HAM RADIO 2014

Experiments with a Sound Card: About noisy Resistors, Shift Registers and Transfer Functions

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

DG8SAQ

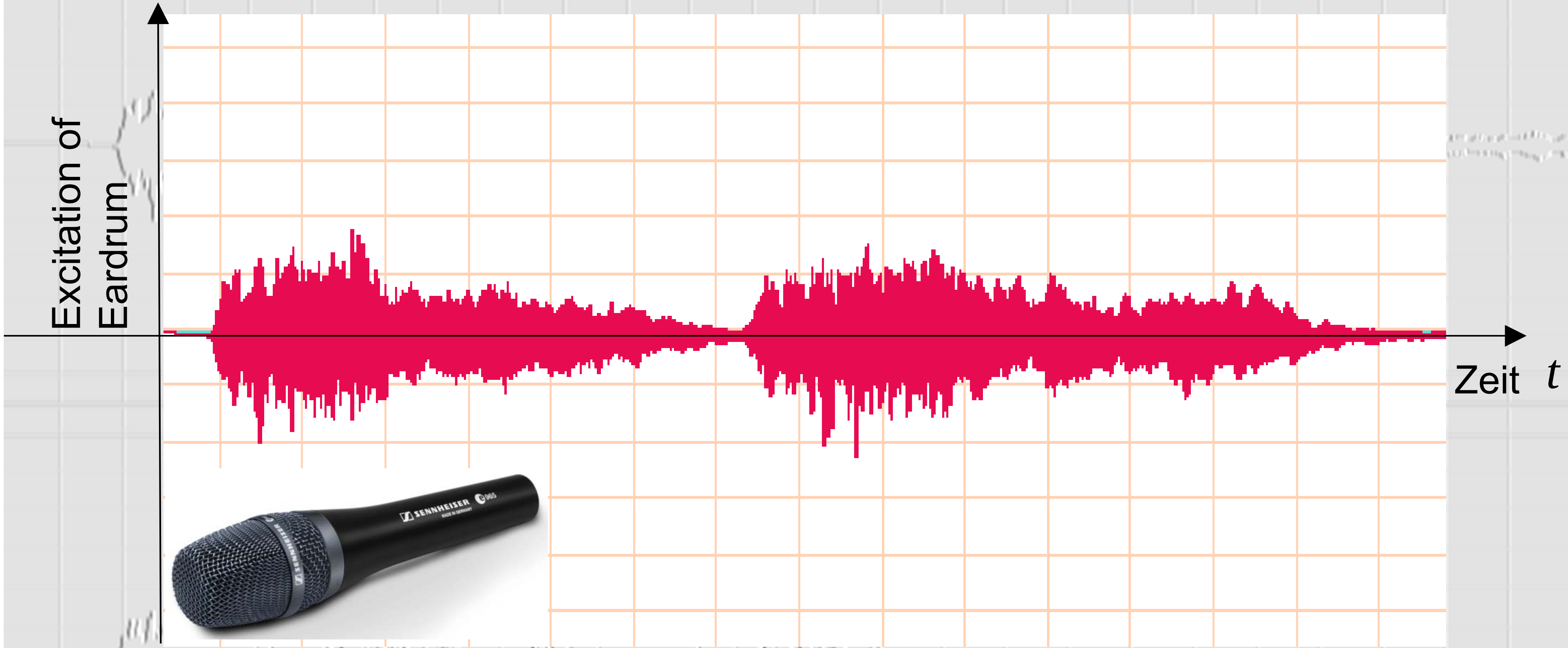
Hochschule Ulm

Prittwitzstrasse 10

89075 Ulm

Technik
Informatik & Medien
Hochschule Ulm
University of Applied Sciences

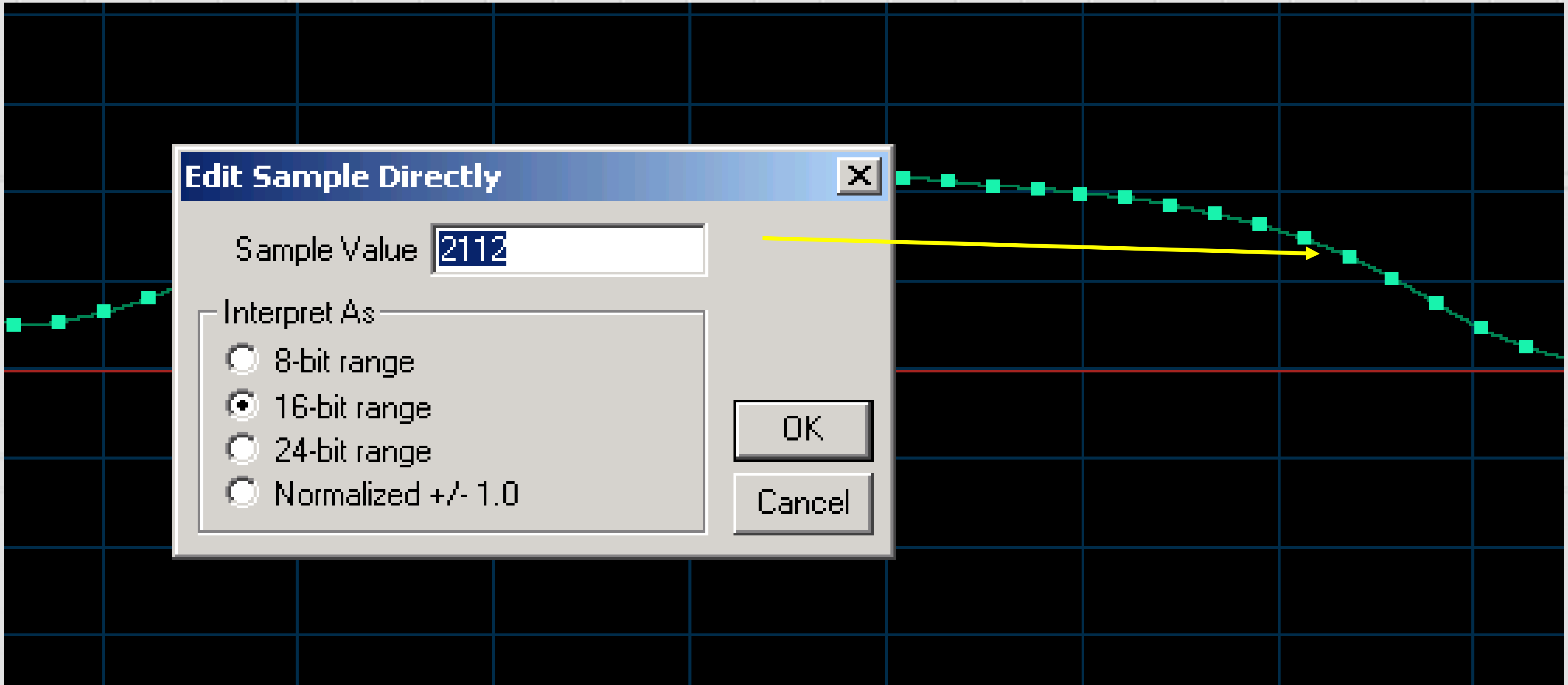
Sound …



… can be converted to AC with a microphone.

Hochschule Ulm

A Sound Card measures ac periodically and digitally

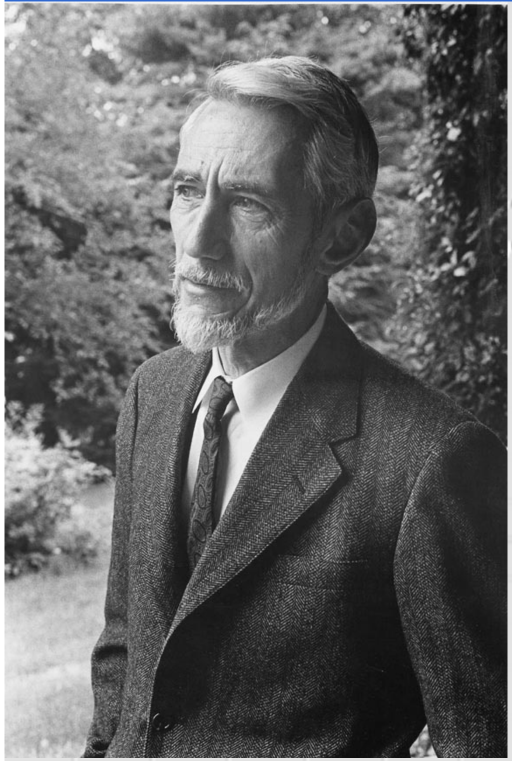


Sample Rate: Number of Measurements per Time Unit

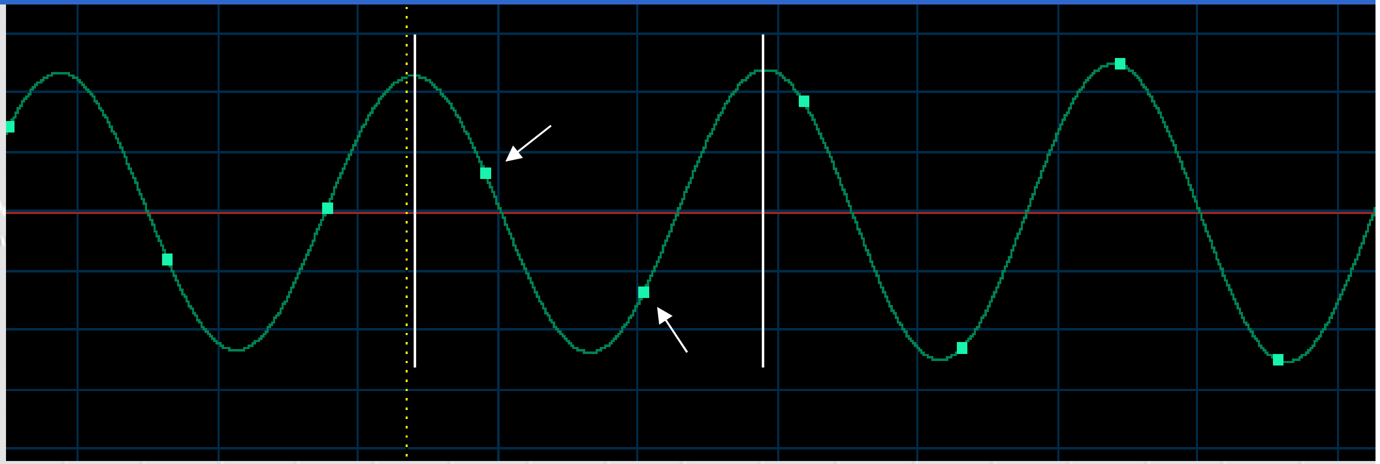
16 Bit Resolution: 2^{16} possible different Measurement Results

Hochschule Ulm

Nyquist-Shannon Sampling Theorem from 1948



Claude Elwood Shannon
(* 1916; † 2001)
US-American Mathematician,
Founder of Information Theory.



More than two samples per period for highest frequency

→ Original signal can exactly be reconstructed from the samples.

Hochschule Ulm

High Quality Sound Card in Theory …

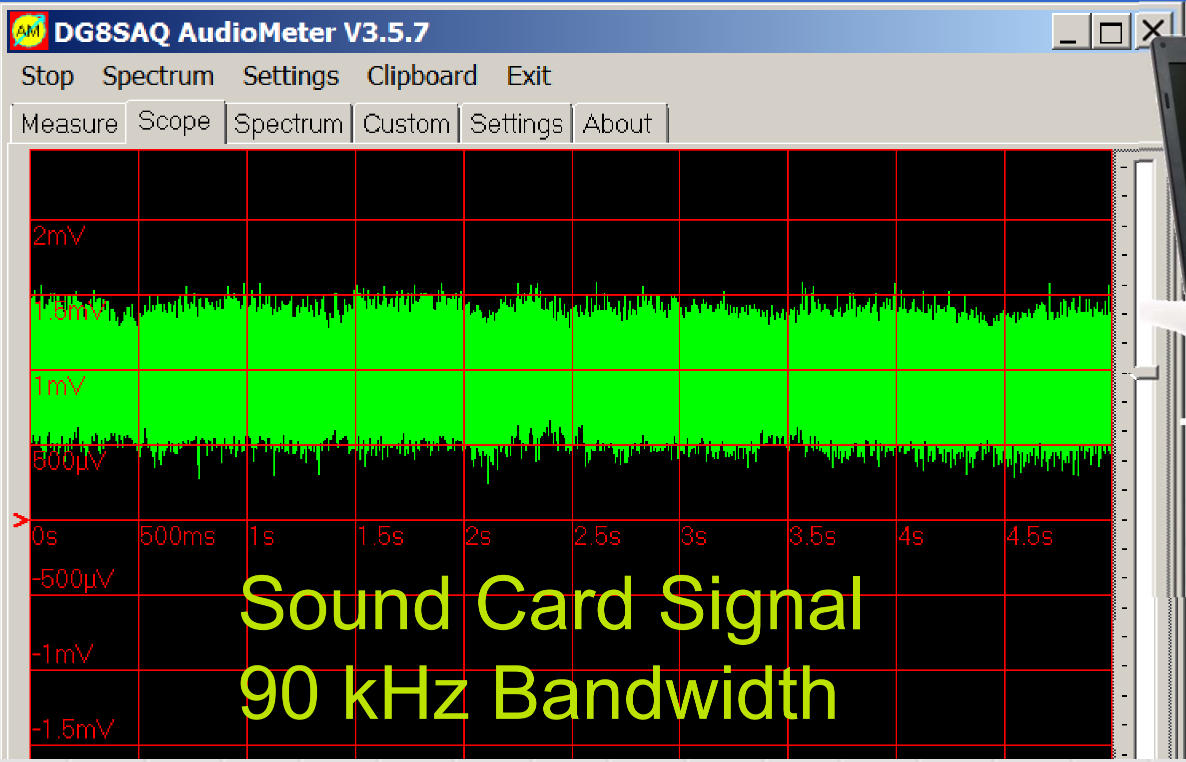
192 ksps Sample Rate:
192 000 Measurements per Second
→ Up to 90 kHz processable.

24 Bit Resolution:
→ Theoretical Dynamic Range
$2^{24} : 1 = 16 \cdot 10^{6} \equiv 144$ dB
e.g. 60 nV Resolution for 1 V full Scale

Applications: - VLF Reception
- RMS Voltmeter

Hochschule Ulm

… and in Reality:
Direct DCF77 Reception with Sound Card



Passive 77,5 kHz ferrite antenna directly connected to notebook audio input

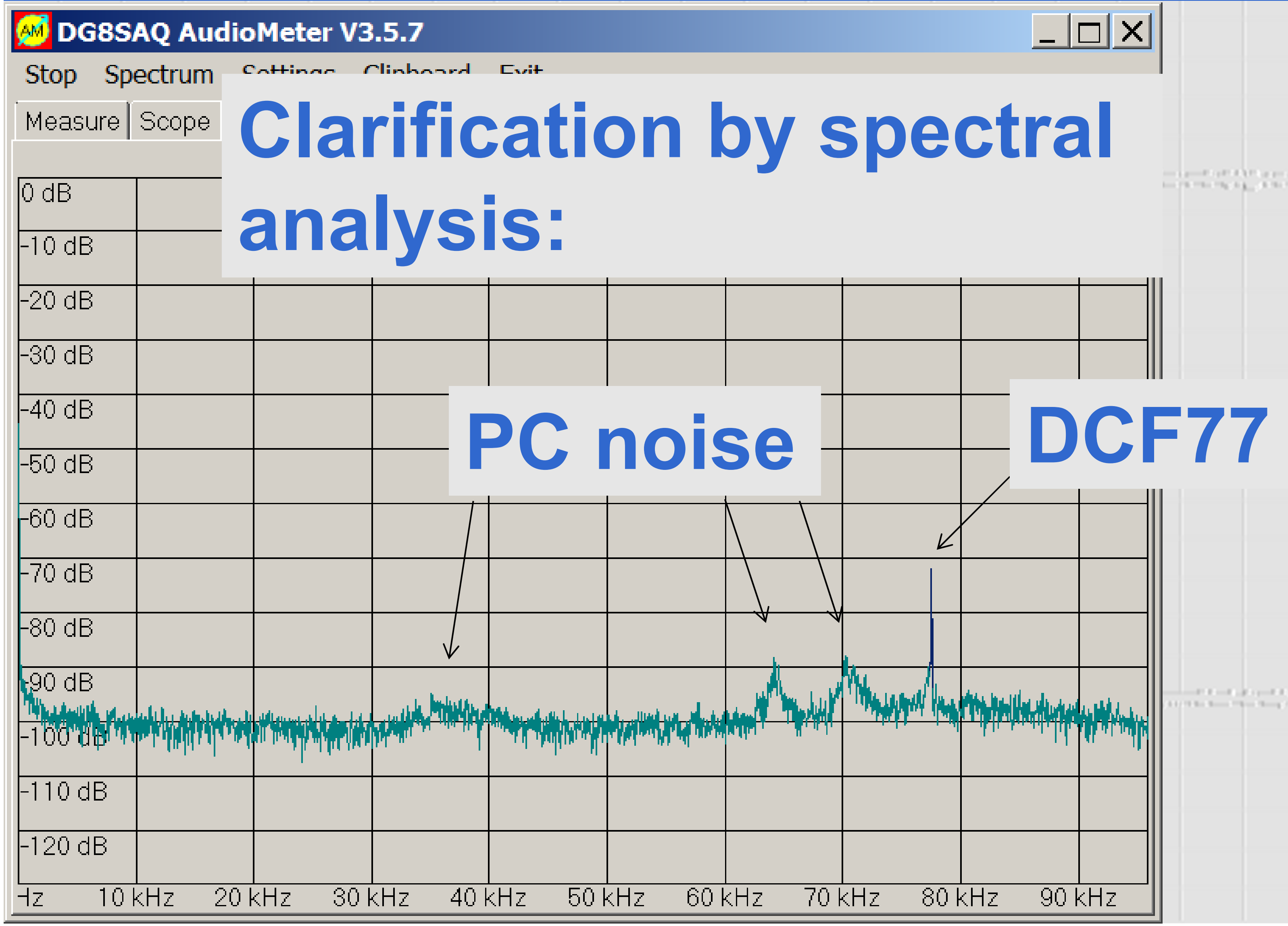
RX signal is lost in noise!

Hochschule Ulm

http://www.sdr-kits.net/DG8SAQ/AudioMeter3.zip

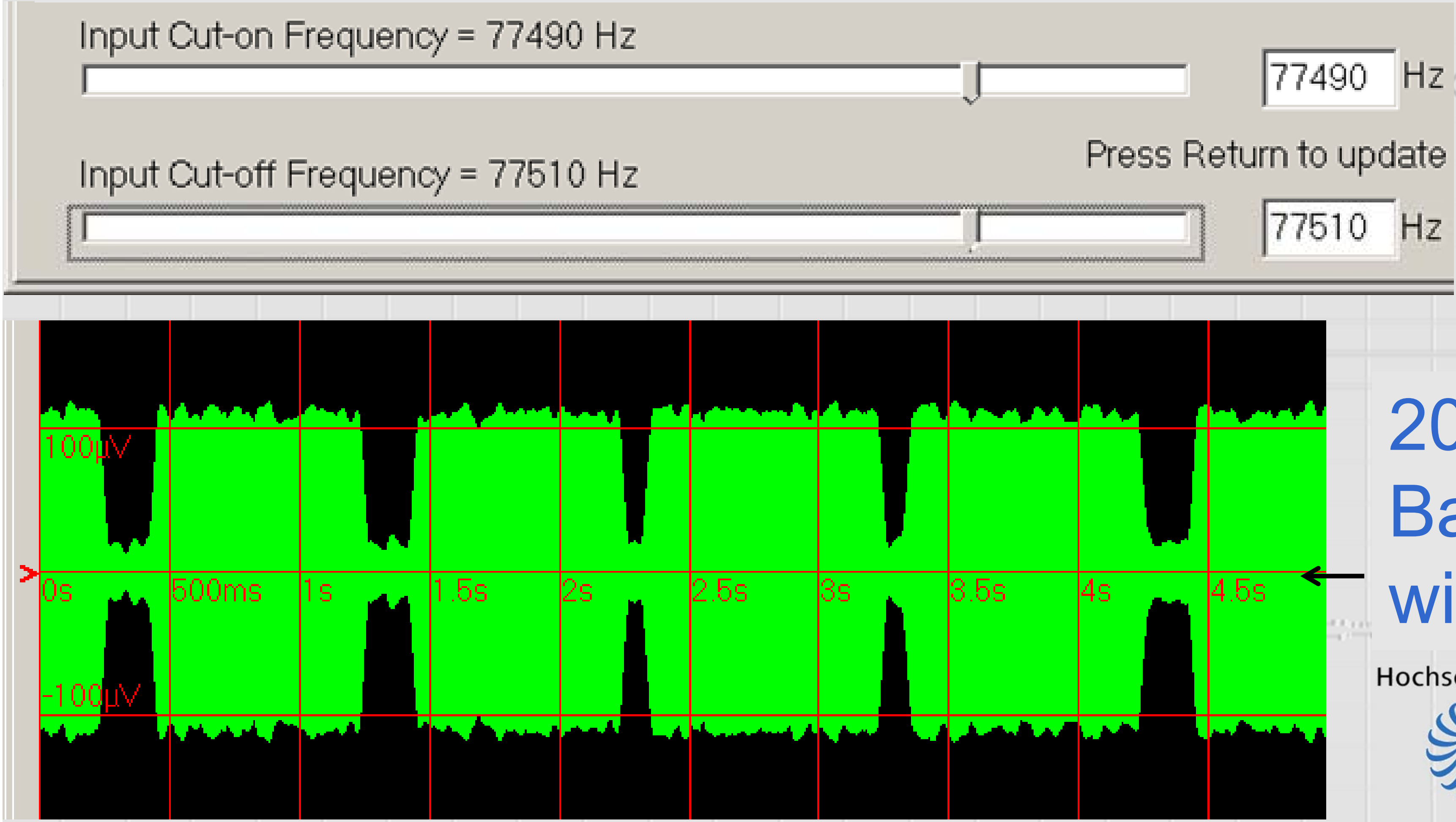
Direct DCF77 Reception with Sound Card (2)

Clarification by spectral analysis:



Direct DCF77 Reception with Sound Card (3)

Noise can be removed by digital filtering:

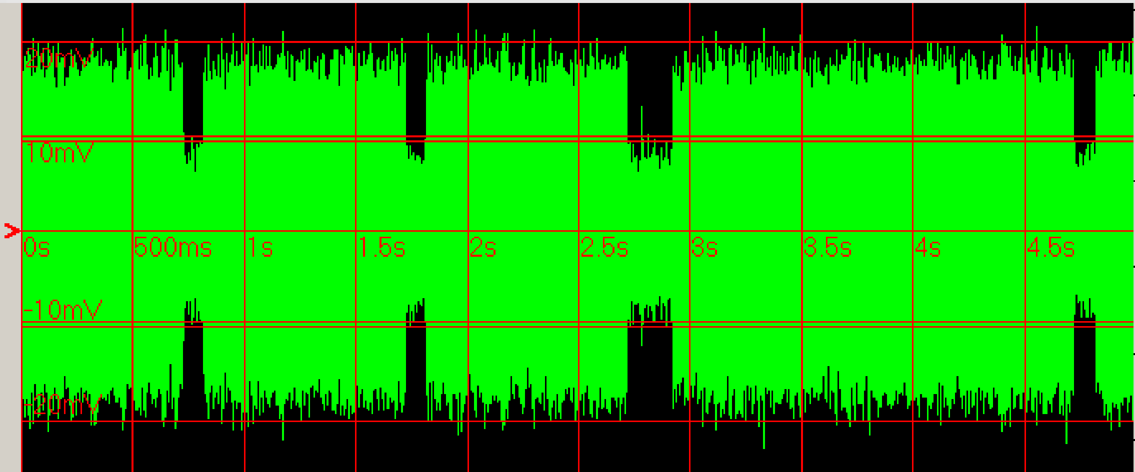


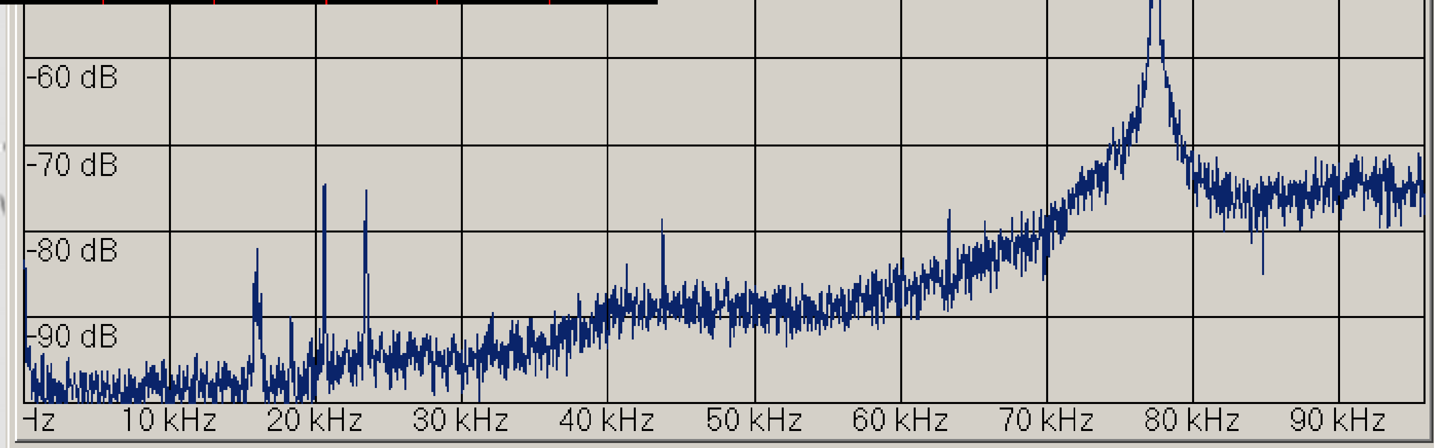
20 Hz Band-width

Hochschule Ulm

Direct DCF77 Reception with Sound Card (4)

Much better Sound card from professional music sector: **E-MU 0204**:





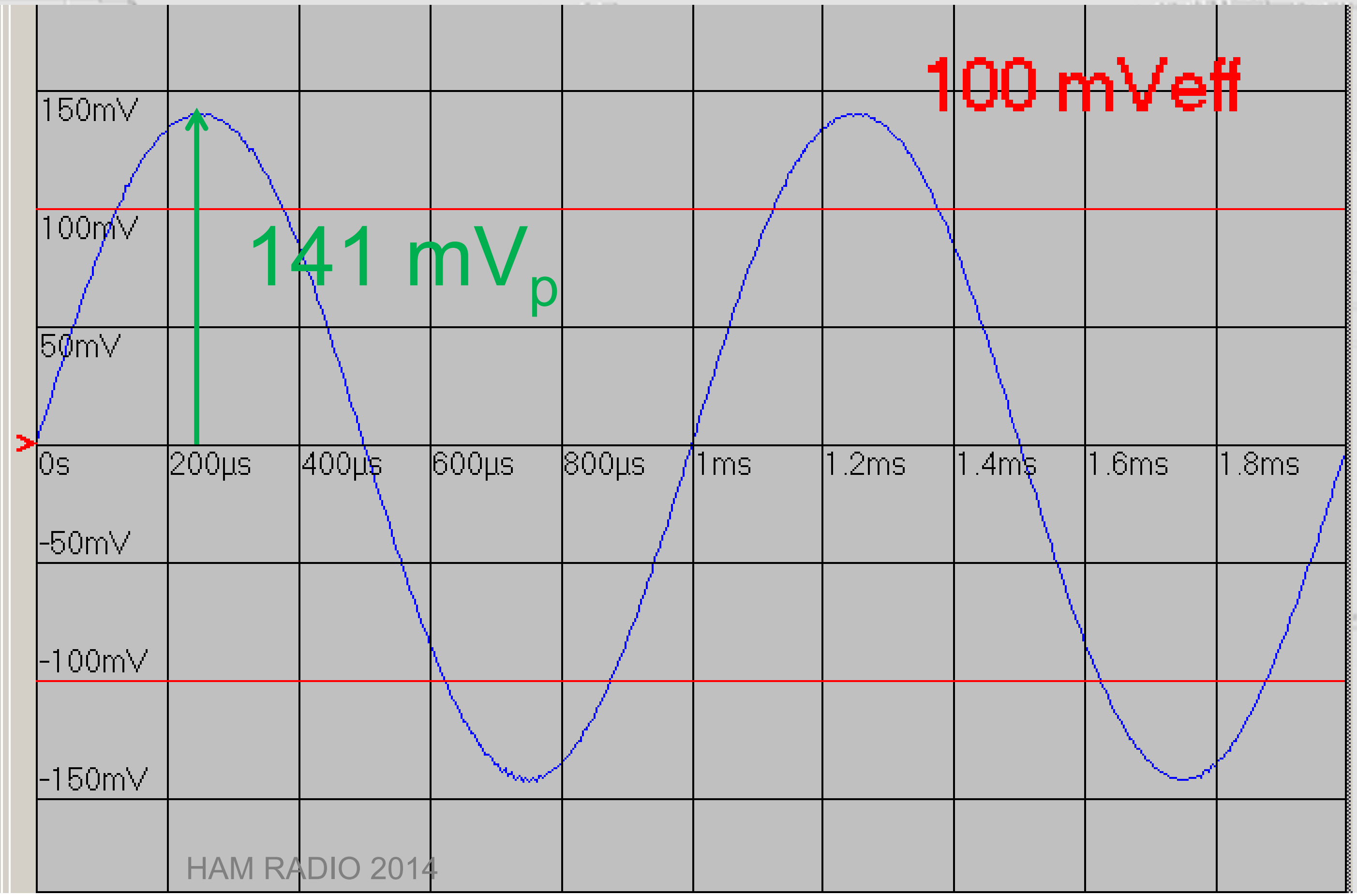
↑

90 kHz Band-width!!

RMS Voltmeter using a Sound Card

RMS voltage from average power:

$$\bar{P} = \frac{U_{eff}^{2}}{R}$$

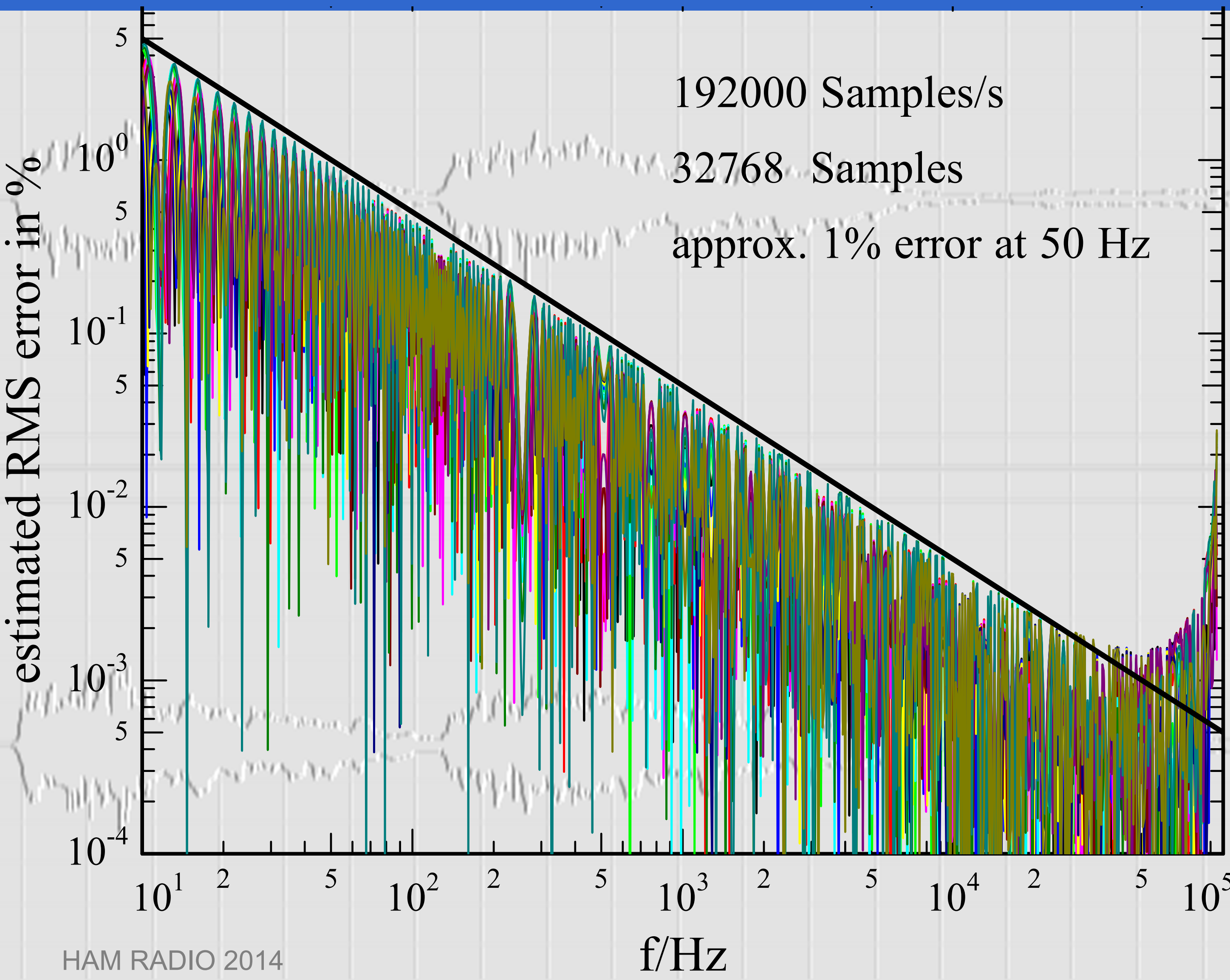


Sine wave:

$$U_{eff} = \frac{U_p}{\sqrt{2}}$$

Hochschule Ulm

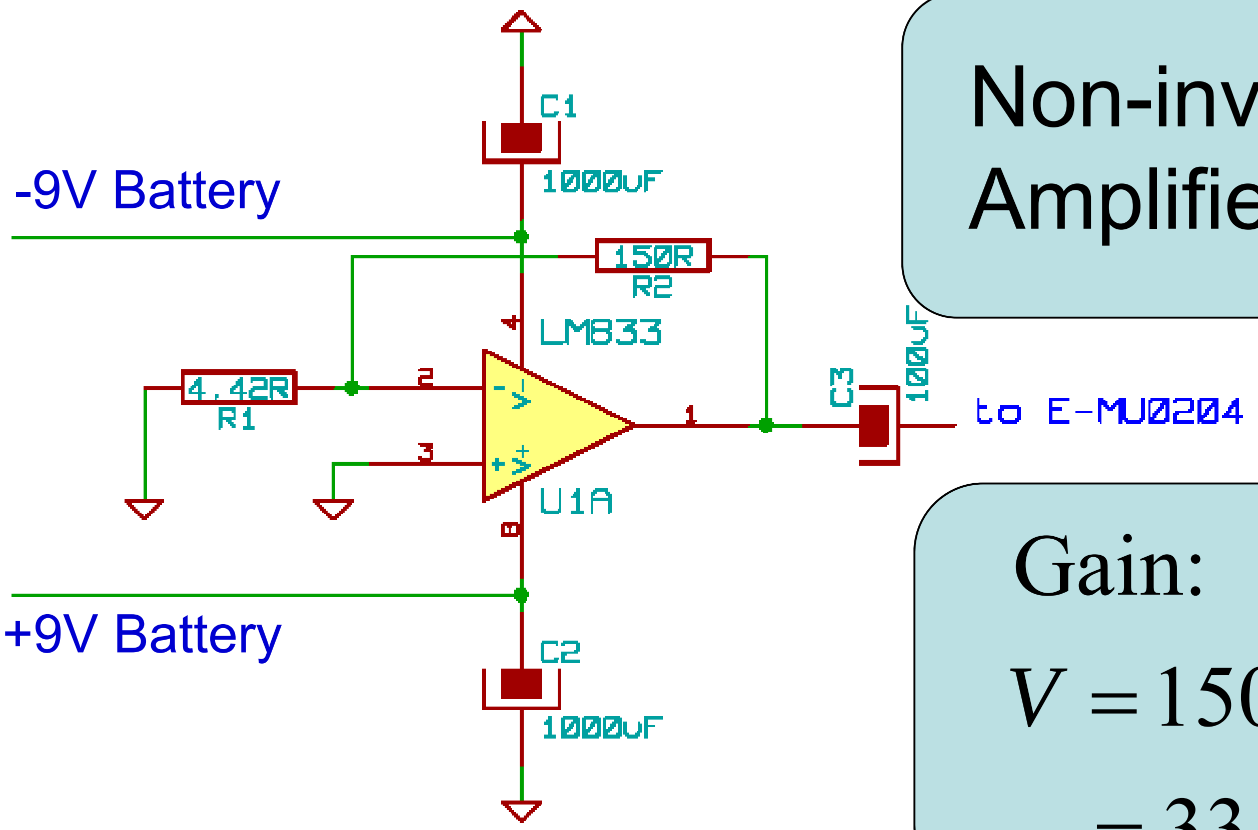
RMS-Voltage:
Error by finite Time Cut-off



0,17s sample length, averaging reduces error!

Hochschule Ulm

Measuring the RMS Noise of OPA LM833



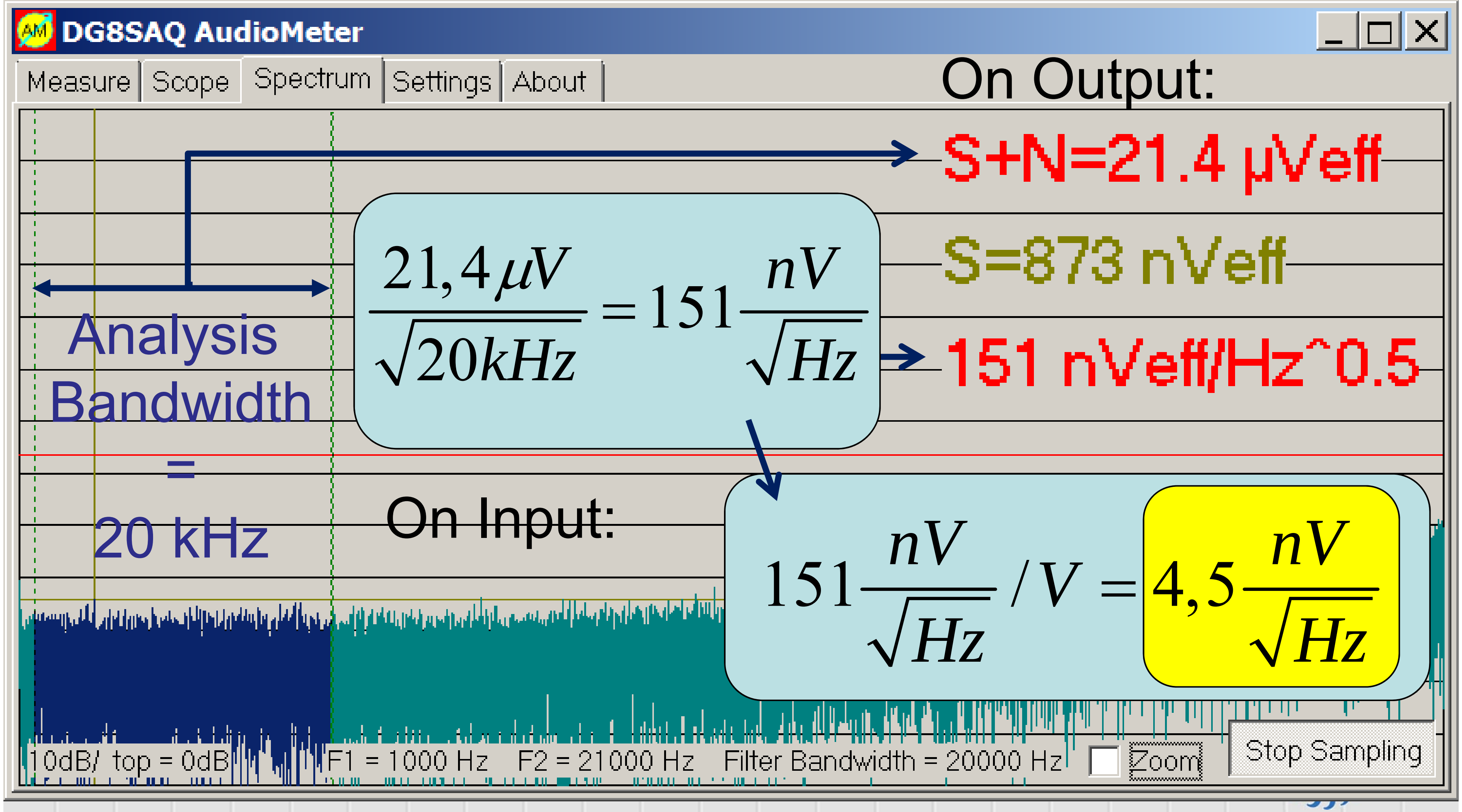
Non-inverting Amplifier

Gain:

$$V = 150\Omega / 4{,}42\Omega$$
$$= 33{,}9$$

Data Sheet LM833:
„Low Input Noise Voltage: 4.5nV/√Hz"

Measuring the RMS Noise of OPA LM833 (2)



What does this mean?

$$4{,}5\frac{nV}{\sqrt{Hz}}$$ e.g. at 50 Ω:

$$P=\frac{U^2}{R}\Rightarrow\frac{\left(4{,}5\frac{nV}{\sqrt{Hz}}\right)^2}{50\Omega}=4\cdot10^{-19}\,\frac{W}{Hz}$$

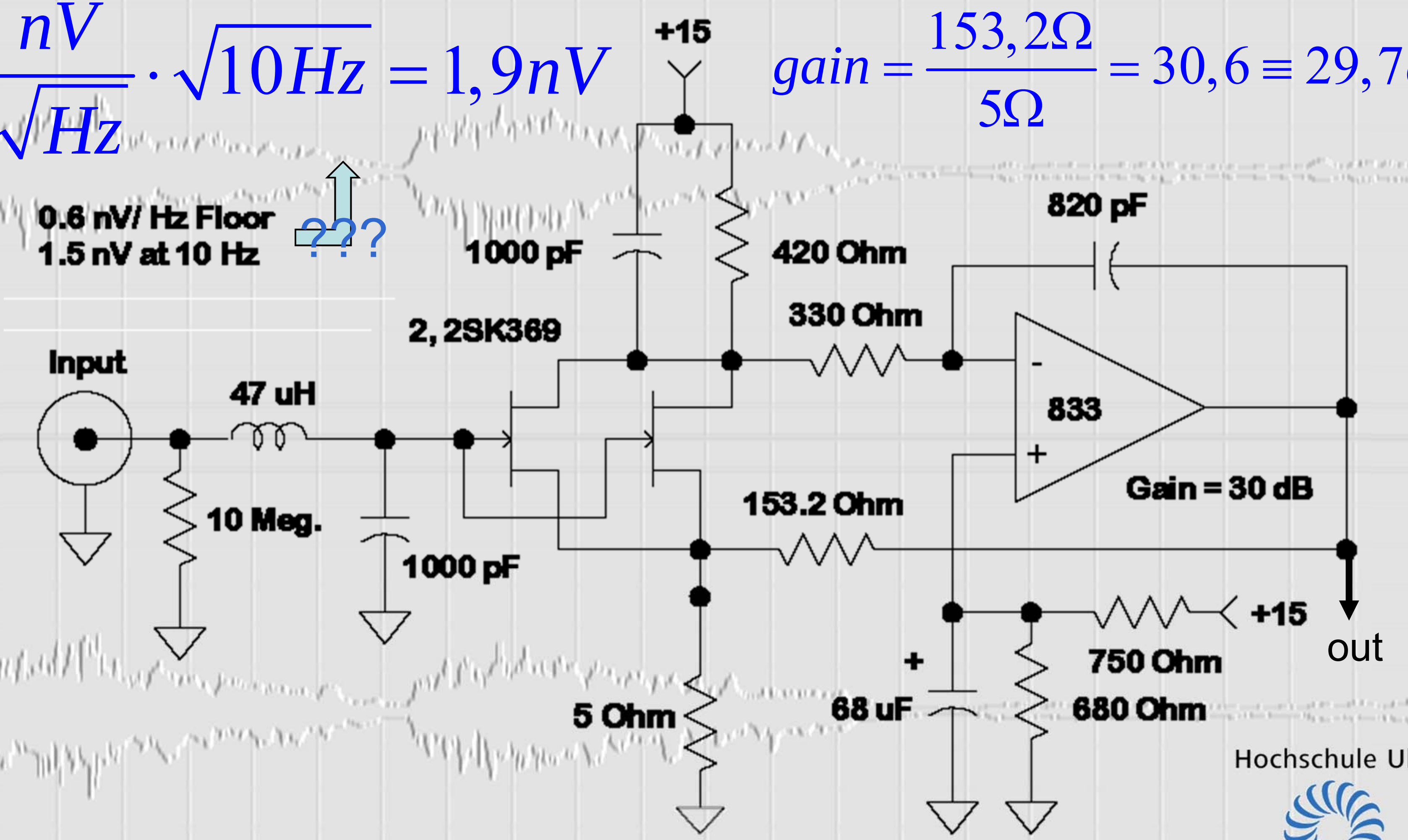
- This is a spectral power density!
- On a BPF output with e.g. 10 kHz bandwidth we will see $4\cdot10^{-19}\cdot10^{4}$ W = $4\cdot10^{-15}$ W noise power.

Hochschule Ulm

Amplifier with even lower Noise (by Charles Wenzel)

$$0,6\frac{nV}{\sqrt{Hz}}\cdot\sqrt{10Hz}=1,9nV$$

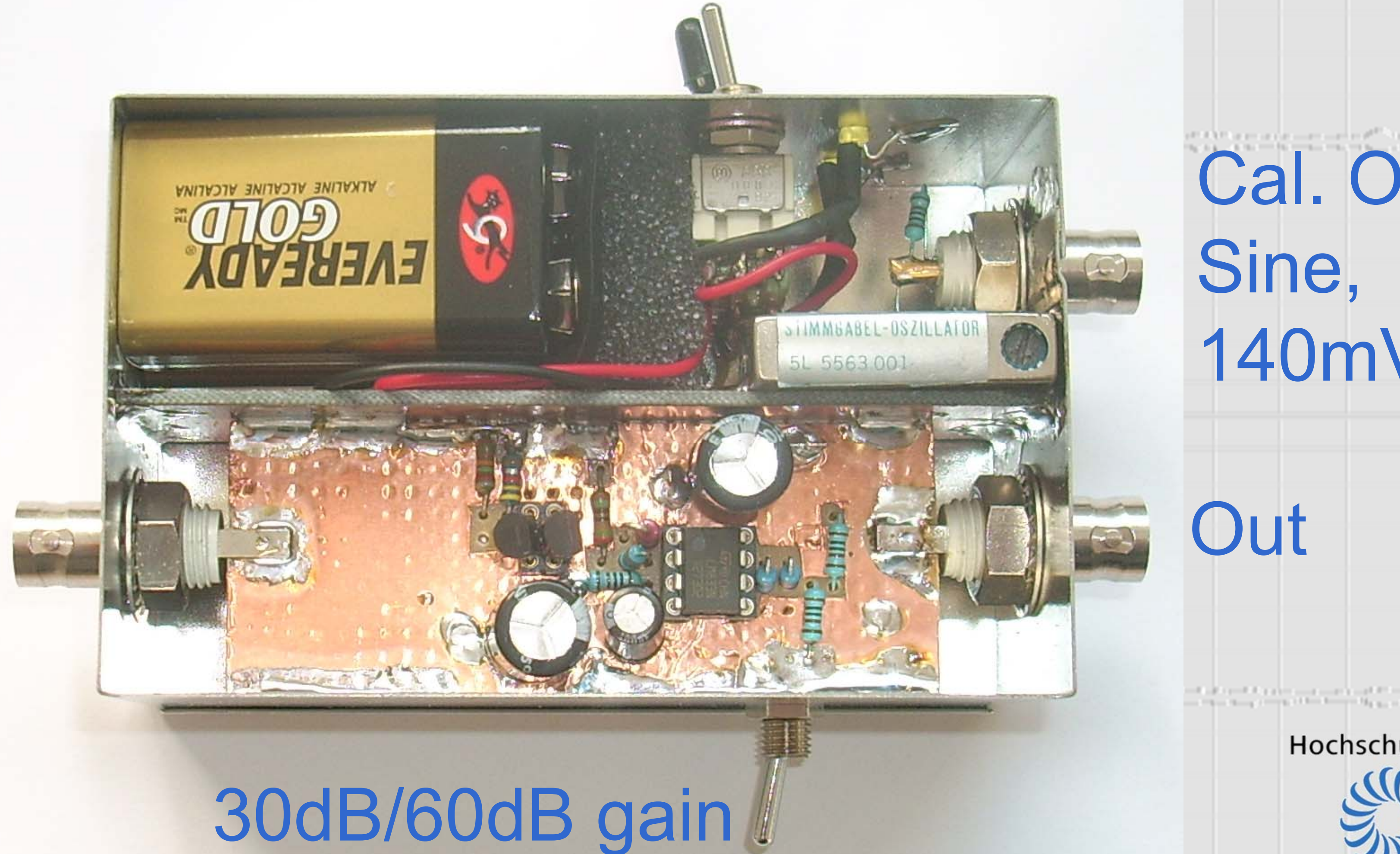
$$gain=\frac{153,2\Omega}{5\Omega}=30,6\equiv 29,7dB$$



http://www.wenzel.com/pdffiles1/pdfs/lowamp.pdf

Hochschule Ulm

Two Stage Wenzel Amplifier
30dB/60dB switchable Gain



In

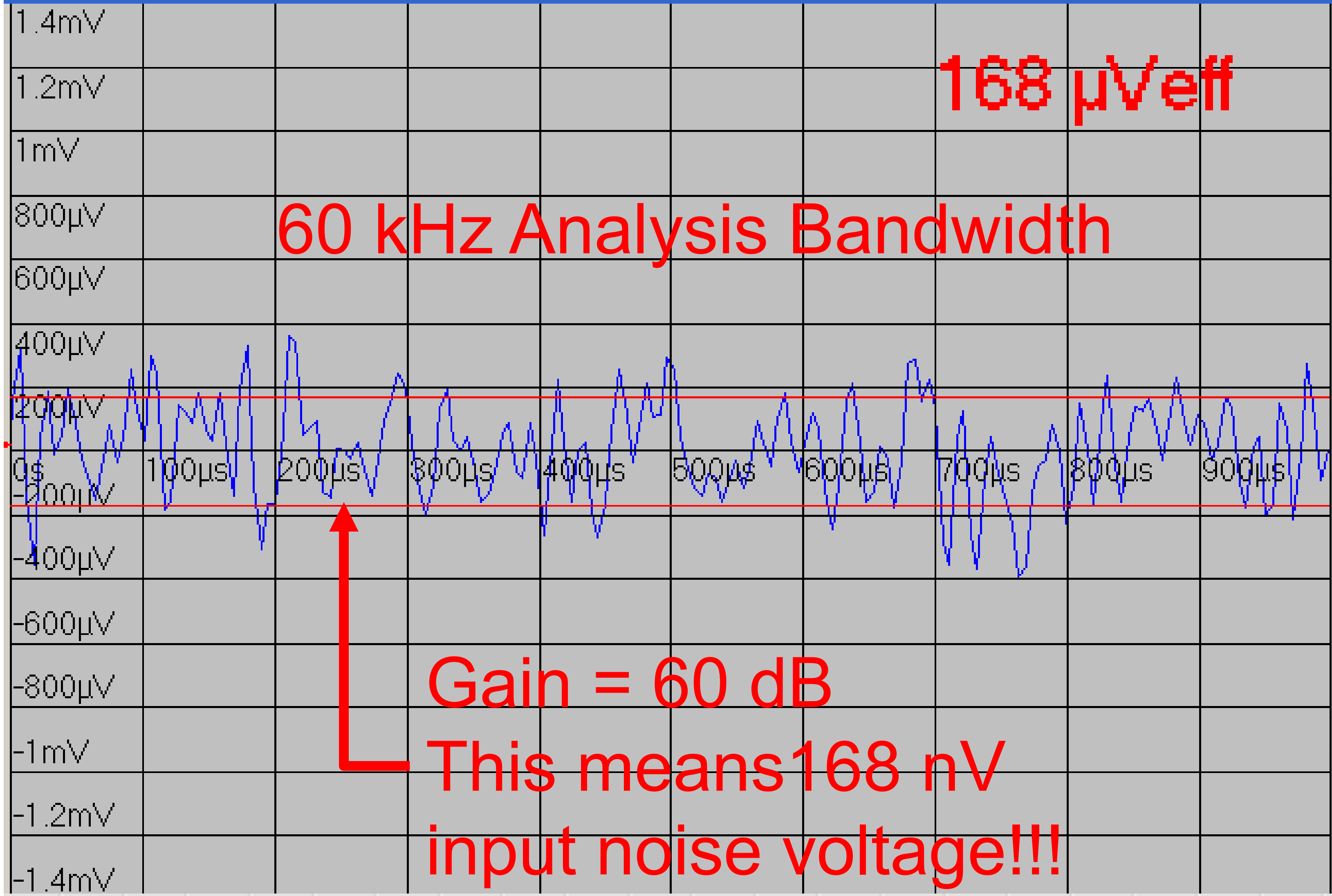
Cal. Out
Sine,
140mVpp

Out

30dB/60dB gain

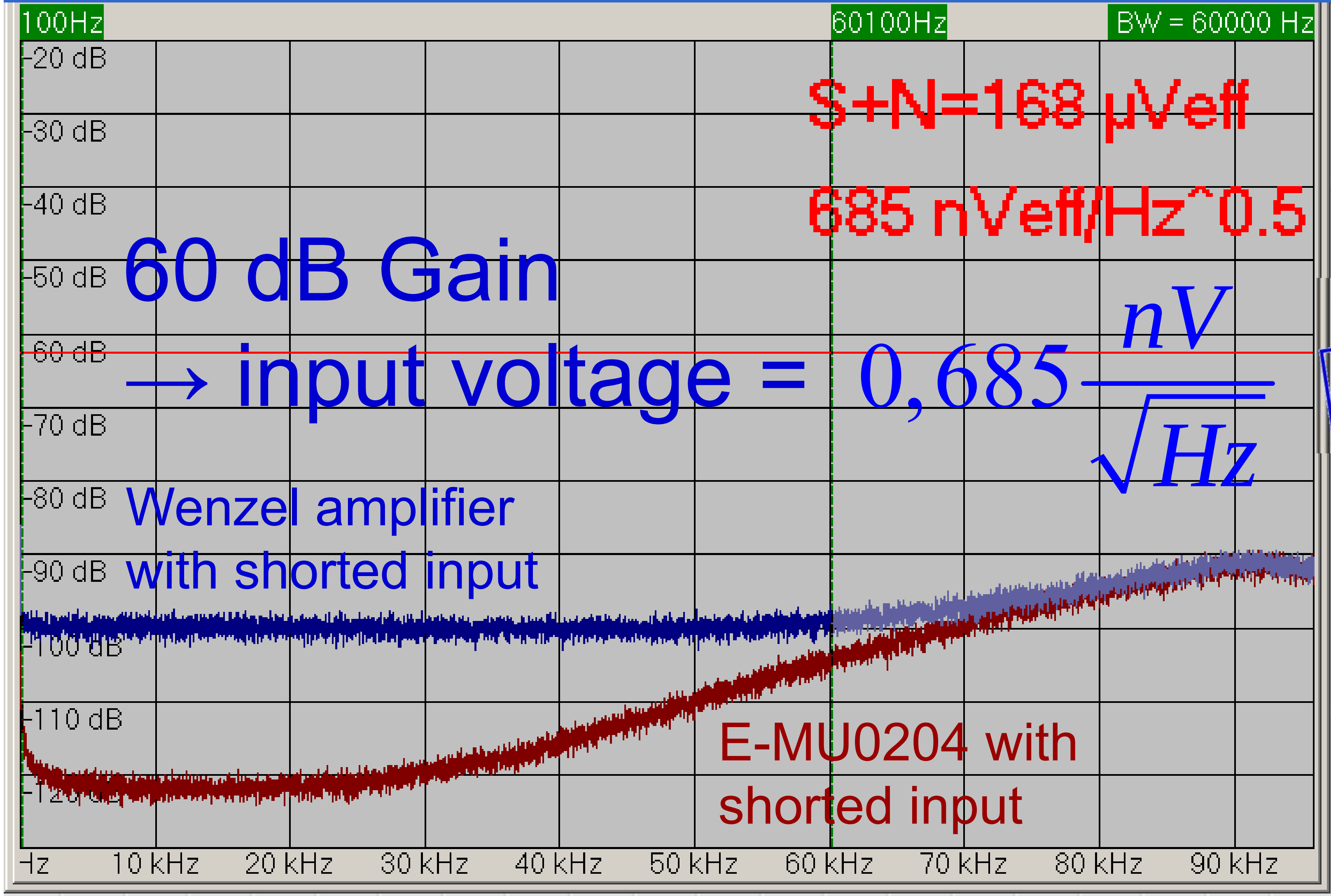
Hochschule Ulm

Wenzel Amplifier with shorted Input: Output Voltage



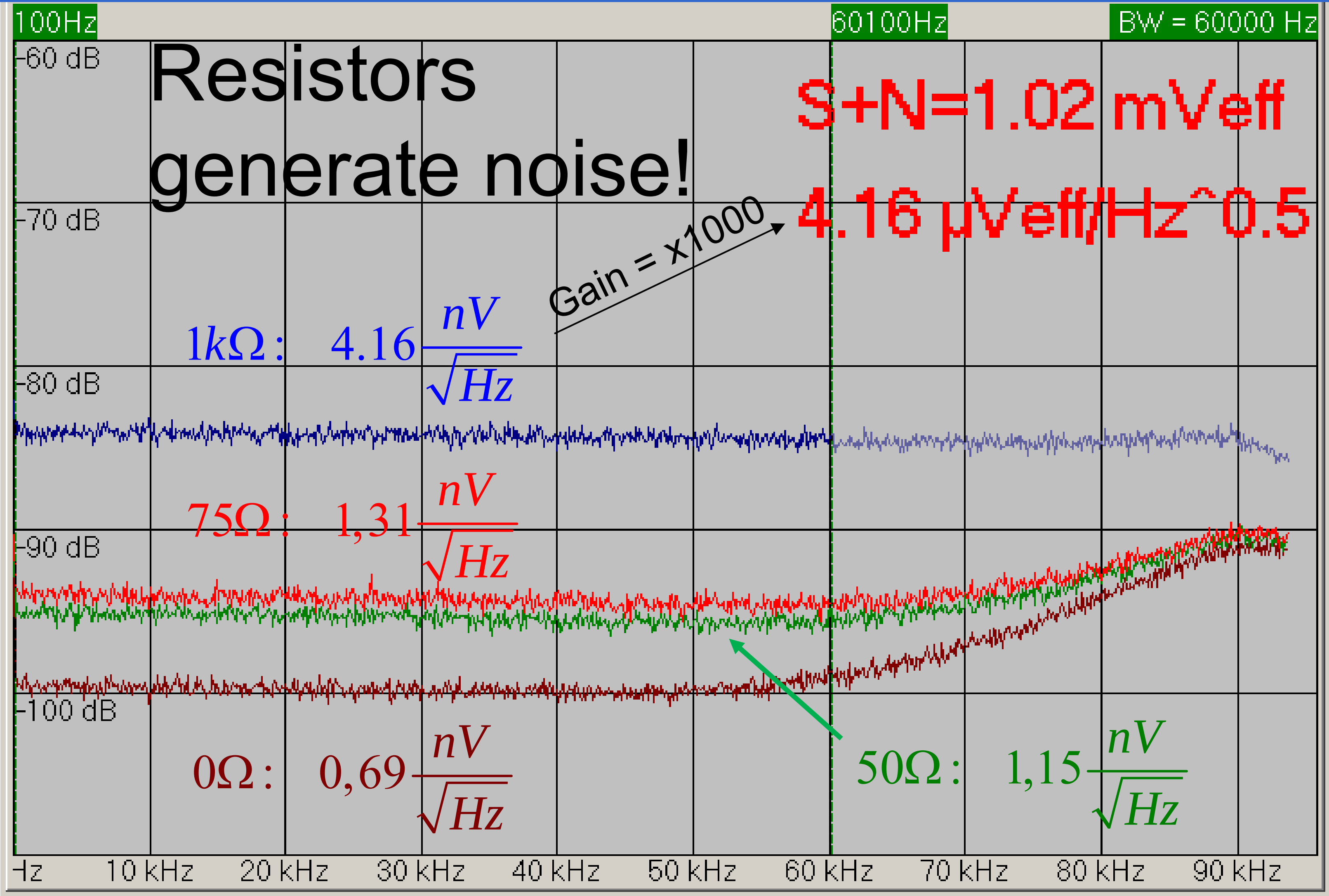
Hochschule Ulm

Wenzel Amplifier with shorted Input: Output Voltage (2)



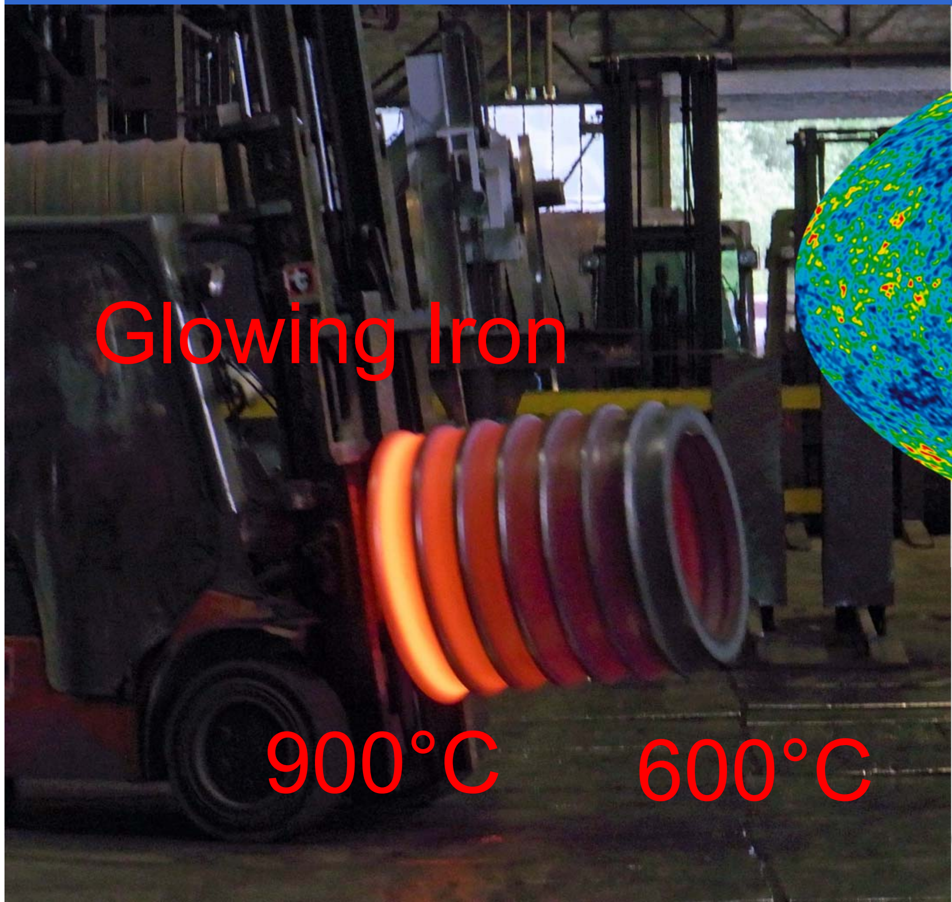
Hochschule Ulm

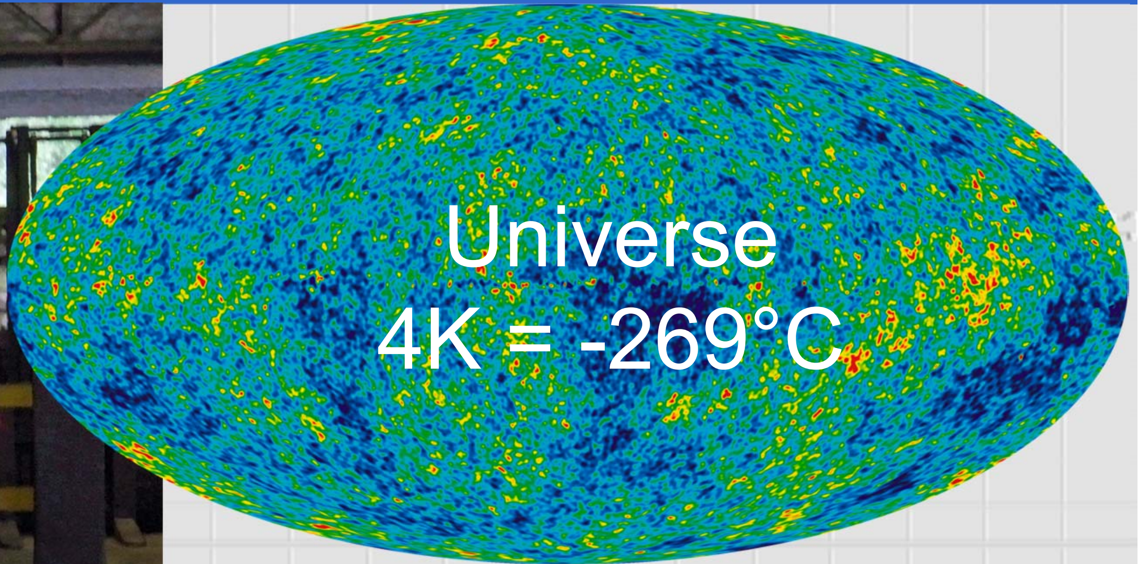
Measuring Resistor Noise with Wenzel Amplifier



Hochschule Ulm

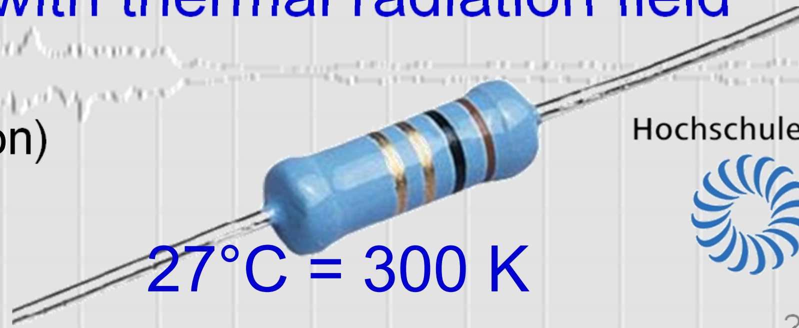
Warm Objects radiate!





http://map.gsfc.nasa.gov/

Resistor in thermal equilibrium
with thermal radiation field



http://de.wikipedia.org/wiki/Glut_(Light Radiation)

Hochschule Ulm

Resistors generate a thermal Noise Power Density

$$\frac{\Delta P}{\Delta f} = \frac{1}{\Delta f}\frac{U_{eff}^{\;2}}{R} = 4\frac{hf}{e^{hf/kT}-1}$$

Quantum nature

Bose-Einstein-Statistics

$$\text{for} \quad f << \frac{kT}{h} \approx 6\,\text{THz} \quad \text{at } 300\text{K} \quad \Rightarrow$$

Nyquist formula:

$$\frac{U_{eff}}{\sqrt{\Delta f}} = \sqrt{4kTR}$$

=> White noise far into GHz range

Hochschule Ulm

Thermal Resistor Noise:
Theory vs. Experiment

R / Ohm	Nyquist	measured	corrected
0	0,00	0,69	0,00
50	0,91	1,15	0,92
75	1,11	1,31	1,11
1000	4,07	4,16	4,10

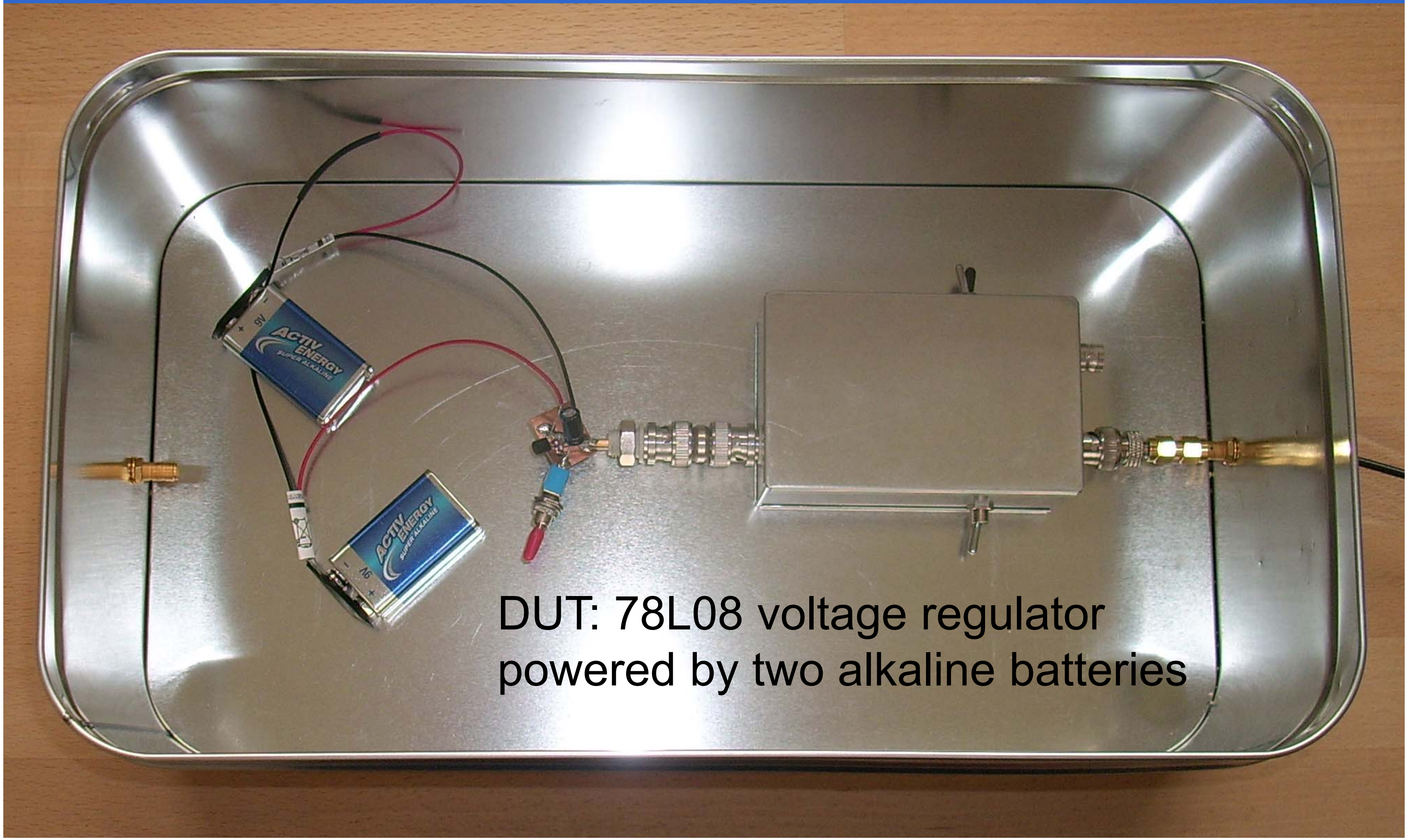
all levels in $nV / \sqrt{Hz}$

Amplifier noise power must be subtracted from measured values:

$$U_{corr} = \sqrt{U_{meas}^{2} - \left(0{,}69 \frac{nV}{\sqrt{Hz}}\right)^{2}}$$

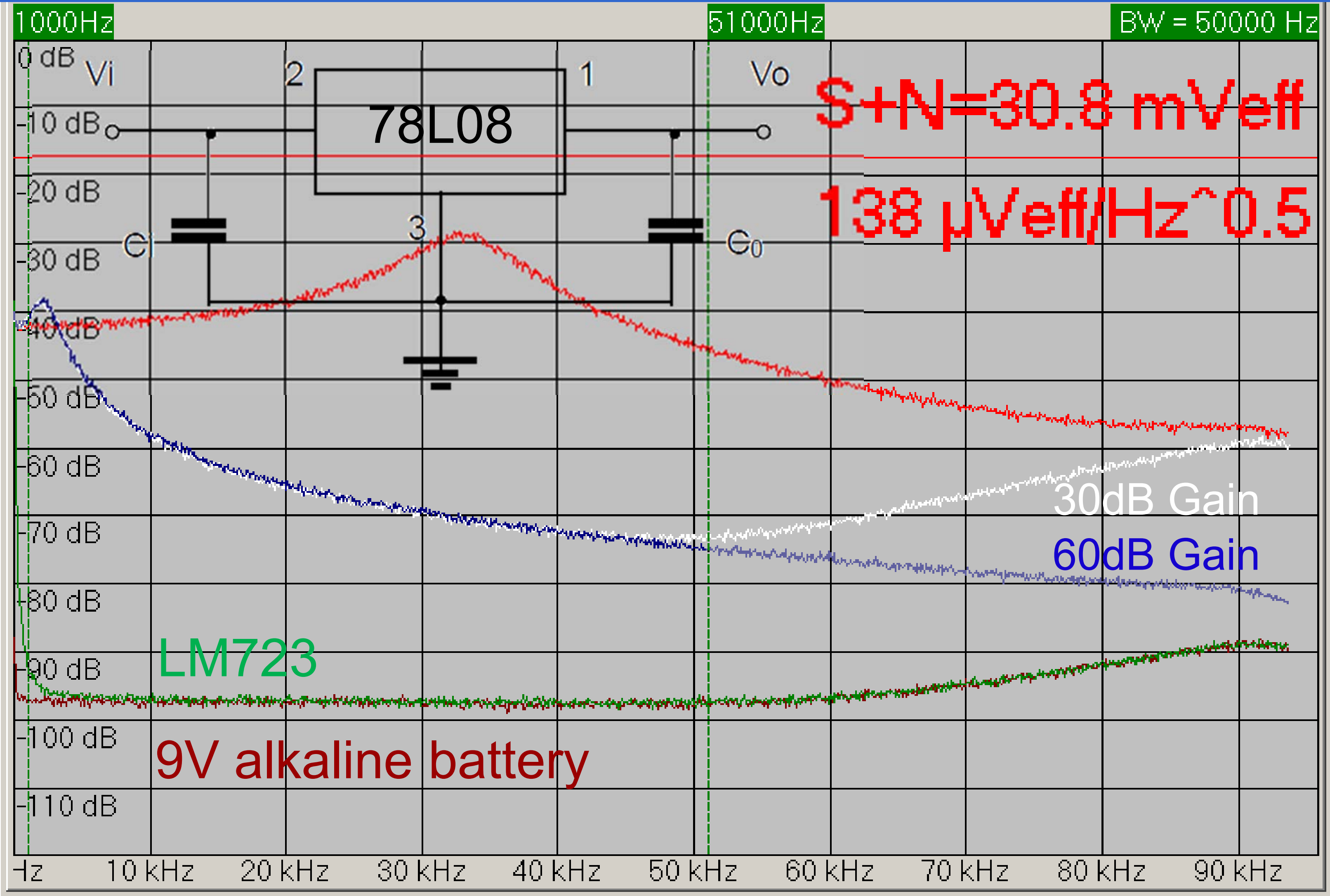
Hochschule Ulm

Power Supplies do produce Noise, too!
Screened Test Chamber:



DUT: 78L08 voltage regulator
powered by two alkaline batteries

Noise Voltages of various Power Supplies



78L08:

Ci=1uF

Co=1uF

Co=100uF

Hochschule Ulm

Noise Voltages of various Power Supplies (2)

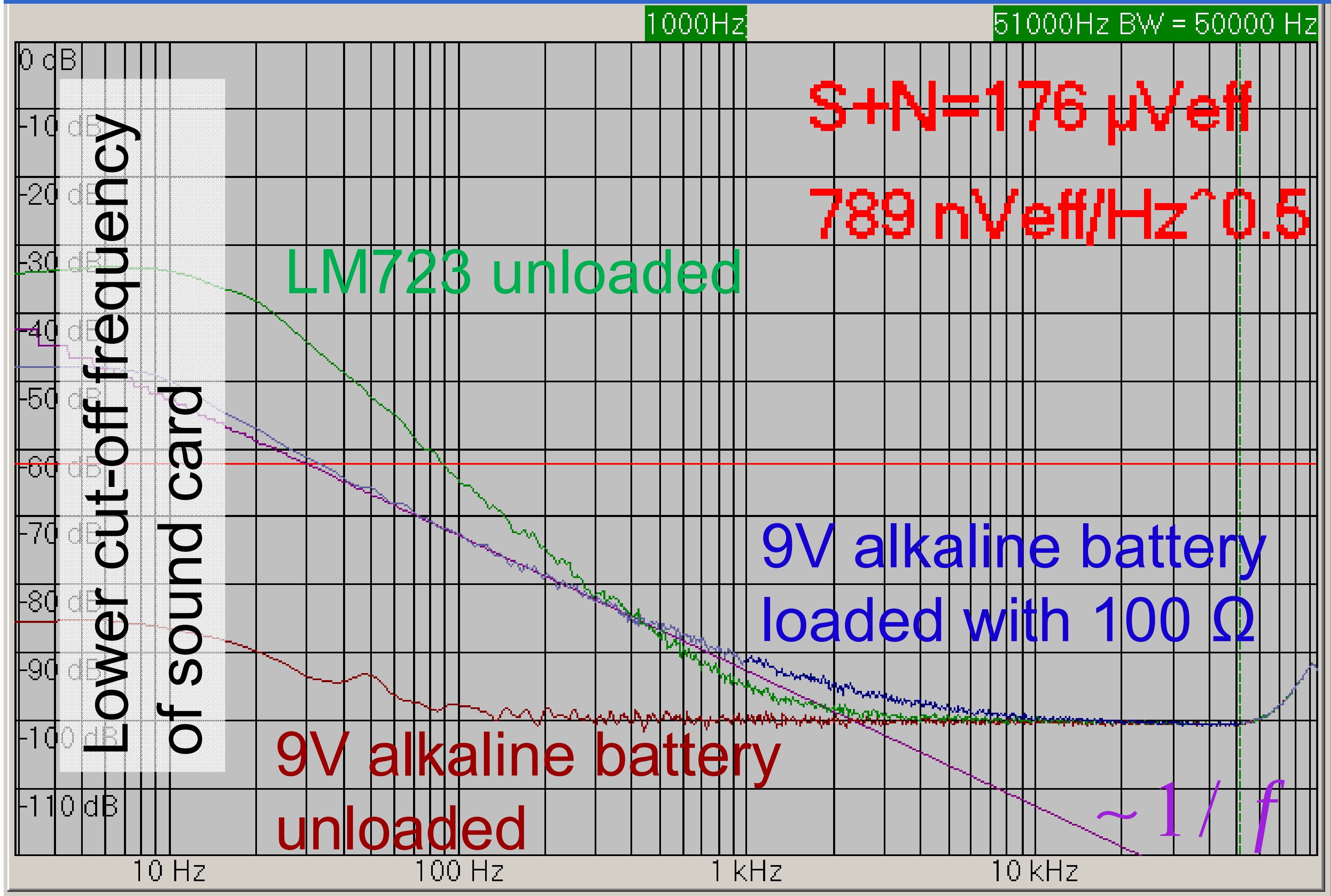
	measured	corrected *
Alkaline Battery	0,72	0,19
NiMH Accu	0,71	0,15
LM723	0,74	0,26
78L08 Co=1uF	880	880
78L08 Co=100uF	140	140

* amplifier noise of 0,69 nV/√Hz subtracted power wise.

all levels in $nV / \sqrt{Hz}$

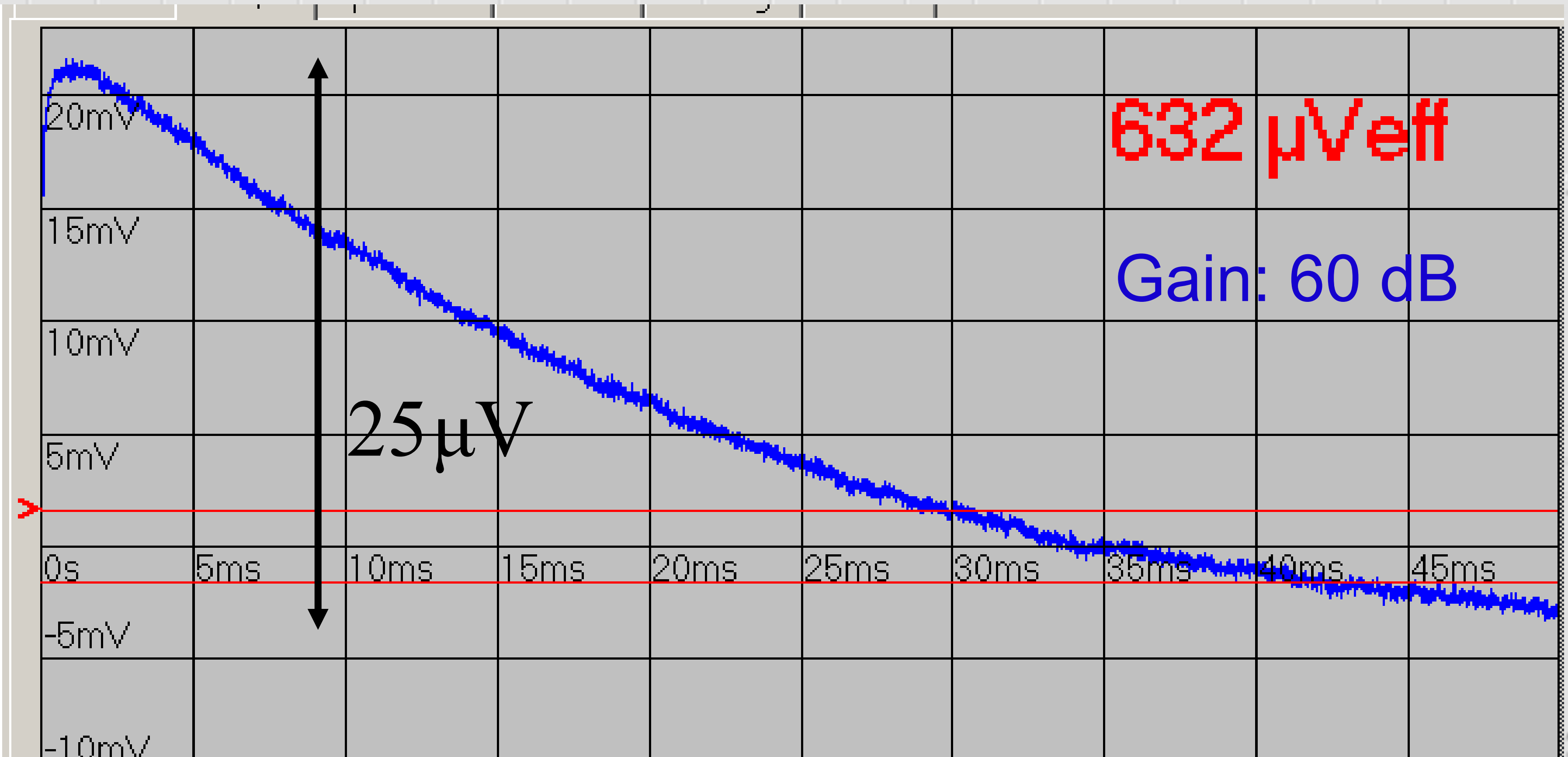
Hochschule Ulm

Noise Voltages of various Power Supplies (3)



Hochschule Ulm

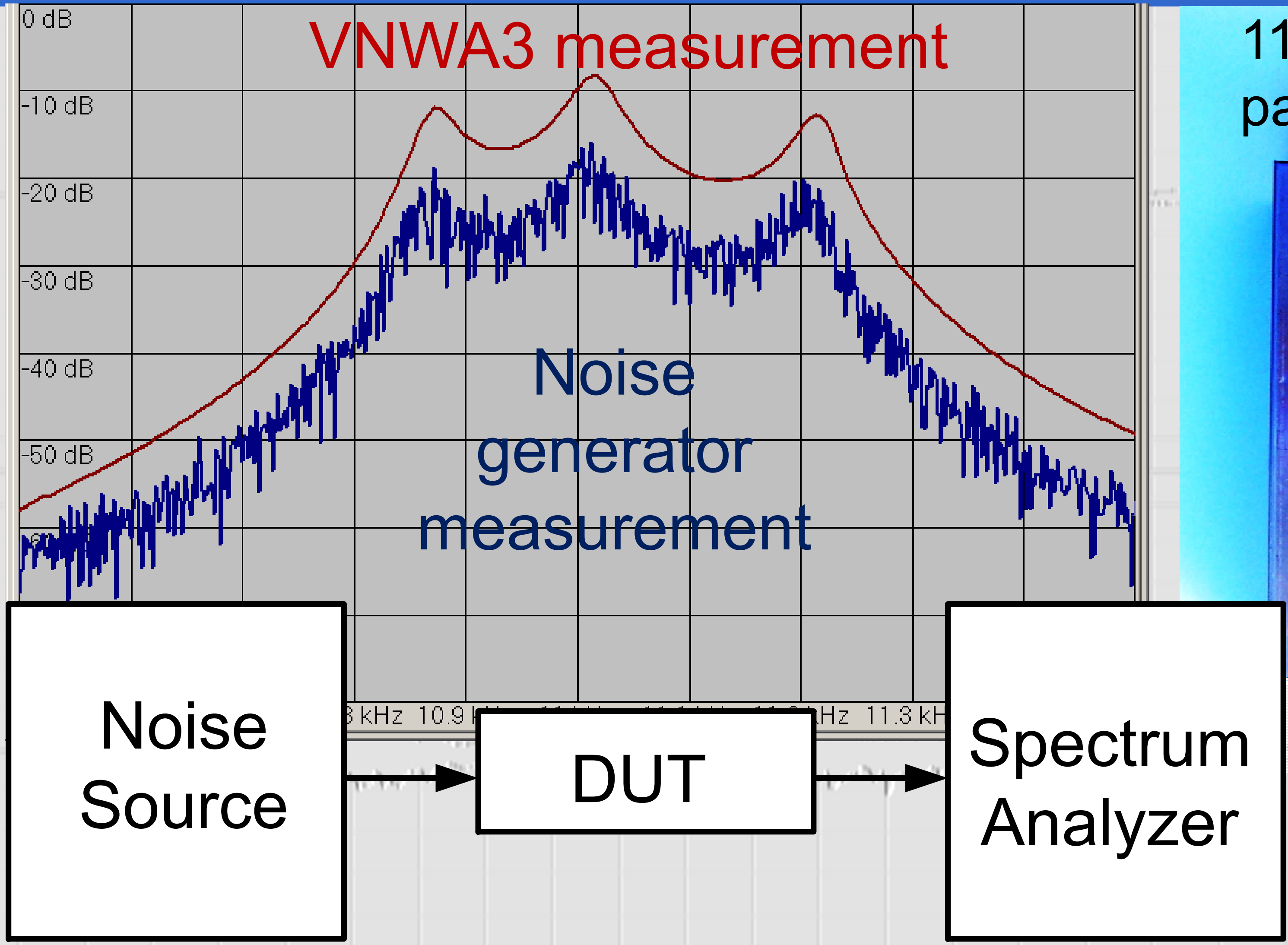
Loaded Batteries do create sporadic Voltage Transients

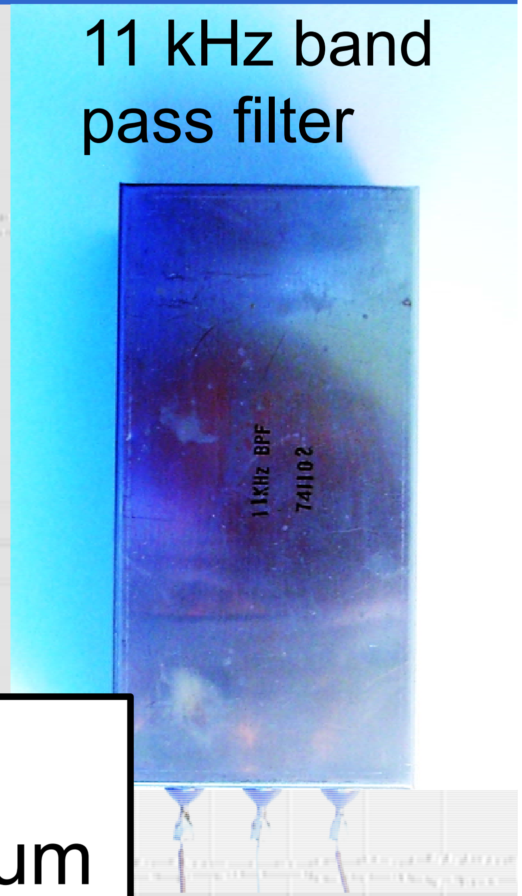


9V alkaline battery loaded with 100 Ω

Hochschule Ulm

Noise can be used to measure Transfer Functions





Hochschule Ulm

Measuring Transfer Functions: Noise Excitation vs. Frequency Sweep

Pros Noise Excitation:

- All frequencies probed at the same time
- DUT settles to all frequency at the same time

Cons Noise Excitation:

- Less power per frequency
- Highly linear DUT and signal processing required

Hochschule Ulm

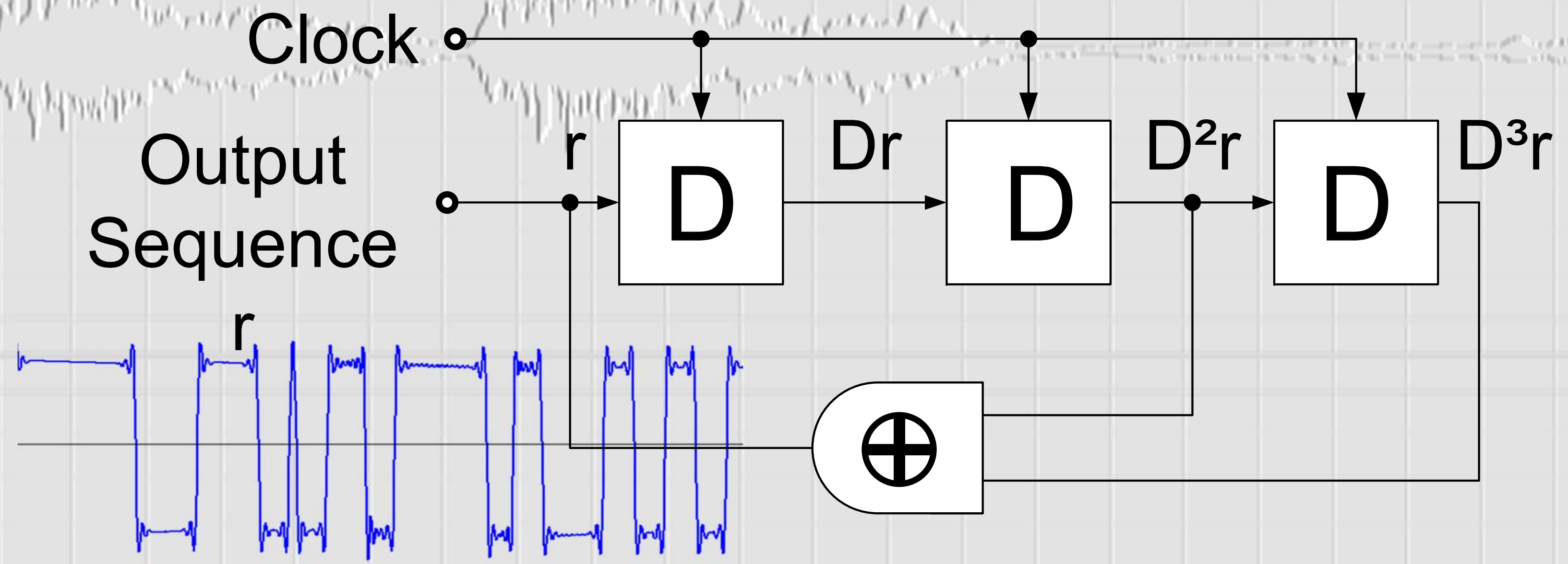
Ideal Noise Excitation

- Highest possible power per frequency for given peak amplitude
- Constant frequency spectrum
- Periodically for optimum DUT settling

Hochschule Ulm

Ideal „Noise“ Excitation: Shift Register Sequences

Shift Register with Feedback, e.g.



$$r = D^2 r \oplus D^3 r \;\Leftrightarrow\; \left(D^3 \oplus D^2 \oplus 1\right) r = 0$$

Generator Polynomial

Hochschule Ulm

Maximum Length Shift Register Sequences = Pseudorandom Binary Sequences (PRBS)

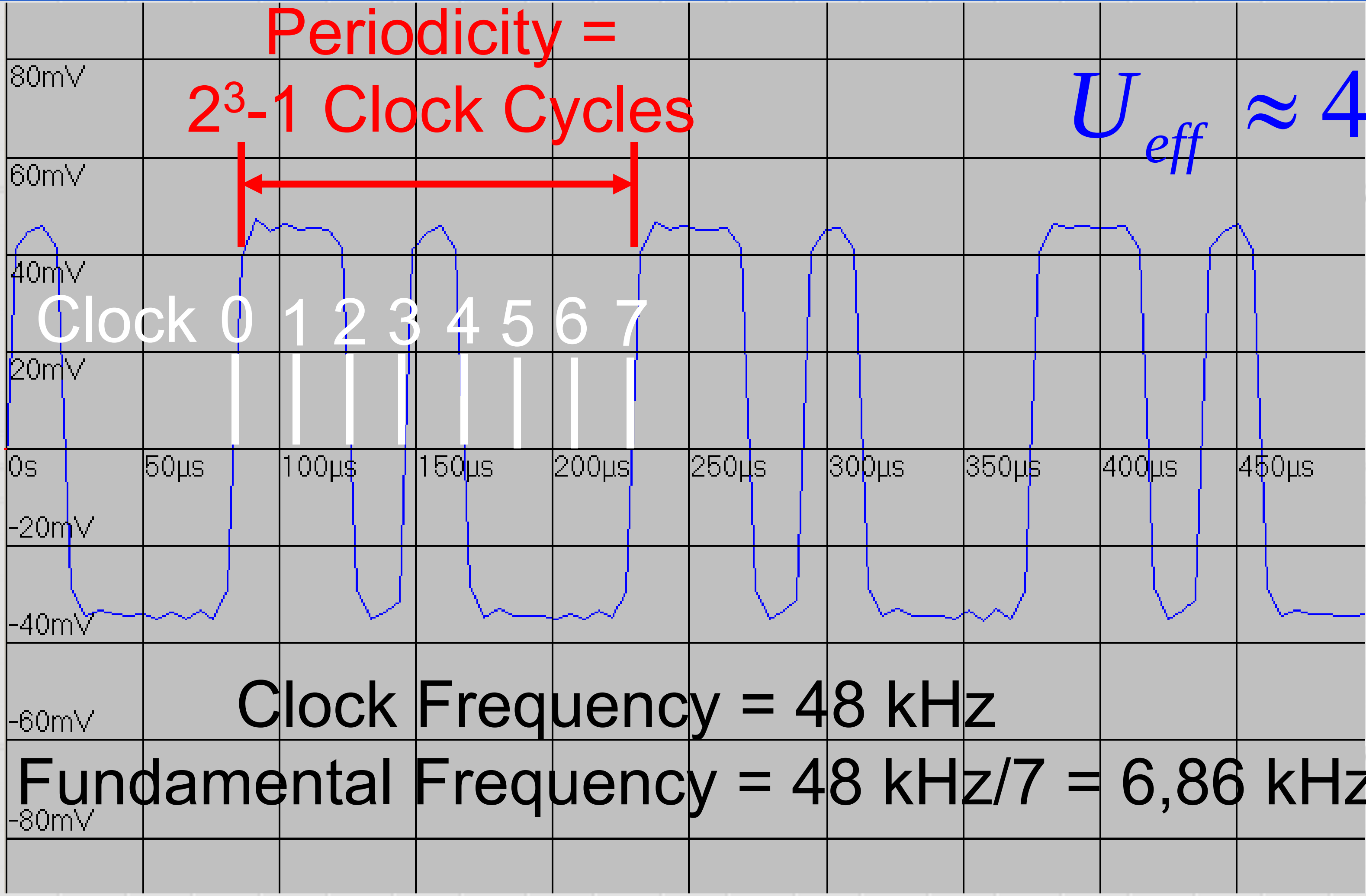
- n Stage Shift Register
- Generator Polynomial irreducible

- Periodicity = 2^n-1 Clocks, i.e. maximum
- Contains 2^n-1 Frequencies *
- Sequence δ-correlated

* within Nyquist range

Hochschule Ulm

Example: 3 Stage Shift Register



$U_{eff} \approx 40\ \text{mV}$

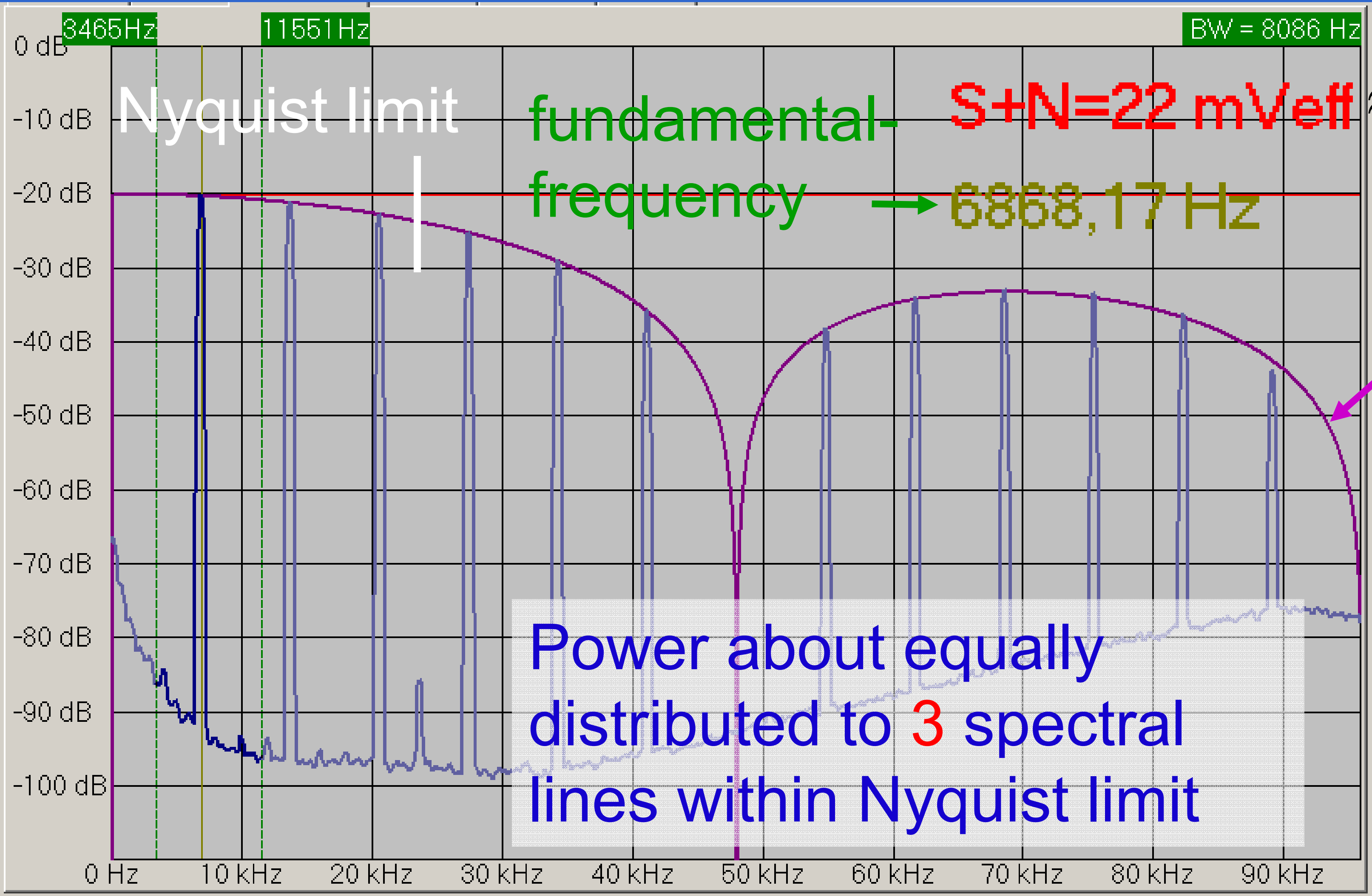
DC-free

Clock Frequency = 48 kHz

Fundamental Frequency = 48 kHz/7 = 6,86 kHz

Hochschule Ulm

Example: 3 Stage Shift Register (2)
SA only sees positive Frequencies!



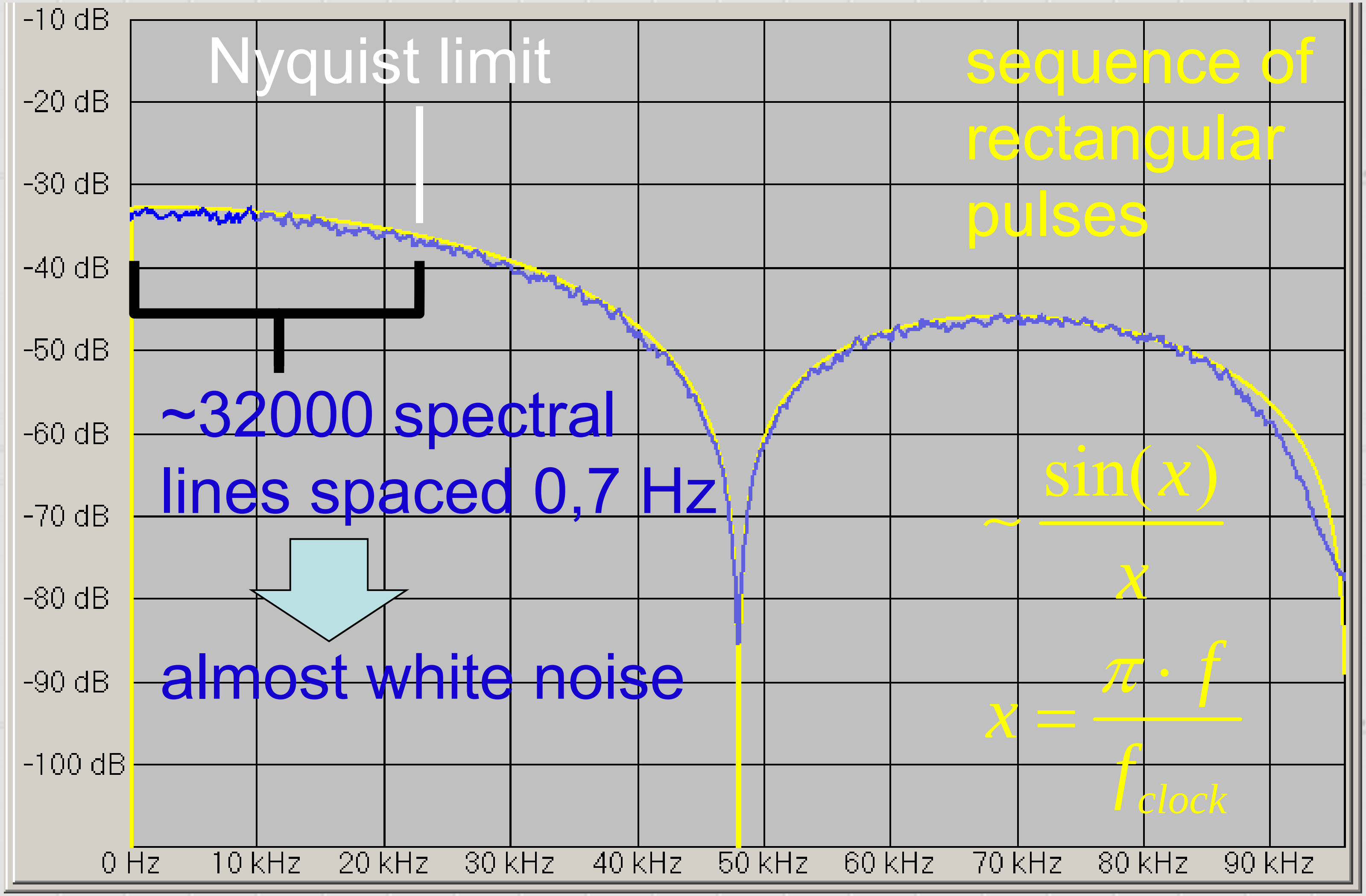
$$\approx \frac{40\ \mathrm{mV}}{\sqrt{3}}$$

$$\sim \frac{\sin(x)}{x}$$

$$x = \frac{\pi \cdot f}{f_{clock}}$$

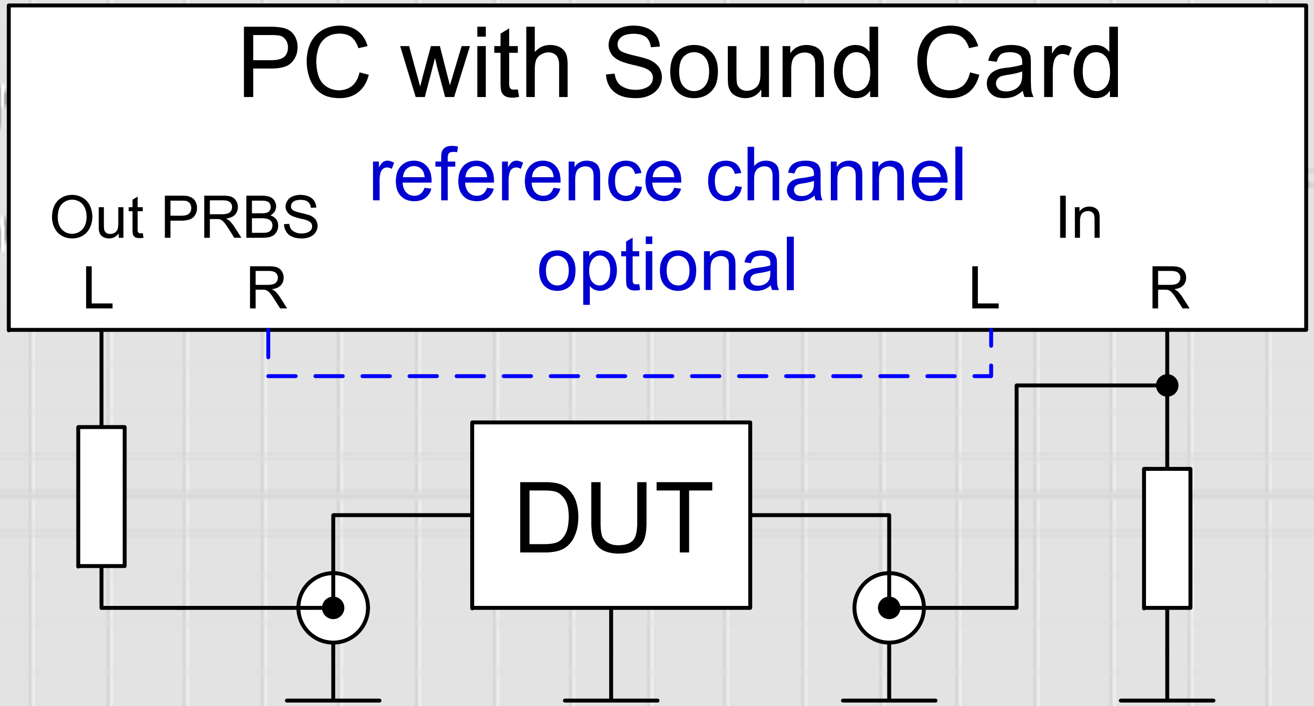
Hochschule Ulm

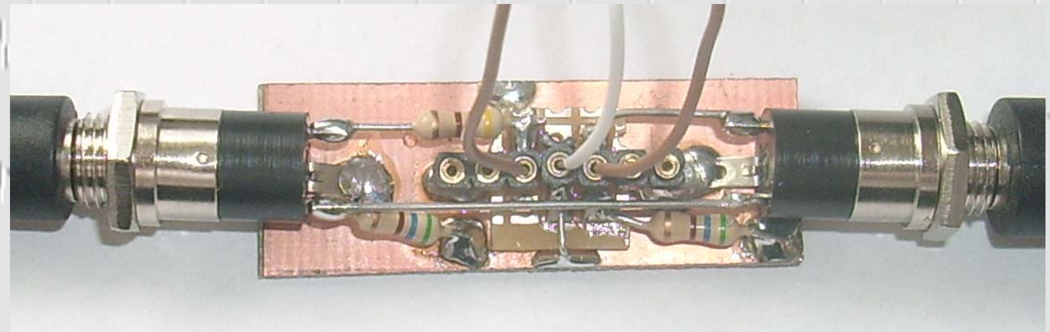
Example: 16 Stage Shift Register with 48 kHz Clock Frequency



Hochschule Ulm

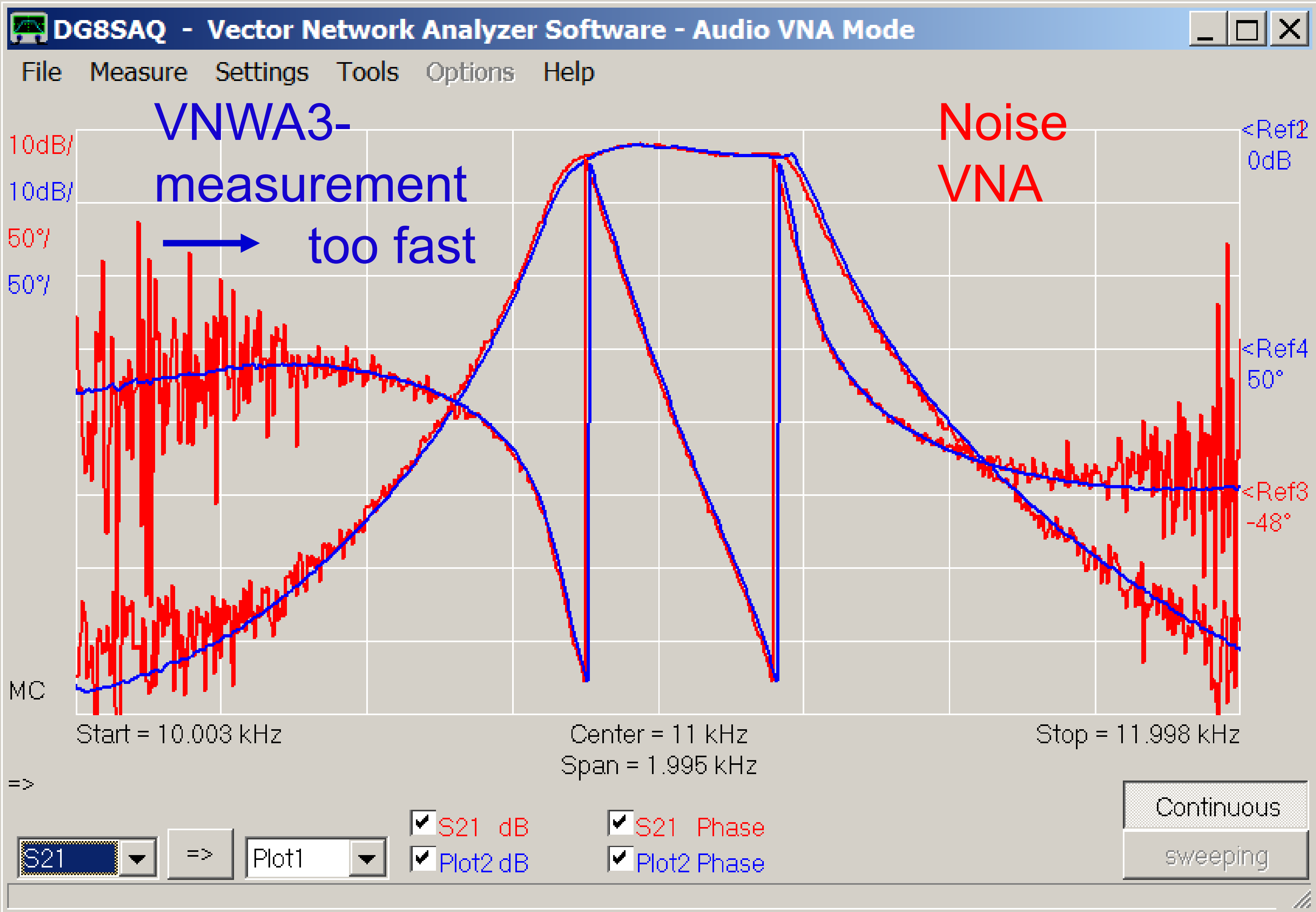
Noise-VNA measures Transmission





Hochschule Ulm

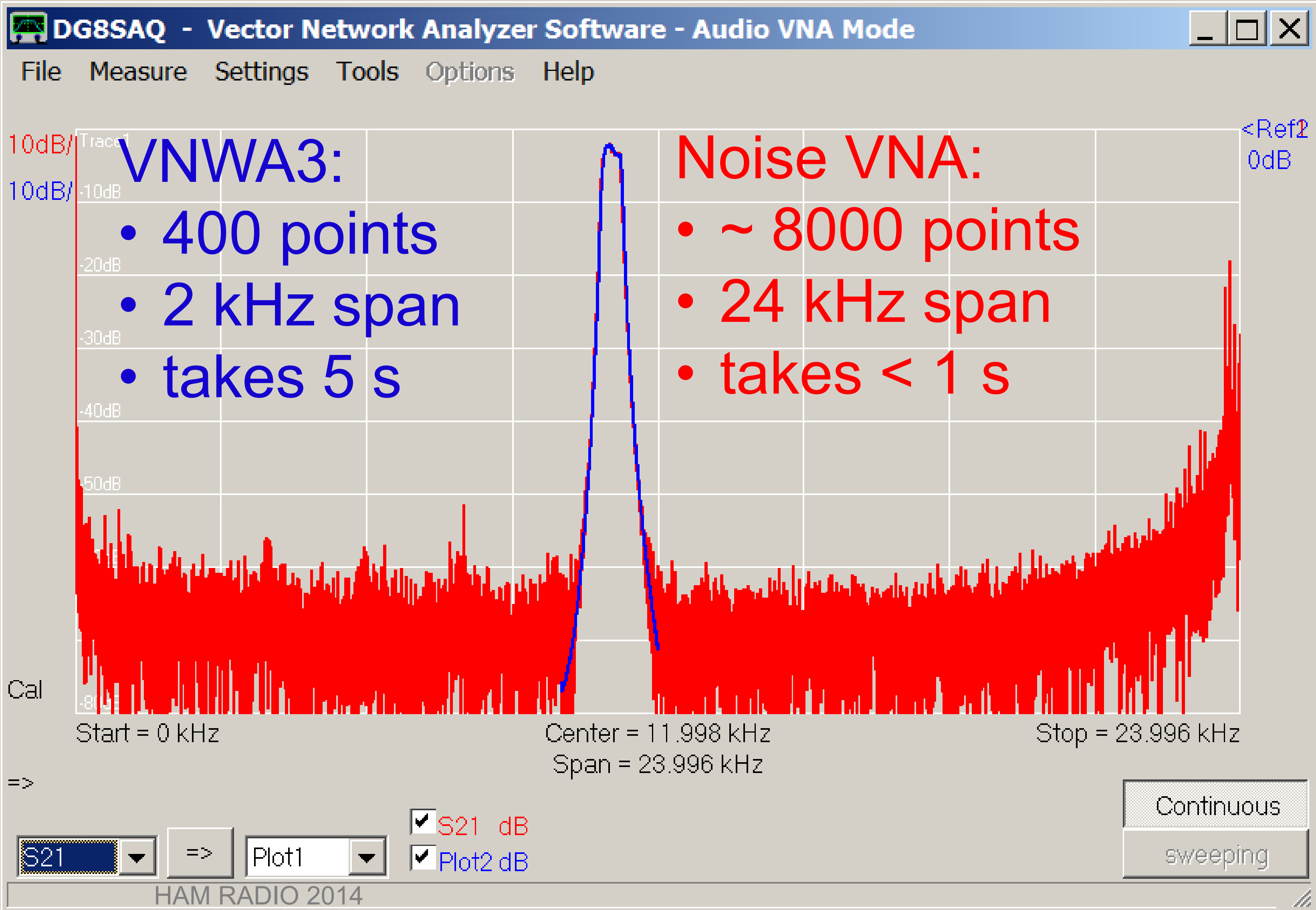
11 kHz Band Pass Filter: Magnitude and Phase!



500 Ω Ports

ochschule Ulm

11 kHz Band Pass Filter (2)



VNWA3:

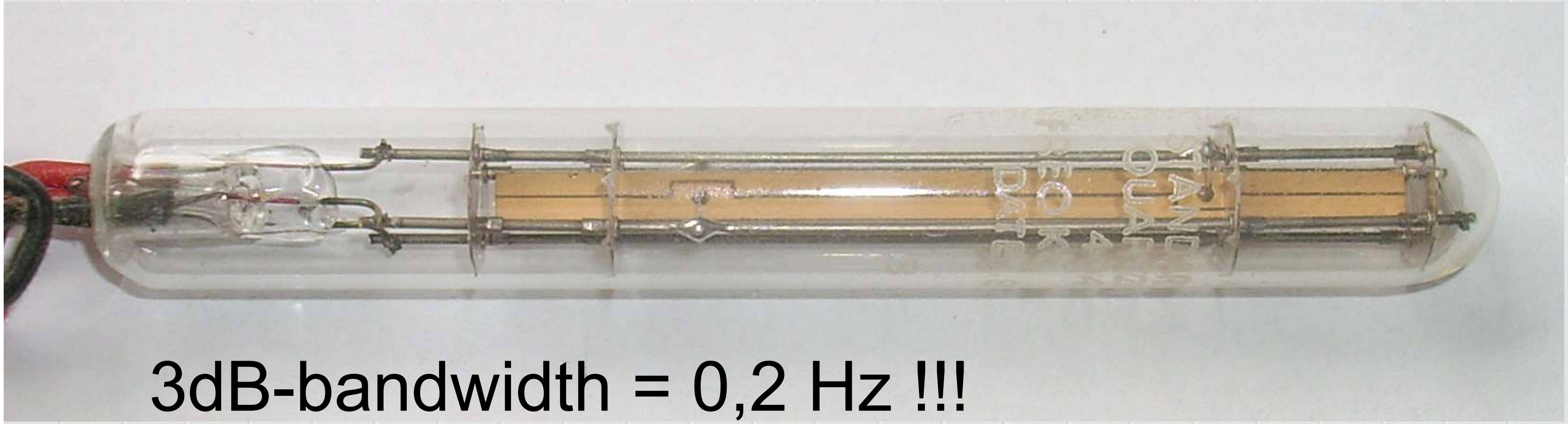
- 400 points
- 2 kHz span
- takes 5 s

Noise VNA:

- ~ 8000 points
- 24 kHz span
- takes < 1 s

500 Ω Ports

4 kHz Quartz Crystal

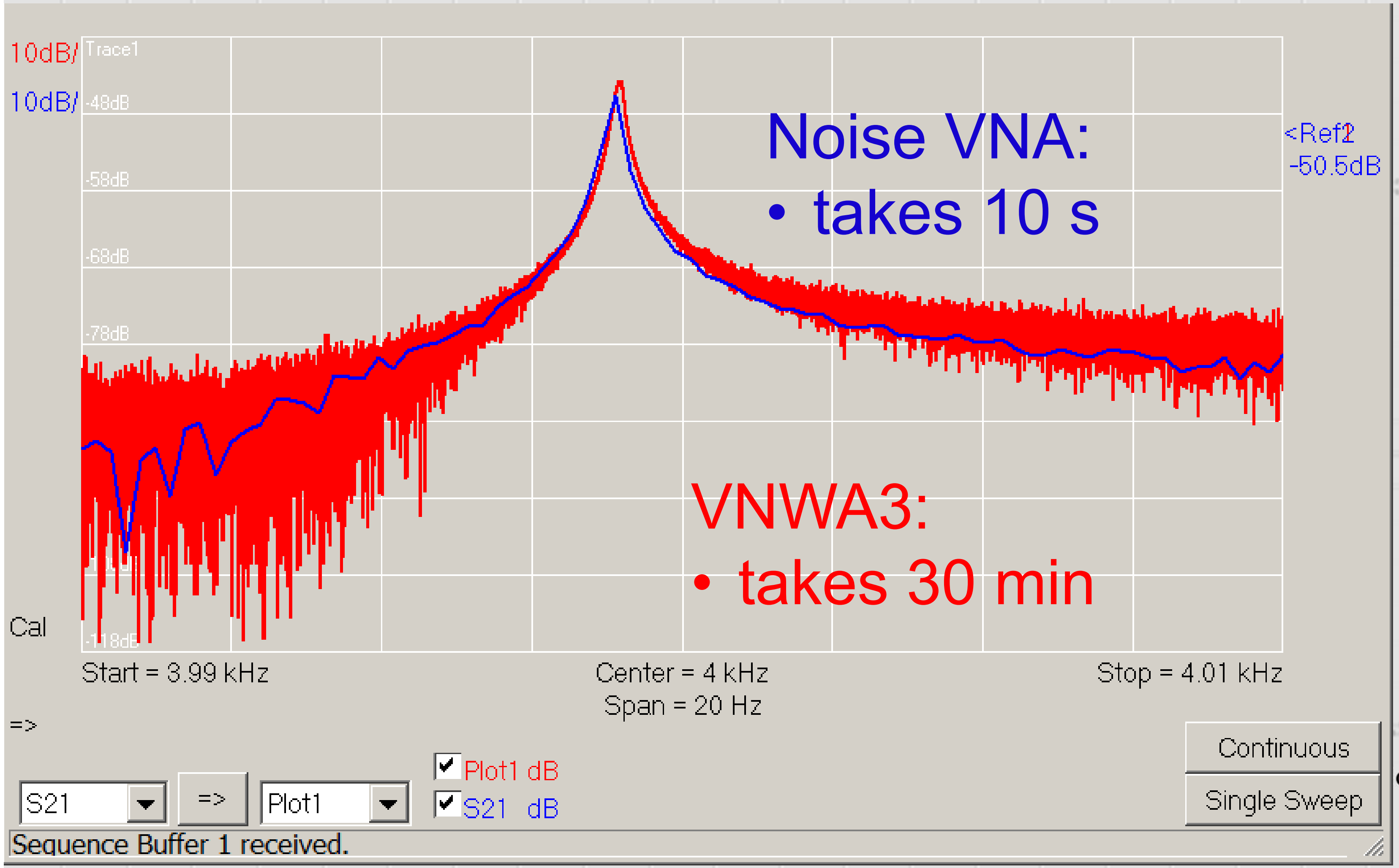


3dB-bandwidth = 0,2 Hz !!!

Requires > 5 s, settling time after frequency step!

Hochschule Ulm

4 kHz Quartz Crystal (2)



ochschule Ulm

Measurement Time vs. Signal-to-Noise Ratio

Doubling of measurement time:

→ 2-fold noise *power* N

→ 2-fold signal *voltage*

→ 4-fold signal *power* S

→ 2-fold S/N

Doubling of measurement time yields 3 dB signal-to-noise improvement.

Hochschule Ulm

Measurement Time Noise VNA vs. VNWA Example: Sequence Length = 511

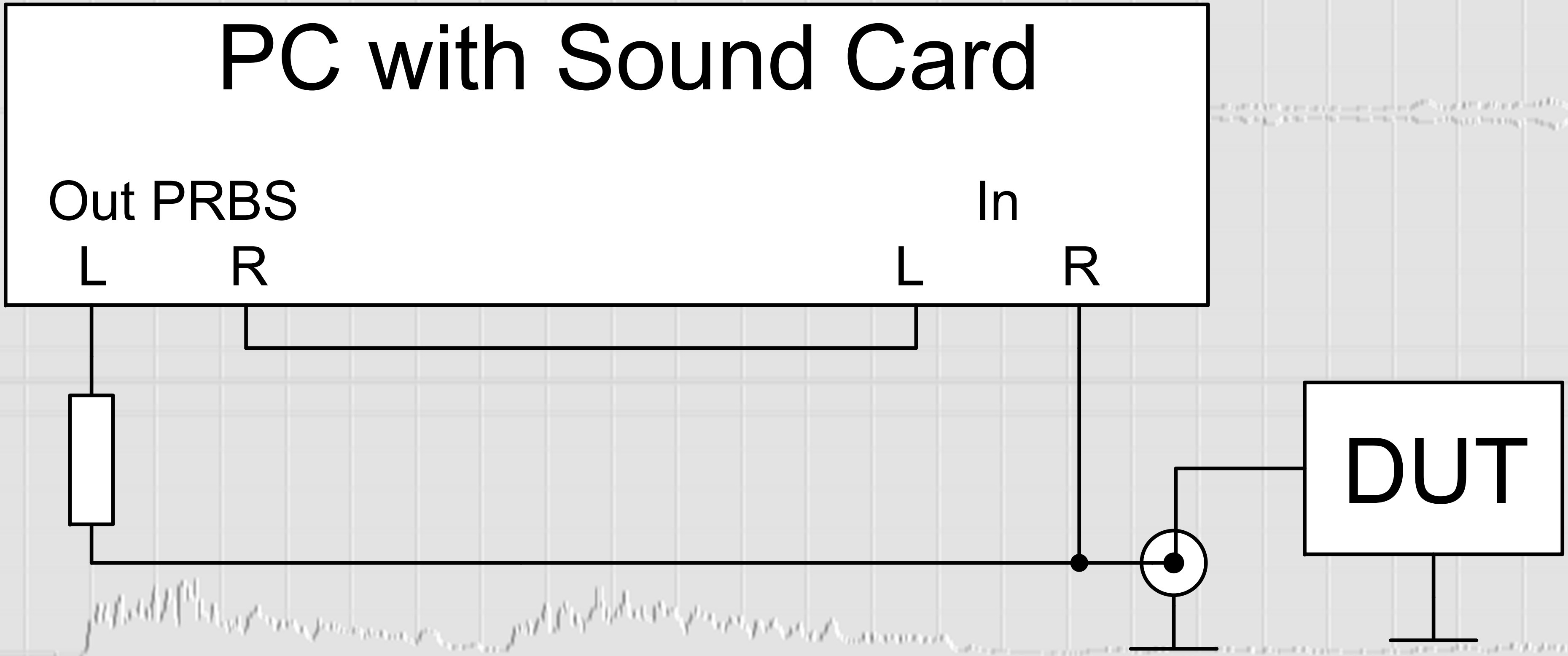
equal peak-to-peak input voltages U_0 for both cases
measurement time per frequency =T_0 , settling time = T_E

VNWA	Noise VNA ✓
→ sine excitation	→ digital excitation
→ $P=U_0^2/2R$	→ $P=U_0^2/R$ → 3 dB gain
→ 255 frequency points ≈ 2^8 points	→ distributed to 255 spectral lines
→ $T \approx 2^8 \cdot T_0 + 2^8 \cdot T_E$	→ $T \approx 2^7 \cdot T_0 + 1 \cdot T_E$

- 3dB gain by digital excitation
- Dramatically reduced settling time

Hochschule Ulm

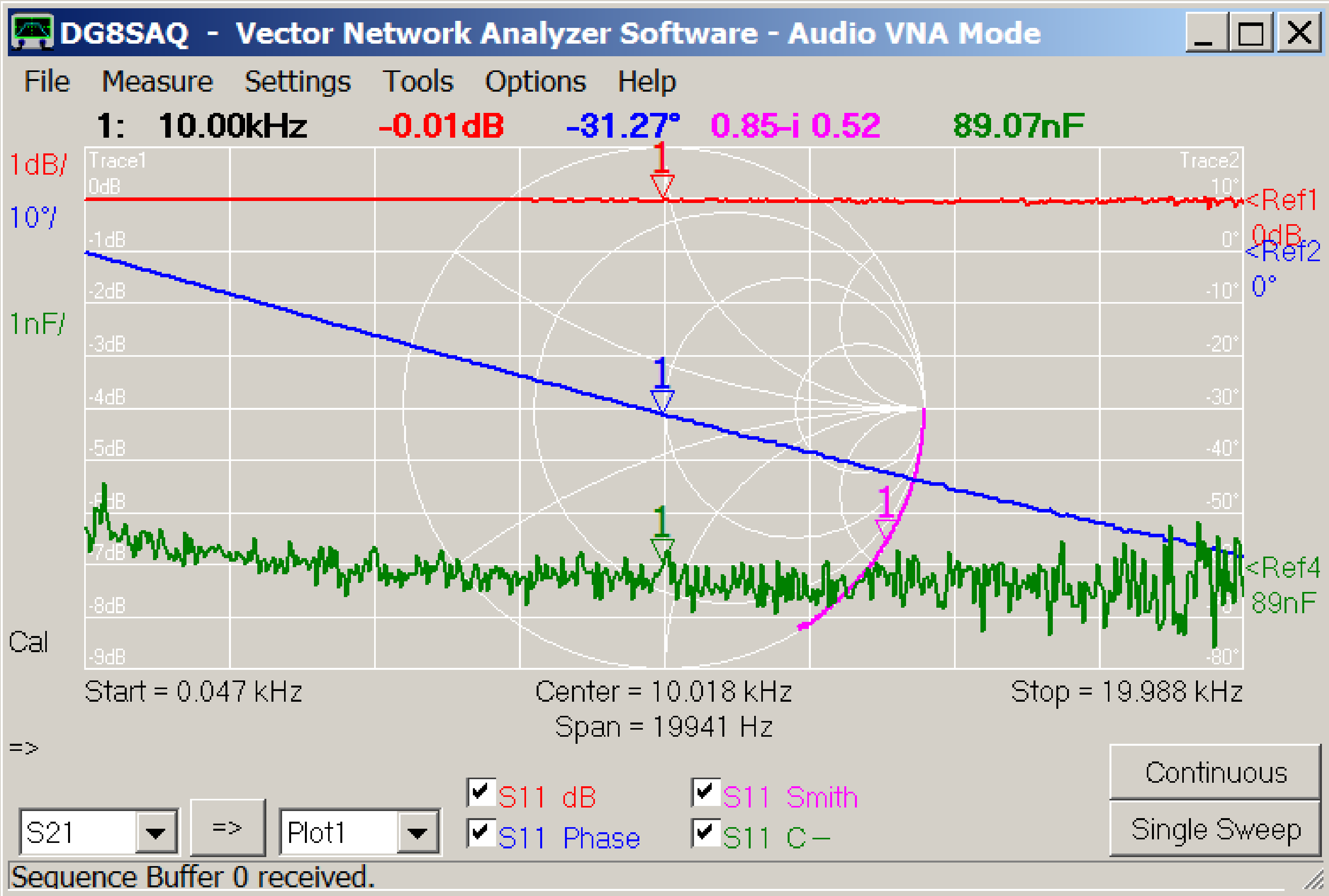
Noise VNA can also measure Reflection



Hochschule Ulm

My Noise VNA for Reflection Measurements

Reflection Measurement of a 100 nF Capacitor with the Noise VNA



schule Ulm

The END

Many thanks for watching!

Hochschule Ulm