Electronic Measurements for Amateur Radio

Rocky Mountain Ham University – December 2022

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Speaking Today

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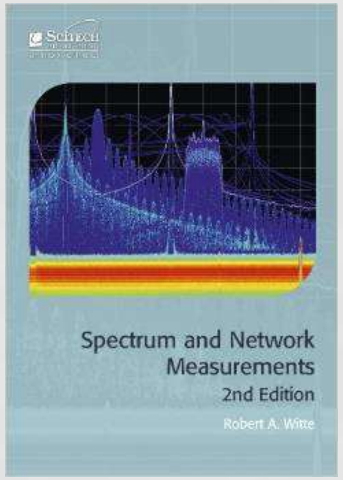
My technical background is Electrical Engineering and I have worked for decades in the electronic test and measurement industry (HP, Agilent Technologies, Keysight Technologies)

Ham radio interest: the confluence of VHF ham radio, mountains and exploring (SOTA, POTA).

And I like to write stuff.



Agenda

Topic	Comments	Time
Introduction	Measurement concepts, frequency range, Digital Multimeters SWR / Power meters	8:30 – 9:20
Break		
Oscilloscope Measurements	Time domain, oscilloscopes, probes	9:30 to 10:20
Break		
Vector Network Analyzer measurements	S-parameters, transmission, Reflection, NanoVNA	10:30 to 11:20
Spectrum Analyzer Measurements	Frequency domain, spectrum analyzers, TinySA, SDR receiver	11:00 to 11:30
Discussion and wrap up		11:30 to noon

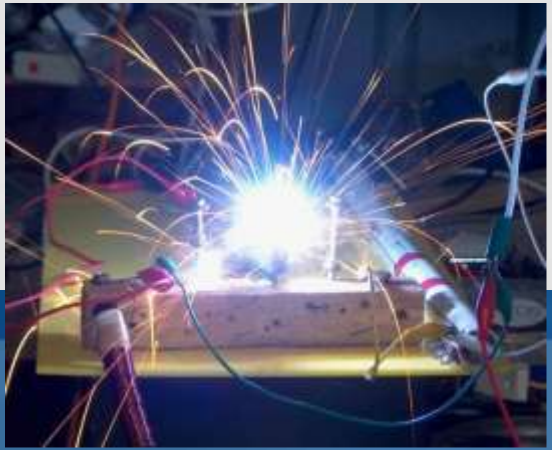
Why do we need electronic measurements?

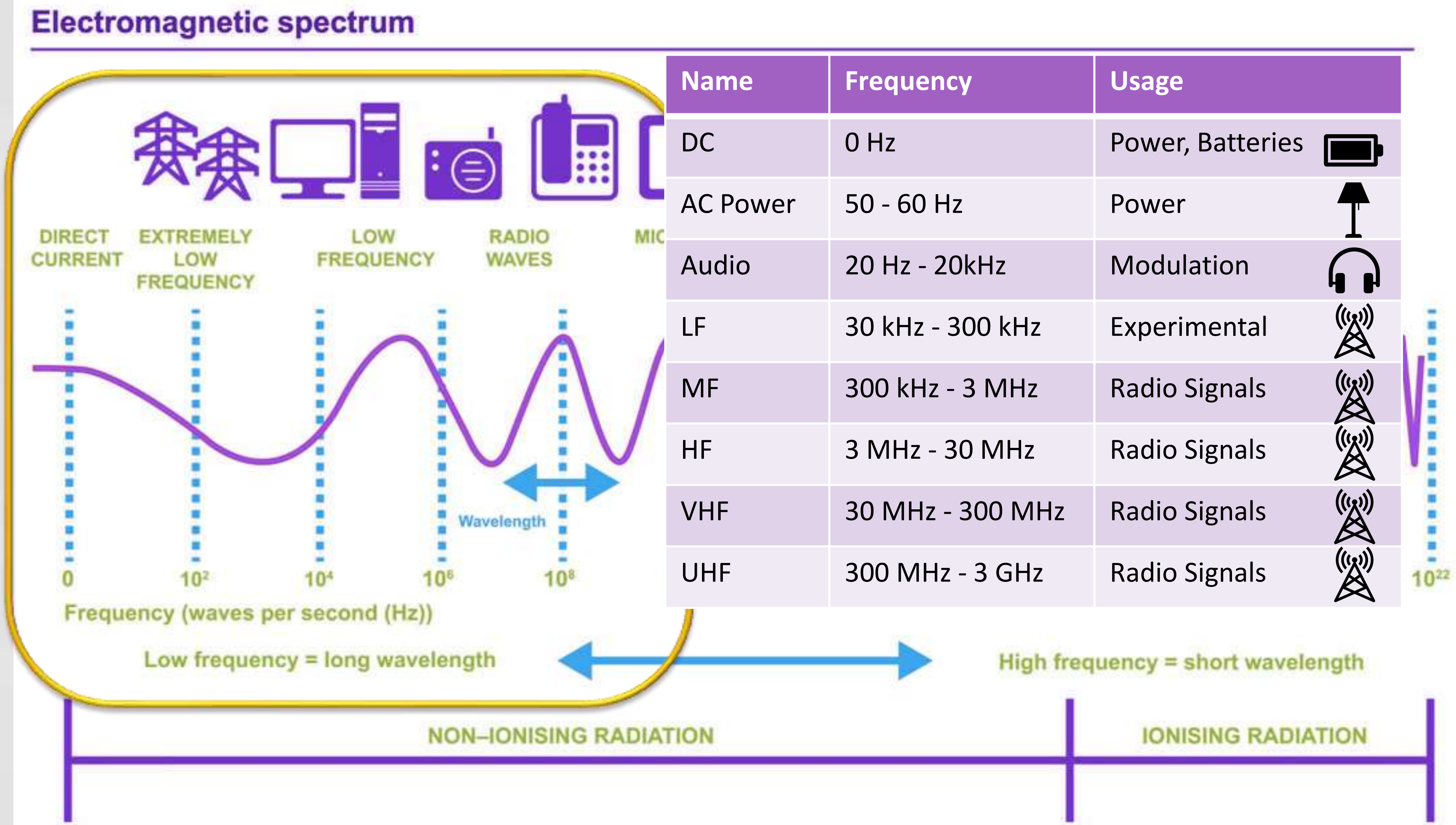
- Bob's First Law of Electronic Measurement

  With electricity, most of the time we cannot observe what is going on without measuring instruments.

- Bob's Second Law of Electronic Measurement

  When we can observe electricity directly, it is often a bad thing.





Name	Frequency	Usage
DC	0 Hz	Power, Batteries
AC Power	50 - 60 Hz	Power
Audio	20 Hz - 20kHz	Modulation
LF	30 kHz - 300 kHz	Experimental
MF	300 kHz - 3 MHz	Radio Signals
HF	3 MHz - 30 MHz	Radio Signals
VHF	30 MHz - 300 MHz	Radio Signals
UHF	300 MHz - 3 GHz	Radio Signals

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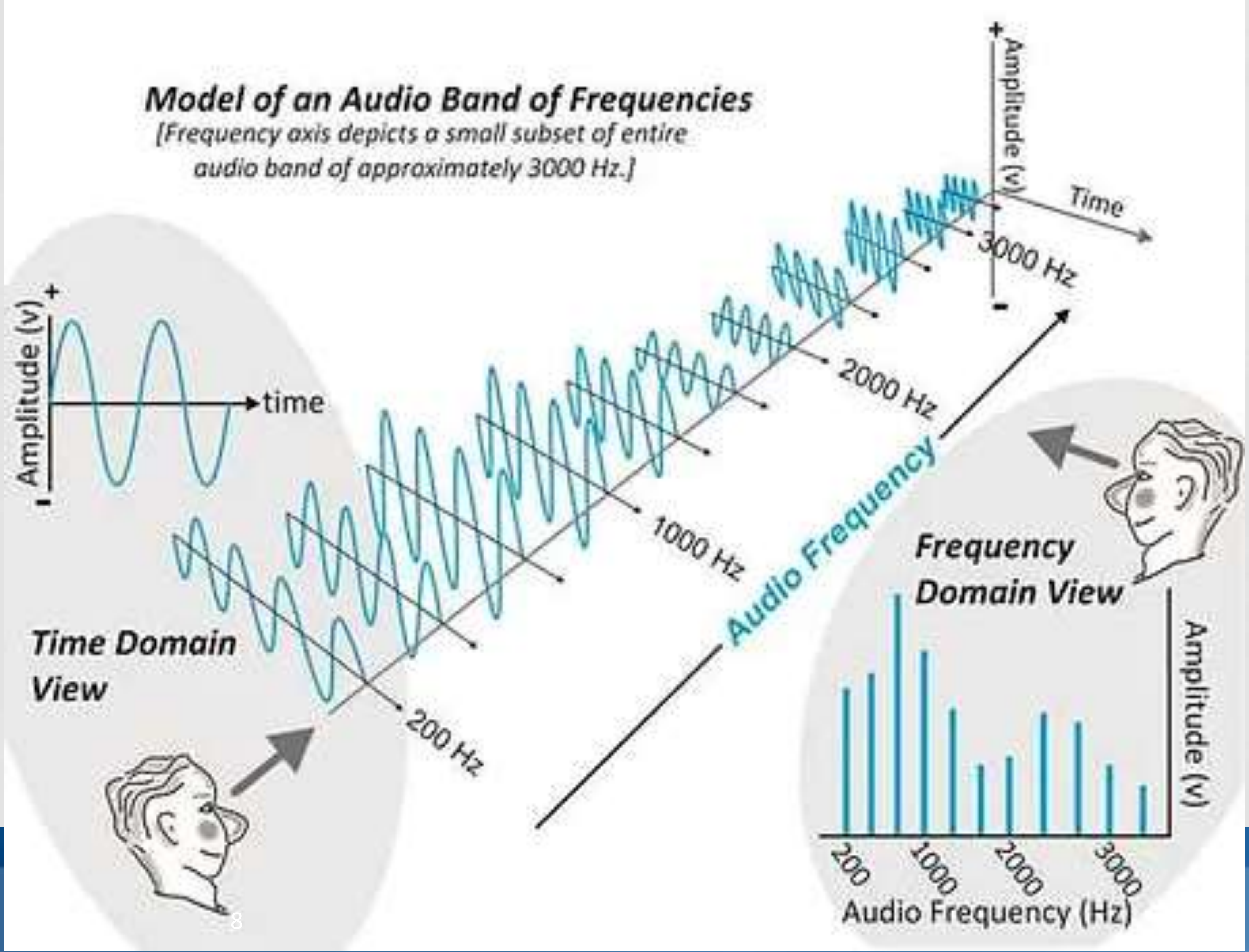
Oscilloscope

Time domain measurements

Time Domain & Frequency Domain



Graphic: HamRadioSchool.com

Name	Frequency	Usage
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VHF	30 MHz - 300 MHz	Radio Signals
UHF	300 MHz - 3 GHz	Radio Signals

Vector Network Analyzer

Spectrum Analyzer

Frequency domain measurements

Measurement Terminology

All measurements contain some error.

Accuracy: closeness of the agreement between measurement result and true value

Uncertainty of measurement: quantified doubt about the result of a measurement

Repeatability (of an instrument or of measurement results): closeness of the agreement between repeated measurements of the same property under the same conditions

Resolution: smallest difference that can be meaningfully distinguished (e.g., a change of 1 in the last place of a digital display)

Reference: A Beginner's Guide to Uncertainty of Measurement, Stephanie Bell, National Physical Laboratory, UK, March 2001

Decibels

Handy Rules:
Twice the power = 3 dB
10x the power = 10 dB

Decibels are defined in terms of power ratio

$A_{dB} = 10 \log (P_1/P_2)$

Examples:

P_1= 10 watts, P_2= 5 watts $A_{dB} = 10 \log (10/5) = 3.01$ dB

P_1= 5 watts, P_2= 10 watts $A_{dB} = 10 \log (5/10) = -3.01$ dB

Examples:

P_1= 100 watts, P_2= 10 watt $A_{dB} = 10 \log (100/10) = 10.0$ dB

P_1= 10 watts, P_2= 100 watts $A_{dB} = 10 \log (10/100) = -10.0$ dB

Decibels

Decibels can also be used for voltages

A_{dB} = 10 log (P_1/P_2)

$$A_{dB} = 10 \log \frac{(\frac{V_1^2}{R})}{(\frac{V_2^2}{R})} = 10 \log (\frac{V_1}{V_2})^2 = 20 \log(\frac{V_1}{V_2})$$

Handy Rules:
Twice the voltage = 6 dB
10x the voltage = 20 dB

Examples:

V_1= 10 volts, V_2= 5 volts A_{dB} = 20 log (10/5) = 6.02 dB

V_1= 5 volts, V_2= 10 volts A_{dB} = 20 log (5/10) = -6.02 dB

Examples:

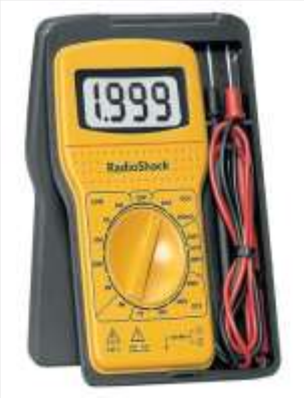
V_1= 100 volts, V_2= 10 watt A_{dB} = 20 log (100/10) = 20.0 dB

V_1= 10 watts, V_2= 100 watts A_{dB} = 20 log (10/100) = -20.0 dB

The Multimeter

- Also known as voltmeter, VOM (Volt-Ohm-mA meter),DVM (Digital Voltmeter), or DMM (Digital Multimeter)
- Voltmeter, ammeter and ohmmeter combined into one instrument
- DC and AC measurements
- Some models have diode test, continuity, capacitance, inductance, frequency, temperature
- Bench or handheld form factor
- Mostly digital meters, some analog meters

Lots of Meters Out There



Quick Guide to Buying a DMM

What? You don't have a Multimeter?

Buy a digital meter (forget the analog ones)

Should have DC volts, AC volts, resistance and AC & DC current

Should have a minimum of 600 V Cat II (IEC 1010) rating

Other features to consider:

- Continuity test mode ("beeper")
- Diode test mode
- Autorange
- "Analog" Bar graph
- Battery test mode
- True RMS

A classic analog multimeter: Simpson Model 260

Multimeter,TACKLIFE DM03 Auto Ranging Multi Tester, Measures AC & DC Voltage and Current, Resistance, Continuity, Frequency, Diode Electronic Tester, Digital Multimeter with Backlit LCD

by TACKLIFE

184 customer reviews

| 78 answered questions

Price: $13.97 ($0.01 / Count) prime

Get $70 off instantly: Pay $0.00 upon approval for the Amazon Prime Rewards Visa Card.

Note: Available at a lower price from other sellers, potentially without free Prime shipping.

Arrives before Christmas.

Size: **DM03**

DM03 **$13.97 ($0.01 / Count)** prime	DM08 $9.97 prime

Multimeter with AC Current Clamp

Current measurement is done via clamping the wire

The clamp acts as the core of a transformer

AC-only current measurement

Uni-Trend UT202A $28 on Amazon

Clamp meters are available that measure DC current but are more expensive

Standing Wave Ratio

Bob Witte, KØNR
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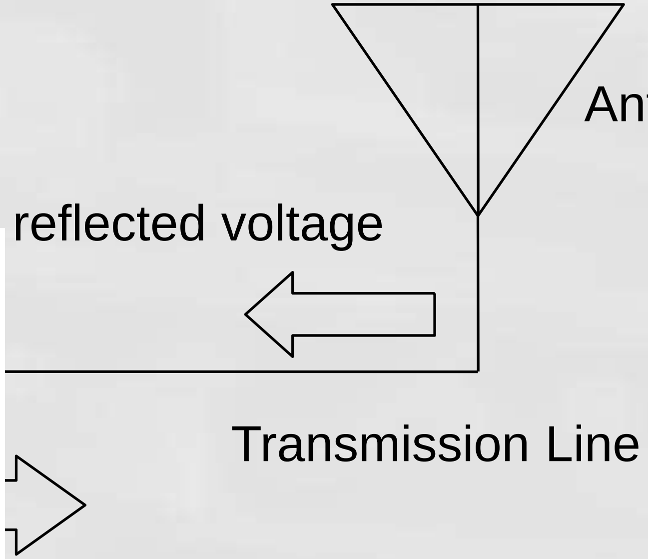
Standing Wave Ratio (SWR)

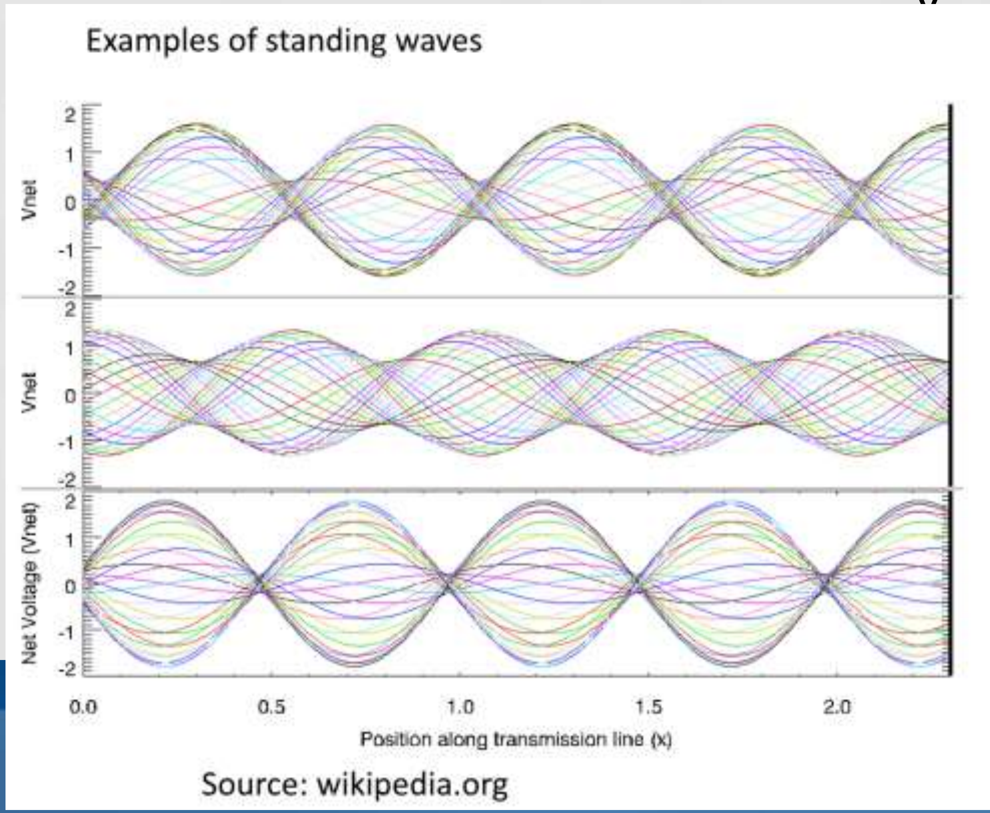
- SWR = *Standing Wave Ratio,* more properly called *Voltage Standing Wave Ratio (VSWR)*
- Measures the match between source (transmitter) and load (antenna).
- Perfect match is SWR = 1.0 (1:1)
- Anything greater than 1.0 is less than perfect
- SWR is always $\geq$ 1.0

SWR Measurement

$$SWR = \frac{V_{max}}{V_{min}} = \frac{V_F + V_R}{V_F - V_R}$$



V reflected voltage



Source: wikipedia.org

rd voltage

ntenna are all nominally the
eur radio work).

The Fundamental Measurement

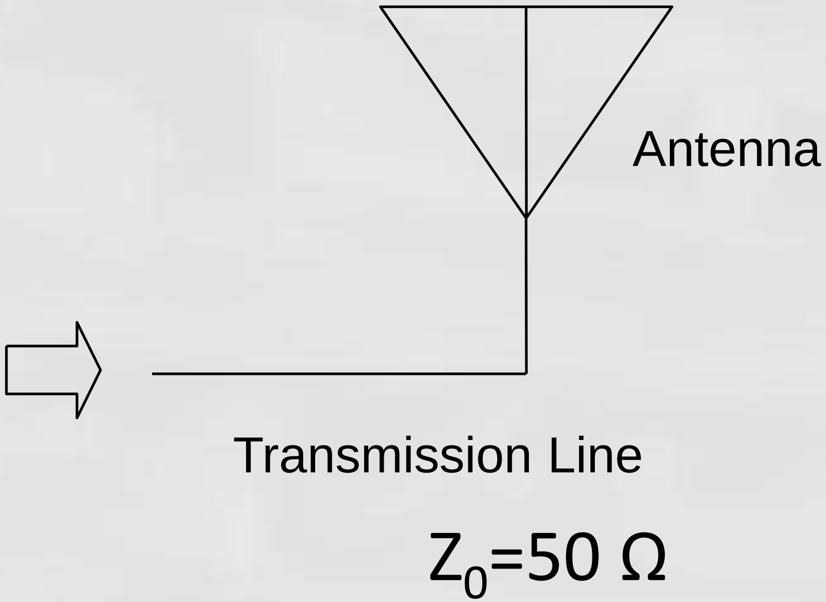
What is the impedance looking into this port?

$Z = R + jX$

$SWR = Z_L/Z_0$ or Z_0/Z_L

whichever is ≥ 1, for Z_L real

Example:
What is the SWR with Z_L=100Ω ?
SWR = 100/50 = 2



ρ = reflection coefficient= V_R/V_F

RL = return loss (dB) = - 20 log (ρ)

SWR Readings

- Perfect match is SWR = 1.0
- Anything greater than 1.0 is less than perfect
- SWR is always ≥ 1.0
- SWR is sometime shown in this format 1:1, 2:1 or even “1 to 1” and “2 to 1”.
- SWR < 2 is a pretty good match
- SWR >3 is a poor match
- SWR >5 is a very poor match

SWR, Reflection Coeff., Return Loss

TABLE 11-1. TABLE OF REFLECTION COEFFICIENT, RETURN LOSS AND STANDING WAVE RATIO

Reflection coefficient	Return loss	Standing wave ratio
1.00	0.00	∞
0.90	0.92	19.00
0.80	1.94	9.00
0.70	3.10	5.67
0.60	4.44	4.00
0.50	6.02	3.00
0.40	7.96	2.33
0.30	10.46	1.86
0.20	13.98	1.50
0.10	20.00	1.22
0.09	20.92	1.20
0.08	21.94	1.17
0.07	23.10	1.15
0.06	24.44	1.13
0.05	26.02	1.11
0.04	27.96	1.08
0.03	30.46	1.06
0.02	33.98	1.04
0.01	40.00	1.02
0.00	∞	1.00

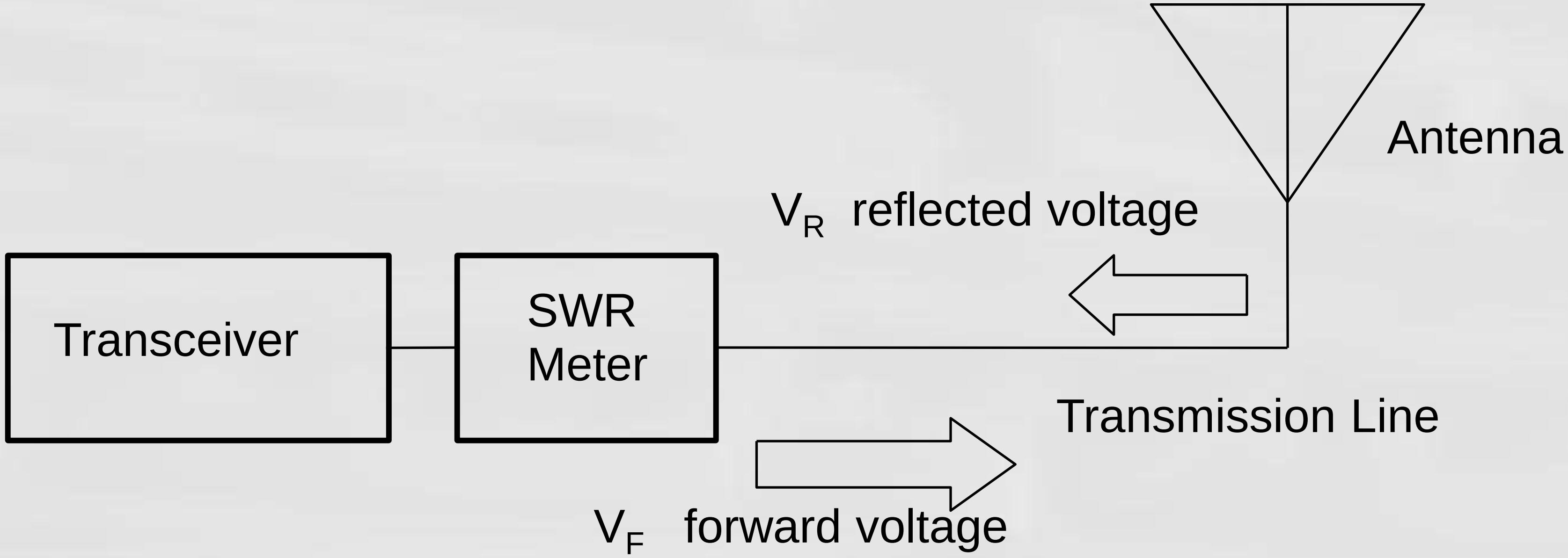
<u>50 Ω Load</u>
SWR = 1.0
ρ = 0
RL = ∞

<u>150 Ω Load</u>
SWR = 3.0
ρ = 0.5
RL = 6.02 dB

<u>Open</u>
SWR = ∞
ρ = 1
RL = 0 dB

SWR Meter

Sometimes called a *Reflectometer*

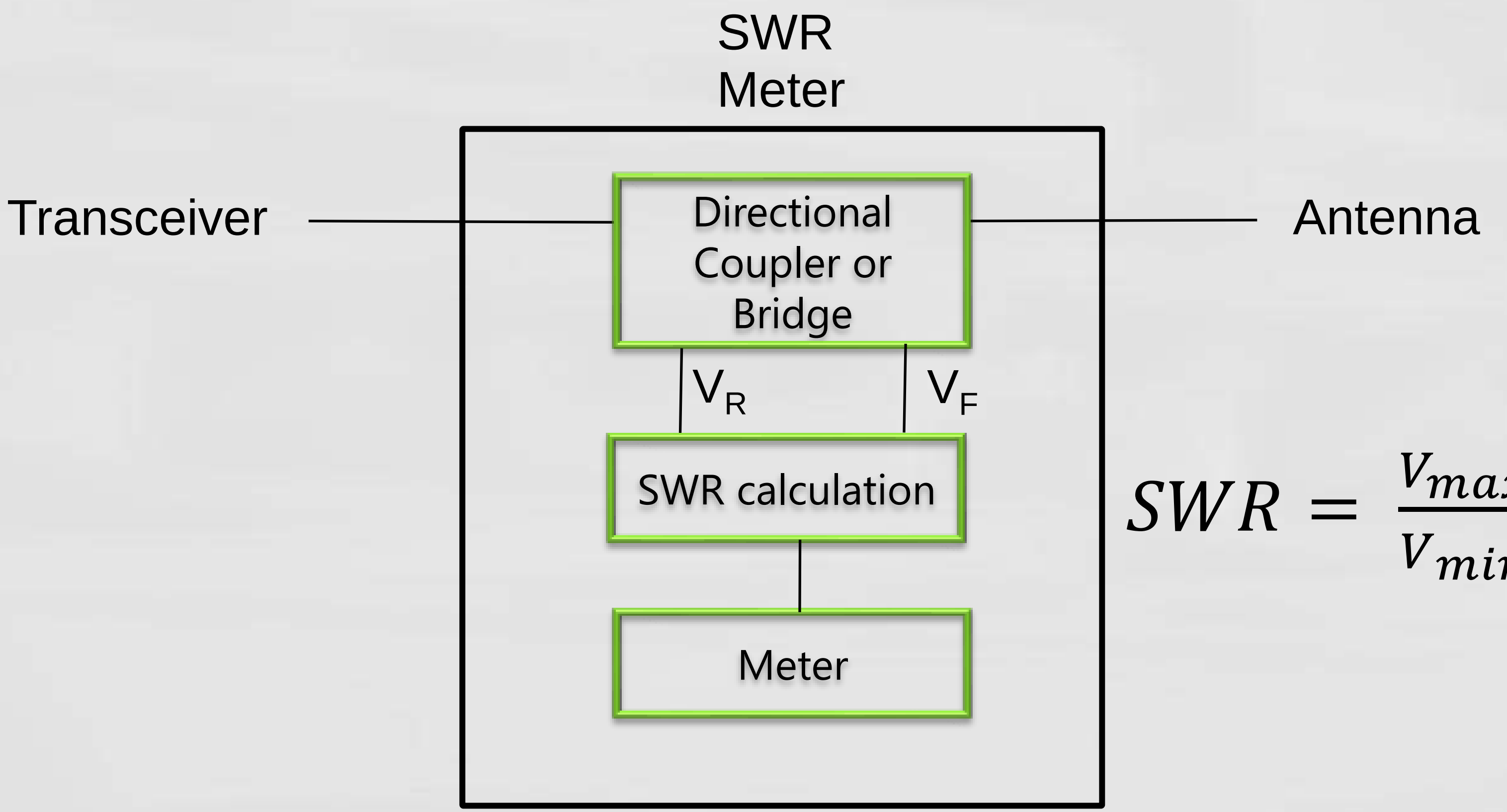


SWR meter is inserted into the transmission line, which usually requires an additional cable between transceiver and SWR meter.

The SWR Meter can be built into the transceiver.

SWR Meter

Sometimes called a *Reflectometer*



$$SWR = \frac{V_{max}}{V_{min}} = \frac{V_F + V_R}{V_F - V_R}$$

SWR Meters

Diamond SX-200 SWR/Power Meter

Cal
Adjust

SWR and Power Meter

Freq Range:
 1.8-200 MHz

Power Ranges:
 5W, 20W and 200 W

Price: ~$100

Power
Cal
SWR

Comet CMX-400

Note the use of the cross-needle meter to avoid the need to "cal" the measurement

Telepost LP-100A Digital Vector Wattmeter

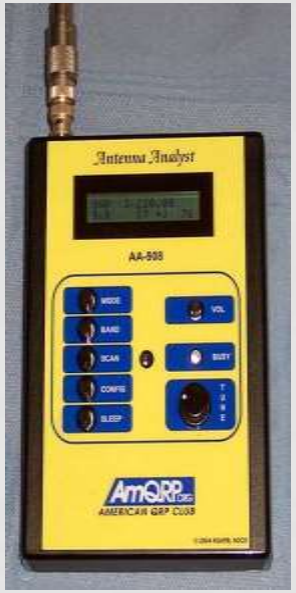
Advanced meter with digital bar graph, power and SWR in real time

Surecom SW-33 SWR/Power Meter

Mark II 100 W 125-525 MHz Mini Digital VHF UHF Two-Way Radio Handheld Power & SWR Meter

$36 amazon.com

Antenna Analyzers



MFJ-259B Antenna Analyzer

Frequency Range: 1.8 – 170 MHz
Price: ~$250
Measure:
- SWR, Return Loss
- Impedance, Reactance, Resistance

Default measurement mode is:
- Impedance, $Z = R + jX$
  (R= resistance, X = reactance)
- SWR

Also:
- Impedance, $Z = Z_{mag} \angle \theta$
- Reflection coefficient
- Return Loss

MFJ-259B Antenna Analyzer

MFJ-259B Antenna Analyzer

Usage Tips

- Best accuracy near 50 ohms (SWR=1)
- Don't use in high RF environment
- Input circuitry is sensitive
- Discharge antennas before connecting
- Do not apply external voltages to test port
- Don't over-interpret the results (the analyzer is just looking at the impedance match against 50Ω)

Comet CAA-500 Antenna Analyzer

Frequency Range:
1.8 to 500 MHz

Price: ~$430

Rig Expert AA-230 Antenna Analyzer

Measure SWR, Return Loss, Cable Loss

100 kHz to 230 MHz.

Graphical display plots SWR versus frequency

Time Domain Reflectometer mode can be used to locate the precise location of a fault within the feedline system.

~$550

AAI N1201SA RF Vector Impedance Analyzer

Frequency Range: 137.5 MHz to 2.7 GHz
Measured parameters:
Resistance, reactance, SWR, s11
Connector SMA
Impedance measurement range: 0.1 to ~1000

$160 ebay.com

VHF/UHF Antenna Analyzer (AAI N1201SA)

Q&A

What questions do you have?

Oscilloscope Measurements

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Monument, CO

Many of these slides are adapted from Keysight Technologies slides

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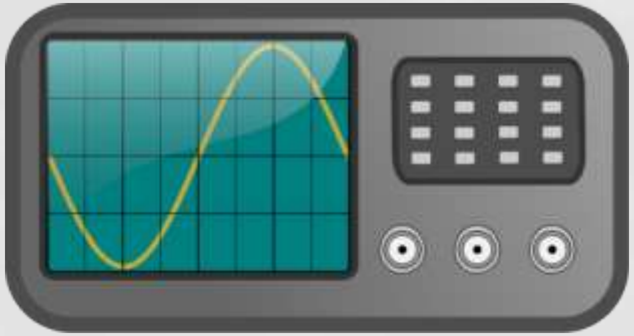
Discussion and wrap up		11:30 to noon

What is an oscilloscope?



os·cil·lo·scope (ə-sĭl'ə-skōp')

- Oscilloscopes convert electrical input signals into a visible trace on a screen.
- Oscilloscopes display voltage vs time (time domain) of dynamic waveforms.
- Oscilloscopes are used by engineers and technicians to test, verify, and debug electronic designs.

Names for Oscilloscopes

Scope – Most commonly used terminology

DSO – Digital Storage Oscilloscope

Digital Scope

Digitizing Scope

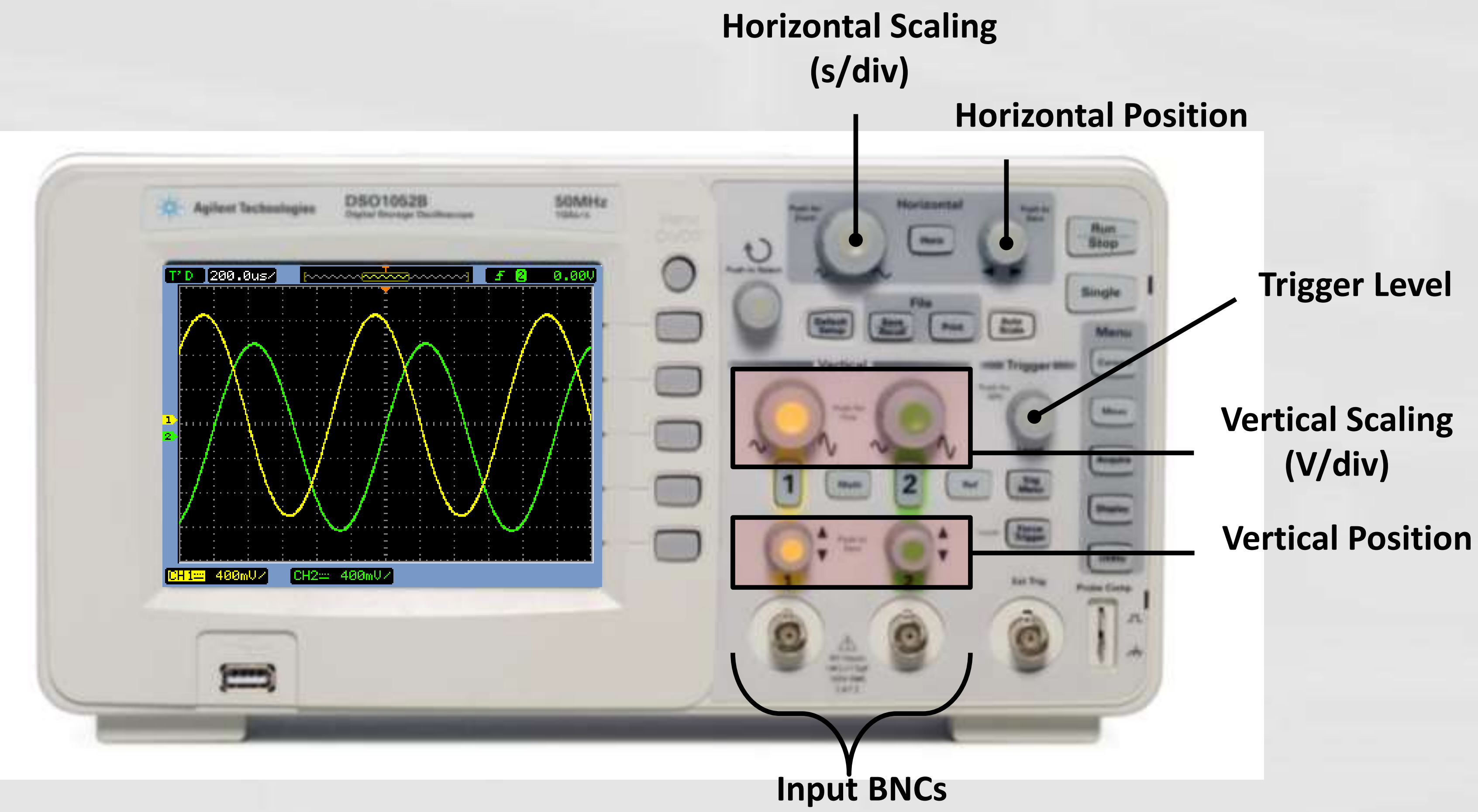
Analog Scope – Older technology oscilloscope, but still around today.

CRO – Cathode Ray Oscilloscope (pronounced "crow").

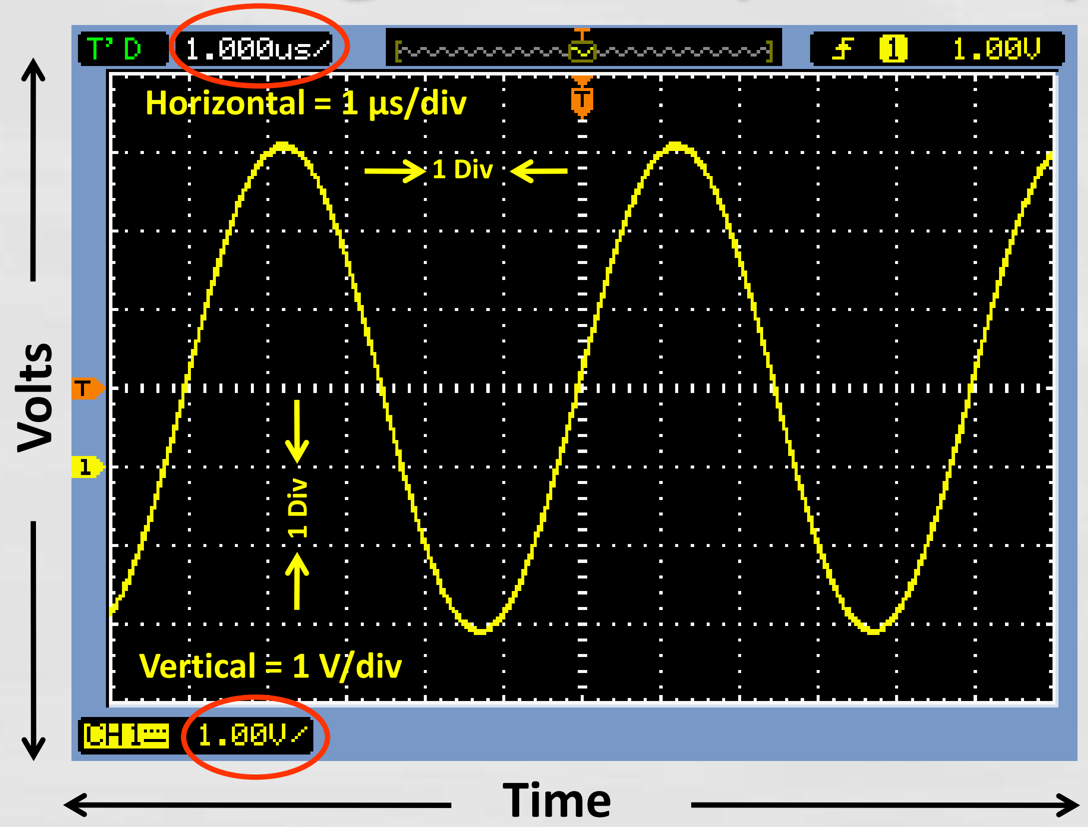
O-Scope

MSO – Mixed Signal Oscilloscope (includes logic analyzer channels of acquisition)

Primary Oscilloscope Setup Controls

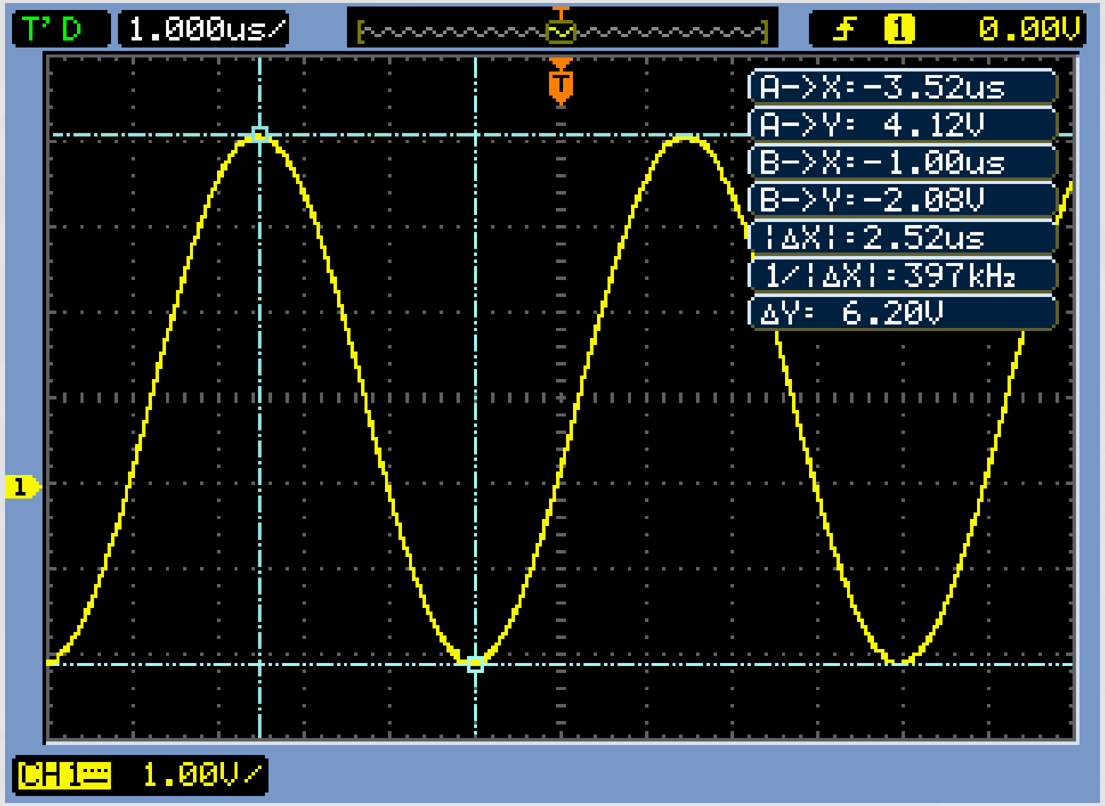


Understanding the Scope's Display



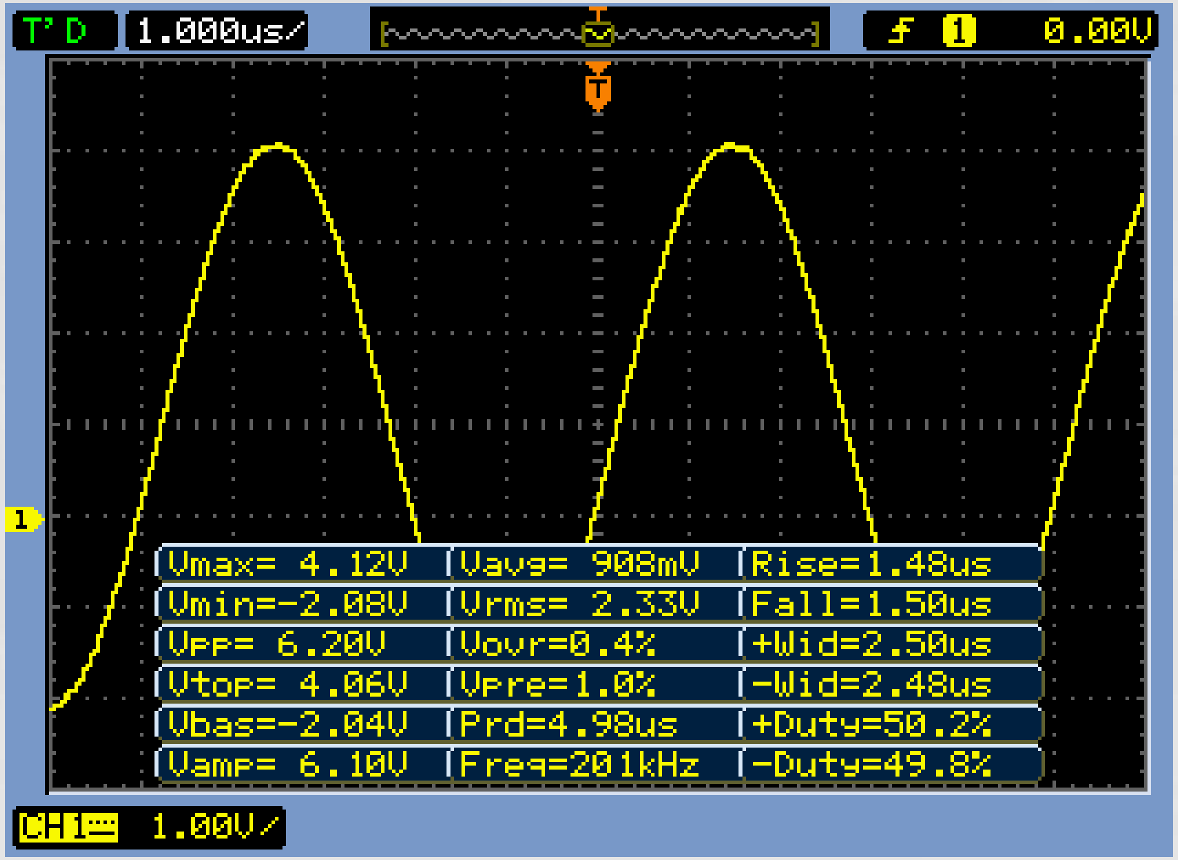
- Waveform display area shown with grid lines (or divisions).
- Vertical spacing of grid lines relative to Volts/division setting.
- Horizontal spacing of grid lines relative to sec/division setting.

Making Measurements – using cursors



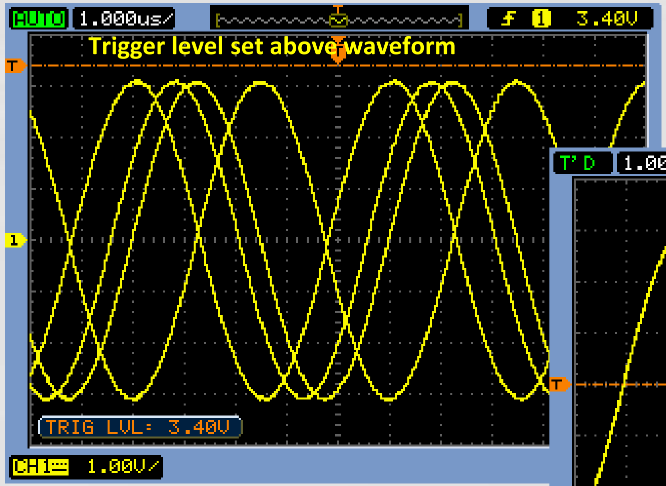
- Manually position A & B cursors to desired measurement points.
- Scope automatically multiplies by the vertical and horizontal scaling factors to provide absolute and delta measurements.

Automatic Waveform Measurements

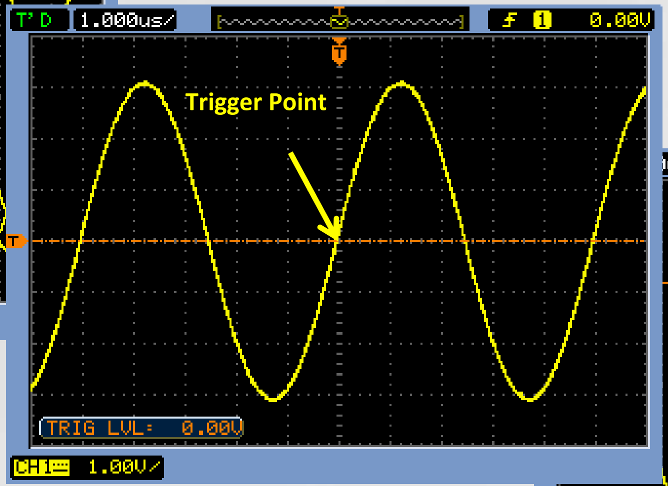


- Select automatic parametric measurements with a continuously updated readout.

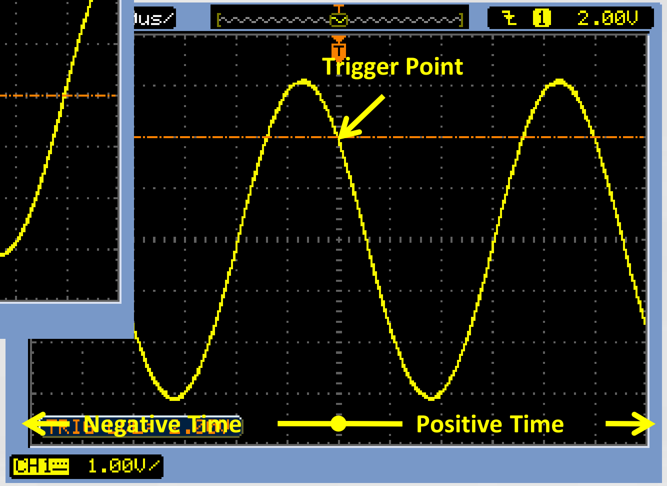
Triggering Examples



Untriggered
(unsynchronized picture taking)



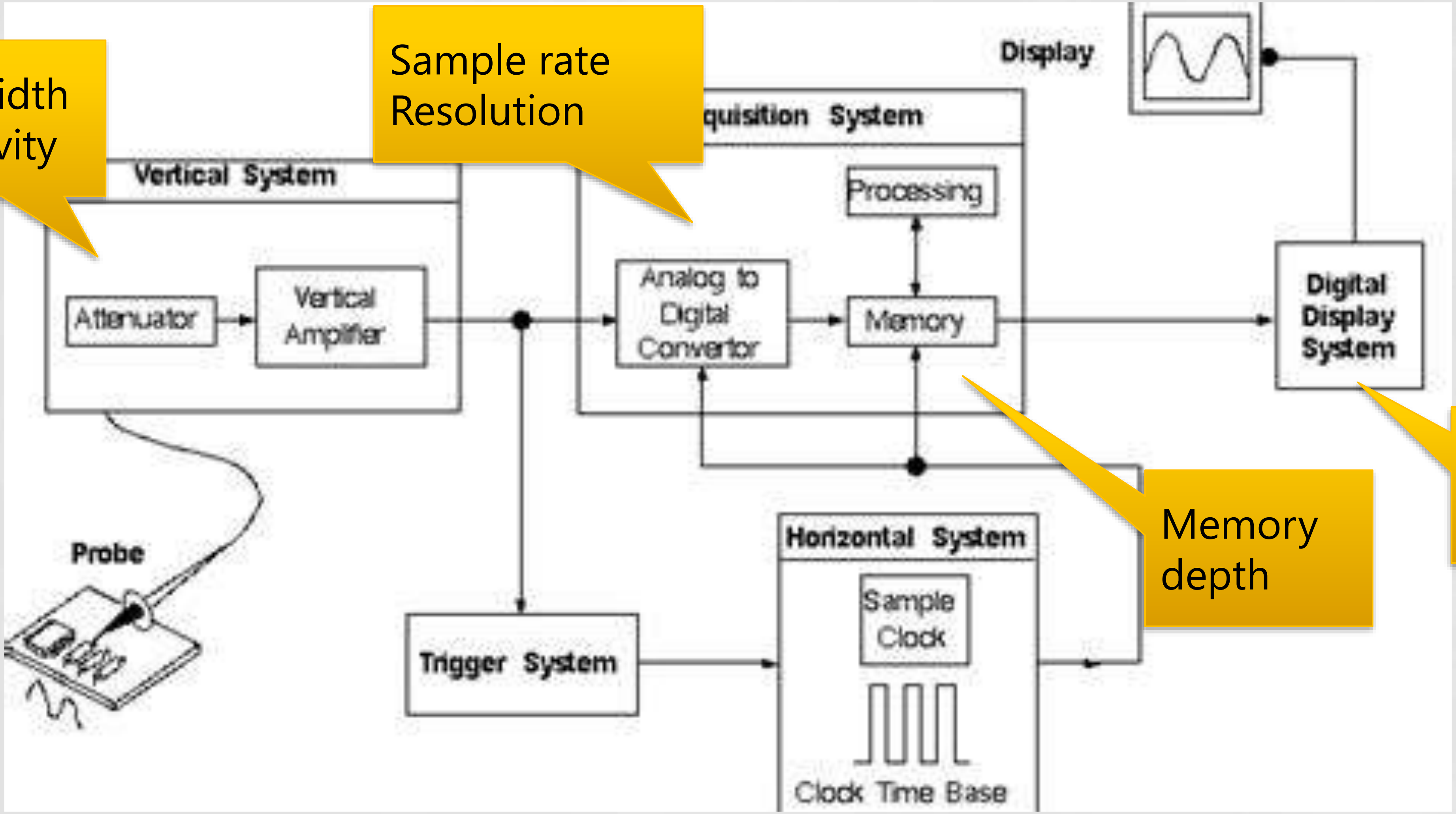
Trigger = Rising edge @ 0.0 V



Trigger = Falling edge @ +2.0 V

Edge Trigger is most common: rising or falling edge, voltage level

Digital Oscilloscope Block Diagram



Bandwidth
Sensitivity

Sample rate
Resolution

Memory
depth

Display
algorithms

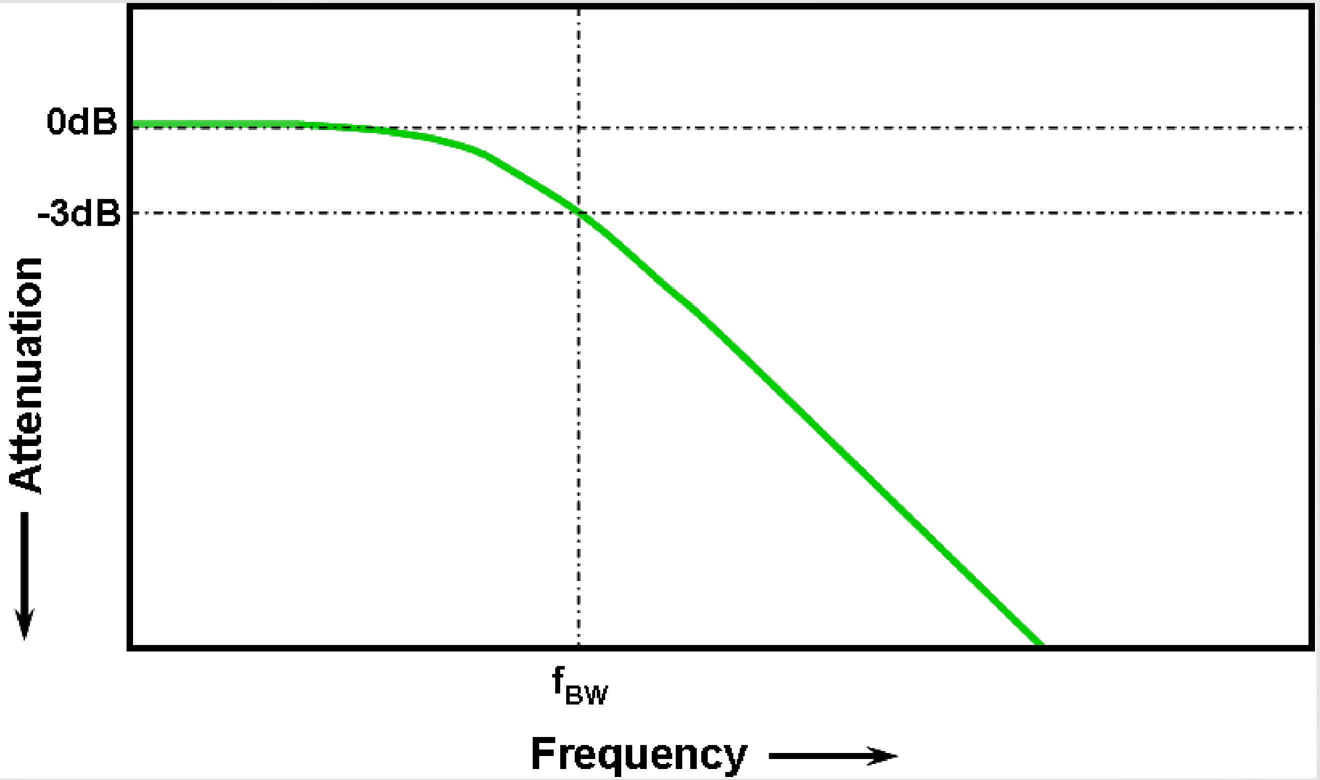
Bob Witte, KØNR bob@k0nr.com

Oscilloscope Performance Specifications

"Bandwidth" is the most important oscilloscope specification

All oscilloscopes exhibit a low-pass frequency response.

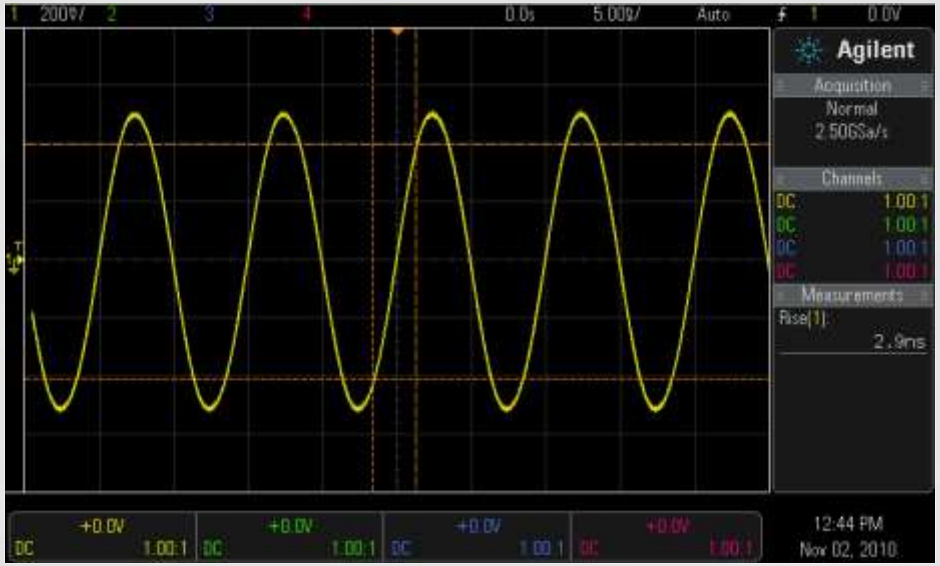
The frequency where an input sine wave is attenuated by 3 dB defines the scope's bandwidth.



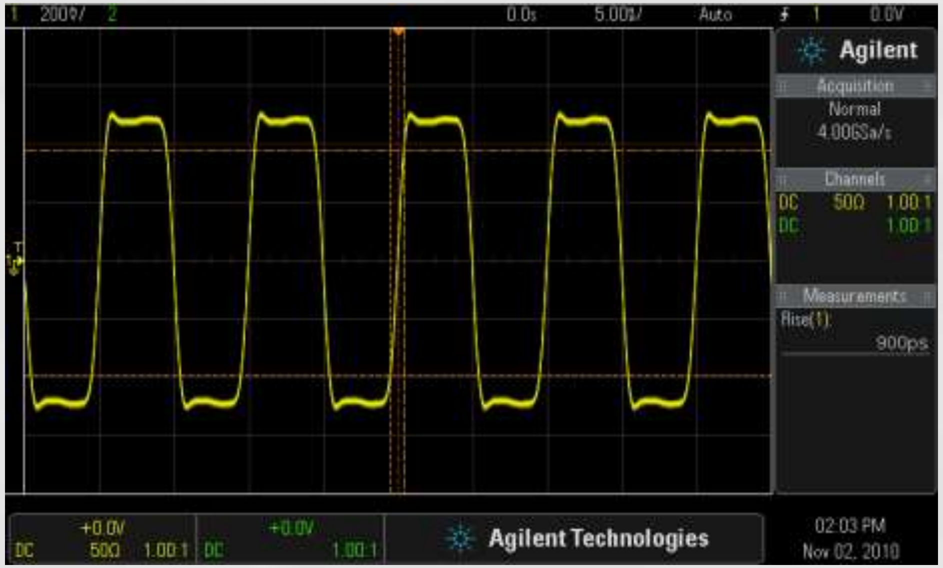
Oscilloscope "Gaussian" Frequency Response

Selecting the Right Bandwidth

Input = 100-MHz Digital Clock



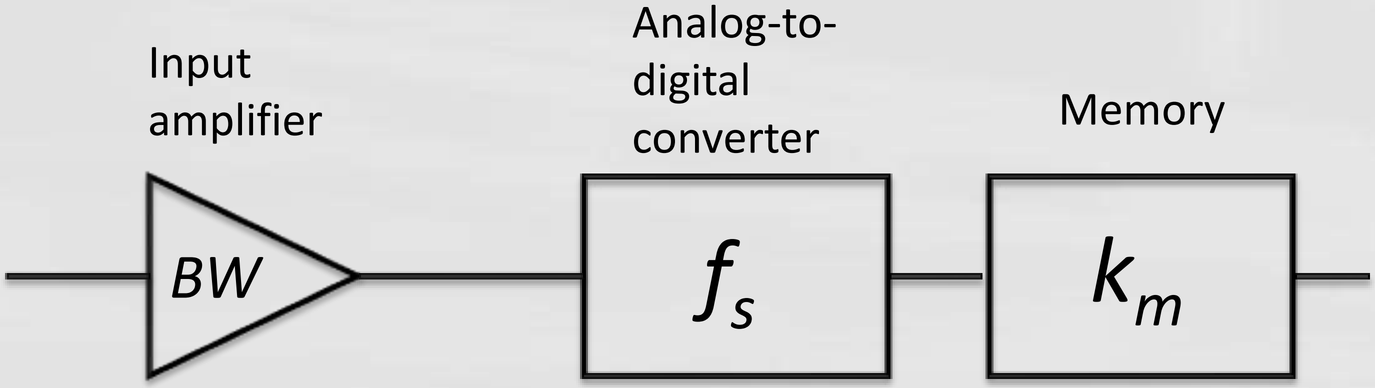
Response using a 100-MHz BW scope

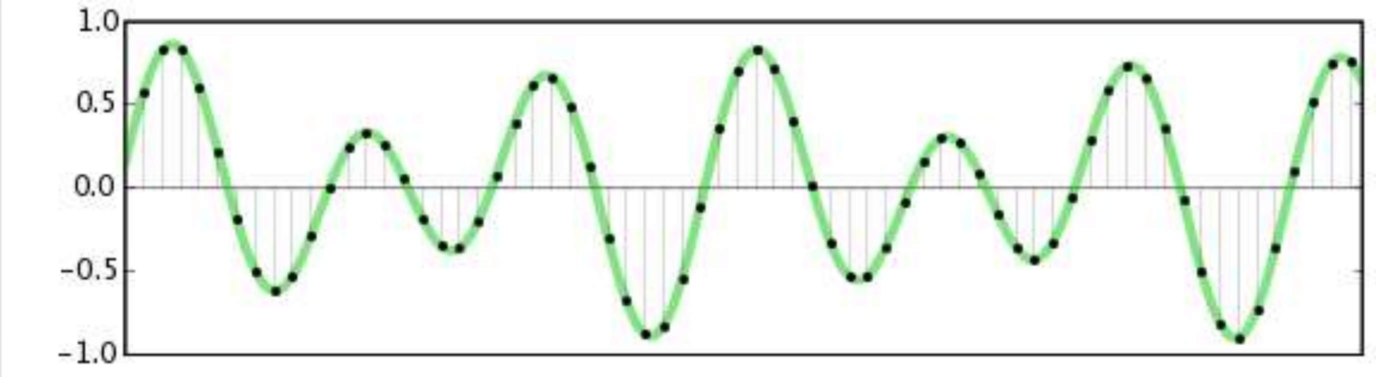


Response using a 500-MHz BW scope

- Required BW for analog applications: ≥ 3X highest sine wave frequency.
- Required BW for digital applications: ≥ 5X highest digital clock rate.
- More accurate BW determination based on signal edge speeds

Bandwidth, Sample Rate and Memory Depth





<u>Nyquist:</u>

Sample rate must be > 2x the bandwidth

$f_s > 2 \times BW$

Oscilloscopes are typically 4x to 10x

<u>Time capture:</u>

$T = k_m \times (1/f_s)$

Suppose we want to capture 100 msec of time at 1 GSa/s

$k_m = T f_s = 0.1 \times 1\ E{+}09 = 100\ Msamples$

More memory is better!

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Oscilloscope inputs

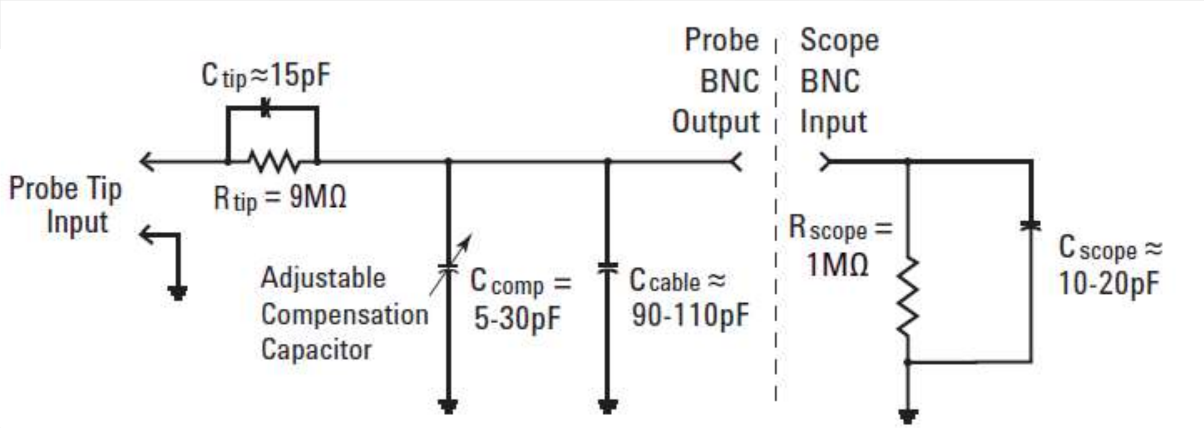
BNC input connectors
1 MΩ / 13 pF

Damage level: 150 to 300 V RMS

Higher bandwidth scopes have 50Ω selectable inputs.
Economy scopes need to use a 50Ω feedthrough termination

Bob Witte, KØNR bob@k0nr.com

Passive 10:1 Voltage Divider Probe



Passive 10:1 Probe Model

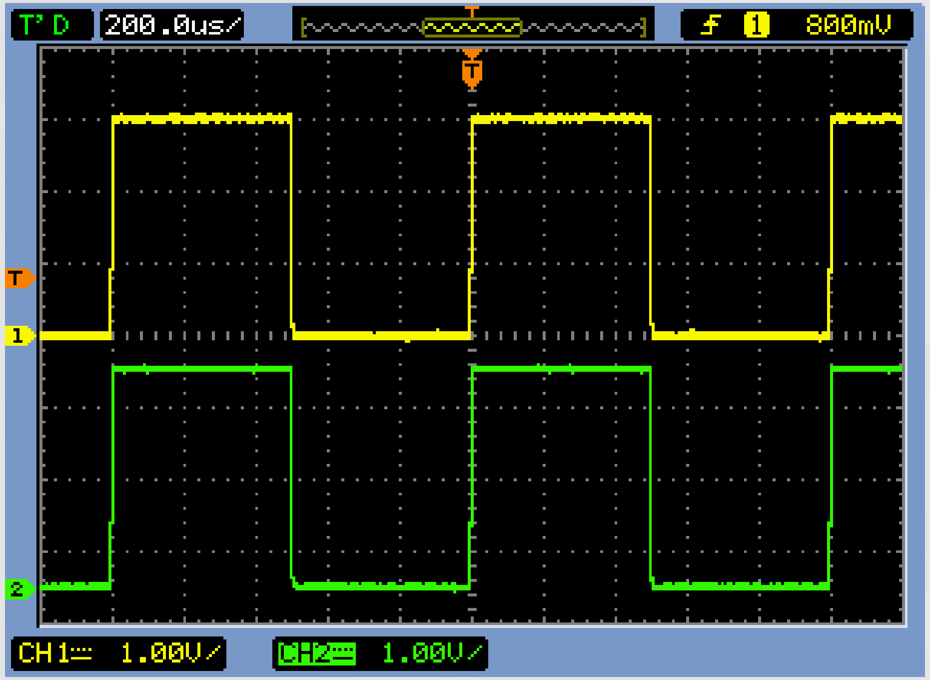
<u>Passive:</u> Includes no active elements such as transistors or amplifiers.

<u>10-to-1:</u> Reduces the amplitude of the signal delivered to the scope's BNC input by a factor of 10. Also increases input impedance by 10X.

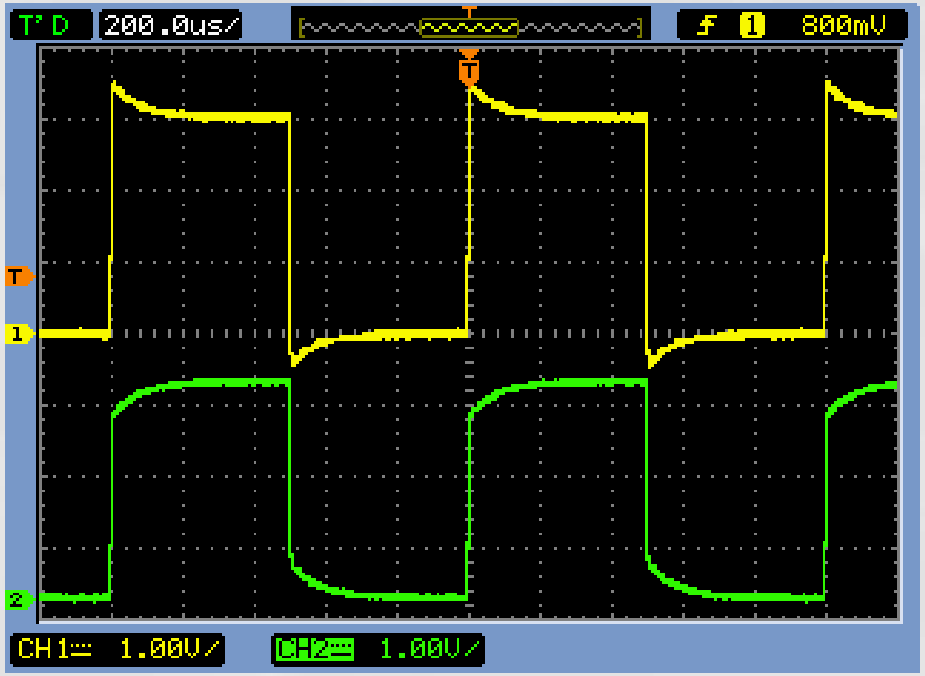
Note: All measurements must be performed relative to ground!

The scope chassis and BNC connector are normally connected to green wire ground.

Compensating the Divider Probes



Proper Compensation



Channel-1 (yellow) = Over compensated
Channel-2 (green) = Under compensated

- Connect Channel-1 and Channel-2 probes to the “Probe Comp” terminal.
- Adjust V/div and s/div knobs to display both waveforms on-screen.
- Using a small flat-blade screw driver, adjust the variable probe compensation capacitor (C_{comp}) on both probes for a flat (square) response.

Practical Ham Radio Scope Usage

- Measuring audio signals (modulation, receiver audio, sound card audio)
- Measuring digital signals (Raspberry Pi, serial ports, I^2C, SPI, etc.)
- Monitor transmitted RF (needs connection method and sufficient bandwidth)

Affordable Digital Scopes

Keysight 1000 X-Series
2 Channel, 50 MHz, 1 GSPS
$601

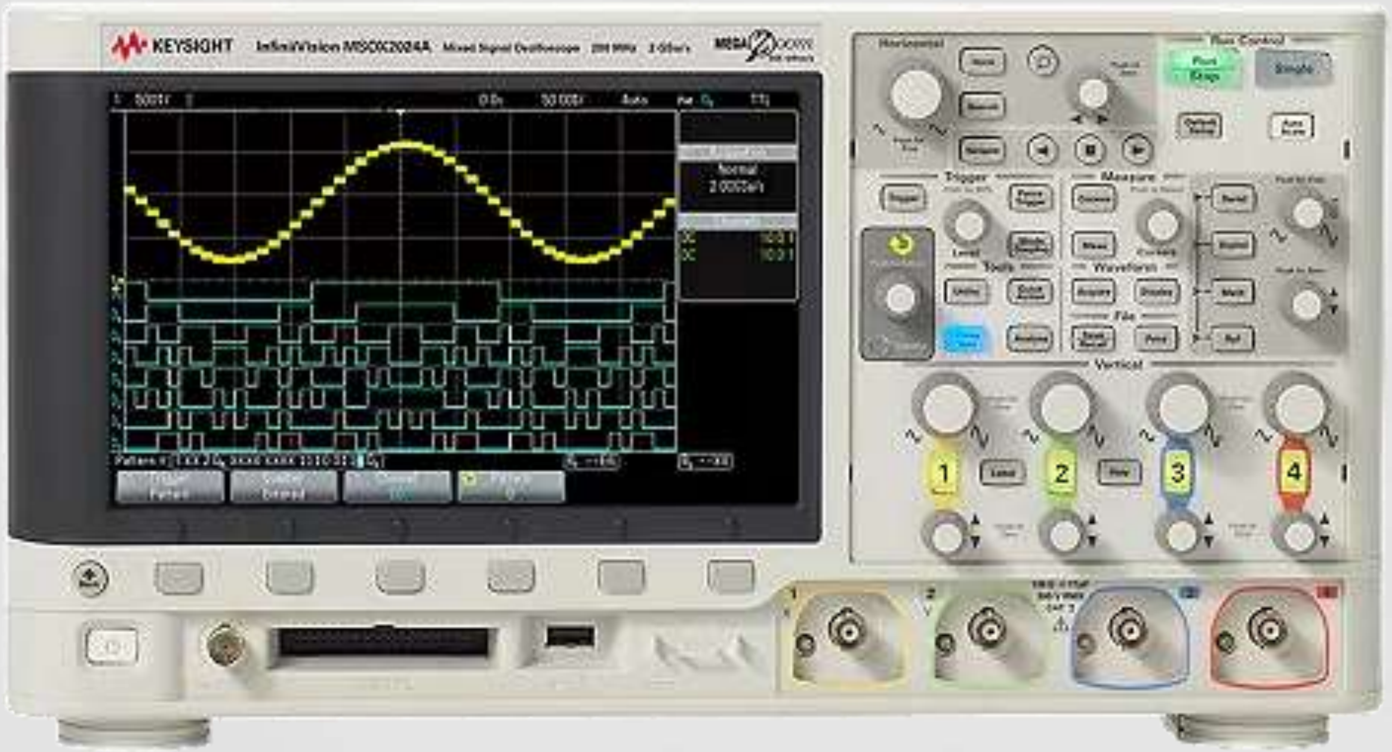
Tektronix TBS1000C Series
2 Channel, 50 MHz, 1 GSPS
$563

Rigol DS1102Z-E
2 channel, 100 MHz, 1 GSPS
$329

Siglent SDS1202X-E
2 Channel, 200 MHz, 1 GSPS
$339

Hantek DSO5102P
2 Channel, 100 MHz, 1 GSPS
$259

Oscilloscope Differentiating Features



- Bandwidth (sample rate)
- Number of channels
- Memory depth
- Display size & quality
- Waveform generator
- Logic channels (MSO)
- Digital voltmeter
- Frequency counter
- Serial protocol decode
- Fast Fourier Transform analysis

BitScope Micro

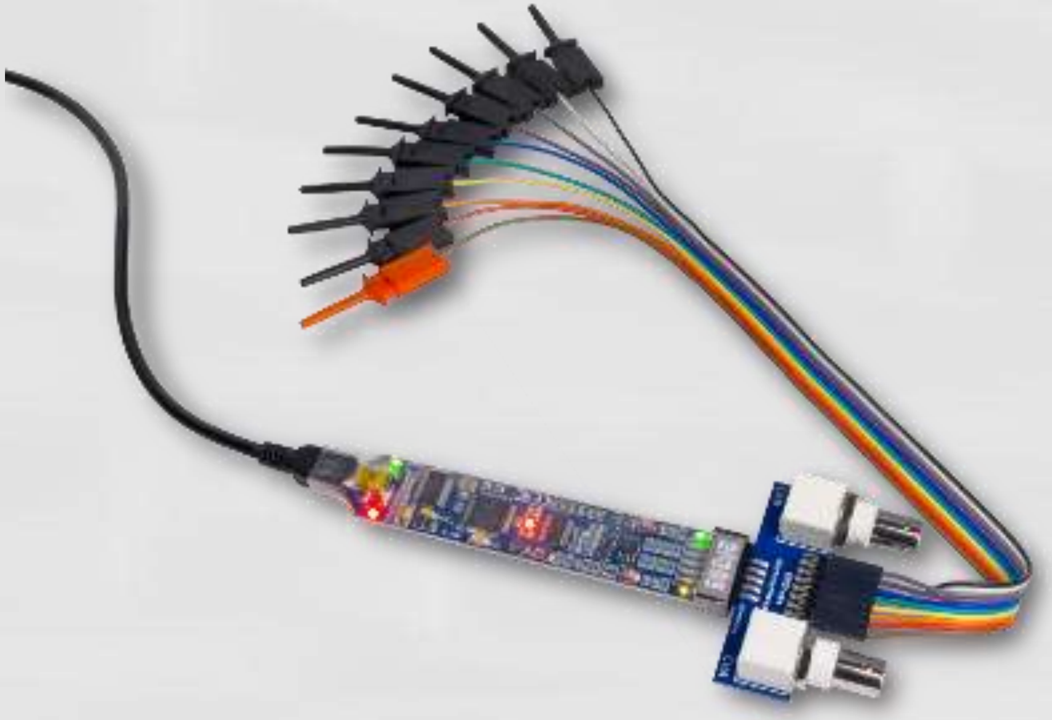
20 MHz bandwidth
2 analog channels

6 digital channels

Mixed signal scope
Waveform generator

Sample rates to 40 MS/s
12 kB buffer

USB cable
Price $165



bitscope.com

Digilent Analog Discovery 2

- 2-channel oscilloscope (100MS/s, 30MHz bandwidth)
- Two-channel arbitrary function generator (100MS/s, 12MHz bandwidth)
- 16-channel digital logic analyzer
- 16-channel pattern generator (3.3V CMOS, 100MS/s)
- Single channel voltmeter (AC, DC, ±25V)
- Network Analyzer – Bode, Nyquist, Nichols transfer diagrams of a circuit. Range: 1Hz to 10MHz
- Spectrum Analyzer
- Digital Bus Analyzers (SPI, I^{2}C, UART, Parallel)
- Protocol Analyzer - SPI, I2C, and UART
- Price $399

What about analog scopes?

Sure, why not?

Lots of good used gear available

Missing modern "digital" features

(waveform storage, pre-trigger information, automatic measurements)

Q&A

What questions do you have?

Vector Network Measurements

Bob Witte, KØNR
bob@k0nr.com
Monument, CO

Agenda

Topic	Comments	Time
Introduction	Frequency, measurement concepts, Digital Multimeters SWR / Power meters	8:30 – 9:20
Break		
Oscilloscope Measurements	Time domain, oscilloscopes, probes	9:30 to 10:20
Break		
Vector Network Analyzer measurements	S-parameters, transmission, Reflection, NanoVNA	10:30 to 11:20
Spectrum Analyzer Measurements	Frequency domain, spectrum analyzers, TinySA, SDR receiver	11:00 to 11:30
Discussion and wrap up		11:30 to noon

Name	Frequency	Usage
DC	0 Hz	Power, Batteries
AC Power	50 - 60 Hz	Power
Audio	20 Hz - 20kHz	Modulation
LF	30 kHz - 300 kHz	Experimental
MF	300 kHz - 3 MHz	Radio Signals
HF	3 MHz - 30 MHz	Radio Signals
VHF	30 MHz - 300 MHz	Radio Signals
UHF	300 MHz - 3 GHz	Radio Signals

Vector Network Analyzer

Spectrum Analyzer

Frequency domain measurements

Vector Network Analyzer Measurement

VNA has a signal source that delivers a sine wave to the device under test

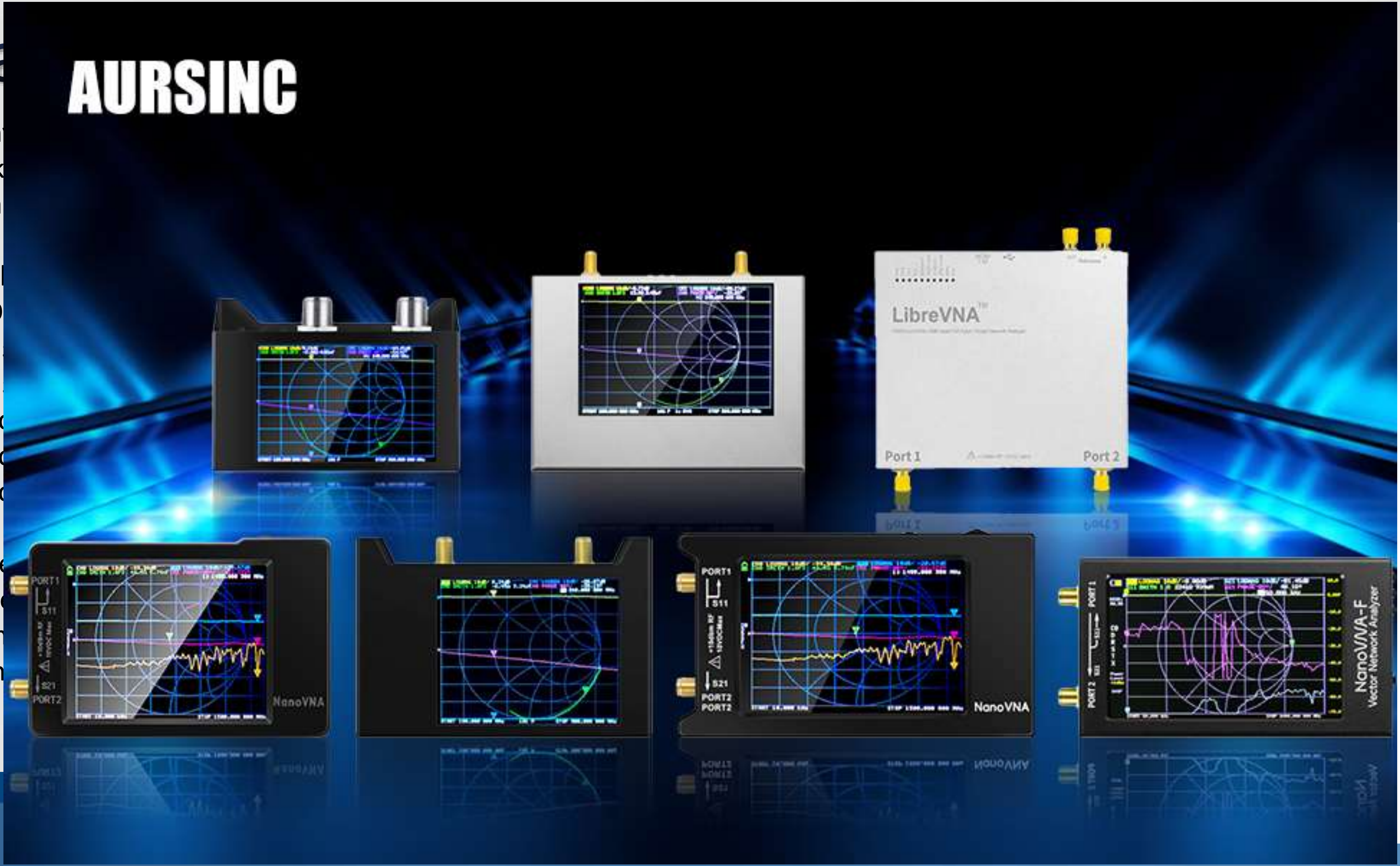
The VNA has multiple receivers to measure the network's magnitude/phase response

Bob Witte, KØNR bob@k0nr.com

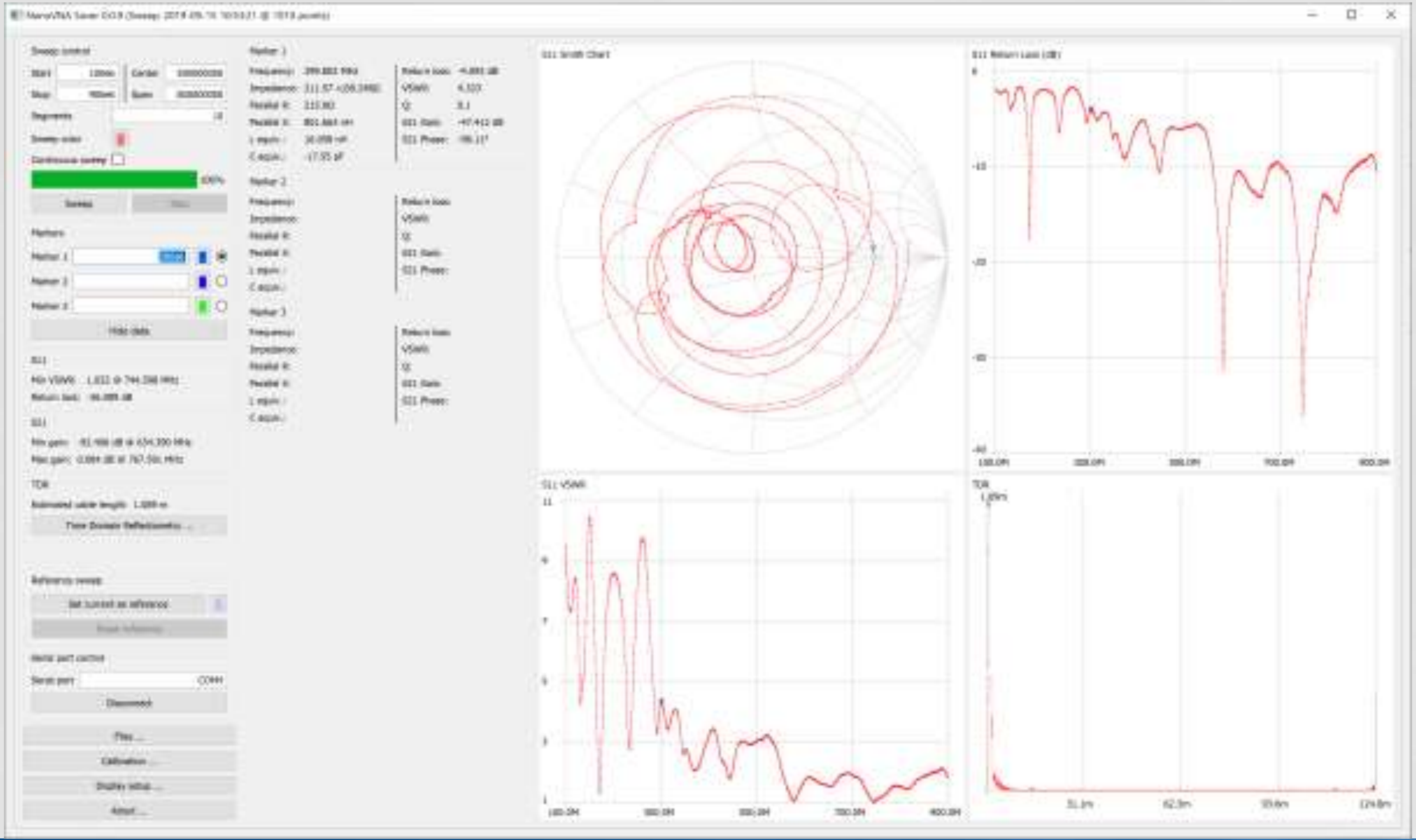
Na

Man
Cal k
Ama

Displ
RF O
Mea
Mea
70c
60c
40c
USB
Powe
pow
300n
Num



NanoVNA-Saver Software

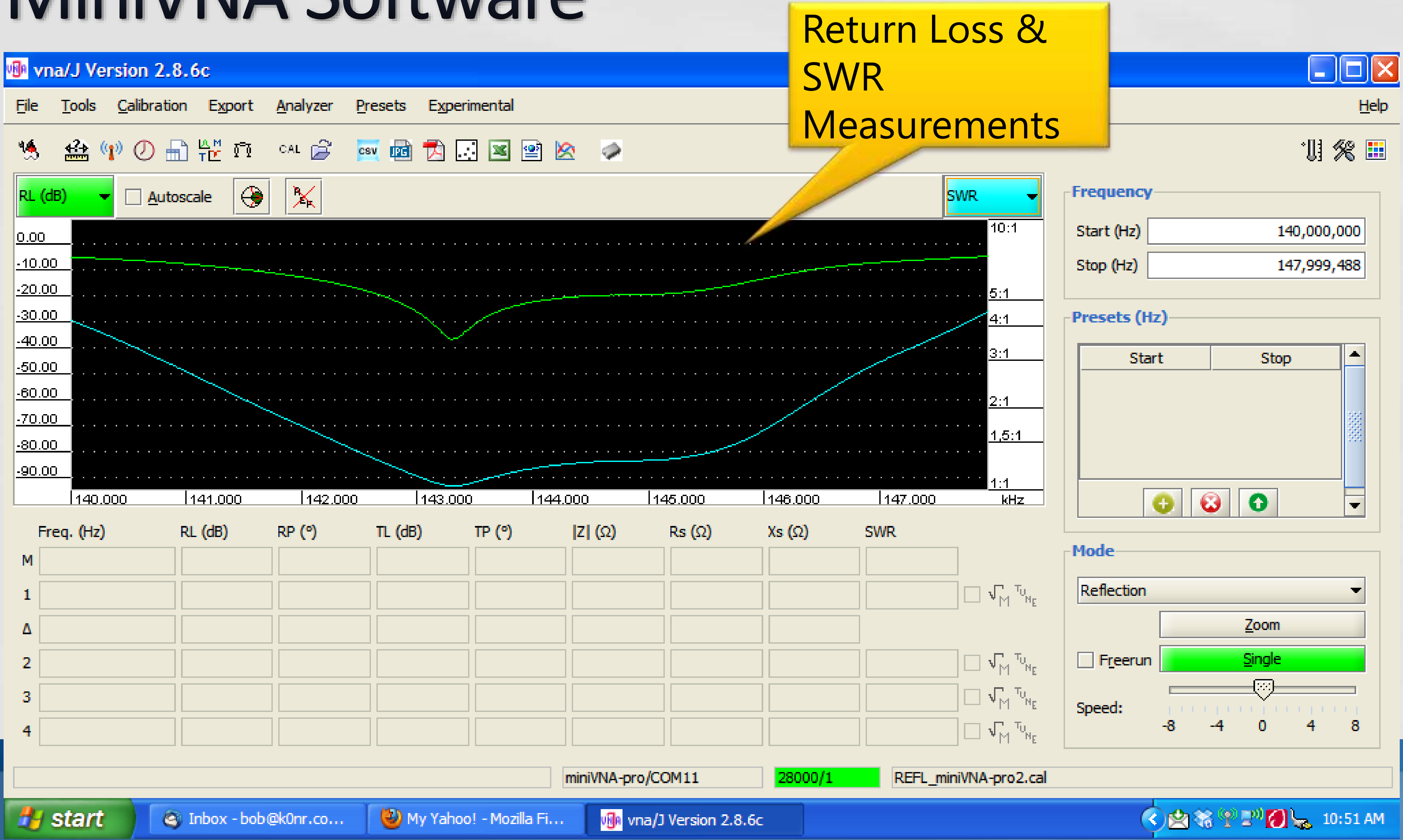


Vector Network Analyzer – miniVNA Pro

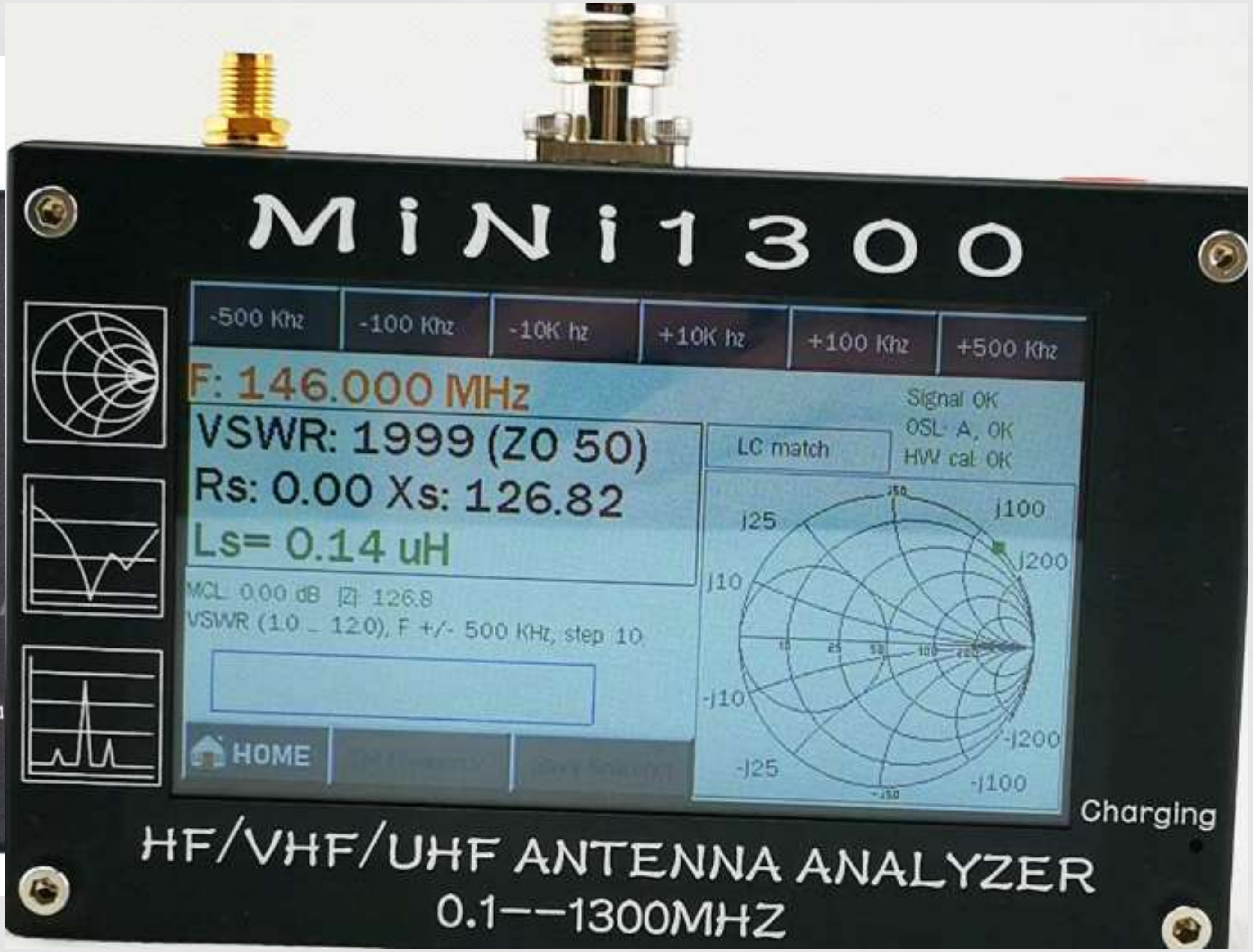
miniVNA Pro
Freq range:
100 KHz to 200 MHz
Range of Z: 1 to 1000 ohm
Dynamic range:
up to 90 dB in Transmission
& 50 dB in Reflection
Two port VNA with S11 and S21

Price: ~$550

MiniVNA Software

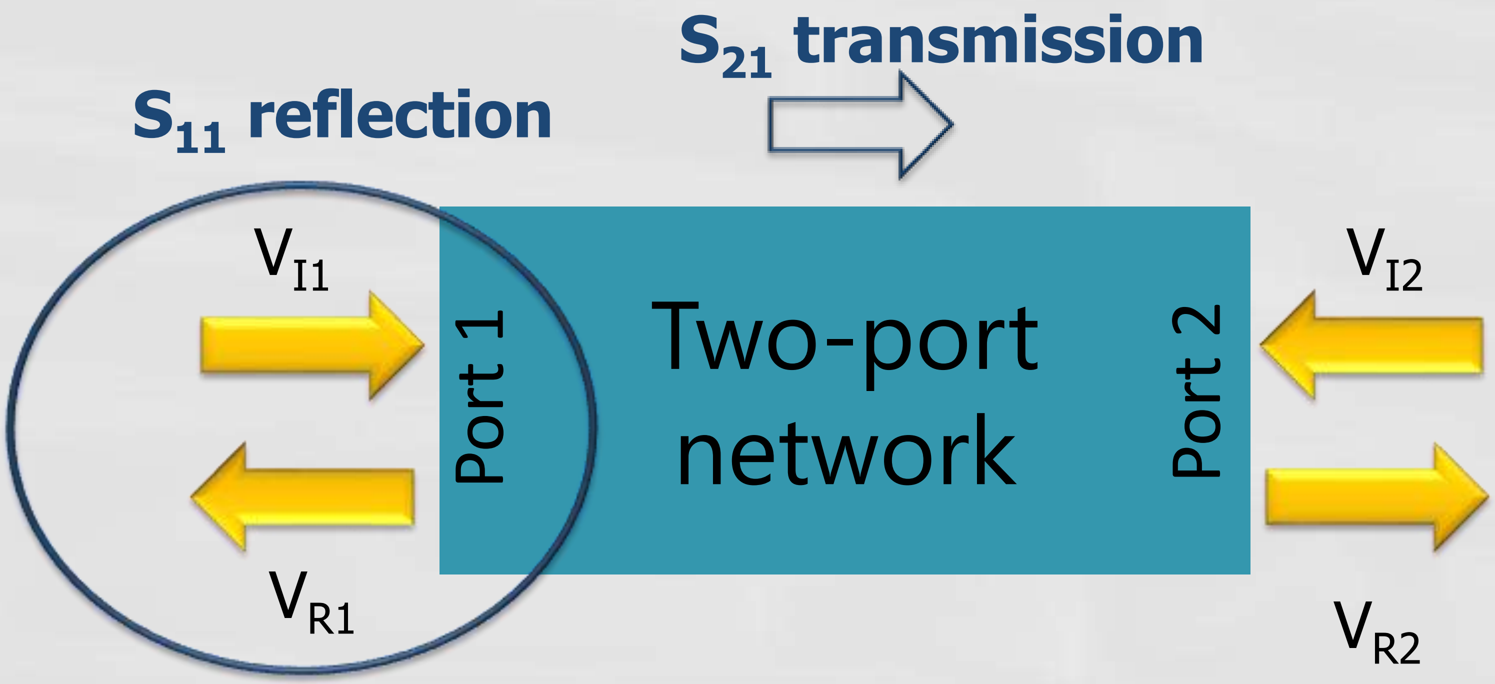


Vector Network Analyzer – Micro 1300



Scattering parameters (S parameters)

NanoVNA Measures S_{11} and S_{21}

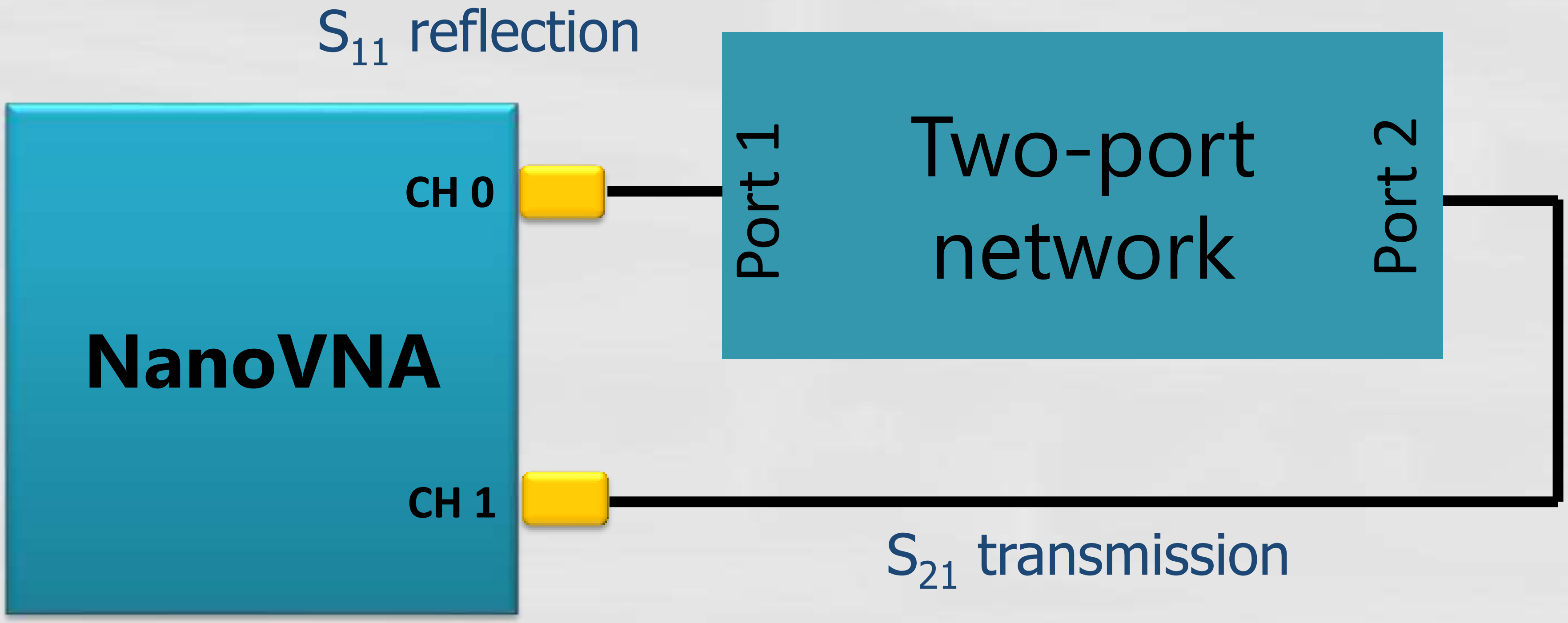


$$V_{R1} = S_{11} V_{I1} + S_{12} V_{I2}$$

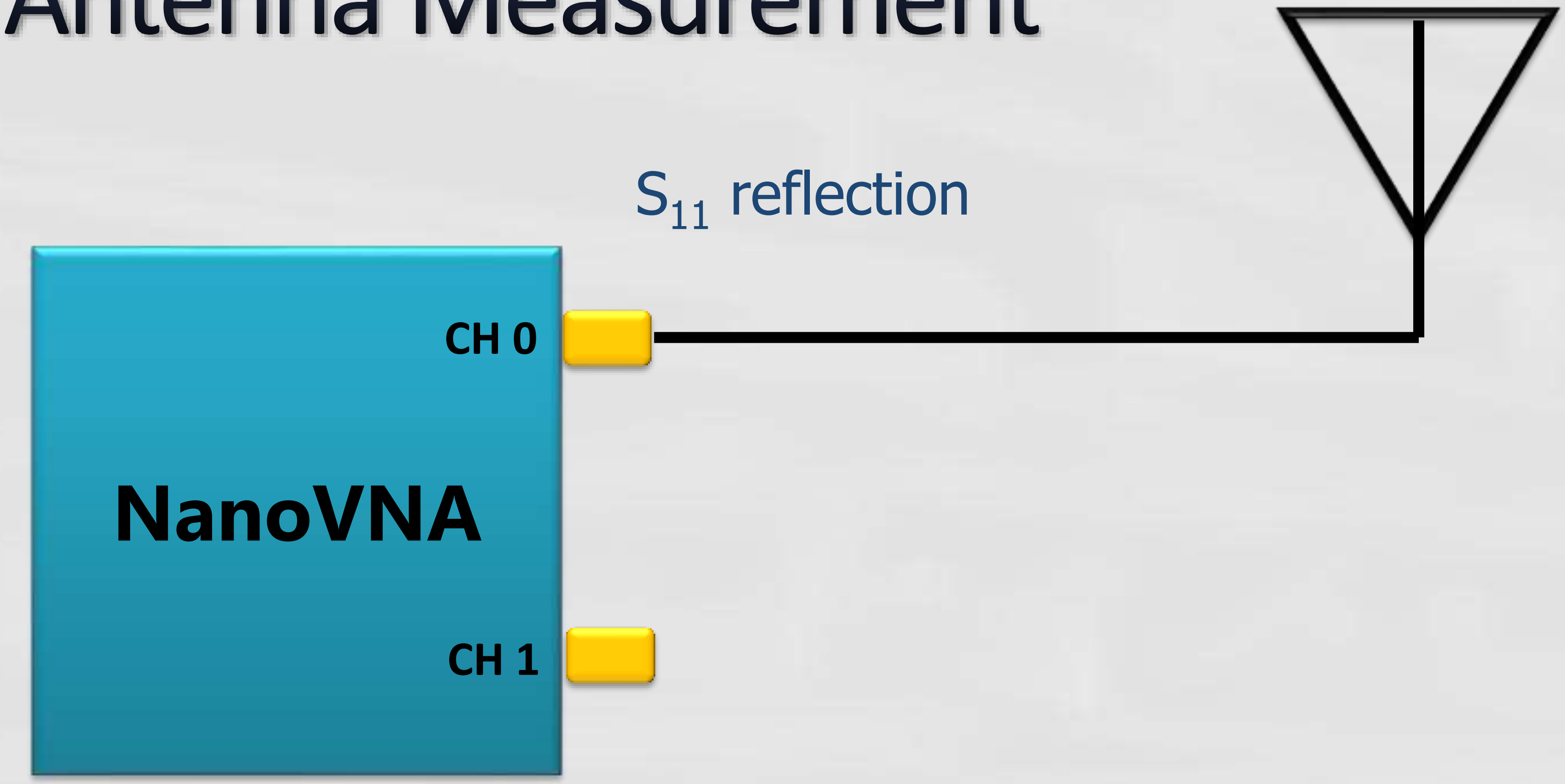
$$V_{R2} = S_{21} V_{I1} + S_{22} V_{I2}$$

S_{11} = input reflection coefficient
S_{21} = forward transmission coefficient
S_{12} = reverse transmission coefficient
S_{22} = output reflection coefficient

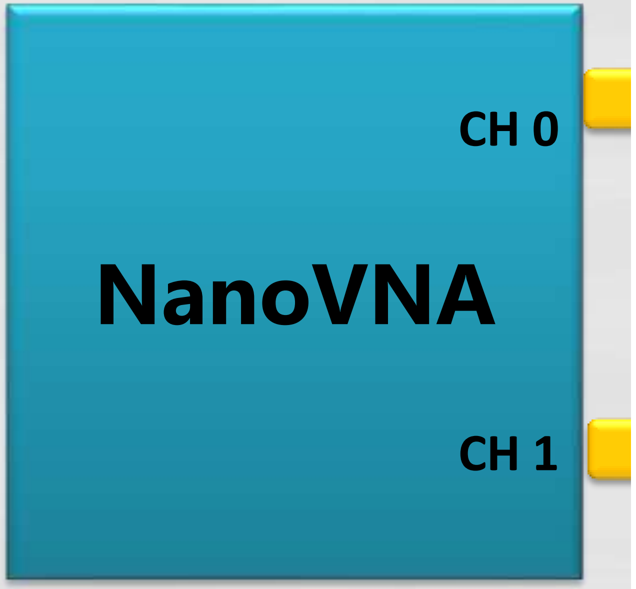
NanoVNA Configuration



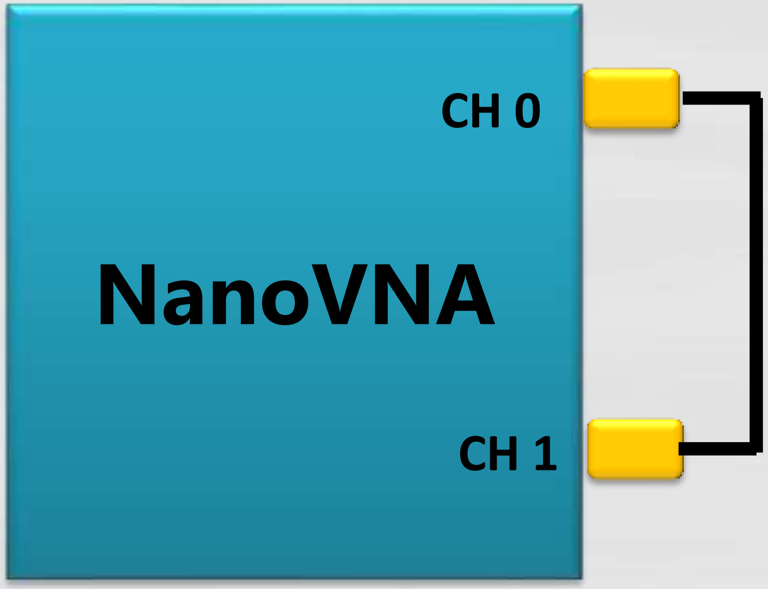
Antenna Measurement



VNA Calibration



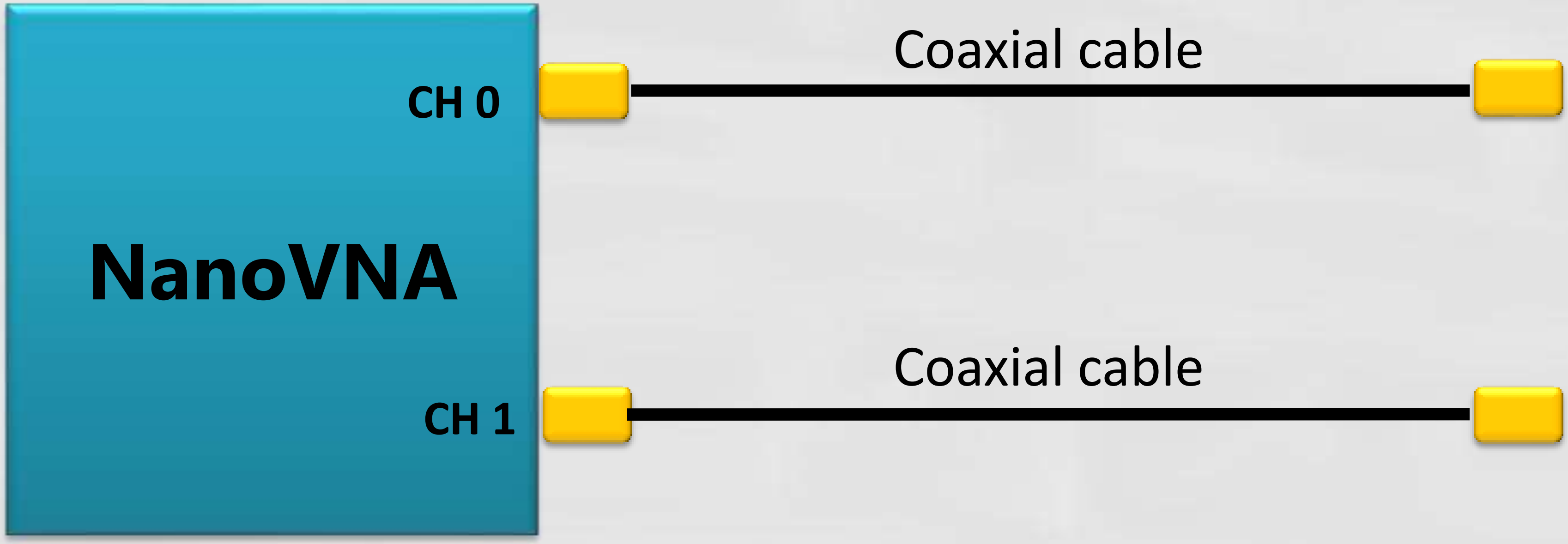
VNA Calibration



Transmission

1) Open
2) Through

VNA Calibration – long cables



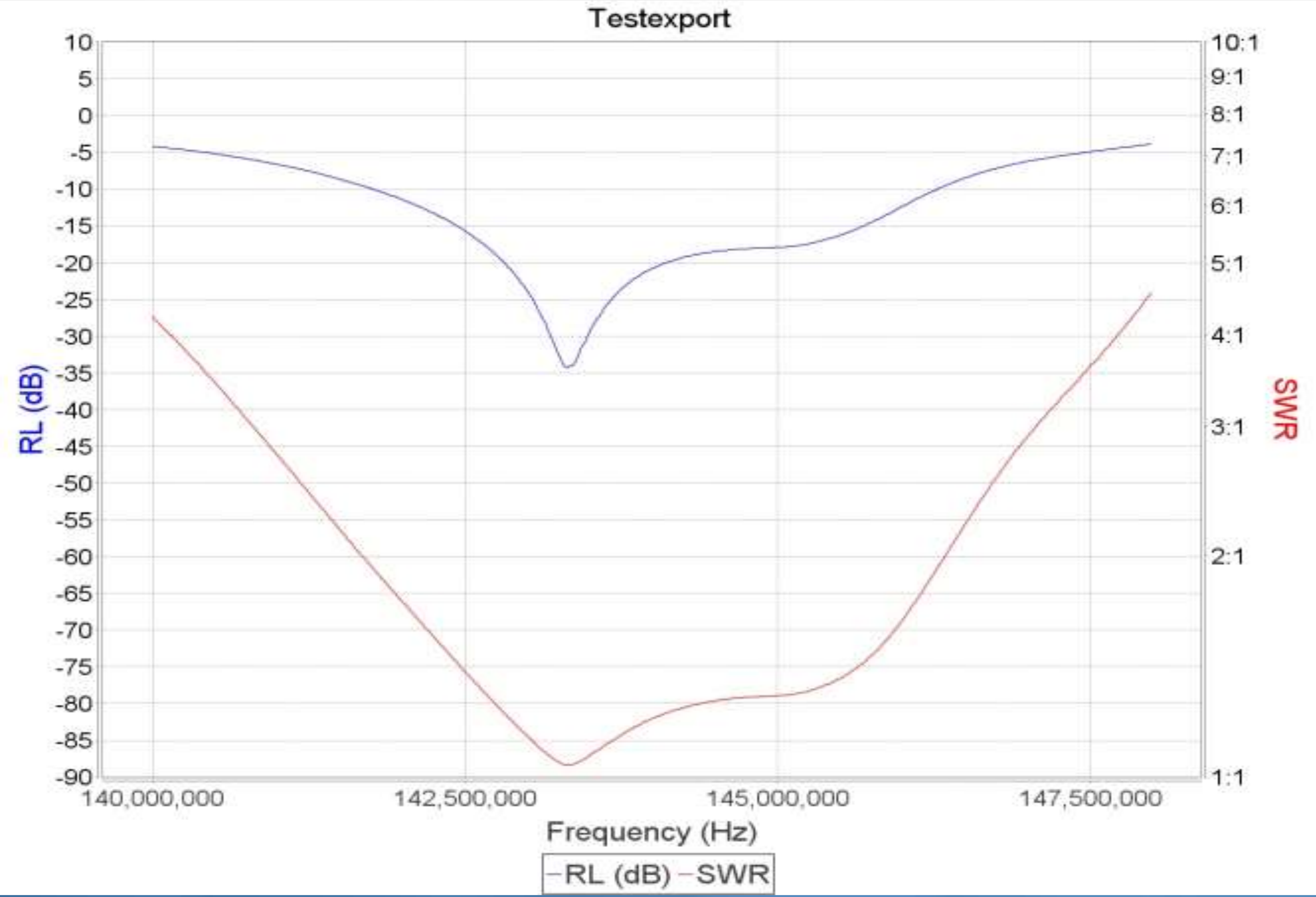
Attach Open, Short, Load, Through here

Cable losses are calibrated out

M^2 2M9SSB

VNA Measurement – 2m Antenna

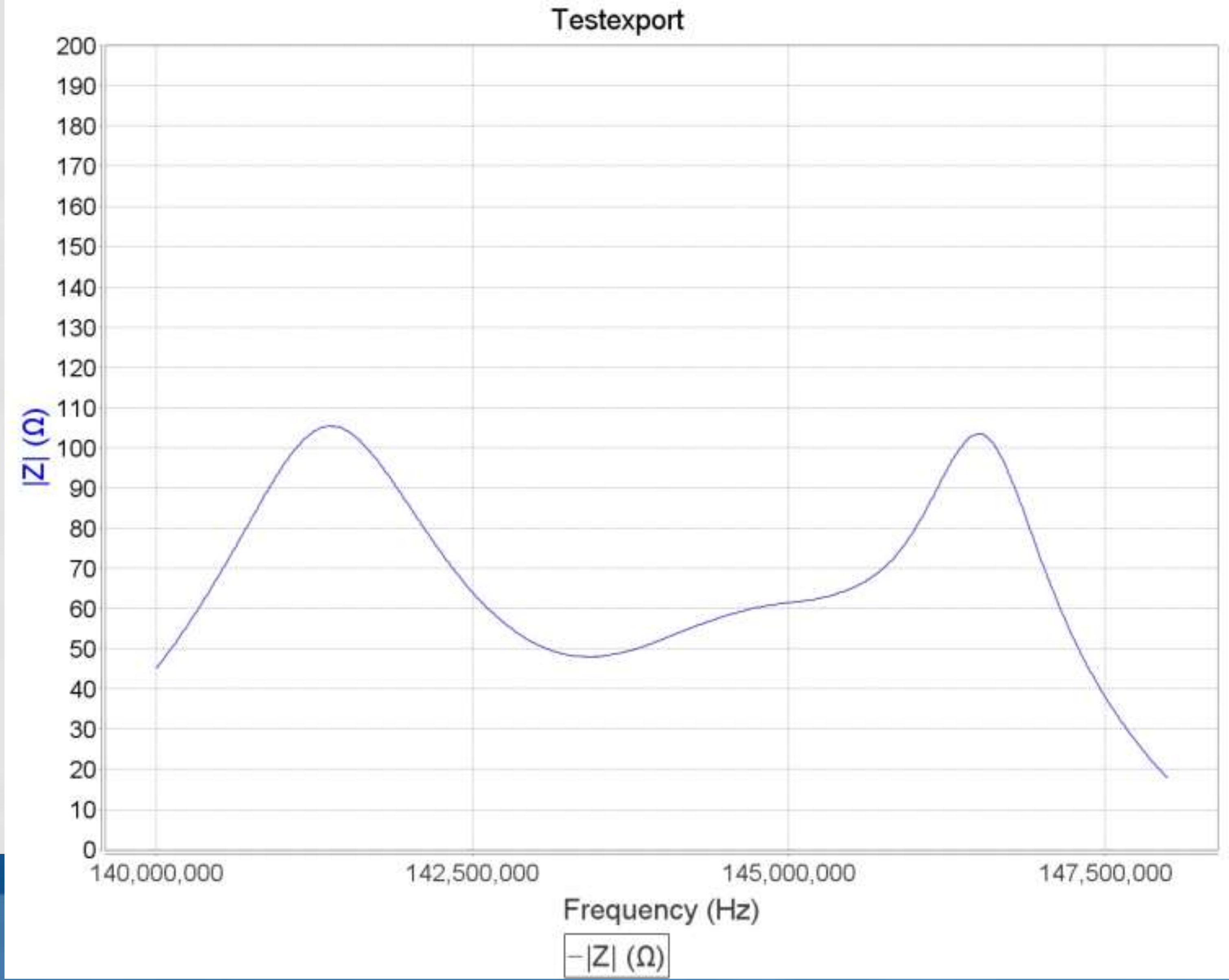
Measured
SWR
and
Return Loss



Bob Witte KØNR

VNA Measurement – 2m Antenna

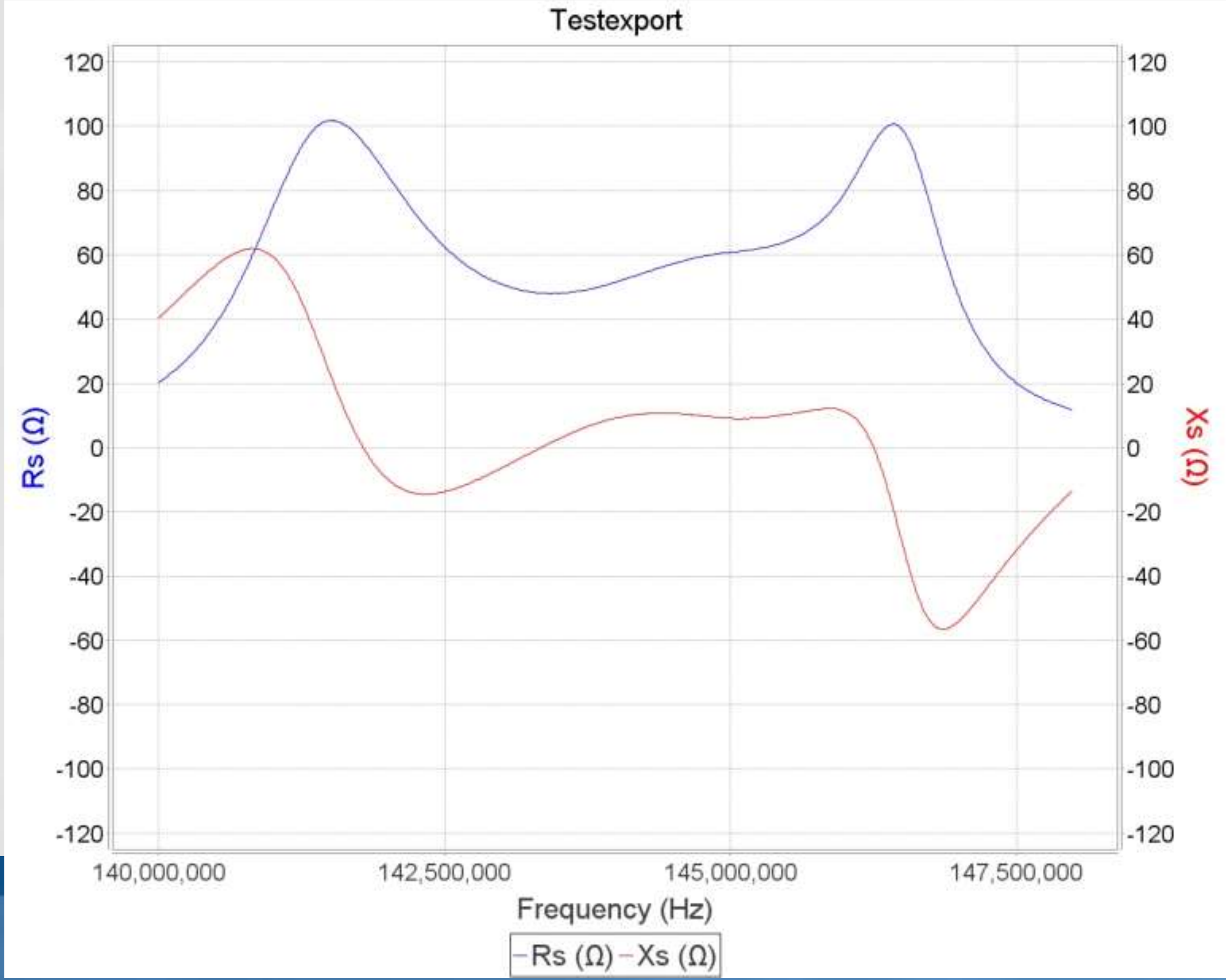
Measured
|Z|



VNA Measurement – 2m Antenna

Measured

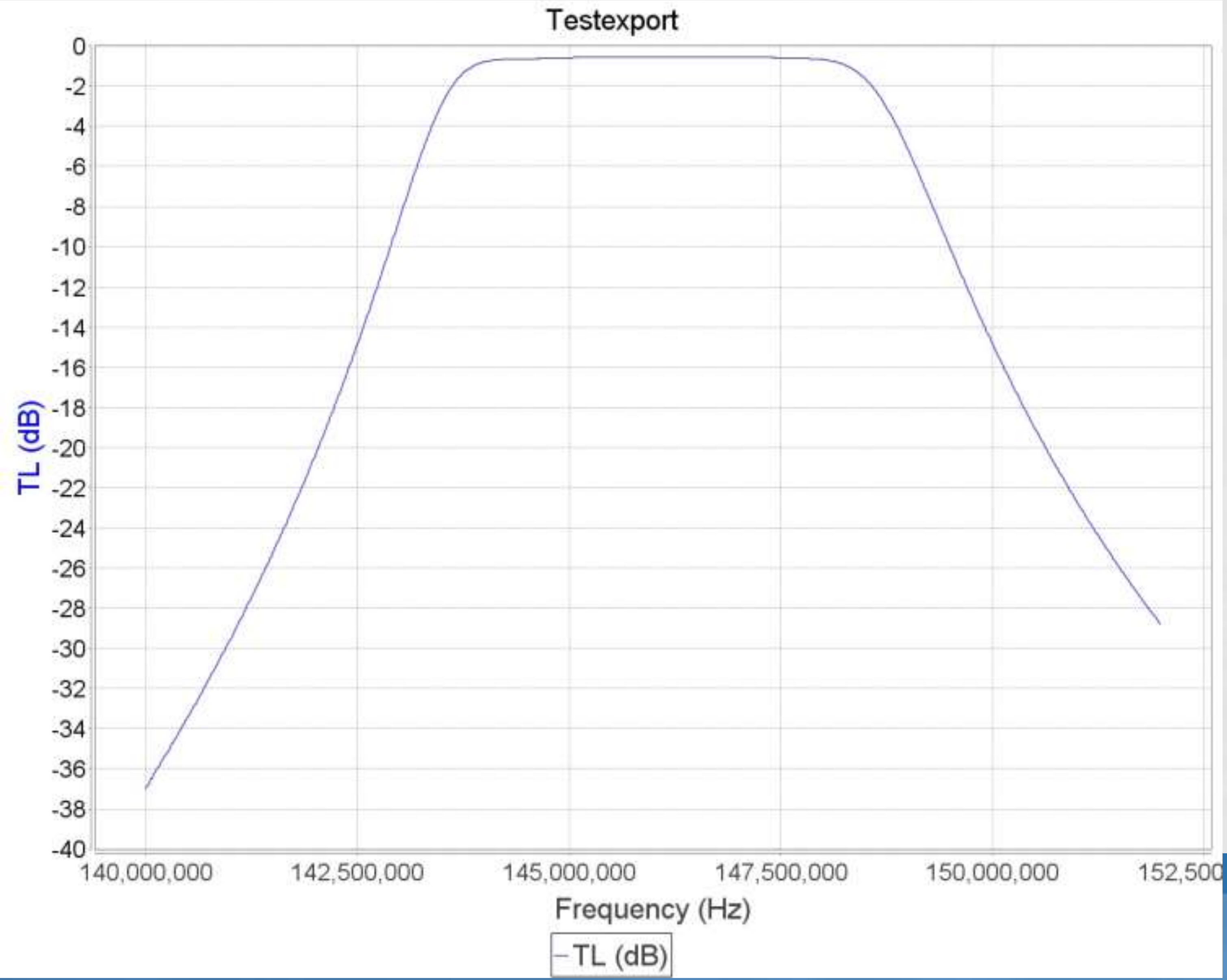
R and X



VNA Transmission Measurement

DCI

2 meter Bandpass Filter

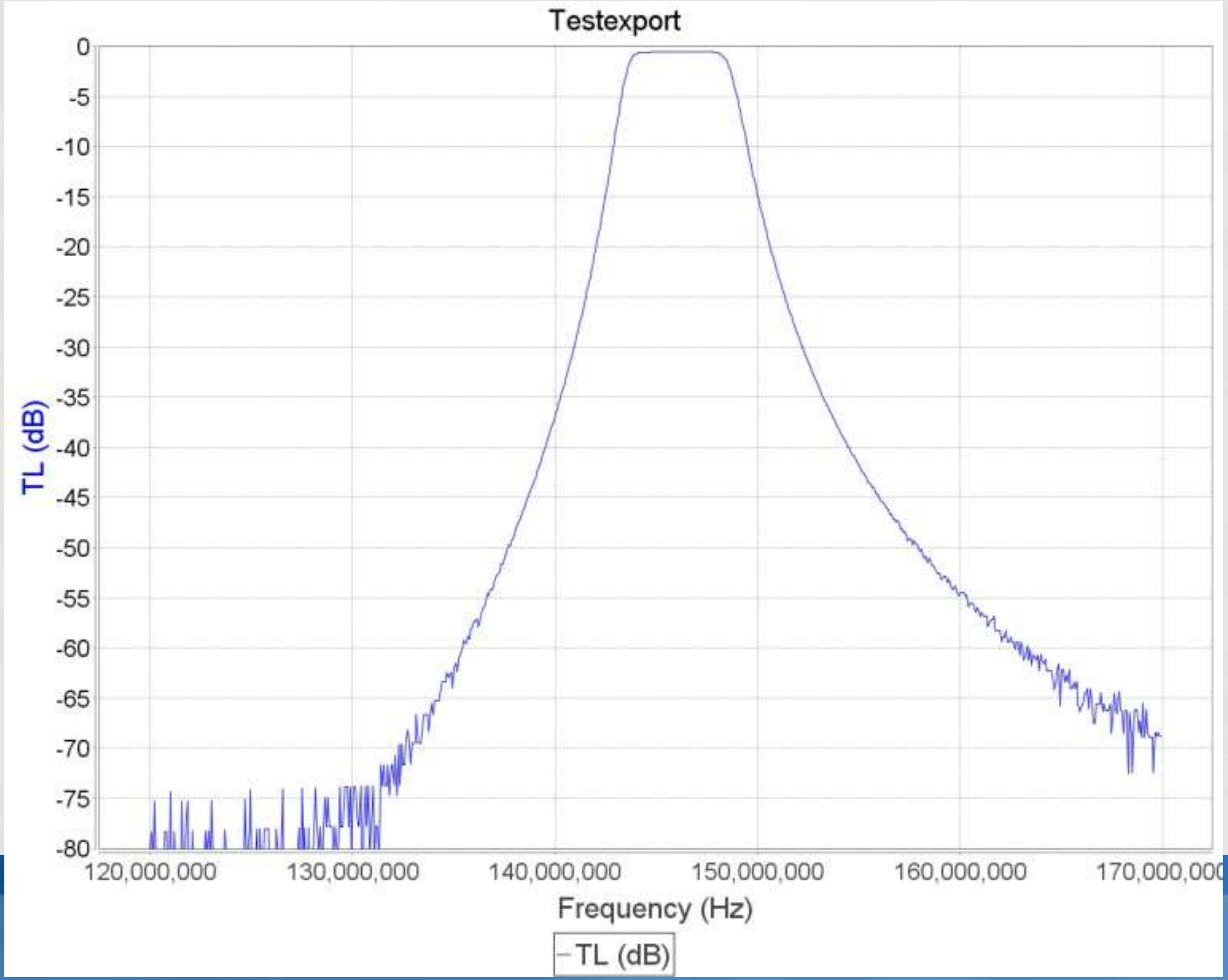


VNA Transmission Measurement

DCI

2 meter

Bandpass Filter



Q&A

What questions do you have?

Spectrum Analyzer Measurements

Bob Witte, KØNR
bob@k0nr.com
Monument, CO

Name	Frequency	Usage
DC	0 Hz	Power, Batteries
AC Power	50 - 60 Hz	Power
Audio	20 Hz - 20kHz	Modulation
LF	30 kHz - 300 kHz	Experimental
MF	300 kHz - 3 MHz	Radio Signals
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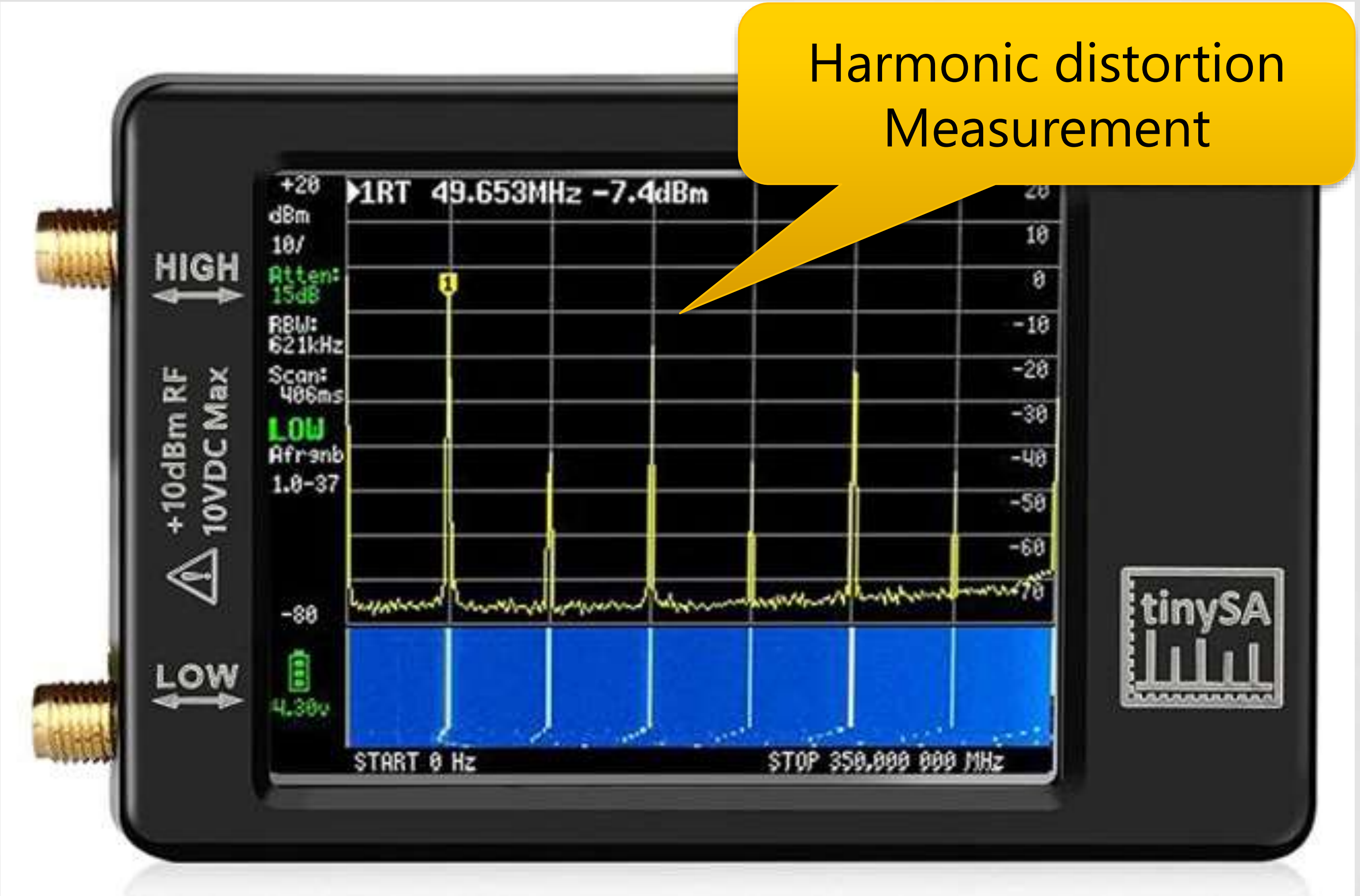
VHF	30 MHz - 300 MHz	Radio Signals
UHF	300 MHz - 3 GHz	Radio Signals

Vector Network Analyzer

Spectrum Analyzer

Frequency domain measurements

TinySA Spectrum Analyzer



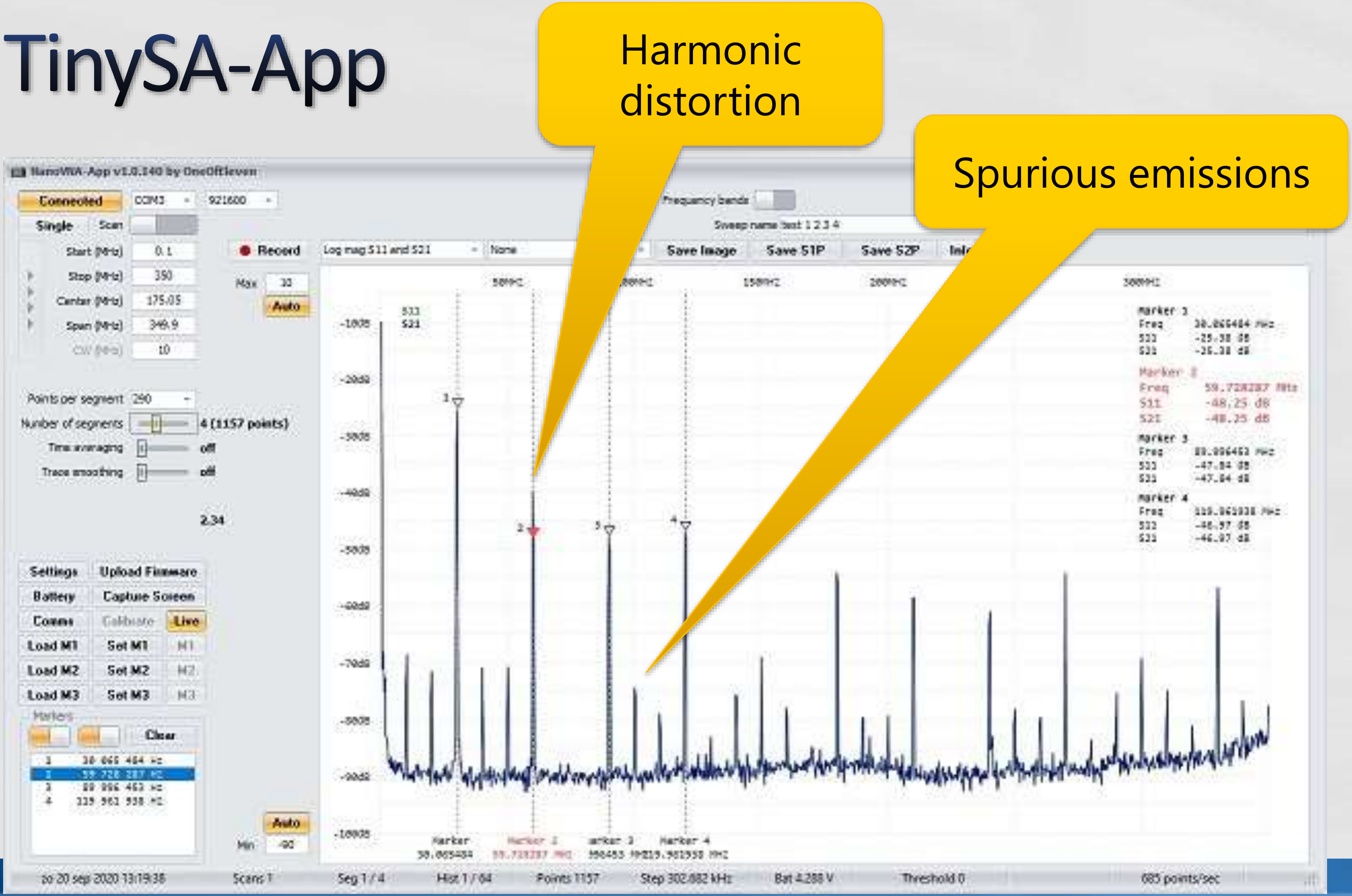
Low input:
0.1MHZ-350MHz
High input:
240MHz-960MHz

RBW: 6kHz to 640kHz
Dynamic range: ~70 dB
Signal Generator mode
Display 2.8 inch

Price: ~$70

Bob Witte, KØNR bob@k0nr.com

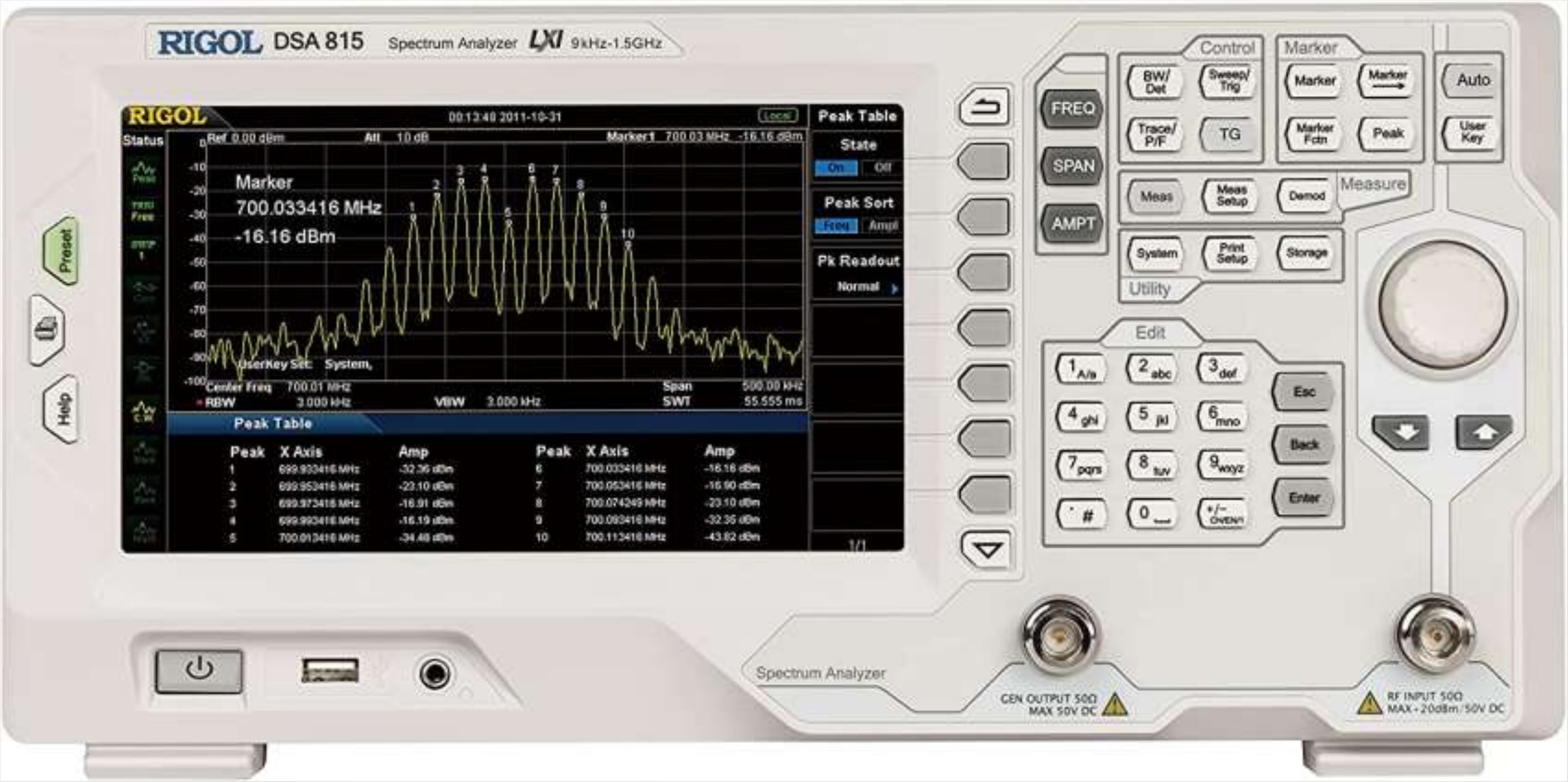
TinySA-App



Bob Witte, KØNR

bob@k0nr.com

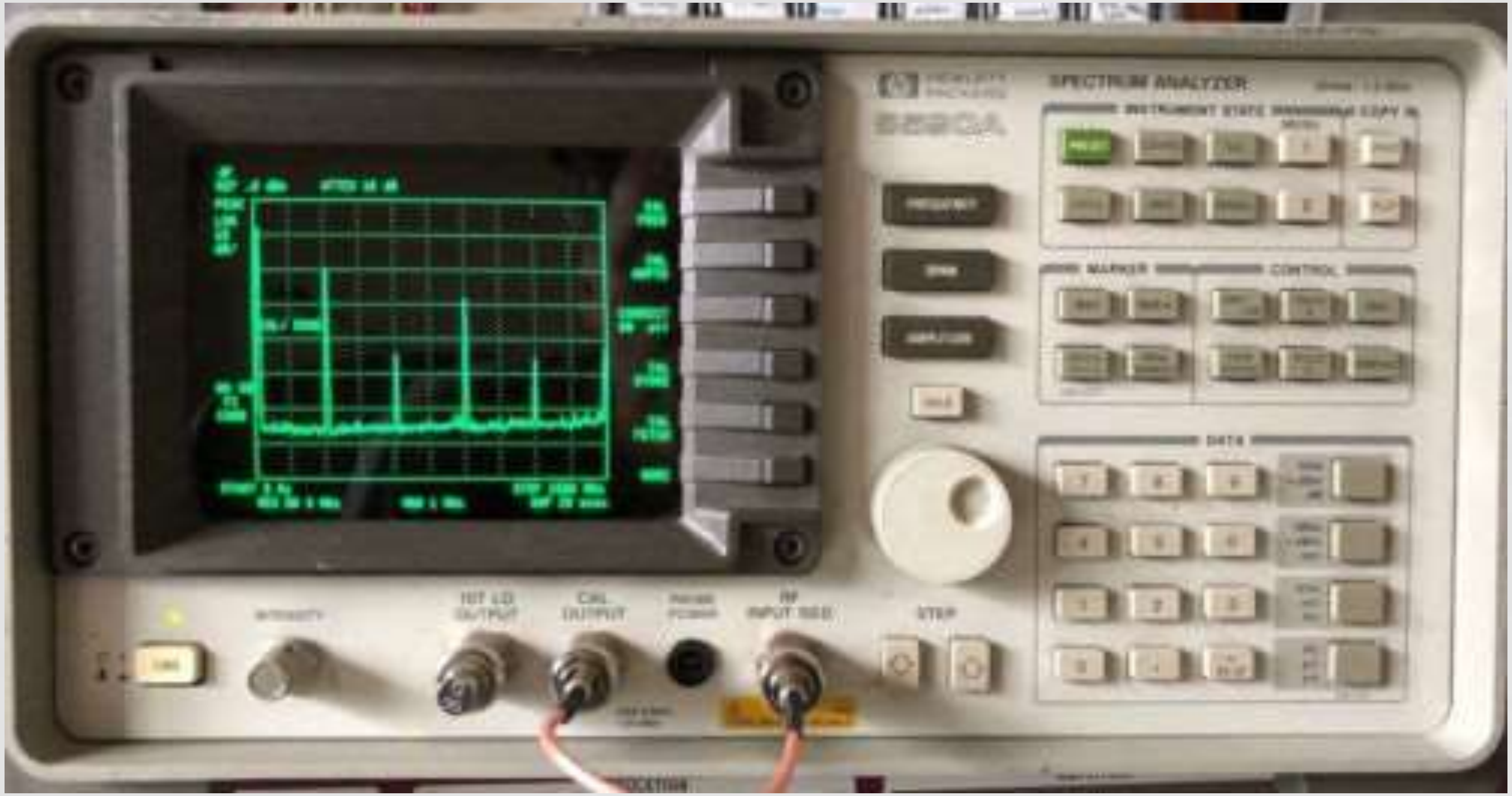
Rigol DSA815 Spectrum Analyzer



Frequency Range:
9 kHz up to 1.5 GHz
RBW: 10 Hz (min)
DANL: -161 dBm
Level Measurement
Uncertainty < 0.8 dB

Price: $999

Used Spectrum Analyzer



HP 8590A
Spectrum Analyzer

Frequency range
10 KHz - 1.5 Ghz
Price $500?

Software Defined Radio (SDR)

Mini USB RTL-SDR

R820T tuner IC
25MHz-1750MHz
~$20

SDRplay

Radio Spectrum Processor 1A
14-bit SDR

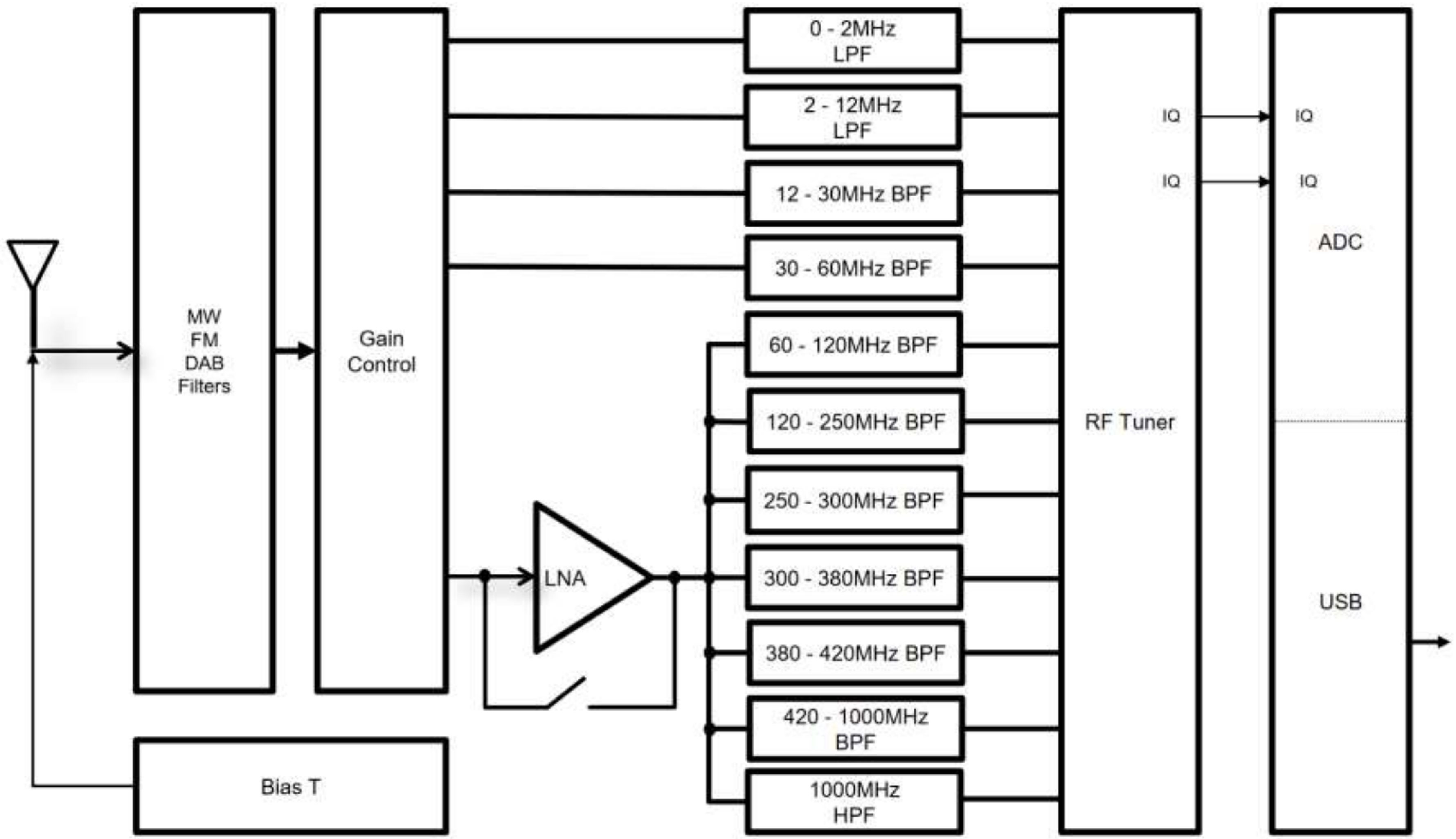
The SDRplay RSP1A is a major upgrade to the popular RSP1—it is a powerful wideband full featured 14-bit SDR which covers the RF spectrum from 1kHz to 2GHz. All it needs is a PC and an antenna to provide excellent communications receiver functionality. Combined with the power of readily available SDR receiver software (including 'SDRuno' supplied by SDRplay) you can monitor up to 10MHz of spectrum at a time. Documented API allows developers to create new demodulators or applications around the platform.

KEY BENEFITS

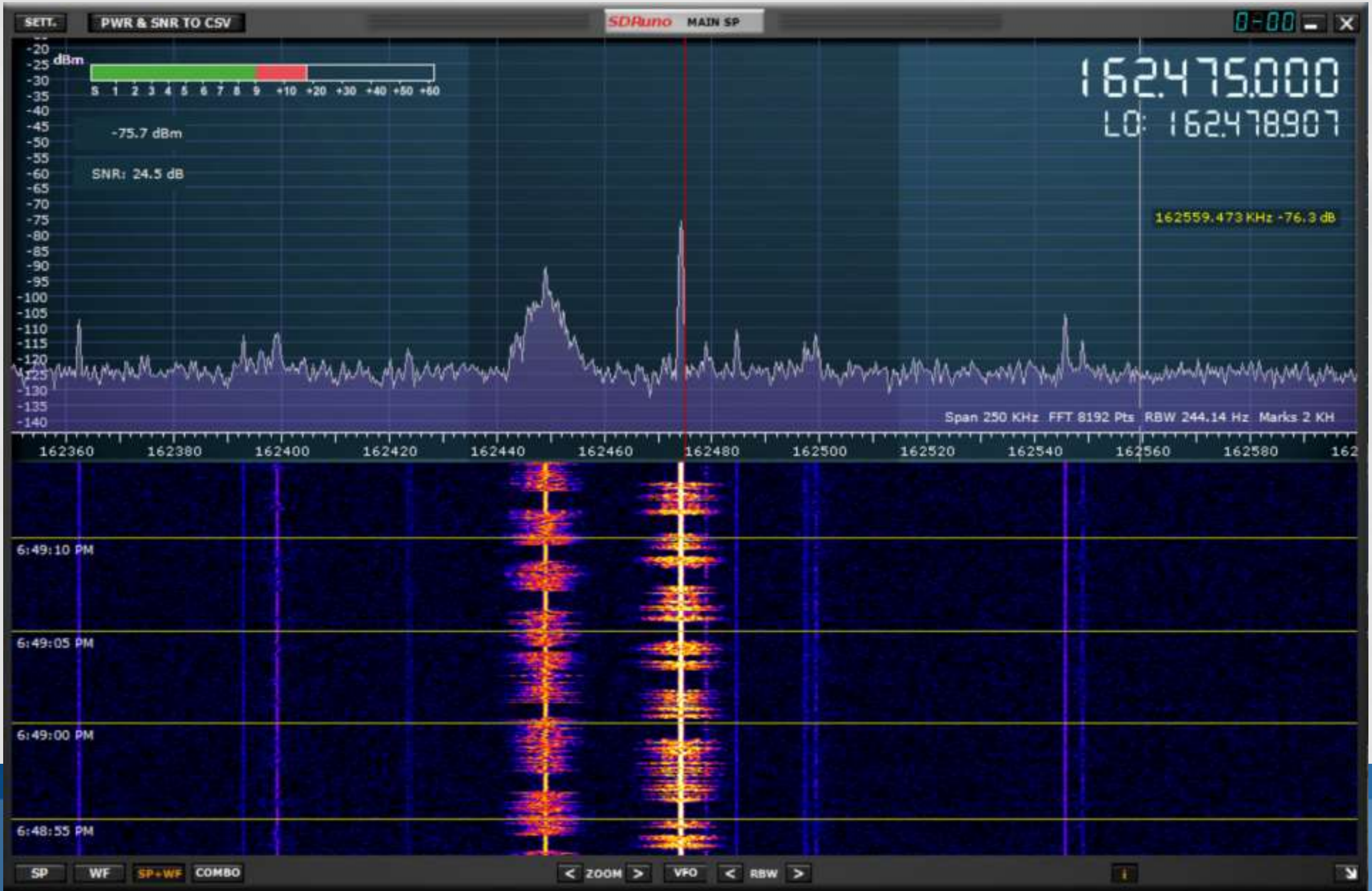
- Covers all frequencies from 1kHz through LF, MW, HF, VHF, UHF and L-band to 2GHz, with no gaps
- Excellent dynamic range for challenging reception conditions
- Low levels of spurious responses
- Works with all the popular SDR software (including HDSDR, SDR Console, Cubic SDR and SDRuno)

RSP-1A
Price
$109

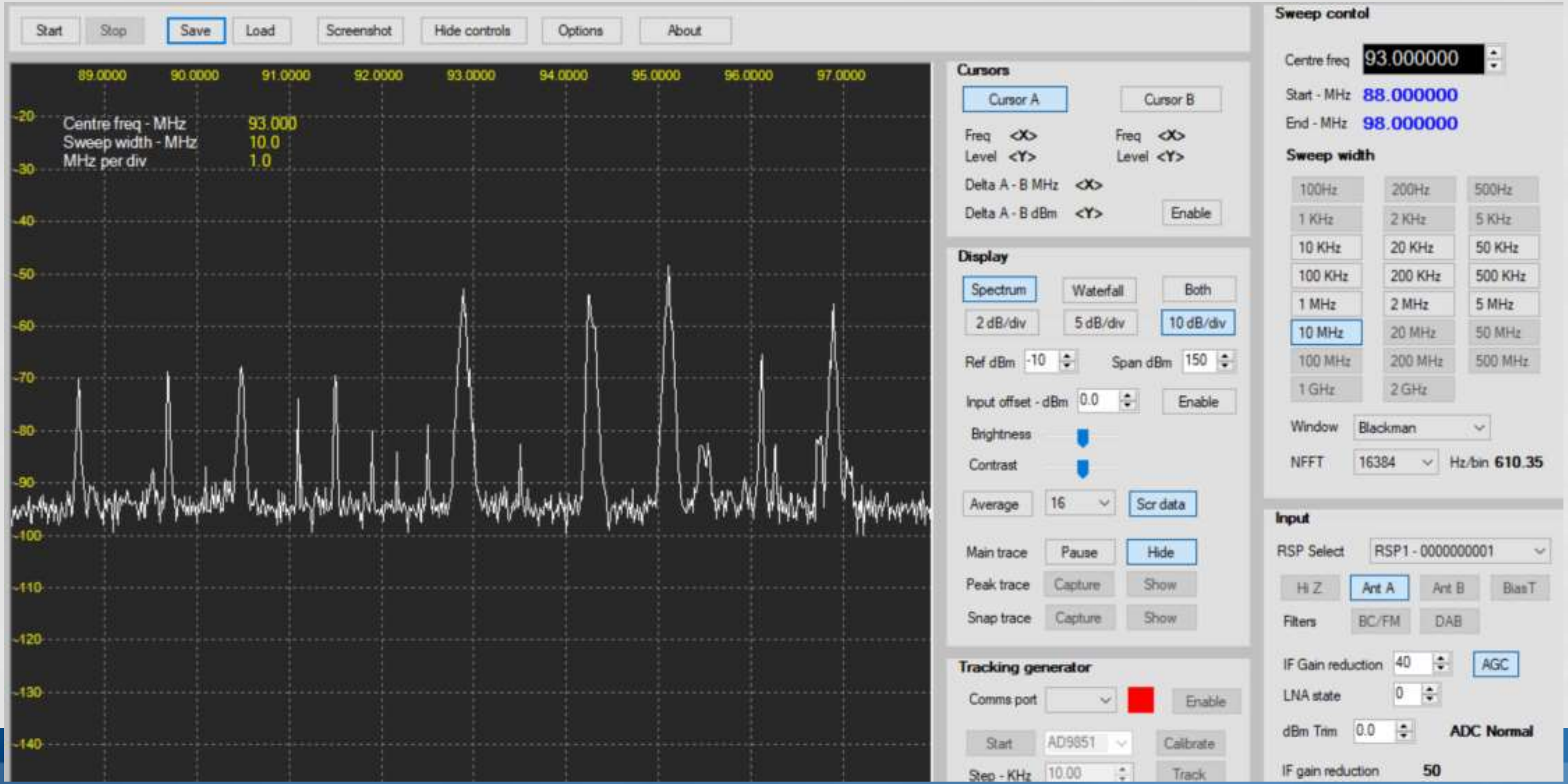
Block Diagram



SDRuno Software



SDR Spectrum Analyzer Software



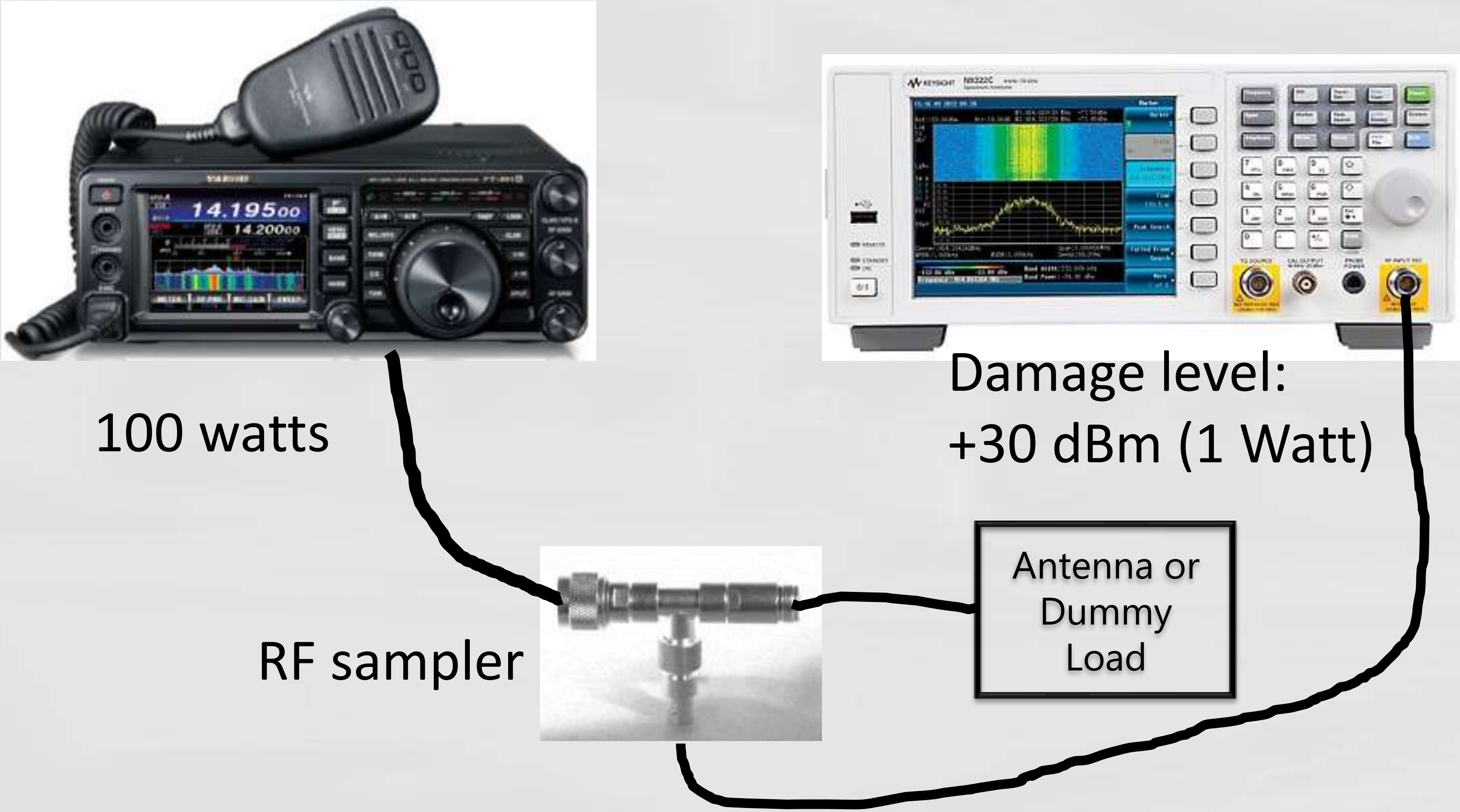
Connecting to Transmitters

100 watts

Damage level:
+30 dBm (1 Watt)

20 to 30 dB
power
attenuator

Connecting to Transmitters



Q&A

What questions do you have?

Thank You !!!