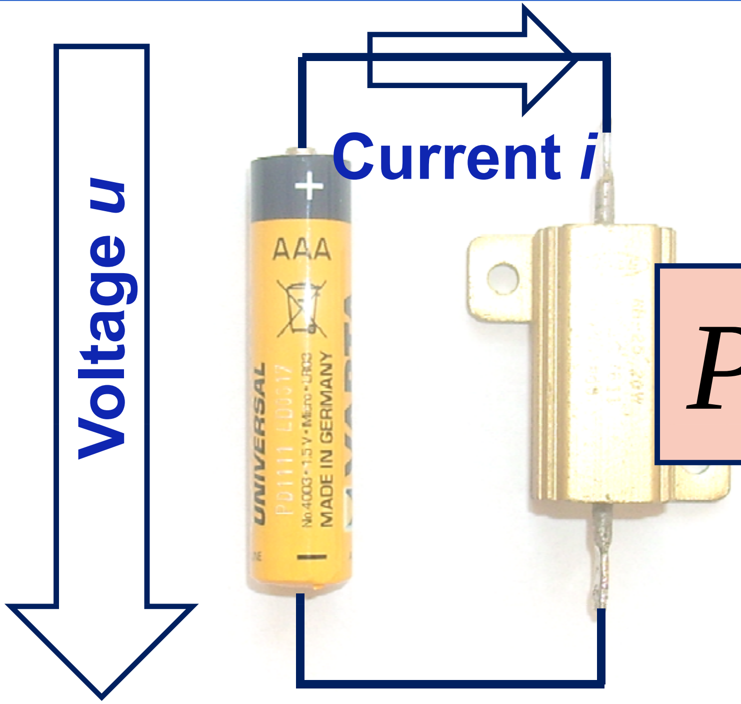
A different angle to dc: Dissipated power in resistor *R*



$$P = a^2 - b^2$$

because

$$P = u \cdot i$$

$$= (a+b)\cdot(a-b)$$

$$= a^2 - b^2$$

if $\quad R = R_0 \Rightarrow b = 0$

$$\Rightarrow P = a^2$$

Hochschule Ulm

Conclusion: a and b instead of current and voltage

$$P = a^2 - b^2$$

Power $P \leq a^2$

If $b=0$, i.e. $R=R_0$ then $P = a^2$

a and *b* contain identical information as *u* and *i*:

$$\begin{matrix} u = a + b \\ i = a - b \end{matrix} \quad \Leftrightarrow \quad \begin{matrix} u + i = 2a \\ u - i = 2b \end{matrix}$$

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The Golden RF Reference Resistance: Characteristic Line Impedance Z_0

Most power dissipated in Z for b = 0, i.e. *Z=Z_0, i.e. for matched line termination!*

a = wave incident to *Z*
b = wave reflected from *Z*

$$\begin{cases} \boxed{P = |a|^2 - |b|^2} \\ \text{and} \qquad b = 0 \\ \text{if} \qquad Z = Z_0 \end{cases}$$

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Now we apply ac!
Complex Reflection Coefficient *S* = *b/a*

a, *b* = complex numbers, contain amplitude and phase information, because we apply ac.

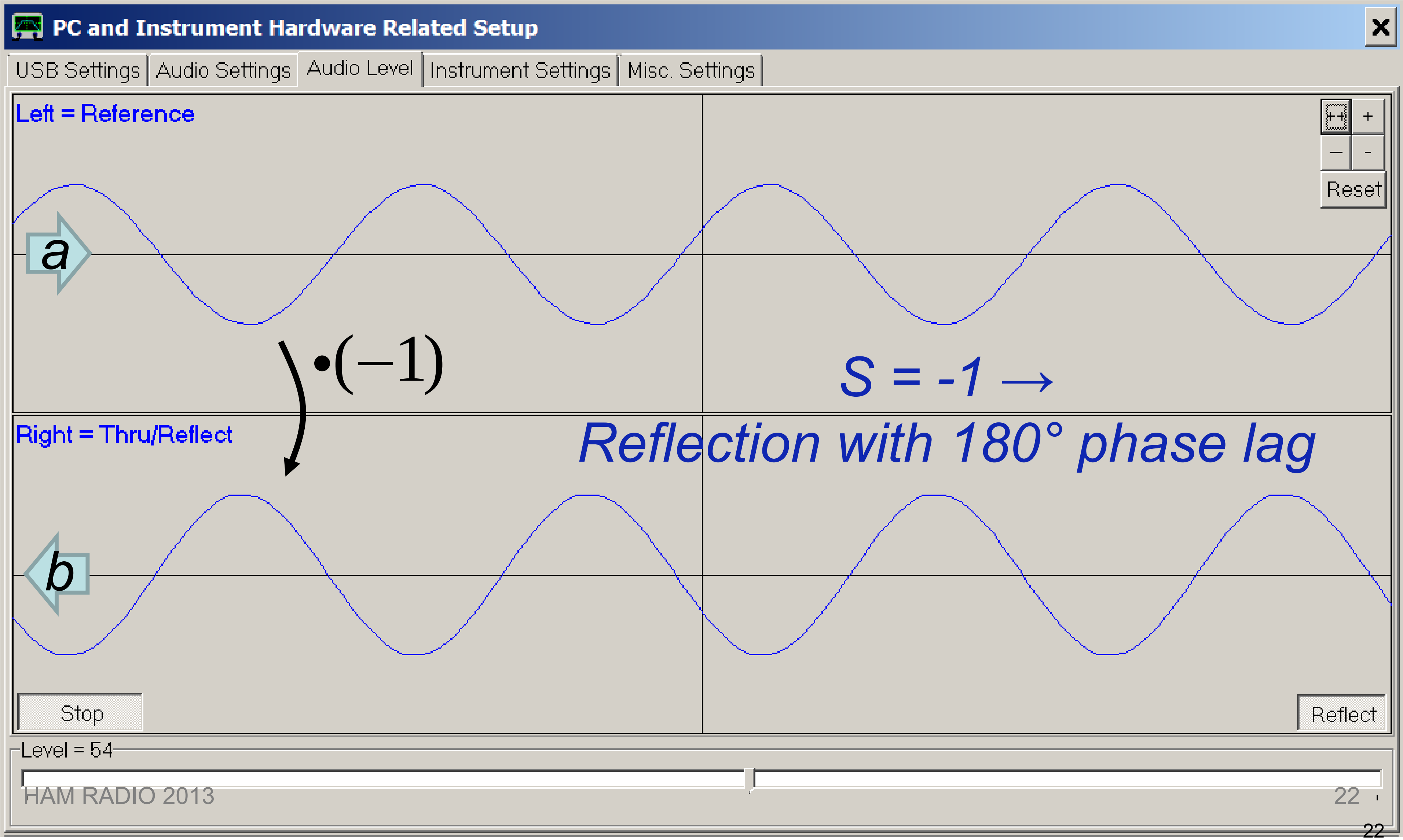
$$S = \frac{b}{a} = \frac{u-i}{u+i} = \frac{\frac{u}{i}-1}{\frac{u}{i}+1} = \frac{z-1}{z+1}$$

with $z = \frac{Z}{Z_0}$

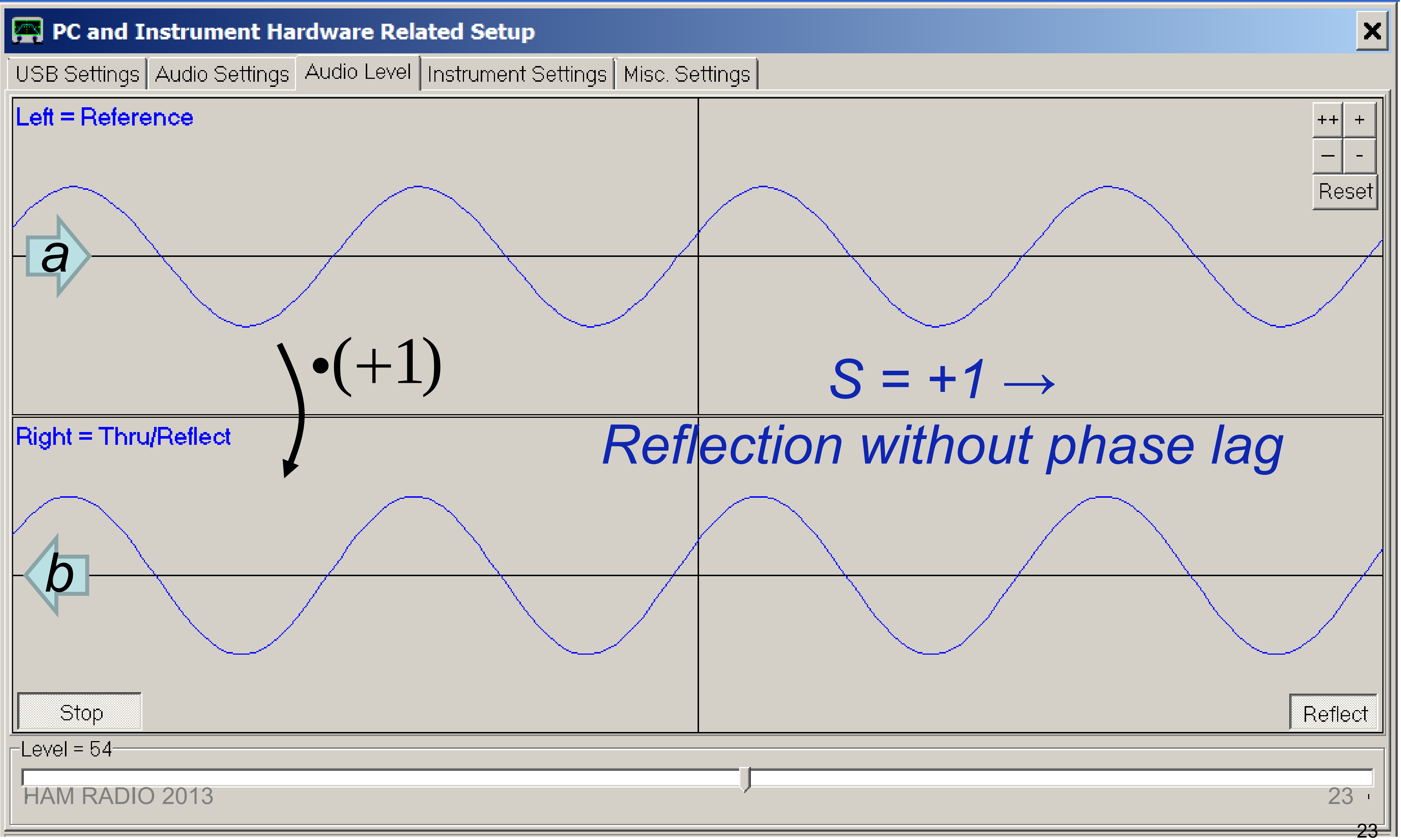
e.g. Short: $z = 0 \rightarrow S = -1$

Hochschule Ulm

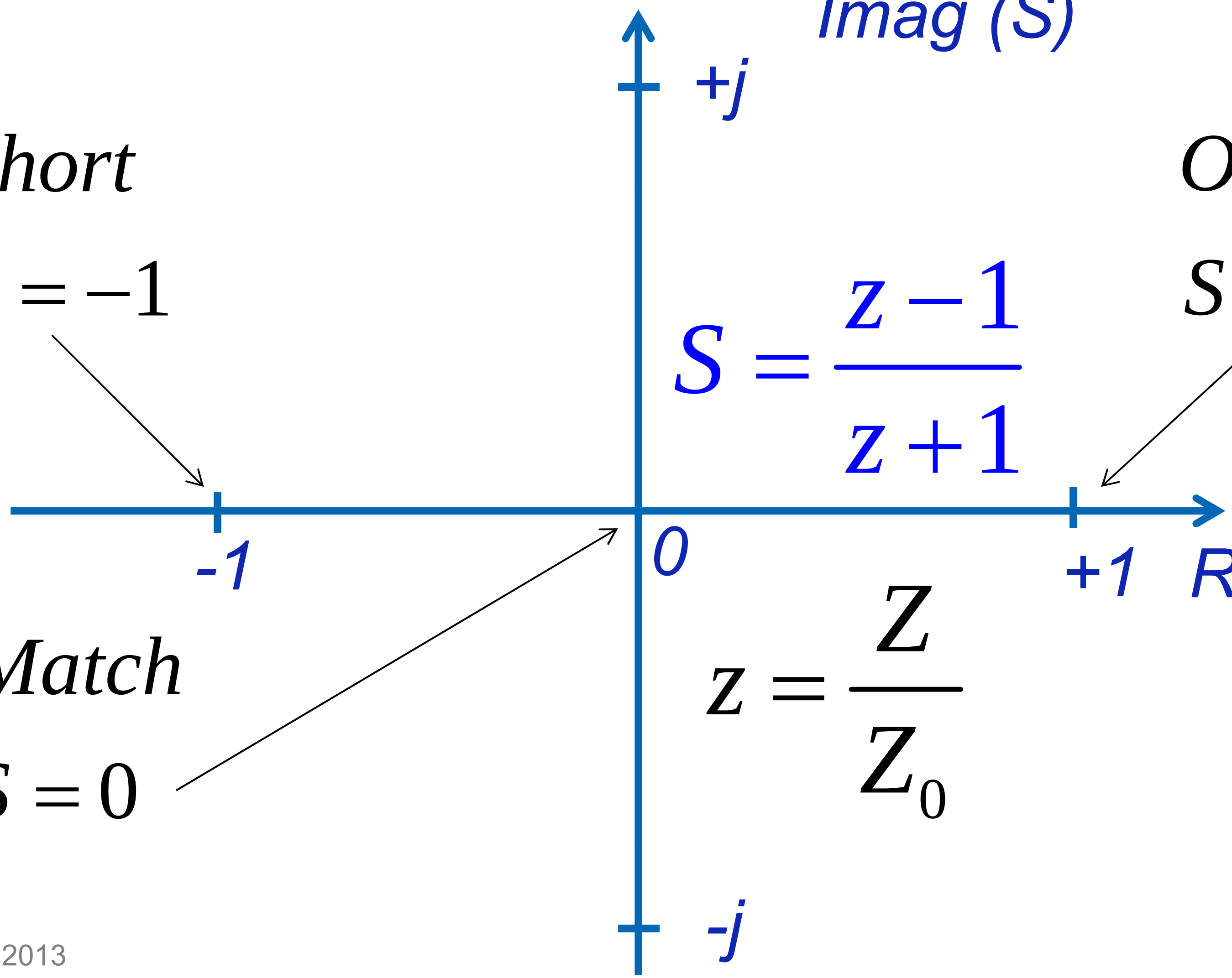
We can see a and b using the VNWA
E.g. Short Circuit S=-1



We can see a and b using the VNWA
E.g. Open Circuit S=+1:



Complex Reflection Coefficient $S = b/a$ …



Short

$$S = -1$$

Open

$$S = +1$$

Match

$$S = 0$$

$$S = \frac{z-1}{z+1}$$

$$z = \frac{Z}{Z_0}$$

Hochschule Ulm

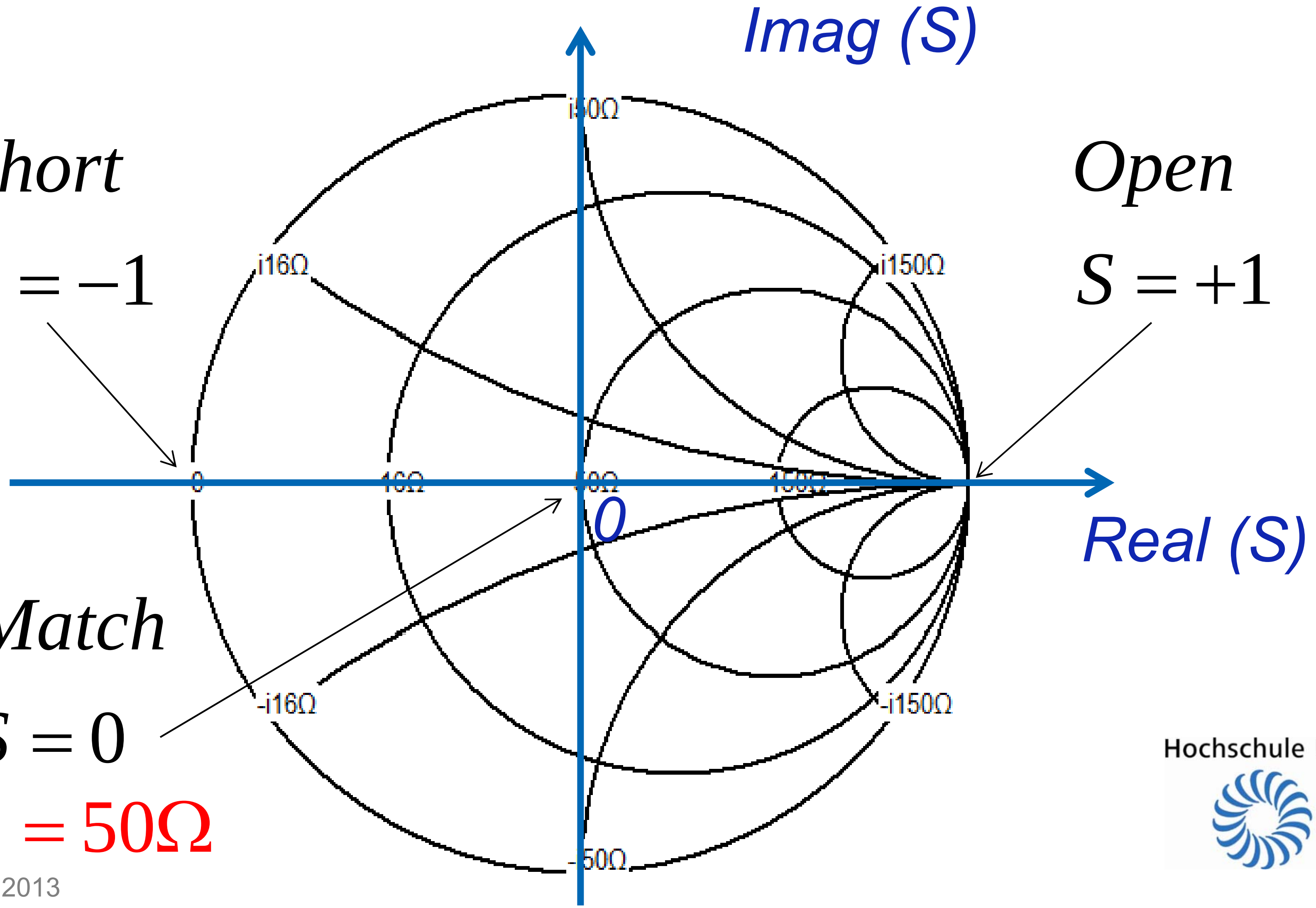
Complex Reflection Coefficient $S = b/a$ and Smith Chart

Short

$S = -1$

Open

$S = +1$



Match

$S = 0$

$Z_0 = 50\Omega$

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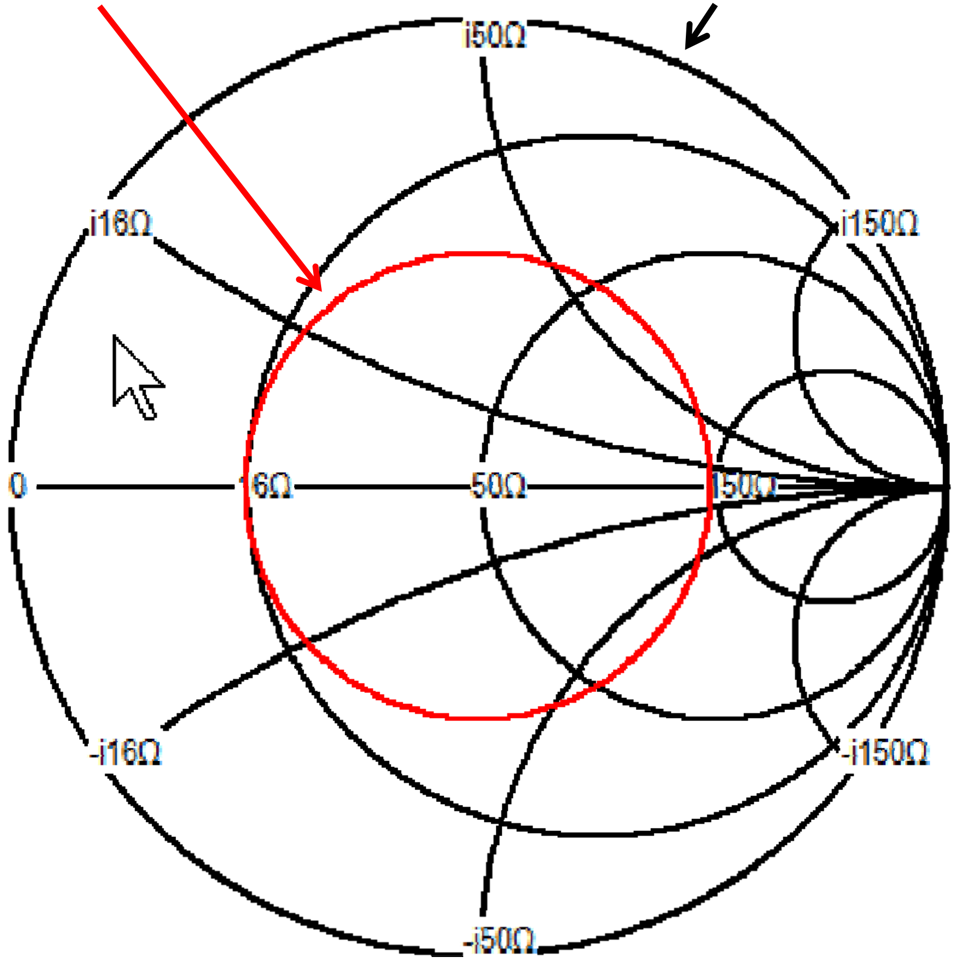
Complex Reflection Coefficient *S* = *b/a* and Voltage Standing Wave Ratio VSWR

$|S| = 0,5 \quad VSWR = 3$

$|S| = 1 \quad VSWR = \infty$

0,5·0,5=25%
reflected power



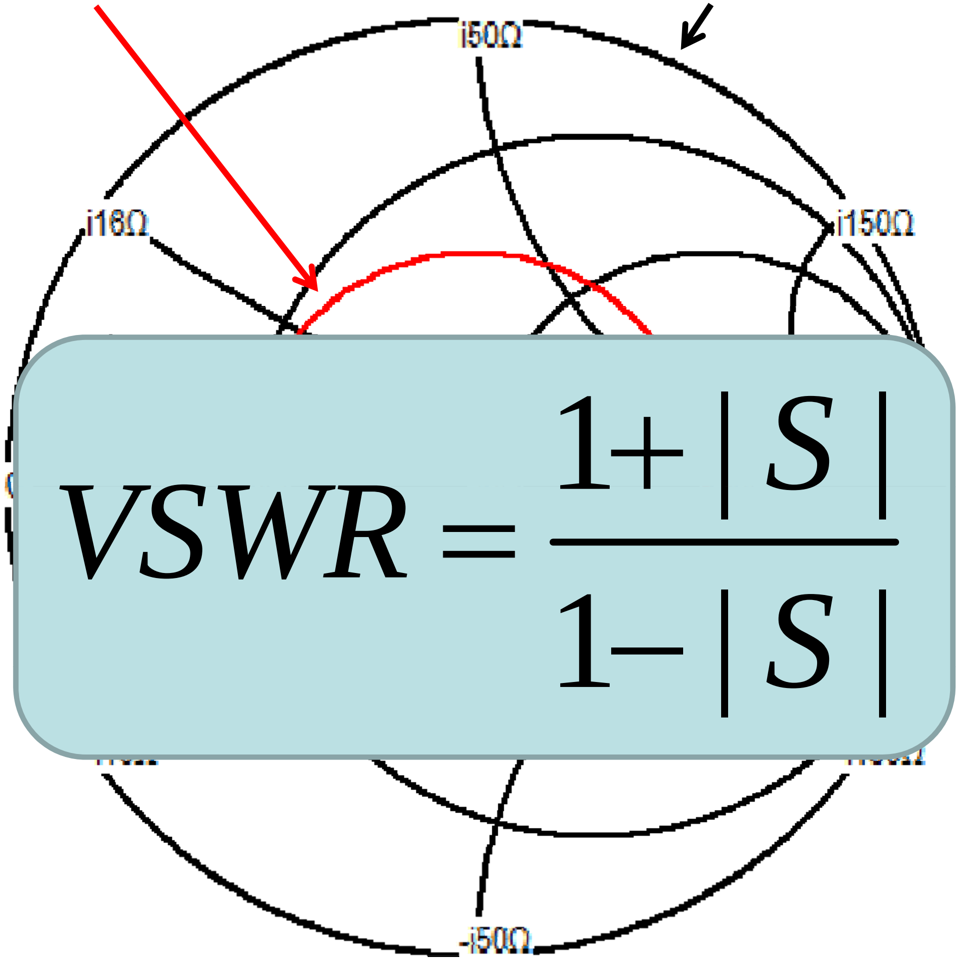
1·1=100%
reflected power

Hochschule Ulm

Complex Reflection Coefficient $S = b/a$ and Voltage Standing Wave Ratio VSWR

$|S| = 0,5 \quad VSWR = 3$

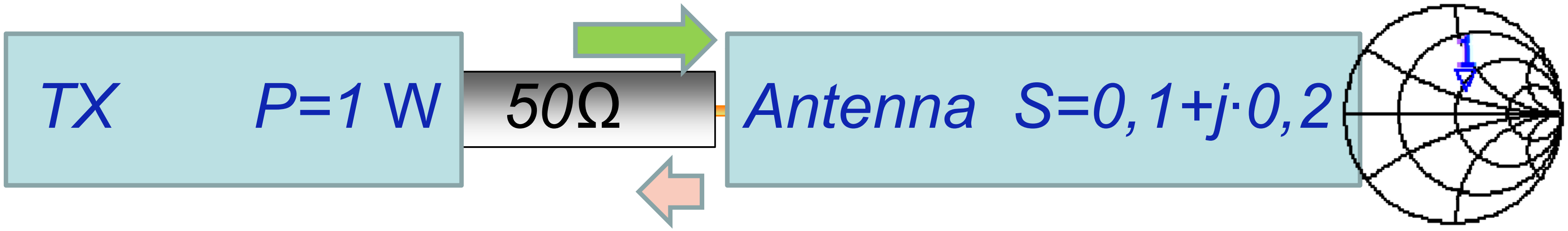
$|S| = 1 \quad VSWR = \infty$



$$VSWR = \frac{1+|S|}{1-|S|}$$

Hochschule Ulm

Complex Reflection Coefficient $S = b/a$
Calculus Example: Reflected Power



$$a = \sqrt{1\,\mathrm{W}} = 1\sqrt{\mathrm{W}}$$

$$b = S \cdot a = (0{,}1 + j0{,}2) \cdot \sqrt{1\,\mathrm{W}} = 0{,}1\sqrt{\mathrm{W}} + j0{,}2\sqrt{\mathrm{W}}$$

Reflected Power:

$$P_r = |b|^2 = 0{,}1^2 + 0{,}2^2\ \mathrm{W} = 0{,}05\,\mathrm{W}$$

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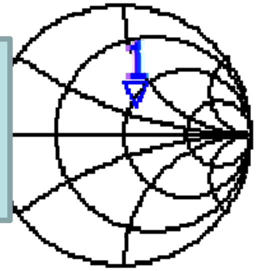
Complex Reflection Coefficient $S = b/a$
Calculus Example: VSWR

TX *P=1 W* — 50Ω — *Antenna* *S=0,1+j·0,2*



$$a = 1\sqrt{\mathrm{W}} \qquad b = 0{,}1\sqrt{\mathrm{W}} + j0{,}2\sqrt{\mathrm{W}}$$

<u>VSWR:</u>

$$|S| = \sqrt{0{,}1^2 + 0{,}2^2} \approx 0{,}22$$

$$VSWR = \frac{1+|S|}{1-|S|} \approx \frac{1+0{,}22}{1-0{,}22} \approx 1{,}6$$

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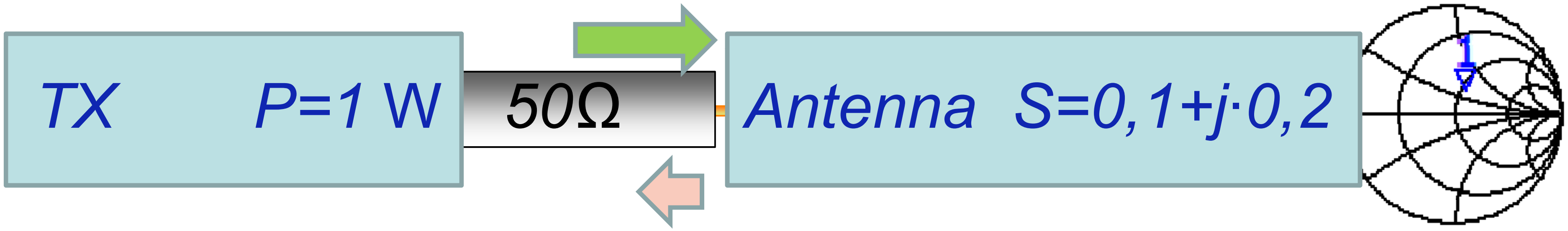
Complex Reflection Coefficient *S = b/a*
Calculus Example: Antenna Voltage



$$a = 1\sqrt{\mathrm{W}} \qquad b = 0{,}1\sqrt{\mathrm{W}} + j0{,}2\sqrt{\mathrm{W}}$$

__Effective Voltage at Antenna:__

$$u = a + b = 1{,}1\sqrt{\mathrm{W}} + j0{,}2\sqrt{\mathrm{W}}$$

$$U = u \cdot \sqrt{Z_0} = u \cdot \sqrt{50\ \Omega} \approx 7{,}8\ \mathrm{V} + j1{,}4\ \mathrm{V}$$

$$\mathrm{U}_{eff} = \left|\mathrm{U}\right| = \sqrt{7{,}8^2 + 1{,}4^2}\ \mathrm{V} \approx 7{,}9\ \mathrm{V}$$

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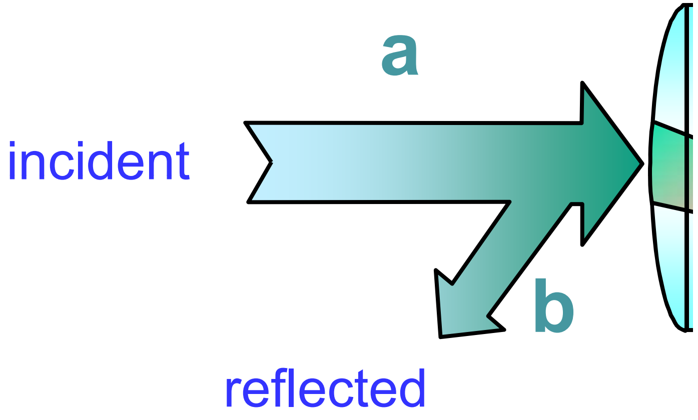
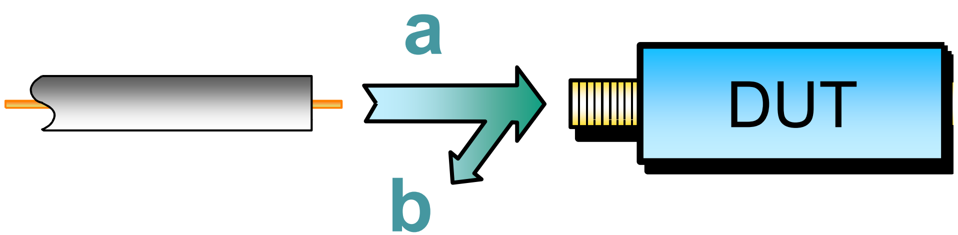
Complex Reflection Coefficient $S = b/a$
We call it Scattering Parameter now!

Optics



Scattering and absorption of waves at <u>*one*</u> port

Elektrical



DUT : DEVICE UNDER TEST

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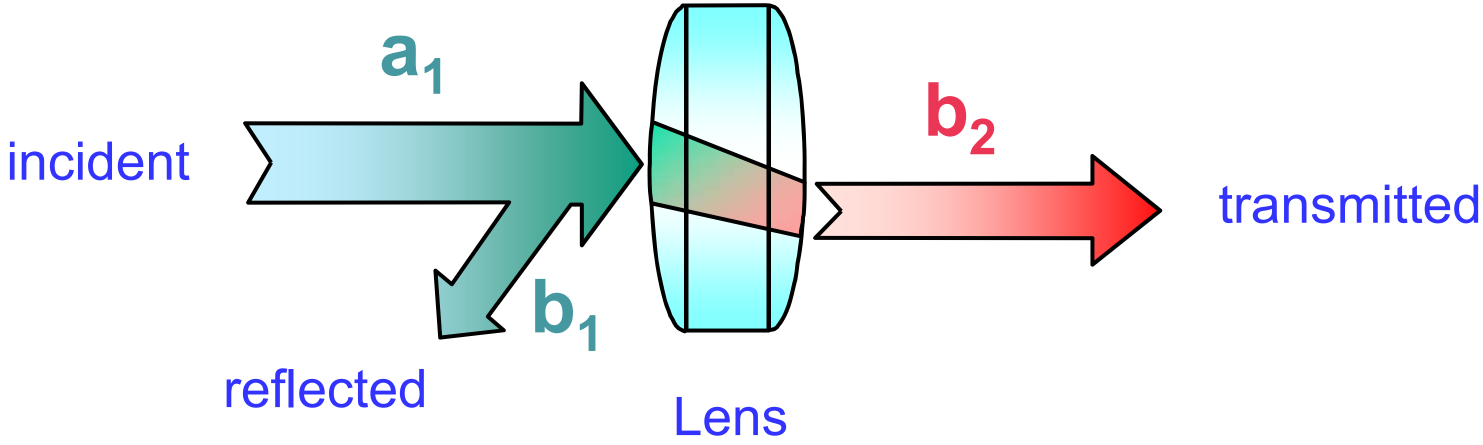
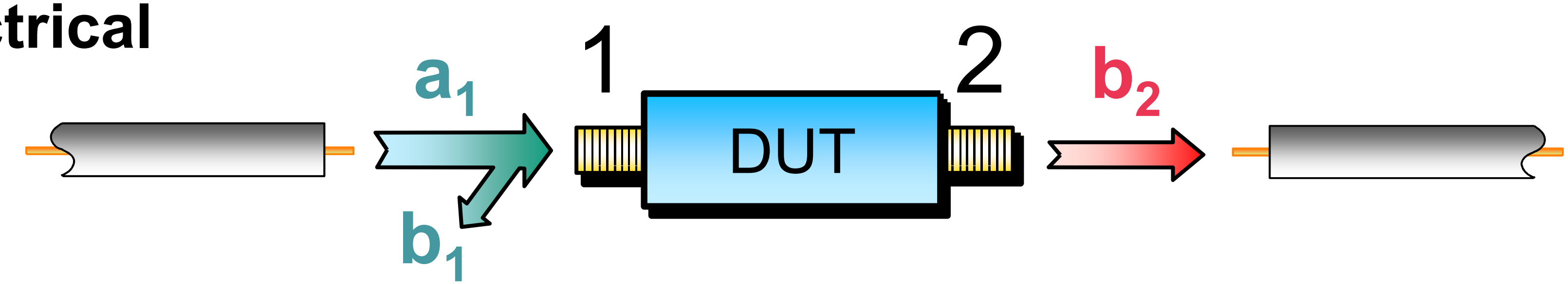
Scattering Parameters or short S-Parameters: Now two Ports!

Optics



Electrical



DUT : DEVICE UNDER TEST

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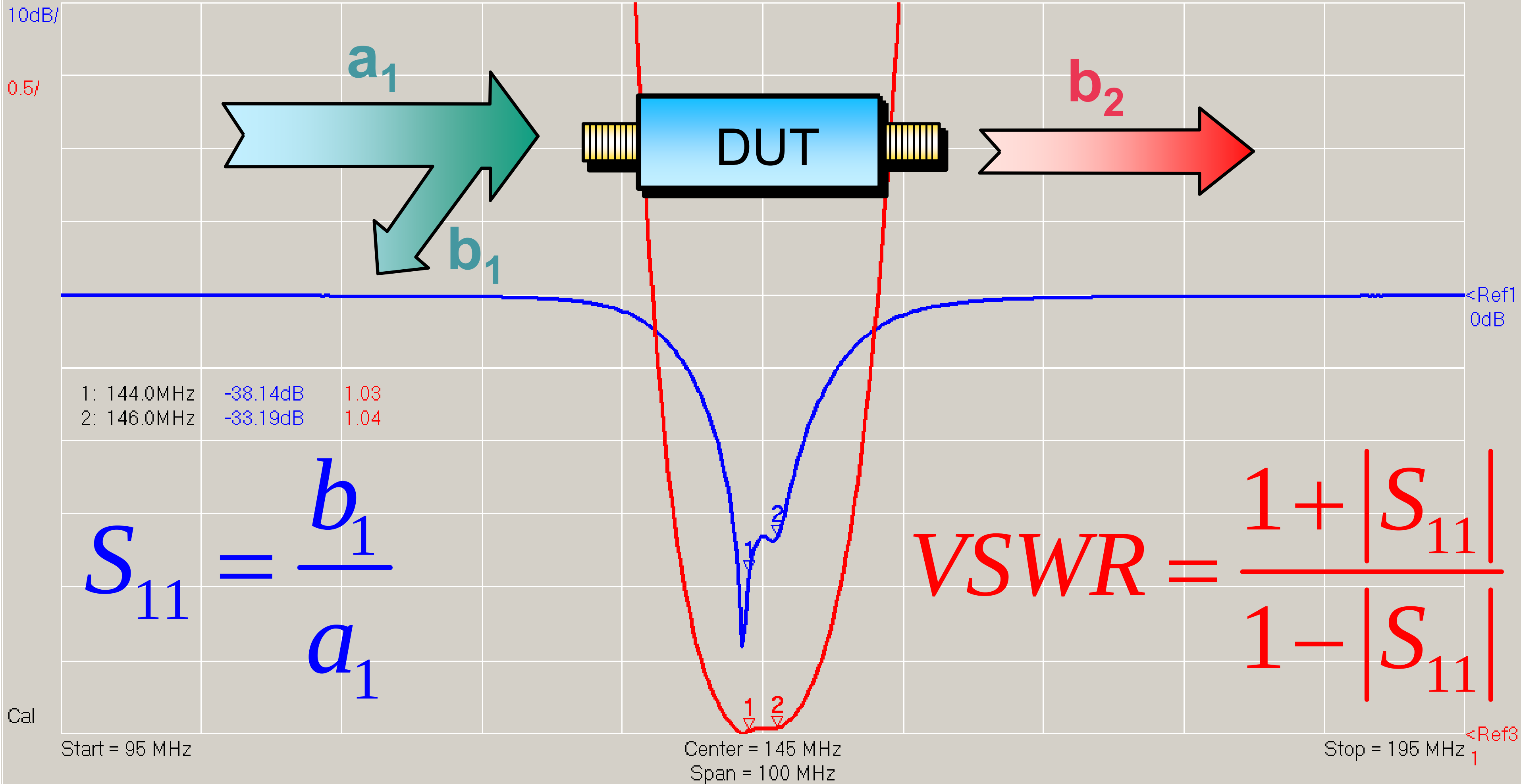
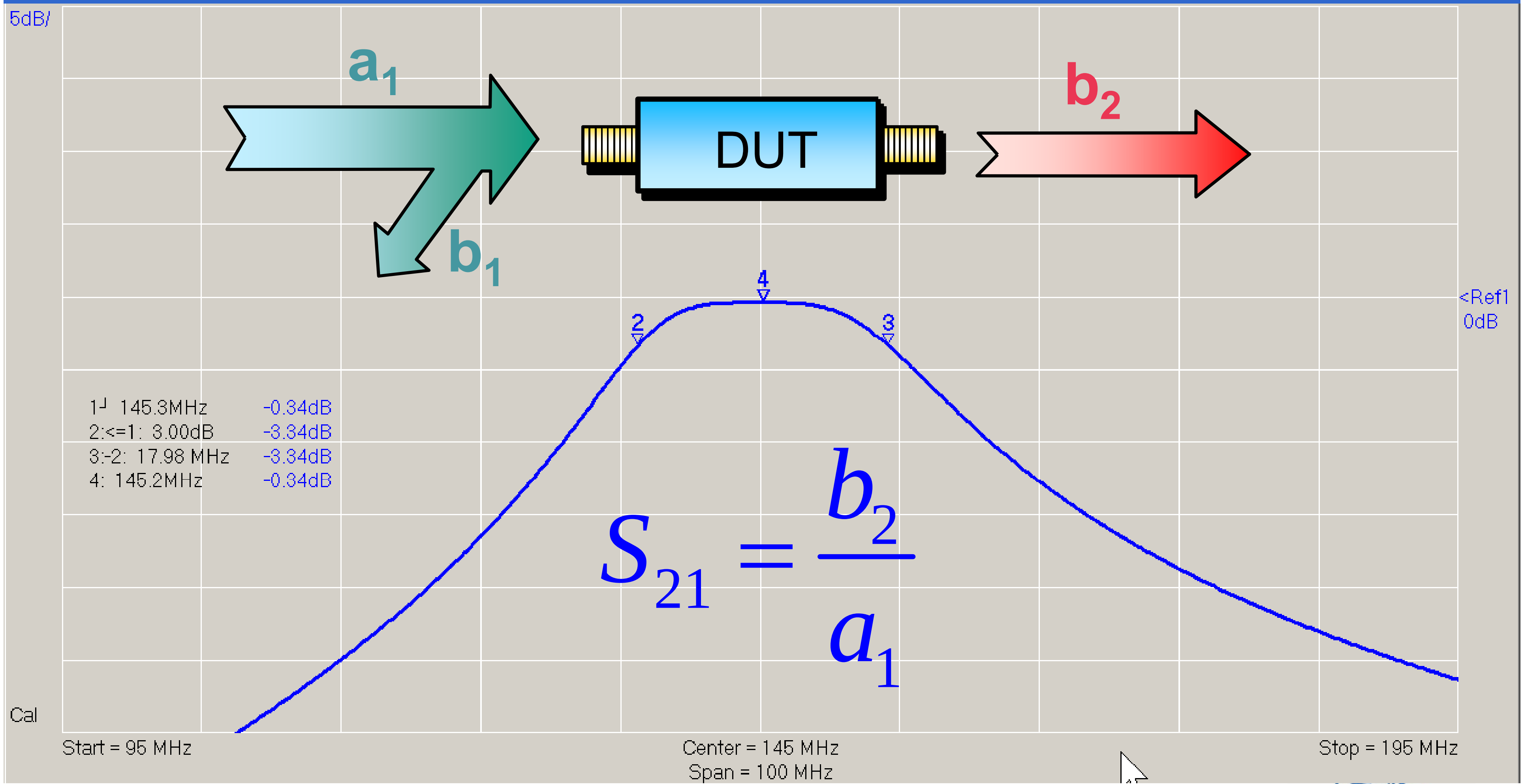
S-Parameter S_{11} (used to be S)

$|S_{11}| \rightarrow$ Return Loss

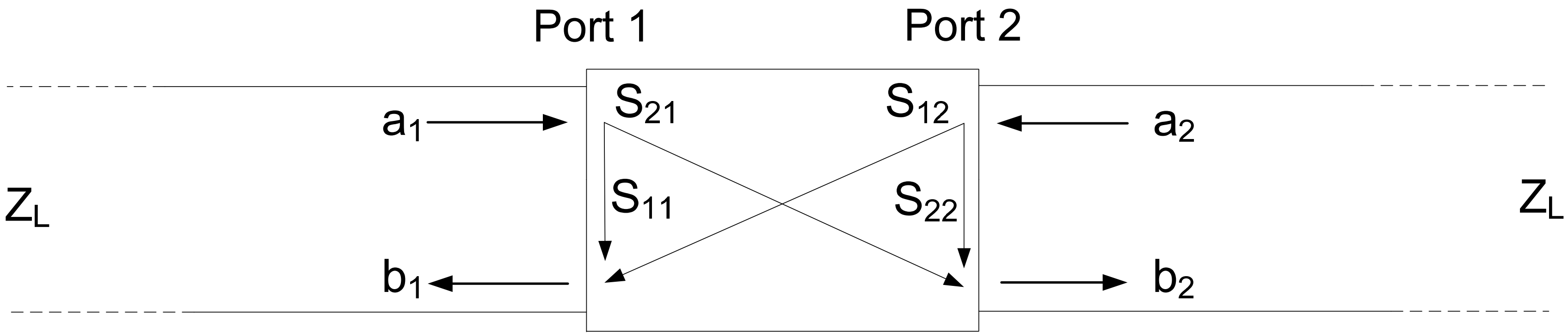


S-Parameter S_{21}

$|S_{21}|$ = Transmission Gain



General:
S-Parameters S_{ik}



$$\boxed{S_{ik} = \frac{b_i}{a_k}} \quad i,k = 1 \ldots \text{number of ports}$$

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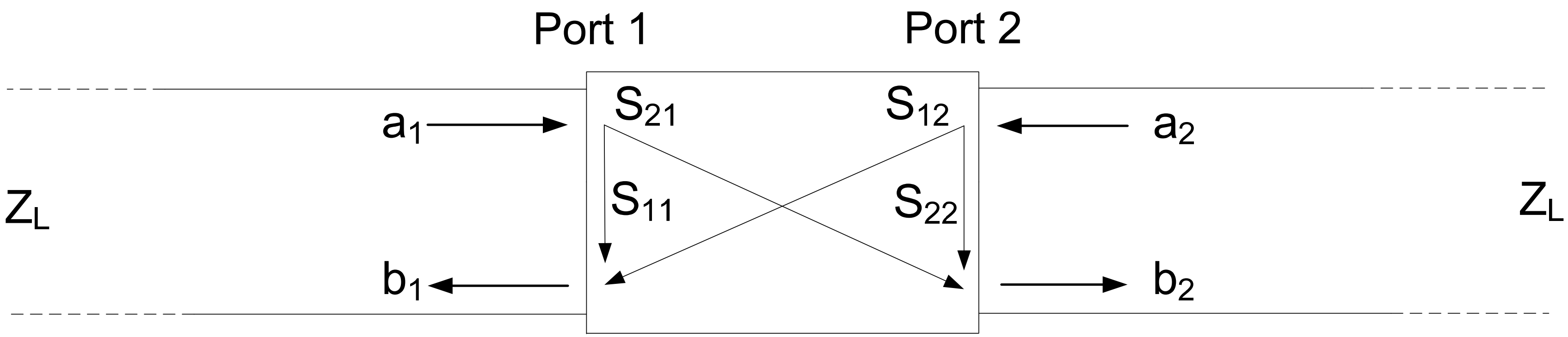
General:
S-Parameters S_{ik}



2-Port Device

Scattering parameters S_{11}, S_{21}, S_{12}, S_{22}

completely describe linear two port device!

=> useful for simulations

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BREAK ???

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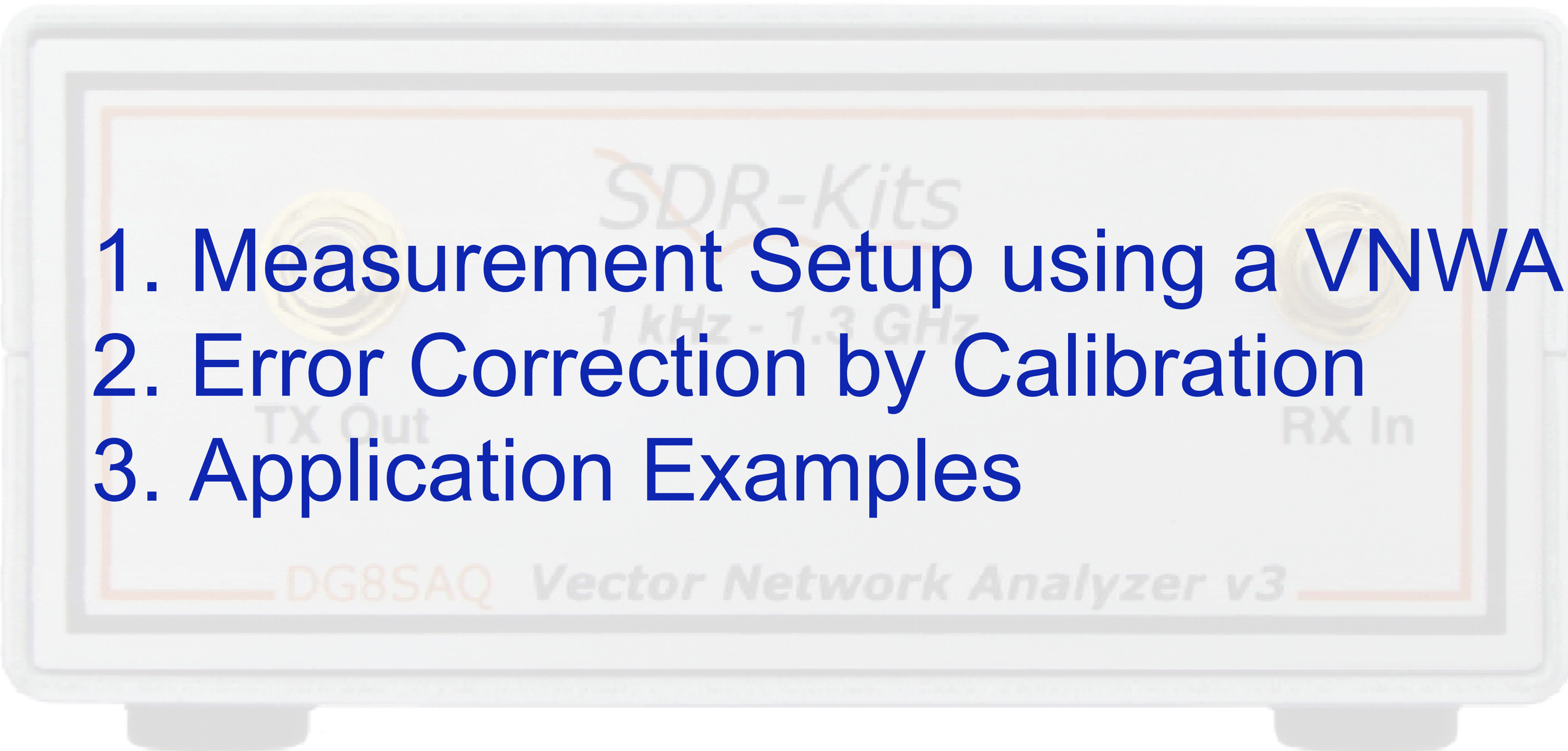
Measuring S-Parameters using a Vector-Network Analyzer



1. Measurement Setup using a VNWA
2. Error Correction by Calibration
3. Application Examples

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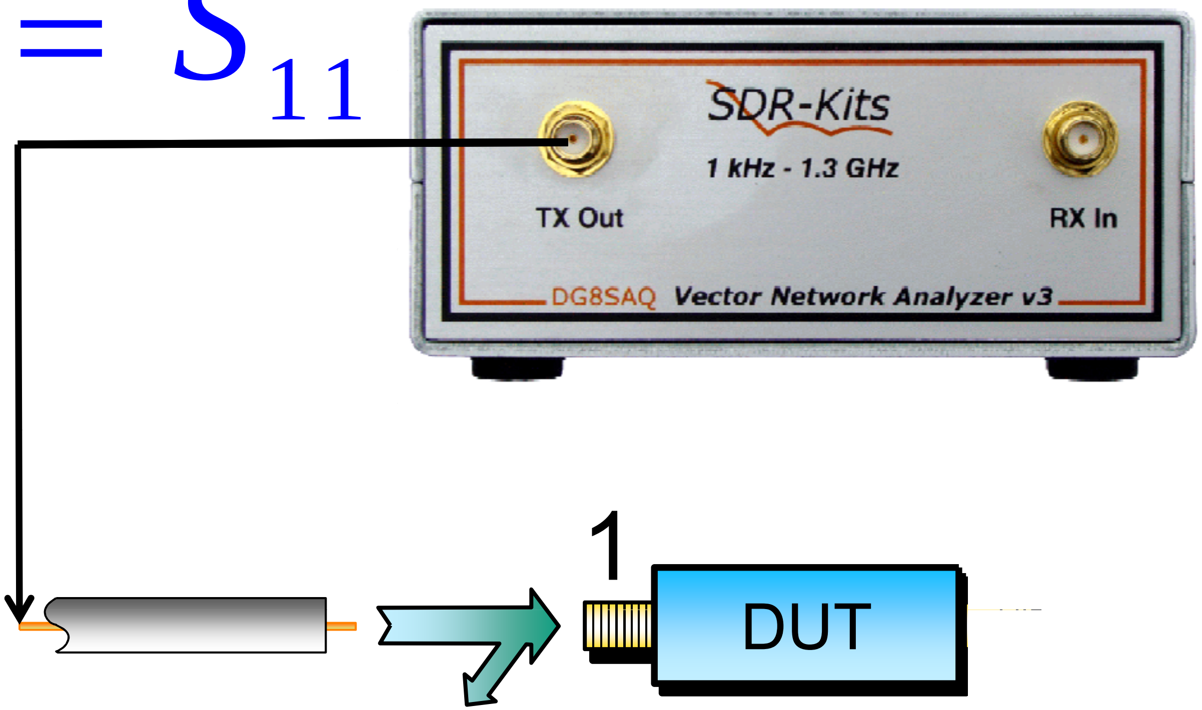
Measurement Setup using a VNWA
Example 1-Port Device:

$$S = S_{11}$$



DUT : DEVICE UNDER TEST

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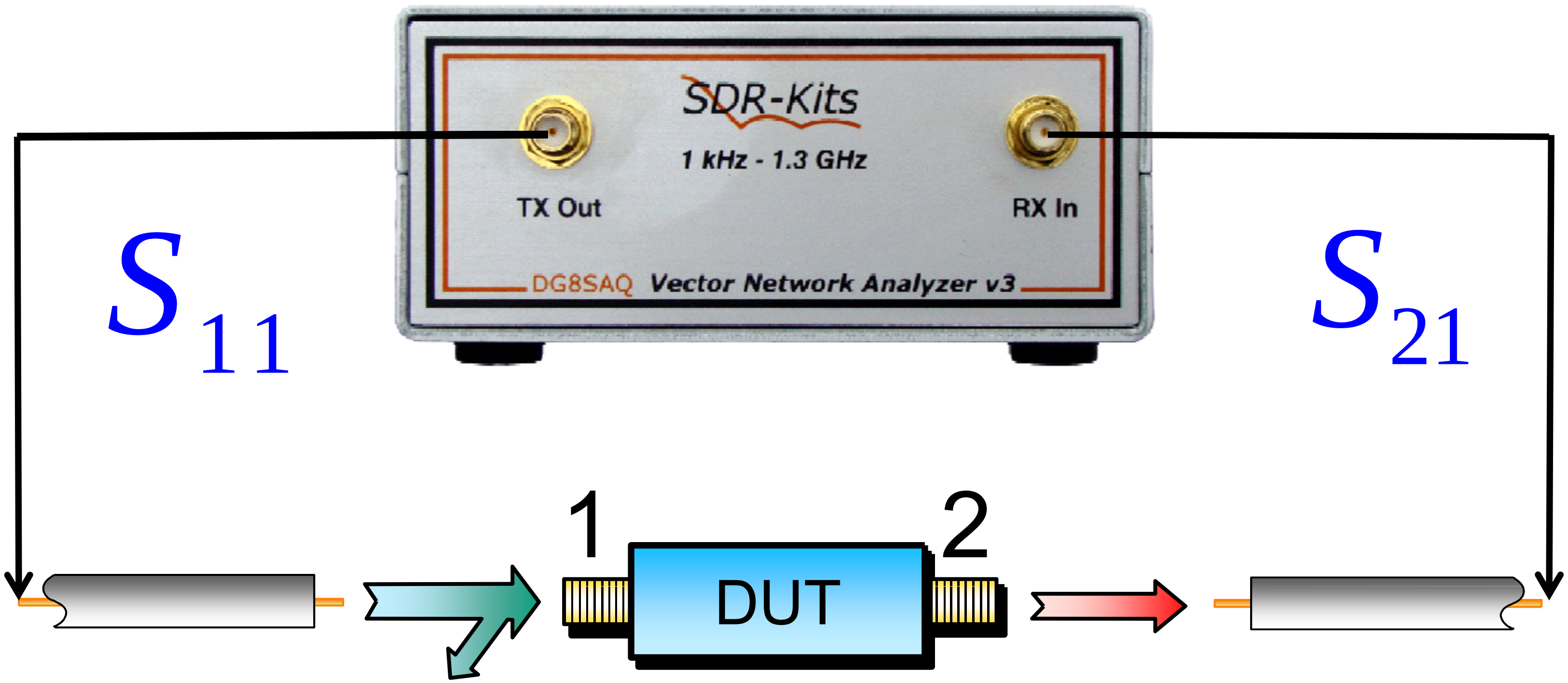
Measurement Setup using a VNWA
Example 2-Port Device forward:



DUT : DEVICE UNDER TEST

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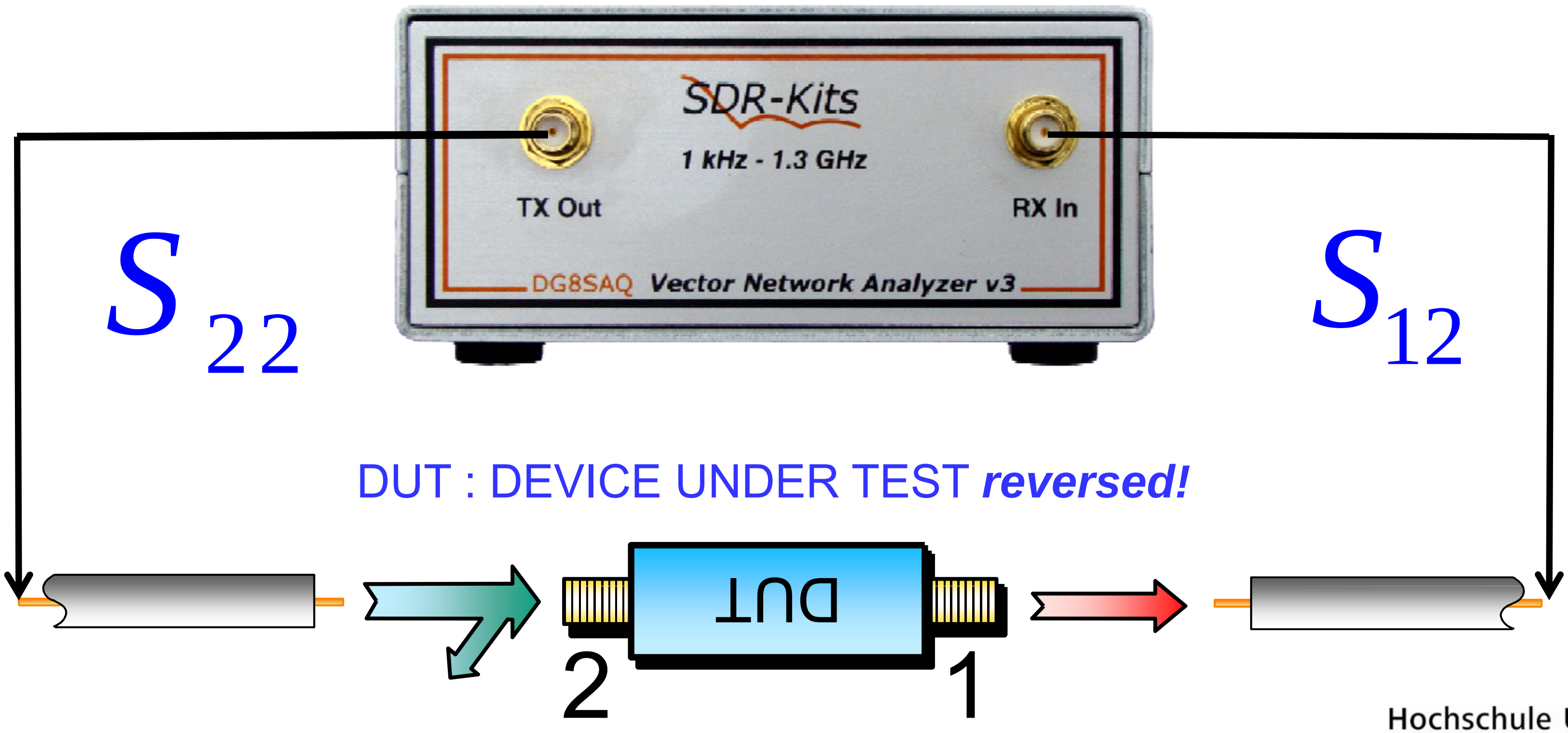
Measurement Setup using a VNWA
Example 2-Port Device reverse:



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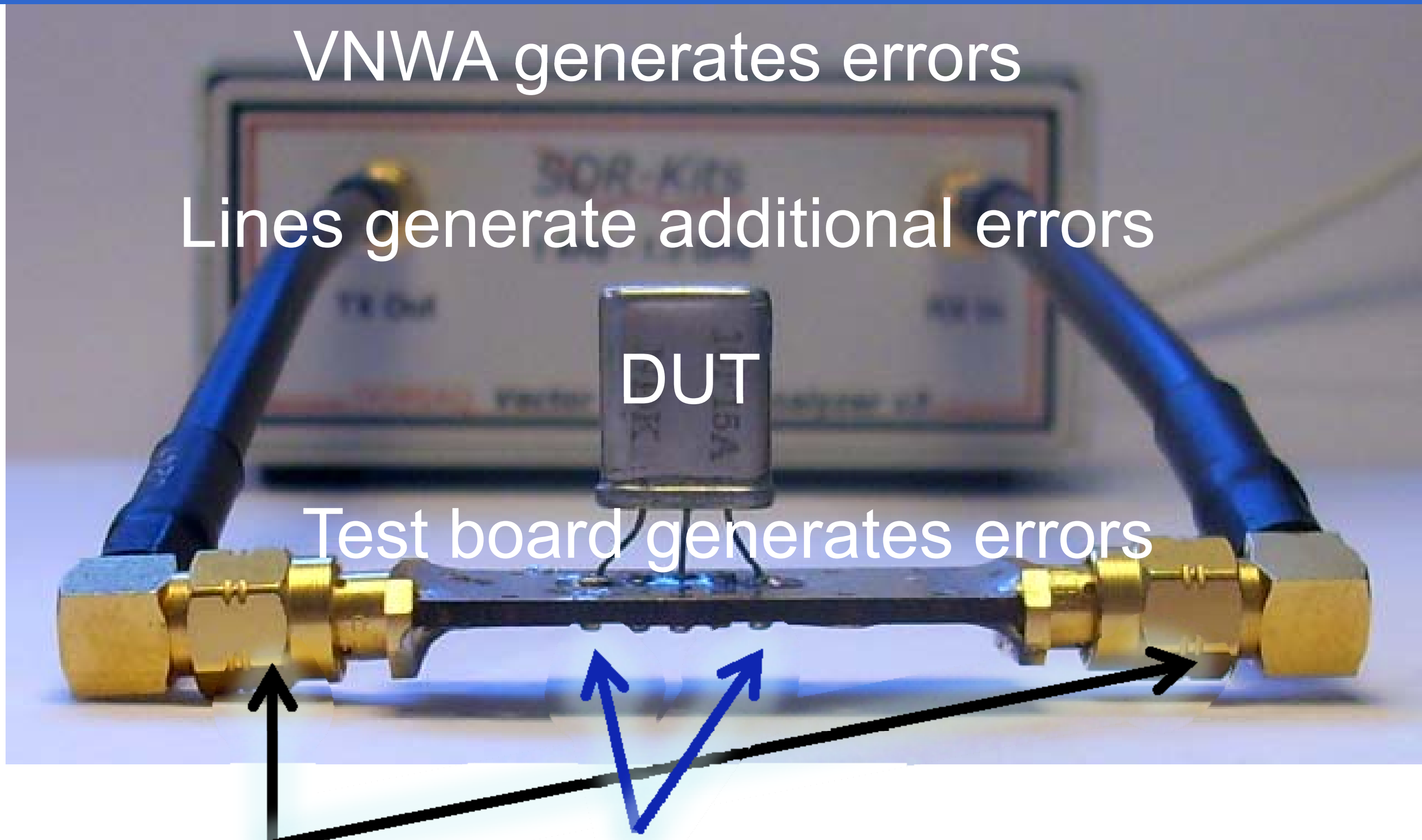
Error Correction by Calibration
Error Sources



We calibrate here! We want to measure here!

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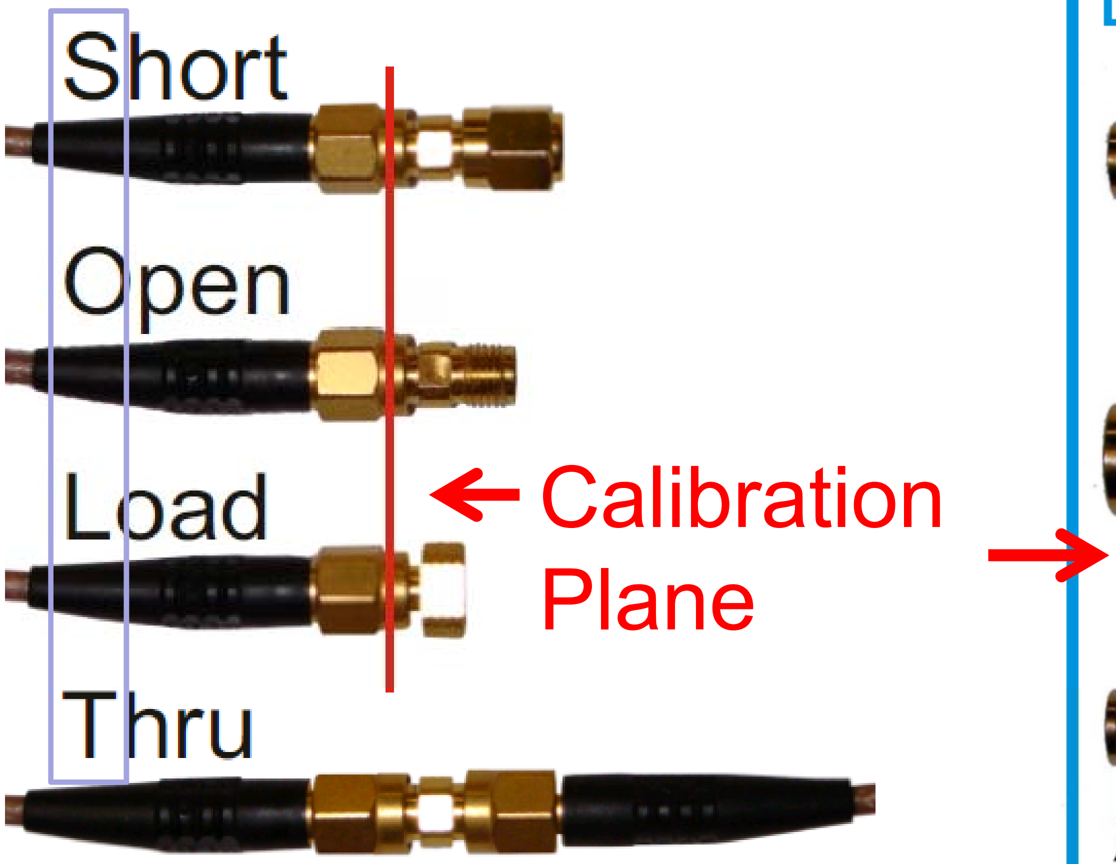
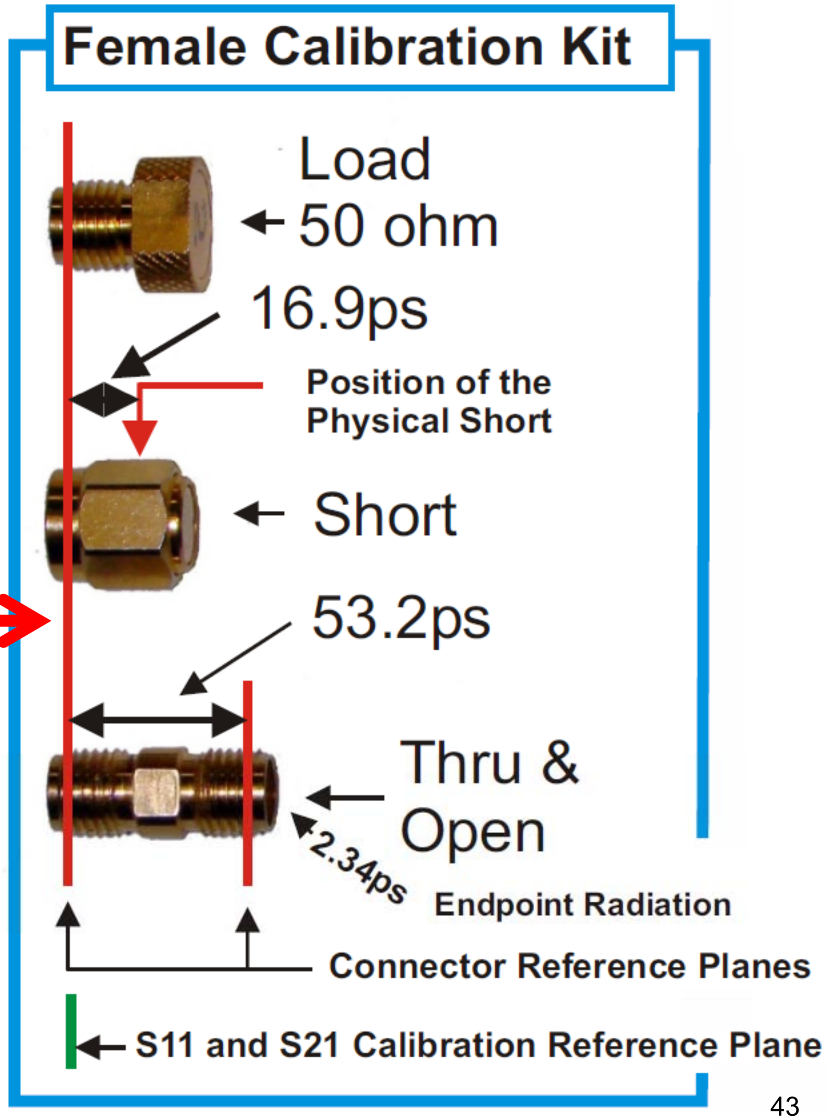
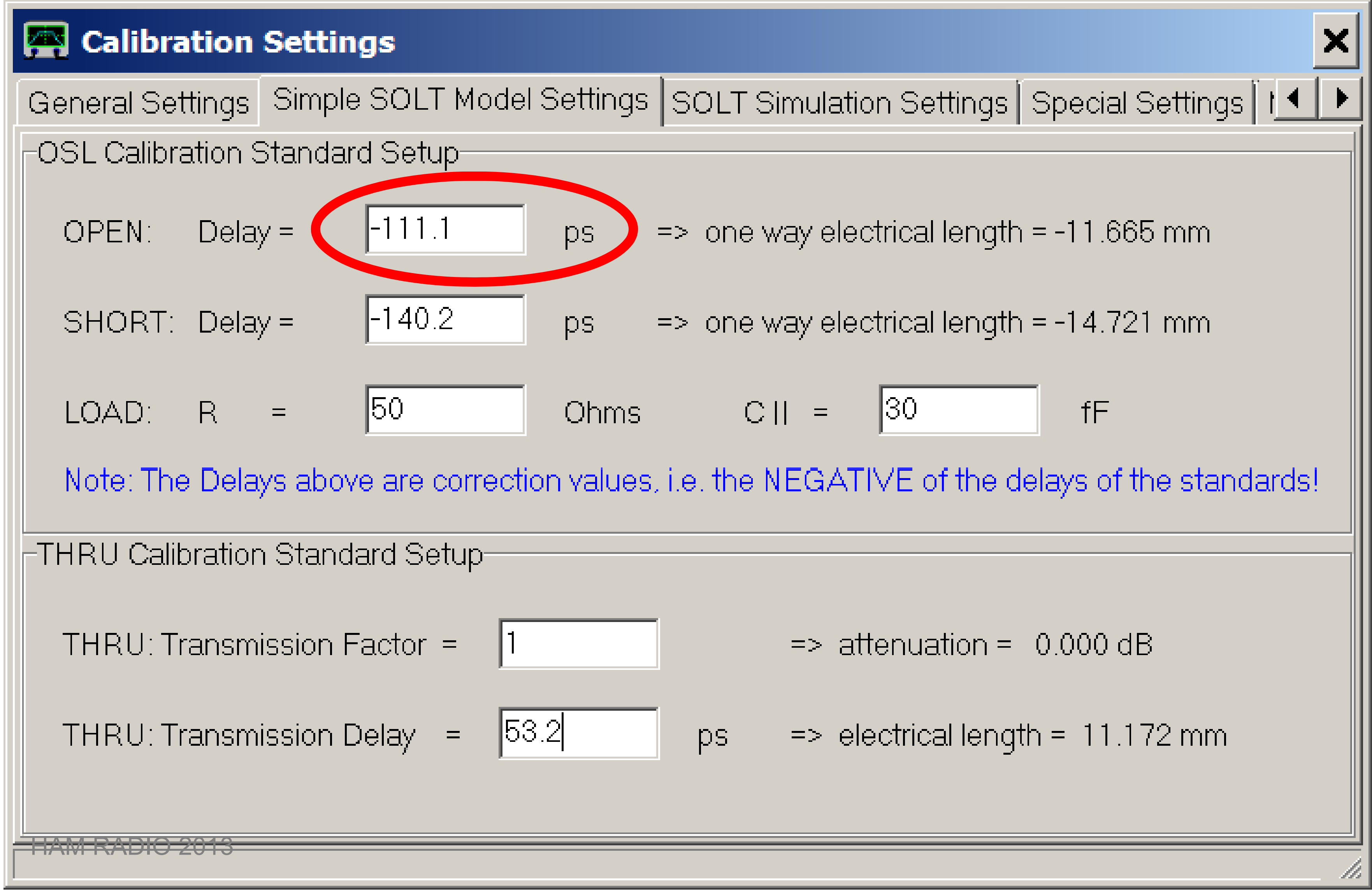
SOLT-Calibration removes Errors from VNWA and Test Cables…



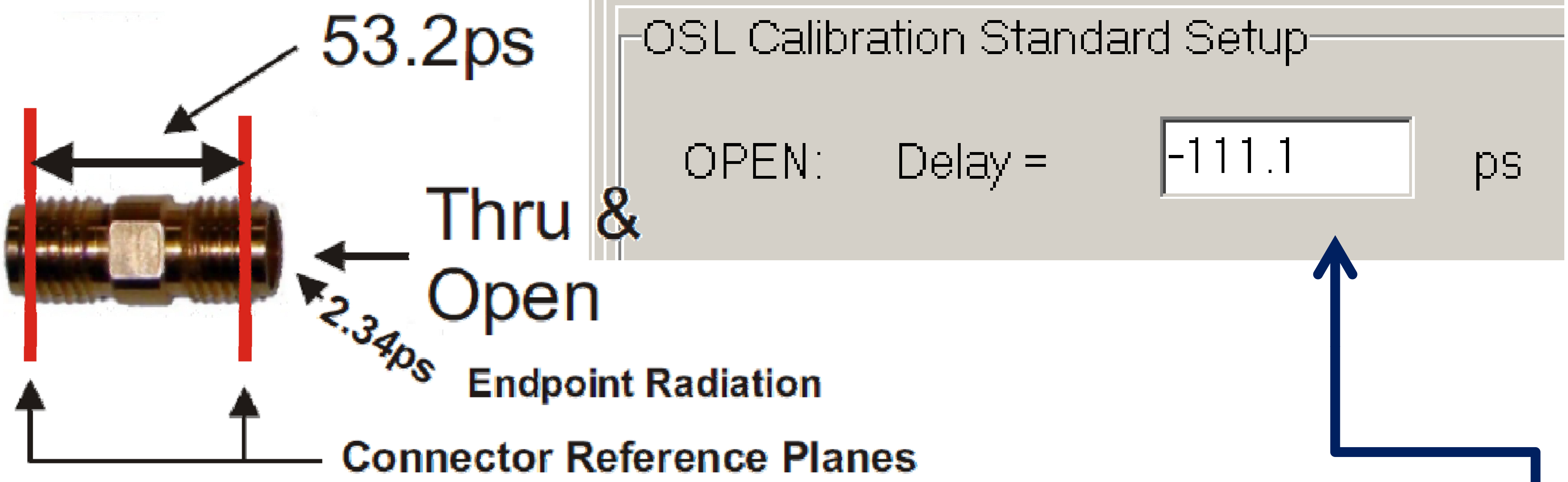


http://www.hamcom.dk/VNWA/

… as long as the Properties of the Calibration Standards are known!



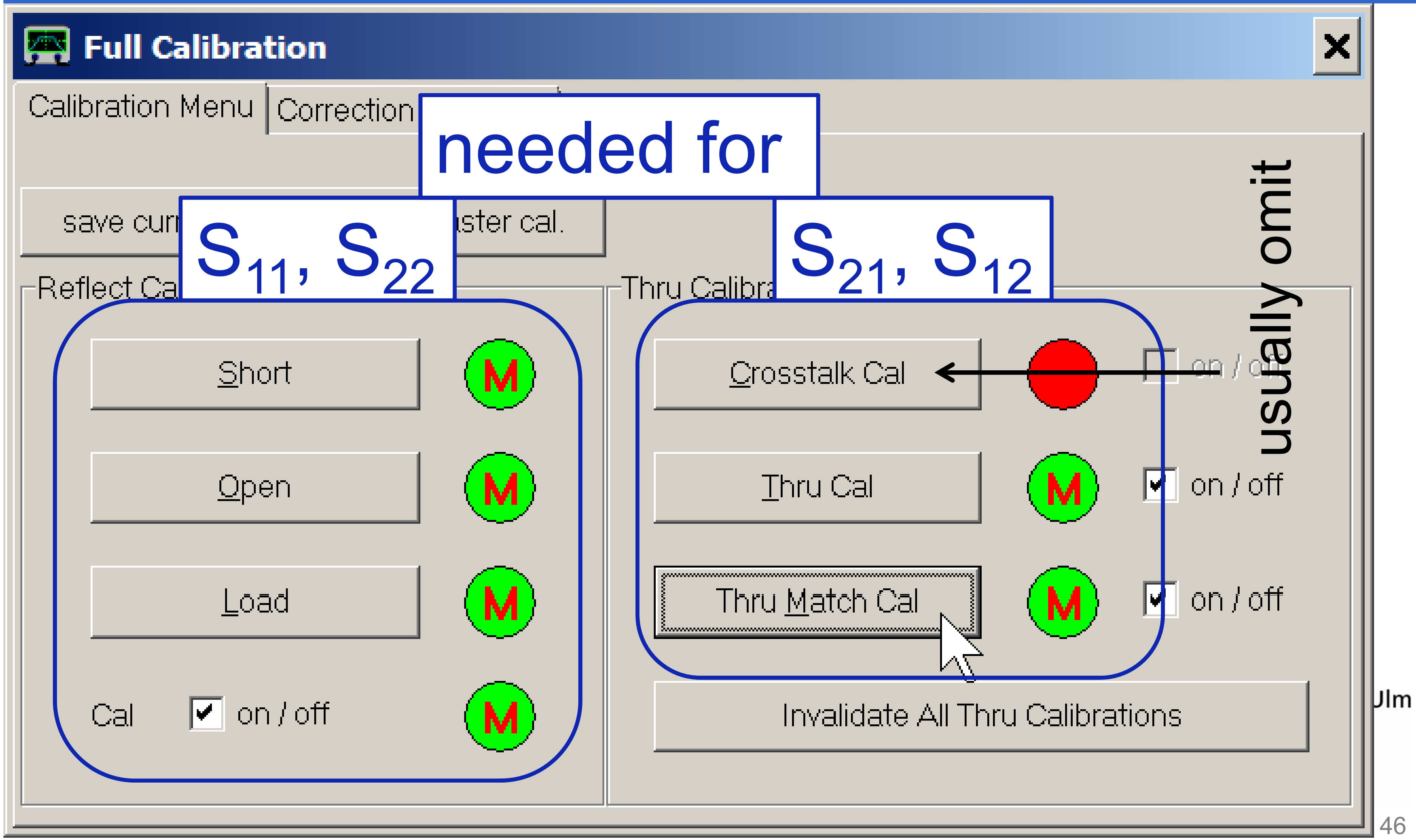
Example: Open Standard



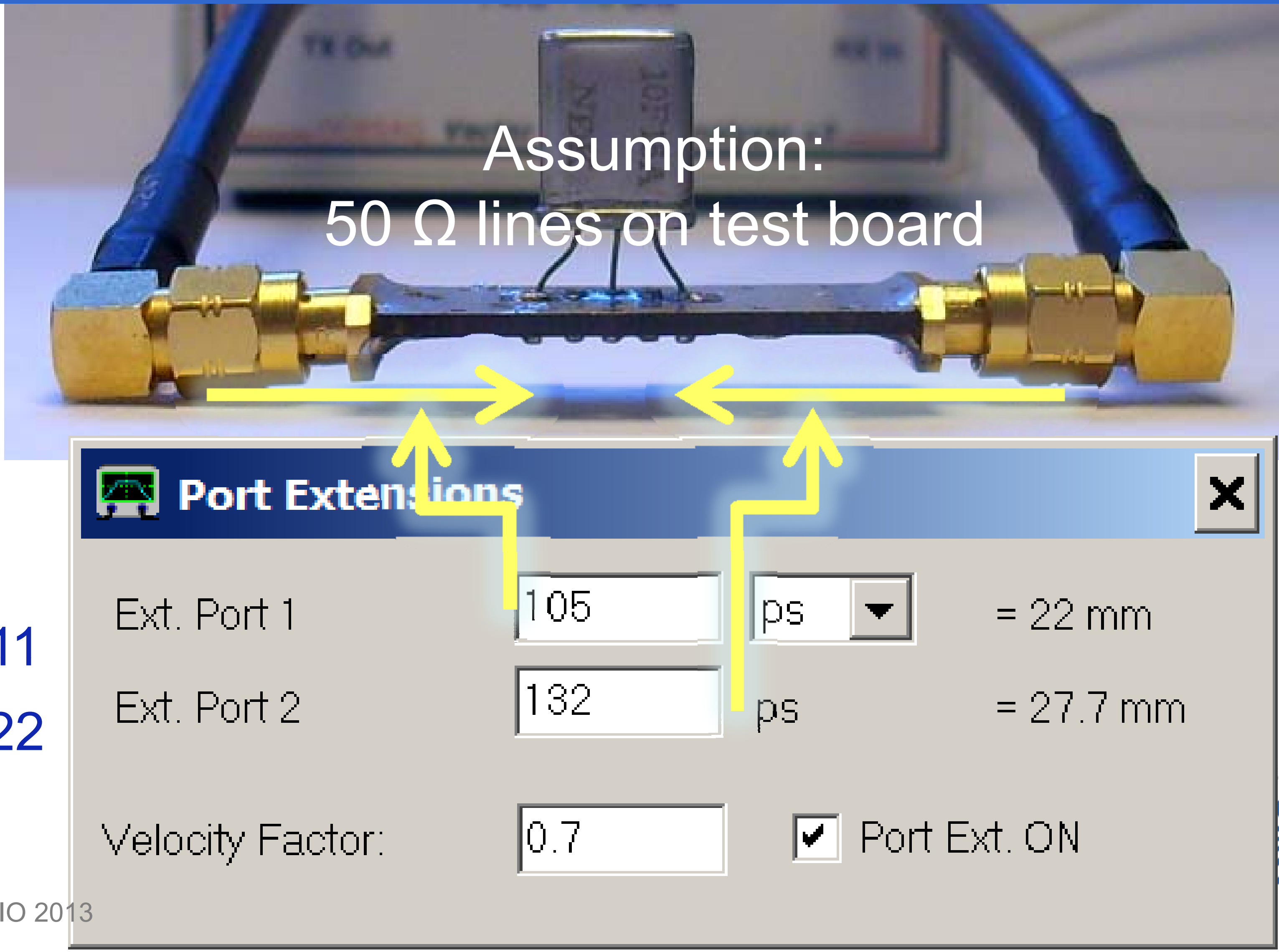
Signal travels standard twice, namely forth and back:

$$\tau = -2 \times (53{,}2\ \text{ps} + 2{,}34\ \text{ps}) = -111.08\ \text{ps}$$

Now, connect standards to VNWA and calibrate



Delay Correction with Port Extensions



S_{11}
S_{22}

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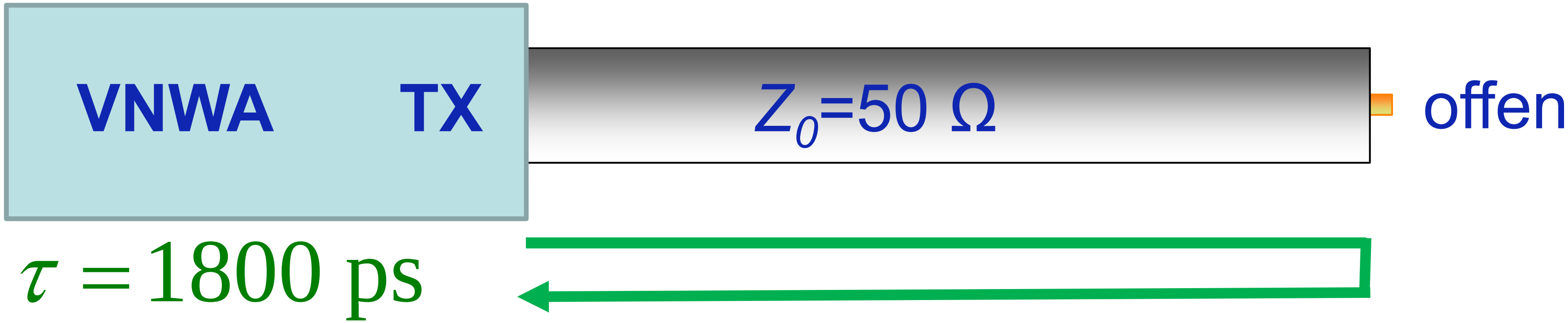
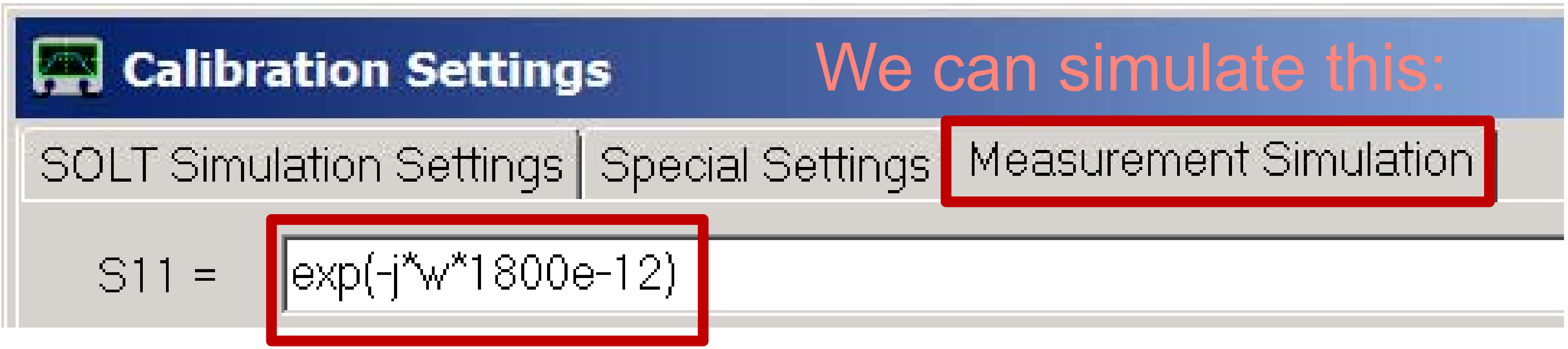
Wrong Cal Parameters cause Port Mismatch
Example: open 50 Ohms – Line (1)



$\tau = 1800$ ps



i.e. $|S_{11}| = 1$ total power reflected

Phase(S_{11})=-ω·1800 ps

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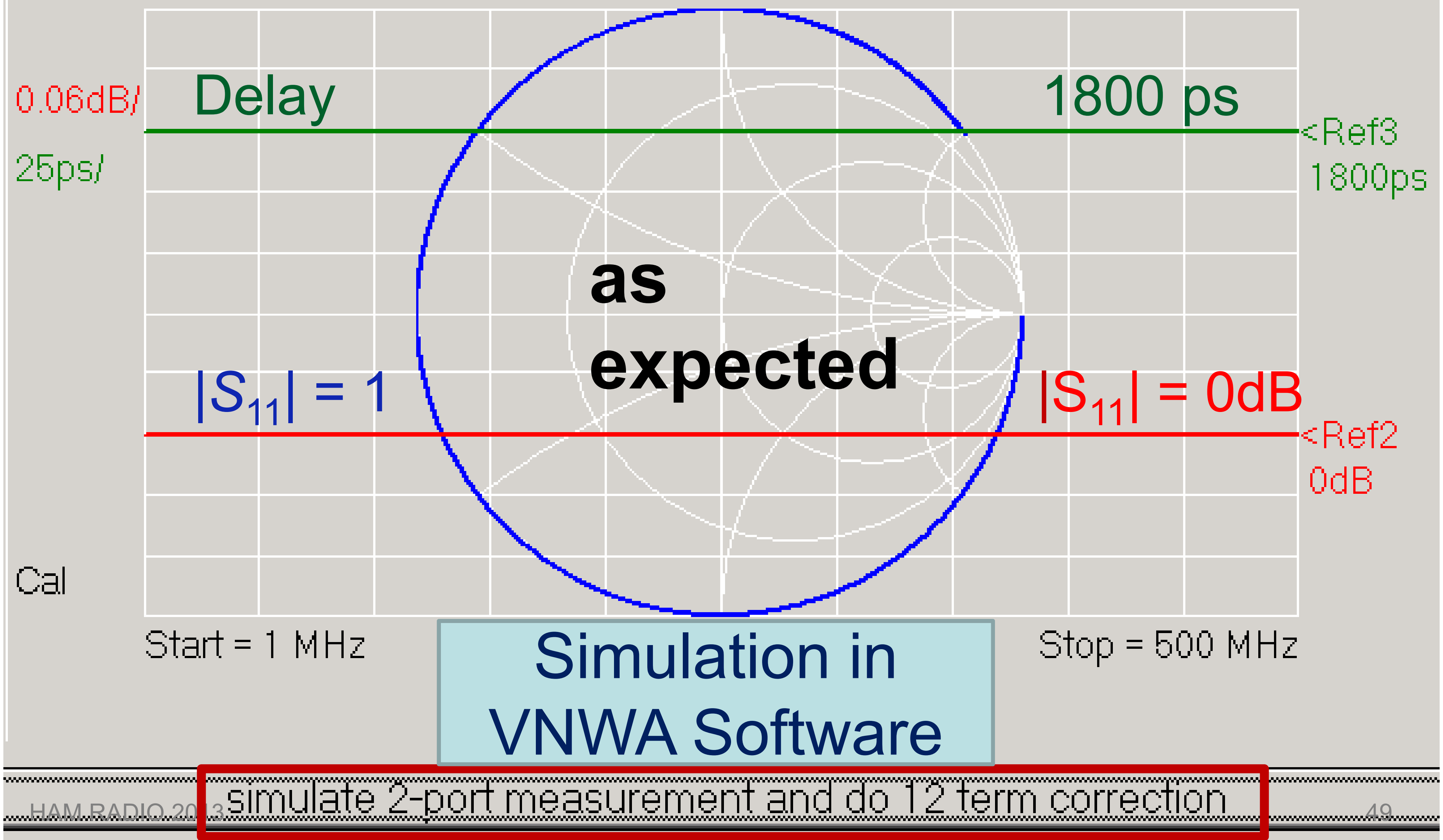
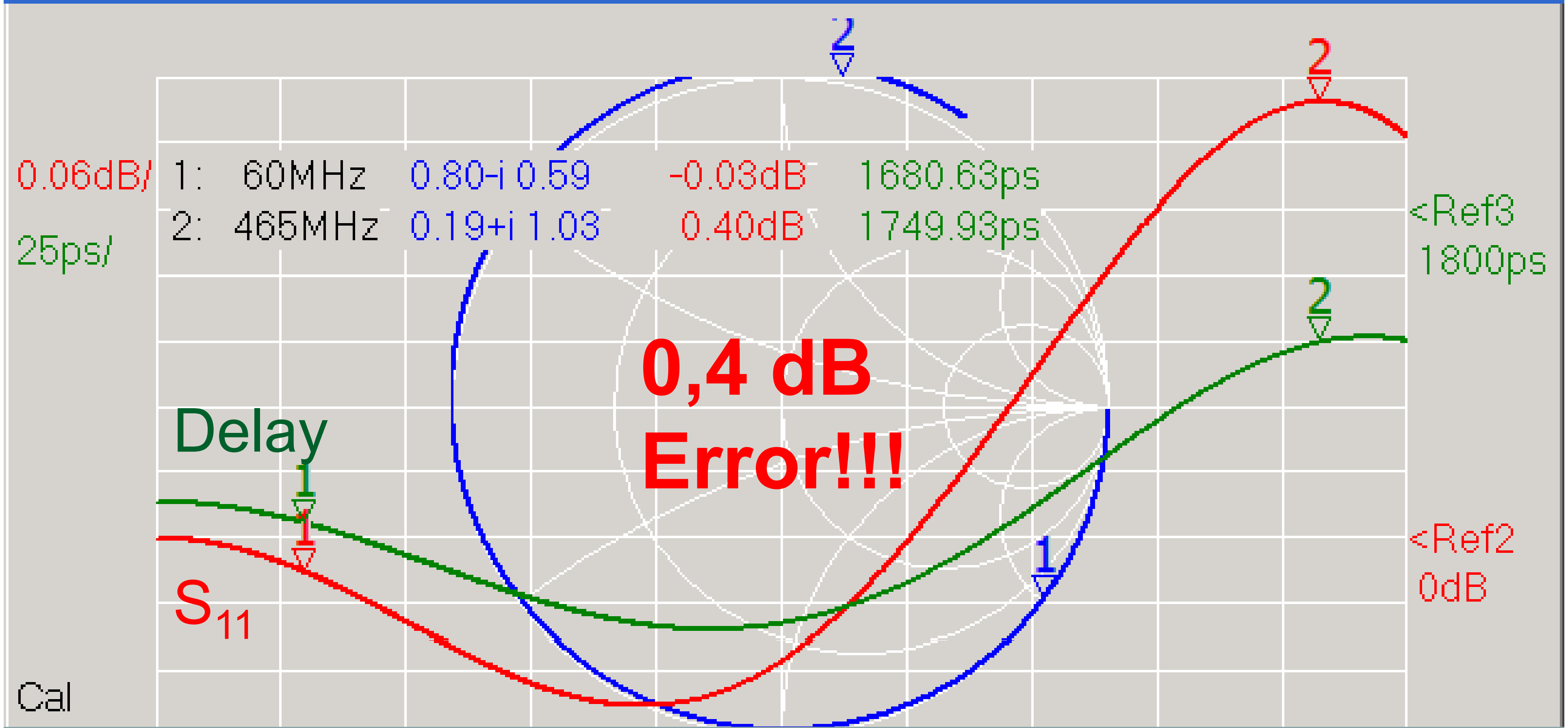
Example: open 50 Ohms – Line (2) Simulated with Amphenol Female Parameters



Example: open 50 Ohms – Line (3)
Let software think standards are ideal:



Previously simulated measurement data corrected again using ideal cal parameters

Applications …

Hochschule Ulm

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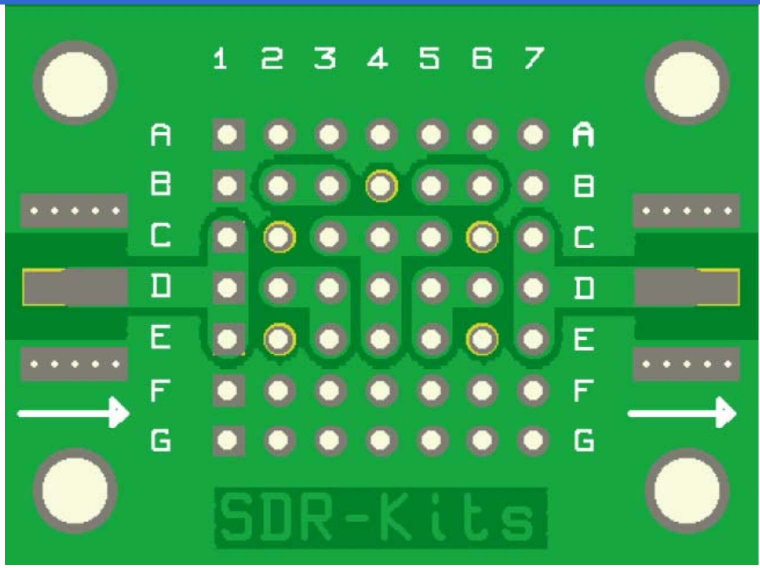
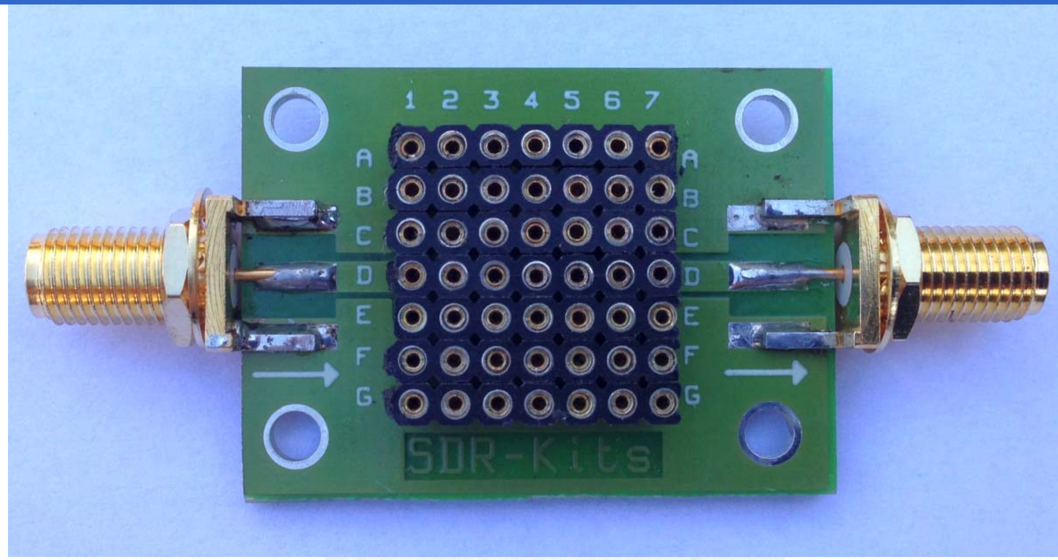
Test Board for HF Experiments





Calibration Standards:

Short:

Load = 47Ω:

Open = n.c.

Thru:

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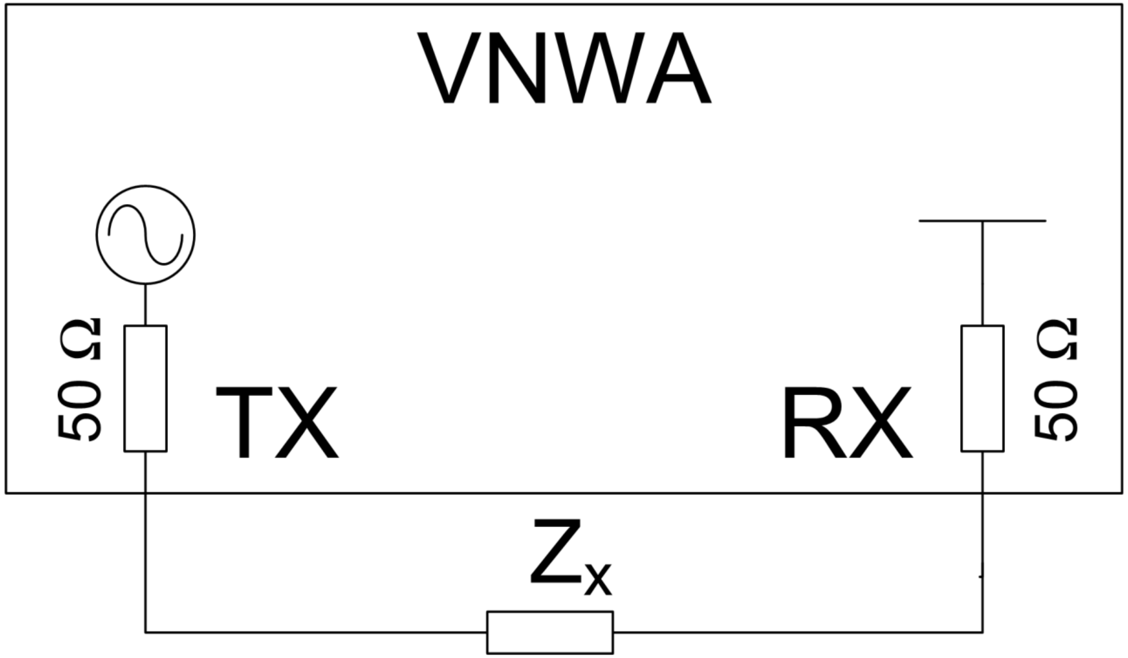
Measuring „Load"-Resistor without SOL-Calibration?



Z_x = 47 Ω yield ≈3,4 dB insertion loss.

Works, because VNWA TX and RX port impedances are exactly 50 Ω.

- only Thru calibration required!

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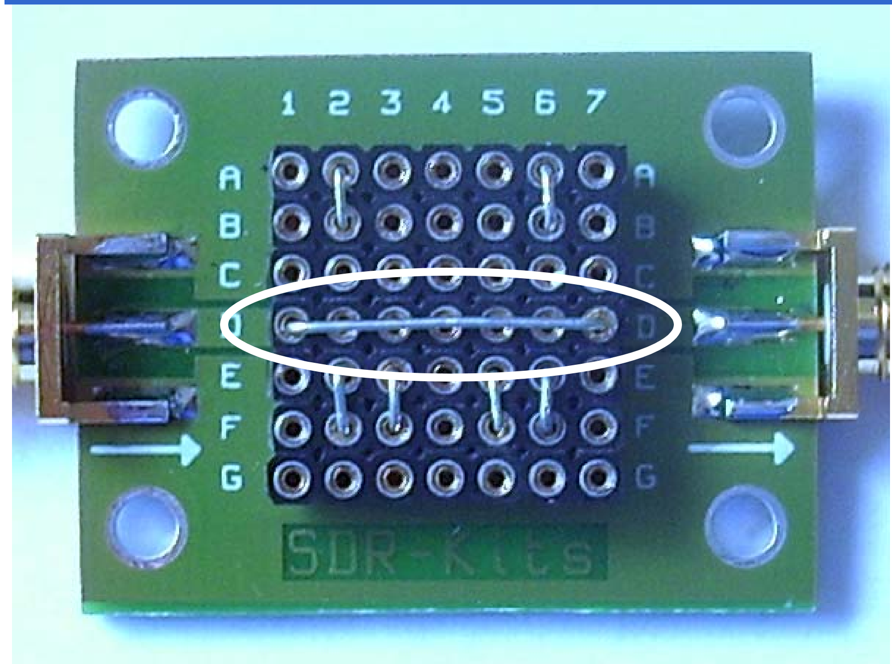
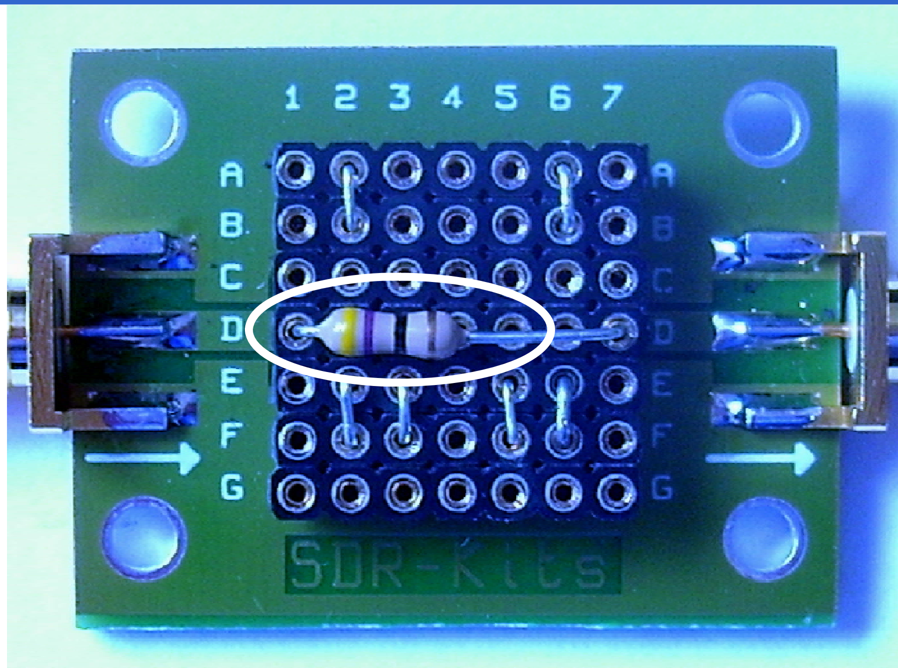
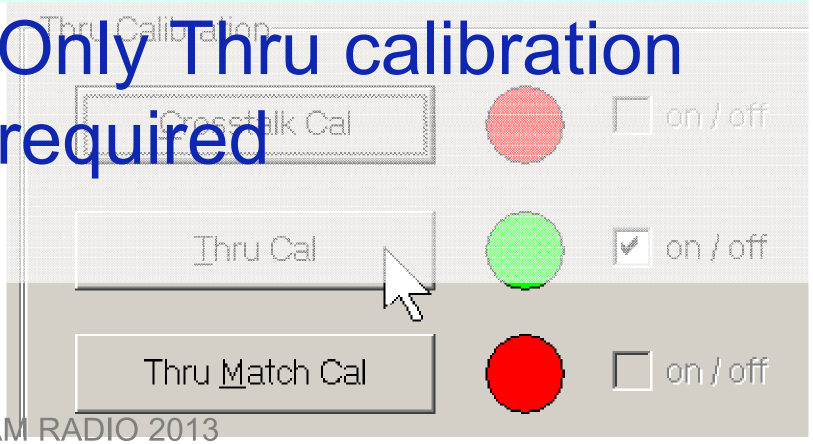
Measuring „Load“-Resistor in Transmission (= S_{21}-Measurement)





Only Thru calibration required



Measurement:
Resistor between TX and RX

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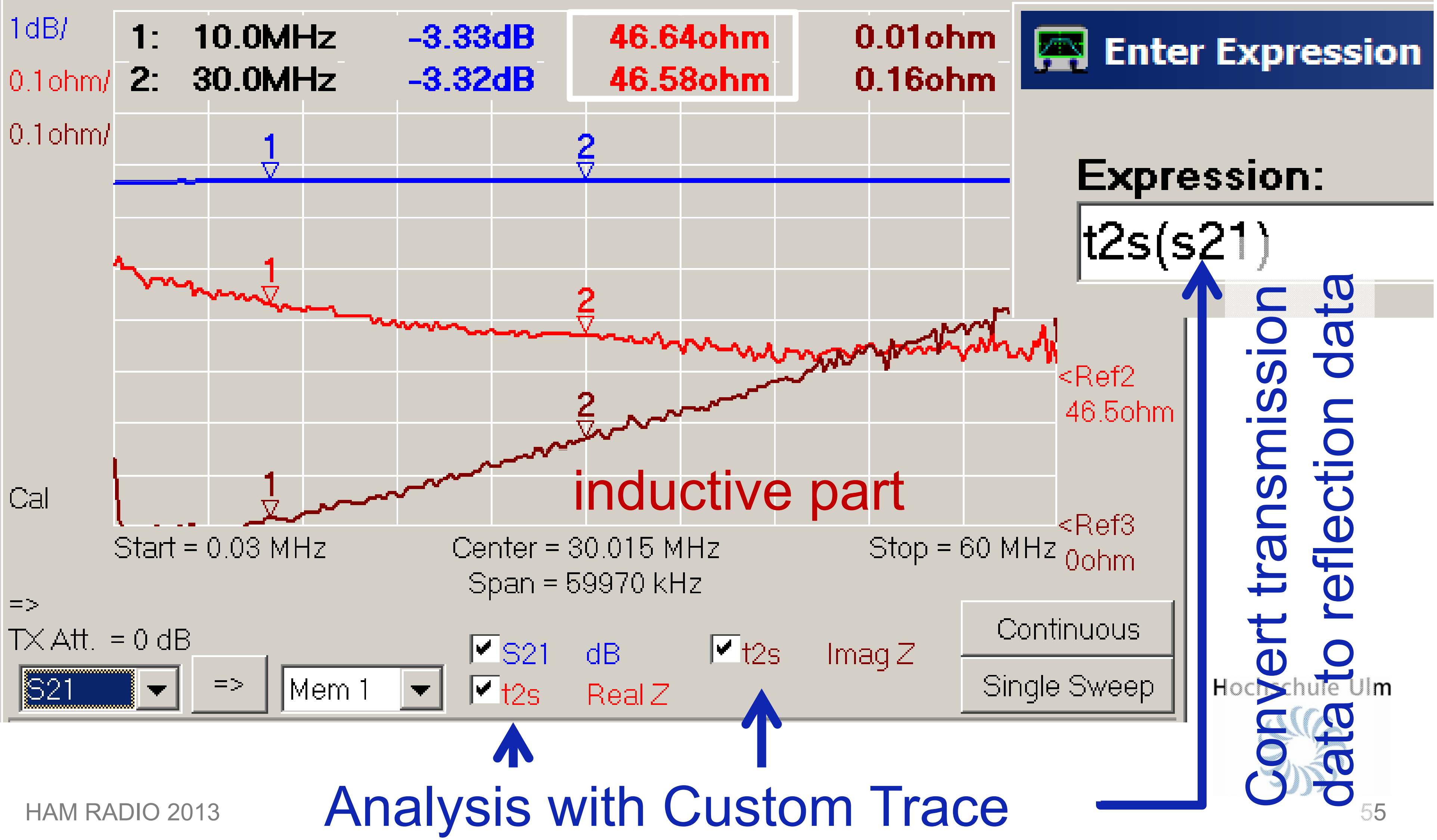
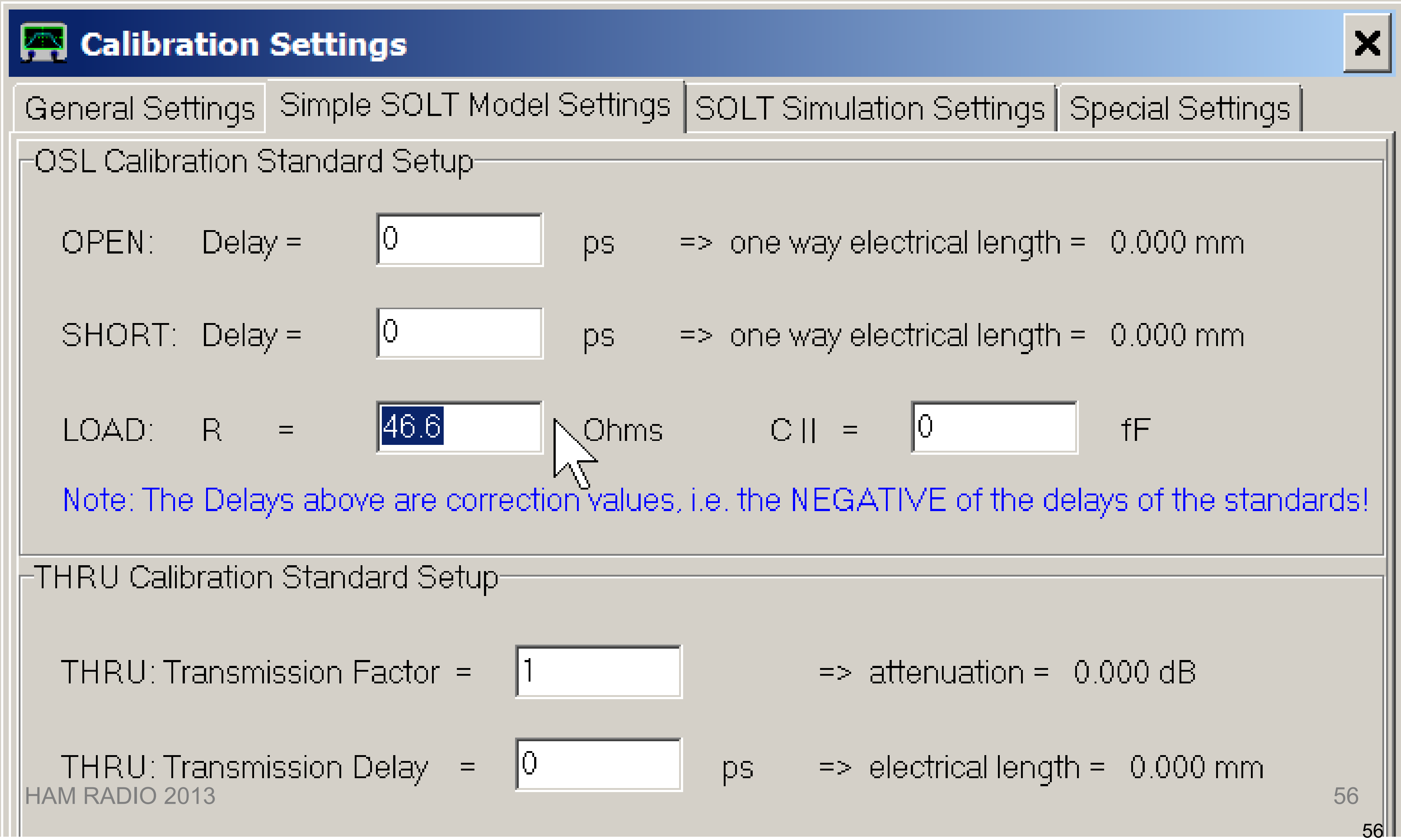
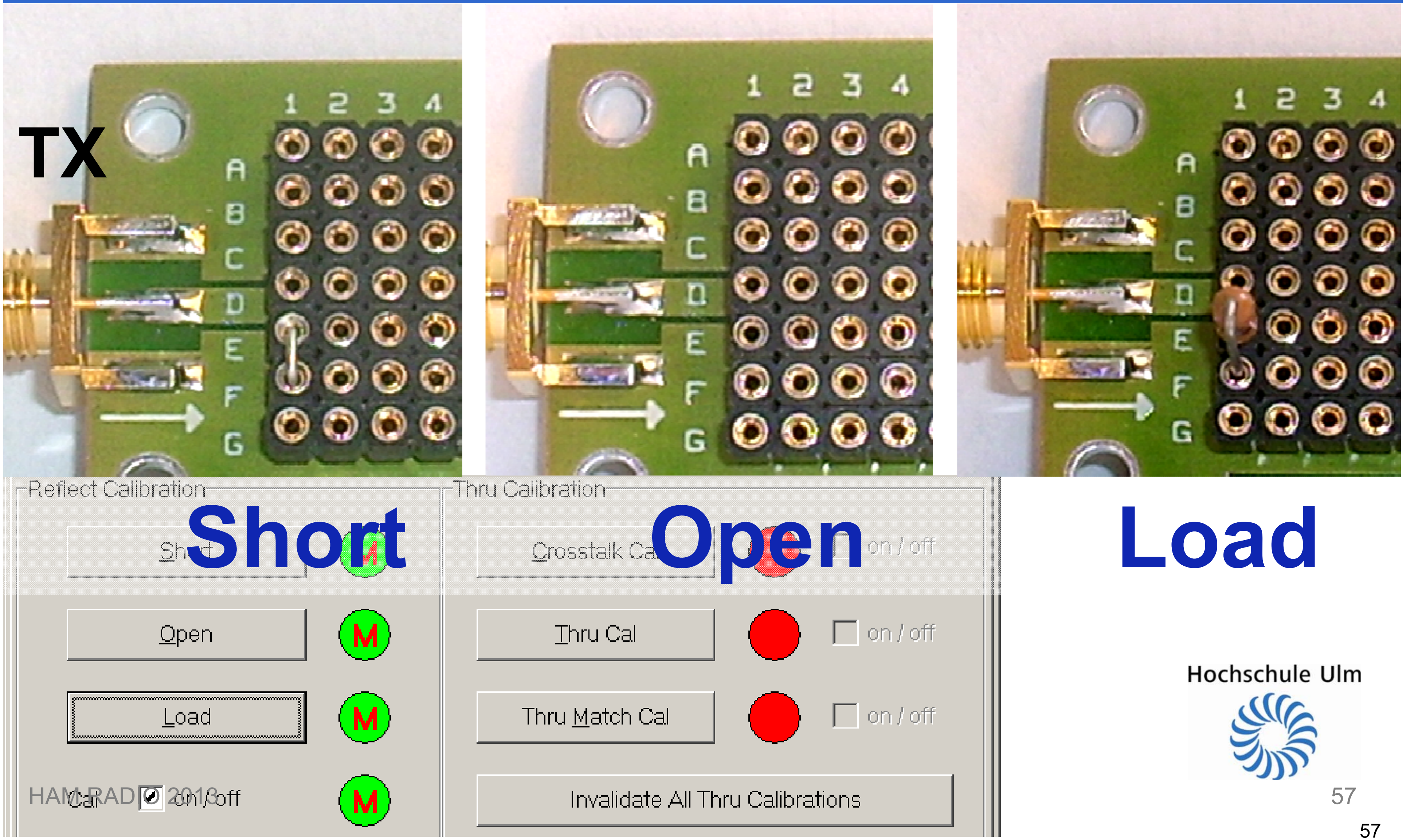
Measuring „Load"-Resistor
Result = 46,6 Ω



Simple Calibration Standard Model: Only measured Load-Resistance



SOL-Calibration for S_{11}-Measurement



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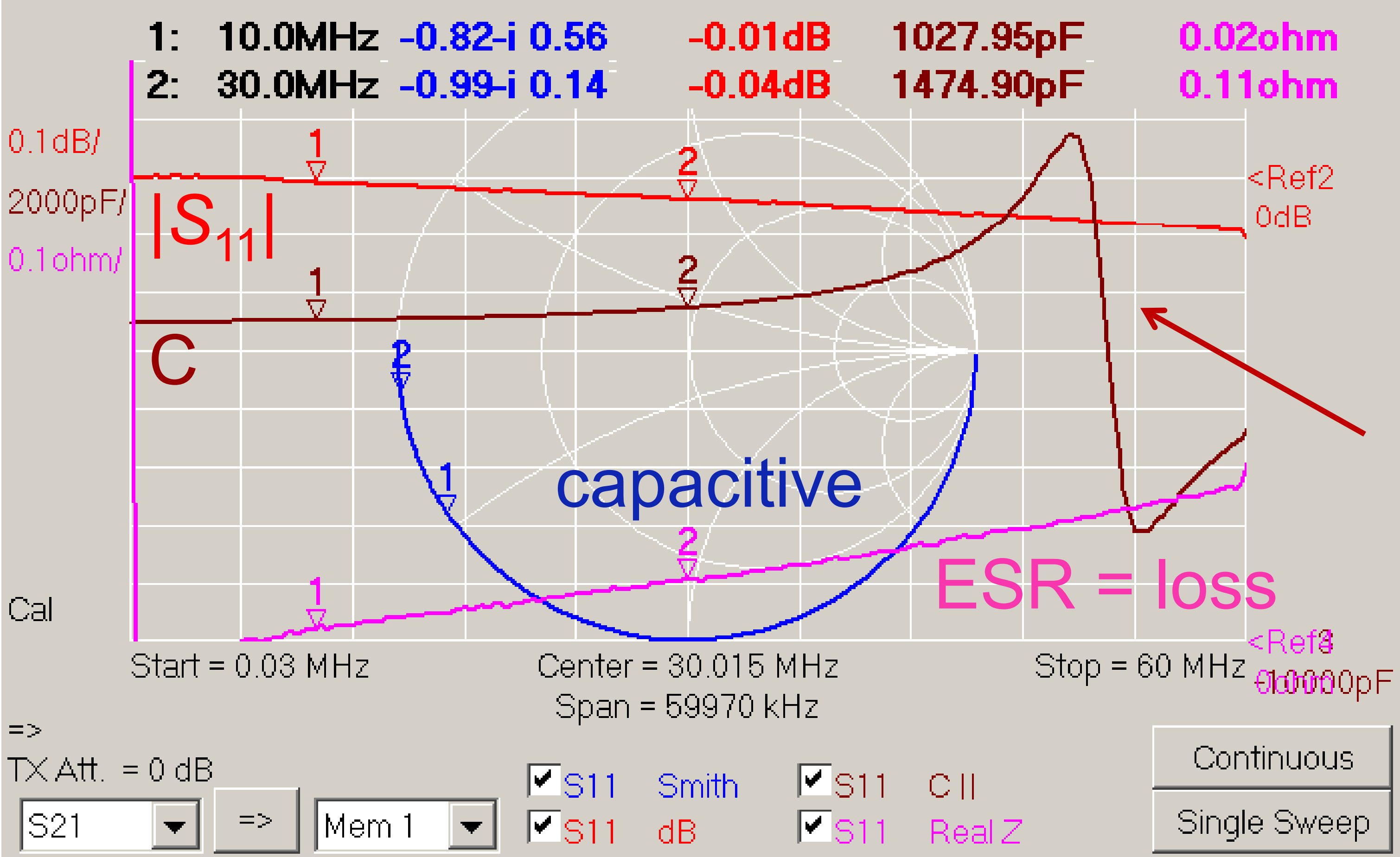
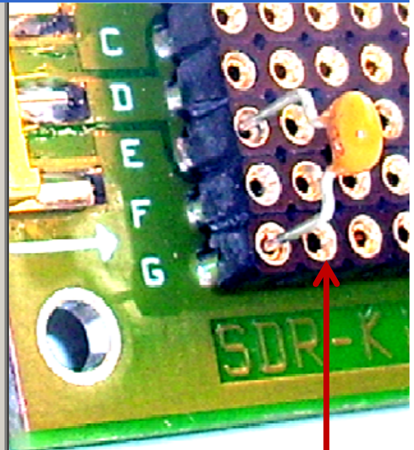
Reflexion Measurement (S_{11}) of a 1 nF Capacitor





Resonance due to component wires

Capacitor reflects almost total power, $|S_{11}| \approx 0$ dB

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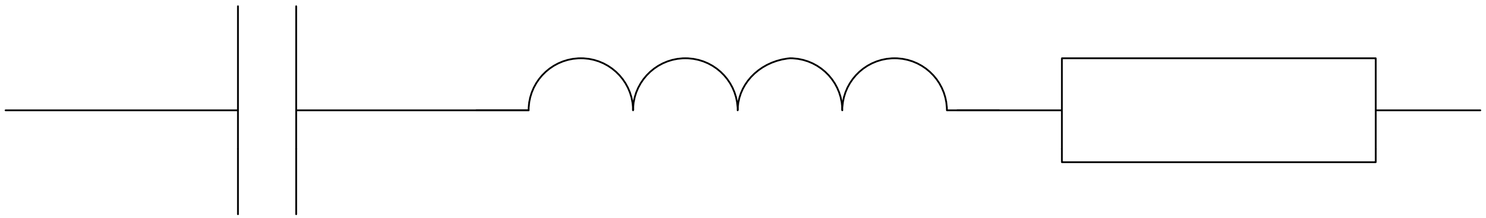
Modelling of Measurement Result in VNWA using Custom-Trace

Enter Expression 2 for trace 2:

Impedance to Reflecion coefficient

Expression:

$\boxed{z2s}$(1/(j*w*0.984e-9)+j*w*9.3e-9+0.22)

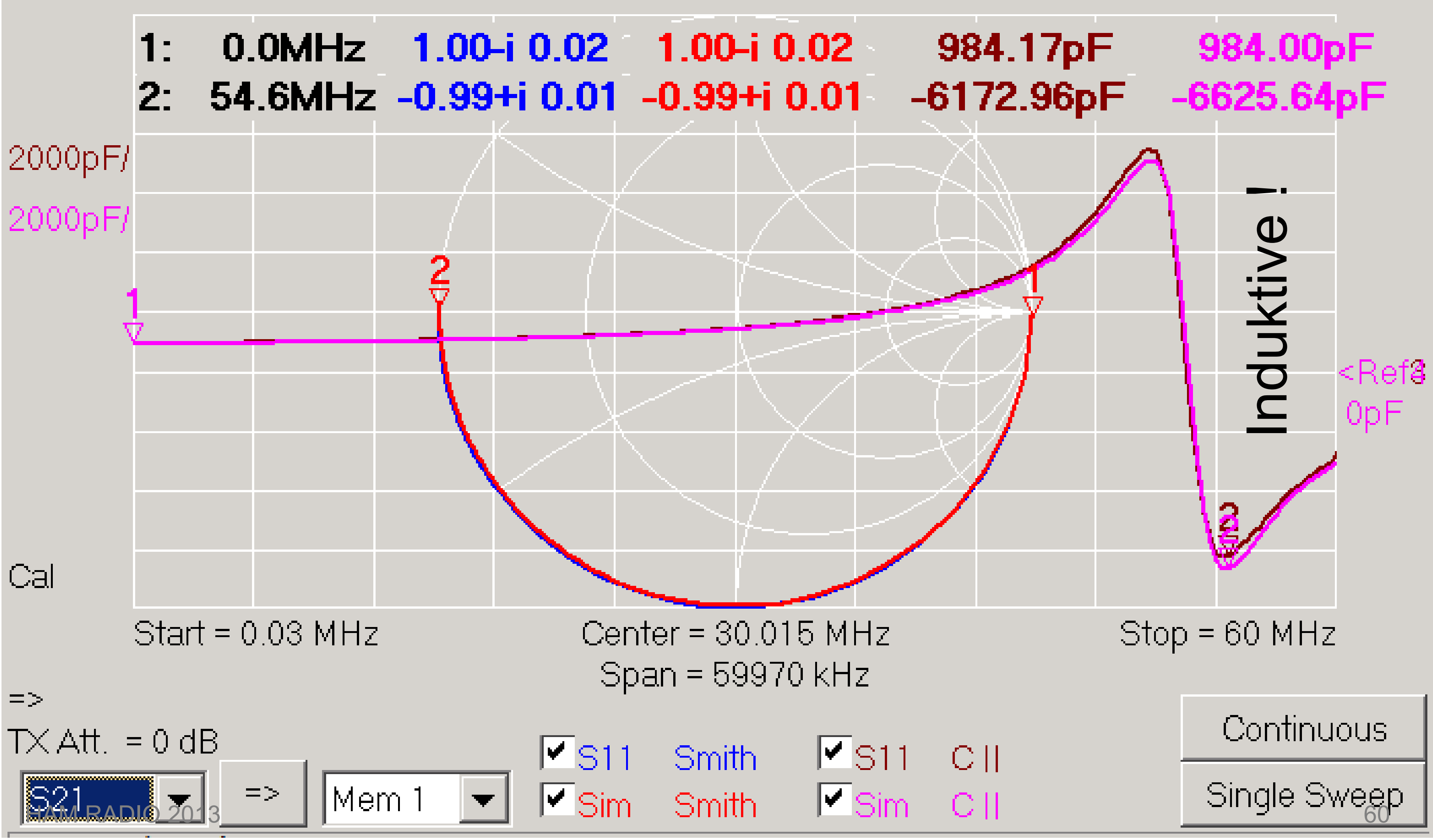


0,984 nF 9,3 nH 0,22 Ω

einfaches Modell

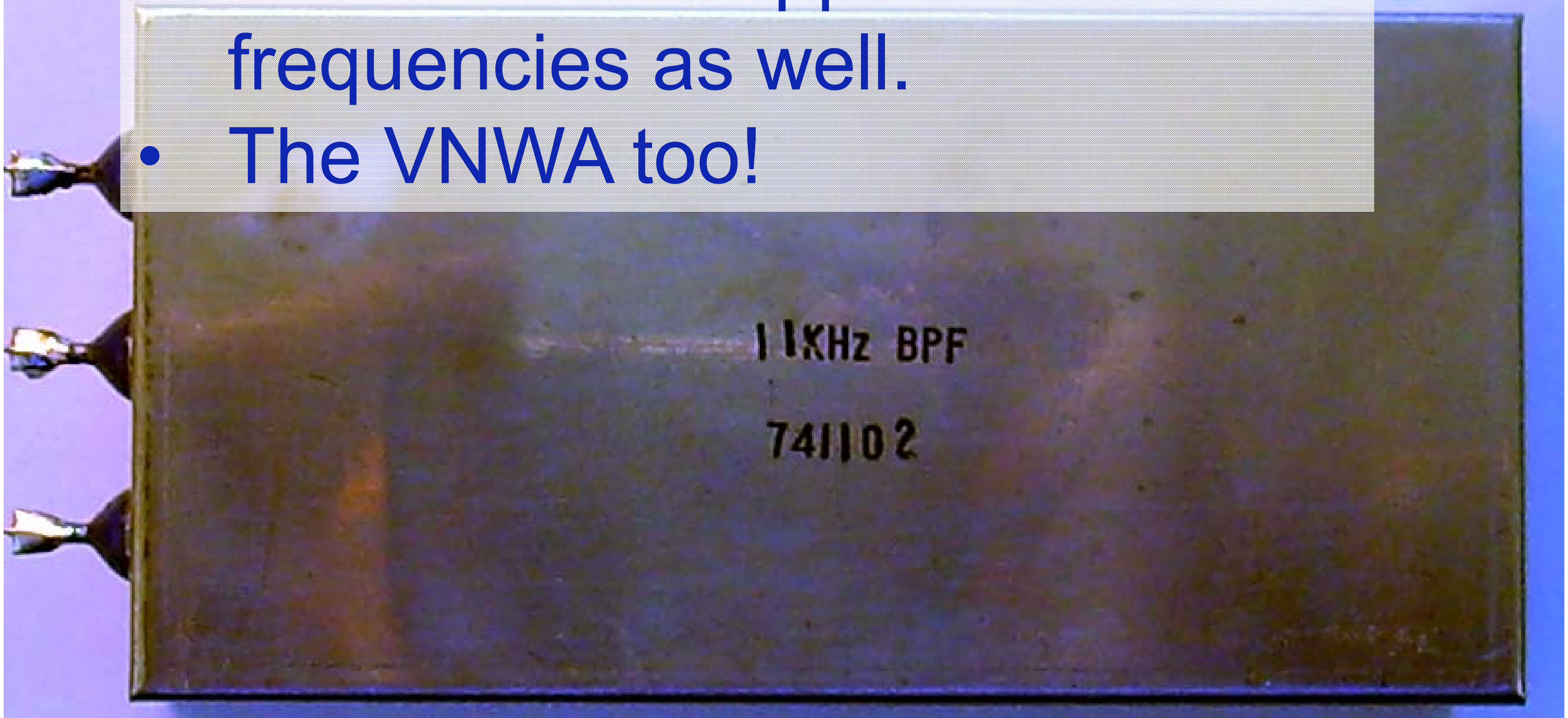
Hochschule Ulm

The Model is quite accurate!



Two Port Measurement of a 12 kHz Band Pass Filter

- S-Parameters applicable to low frequencies as well.
- The VNWA too!



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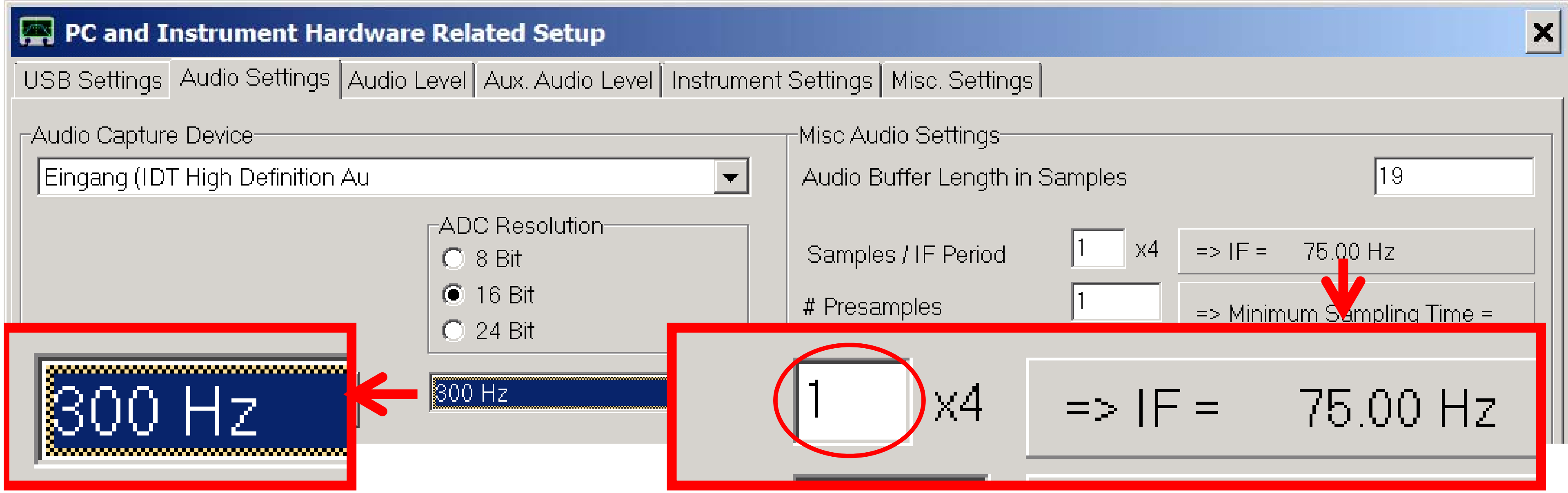
Special VNWA Settings for low Frequencies



Lowest sample rate 300 Hz
→ Nyquist limit 150 Hz
→ Measurements down to ≈150 Hz possible

IF must be within Codec frequency range (20 Hz…16kHz)

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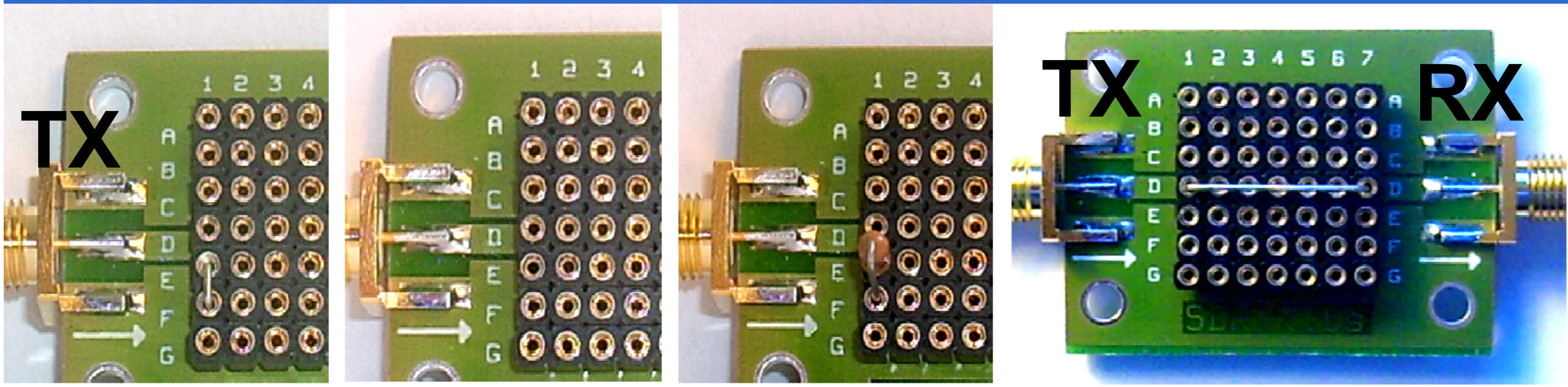
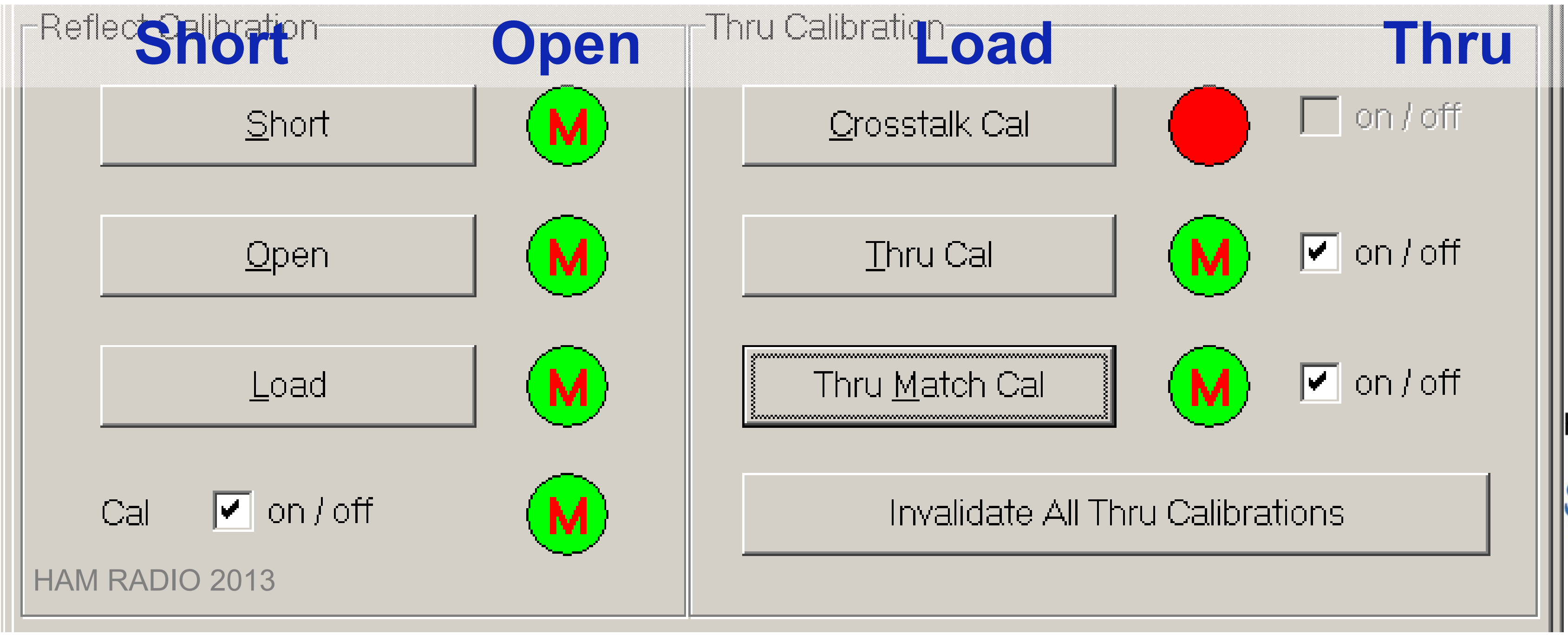
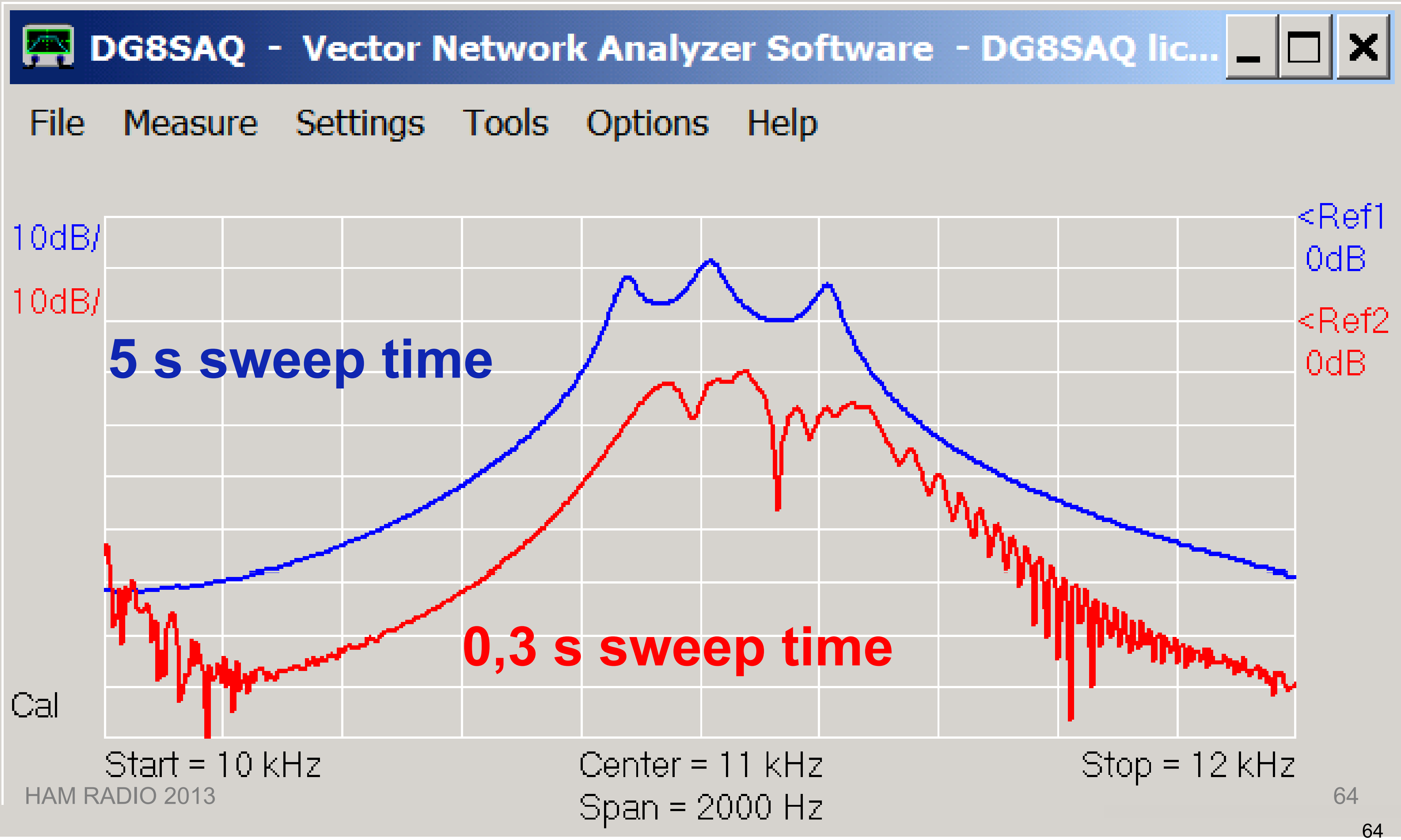
SOLT-Calibration for 2-Port Measurements

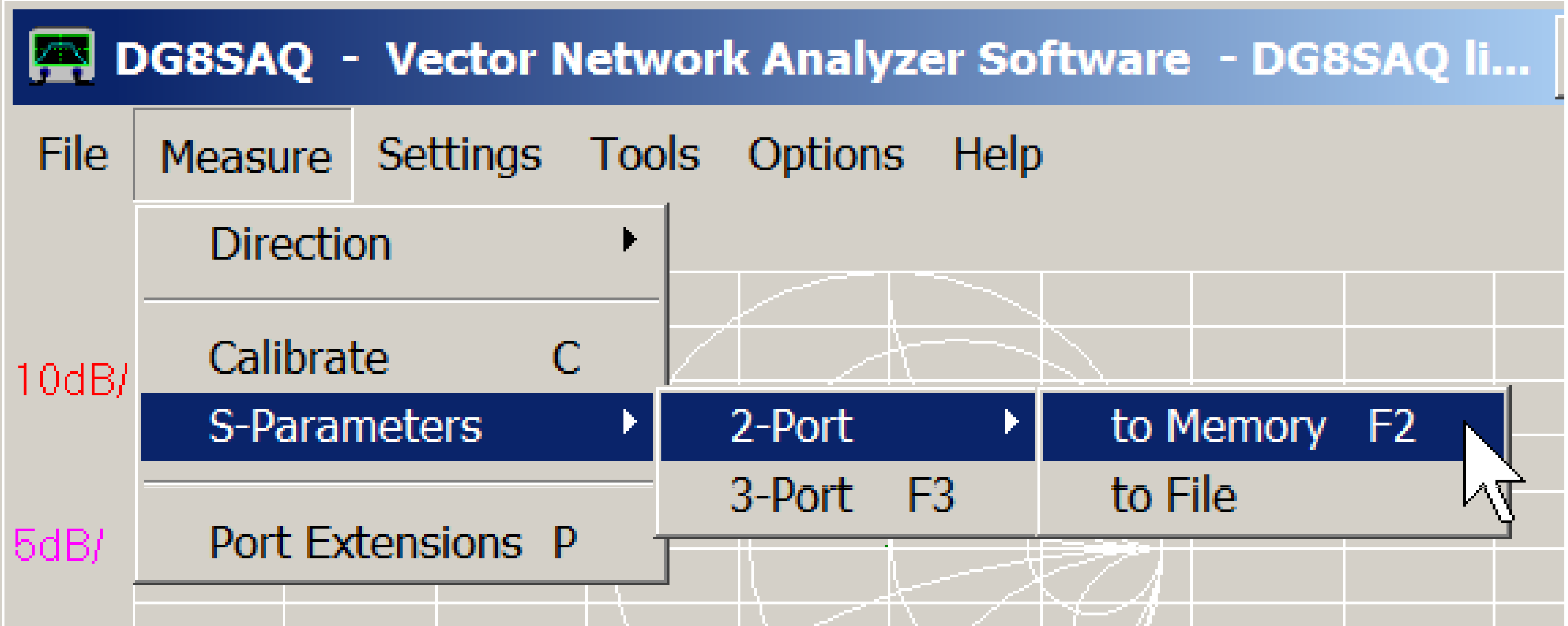




Beware: Steep Skirt Filters require Time to settle to changing Stimulus!



Two Port Measurement of a 12 kHz Band Pass Filter



We need to measure all four S-parameters (S_{11}, S_{21}, S_{12}, S_{22}) …

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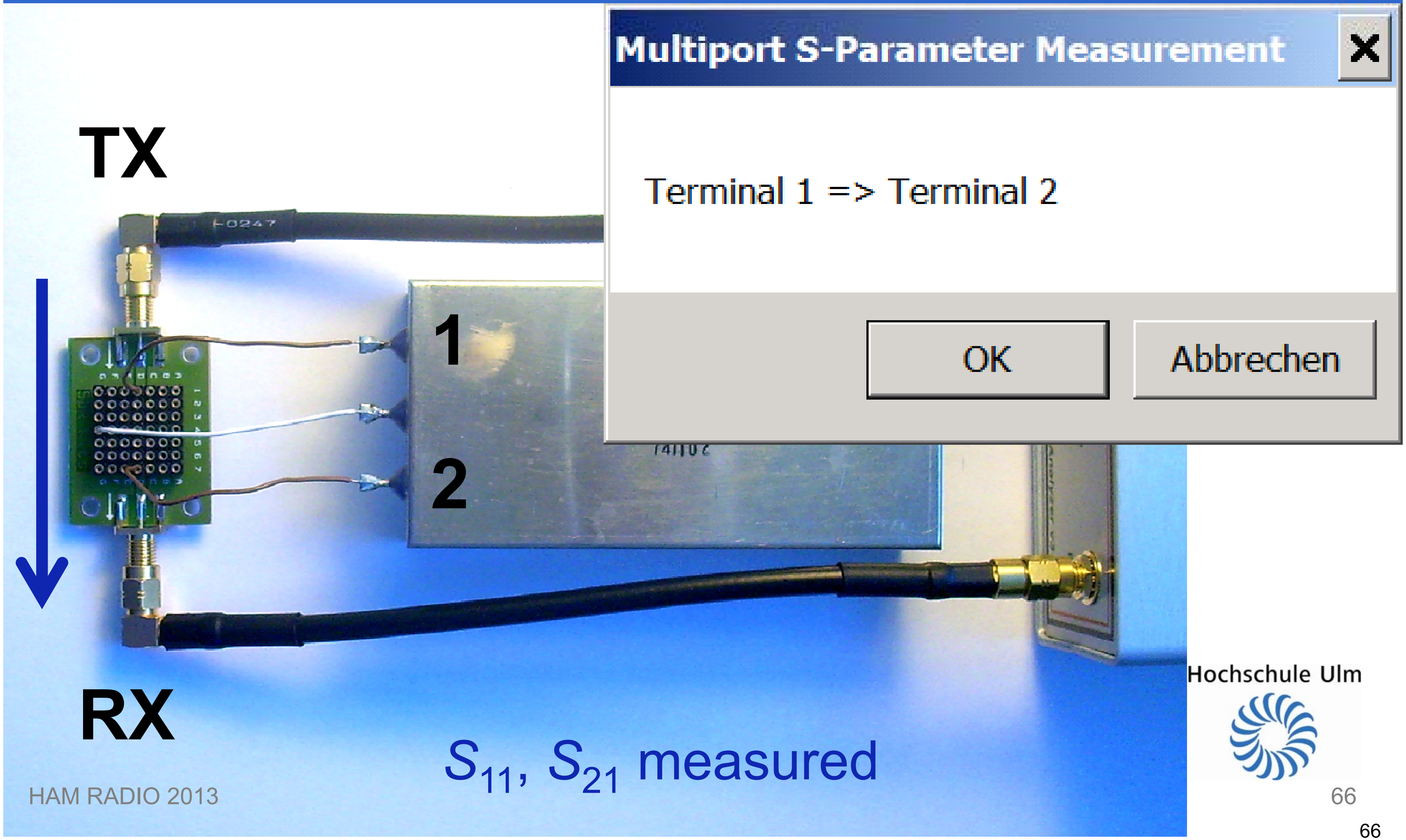
Two Port Measurement of a 12 kHz Band Pass Filter: Forward Measurement



S_{11}, S_{21} measured

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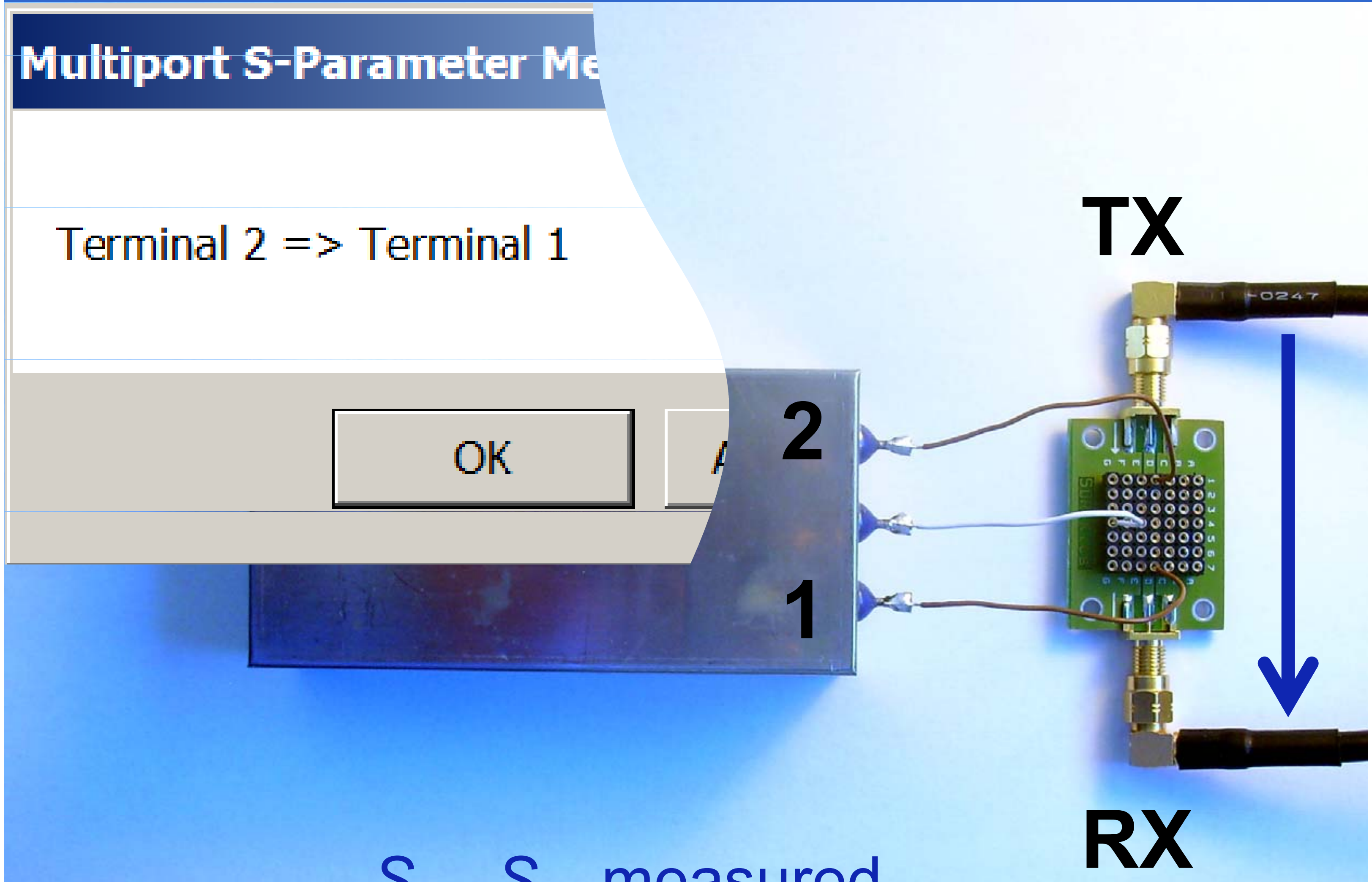
Two Port Measurement of a 12 kHz Band Pass Filter: Reverse Measurement



S_{12}, S_{22} measured

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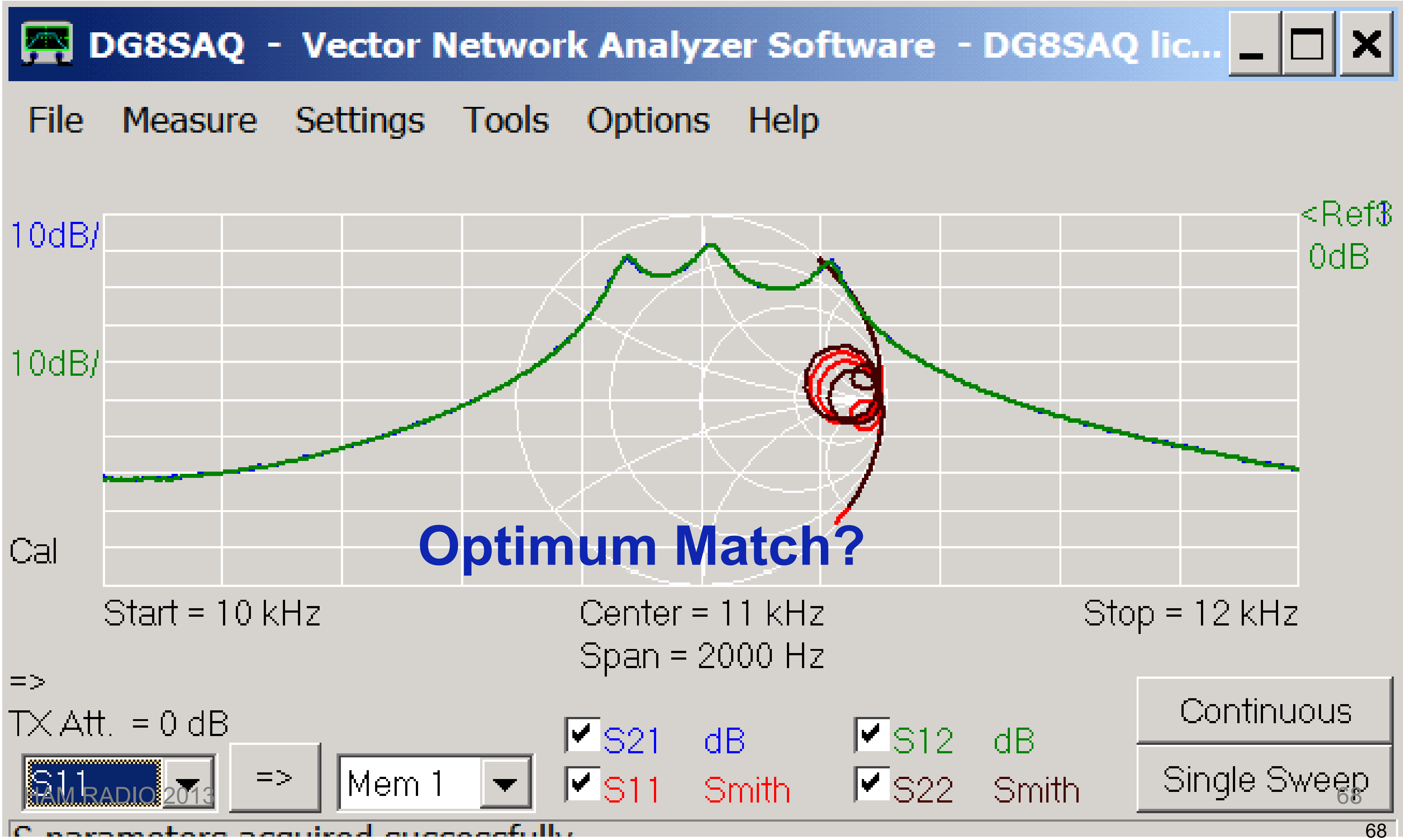
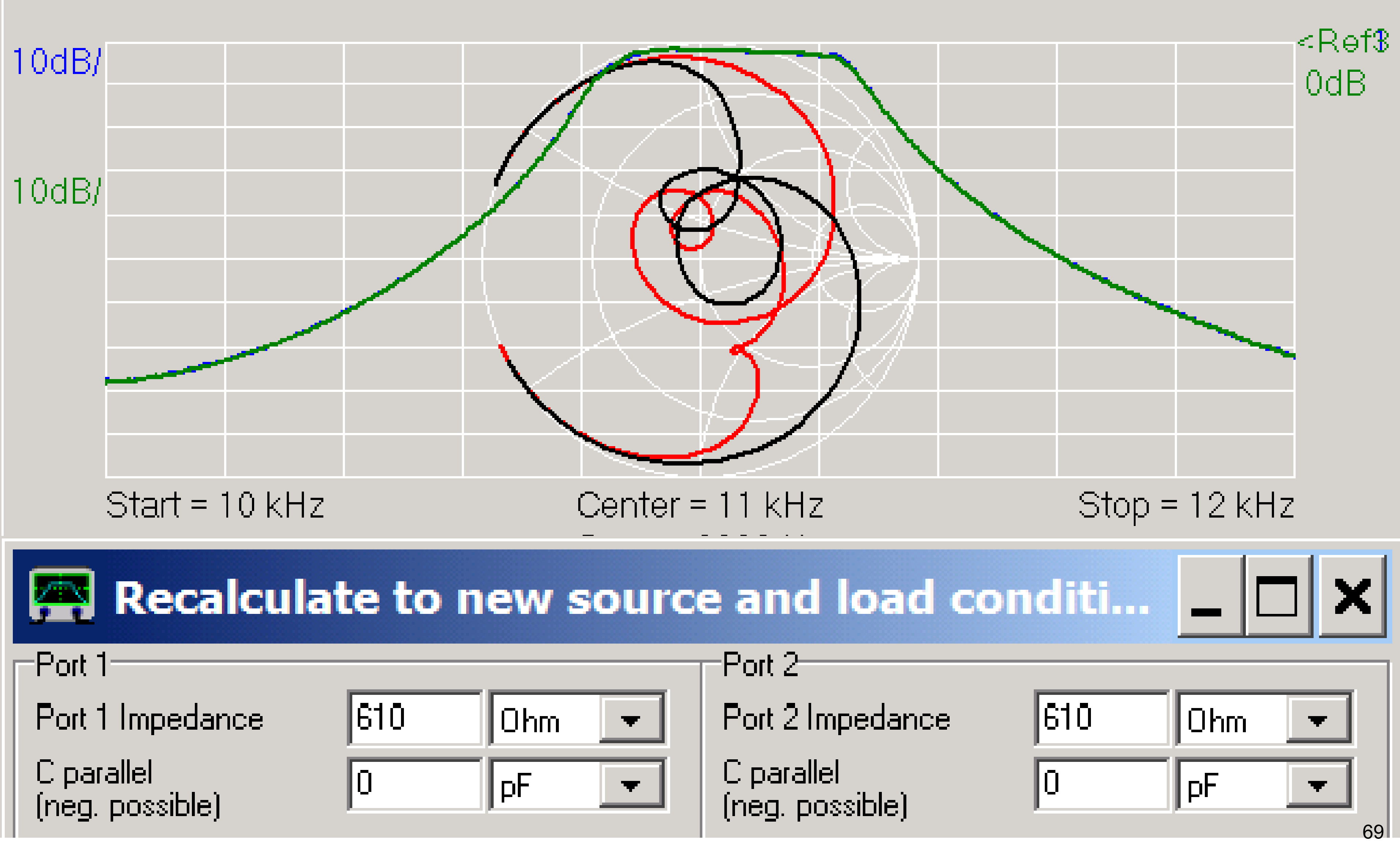
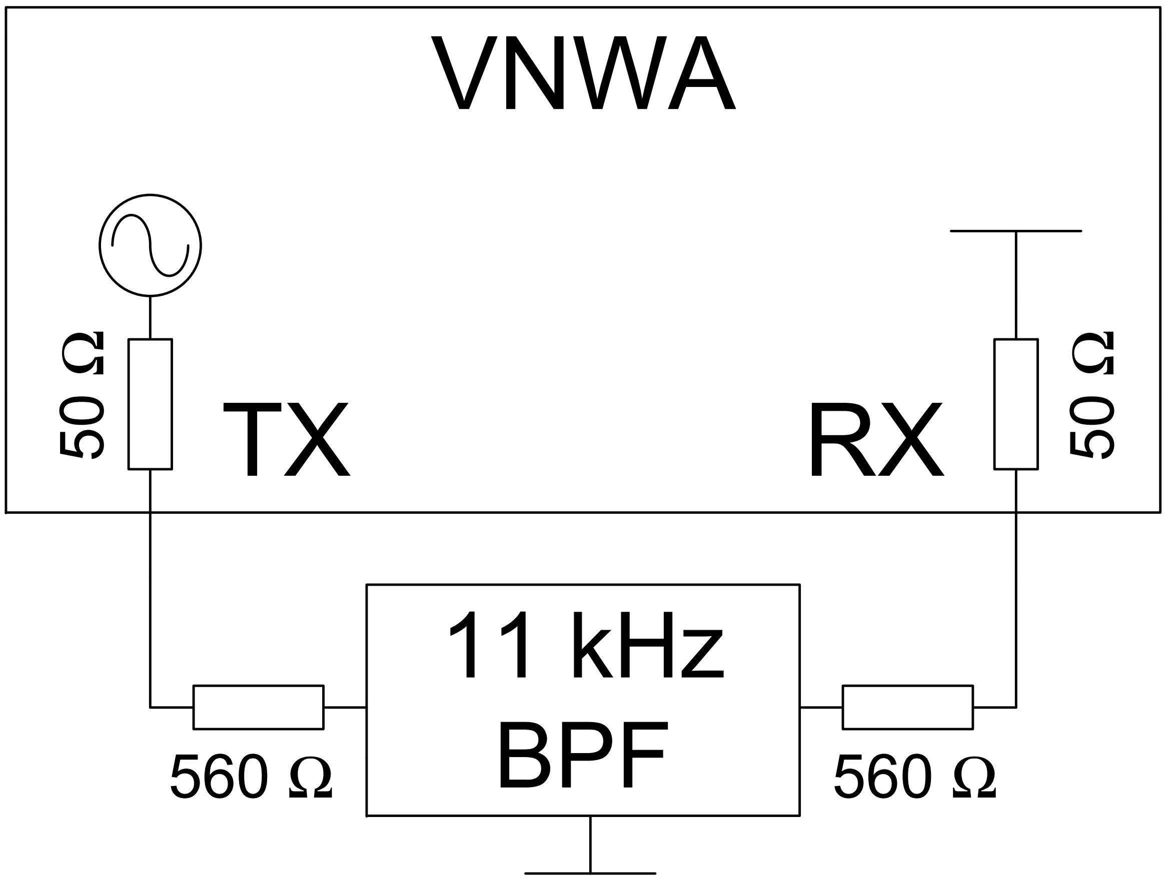
What are measured 2-Port S-Parameters good for?



Matching Analysis: VNWA Matching Tool
Optimum: $Z_{in} = Z_{out} = 610\ \Omega$



Forced Impedance Match using Resistors



$50\ \Omega + 560\ \Omega = 610\ \Omega$

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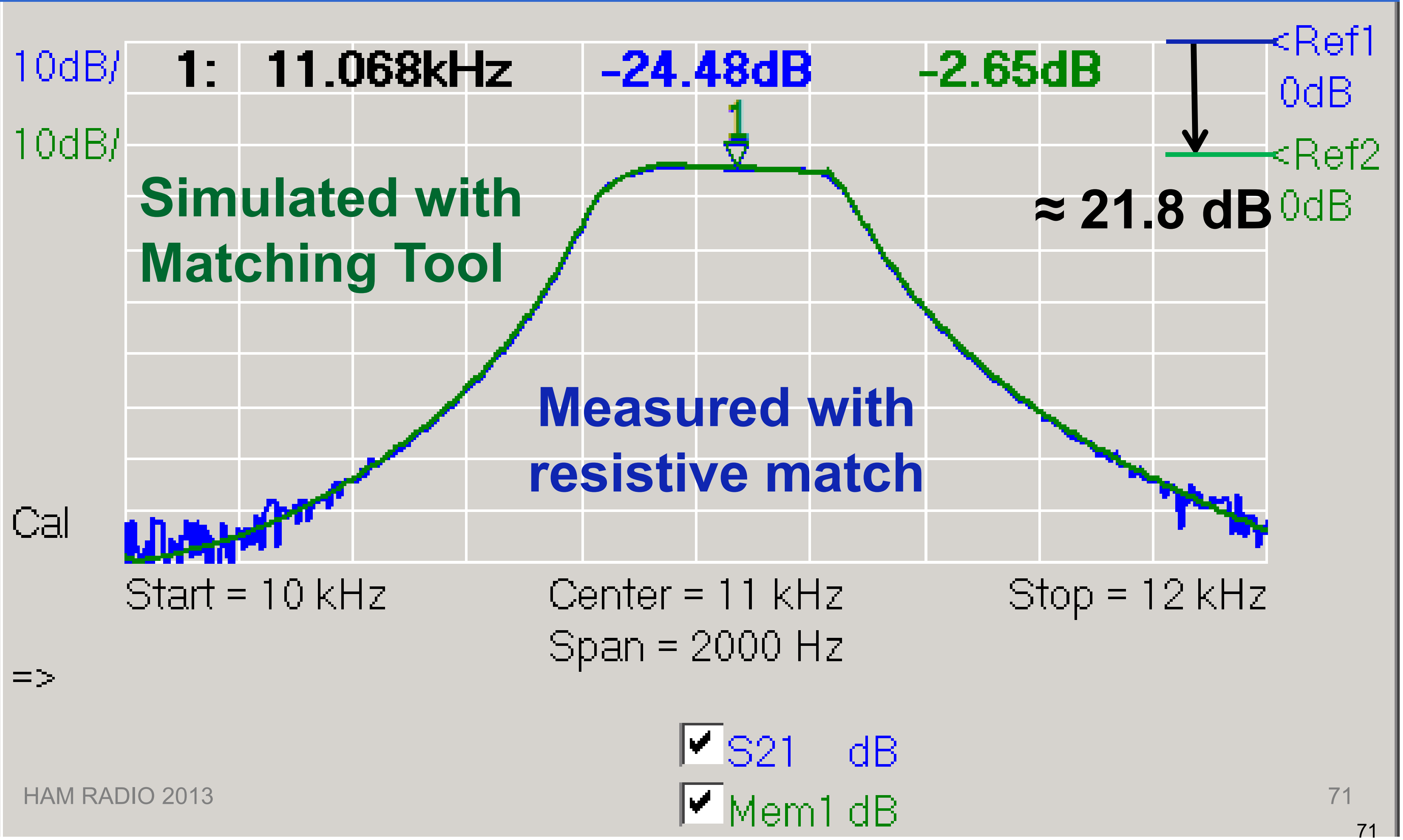
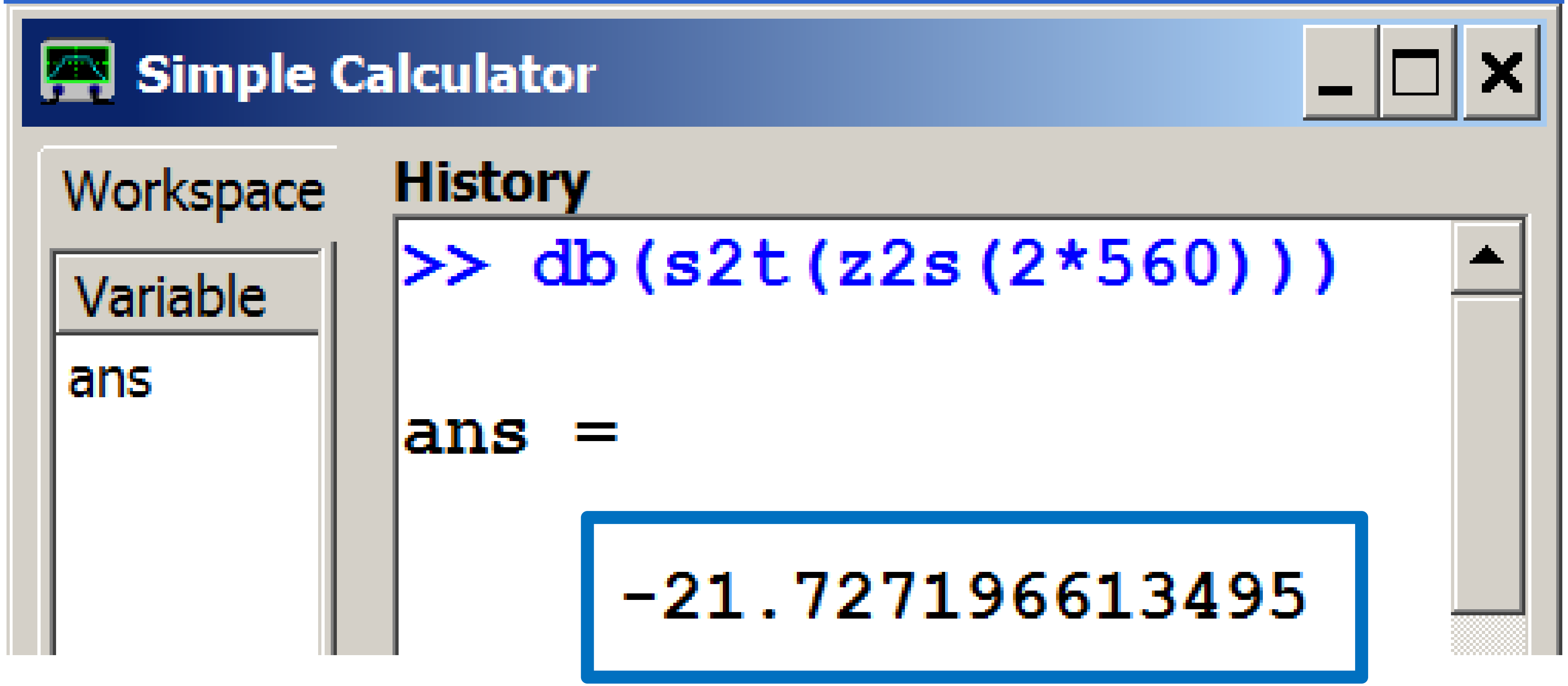
Match works except for increased Loss



Effect of two 560 Ω Resistors in Signal Path: VNWA Complex Calculator



21,7 dB additional attenuation ✓

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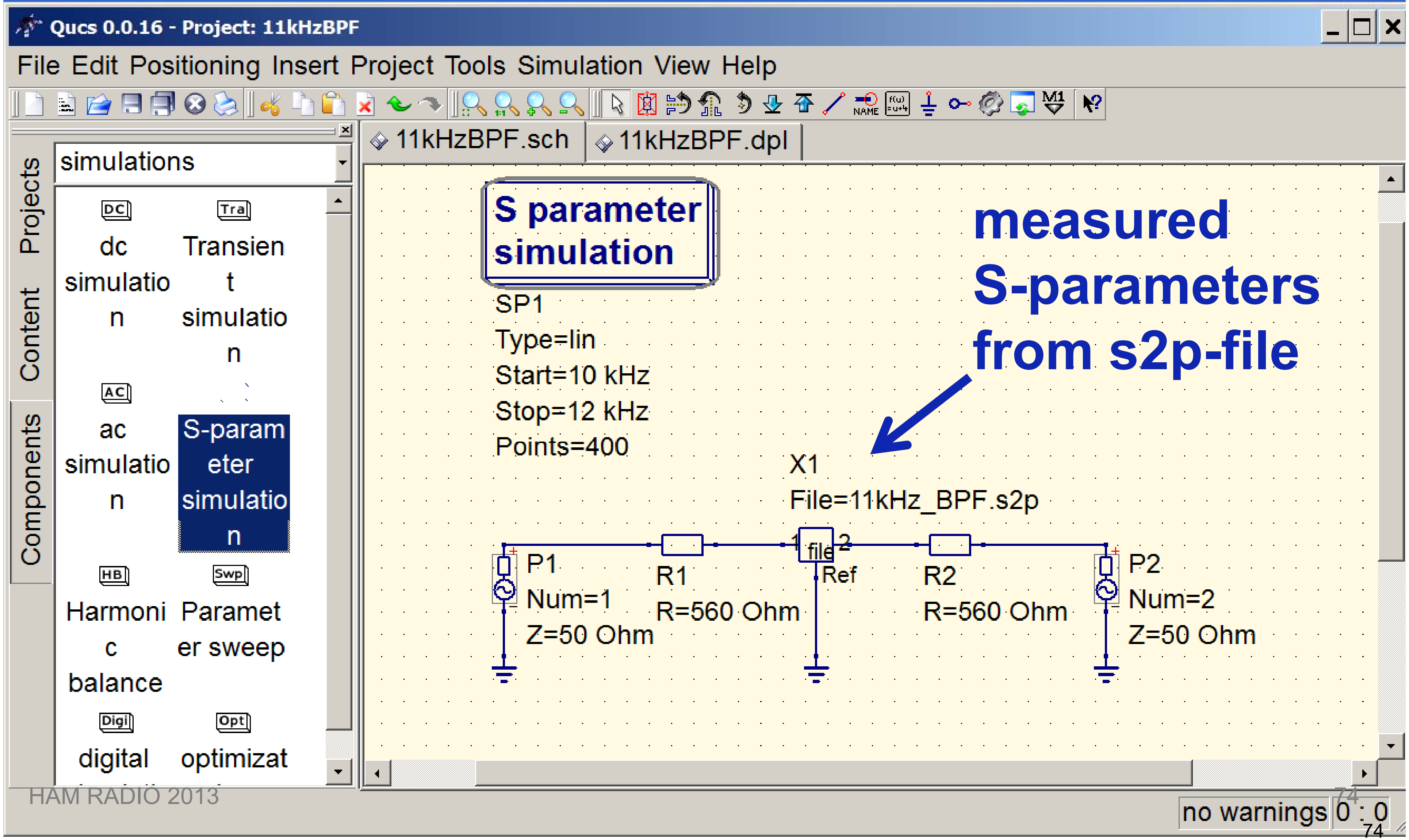
This can also be „properly“ simulated!
Simulation Tool QUCS

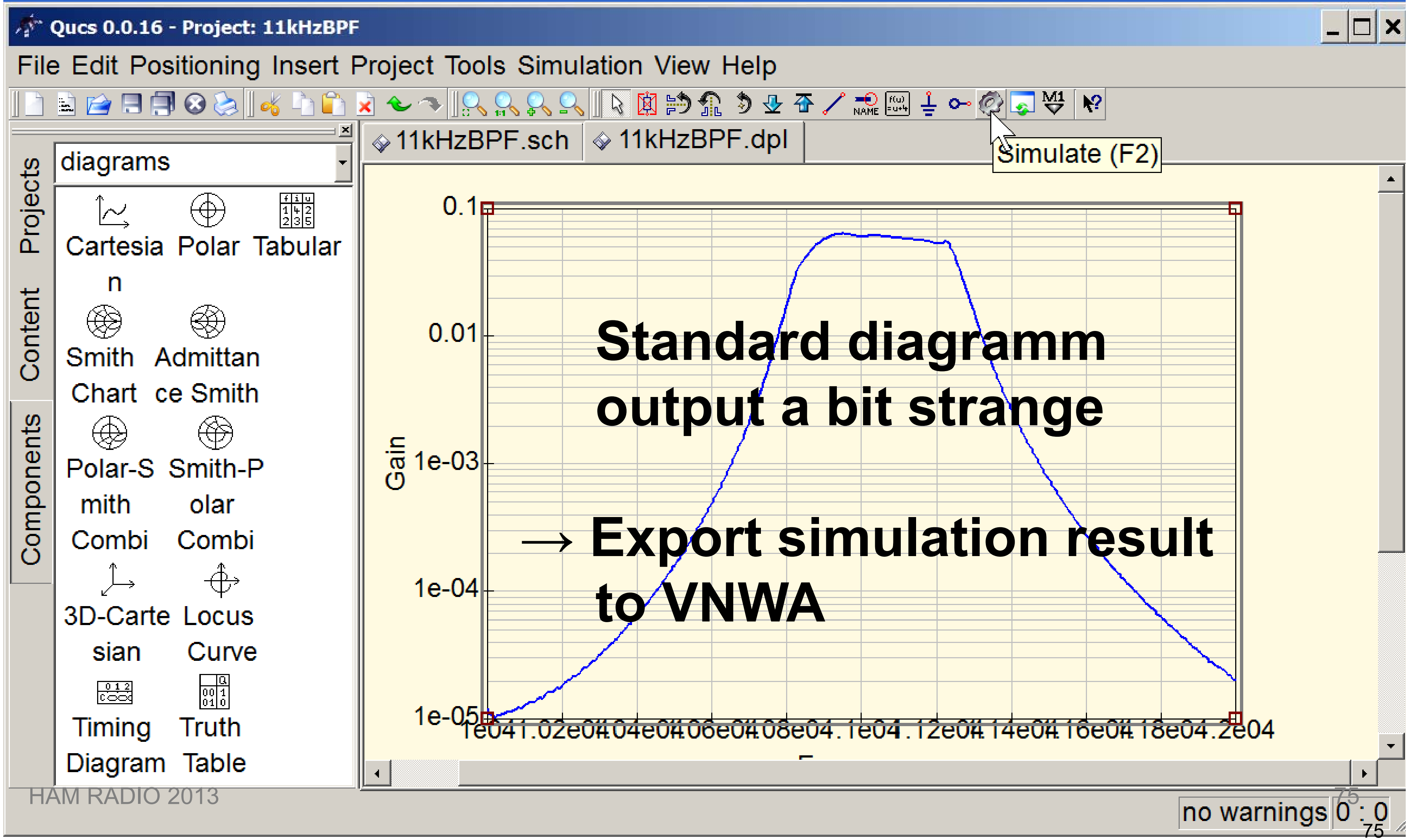
Qucs
Quite Universal Circuit Simulator

- http://qucs.sourceforge.net/
- **Universal circuit simulator**
- **Free**
- **No restrictions**
- **Easy to use**
- **Grafics and data export needs brush up**

Measured S-Parameters in QUCS



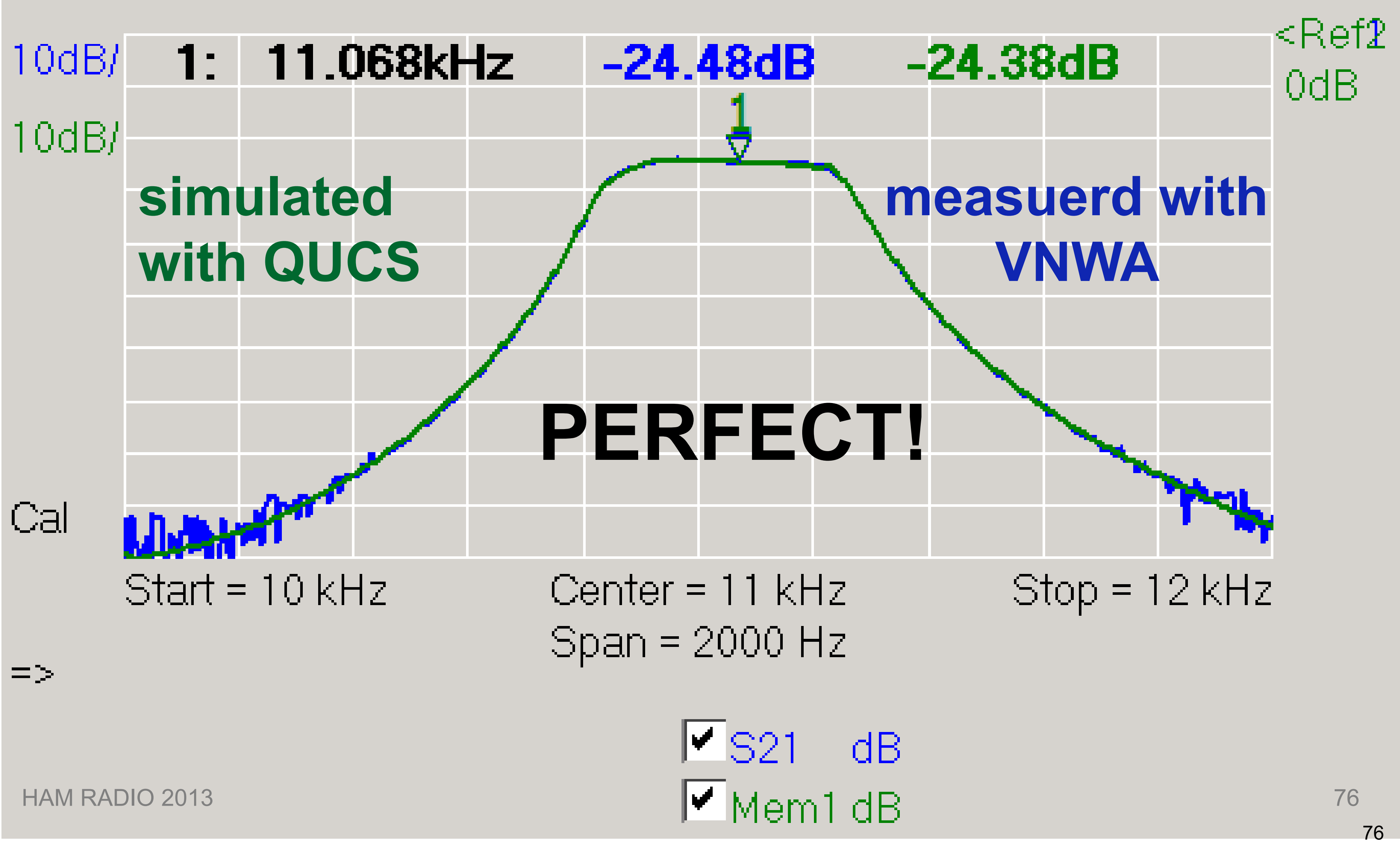
Matching Simulation in QUCS



Standard diagramm output a bit strange

→ Export simulation result to VNWA

Comparison QUCS-Simulation vs. Measurement

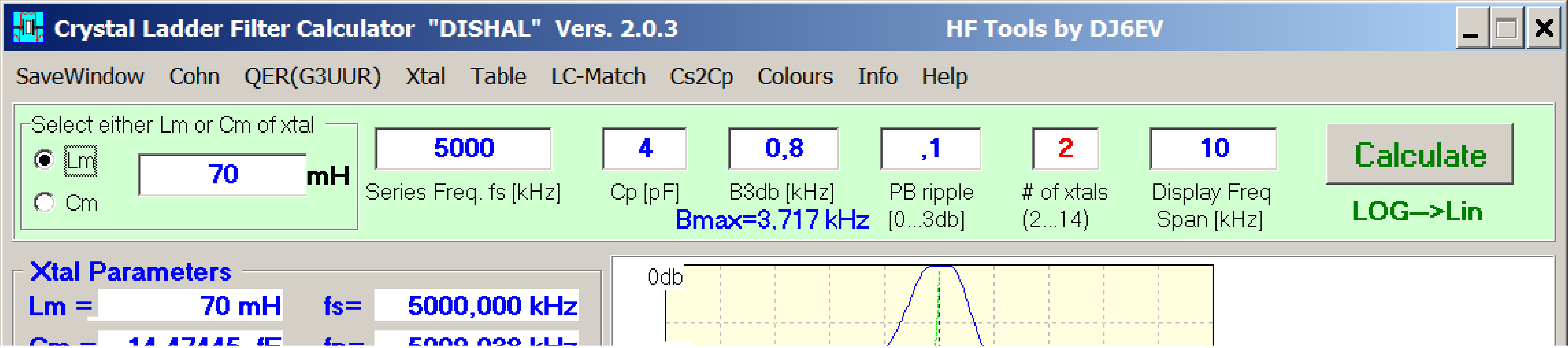


Free Filter Design Software (1): Elsie – for LC-Filters

- http://tonnesoftware.com/elsiedownload.html
- LC-Filter Designer and Analyzer
- Student version restricted to 7 dipols
- Numerical simulation results export easily to s2p-file!

Hochschule Ulm

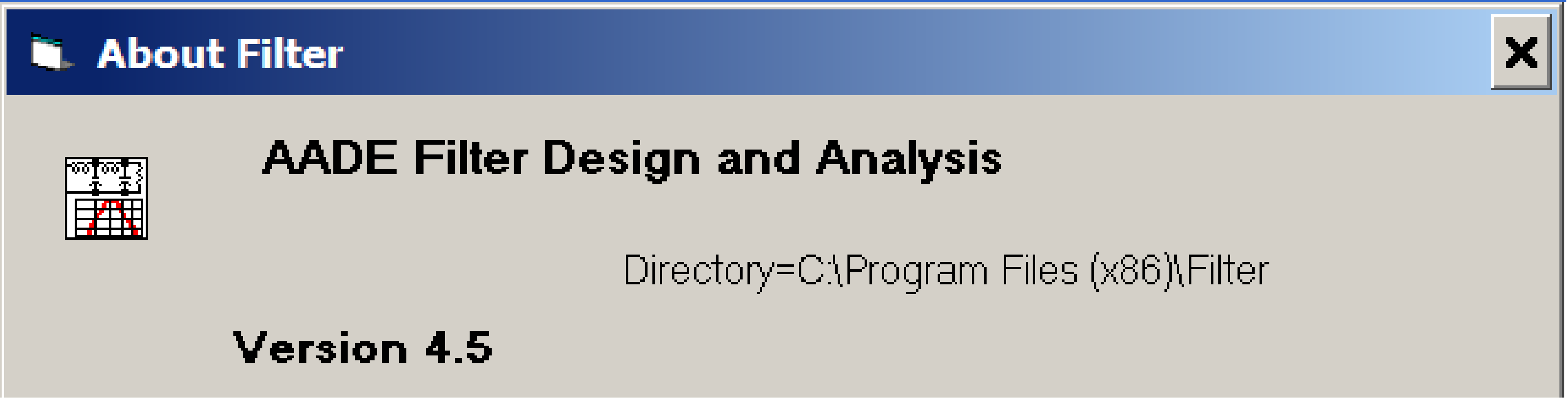
Free Filter Design Software (2): Dishal – for Crystal Filters



- http://www.bartelsos.de/dk7jb.php/quarzfilter-horst-dj6ev
- **Crystal filter designer and analyzer**
- **Simulates without crystal losses**
- **S_{21}-simulation results can be exported**

Hochschule Ulm

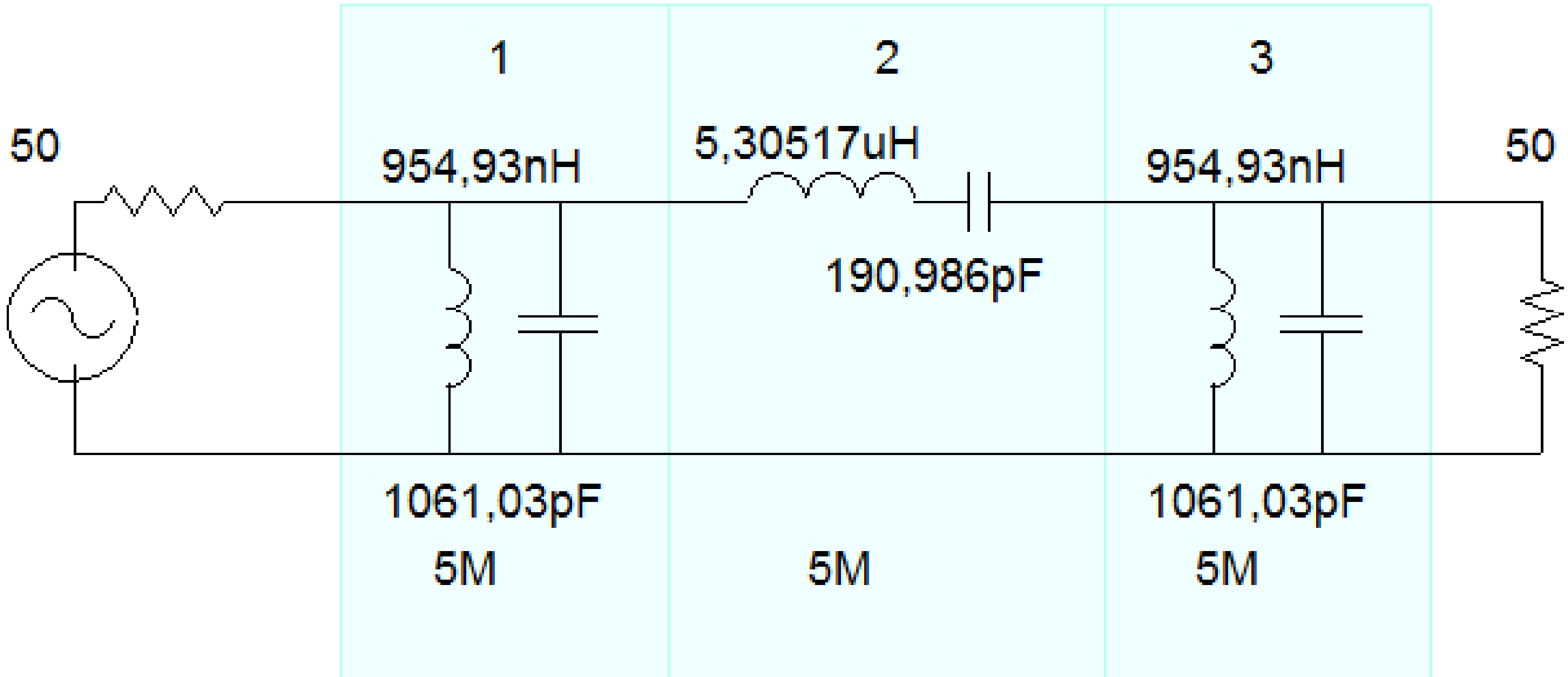
Free Filter Design Software (3): AADE Filter Design - for all filters



- http://aade.com/filter32/download.htm
- Univeral filter designer and analyzer
- Free, but with nag screen
- Easy to use
- Numerical simulation results cannot be exported

Hochschule Ulm

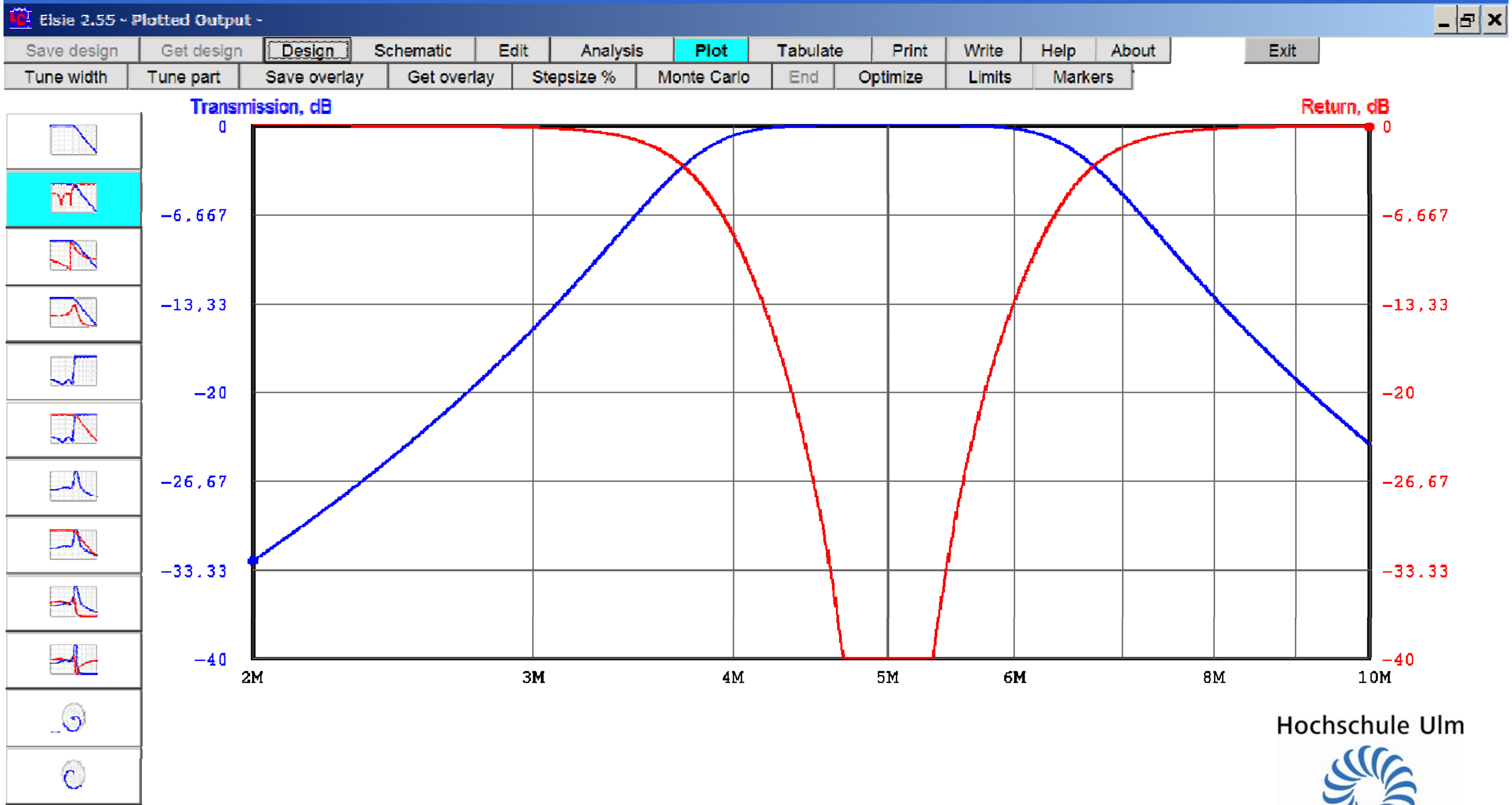
Design 3 Pole Butterworth π-Band Pass for 5 MHz with 3 MHz Bandwidth at 50 Ω



Filter Design with Elsie

Hochschule Ulm

Elsie Simulation Result



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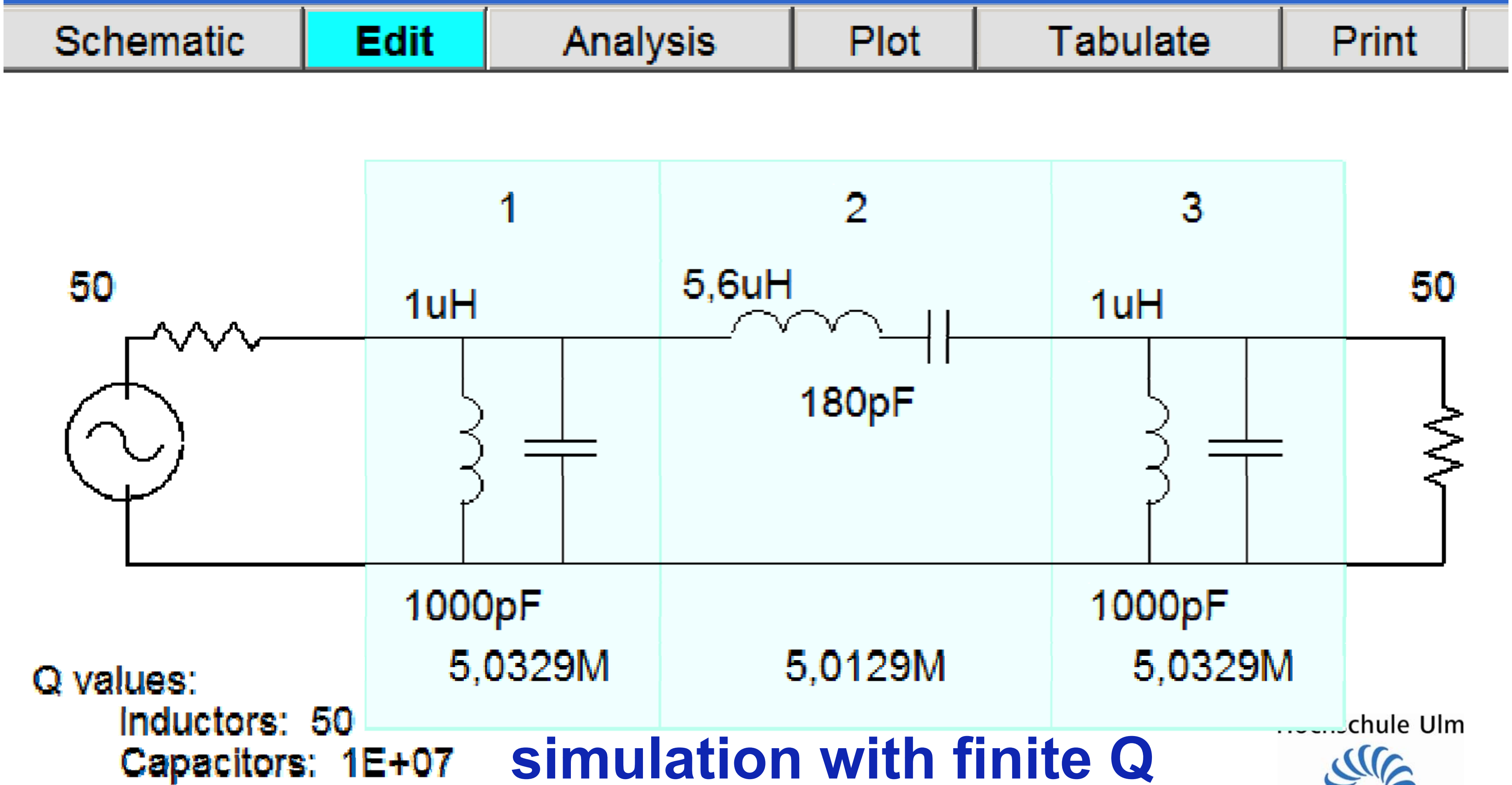
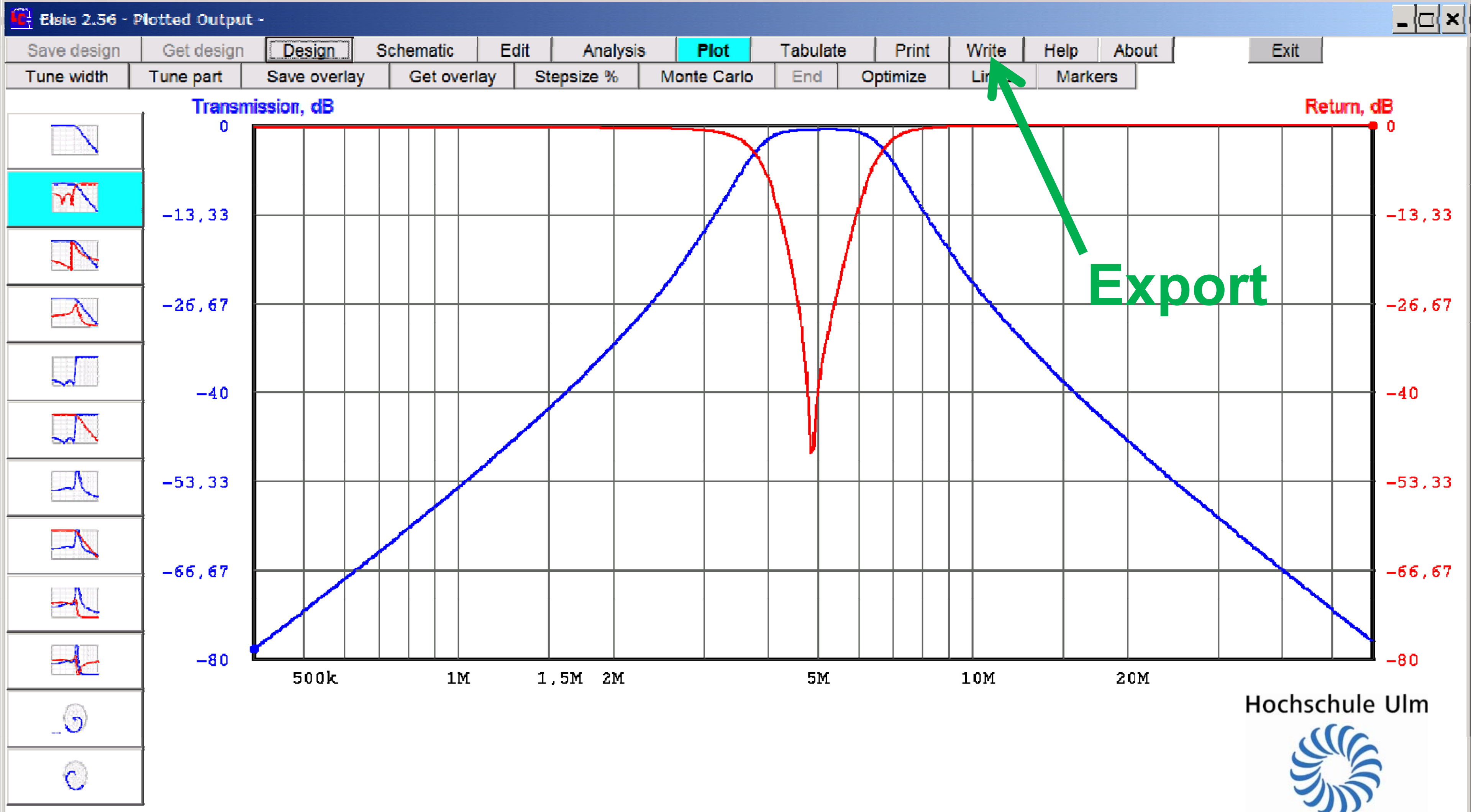
Modify Components to standard Values and finite Q …



simulation with finite Q

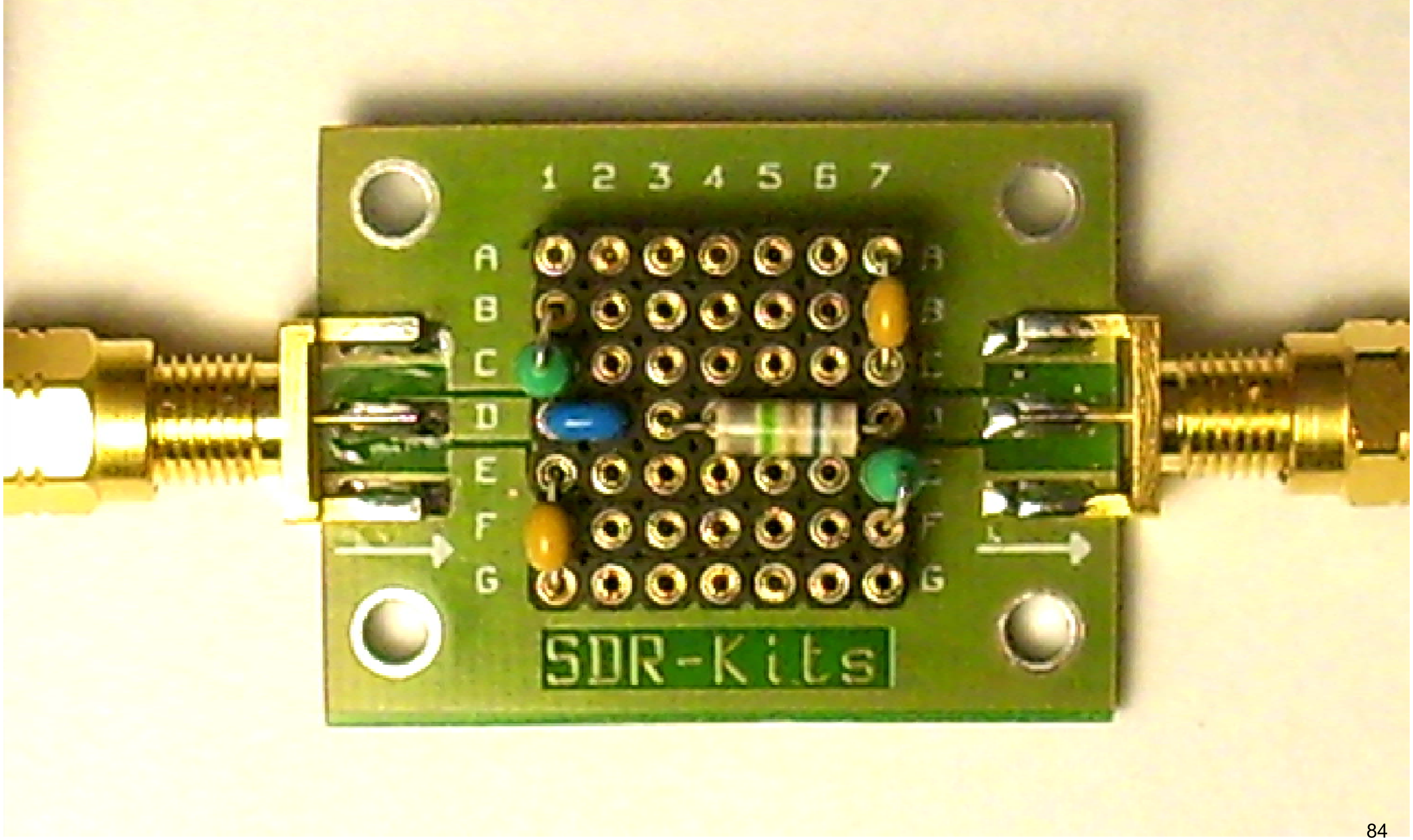
Hochschule Ulm

…and export Simulation into s2p-file for Comparison with Measurement.



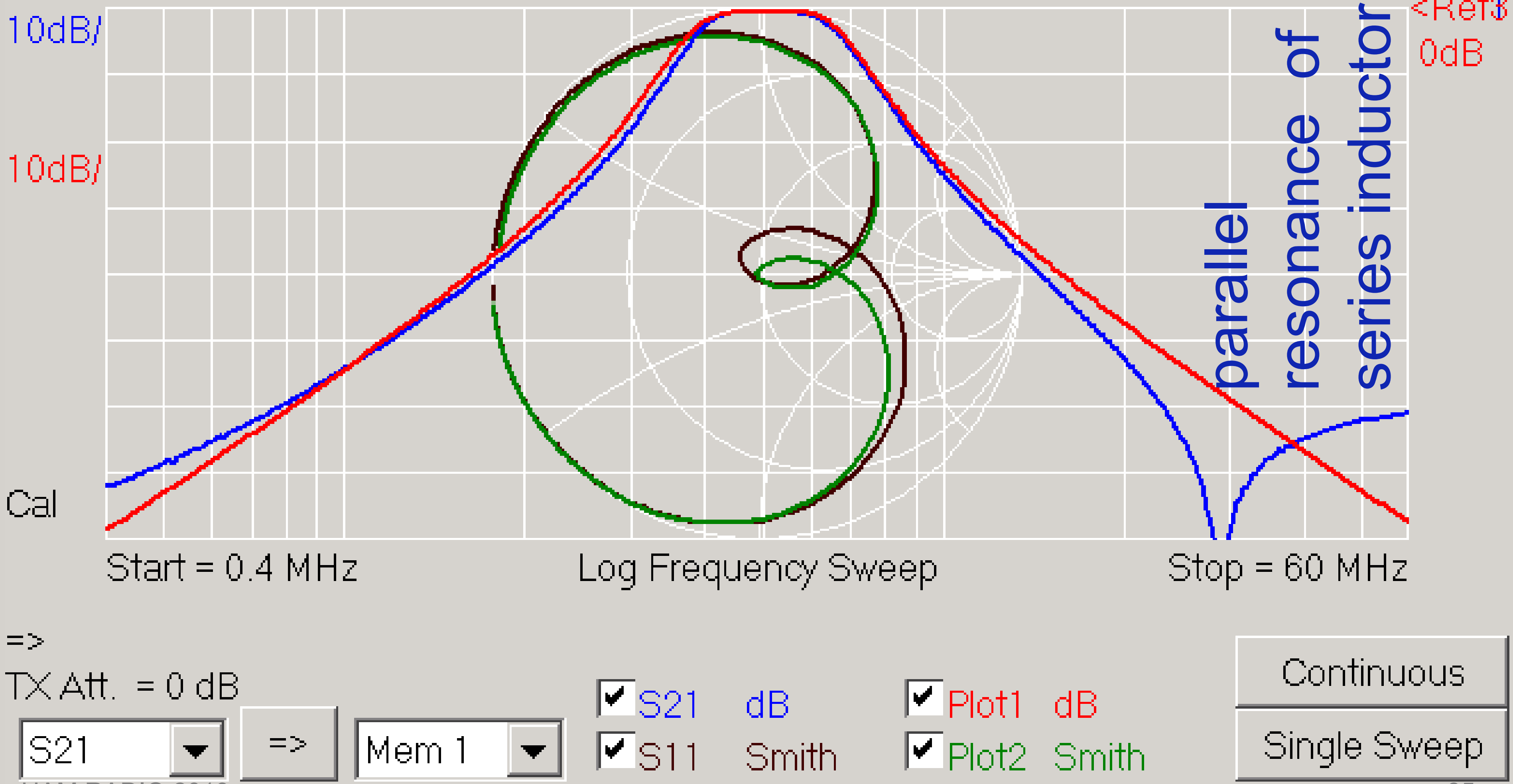
Hochschule Ulm

Filter Hardware

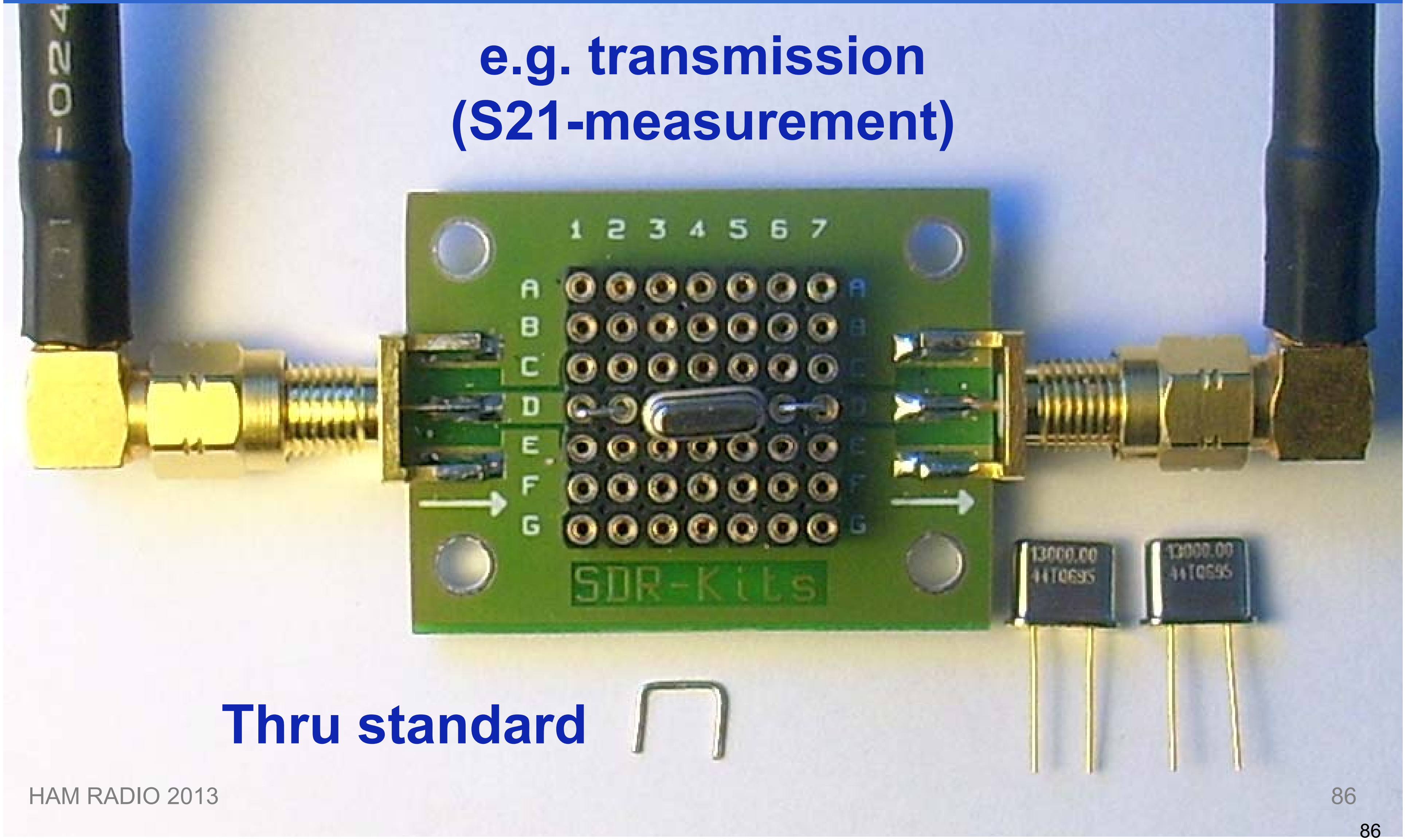


Comparison
Measurement vs. Elsie Simulation

S_{21}, S_{11} measured - Plot1, Plot2 Elsie simulation



Measuring / Selecting Crystals:
VNWA Crystal Analyzer



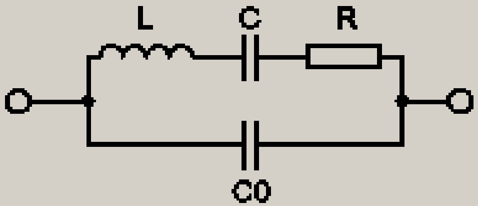
e.g. transmission (S21-measurement)

Thru standard

The VNWA Crystal Analyzer Tool: Find 3 similar Crystals…

Crystal Analyzer - Analysis will be performed into 3-port data spaces s_11 an...

Equivalent Circuit



L = 23.22917 mH

C = 6.456461 fF

R = 27.285283581 Ohm

C0 = 2.46571041216 pF

$f = 1/2\pi\sqrt{L \cdot C}$ = 12.9958869786 MHz

$R \cdot Q = \sqrt{L/C}$ = 1896.7918117 x1000 Q = 69517

auto-optimize

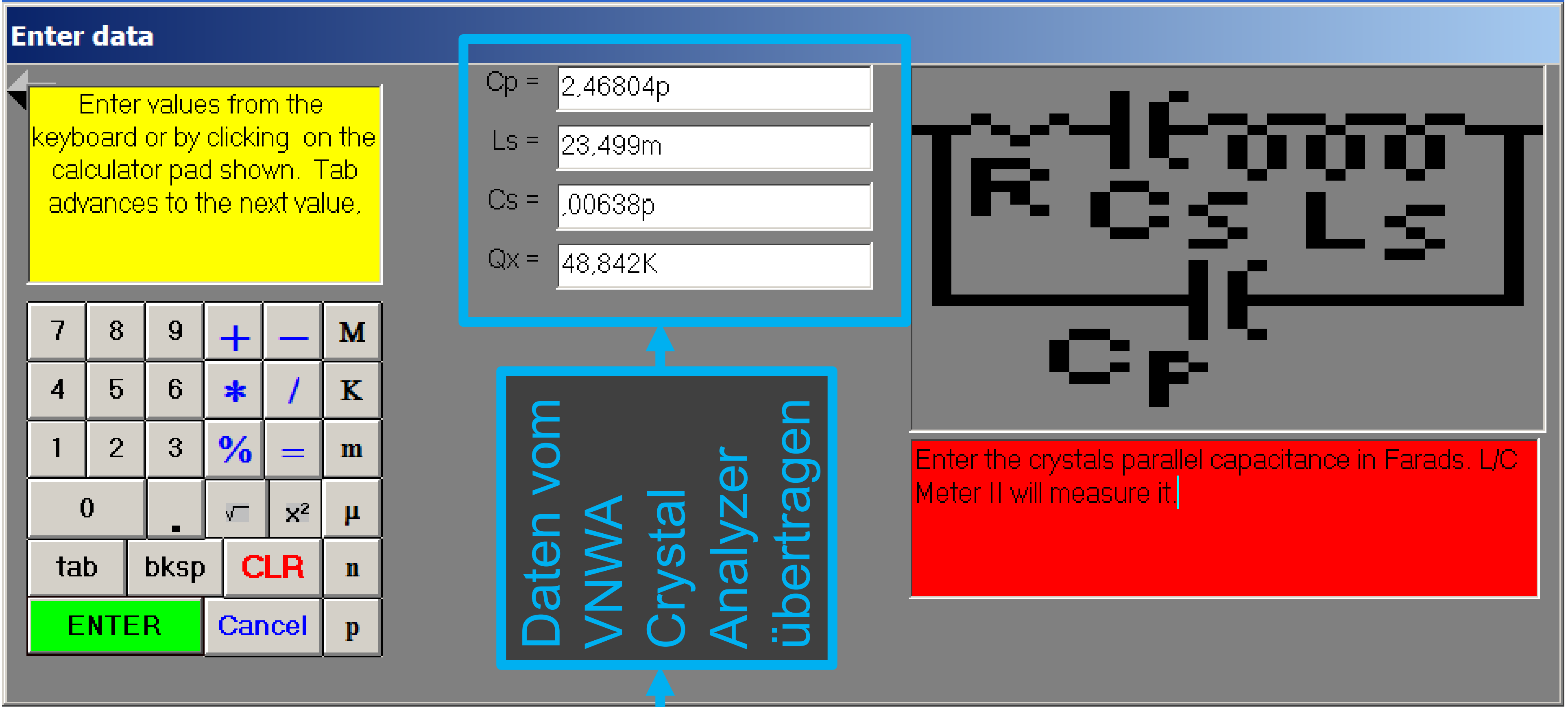
source = S21 Test Jig Impedances = 50 Ohms

Batch Crystal Analyzer

measure save list clear list

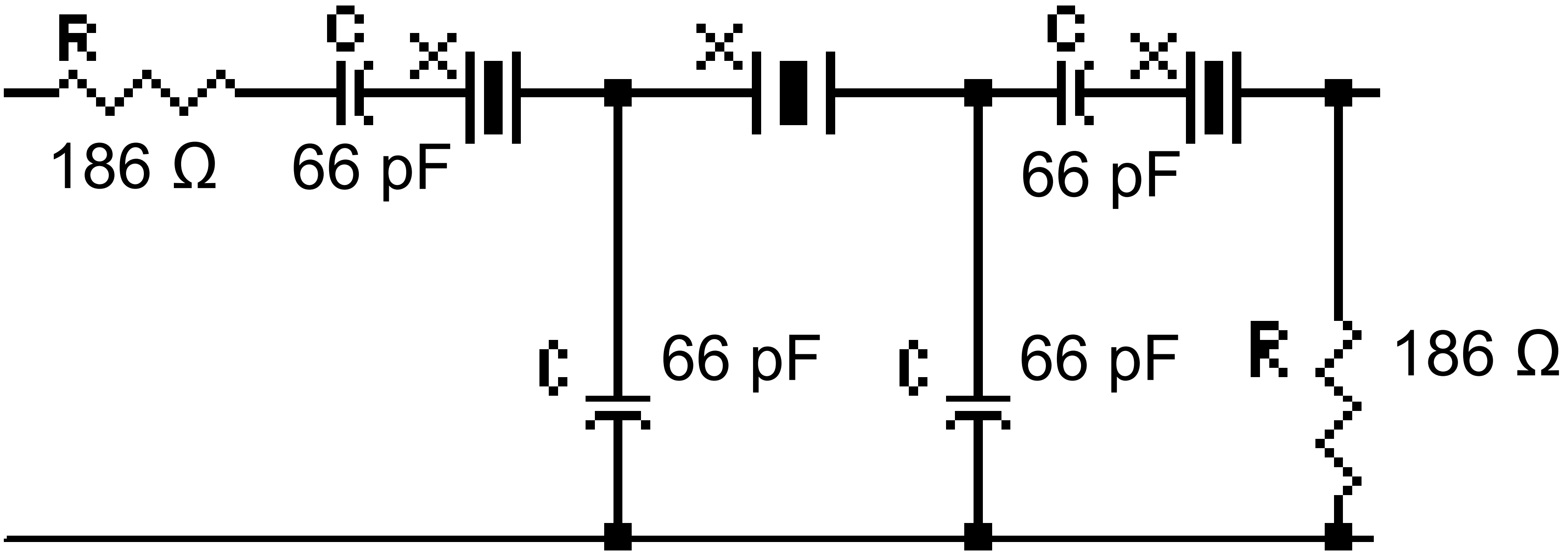
#	f / Hz	Q	L / H	C / F	R / Ohm	C0 / F	figure of m
1	12995915.37	48842	0.02349916516	6.382253945E-15	39.29	2.468043934E-12	0.000775
2	12995927.72	54196	0.02368969902	6.330910084E-15	35.69	2.420346928E-12	0.00116
3	12995886.98	69517	0.02322917961	6.456461114E-15	27.29	2.465710412E-12	0.0015

With these we want to build a Crystal Filter
→ Enter Crystal Parameters into AADE



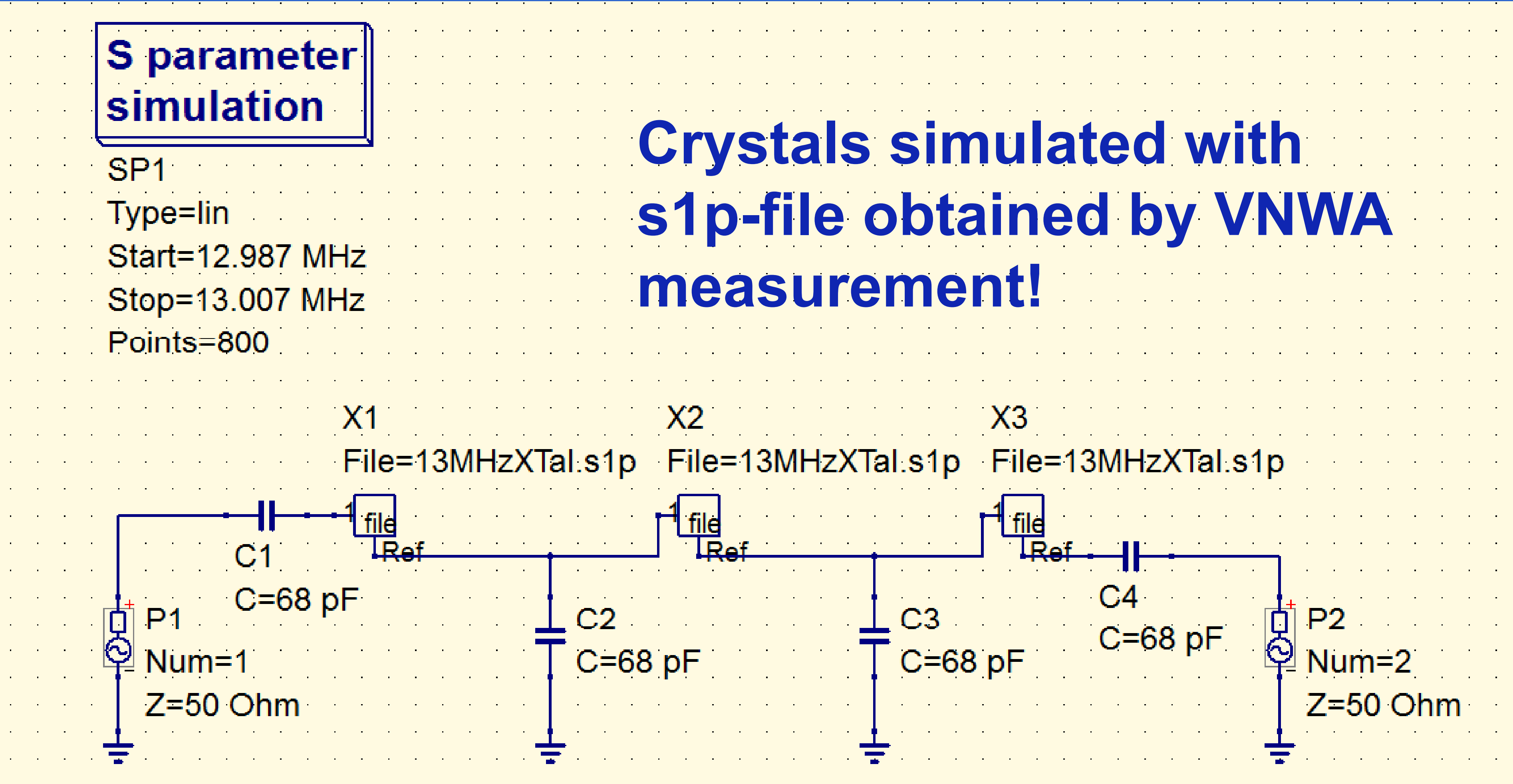
#	f / Hz	Q	L / H	C / F	R / Ohm	C0 / F	figure of m
1	12995915.37	48842	0.02349916516	6.382253945E-15	39.29	2.468043934E-12	0.000775

AADE Minimum Loss (Cohn) Design



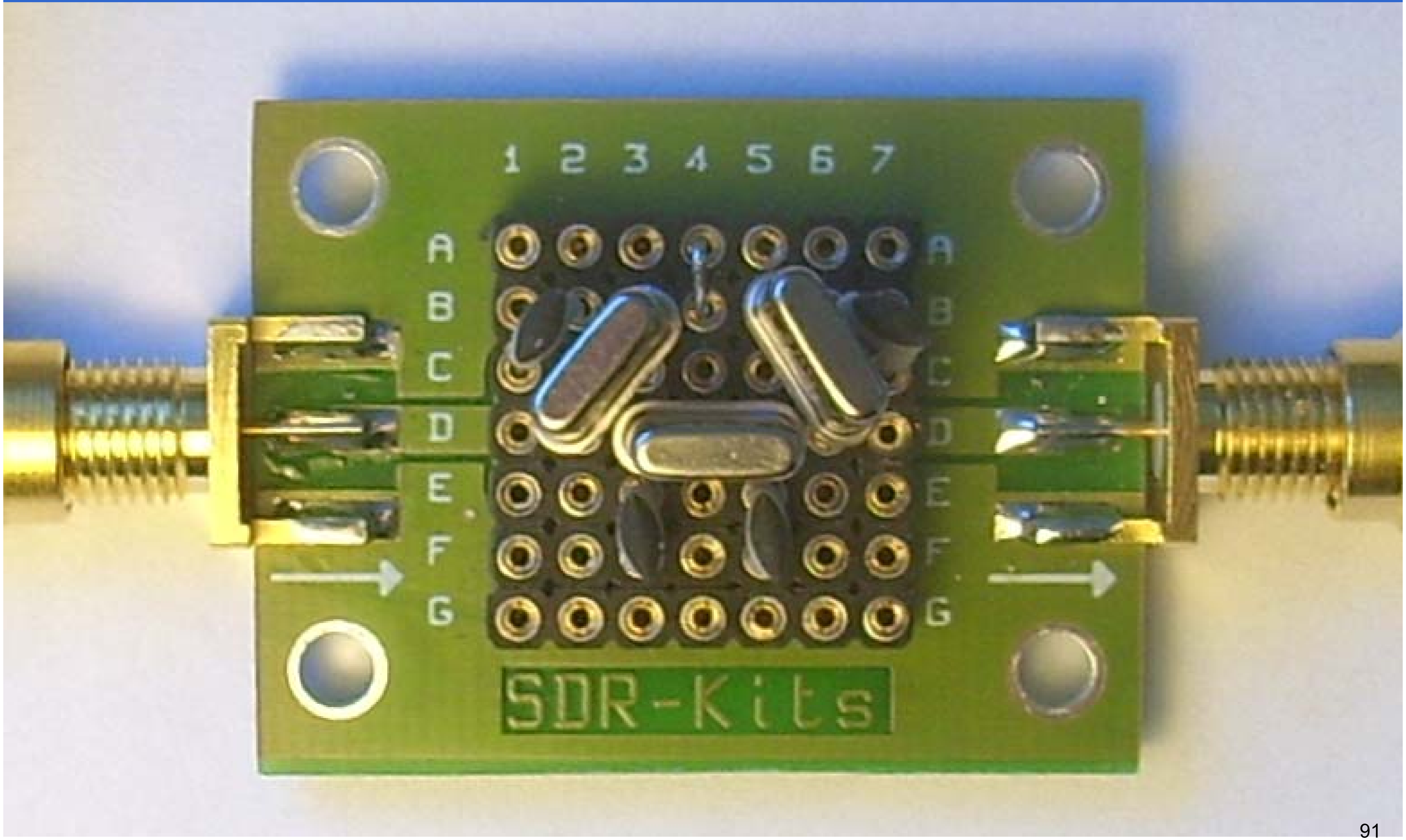
Hochschule Ulm

Simulation in QUCS at 50 Ω using standard Component Values



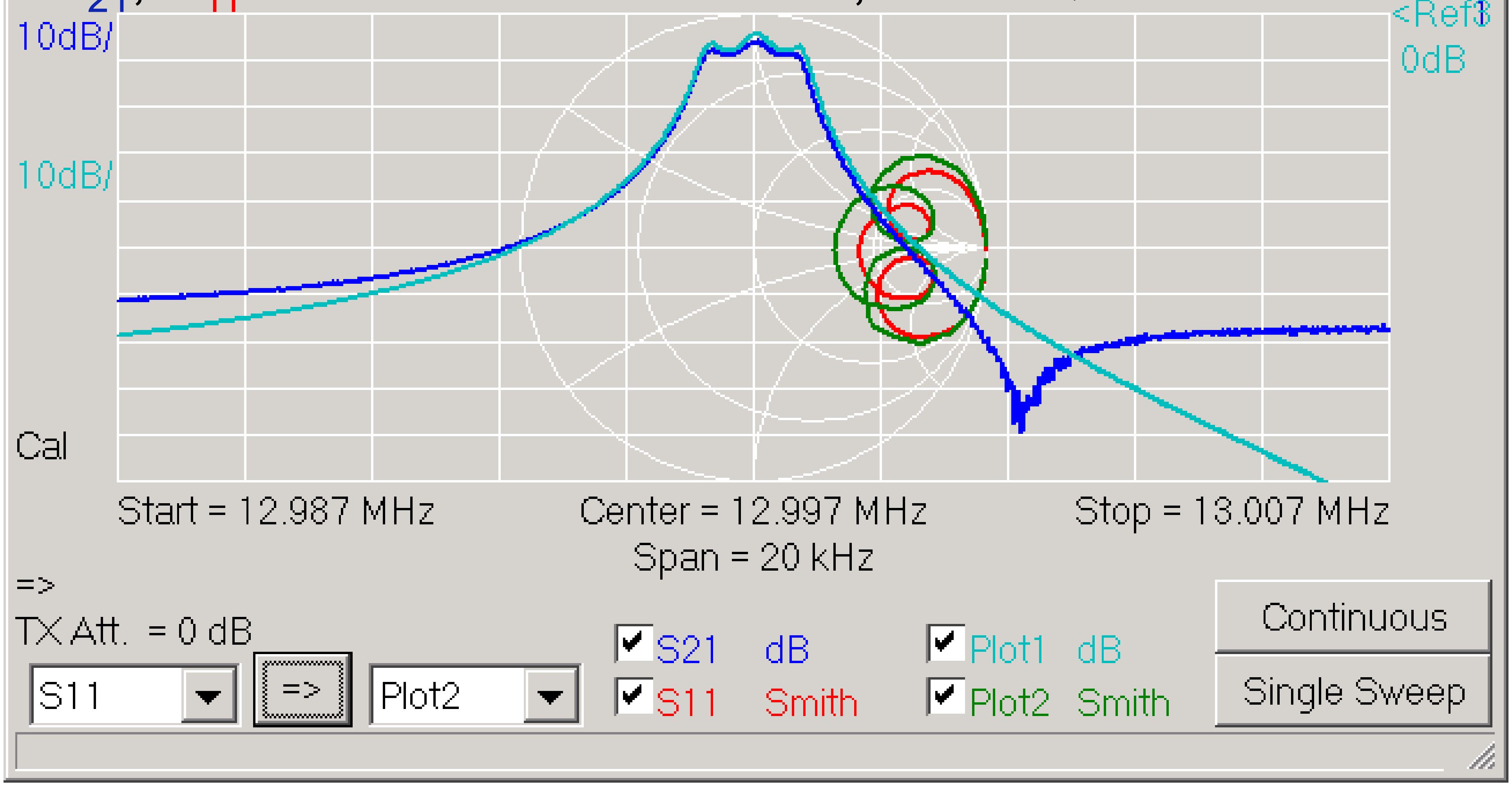
Crystals simulated with s1p-file obtained by VNWA measurement!

Crystal Filter Hardware



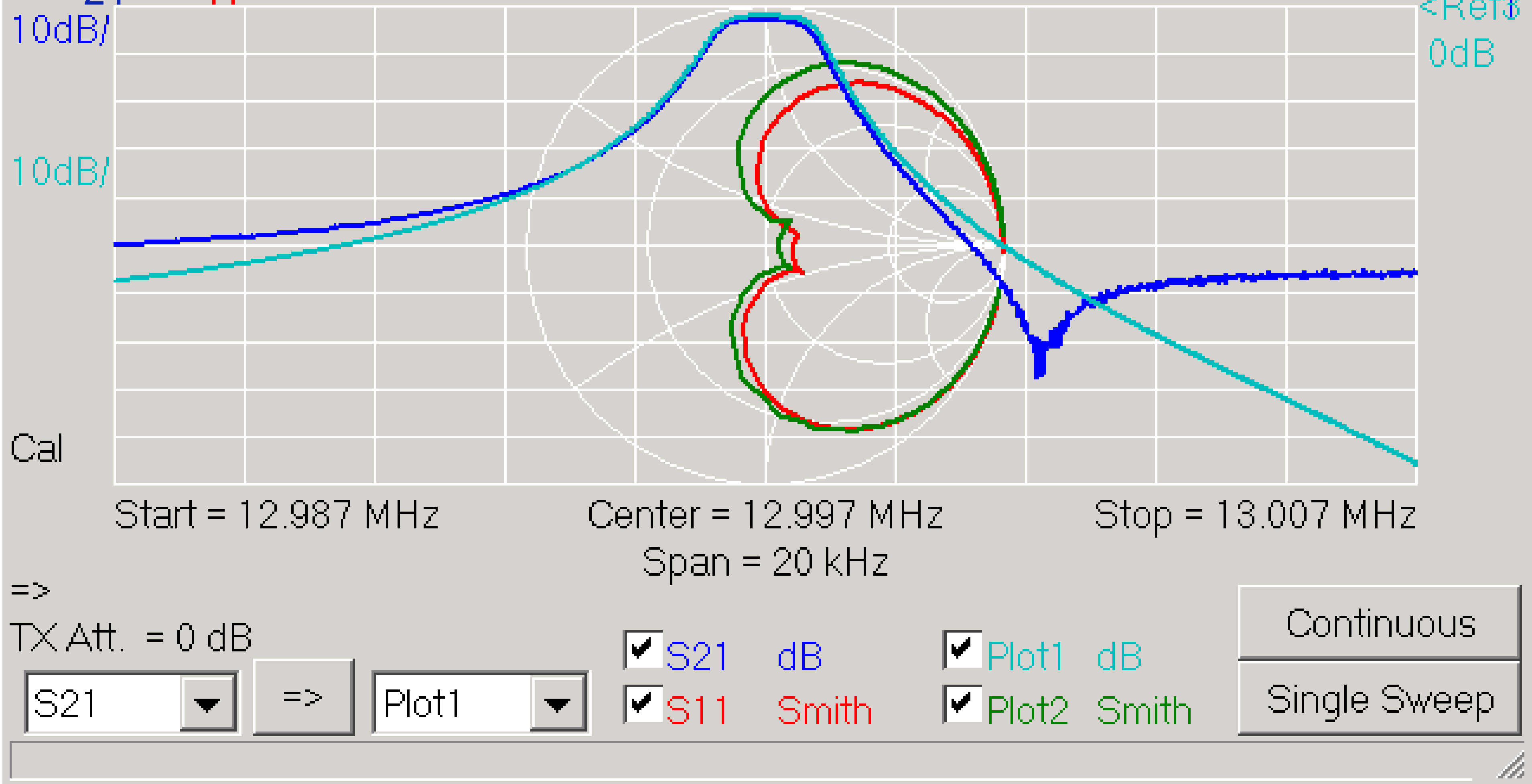
Crystal Filter: Measurement vs. Simulation at 50 Ω

S_{21}, S_{11} measurement - Plot1, Plot2 QUCS simulation



Crystal Filter: Measurement vs. Simulation at 186 Ω

S_{21}, S_{11} measurement - Plot1, Plot2 QUCS simulation



Now, we are able to…

- **Measure components**
- **Design filters**
- **Simulate filters**
- **Measure filters**

Have fun at the workshop!

Hochschule Ulm

Many thanks for your attention!