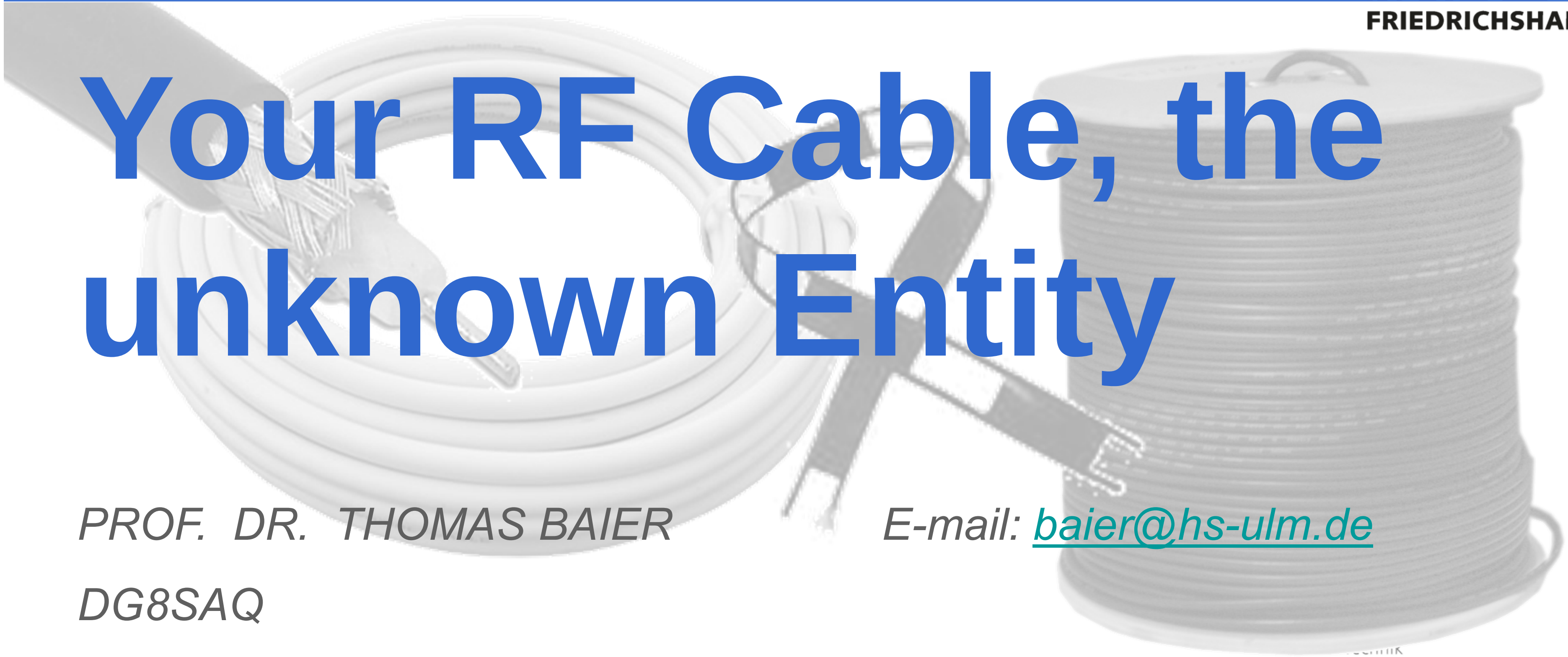

Your RF Cable, the unknown Entity

PROF. DR. THOMAS BAIER *E-mail: baier@hs-ulm.de*

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University of Applied Sciences

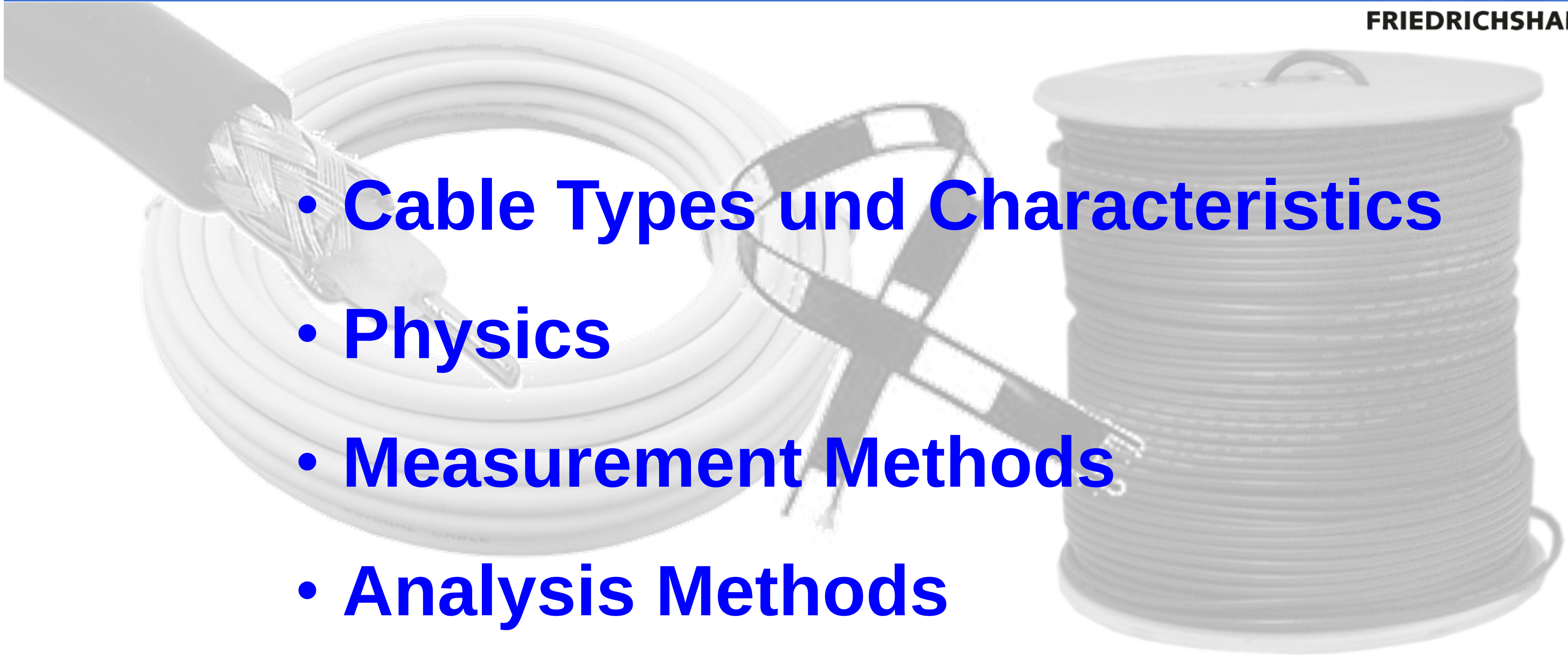
Prittwitzstrasse 10

89075 Ulm

Thanks to: *Dan Maguire AC6LA*

Ferdinand Sigloch DB2SG

Program



- **Cable Types und Characteristics**
- **Physics**
- **Measurement Methods**
- **Analysis Methods**

Cable Types

- Coaxial Line

- Twin-Lead

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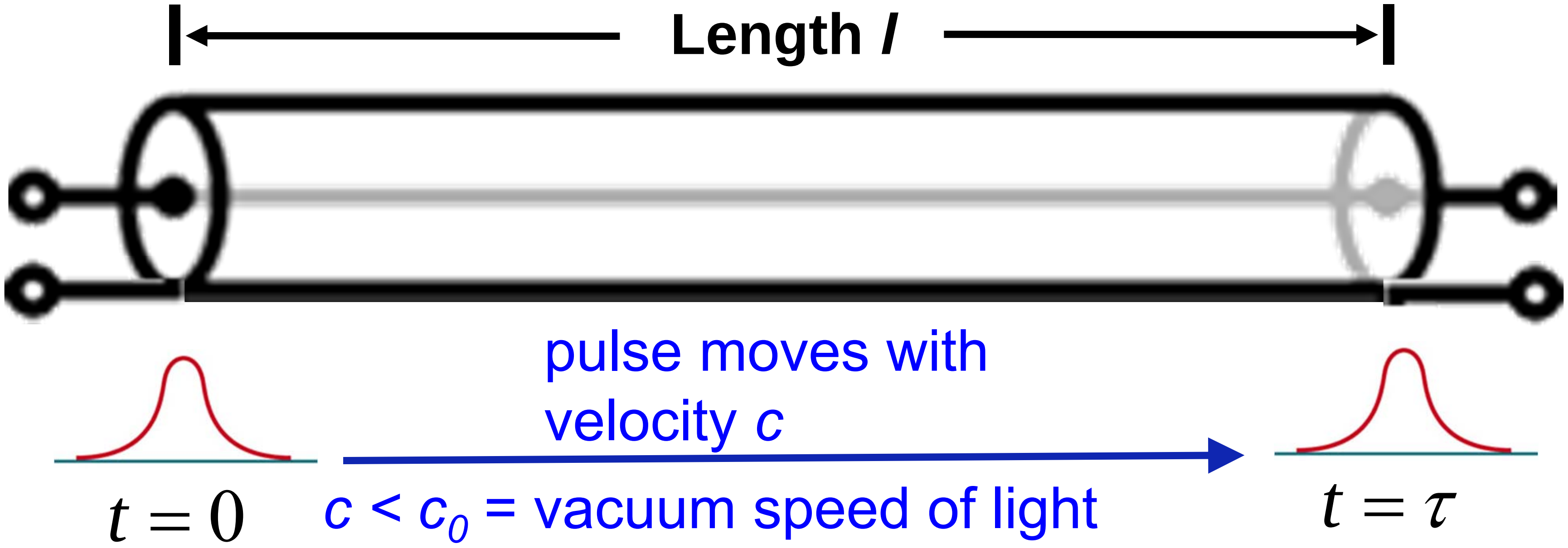
Propagation velocity *c*



Propagation time: τ

Propagation velocity: $c = l / \tau$

Velocity factor: $VF = c / c_0$

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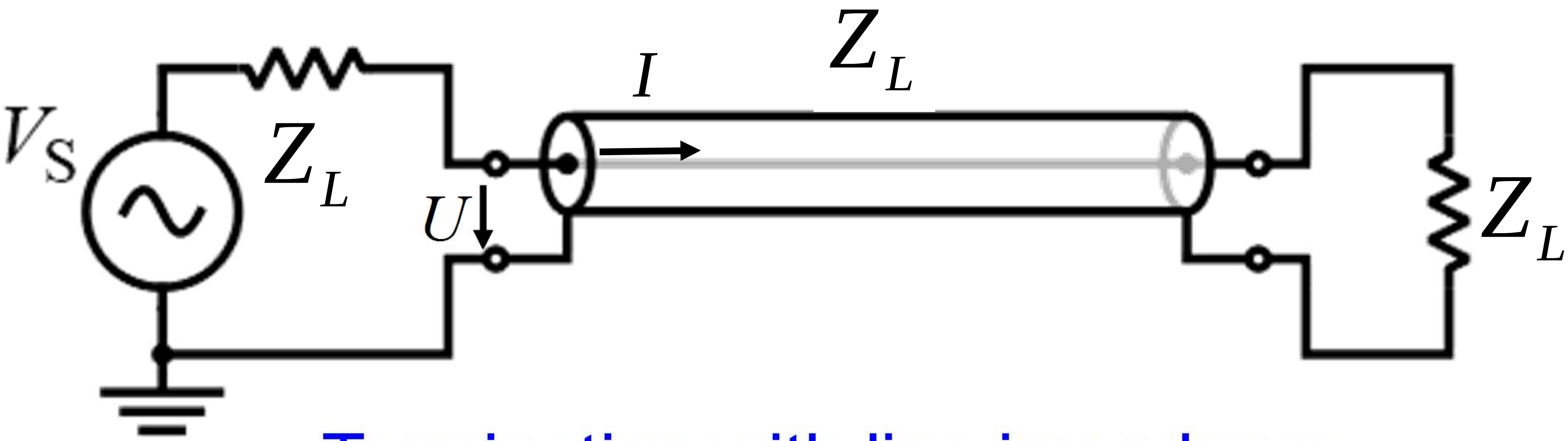
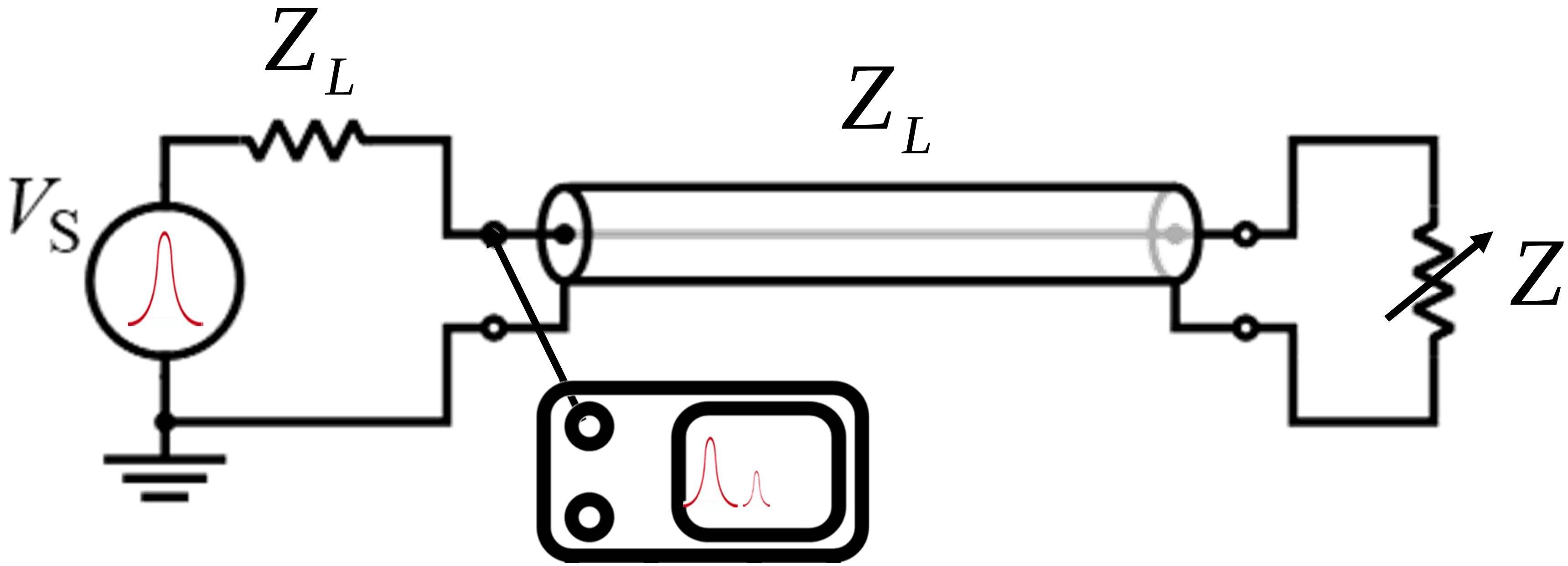
Line Impedance Z_L



Termination with line impedance

$$Z_L = \frac{U}{I}$$

Measuring with Pulse Generator: Pulse Reflectometry (1)



high impedance scope sees outgoing and returning pulses

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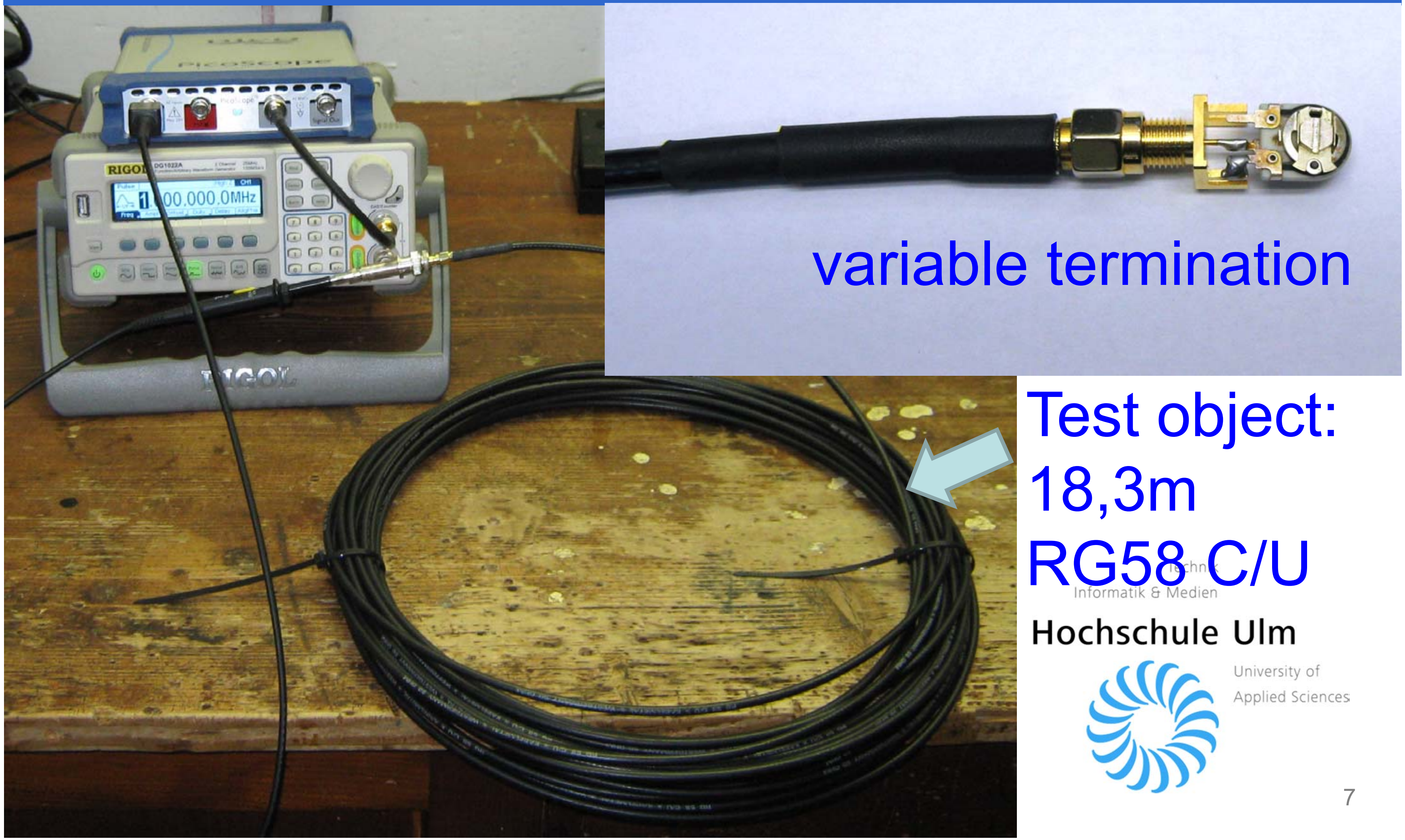
Pulse Reflectometry (2)



Test object:
18,3m
RG58 C/U

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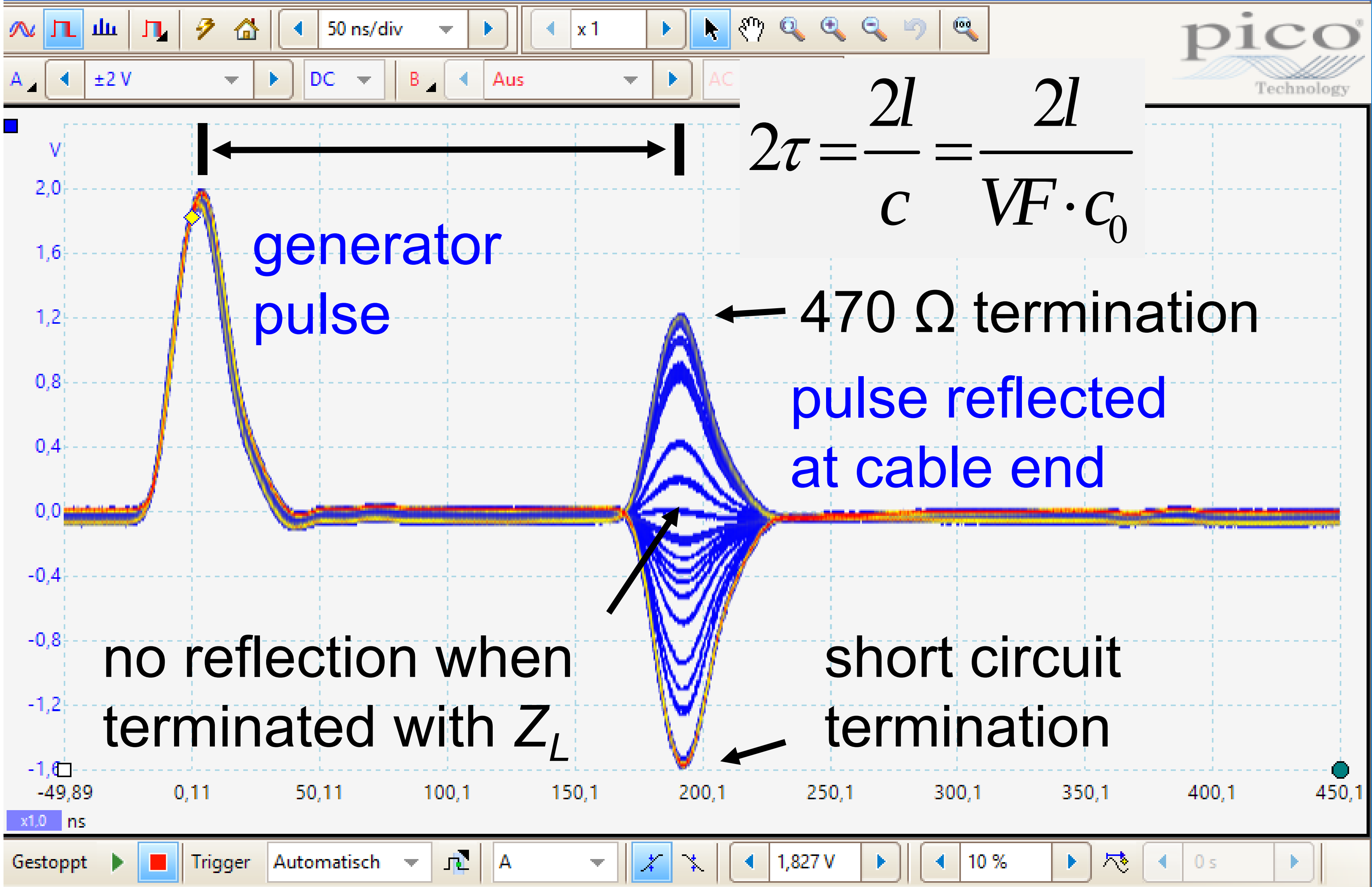
Pulse Reflectometry (3)



$$2\tau = \frac{2l}{c} = \frac{2l}{VF \cdot c_0}$$

Pulse Reflectometry (4)

$$Z = Z_L =$$

Ω ✓

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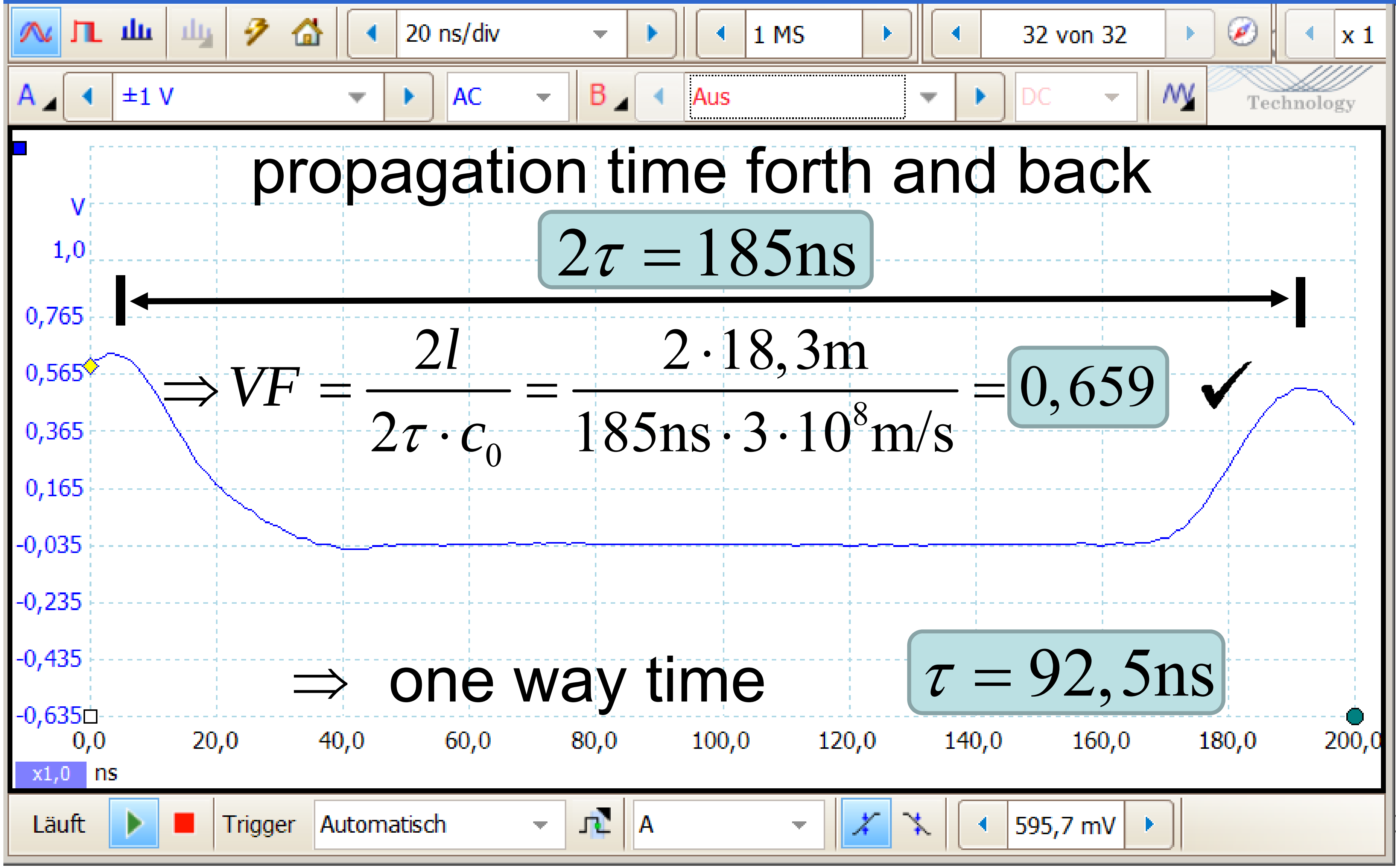
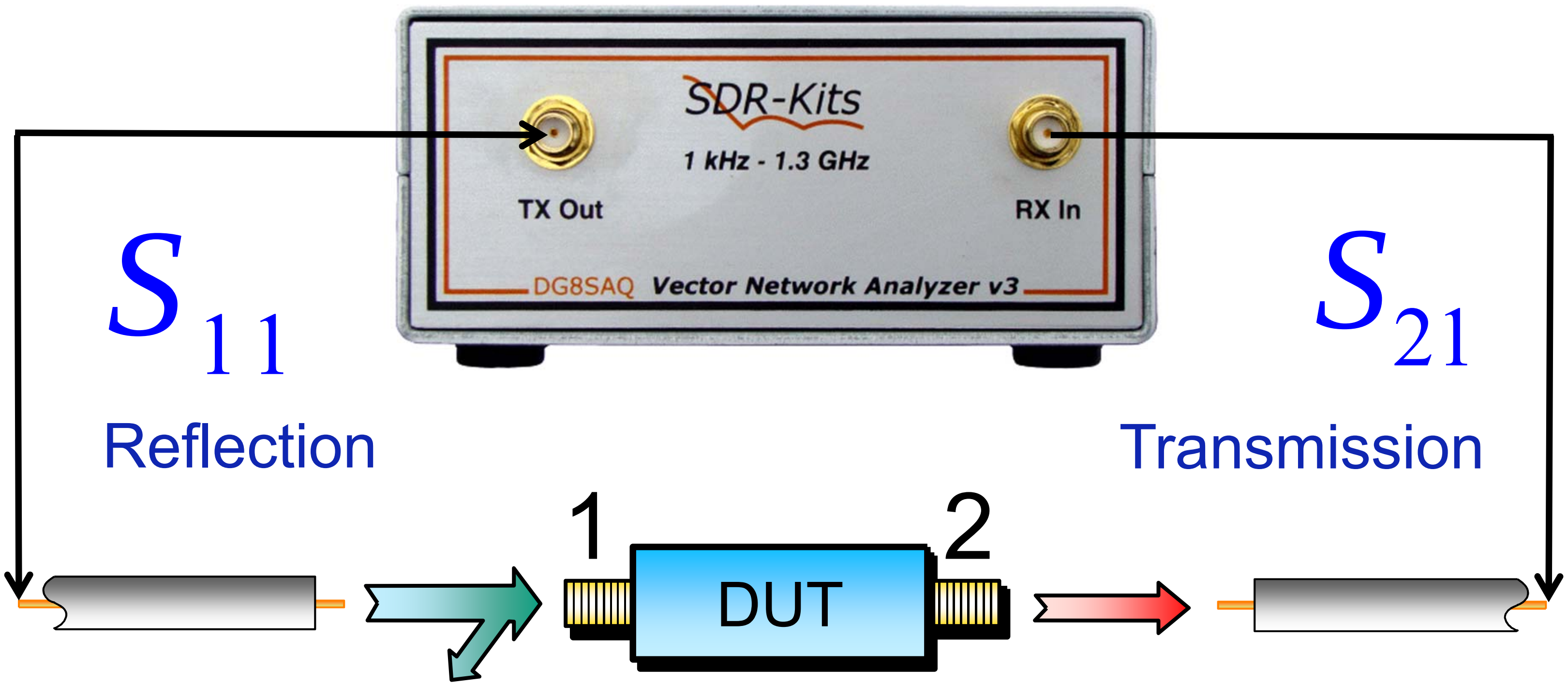
Pulse Reflectometry (5)



More accurate Measurements using a Vector Network Analyzer



DUT : DEVICE UNDER TEST

= Cable

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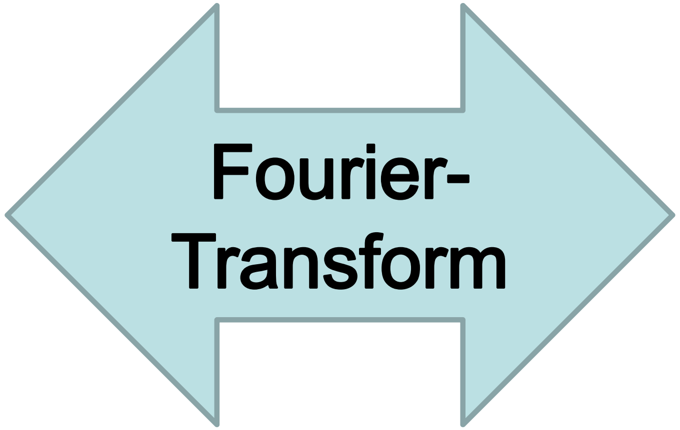
Advantages of Vectorial Network Analysis

- **accurate, high dynamic range**
- **flexible:**

Measuring in Frequency Domain *ω*

- Attenuation
- Match
- Line Impedance
- Group Delay



Time Domain *t*

- Pulse Response
- Step Response

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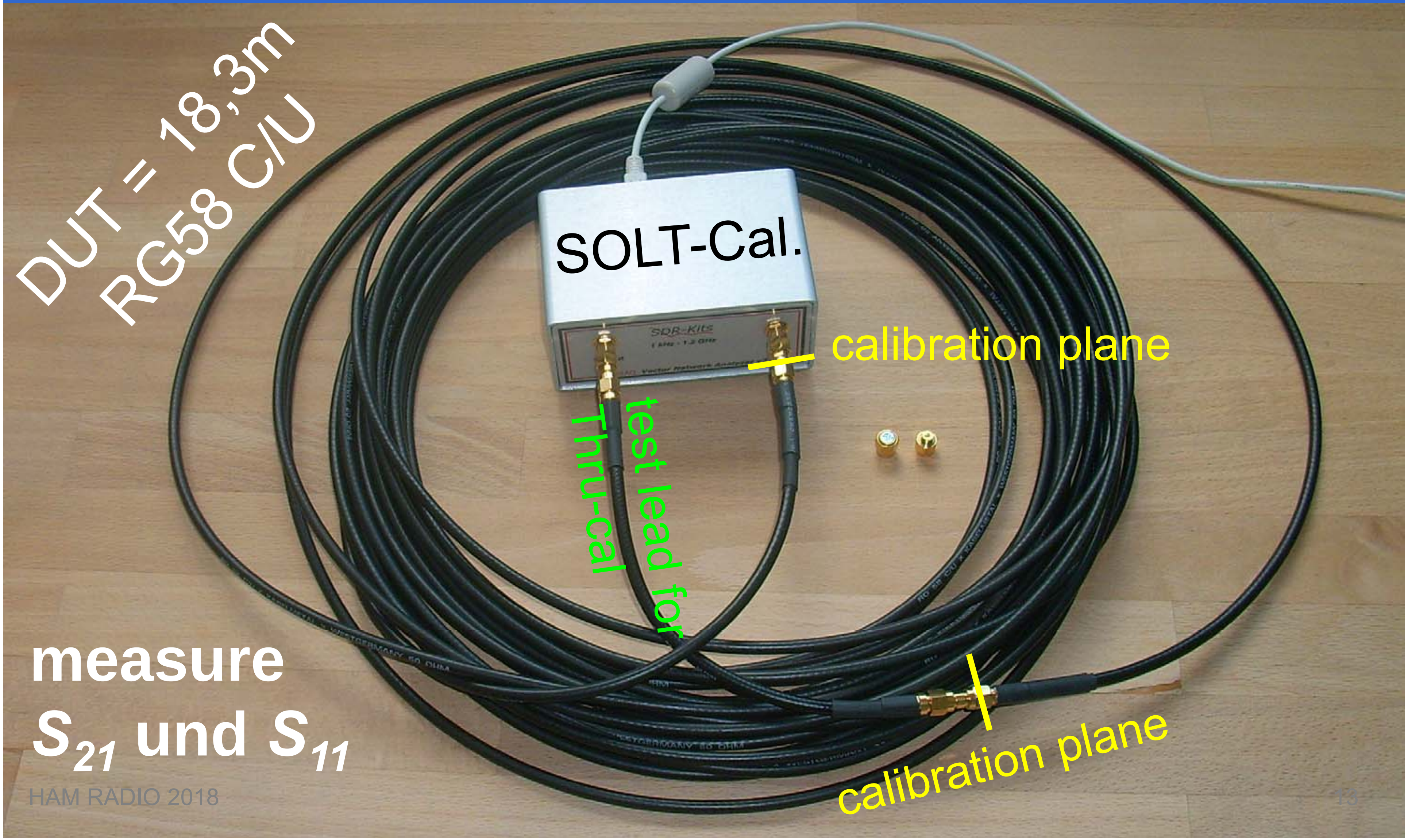
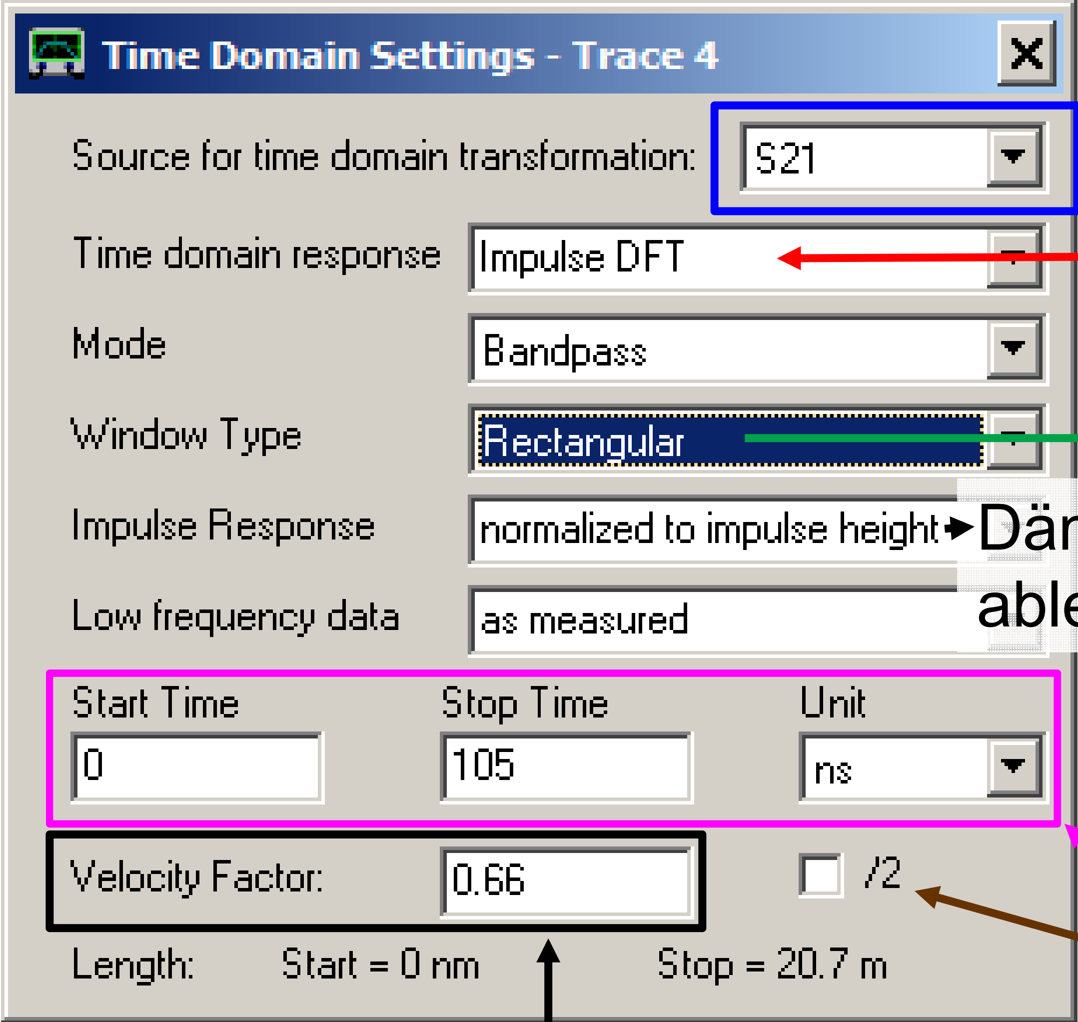
Insertion Loss and Line Impedance of 18.3m RG58 C/U Antenna Cable



Time Domain Analysis using Fourier-Transform (DG8SAQ VNWA Software)



input data to be transformed

Pulse response

windowing function:

time resolution

amplitude resolution improves

Dämpfung ablesbar

plotting range

Propagation time is doubled for reflect signals (S_{11})

velocity faktor

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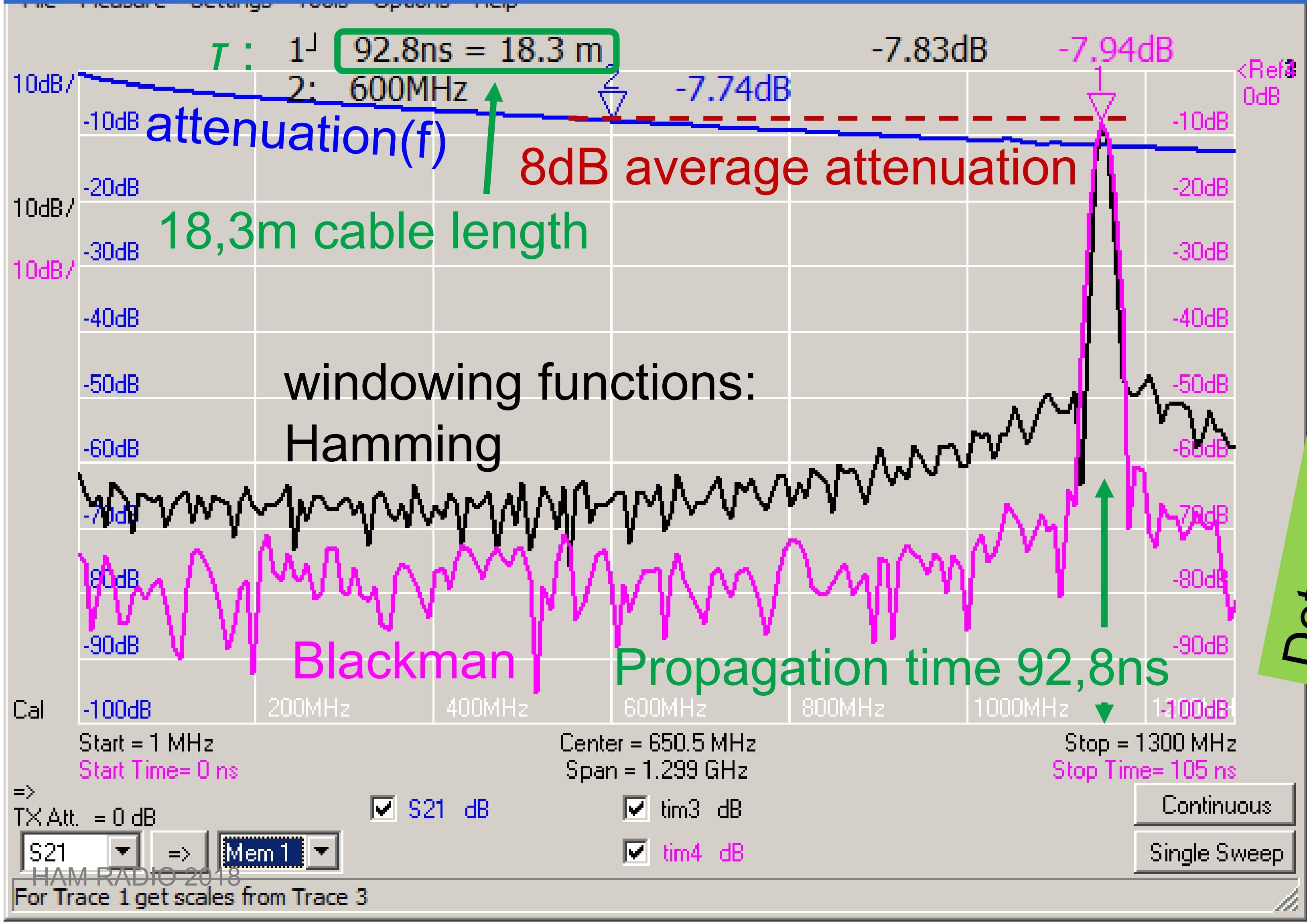
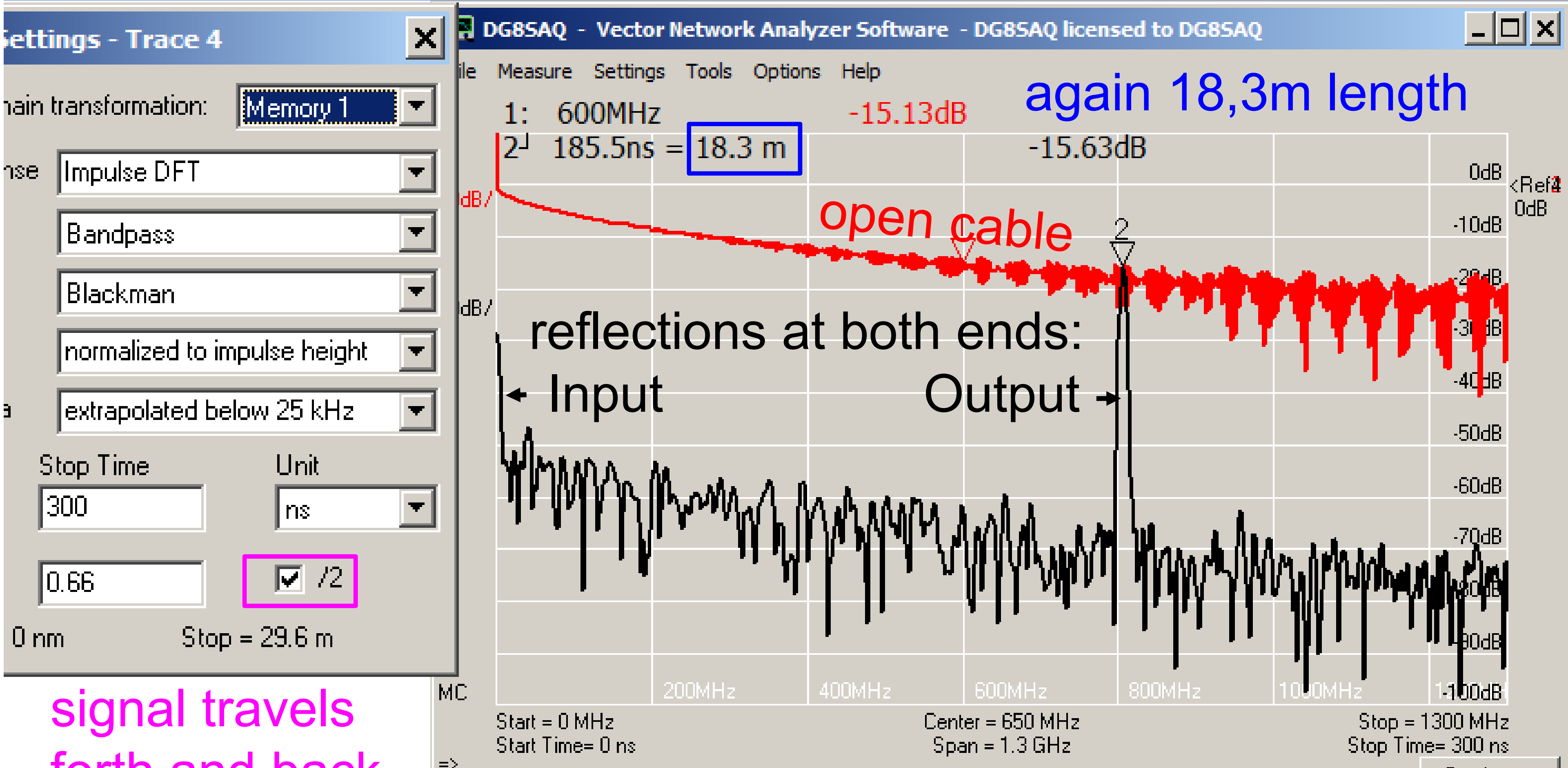
Propagation Delay from Pulse Response of S_{21} Measurement



Determine either cable length or velocity factor

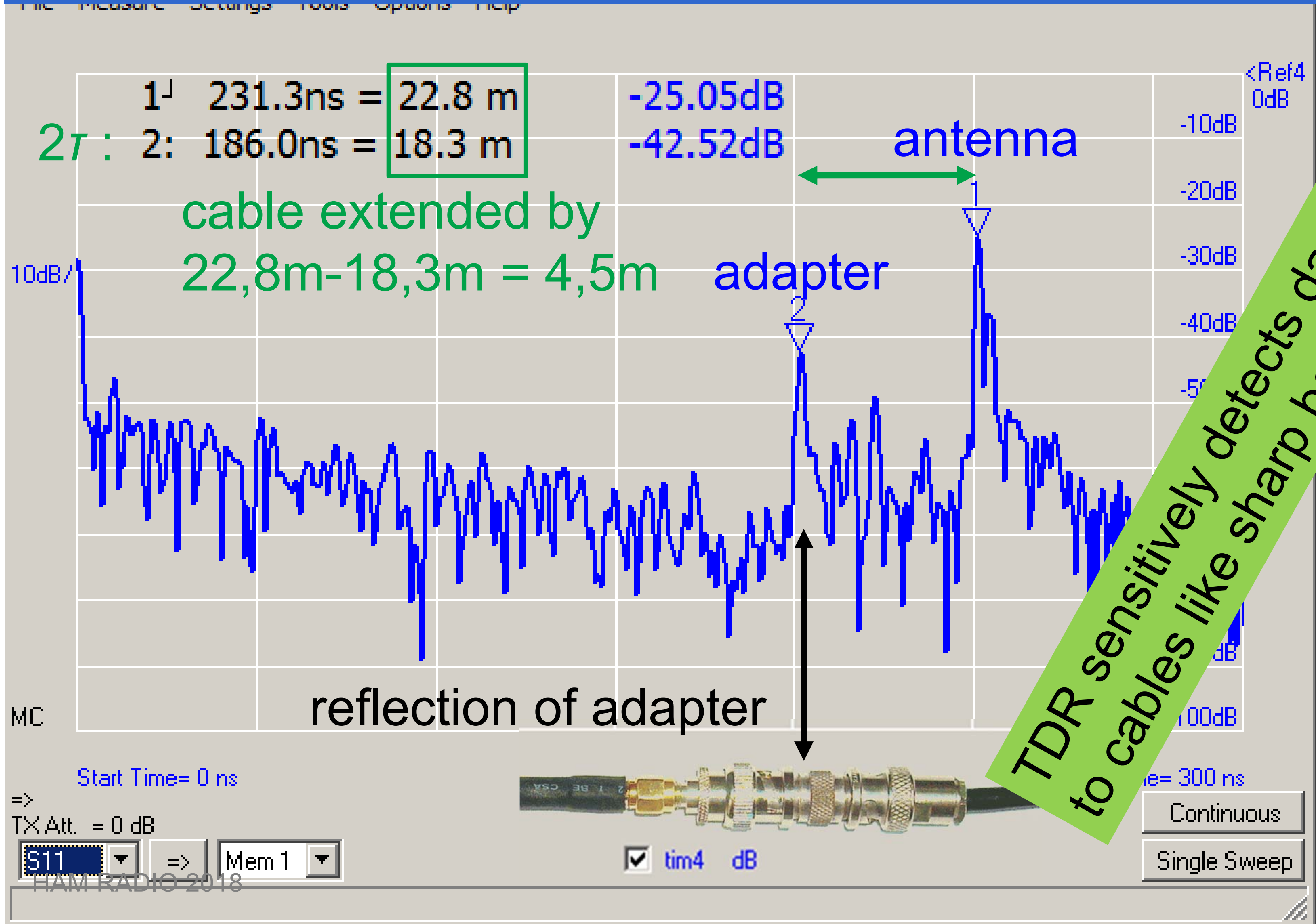
S_{11} of *open ended* Cable in Time Domain: Time Domain **Reflectometry** = TDR



signal travels forth and back

In contrast to pulse generator experiment, here we only see reflected signals.

TDR sees more: Cable Extension + Antenna (S_{11})



TDR sensitively detects damages to cables like sharp bends…

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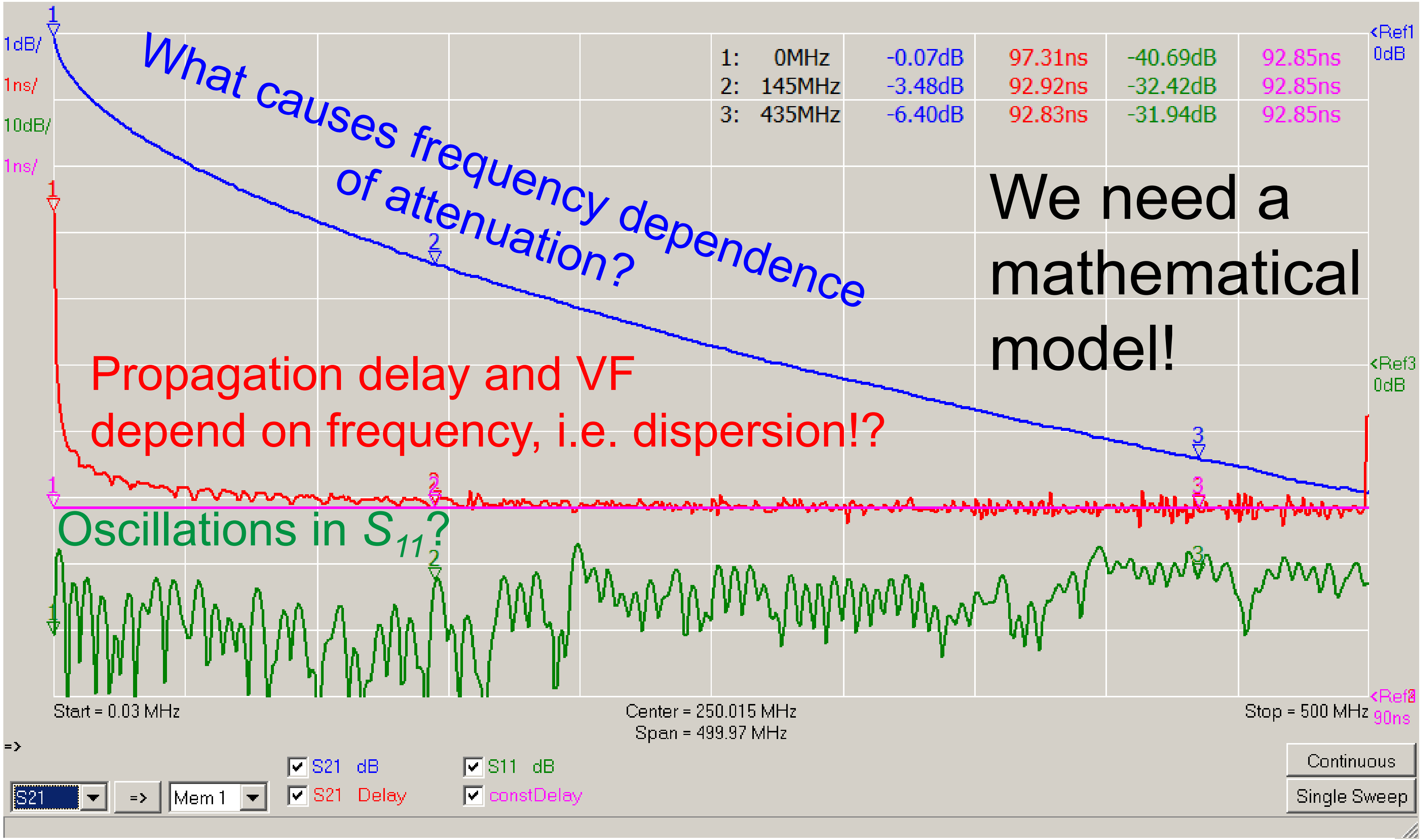
RG58 C/U in Frequency Domain: Open Questions:



Modelling (1)

Relevant properties		Side effects
• Capacitance	⇔	dielectric loss
• Resistance	⇔	dc, skin effekt
• Inductance	⇔	skin effekt

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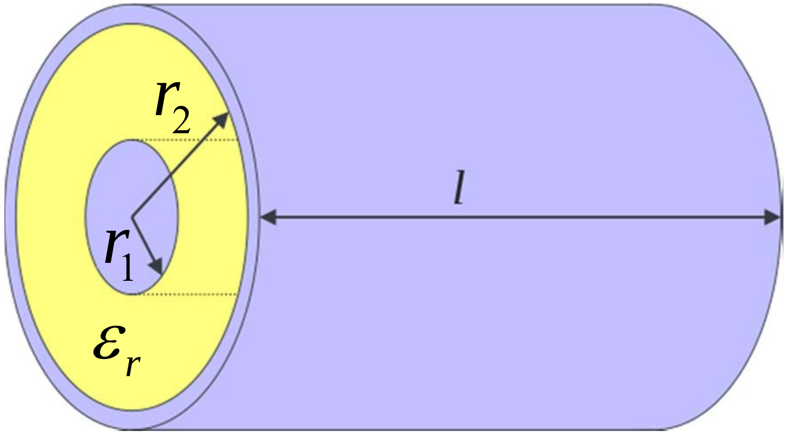
Modelling (2)
A Coax is a Rod Capacitor

$$C' = \frac{C}{l} = \frac{2\pi\varepsilon_0\varepsilon_r}{\ln(r_2/r_1)}$$



Wikipedia

r_1 = 0.45mm
r_2 = 1.5mm
} Data of RG58 C/U From LAPP GROUP

ε_r = 2.25 Polyethylen http://hyperphysics.phy-astr.gsu.edu/hbase/Tables/diel.html

⇨ $$C' = \frac{C}{l} = 104\ \text{pF/m}$$

can be measured…

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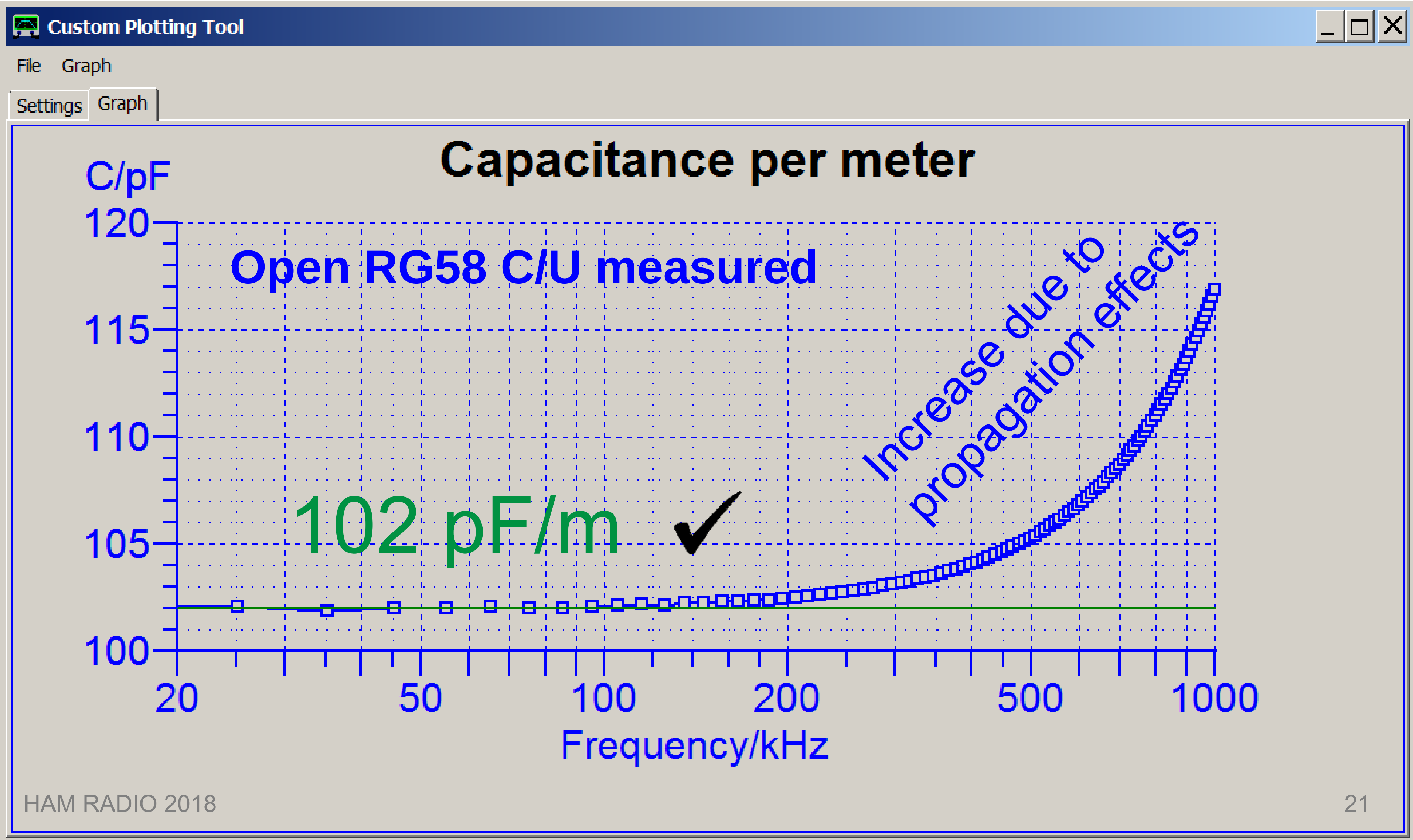
Modelling (3)
Capacitance can be measured



Modelling (4)
Dielektrikum ist komplex, d.h. verlustbehaftet

$$\varepsilon_r = \varepsilon_r' - j \cdot \varepsilon_r'' = \varepsilon_r'(1 - j \cdot \tan(\delta_\varepsilon))$$

δ=loss angle

$$Y_C = j \cdot \omega \cdot C_0 \cdot \varepsilon_r$$

$$= j \cdot \omega \cdot C_0 \cdot \varepsilon_r' \cdot (1 - j \cdot \tan(\delta_\varepsilon))$$

$$= j \cdot \omega \cdot C + \underbrace{\omega \cdot C \cdot \tan(\delta_\varepsilon)}_{\text{Loss} \sim \omega = 2\pi f}$$

C_0 = capacitance without dielectric

$$\Rightarrow C = \varepsilon_r C_0$$

possibly additional dc conductivity G_0:

$$Y_C = j \cdot \omega \cdot C + f \cdot \underbrace{2\pi \cdot C \cdot \tan(\delta_\varepsilon)}_{G_{P0}} + G_0$$

$$\boxed{Y_C = j \cdot \omega \cdot C + f \cdot G_{PO} + G_0}$$

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Modelling (5)
A few Dielectrics

Material	ε_r'	tgδ f = 1MHz	tgδ f = 10GHz
Polyäthylen (PE)	2.25	$2 \cdot 10^{-4}$	$6.6 \cdot 10^{-4}$
Polytetrafluortähylen (PTFE, Teflon)	2.1	10^{-4}	$2.5 \cdot 10^{-4}$
Duroid (Teflon mit Glasfasereinlage)	2.2		10^{-3}

aus „Lineare Elemente der Höchstfrequenztechnik“, Prof. Bächthold, ETH Zürich

$$\Rightarrow G_{PO} = 1.3 \cdot 10^{-13} \frac{\mathrm{S}}{\mathrm{Hz} \cdot \mathrm{m}} \cdots 4.2 \cdot 10^{-13} \frac{\mathrm{S}}{\mathrm{Hz} \cdot \mathrm{m}}$$

PE is an excellent insulator $\Rightarrow G_0 = 0$

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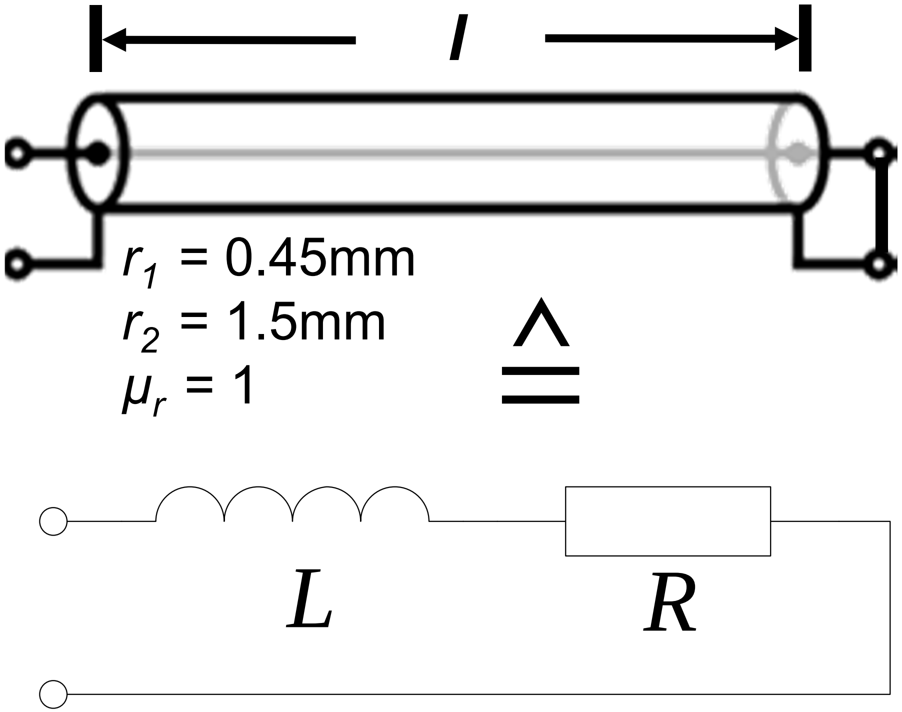
Modelling (6)
Resistance and Inductance per Length

$$R' = \frac{R}{l} = \frac{1}{\sigma_{Cu} \cdot \pi \cdot r_1^2}$$

$$= 25\,\mathrm{m}\Omega/\mathrm{m}$$

(center conductor only)



$$L' = \frac{L}{l} = \frac{\mu_0}{2\pi} \ln(r_2 / r_1)$$

$$= 241\,\mathrm{nH/m}$$

(high frequency limit, no B-field inside conductors)

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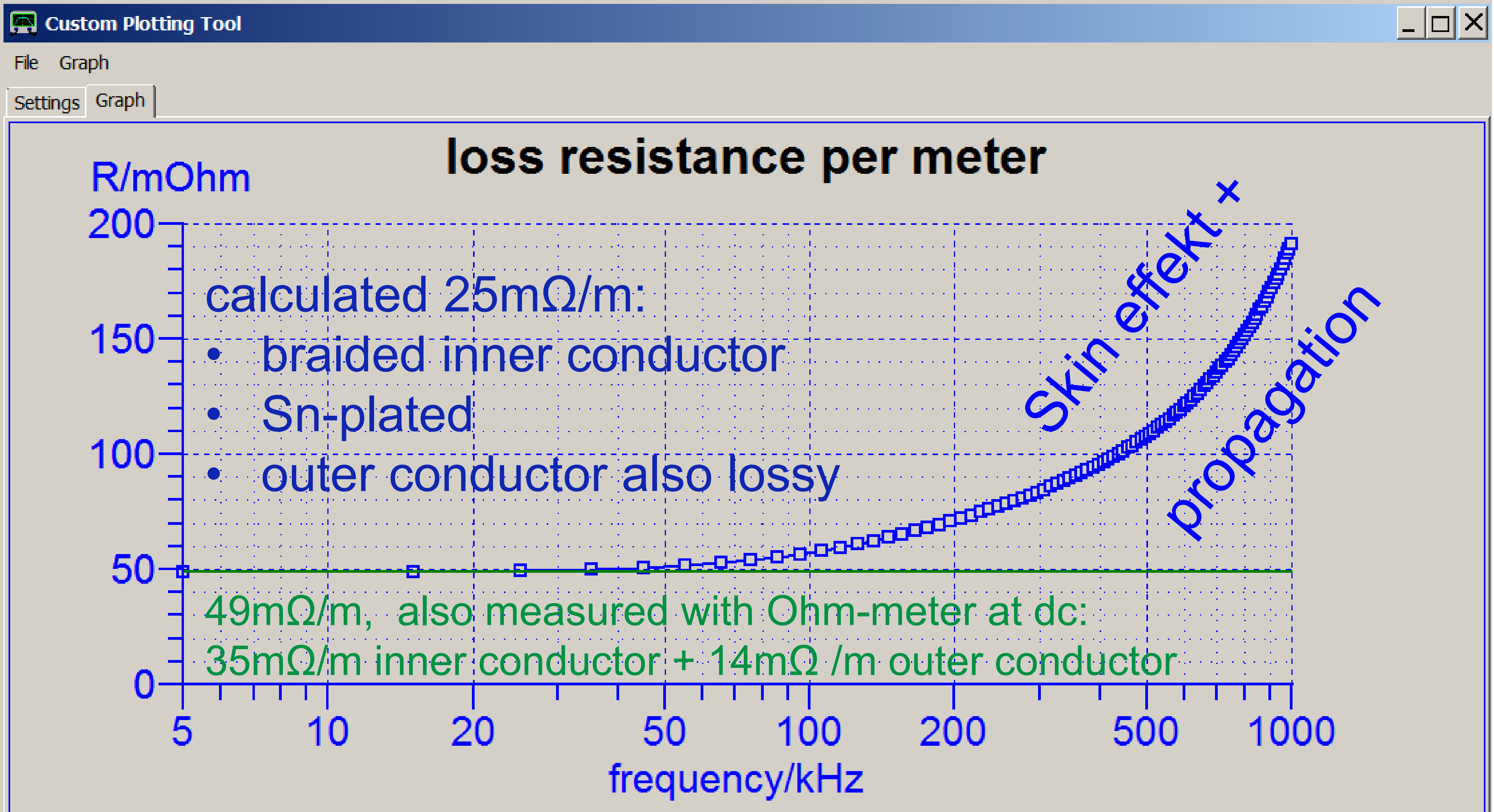
can also be measured…

Shorted Coax is a Resistor at low Frequency

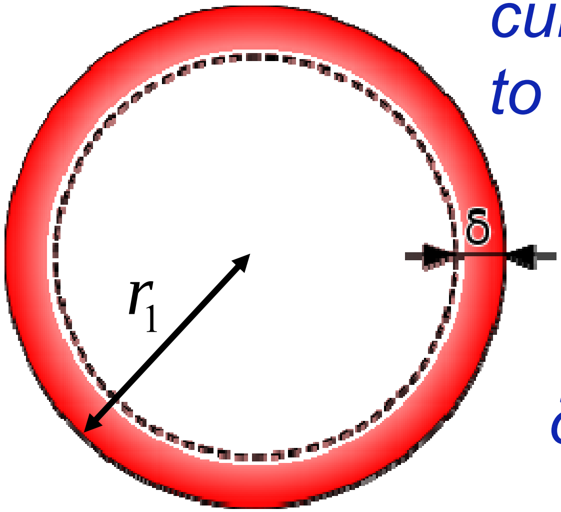


Skin Effect

low frequency

$$R' = \frac{R}{l} = \frac{1}{\sigma_{Cu} \pi r_1^2}$$

high frequency



current confined to surface

$$\delta = \sqrt{\frac{2}{\sigma_{Cu} \cdot \omega \cdot \mu_0}} \sim \frac{1}{\sqrt{f}}$$

δ = penetration depth
= skin depth

$$R' = \frac{1}{\sigma_{Cu} 2\pi r_1 \delta}$$

$$\sim \frac{1}{r_1}\sqrt{f}$$

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Skin Effect in round homogeneous Wire
Result of Maxwells Equations …

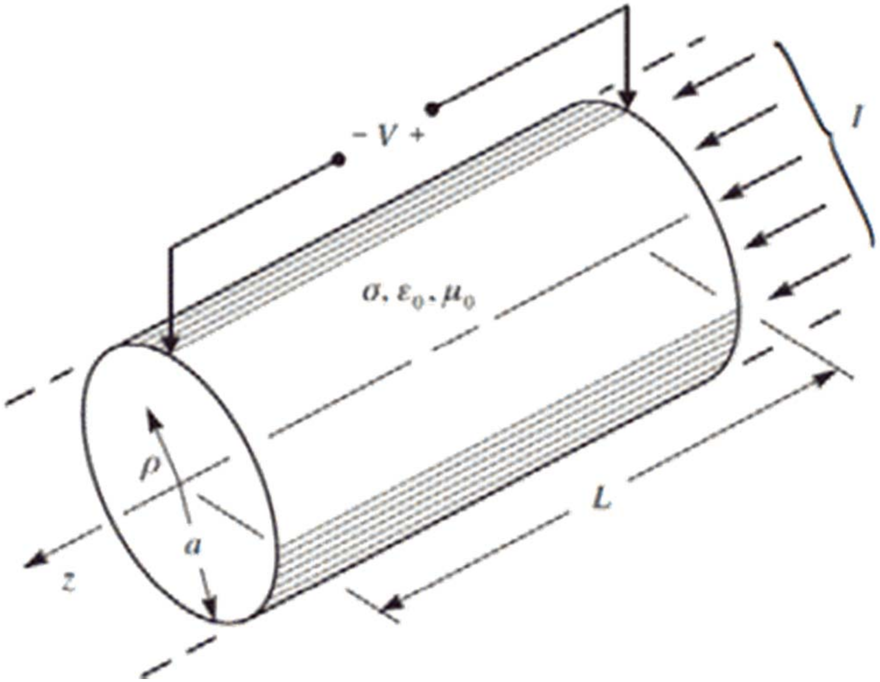
$$z^i(\omega) = r_0 \left\{ \frac{(1 \mp \mathrm{i})a/\delta}{2} \frac{\mathcal{J}_0[(1 \mp \mathrm{i})a/\delta]}{\mathcal{J}_1[(1 \mp \mathrm{i})a/\delta]} \right\}$$

We'll work with this formula!

Impedance per Length (Theory)

$$\delta = \sqrt{\frac{2}{\omega \mu_0 \sigma}}$$

skin depth



$$r_0 = \frac{1}{L}\left[\frac{V|_{\rho=a}}{I}\right] = \frac{R_0}{L} = \frac{1}{\pi a^2 \sigma}$$

dc resistance per length

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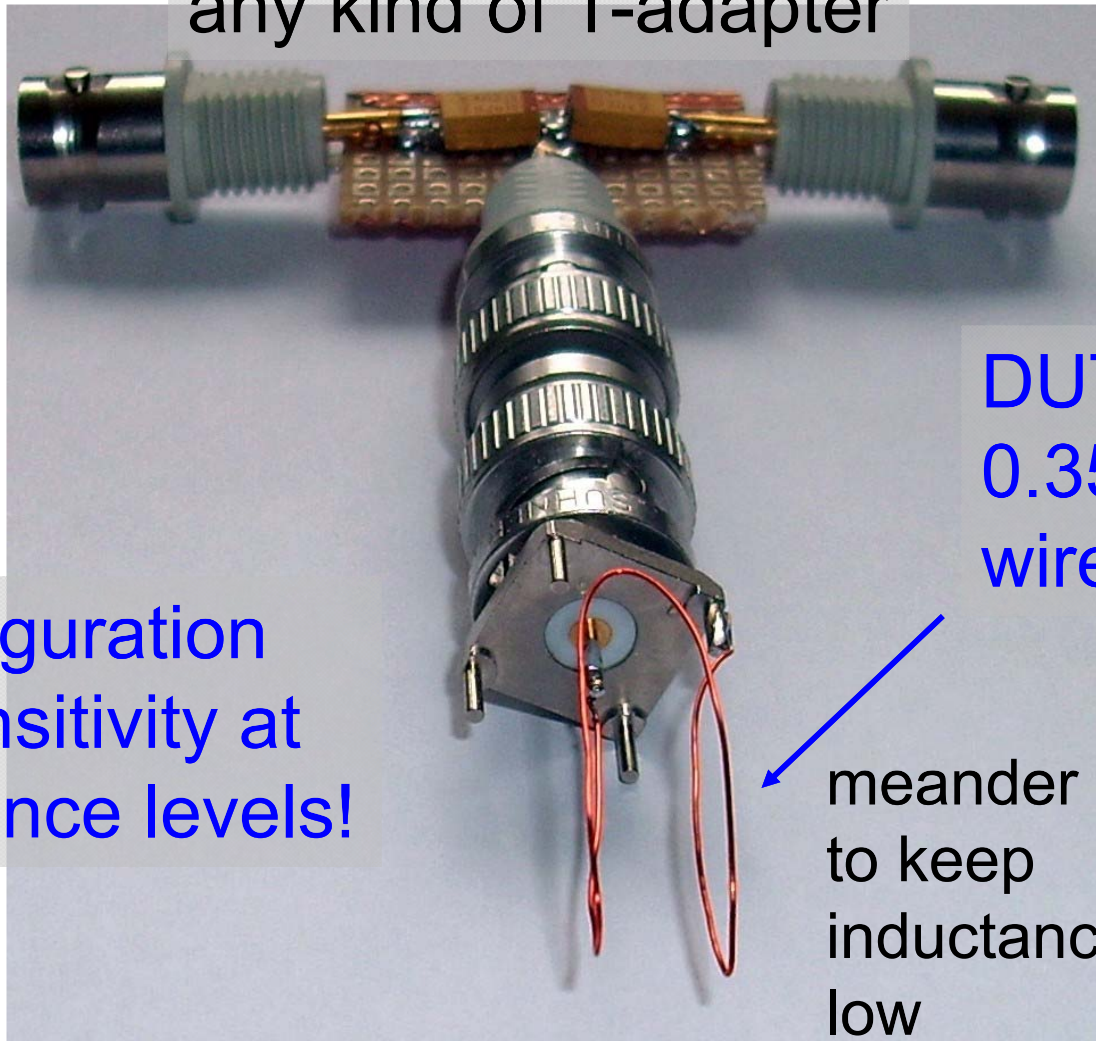
G. S. Smith, Eur. J. Phys. 35, pp.1-13 (2014)

Measurement in Shunt Configuration
DUT: Piece of Copper Wire

any kind of T-adapter

to
VNWA TX

to
VNWA RX



DUT = 10cm
0.35mm CuL-wire

Shunt configuration
for high sensitivity at
low impedance levels!

meander
to keep
inductance
low

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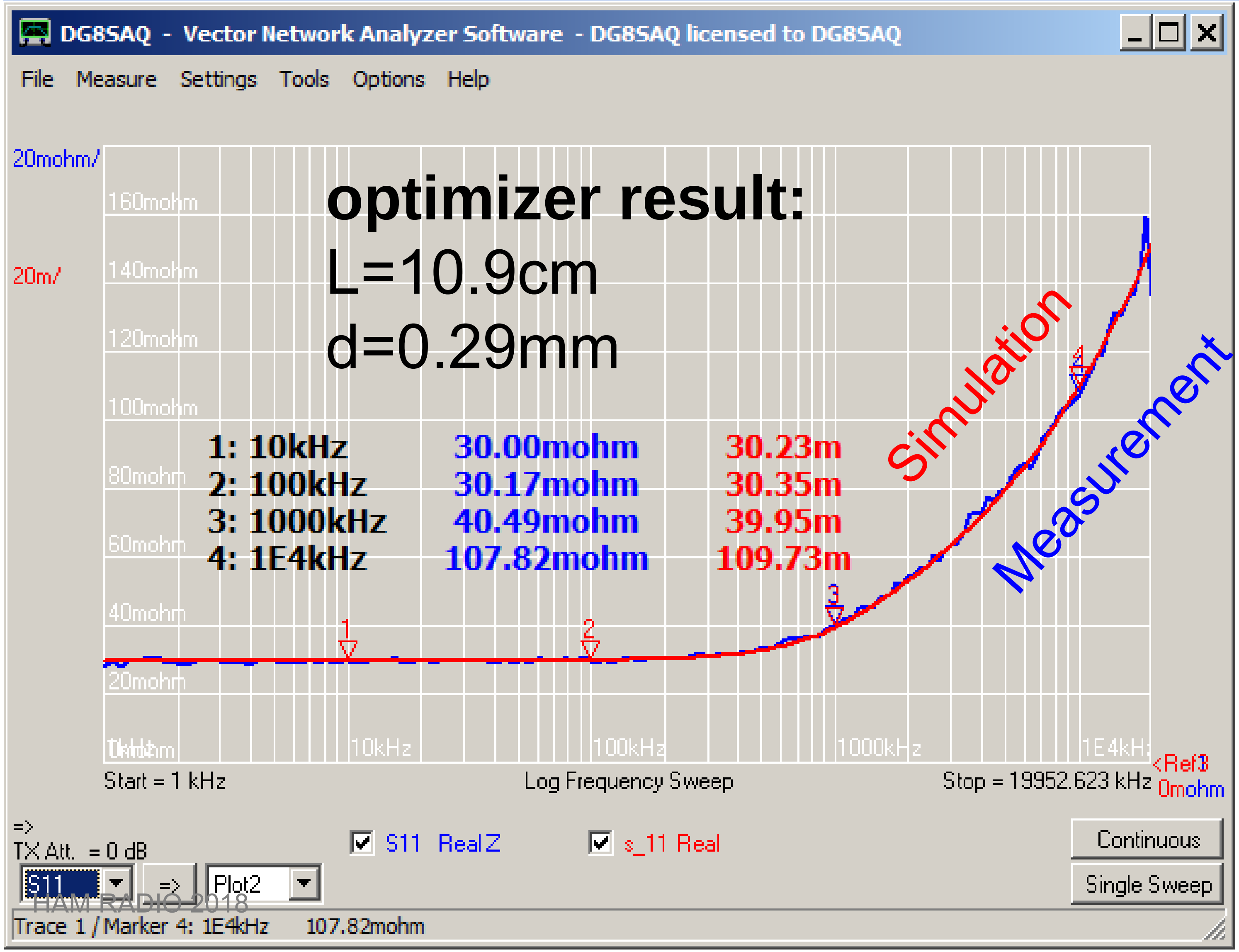
VNWA Optimizer Tool
Simulation vs. Measurement



✔

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Inductance vs. Magnetic Field Energie

energy stored in inductance = *E* = energy stored in magnetic field

$$\frac{1}{2} L \cdot I^2 = E = \frac{1}{2\mu_0} \iiint_{space} B^2 dV$$

$$\Rightarrow L = \frac{1}{I^2 \mu_0} \iiint_{space} B^2 dV$$

$$\Rightarrow L' = \frac{L}{l} = \frac{1}{I^2 \mu_0} \iint_{\text{cross section}} B^2 dF$$

(cylinder symmetry)

Every space segment carrying B-field adds to inductance value!

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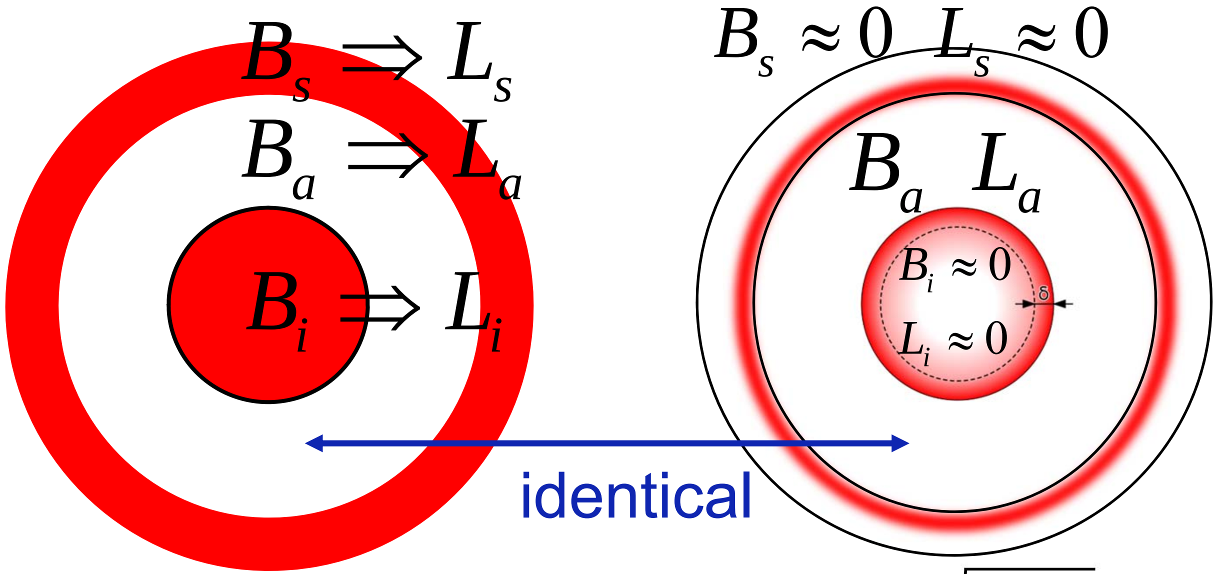
Inductance

low frequency | high frequency



$$L_a' = \frac{L_a}{l} = \frac{\mu_0}{2\pi} \ln\left(\frac{r_2}{r_1}\right)$$

$$= 241\,\mathrm{nH/m}$$ (RG58)

For both cases identical!

$$L_i' = \frac{\mu_0}{8\pi} = 50\frac{\mathrm{nH}}{\mathrm{m}}$$

$$L_s' \approx 6\frac{\mathrm{nH}}{\mathrm{m}}$$ (RG58)

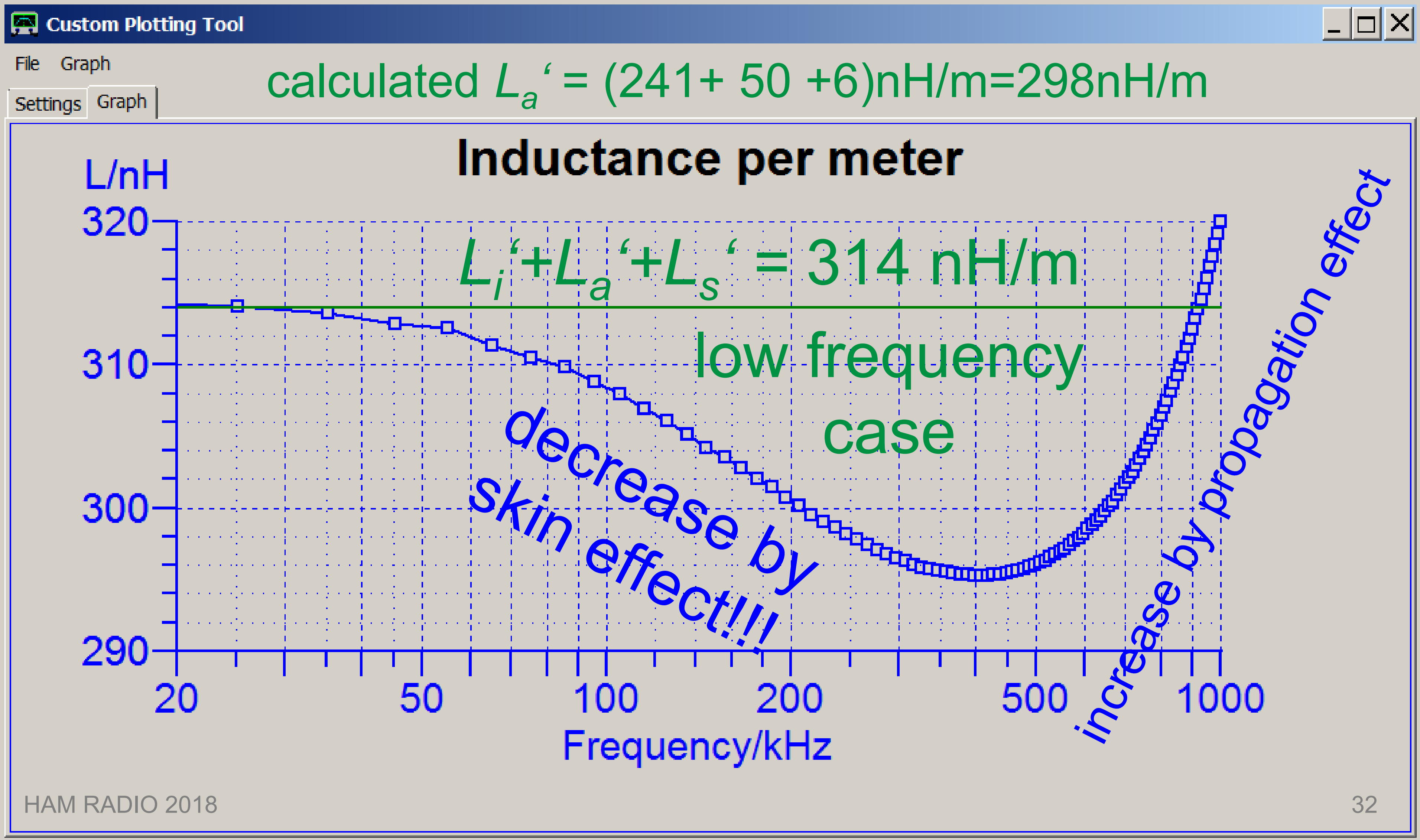
$$L_i' = \frac{1}{2\pi r_1}\sqrt{\frac{\mu_0}{2\sigma_{Cu}}}\frac{1}{\sqrt{\omega}} \sim \frac{1}{\sqrt{f}}$$

$$L_s' \sim 1/\sqrt{f}$$

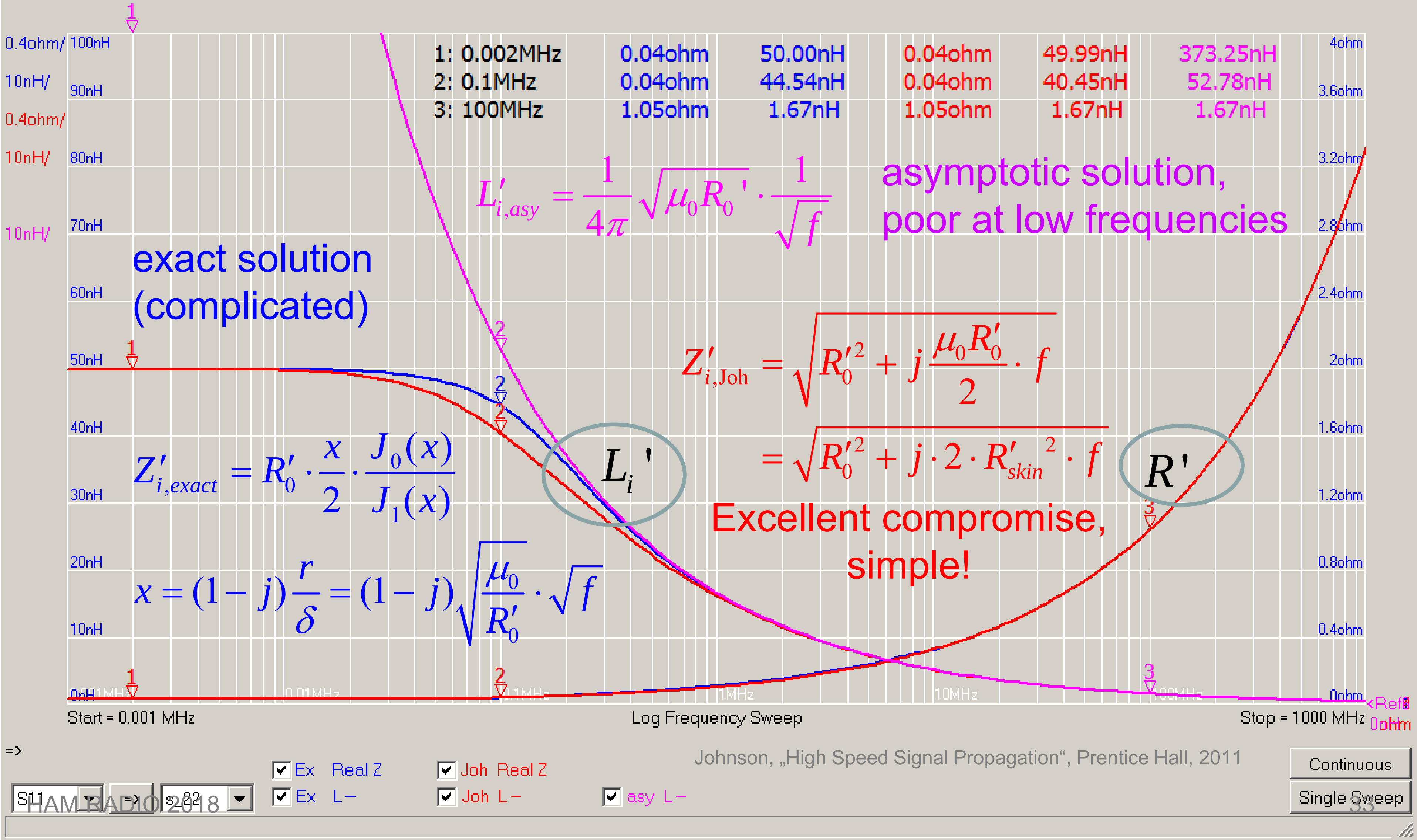
decreases with increasing frequency *f*

$L' = L_i' + L_a' + L_s'$ decreases with increasing frequency *f* !

Induktivitätsmessung am kurzgeschlossenen Koaxkabel



Simple Skin Effect Modell for inner Impedance: Round Wire with Radius r



Johnson, „High Speed Signal Propagation“, Prentice Hall, 2011

Now we know all individual Effects!

- Capacitance
- Resistance
- Inductance

⇒ Effect in Cable?

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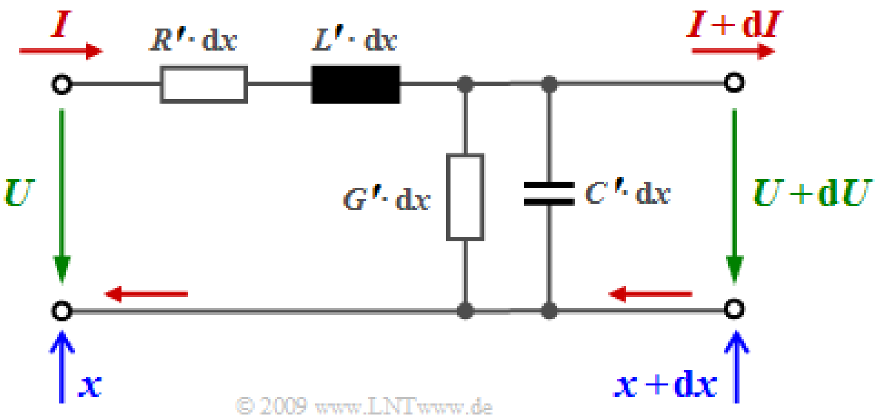
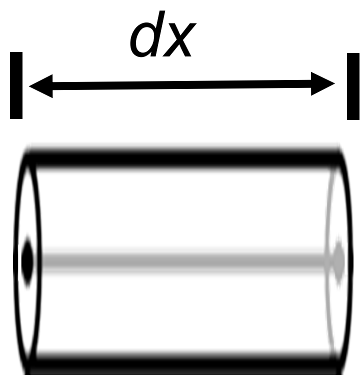
Some RF Transmission Line Theory: Infinitely short Line with Length *dx*



http://www.lntwww.de/Lineare_zeitinvariante_Systeme/Seite2433.html

$\triangleq$



L' = Inductance per Length [H/m]
R' = Wire Resistance per Length [Ω/m]
C' = Capacitance per Length [F/m]
G' = Isolator Conductance per Length [S/m]

$$\frac{dU(x)}{dx} = -(R' + j\omega L') \cdot I(x)$$

$$\frac{dI(x)}{dx} = -(G' + j\omega C') \cdot U(x)$$

mit $\gamma = \sqrt{(R' + j\omega L')(G' + j\omega C')}$

$$Z_L = \sqrt{\frac{R' + j\omega L'}{G' + j\omega C'}}$$

$$\Rightarrow U(x) = a \cdot \cosh(\gamma x) + b \cdot \sinh(\gamma x)$$

Finite length x

Z- and S-Matrix of Line

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Useful Results: High Frequency Limit (i.e. ω is large)

R‘ and *G‘* may be neglected with respect to *ωC‘* and *ωL‘* :

$$\gamma = \sqrt{j\omega L' \cdot j\omega C'} = j\omega\sqrt{L' \cdot C'} = \frac{j\omega}{c} = \frac{j\omega}{C_0 \cdot VF}$$

$$\Rightarrow \sqrt{L' \cdot C'} = \frac{1}{C_0 \cdot VF}$$

Also in this limit:

$$\sqrt{\frac{L'}{C'}} = Z_L = const$$

Thus, *L‘* and *C‘* can be expressed by Z_L and *VF*:

$$L' = \frac{Z_L}{C_0 \cdot VF} \qquad C' = \frac{1}{Z_L \cdot C_0 \cdot VF}$$

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L' and *C'* may be computed from Z_L and *VF*!

Example RG58:

$$Z_L = 50\Omega$$
$$VF = 0,66$$

$$C' = \frac{1}{Z_L \cdot C_0 \cdot VF} = \frac{1}{50\Omega \cdot 3 \cdot 10^8 \,\mathrm{m/s} \cdot 0,66} = 101\,\frac{\mathrm{pF}}{\mathrm{m}}$$ ✓

$$L' = \frac{Z_L}{C_0 \cdot VF} = \frac{50\Omega}{3 \cdot 10^8 \,\mathrm{m/s} \cdot 0,66} = 253\,\frac{\mathrm{nH}}{\mathrm{m}}$$ high freq. limit! ✓

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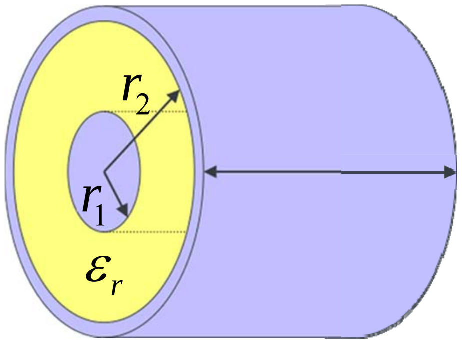
Why 50Ω?

High frequency limit:

$$L' = \frac{\mu_0}{2\pi}\ln\left(\frac{r_2}{r_1}\right), \qquad C' = \frac{2\pi\varepsilon_0\varepsilon_r}{\ln(r_2/r_1)}$$

$$\Rightarrow Z_L = \sqrt{\frac{L'}{C'}} = \frac{60\Omega}{\sqrt{\varepsilon_r}} \cdot \ln\left(\frac{r_2}{r_1}\right)$$



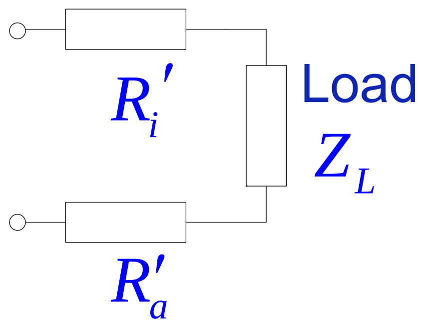
Voltage drop on outer and inner conductor:

$$\Delta U \sim \frac{R_i' + R_a'}{Z_L} \sim \frac{1/r_1 + 1/r_2}{\ln(r_2/r_1)} = \frac{1}{r_2} \cdot \frac{r_2/r_1 + 1}{\ln(r_2/r_1)}$$

Thicker cables have lower loss! (→ r_2)

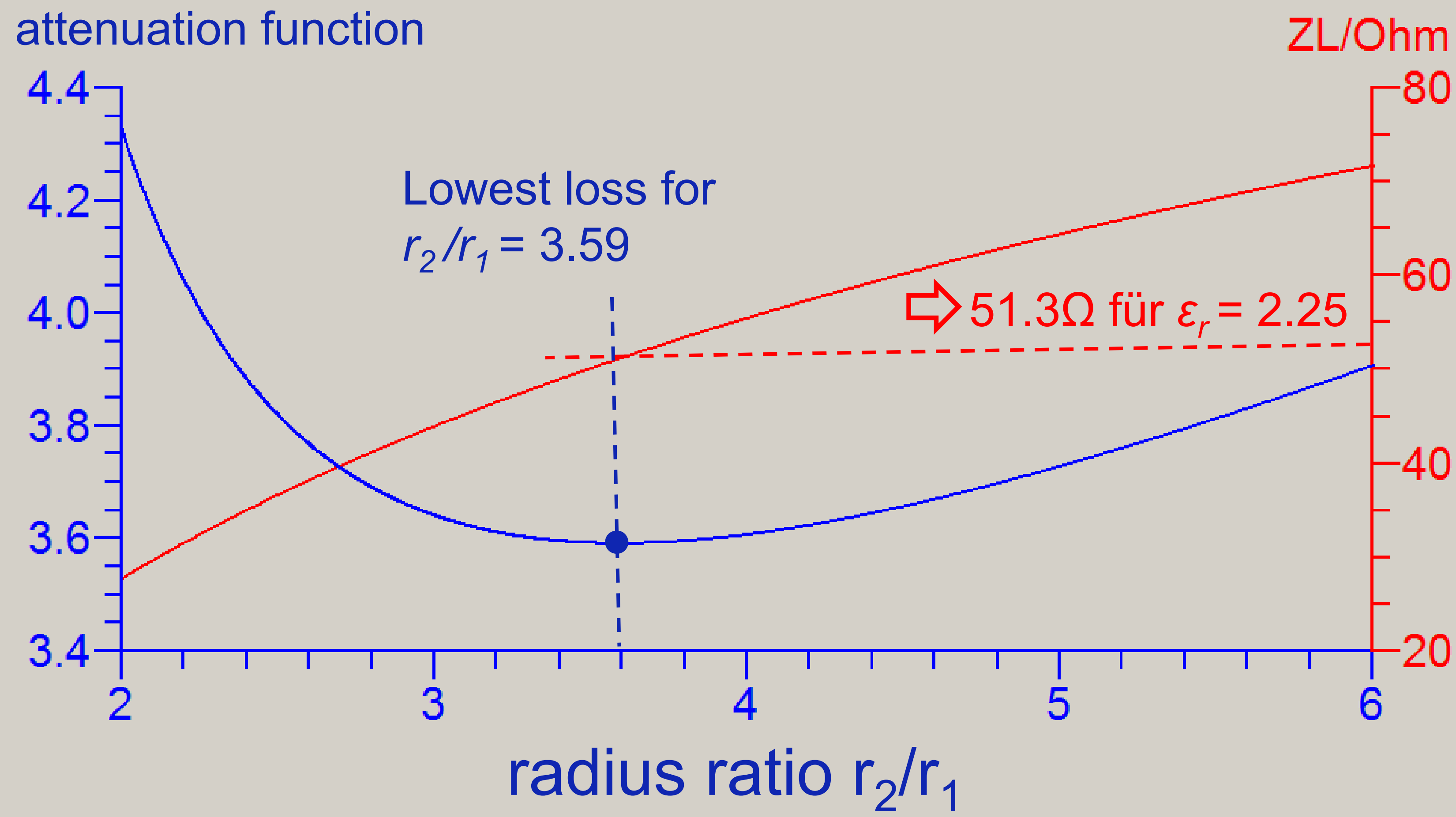
attenuation function: $\frac{r_2/r_1 + 1}{\ln(r_2/r_1)}$

Voltage divider



Line impedance and attenuation function only depend on r_2/r_1 radius ratio!

This is why 50Ω: Minimum Loss!



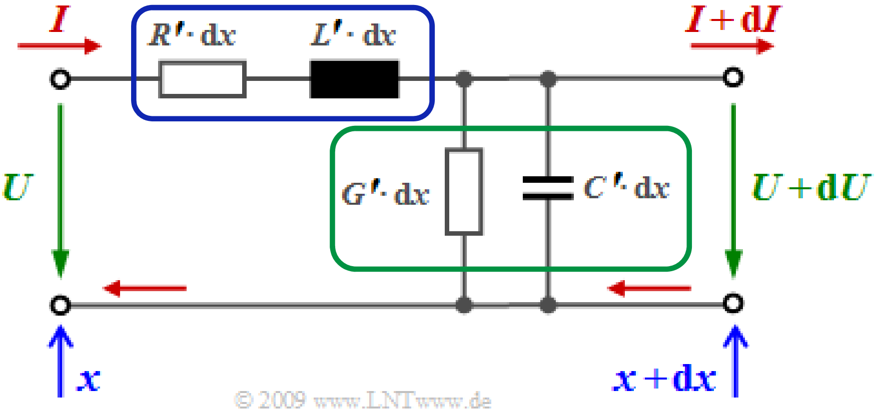
Model Summary

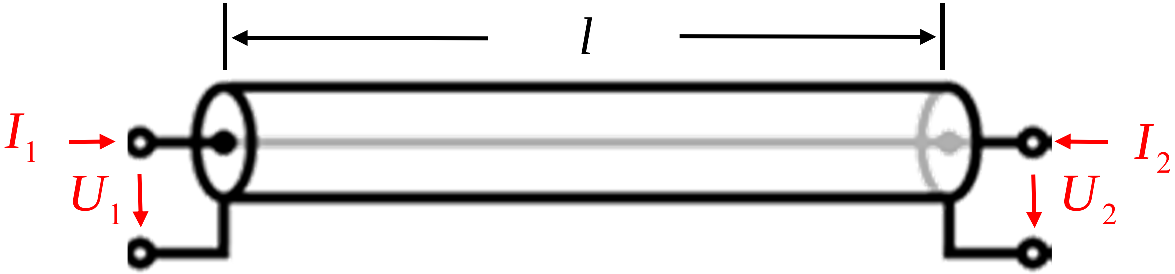
$$R' + j\omega L' = \sqrt{R_0'^2 + j \cdot 2R_{skin}'^2 \cdot f} + j\omega L_a'$$

$$G' + j\omega C' = G_0' + f \cdot G_{PO}' + j \cdot \omega \cdot C_0'$$

$$\gamma = \sqrt{(R' + j\omega L')(G' + j\omega C')}$$

$$Z_L = \sqrt{\frac{R' + j\omega L'}{G' + j\omega C'}}$$





$$\begin{pmatrix} U_1 \\ U_2 \end{pmatrix} = \frac{Z_L}{\sinh(\gamma l)} \begin{pmatrix} \cosh(\gamma l) & 1 \\ 1 & \cosh(\gamma l) \end{pmatrix} \cdot \begin{pmatrix} I_1 \\ I_2 \end{pmatrix}$$

Z-matrix , may be converted to S-matrix

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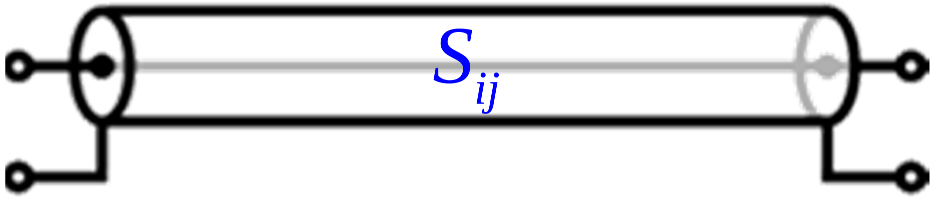
Conversion to *S*-Matrix



$$S_{11} = \frac{R}{\Delta} \qquad S_{21} = \frac{T}{\Delta}$$

$$z_L = Z_L / Z_0 \quad \text{with} \quad Z_0 = \text{reference impedance, i.e. } 50\Omega$$

$$\Delta = e^{2\gamma l} \cdot (z_L{}^2 + 2z_L + 1) - z_L{}^2 + 2z_L - 1$$

$$R = (z_L{}^2 - 1) \cdot (e^{2\gamma l} - 1)$$

$$T = 4 z_L e^{\gamma l}$$

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Special Case Example $Z_L = Z_0$ i.e. $z_L=1$

$$z_L = Z_L / Z_0 = 1$$

$$\Delta = e^{2\gamma l} \cdot (z_L{}^2 + 2z_L + 1) - z_L{}^2 + 2z_L - 1 = e^{2\gamma l} \cdot 4$$

$$R = (z_L{}^2 - 1) \cdot (e^{2\gamma l} - 1) = 0$$

$$T = 4 z_L e^{\gamma l} = 4 \cdot e^{\gamma l}$$

$$\Rightarrow S_{11} = \frac{R}{\Delta} = 0 \qquad S_{21} = \frac{T}{\Delta} = \frac{4e^{\gamma l}}{4e^{2\gamma l}} = e^{-\gamma l}$$

- matched

- loss
- delay

Useful Equation to calculate Line Impedance from measured S_{ij}

$$Z_L = Z_0 \cdot \sqrt{\frac{S_{11}{}^2 - S_{21}{}^2 + 1 + 2S_{11}}{S_{11}{}^2 - S_{21}{}^2 + 1 - 2S_{11}}}$$

Z_0 = reference impedance (i.g. 50Ω)

What do we do now with all that math?

https://commons.wikimedia.org/wiki/File:Man-scratching-head.gif

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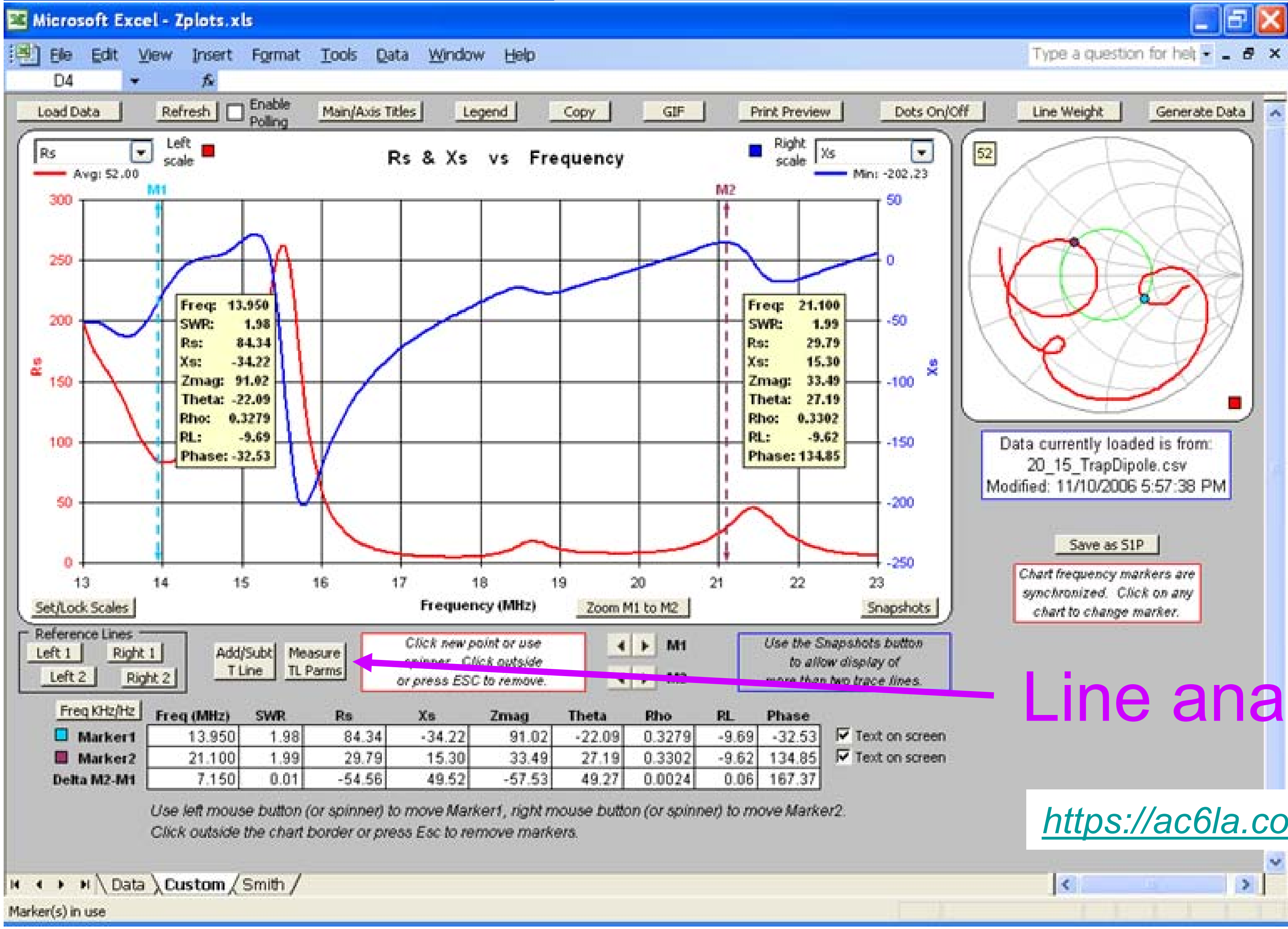
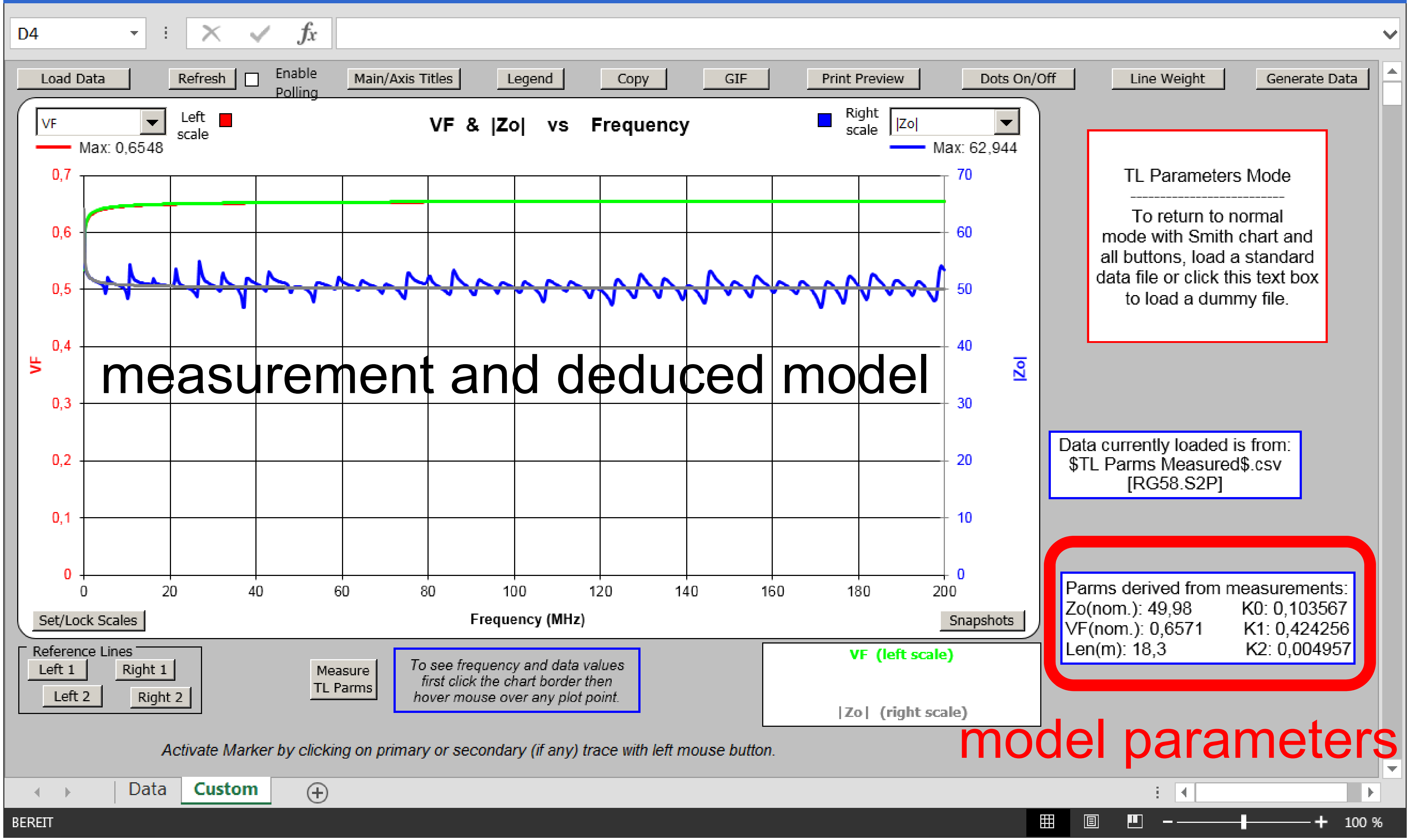
Zplots-Software by Dan Maguire AC6LA: Transmission Line Theory and Modell built-in.



Line analysis

https://ac6la.com/zplots.html

Analysis of RG58 C/U using ZPlots



Model Parameter from ZPlots

Zo(nom.): 49,98 ← line impedance (RF limit)
VF(nom.): 0,6571 ← velocity faktor (RF limit)
Len(m): 18,3 ← length

$$R_0' = k_0 \cdot x \cdot Z_0(\text{nom}) = 39.104 \frac{\text{m}\Omega}{\text{m}}$$

$$R_{skin}' = k_1 \cdot \frac{x \cdot Z_0(\text{nom})}{1000\sqrt{\text{Hz}}} = 0.16019 \frac{\text{m}\Omega}{\text{m}\sqrt{\text{Hz}}}$$

$$G_{PO}' = k_2 \cdot \frac{x \cdot 10^{-6}}{Z_0(\text{nom}) \cdot \text{Hz}} = 7.4924 \cdot 10^{-13} \frac{\text{S}}{\text{m} \cdot \text{Hz}}$$

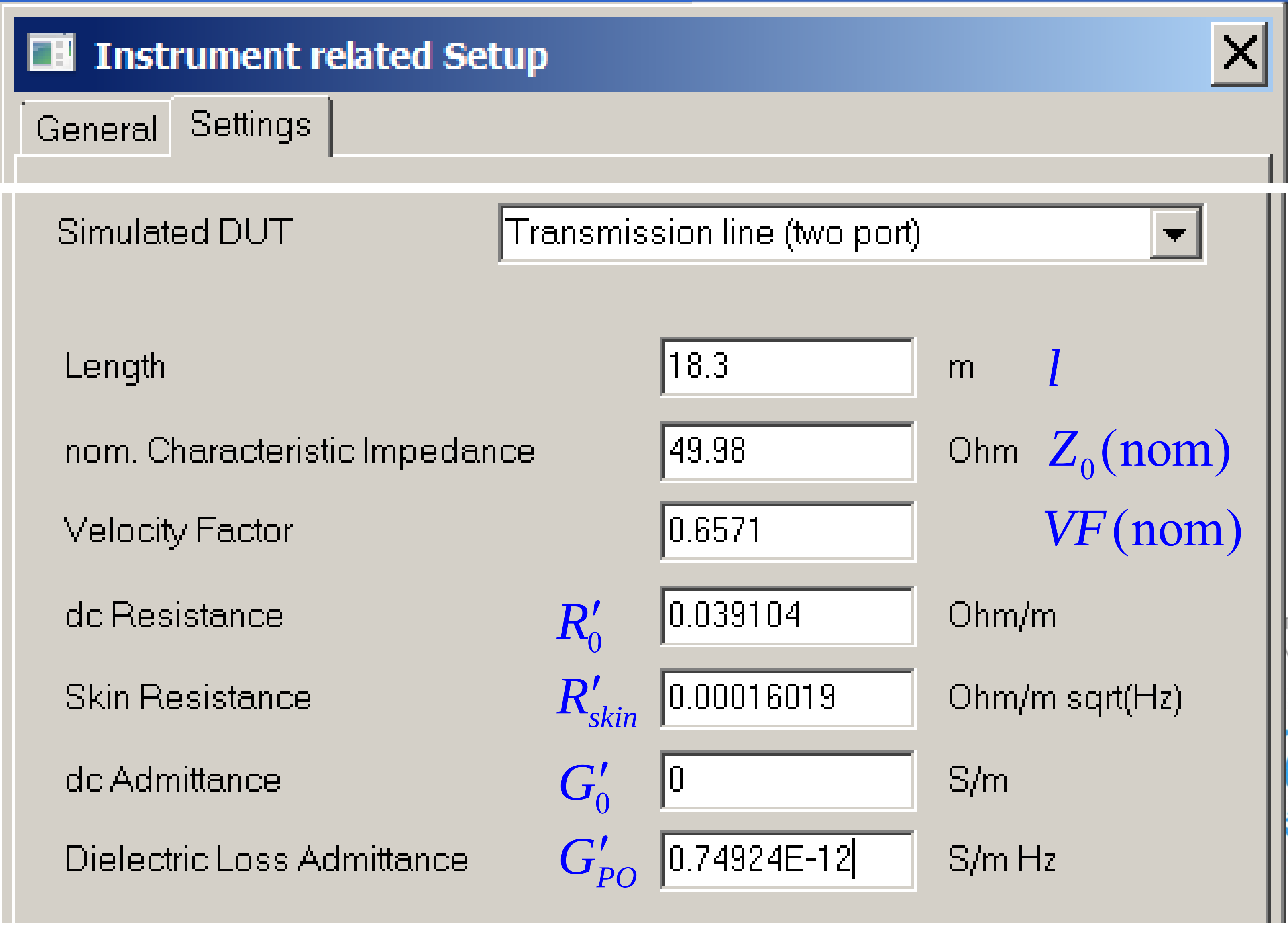
K0: 0,103567
K1: 0,424256
K2: 0,004957

using $x = \frac{2 \cdot \ln(10)}{100\,\text{ft} \cdot 20} = 7.5544 \cdot 10^{-3} \frac{1}{\text{m}}$

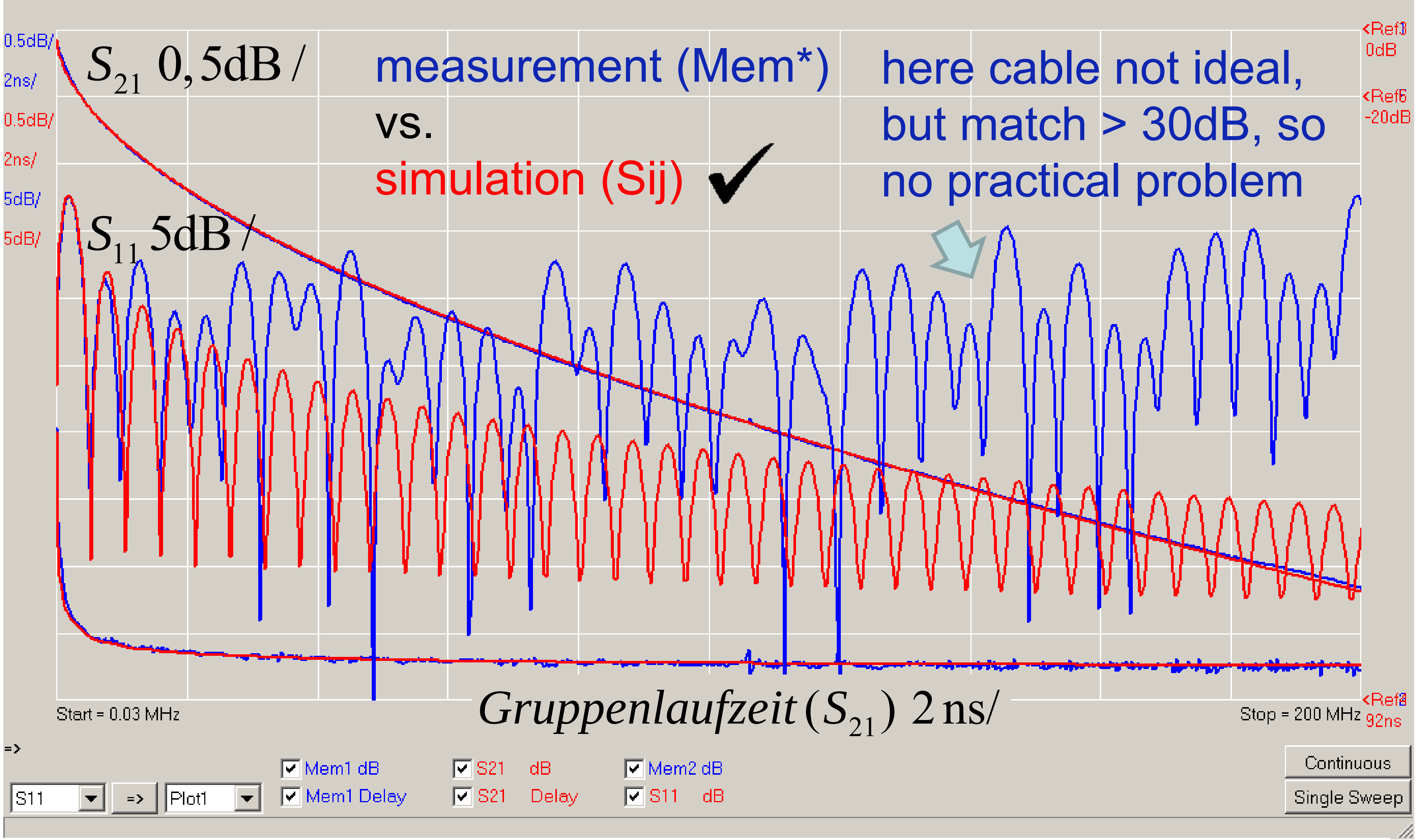
VNWA can simulate this...

VNWA Virtual Demo Device

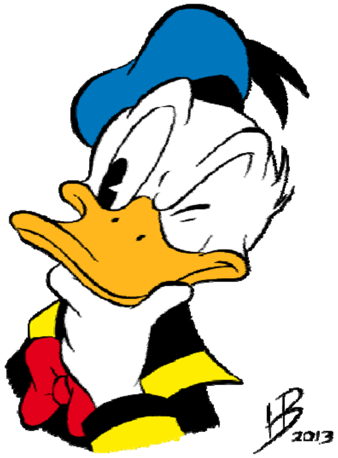
Setup



Parameter Extraktion and Model works fine!



So far so good !???



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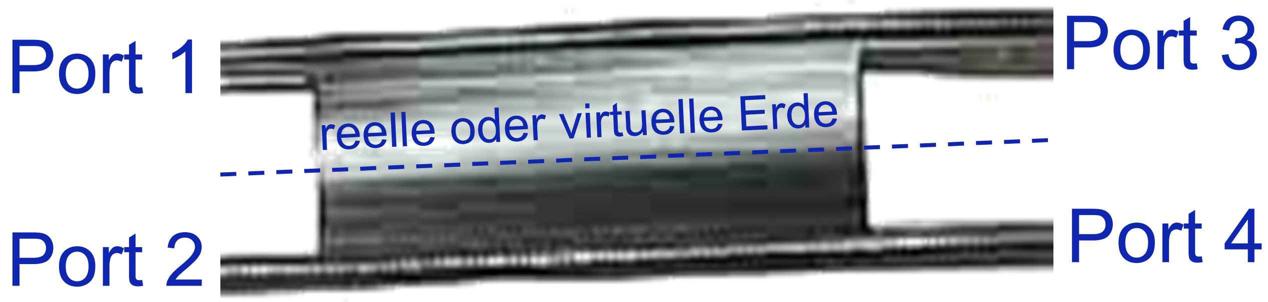
The Twin-Lead actually is a 4-Port Device…



…but in push-pull operation it is a 2-port

How to measure???

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Scattering Parameters do possess Symmetries

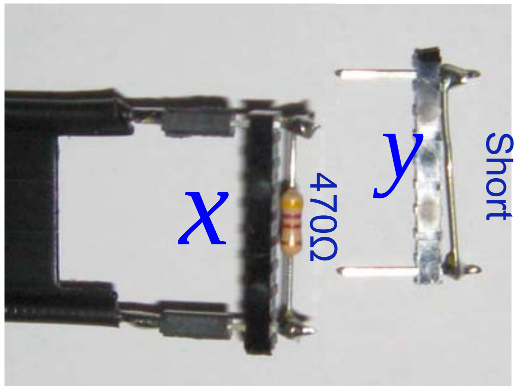
cable mirror symmetric w.r.t. half length $\Rightarrow S_{22} = S_{11}$

cable reciprocal device $\Rightarrow S_{21} = S_{12}$

- just two independent S-parameters S_{21} and S_{11}
- can be determined with two reflection measurements Γ_x, Γ_y using two different cable terminations (x, y e.g. Short, Load)

$$S_{11} = \frac{\Gamma_y \cdot S_x - \Gamma_x \cdot S_y}{(\Gamma_y - \Gamma_x) \cdot S_x \cdot S_y + S_x - S_y}$$

$$S_{21} = \pm \frac{\sqrt{(\Gamma_x - \Gamma_y) \cdot (S_x - S_y) \cdot (\Gamma_x \cdot S_y - 1) \cdot (\Gamma_y \cdot S_x - 1)}}{(\Gamma_y - \Gamma_x) \cdot S_x \cdot S_y + S_x - S_y}$$



with S_x, S_y reflection coefficient termination ***x*** or ***y***

Γ_x, Γ_y reflection coefficient cable with termination ***x*** or ***y***

How to measure a balanced Load using a single-ended VNA?

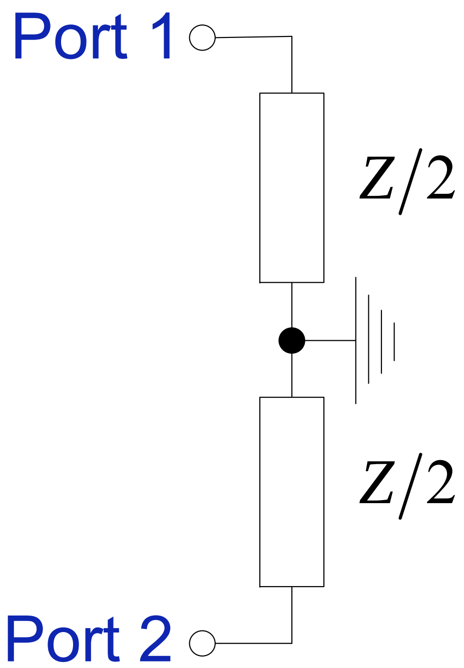
via 2-port measurement!

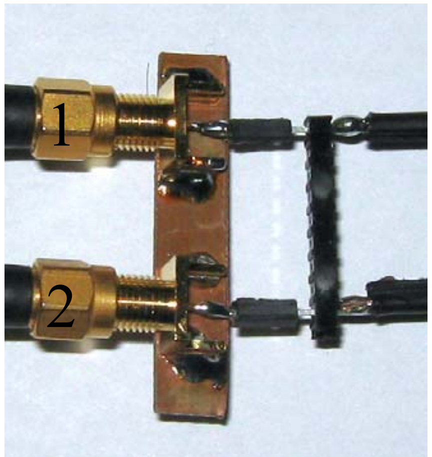
$$Z = \underbrace{Z_{11} + Z_{22} - Z_{21} - Z_{12}}_{\text{measured Z-Matrix elements}}$$

If both ports are identical:

$$Z = 2 \cdot (Z_{11} - Z_{21})$$

can be computed from measured S_{ij} with VNWA custom functions *s_dm* or *s_dm_sym*





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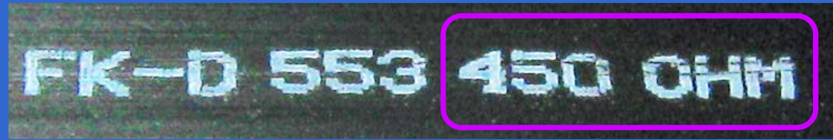
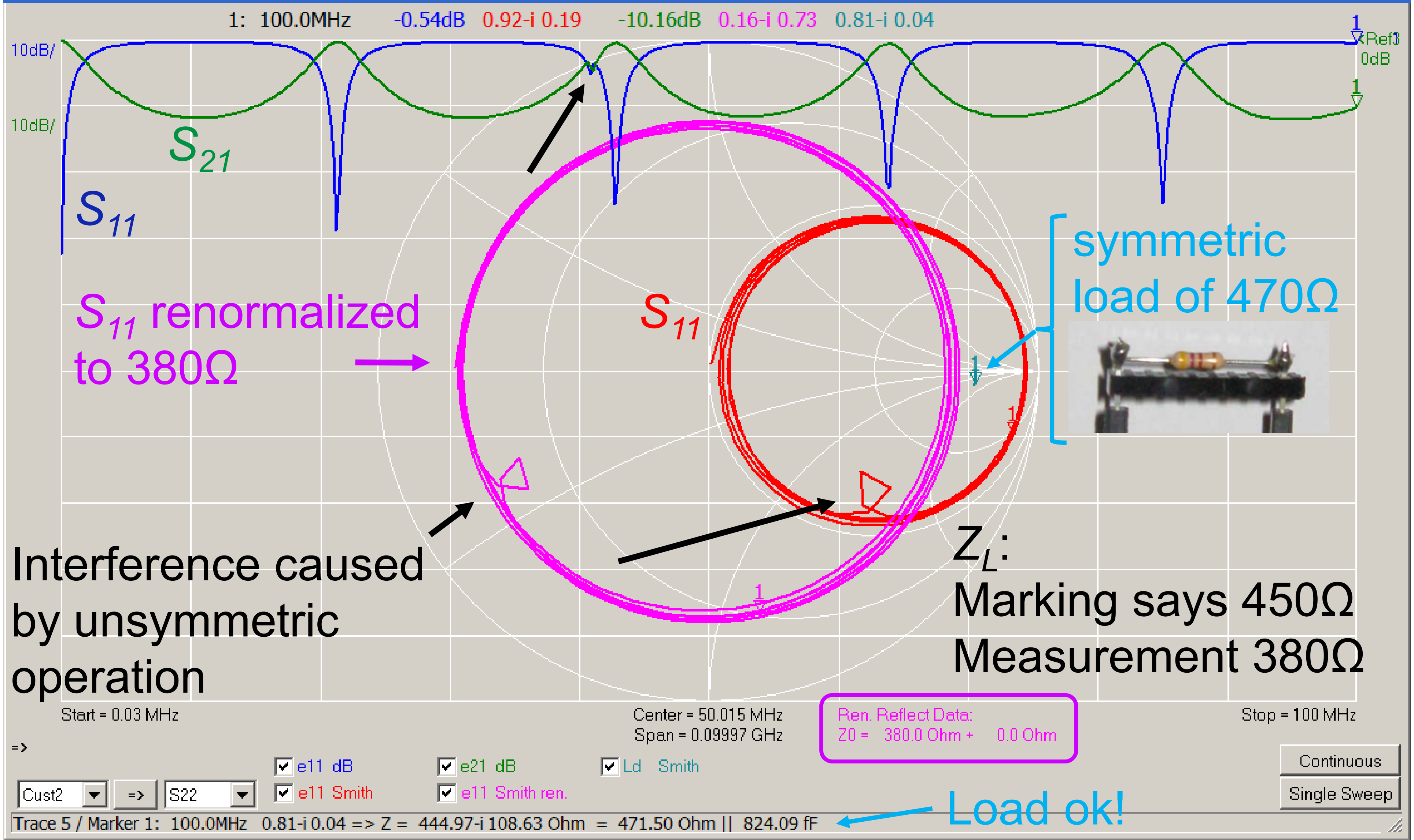
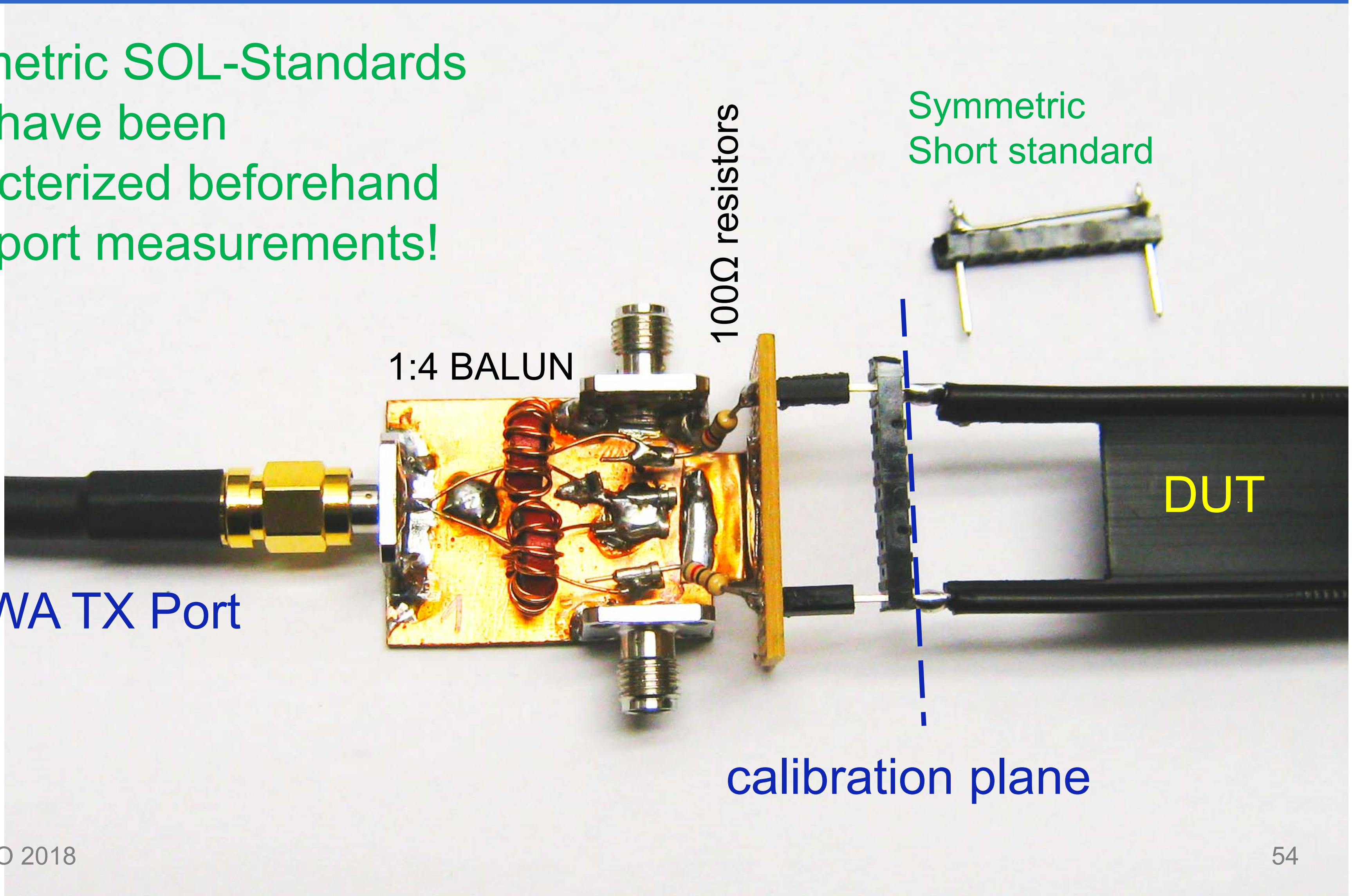
6,2m Twin-Lead from 2-Port Measurement



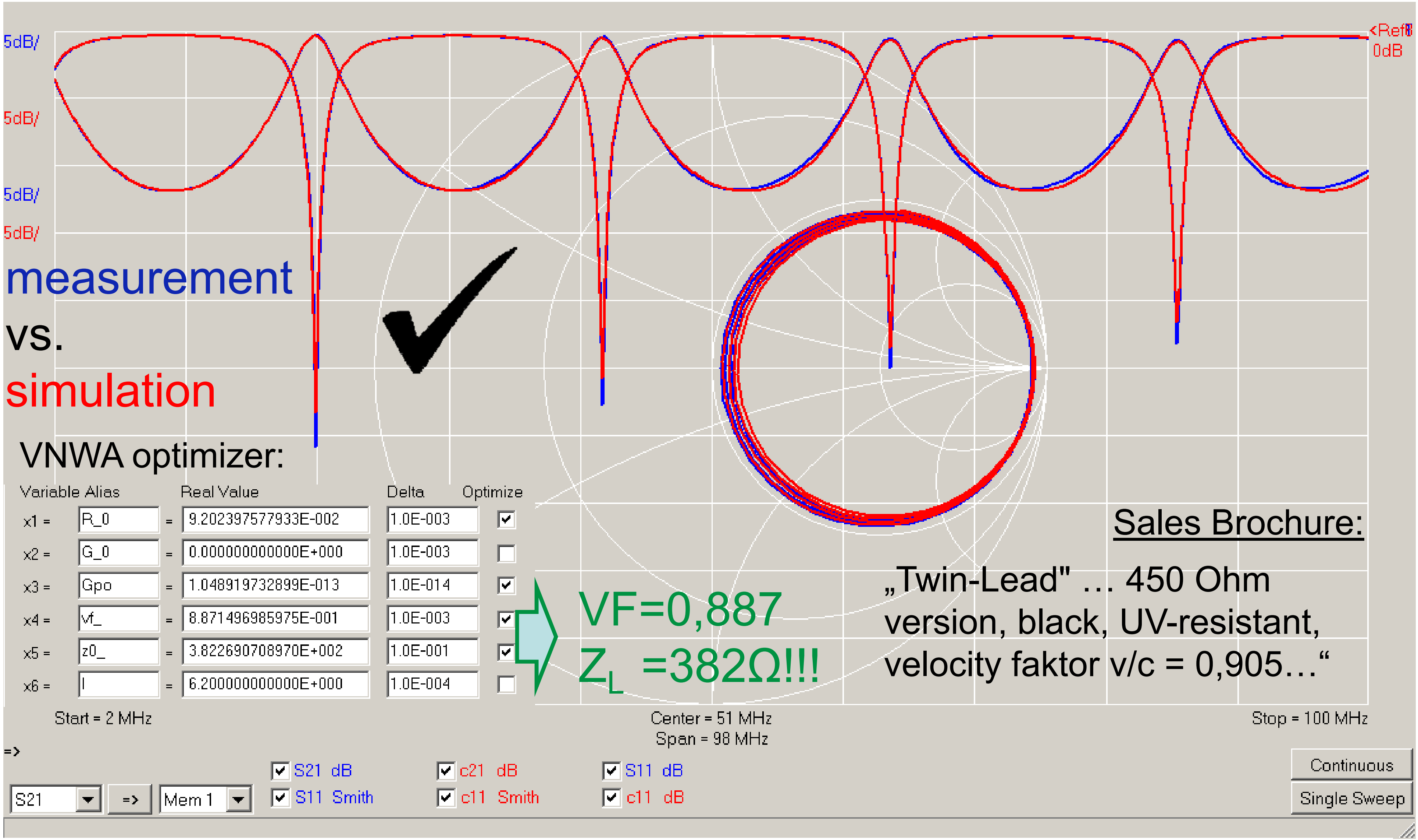


Better: Reflection Measurement using BALUN and symmetric Calibration

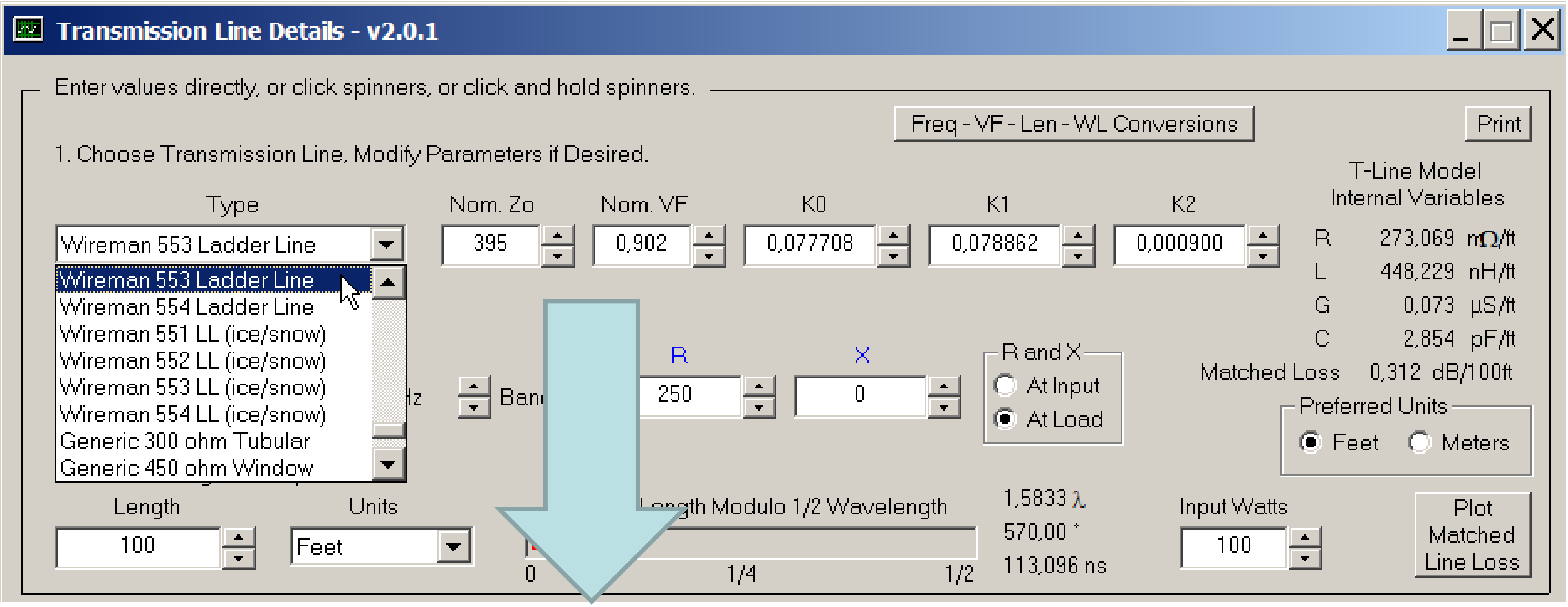
Symmetric SOL-Standards must have been characterized beforehand via 2-port measurements!



Simulation Model identical with Coax Model!



Huge Collection of Cable Parameters: *TLDetails* by Dan AC6LA



https://ac6la.com/tldetails.html

VF=0,902

Z_L =395Ω

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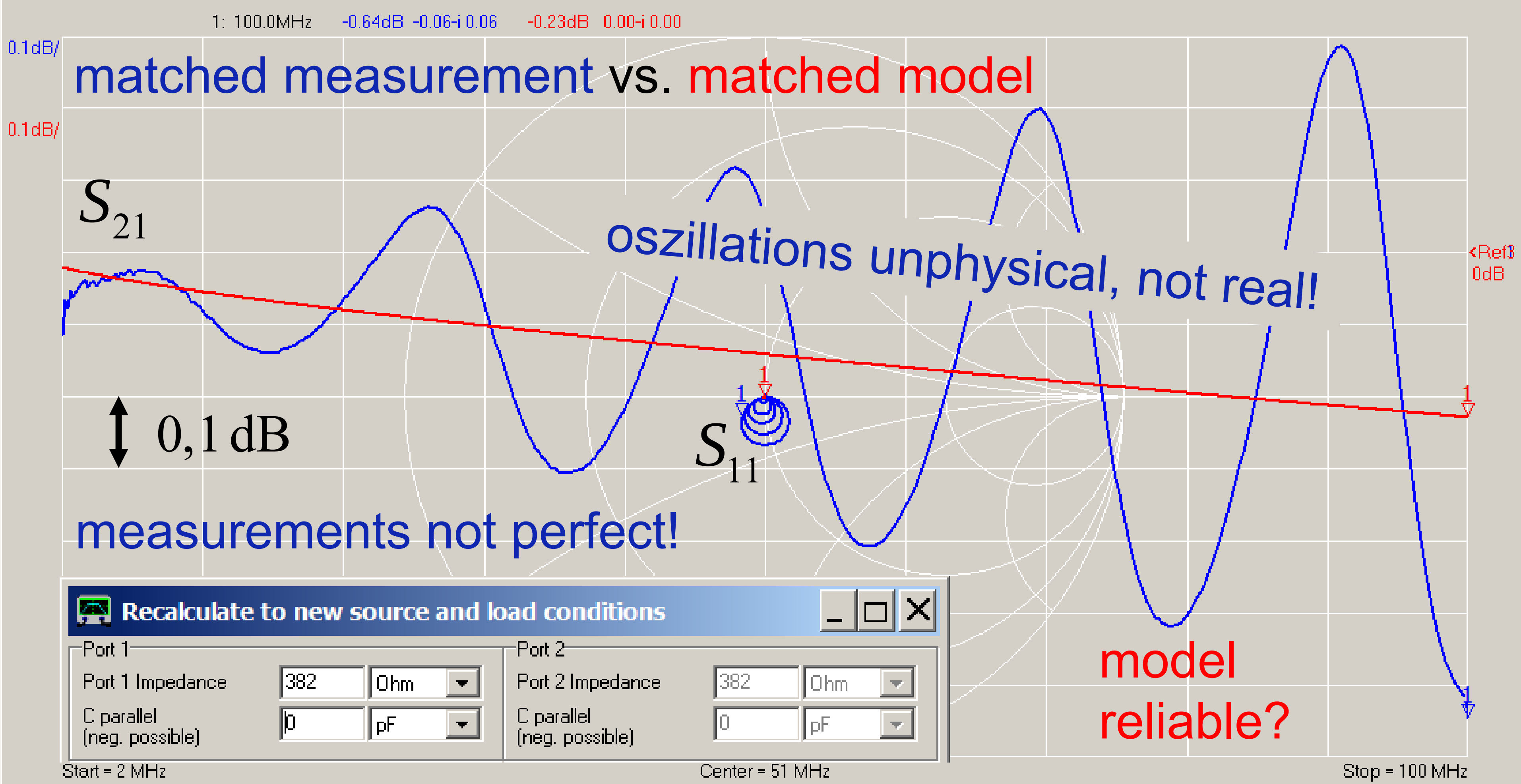
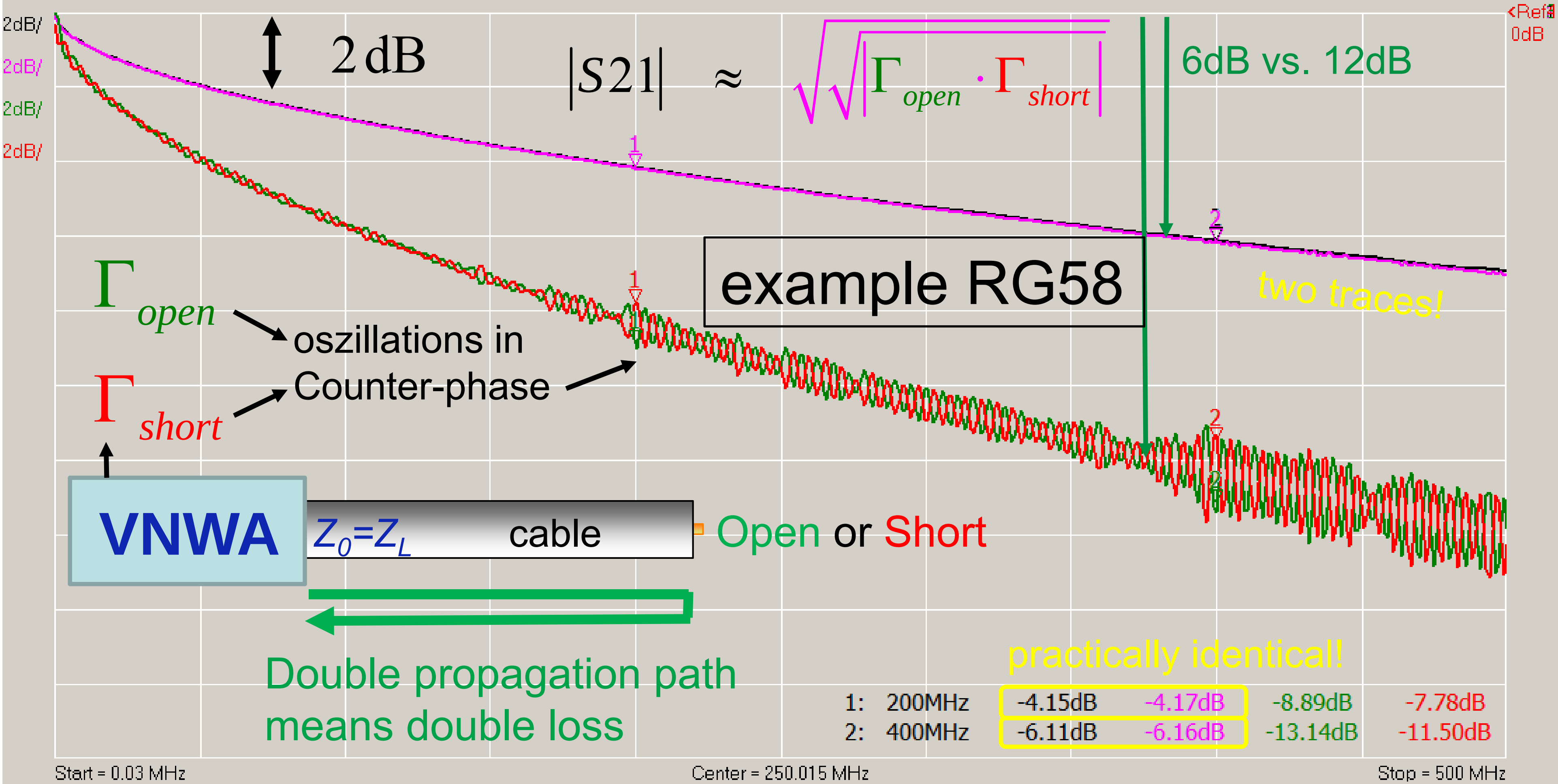
Insertion Loss from simulated Impedance Match to $Z_L = 382\Omega$?



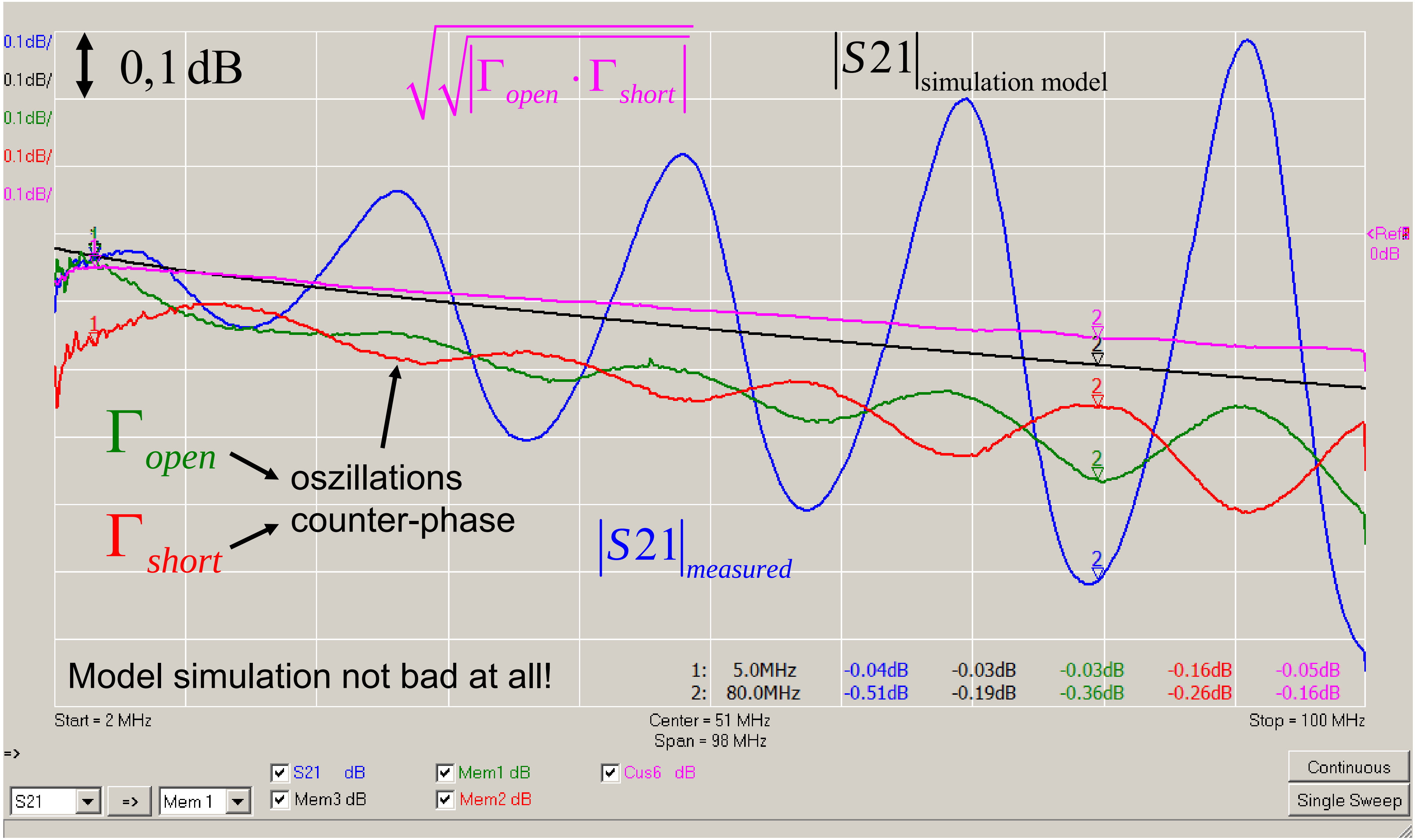
measurement with BALUN, simulation with parameters from VNWA optimizer/ZPlots

Alternate Method to obtain Insertion Loss from Reflection Measurements (RG58)



S_{21} from transmission measurement
reflection coefficients Γ from reflection measurements (S_{11})

Also works for Twin-Lead!



RF-Cables:
Our Achievements

- Underlying physics understood
- Realistic cable models for simulations
- Measurement methods for coaxial cables
- Measurement methods for twin-leads
- Analysis methods (Zplots, Optimizer)

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Vielen Dank für Ihr Interesse!