Oscilloscope Basics

What my Digital Oscilloscope is capable of …

TELEDYNE LECROY
Everywhereyoulook™

oversview

- Probes
  - What is a probe and how to use it
  - Probes limitations, BW, probe tip, GND lead
  - Derating Curve, BW and Isolation
  - System BW
  - Active Differential probes
  - Current Probes

Overview

- Measurements
  - Cursors, parameters
  - Parameter math
  - Trend and Track – See how a measurement evolves over time
  - Examples
  - Create your own custom measurement

Probes

TELEDYNE LECROY
Everywhereyoulook™

What is a probe?

- The probe is the most common connection method between your oscilloscope and your DUT (Device Under Test).
  - A cable connection such as a BNC cable is another possibility.
- The probe is a physical connection between the DUT signal of interest and the oscilloscope.
- In theory a probe could be a simple wire connected to a circuit, in practice it is a complex circuit along with the oscilloscope.

What happens....

...when you connect the probe to the DUT?

1. The probe cannot transfer the true shape of your waveform to the screen of your oscilloscope.

2. The probe will influence the real shape of the waveform.

   2.1 You'll observe a different waveform on your display.

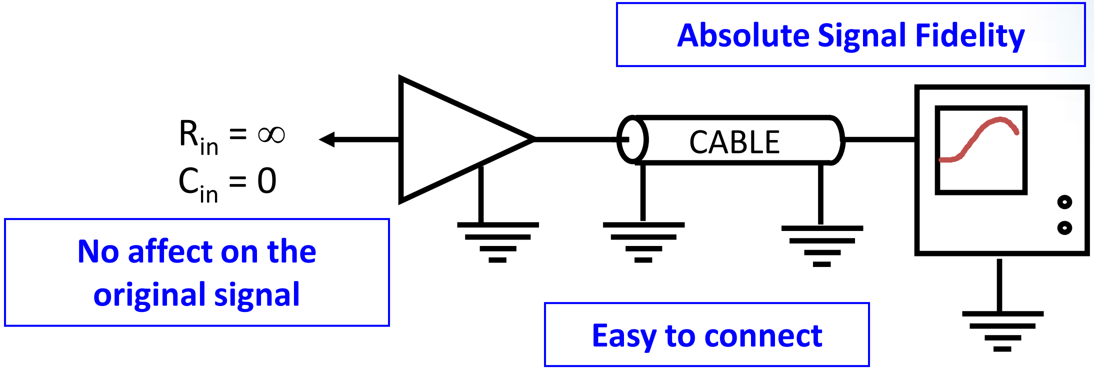
   2.2 Differences will depend on both probe and waveform characteristics

3. The probe can load the DUT.

   3.1 The DUT may operate in a different way due to the probe load.

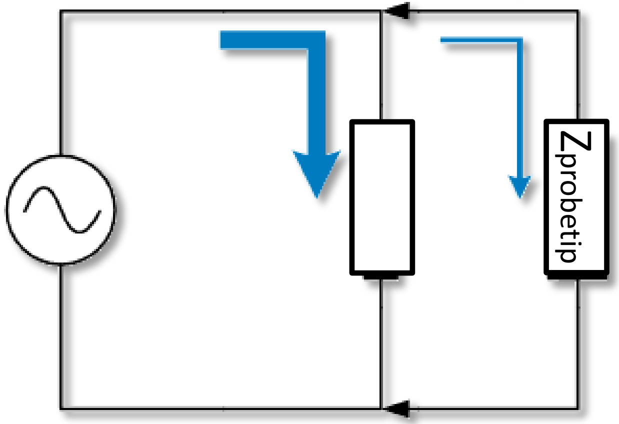
What happens.... in theory

THE IDEAL PROBE



Probes interact with the measured object!

- A connected probe, extract energy from the system
- The probe is an added load, parallel to the circuit
- As a result the probe (can) change the signal
- High impedance is required to minimize the probe loading effect on the circuit and make reliable measurement
  - Every probe's , active or passive, impedance decreases with frequency. The specified high impedance is true only at very low frequency!

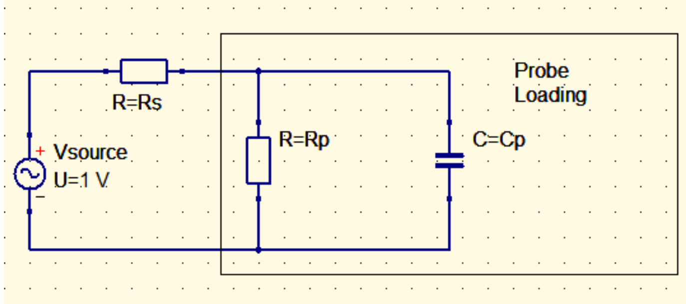


Probe Impedance

• Probe Impedance can be calculated as frequency increases

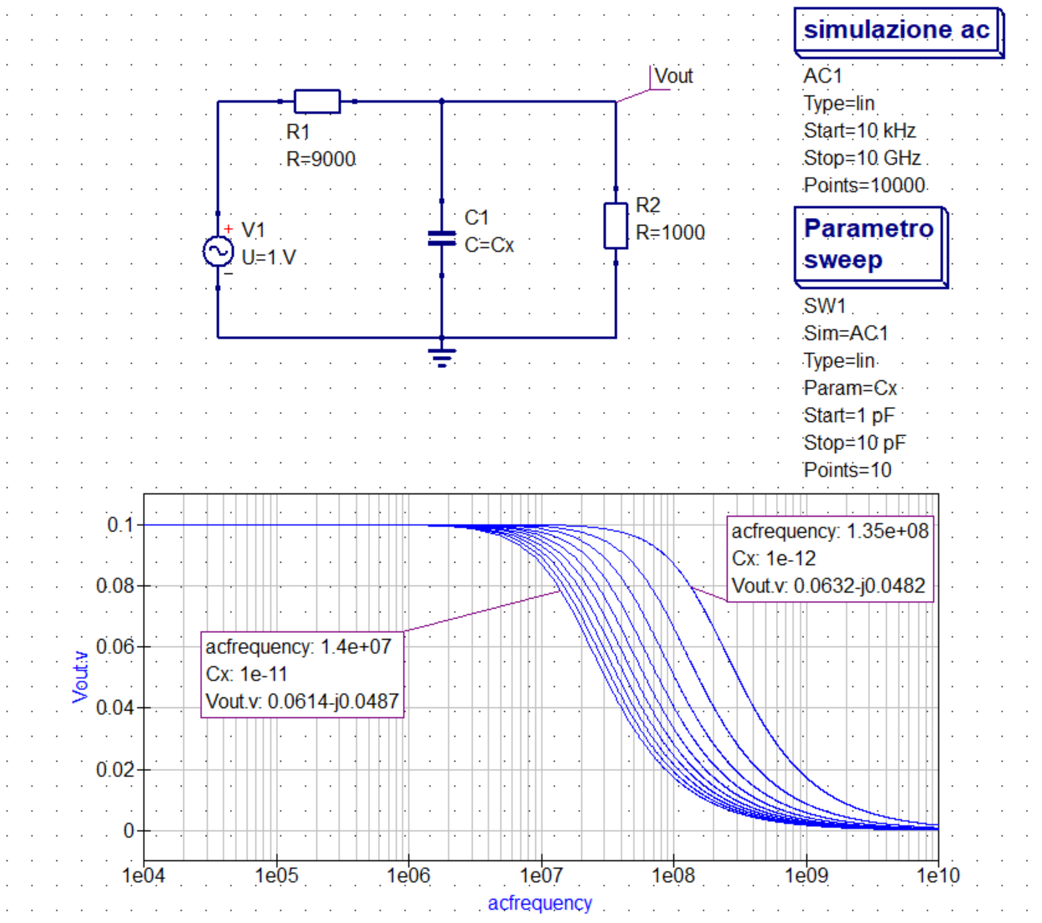
$$z = \frac{R \times \frac{1}{2\pi f C}}{R + \frac{1}{2\pi f C}} = \frac{R}{2\pi f C R + 1}$$

$$2\pi f C \ll R \quad Z \approx R$$



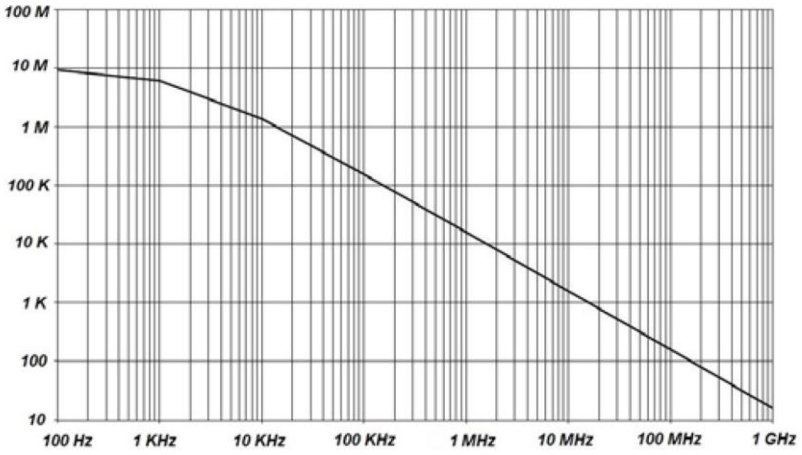
•This means passive probes are great at DC but have some limitations at higher frequencies

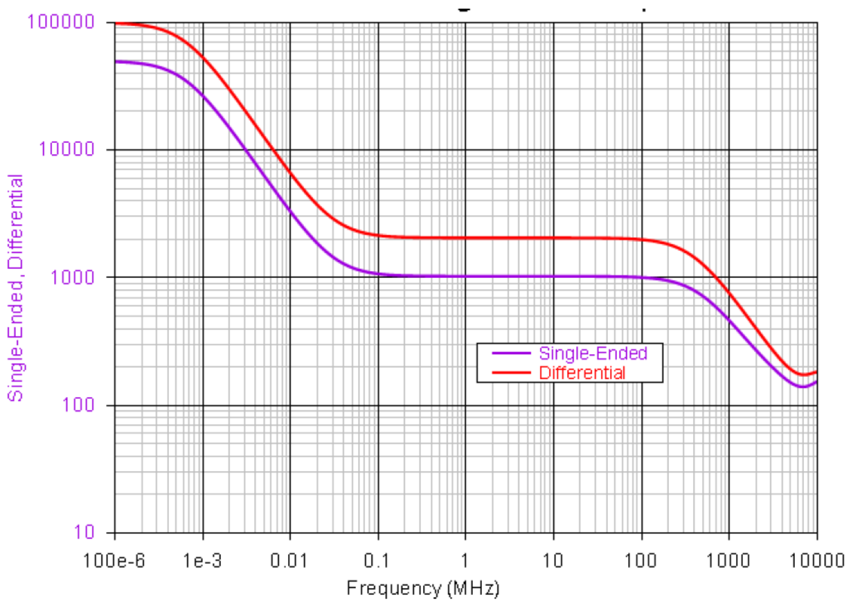
Probe circuit simulation



Example of impedance curve of probes

PP018 Input Impedance Profile

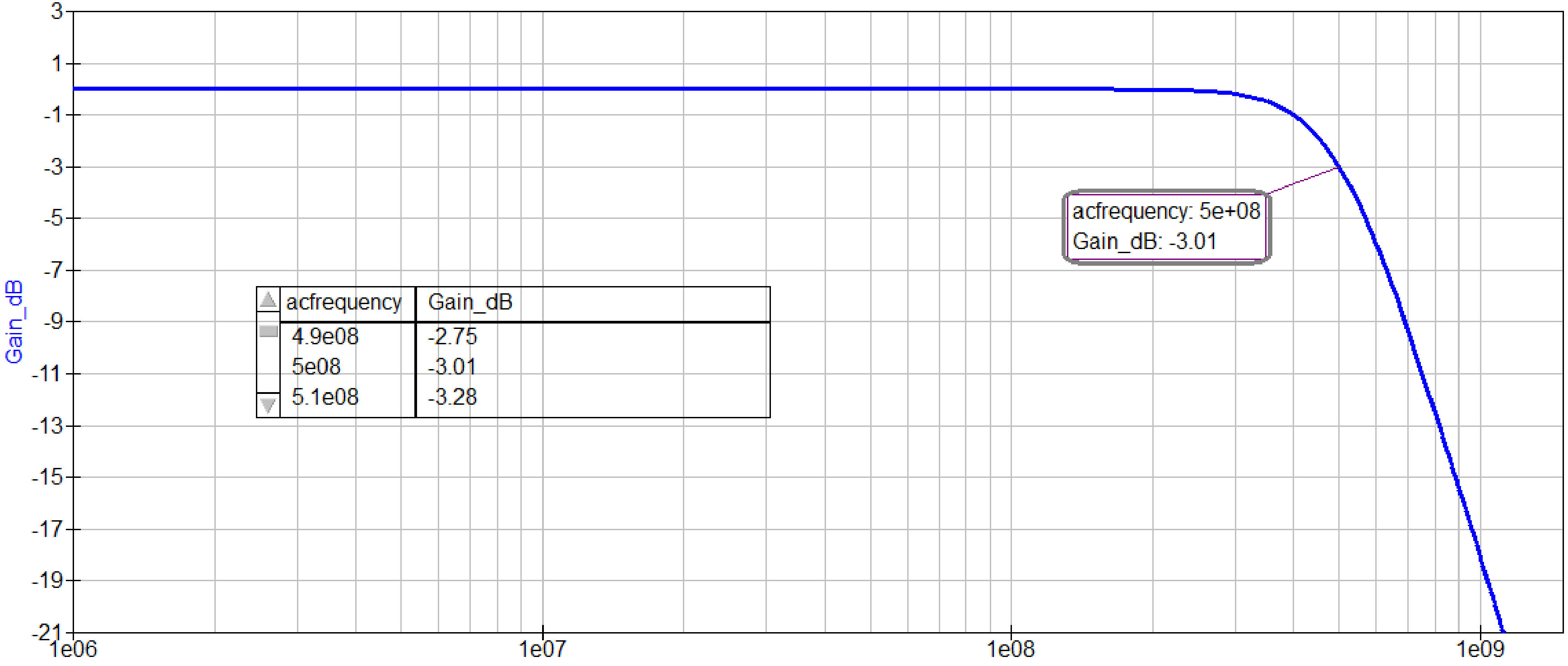




Dx10-SI, Dx10-HiTemp, Dx10-QL-SI, and Dx20-QL-SI Single-ended Impedance

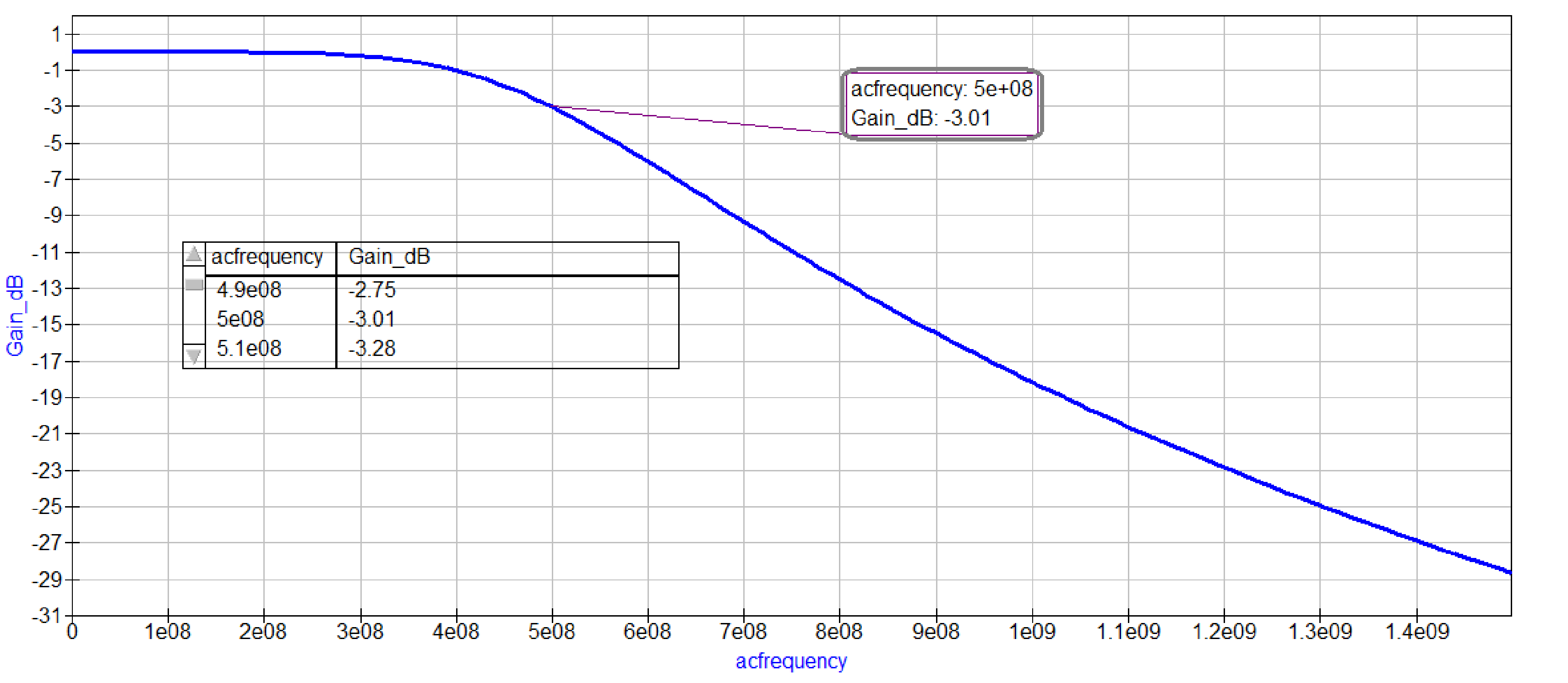
Analoge bandwidth '-3 dB'

- Frequency response of the voltage V_{out}/V_{in}



acfrequency	Gain_dB
4.9e08	-2.75
5e08	-3.01
5.1e08	-3.28

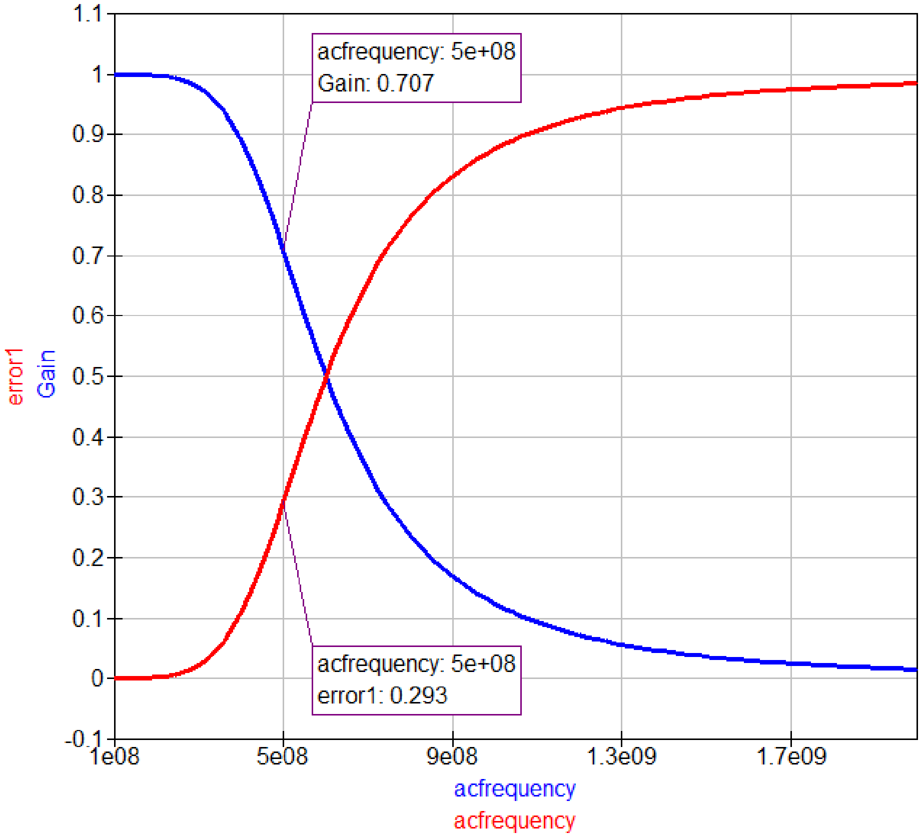
Single pole Bode plot – Frequency Linear scale



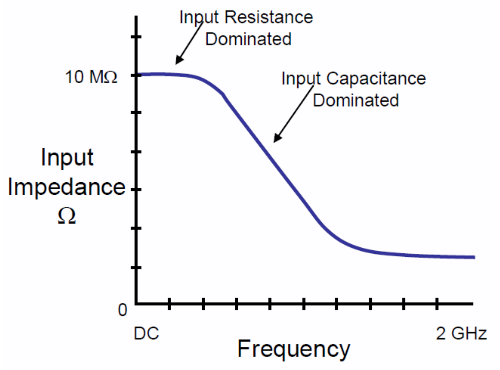
The bode is usually with an horizontal log scale. Plotting it in a linear scale shows that the attenuation is not negligible at much lower frequencies

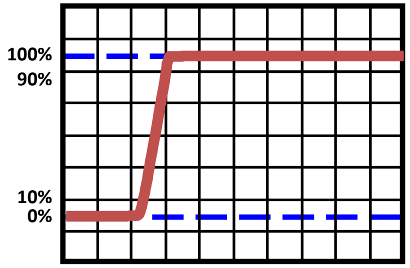
Vertical accuracy is affected by available Band Width

acfrequency	Gain	errorx100
1.6e08	0.999	0.0536
1.8e08	0.999	0.109
2e08	0.998	0.204
2.2e08	0.996	0.361
2.4e08	0.994	0.606
2.6e08	0.99	0.974
2.8e08	0.985	1.51
3e08	0.977	2.25
3.2e08	0.967	3.27
3.4e08	0.954	4.6
3.6e08	0.937	6.31
3.8e08	0.916	8.43
4e08	0.89	11
4.2e08	0.86	14
4.4e08	0.826	17.4
4.6e08	0.789	21.1
4.8e08	0.749	25.1
5e08	0.707	29.3
5.2e08	0.664	33.6
5.4e08	0.622	37.8
5.6e08	0.58	42

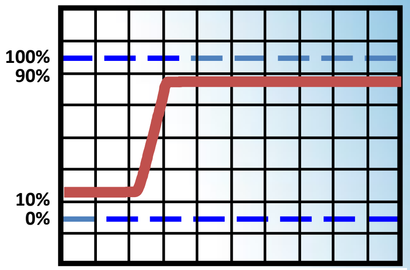


Impedance and frequency response effect on your signal

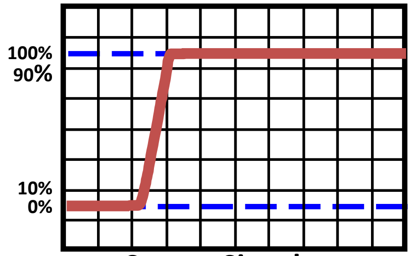




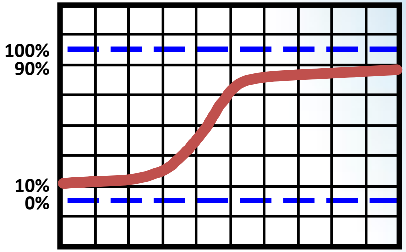
Source Signal



Effects of Input Resistance



Source Signal



Effects of Input Capacitance

Combining scope Bw and Probe BW

We can Measure the total system Performance using the following identities:

$$BW = 0.4/Rise\ Time$$

$$System\ Rise\ time = \sqrt{Rise\ time\ DSO^2 + Rise\ time\ Probe^2}$$

Here is an easy way to determine the System (Probe+ oscilloscope) BW
We can easily measure the rise time of an electrical pulse, knowing the real pulse Rise time (often can be set on the pulse generator or is a known spec of the generator) we can figure out the System Risetime and then

System BW= 0.4/System Risetime

Analog bandwidth for DSO & Probe

System rise time = $\sqrt{Rise\ time\ DSO^2 + Rise\ time\ Probe^2}$

Example:

Rise time DSO:	550ps (630MHz)
Rise time Probe:	660ps (520MHz)

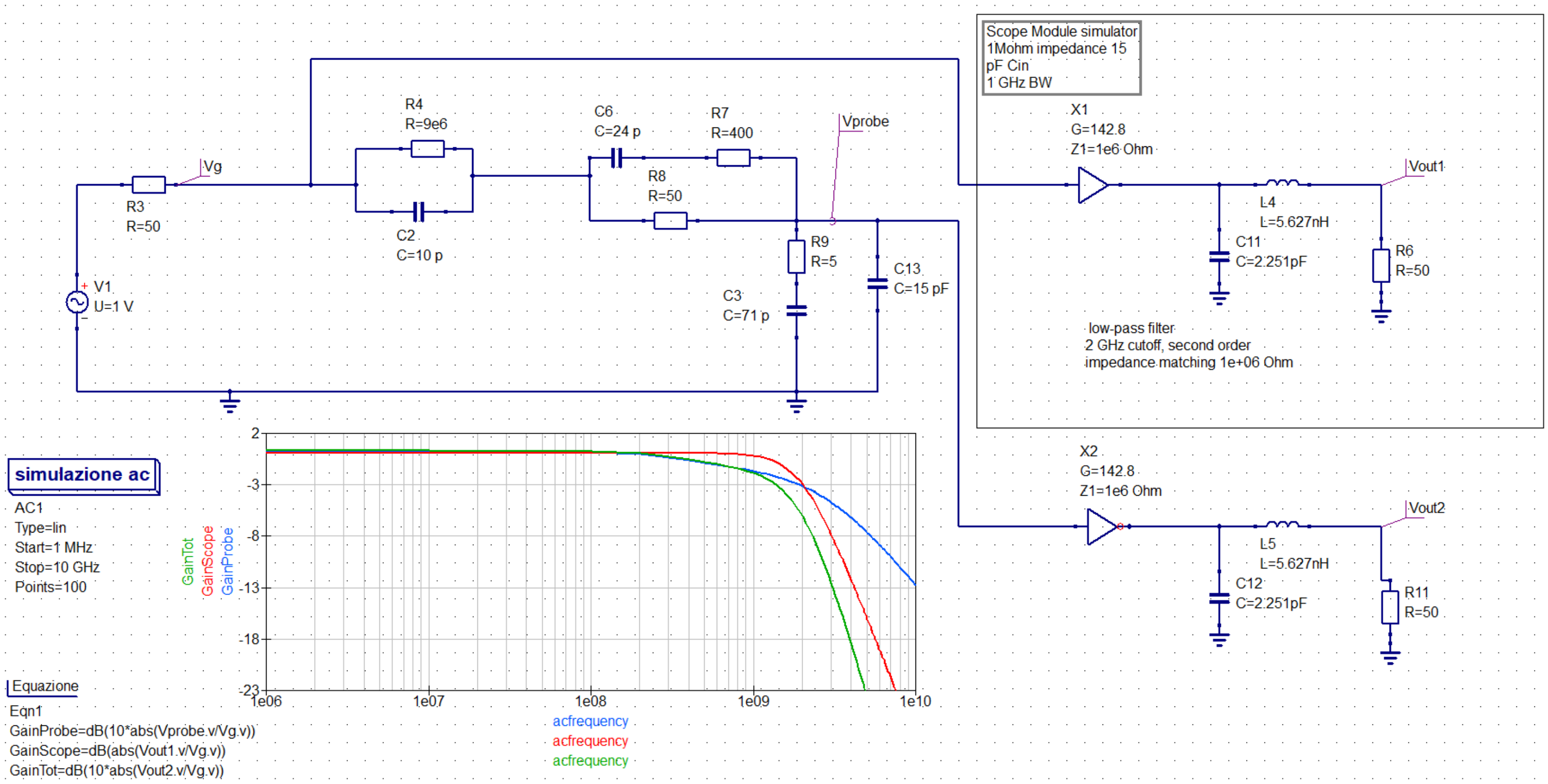
Rise time System = $\sqrt{550ps^2 + 660ps^2}$

Rise time System = 860ps

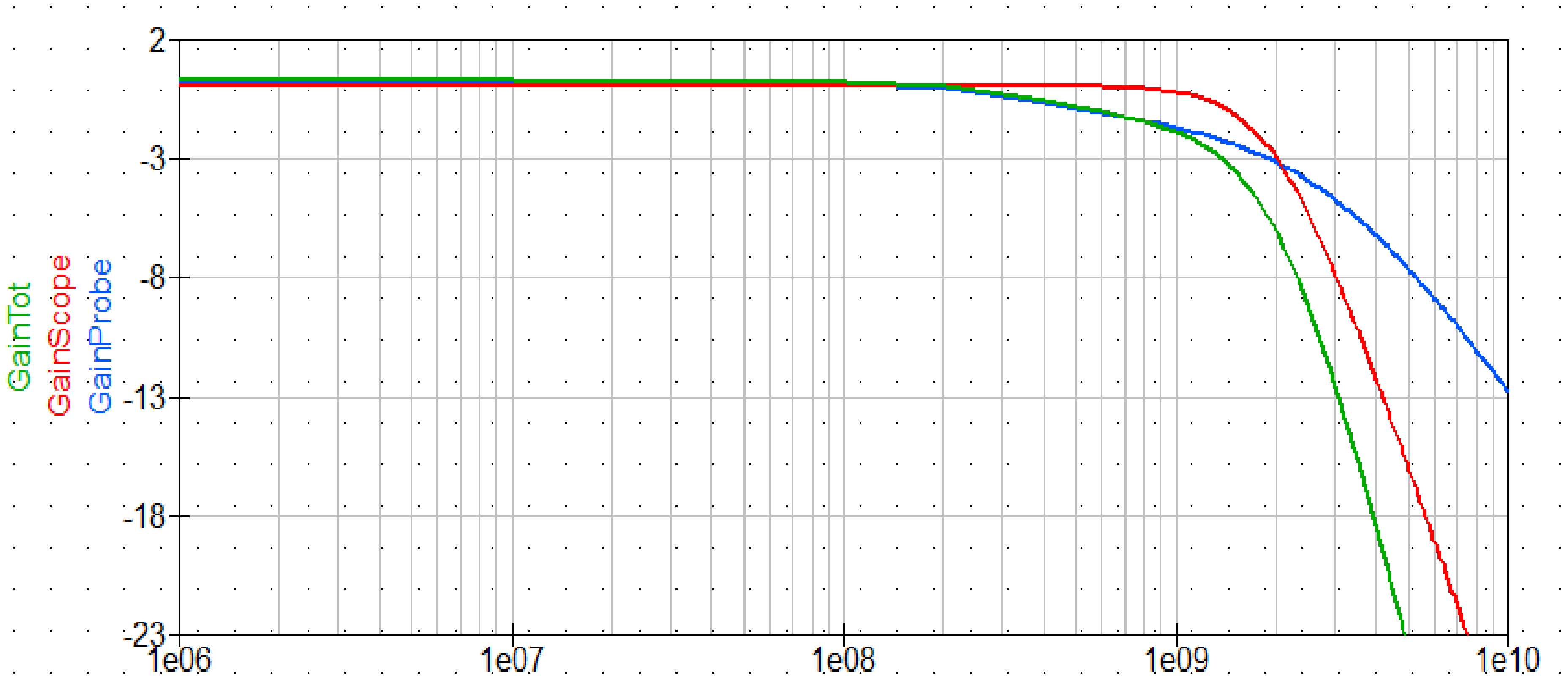
System bandwidth = **405MHz**

$$\sqrt{\frac{1}{\frac{1}{{BW_1}^2}+\frac{1}{{BW_2}^2}}} = \sqrt{\frac{1}{\frac{1}{520^2}+\frac{1}{630^2}}}$$ = 405MHz

Simulation of cascading scope and probe 2GHz each



Bode plot only:

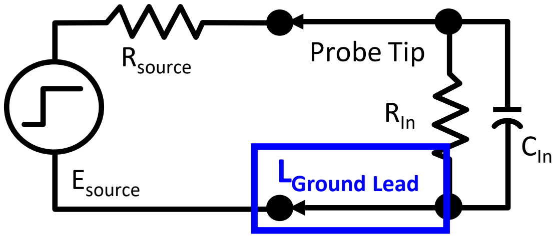


...what about the ground lead?

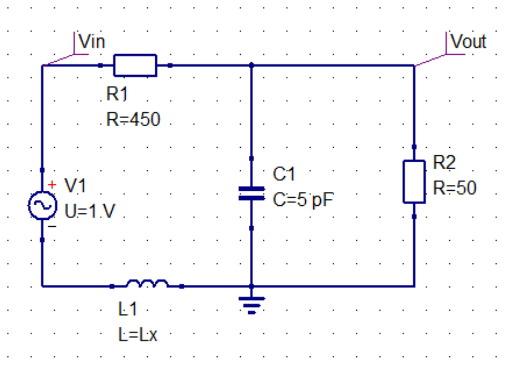
Ground Lead…why should we worry about the ground wire?

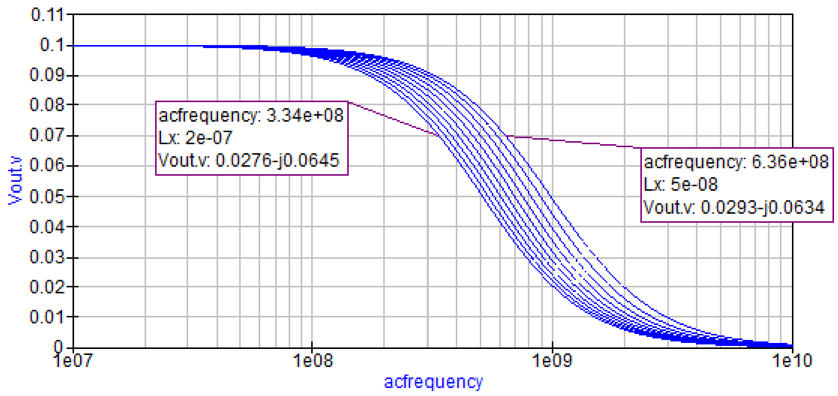
The final piece to the electrical characteristic of a probe is grounding.
Any lead adds inductance to the probe tip or probe ground circuit.
A lead can also act as an antenna and pick up electrical noise from the environment.
That noise is added to the signal.

The longer the ground lead, the higher the probe inductance



Simulation of ground lead inductance



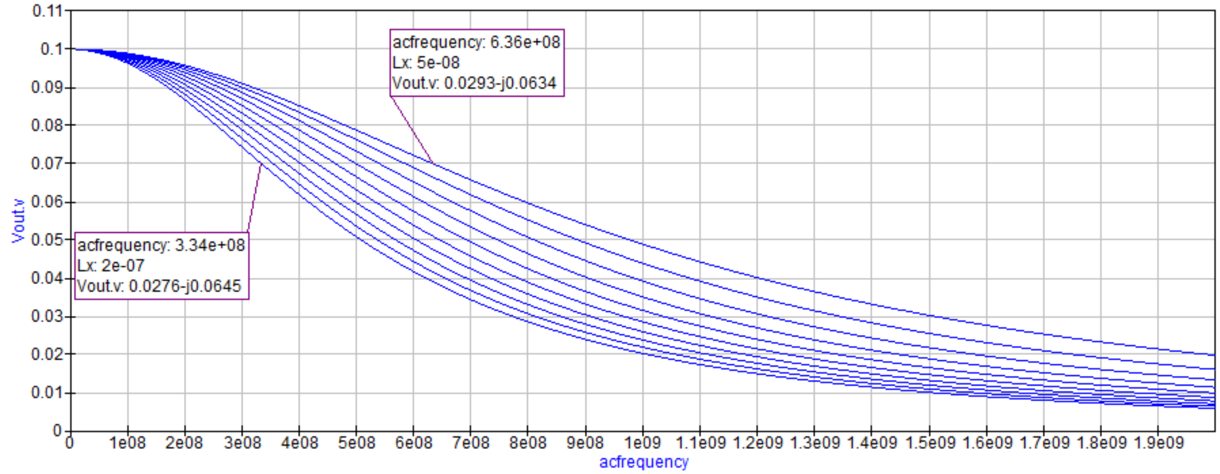


ac simulation

AC1
Type=lin
Start=10 MHz
Stop=10 GHz
Points=10000

Parameter sweep

SW1
Sim=AC1
Type=lin
Param=Lx
Start=50nH
Stop=200nH
Points=10



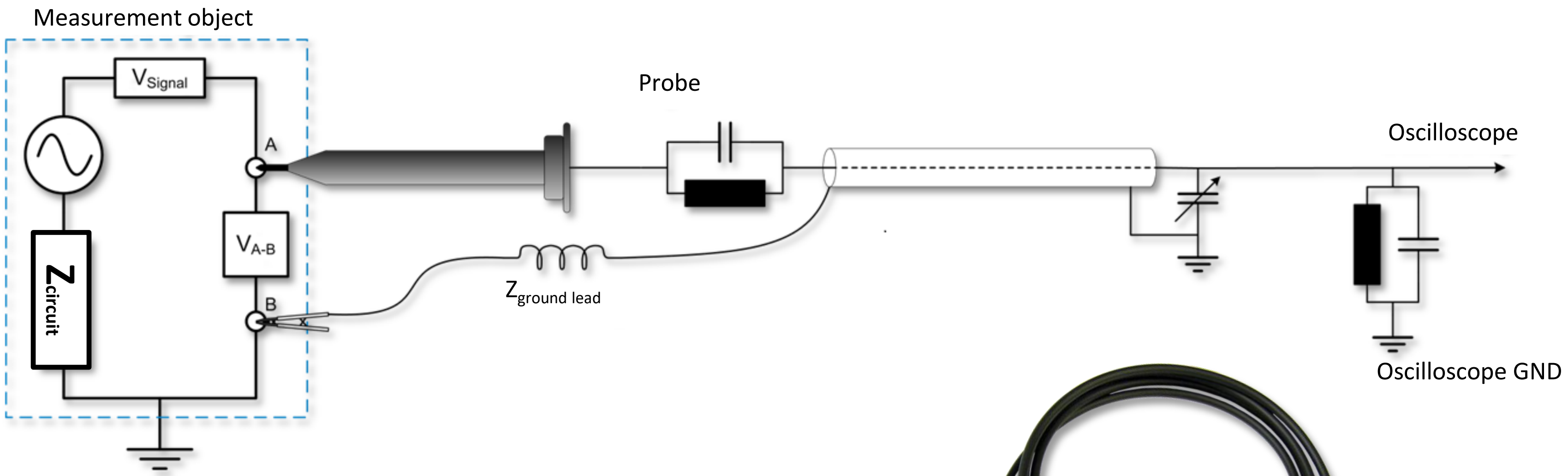
Standard voltage probes divded in two categories

- Passive
  - Standard accessory of oscilloscope
  - No active elements
  - Mechanically and electrically robust
  - Measurements > 100 V possible
  - Max. bandwidth appr. 500 MHz
  - Low impedance at higher frequency

- Active
  - Optionally available
  - Requires power
  - Based on active elements

    (Transistors or FET)
  - More sensitive for damage
  - Better at higher frequency due to low capacity

Passive 10:1 Probe



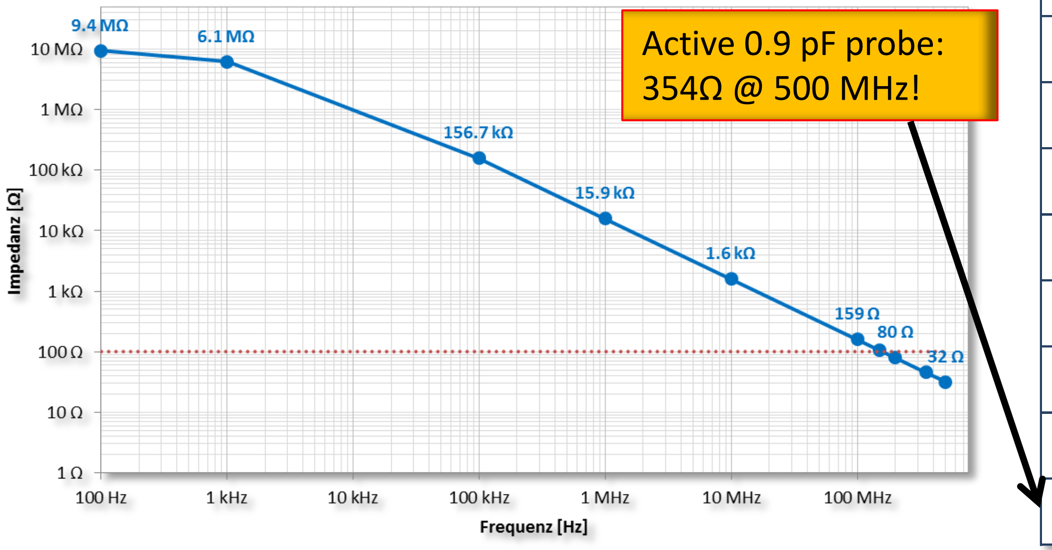
- 10:1 Probes reduce the load on the measurement object due to high impedance
  - 10 MΩ Resistance
  - 10 pF Typical Capacitance

Effect of capacity on probe impedance

- Passive probe: mechanically and electricall robust, 10 MΩ impedance, 10 pF Capacity, up to 500 MHz Bandwidth
- Suitable for lower frequency measurements, but effect on high frequencies
- Impedance as function of frequency:

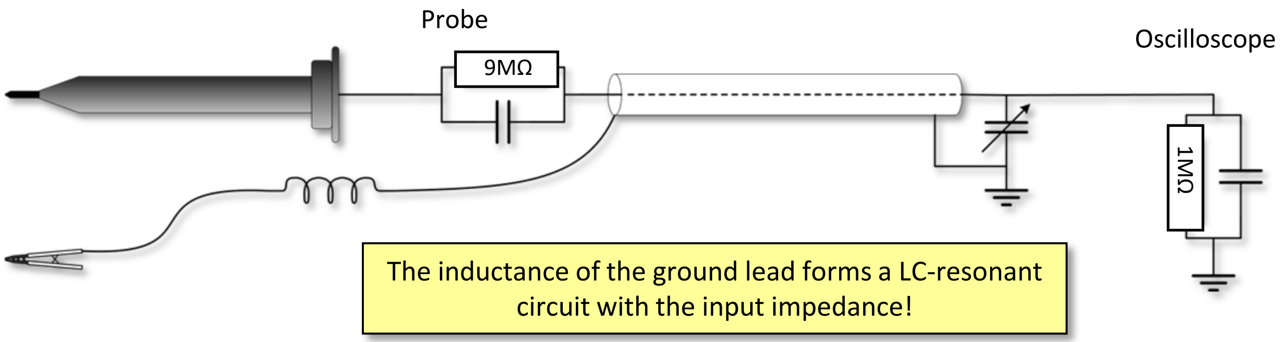
$$Z = \left(\frac{R \times \left(\frac{1}{\omega C}\right)}{R + \left(\frac{1}{\omega C}\right)} \right)$$

$$where \quad \omega = 2\pi f$$



1 kHz	6.1 MΩ
100 kHz	156.7 kΩ
1 MHz	15.9 kΩ
10 MHz	1.6 kΩ
100 MHz	159 Ω
150 MHz	106 Ω
200 MHz	80 Ω
350 MHz	45 Ω
500 MHz	32 Ω

The influence of ground lead inductance?

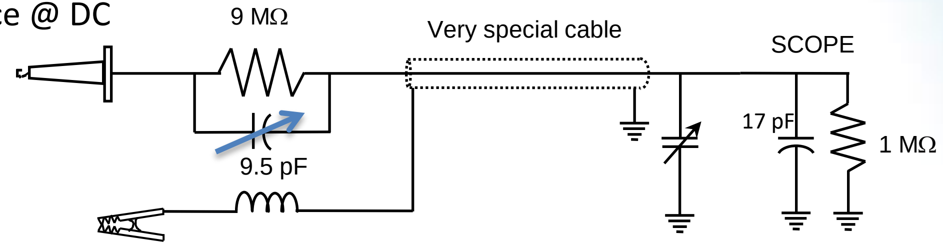


- Every wire on the probe tip or ground lead increases the inductance
- Inductance causes ringing and overshoot in the acquired signal and therefore impacts measurement accuracy
- At the resonance frequency of the circuit, the signal is distorted
- A wire can also pick up radio frequencies like an antenna!

QUCS – Quite Universal Circuit Simulator: https://sourceforge.net/projects/qucs/files/latest/download
Wire inductance calculator: http://www.consultrsr.net/resources/eis/induct5.htm

Inside the 10x Passive Probe

10 M Ohm input impedance @ DC



DC signal at scope is 1/10th DC signal at tip

3 problems with the 10x passive probe:

1. It's not a 10x probe, it's a 1/10th probe! (signal at scope is attenuated from the tip- lost 20 dB of the signal!)

2. If the parallel impedance is 1 Meg and scope as (17 pF capacitance + cable capacitance)…..

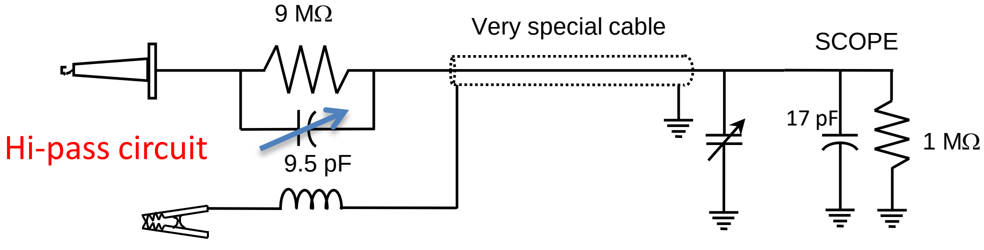
$$RC = 1\text{Meg} \times 100\text{ pF} = 100\text{ usec}$$

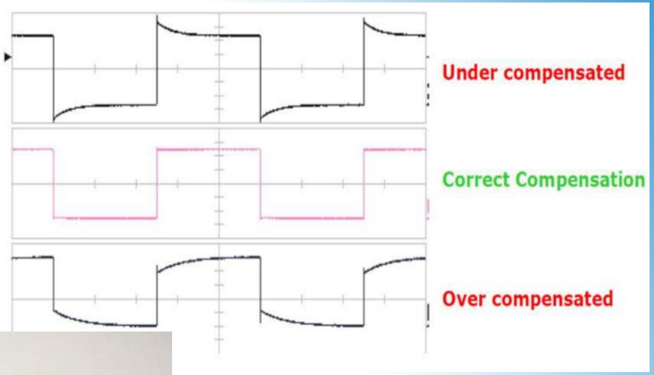
This is a bandwidth ~ 10 kHz!!! OMG! Unusable.

Enter: the equalization circuit

Equalization Circuit

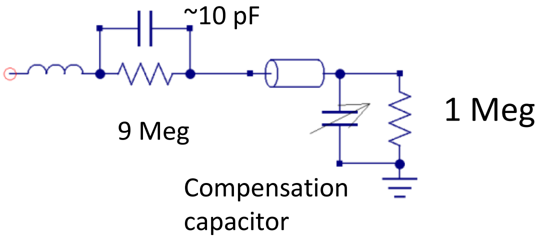
- The probe is a low-pass filter
- Add a high-pass filter in parallel and match their pole frequencies



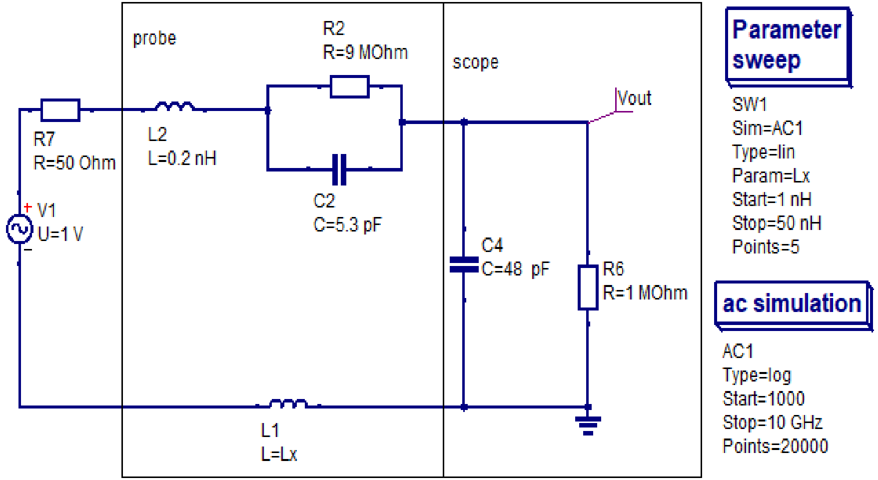


Adjustable equalization circuit

10 M Ohm input impedance @ DC



Simulating the ground lead



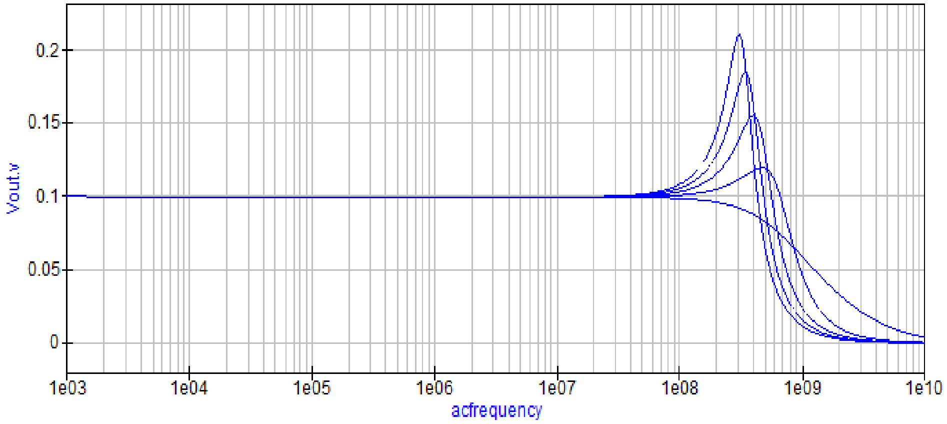
$$L_{wire}=2l\left\{ln\left[\frac{2L}{D}\left(1+\sqrt{1+\left(\frac{D}{2L}\right)^2}\right)\right]-\sqrt{1+\left(\frac{D}{2L}\right)^2}+\frac{\mu}{4}+\frac{D}{2L}\right\}$$

D = wire Diameter in mm

L = wire length in cm

μ = Permeability

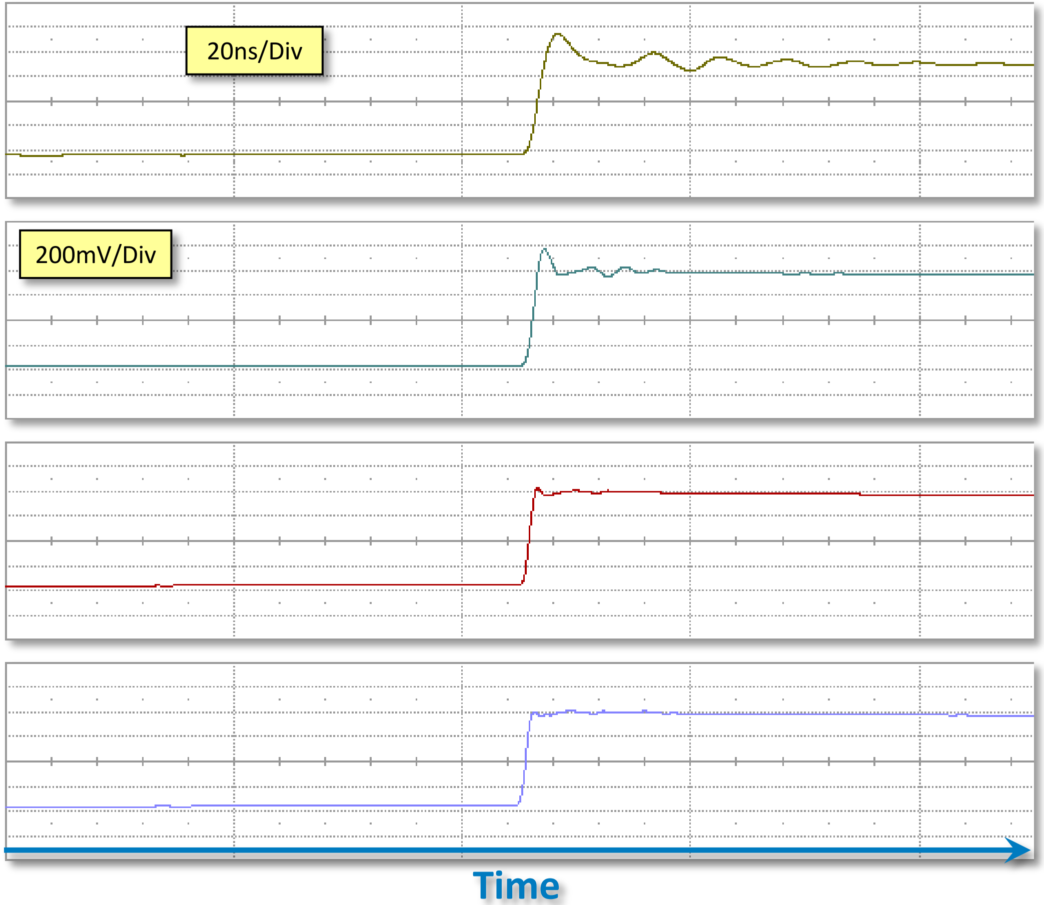
About 6 nH/cm with D =1mm



The ground lead adds a resonance right at the cut off probe frequency, which will add ringing and overshoots on a pulse edge:

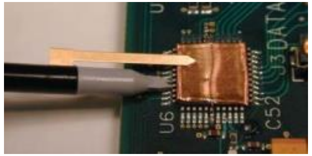
Keep the ground lead as short as possible

Influence of ground wire – time



Standard
Ground lead

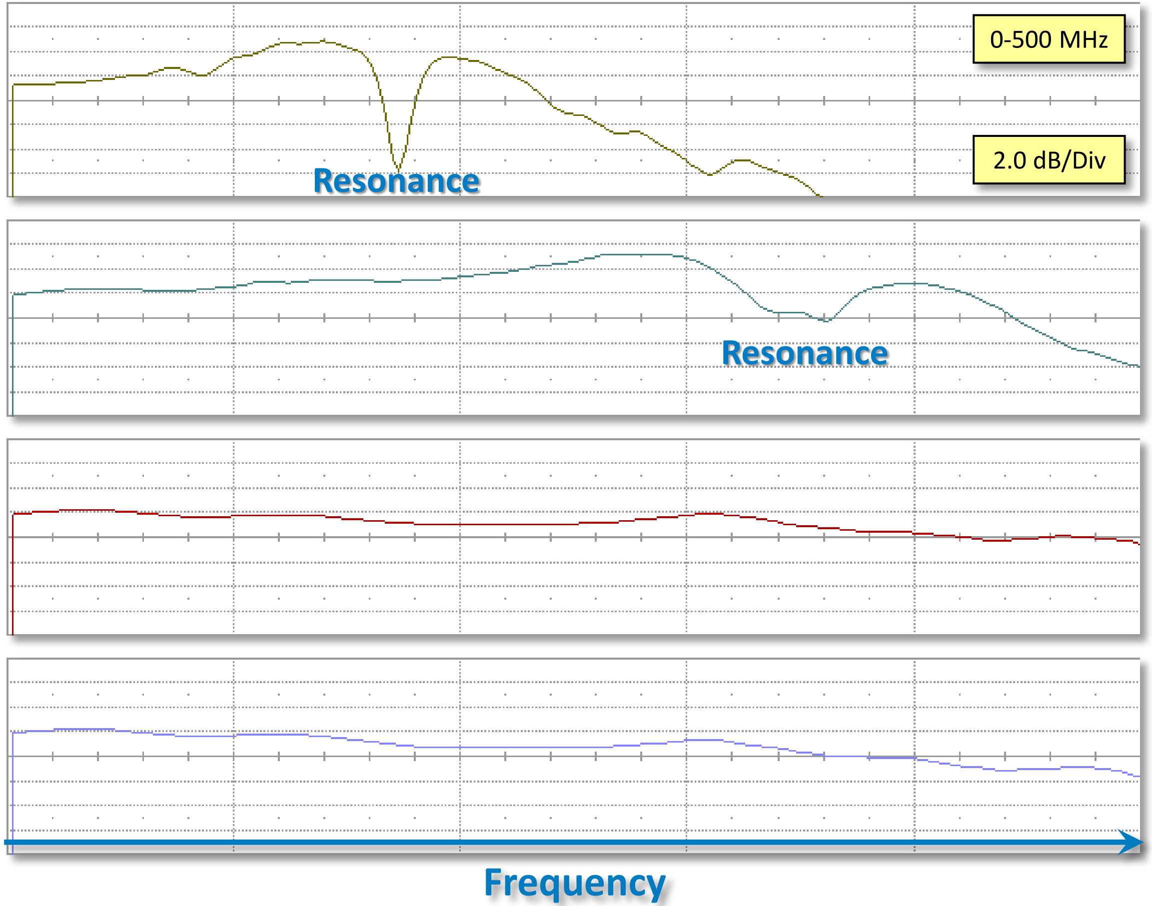
Duo lead
Adapter



'Ground
Blade'

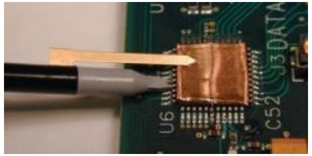
PCB
Adapter

Influence of ground wire – Frequency



Standard Ground lead

Duo lead Adapter



'Ground Blade'

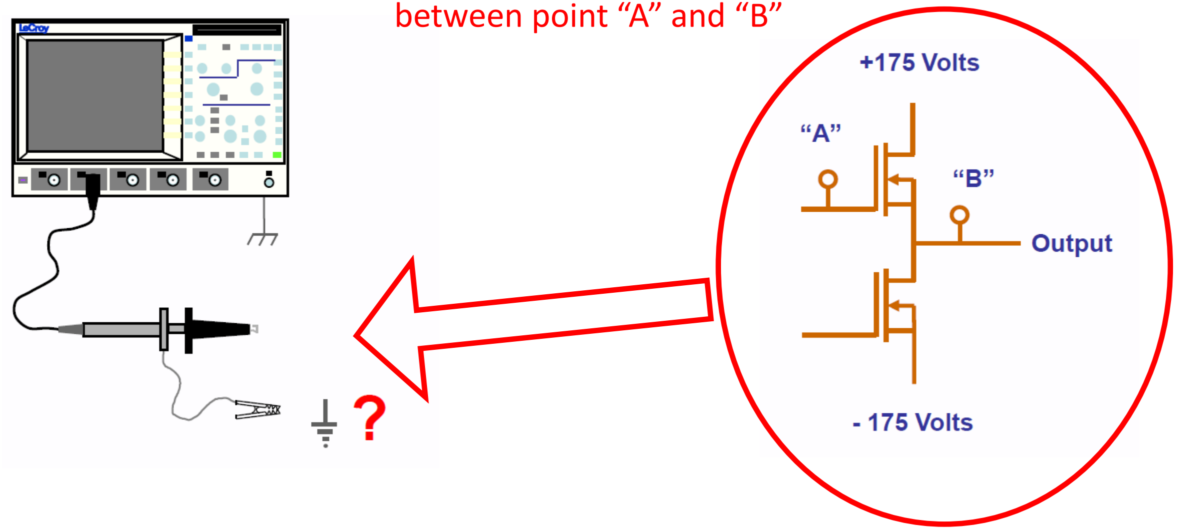
PCB Adapter

Differential Probes are often needed

• General purpose oscilloscopes can only measure “Ground Referenced” voltages however not all measurements are ground referenced

• Consider power supply measurements where the test points are referenced to each other and there is no ground

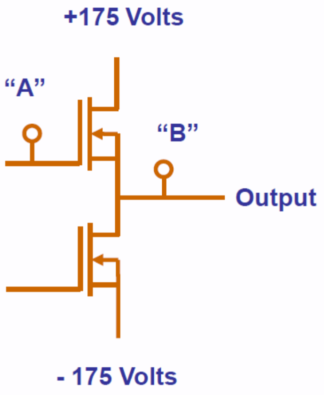
Upper V_{GS} measurement required between point “A” and “B”



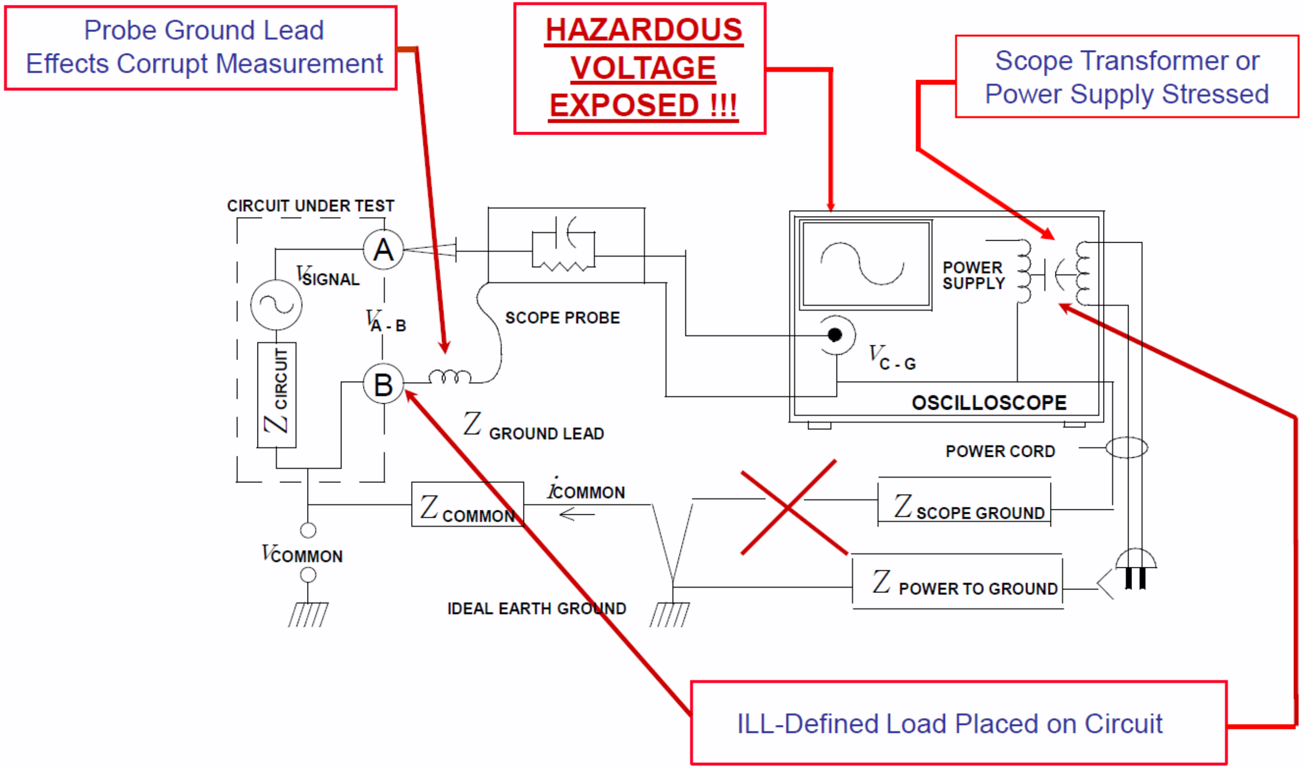
Differential Voltage Measurements

Methods for making differential measurements:

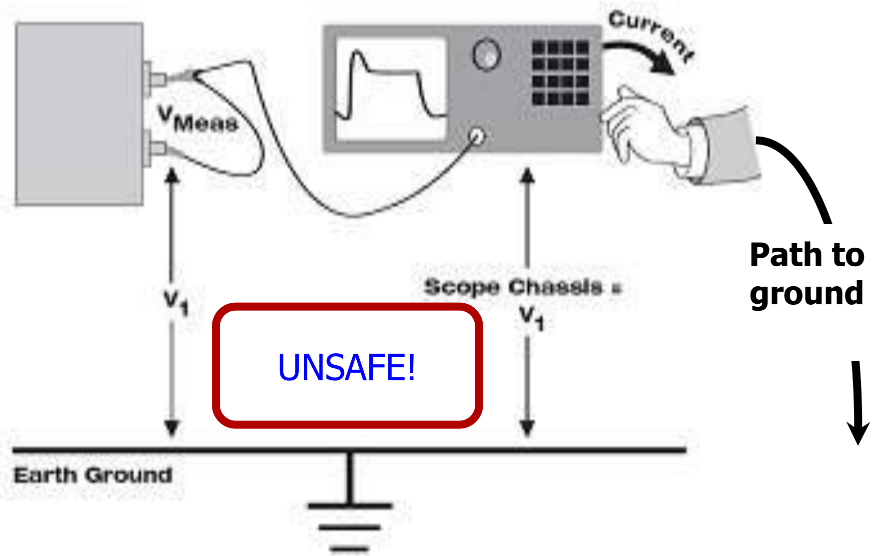
- Float the scope
- Channel “A” minus Channel “B”
- Isolators
- True differential



Floating the scope....

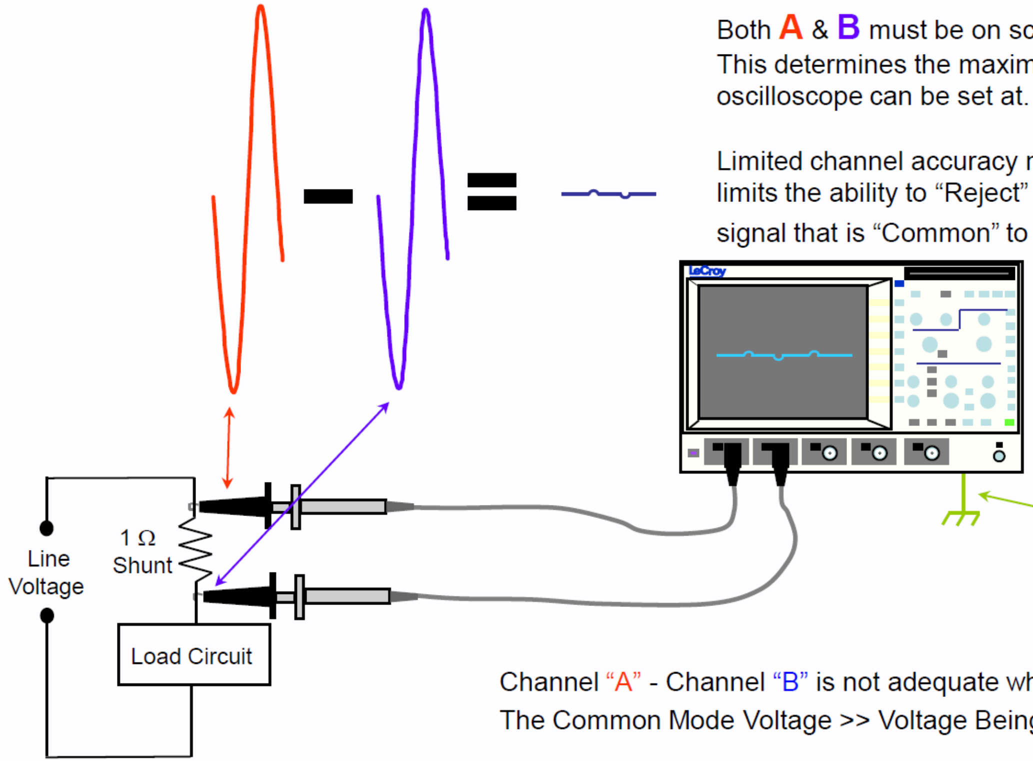


...a shocking esperience... Not Approved and Recommended



Floating the scope could be a SHOCKING experience!!!

"A" minus "B" method



Both A & B must be on screen.
This determines the maximum sensitivity the oscilloscope can be set at.

Limited channel accuracy matching severely limits the ability to "Reject" (Subtract) the signal that is "Common" to both A & B.

Scope remains safely grounded

Channel "A" - Channel "B" is not adequate when:
The Common Mode Voltage >> Voltage Being Measured

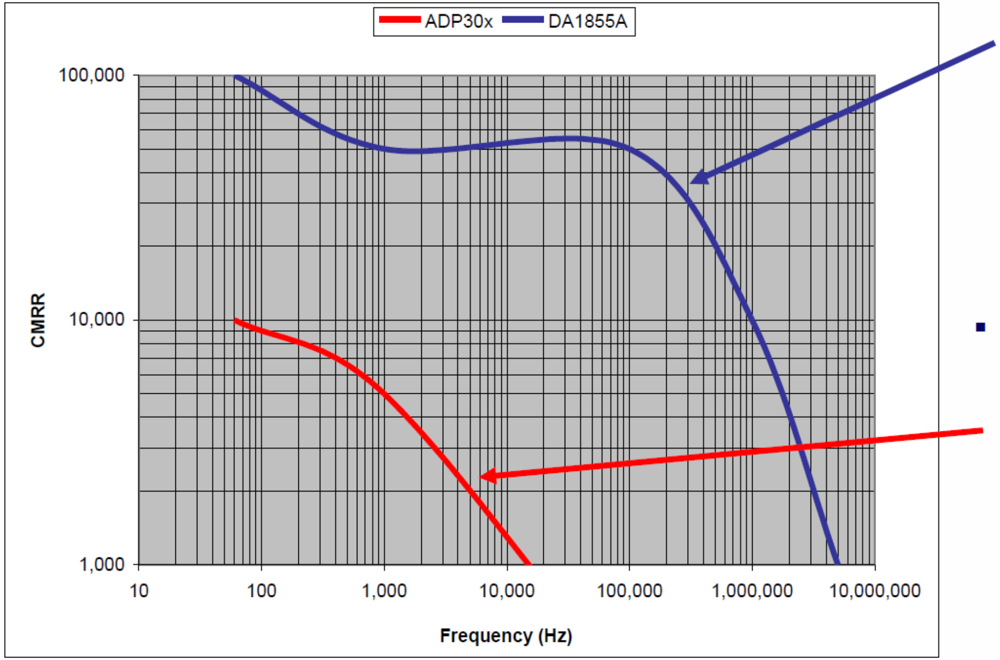
"A" – "B" limitations

- This technique will not work when the signal of interest is much smaller than the common mode
- Scope may not be able to obtain a stable trigger
  - *Must trigger on either Ch A or Ch B, not the difference*
- Poor high frequency CMRR restricts its use to rejecting common mode signals at line frequency or lower
- Channel gain must be carefully calibrated to match probe attenuation
  - *Standard probes and oscilloscope attenuators lack provision to precisely match AC attenuation*

Common Mode Rejection CMR

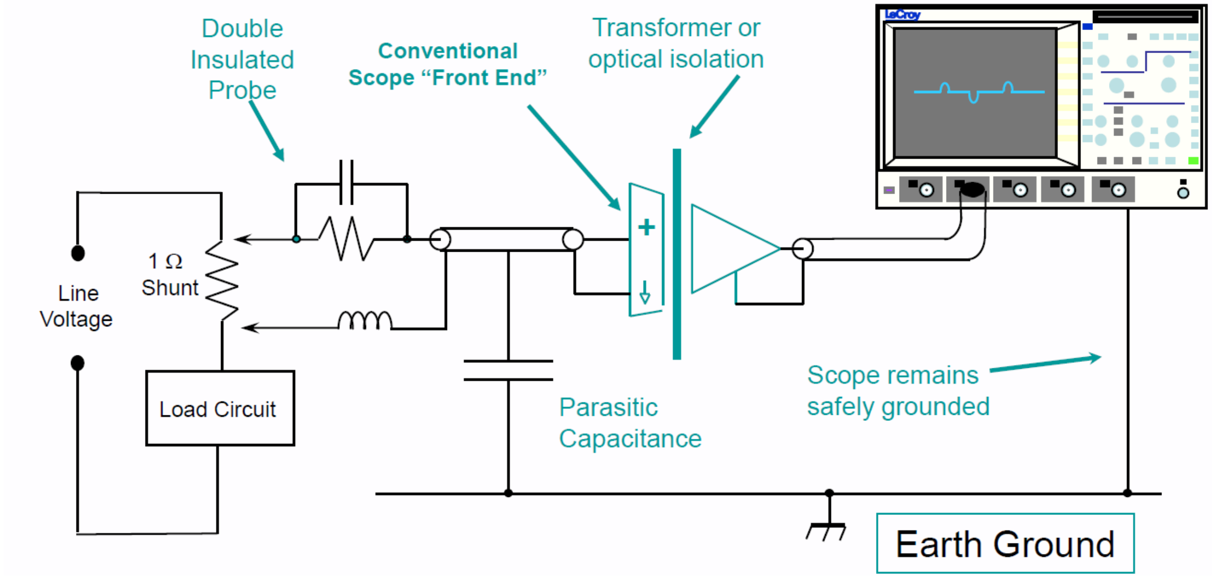
- Common Mode Rejection is the ability of the differential amplifier to eliminate the common mode voltage from the output
- Real world differential almplifiers do not remove all of the common mode signal
- The measure of how effective the differential amplifier is in removing common mode is CMRR – Common Mode Rejection Ratio
- Why do we care about CMRR
  - *Common mode feedthrough sums with the signal of interest and becomes indistinguishable from the true signal*

CMRR changes with frequency



- High Performance Differential Amplifiers start at higher CMRR, up to 100,000:1 and can be maintained across wide frequency bands
- HV Differential probes have good CMRR at DC and low frequency but it cannot be maintained through the entire probe bandwidth

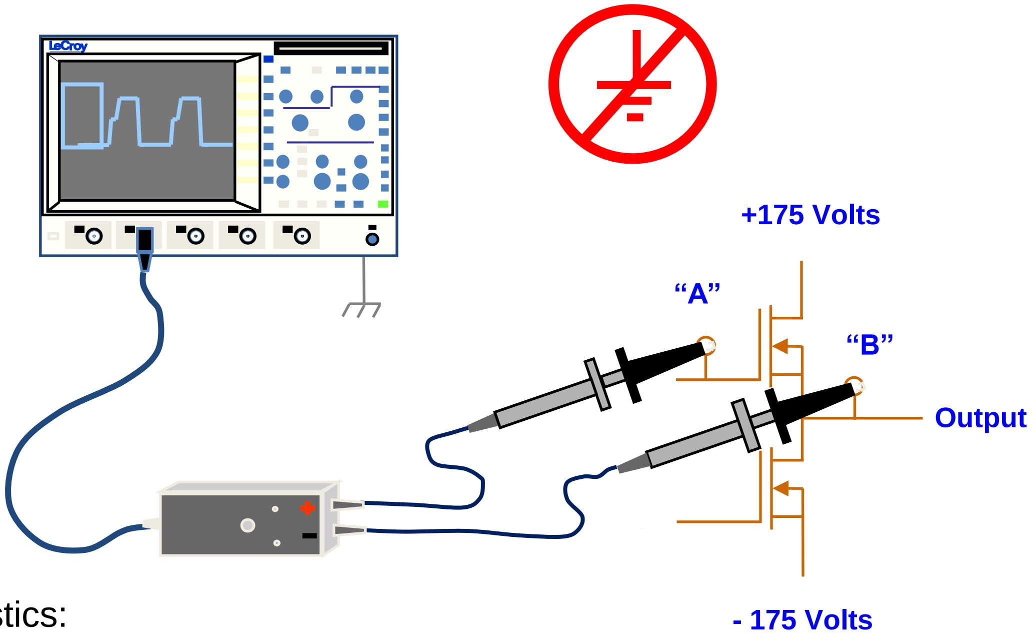
Isolators



- An isolator allows the oscilloscope to make safe floating measurements
  - *Consists of oscilloscope front end protected with insulation which drives a system based on optical or transformer isolation*

- Limitations od Isolators:
  - *Unbalanced inputs*
  - *Parasitic capacitance*
  - *Low CMRR at high frequencies*

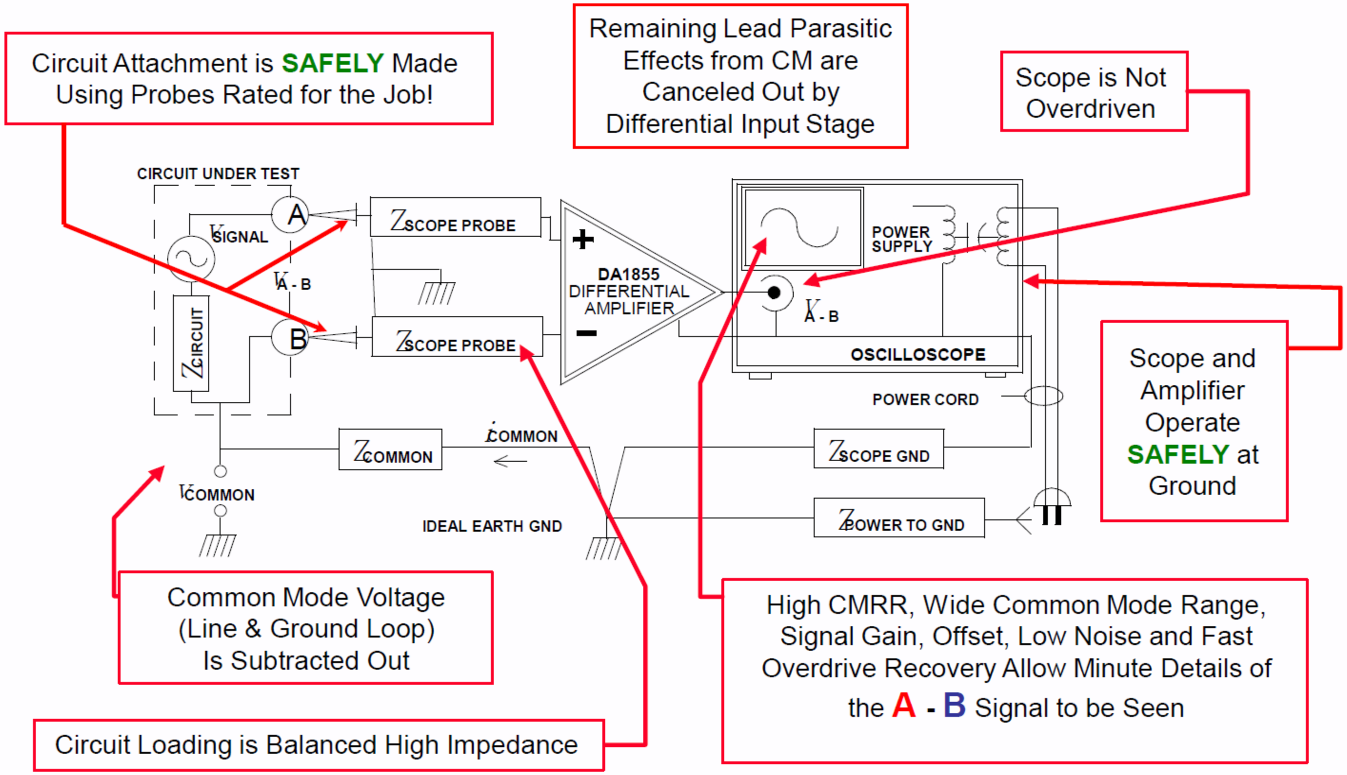
True Differential Measurements



Important Characteristics:

- *Common Mode Range*
- *Common Mode Rejection Ratio*
- *True Balanced Inputs*
  - *Load "sees" high Impedance*
  - *Lead parasitic effects cancel out !*

The differential solution



True differential amplifiers – The Best Solution

- Accurate differential measurements while oscilloscope is safely grounded
- Two high impedance matched inputs
- High CMRR over wide frequency ranges
- Two types of products
  - **High Voltage Active Differential Probes:**
    - *Good performance, low cost but CMRR, Noise and Overdrive Recovery are sacrificed*
    - *CMRR up to 10.000:1*
  - **Differential Amplifier with probe pair:**
    - *Excellent performance, highest CMRR, low noise and excellent overdrive recovery, cost is higher*
    - *CMRR up to 100.000:1*

How can we measure currents?

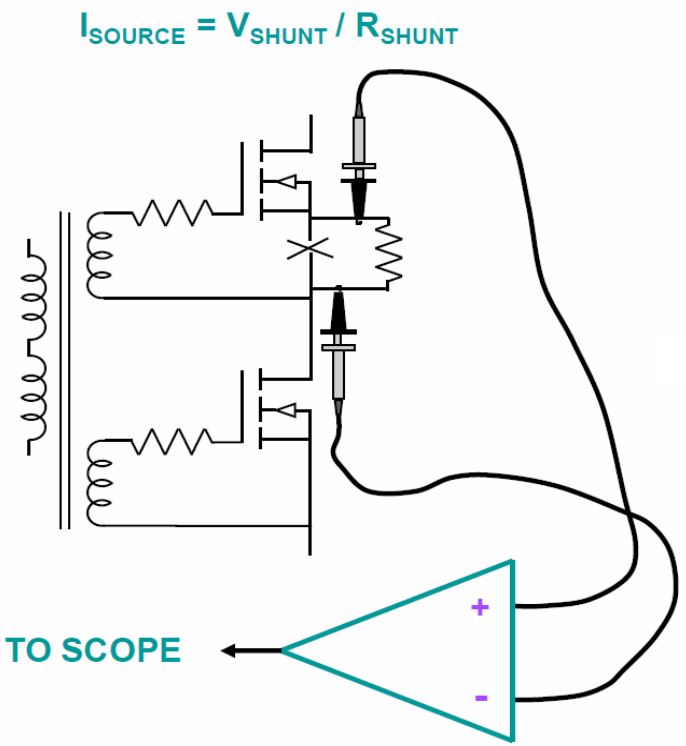
- Shunts
  - *DC to High Frequency AC*
  - *Embedded Sensors*

- Transformers
  - *AC Current Transformers (CT)*
  - *AC Currents Probe*

- Hall Devices
  - *DC to Low Frequency AC*

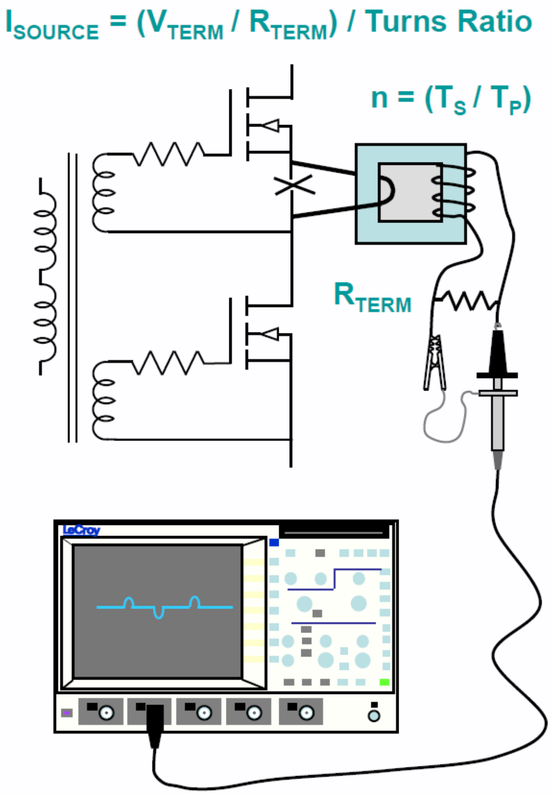
- Transformers + Hall Devices
  - *DC to High Frequency AC*

Shunts



- **Advantages:**
  - *Low inductance coaxial shunts can be very accurate*
  - *Wide Bandwidth – DC to High Frequency*
  - *Wide Dynamic range – high crest factor*
- **Disadvantages:**
  - *Requires differential voltage measurement*
  - *Inserts Impedance (resistence) into Circuit Under Test*
  - *Requires circuit to be broken*

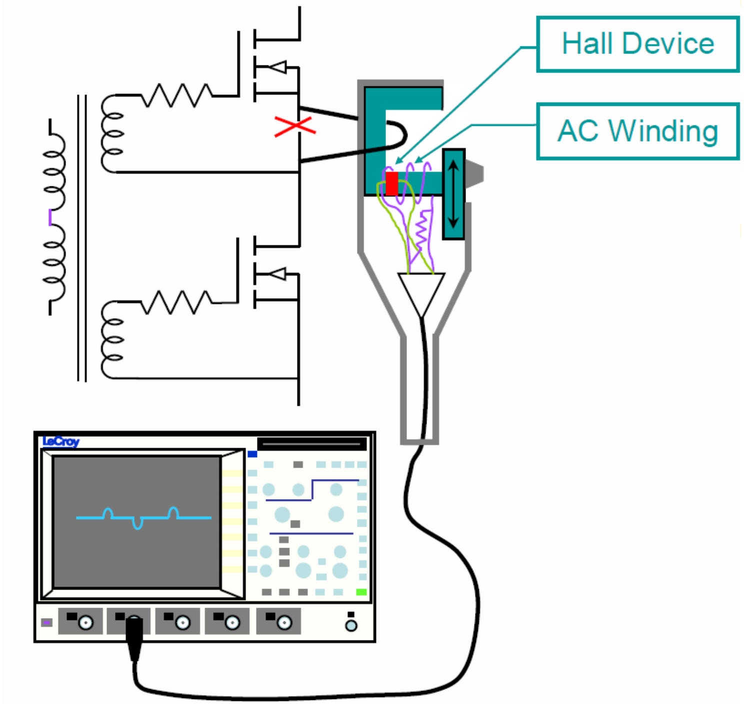
Current Transformer CT



- **Advantages:**
  - *Precision transformers can be very accurate*
  - *Low Cost*

- **Disadvantages:**
  - *Measures only AC*
  - *DC component moves (lowers) the dynamic range for measuring AC components*
  - *Requires circuit to be broken*
  - *Inserts Impedance into Circuit Under Test*

Transformer / Hall Device Current Probes



- **Advantages:**
  - *Measures both AC & DC*
  - *Easy to attach to circuit*
  - *Moderate cost*

- **Disadvantages:**
  - *May require access wire to be added to circuit*
  - *Inserts Impedance into Circuit Under test*

Oscilloscope current probes

- Most oscilloscope current probes use the combination of transformer and Hall technologies.
- These types of probes provide a more general purpose solution because of the ability to measure from DC to high frequency AC
- These types of probes also can be designed with a split core so they can be clamped on to the circuit not requiring a break in the wire

Typical specs: CP030

The AP015 current probe can measure continuous current of 30 A_{rms} and peak pulses of up to 50 A for durations up to 10 seconds. This probe also features an overheating protection circuit, which will display an on-screen warning to the user to prevent damage. A probe unlock detection feature is also built in to the AP015 to ensure accurate measurements.

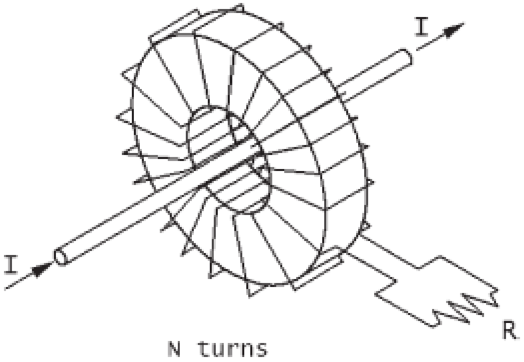
Electrical Characteristics

Max. Continuous Input Current	30 A
Bandwidth	50 MHz
Max. Peak Current at Pulse Width	50 A < 10 s
Rise time (typical)	< 7 ns
Minimum Sensitivity	10 mA/div
Low Frequency Accuracy	1%
Coupling	AC, DC, GND

General Characteristics

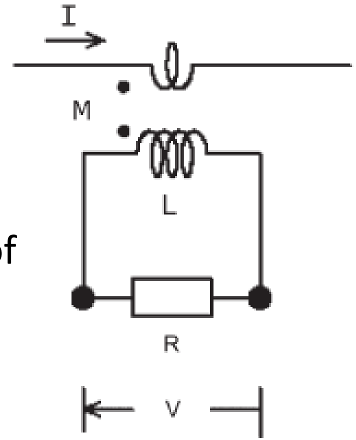
Cable Length	2 m
Weight	300 g
Max. Conductor Size (diameter)	5 mm
Interface	ProBus, 1 MΩ only†
Usage Environment	Indoors
Operating Temperature	0 °C to 40 °C
Max. Relative Humidity	80% (Max. 31 °C)
Max. Altitude	2000 m
Maximum Insulated Wire Voltage	300 V CAT I, 150 V CAT II

Do Current probes have an influence on the signal?



The picture on the left is the real circuit[1] of an AC current probe. I is the current we want to measure and the current transformer is representing the transformer present in any current probe

And the picture on the right represents the equivalent circuit [1].
M is the mutual inductance, L is the inductance of the CP transformer R is the load seen by the transformer



Assuming $I(t)$ has a f = $\omega/2\pi$
M, L and R have 2 effects on the current flowing in the conductor:

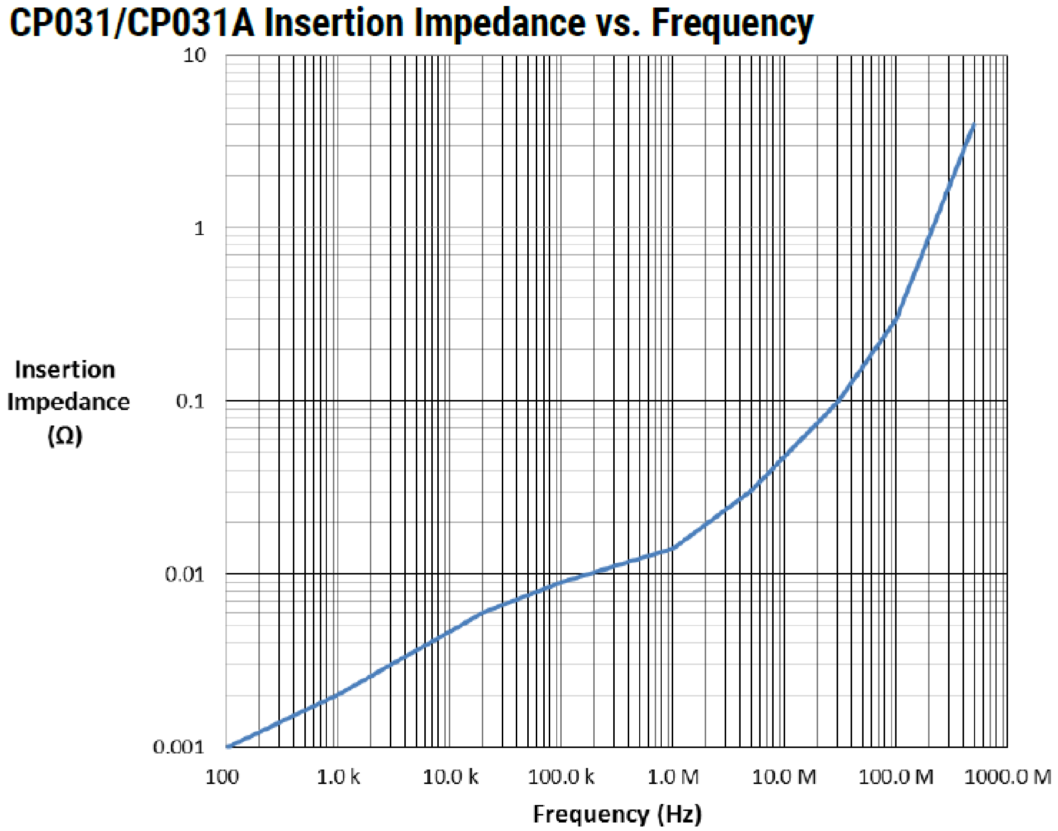
$$Zrefl = \frac{\omega M^2}{R} \Big/ R + j\omega L$$

$$Zintr = j\omega\frac{L}{N^2} - j\omega\frac{L_0}{N^2}$$

The current probe is adding a small and not negligible resistance

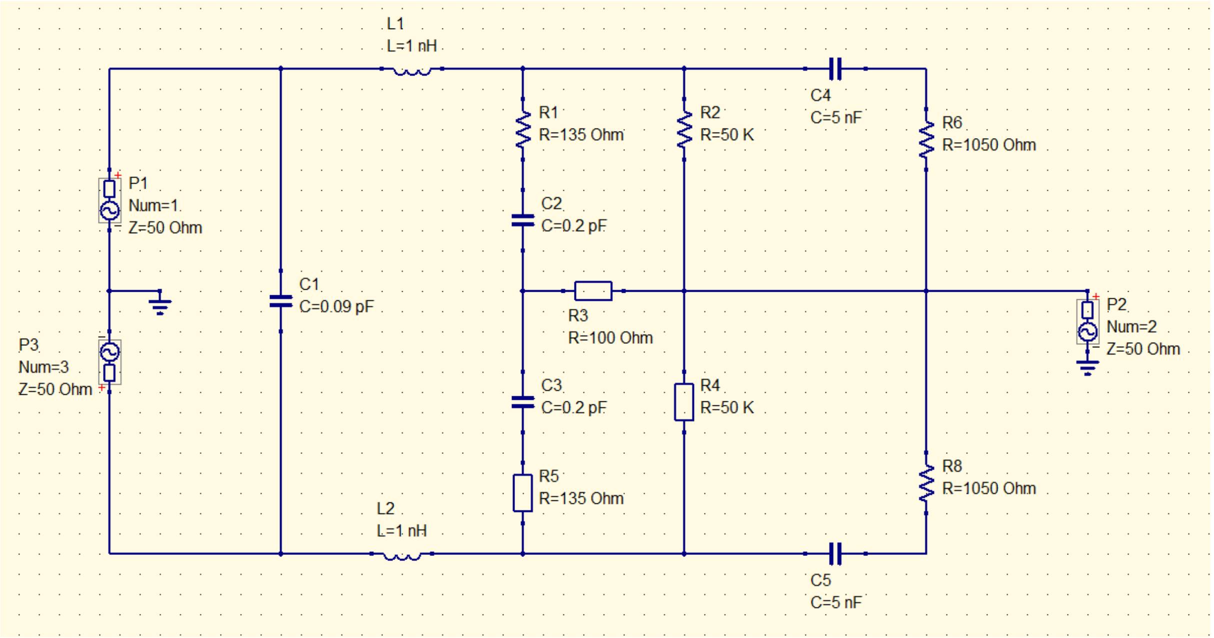
[1] C. F. M. Carobbi and L. M. Millanta, “The loading effect of the radiofrequency current probes,” in *Proc. 23rd Instrum. Meas. Technol. Conf.*, Sorrento, Italy, Apr. 24–27, 2006, pp. 2050–2053.

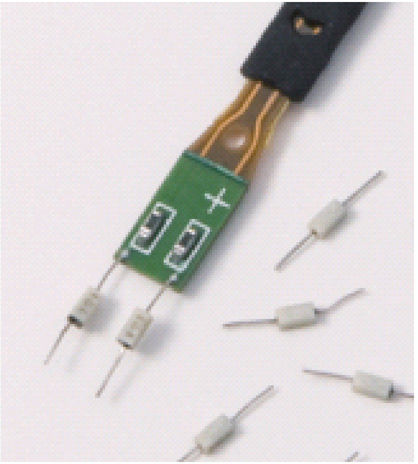
Current Probe Insertion impedance



Most of the times the CP insertion impedance is negligible, but when measuring for example the RDSon of a power mos which can be in the range of few mΩ, we should consider the effect of the probe.

Differential probe can go up to 25GHZ





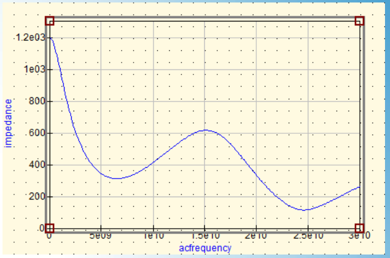
At these frequencies the Probe tip influence is not negligible!

The most reliable is the solder-in

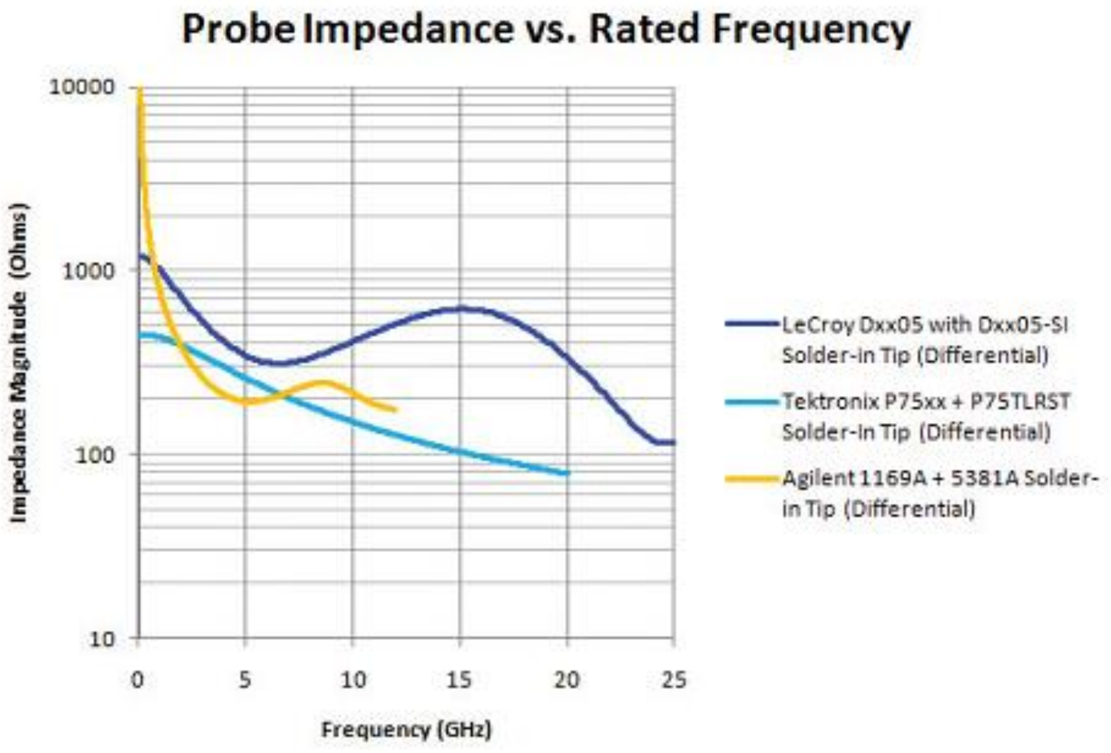
Loading Impedance can be a real problem oh HF circuits

- DC vs. AC Impedance
  - Impedance varies as a function of frequency
    - Near DC, resistance dominates
    - At high frequencies, reactance dominates
  - Frequency dependent measurement error*
    - Error correction methods described later
  - **Look carefully at impedance specs.**
    - Not all manufacturers spec AC and DC impedance separately
      - Some only specify DC impedance (resistance)
    - LeCroy publishes probe loading in the manuals and datasheets

  - **A high DC resistance does not imply a high AC impedance**



Always ask for Impedance derating cureve



LeCroy Probe impedance highest throughout most of the frequency range

Note: starting with high impedance at low frequency does not help to improve impedance at high frequency

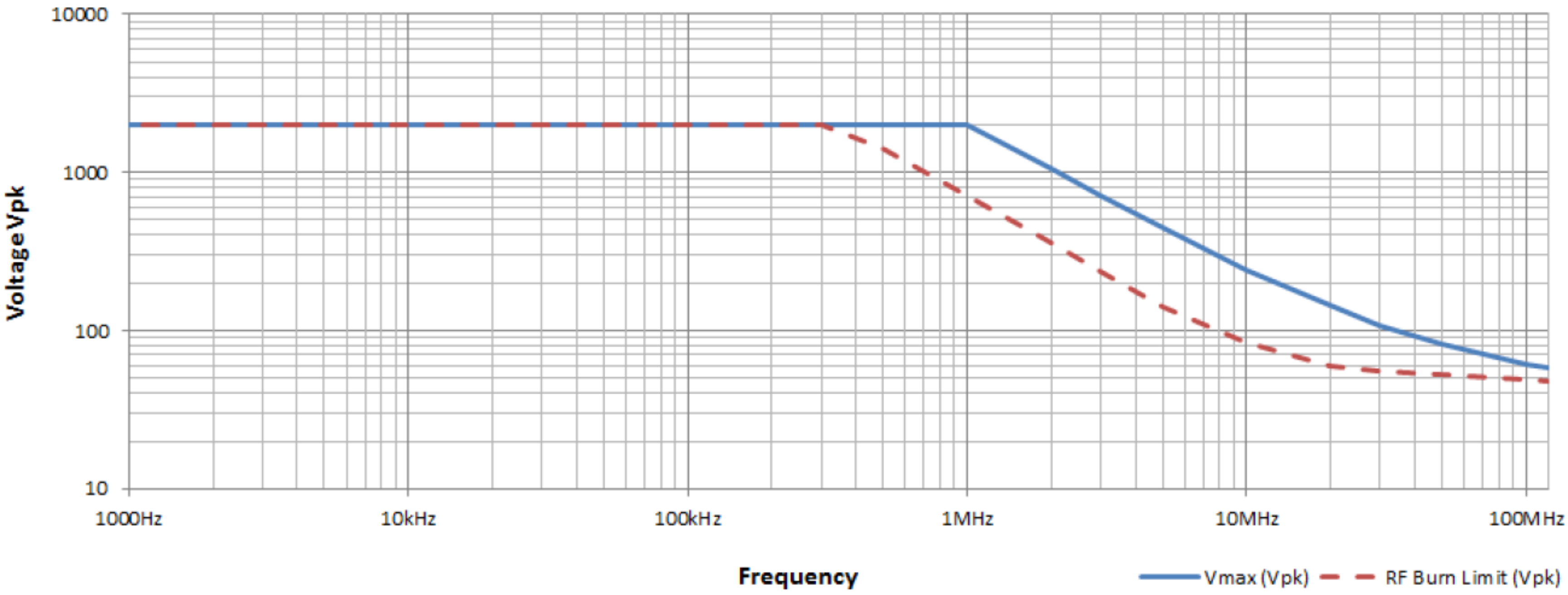
High Voltage Probes

Voltage isolation of High Voltage differential or Passive SE probes is always at DC level. In the same way the impedance decreases with the frequency, the isolation, i.e. the maximum operating voltage, decrease in a similar way.

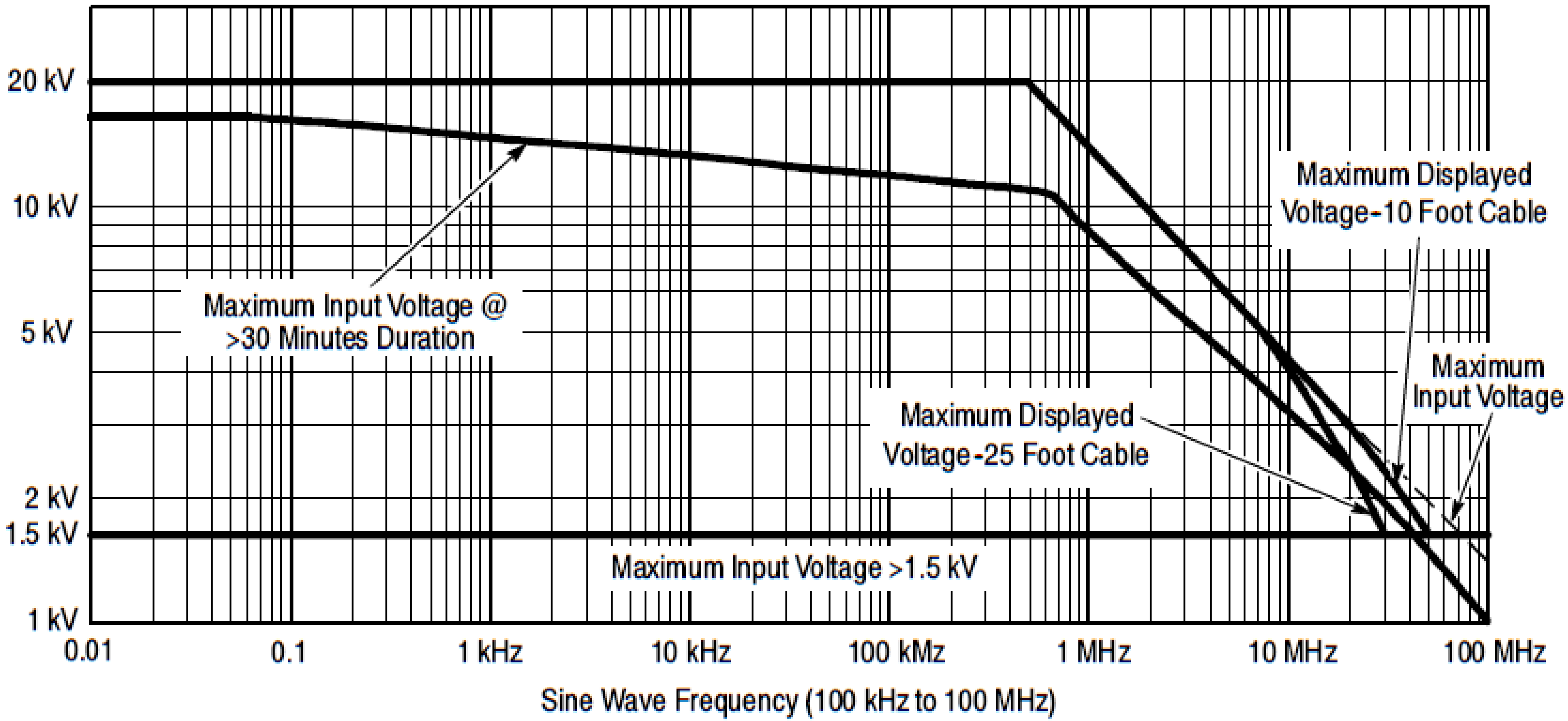
Always ask for the derating isolation curve to make sure you High Voltage probe is safe to be used.

Normal practice :To avoid risk of electric shock, comply with the limit when measuring high-frequency signals with hand-held accessories. Do not exceed the voltage or category rating of the probe or accessories (whichever is less). Keep your fingers behind the finger guard of the probe. Keep the probe body and output cable away from the circuits being measured. Use only the specified accessories

HVD3206 Isolation derating curve: 2KV differential probe



Derating curve of a 20KV passive probe



The Classical 10x Passive Probe (PP023)

Three important tip options: mini-grabber clip, short return clip, coaxial BNC

Measurements

TELEDYNE LECROY
Everywhereyoulook™

Measurements

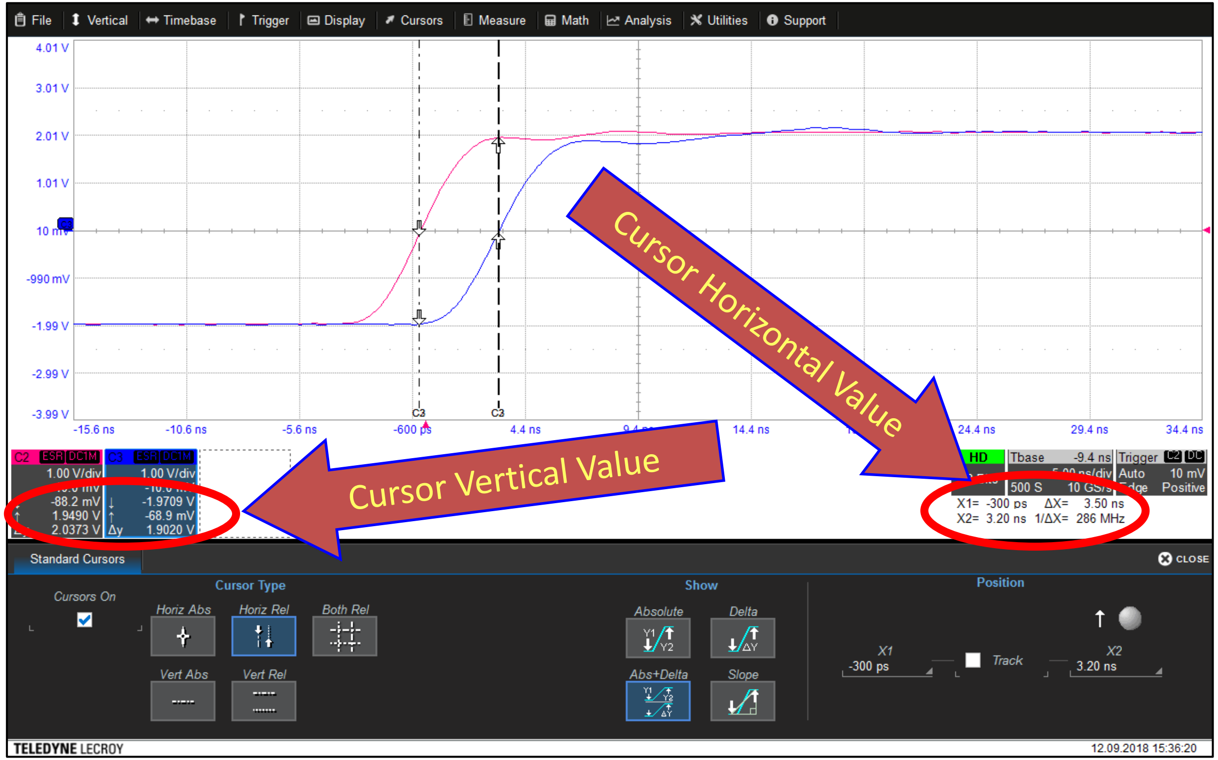
- Two Measurement Methods:
  - 1. Manual cursor readouts
  - 2. Automated parameter measurement

- **1. Cursor Readouts**
  - Fast check of all visible points
  - Screen resolution only
- **2. Parameter Measurements**
  - Setting of the parameter and/or measurement window
  - Full internal resolution
  - Statistics

Measure	P1:ampl(C1)	P2:freq(C1)
value	233.59 mV	3.02531 MHz
mean	233.5006 mV	3.0000267 MHz
min	232.77 mV	2.96531 MHz
max	234.07 mV	3.02832 MHz
sdev	488.9 µV	10.6805 kHz
num	13	767
status	✔	✔
histo		

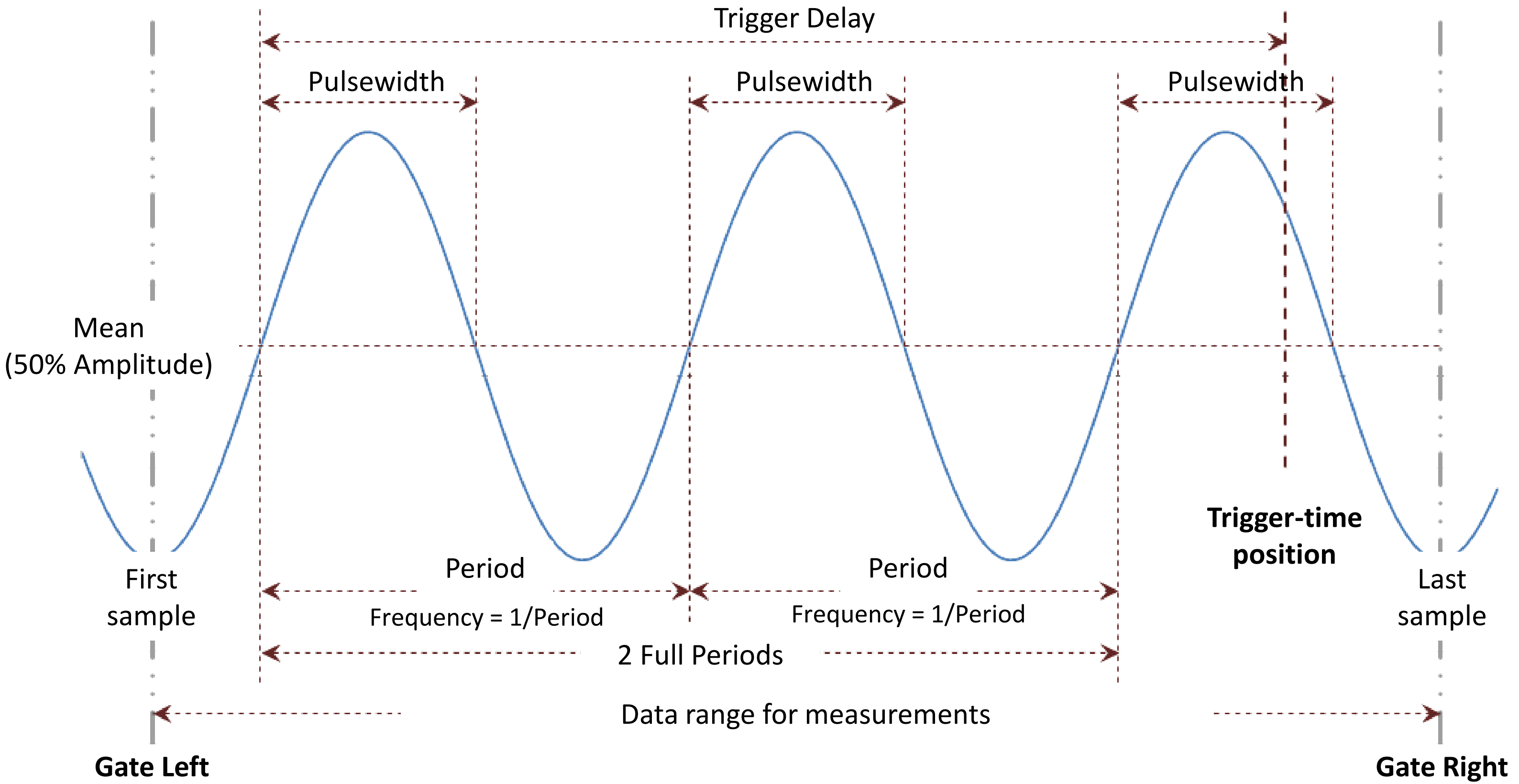
Cursor Measurements - Fundamentals

- In the cursor setup several cursor styles can be selected: absolute or relative, vertical or horizontal
- Vertical cursor values are shown in the channel boxes, horizontal values are shown under de timebase box.
- Cursor positions can be adjusted using front panel controls, using the touch screen or with a connected USB mouse

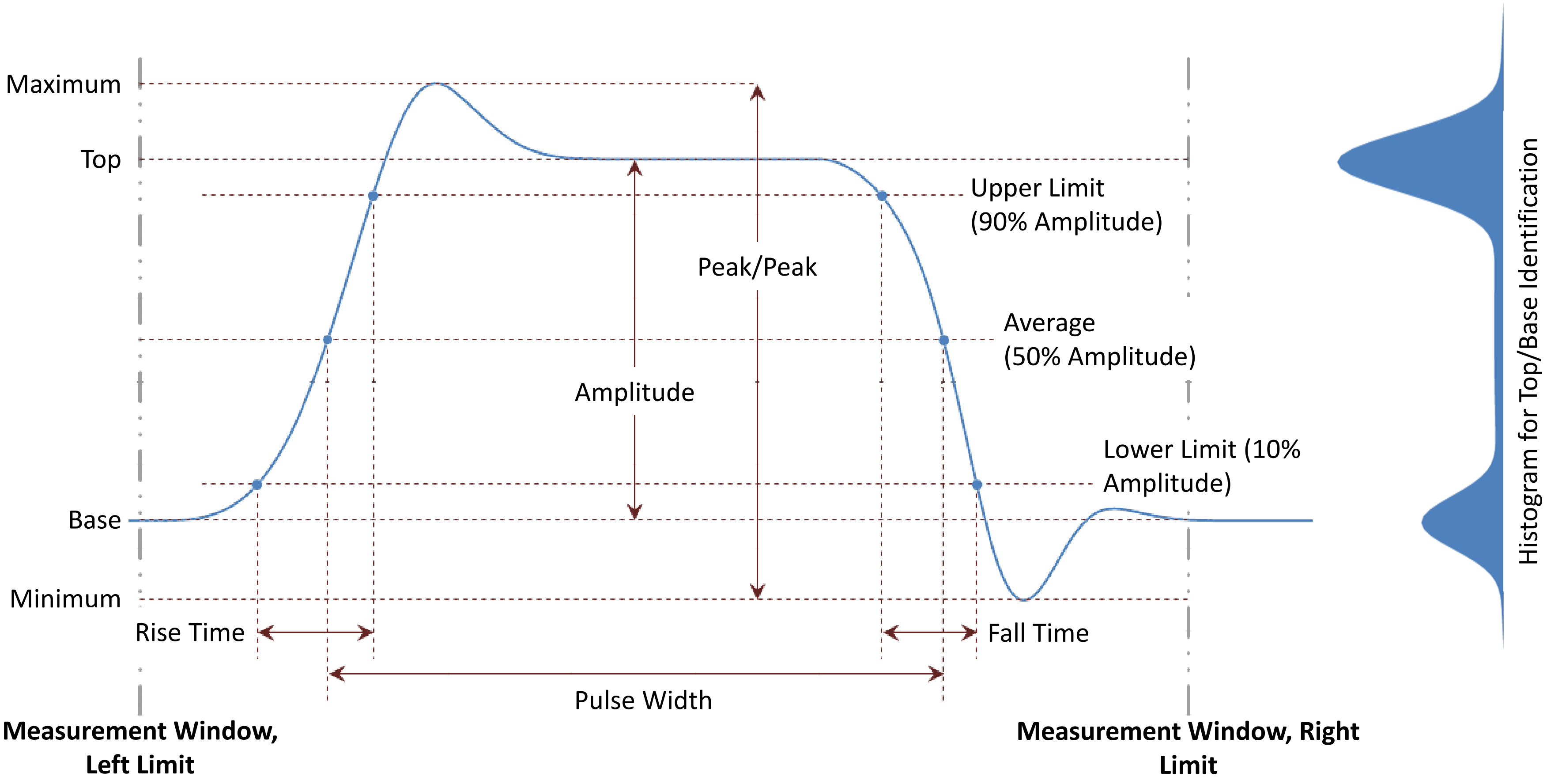


Cursors can display absolute, delta, both, but also Δy/Δx

Parameter Measurements – Definition Horizontal Parameters



Measurements – Definition of Vertical Parameters



Parameter Statistics and Histicons

For each time parameter, **one value per period** is measured

Value: The last measurement in the acquisition, on the right side of the screen

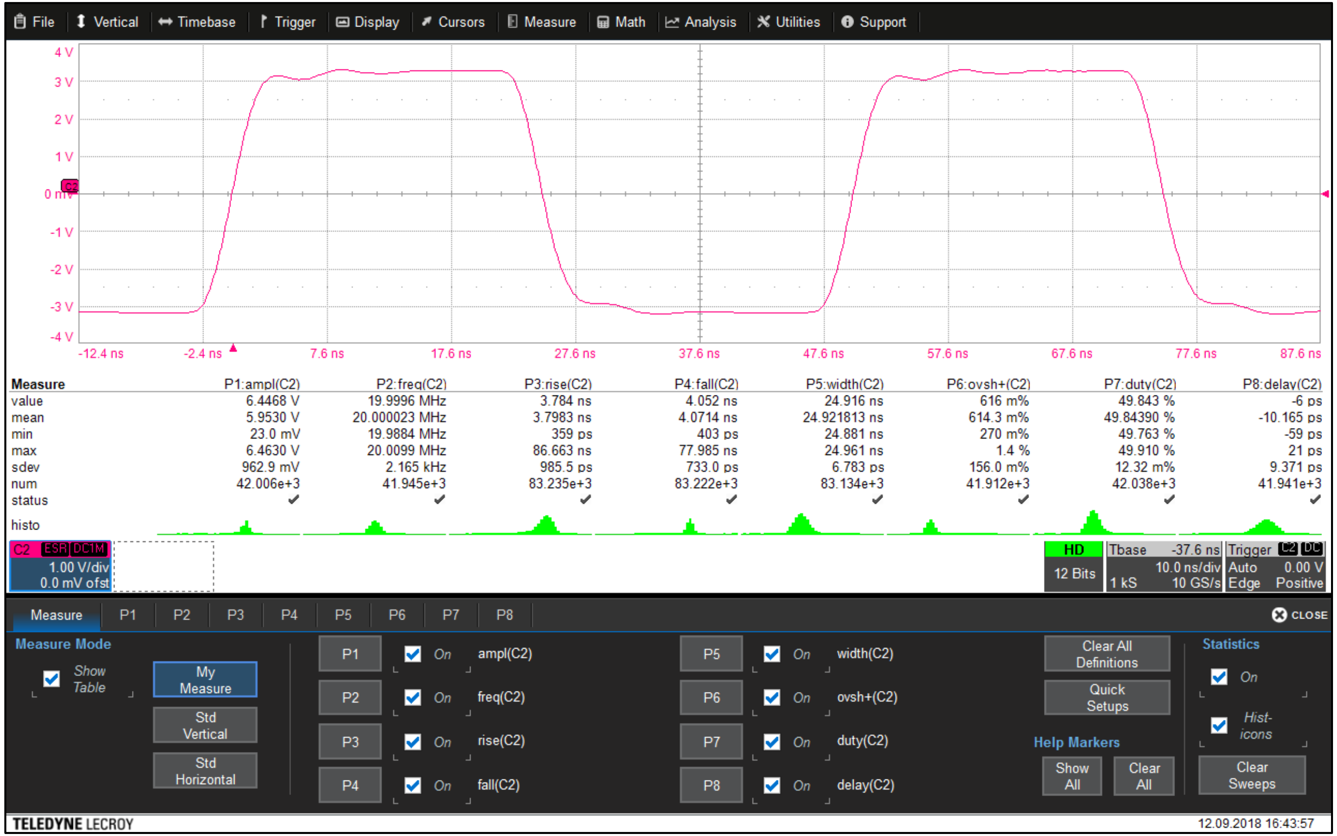
Mean: mean value from all measurements

Min: Minimum value from all measurements

Max: Maximum value from all measurements

Sdev: Standard deviaton from all measurements

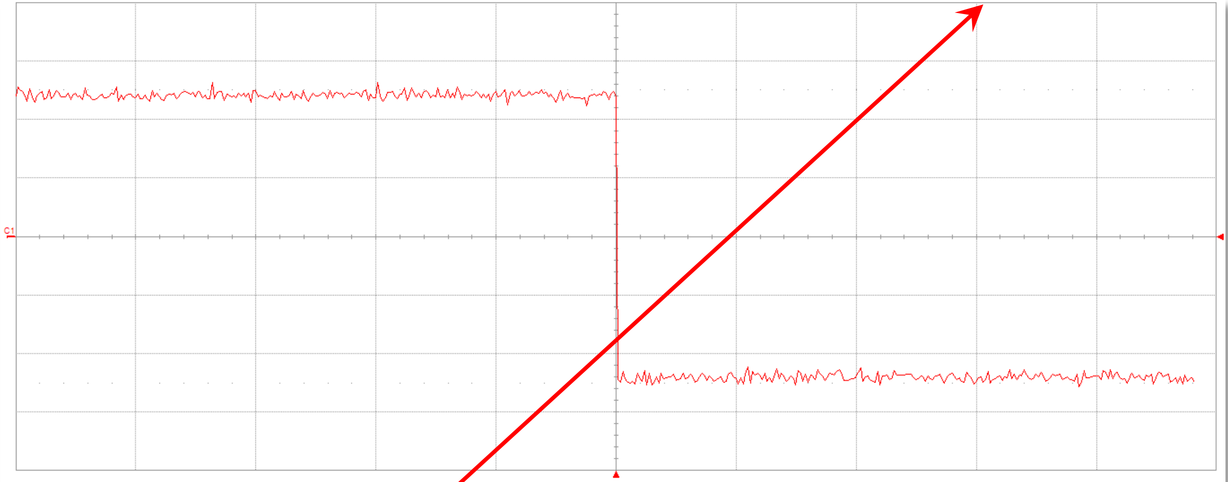
Num: number of measurements used for the statistics as described above



Measurements – Parameter Qualification

- Qualification of parameters to indicate whether the respective measurement is correct

P1:rise(C1)	P2:fall(C1)	P3:ampl(C1)
---	< 317 ps	240.75 mV
0	1	1



Measure	P1:rise(C1)	P2:fall(C1)	P3:ampl(C1)
value	30.737 ns	< 317 ps	240.75 mV
mean	30.73691 ns	< 317.42 ps	240.7480 mV
min	30.737 ns	< 317 ps	240.75 mV
max	30.737 ns	< 317 ps	240.75 mV
sdev	---	---	---
num	1	1	1
status			

- 'Rise Time': no value due to lack of rising edges
- 'Fall Time': possible, but not enough samples available on the edge
- 'Amplitude': correct measurement

Histogram, Track en Trend

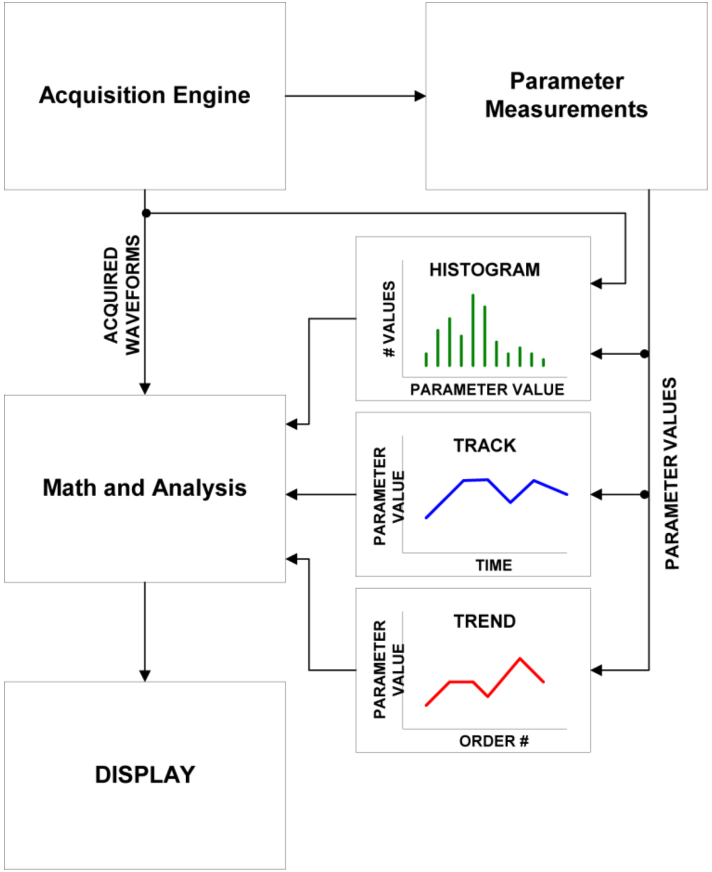
One of the strongest functionalities of Teledyne LeCroy oscilloscope is the ability to (re-)use measurement results as input for further analysis in the form of a histogram, track or trend. These analysis fuctions can be the source for other measurements.

Example:

P1 = Freq(C1)

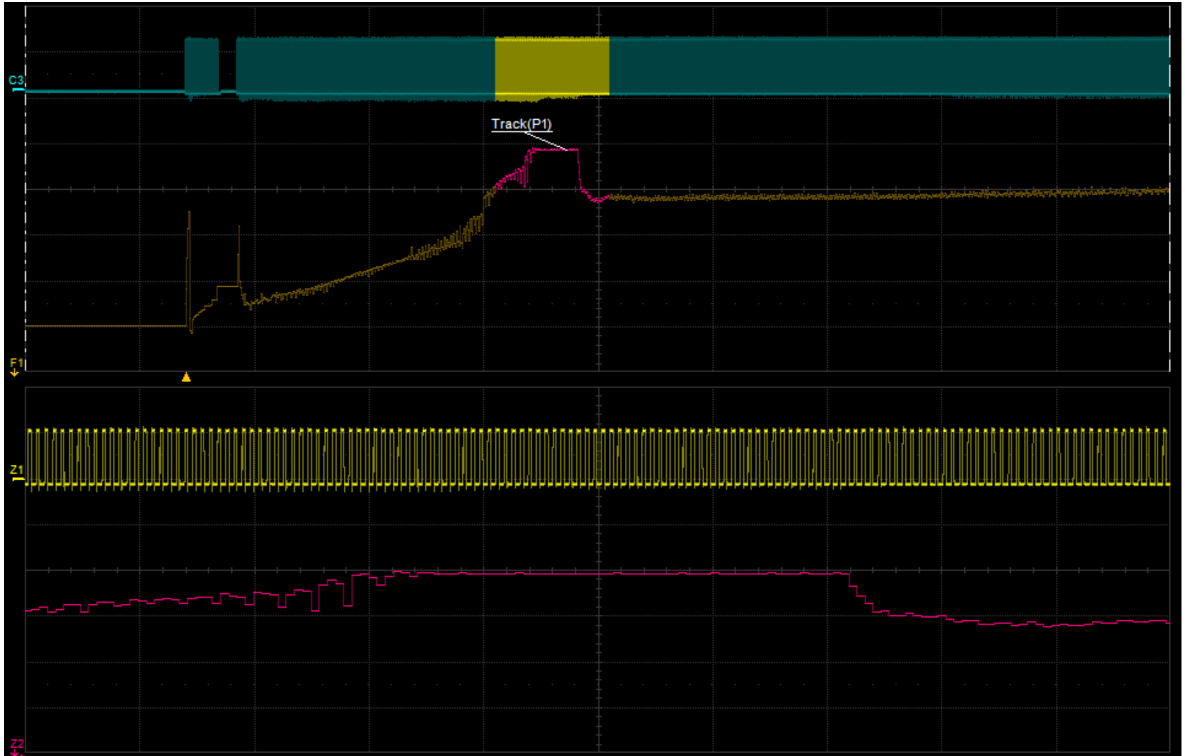
F1 = Histogram (P1)

P2 = Median (F1)



Track Function

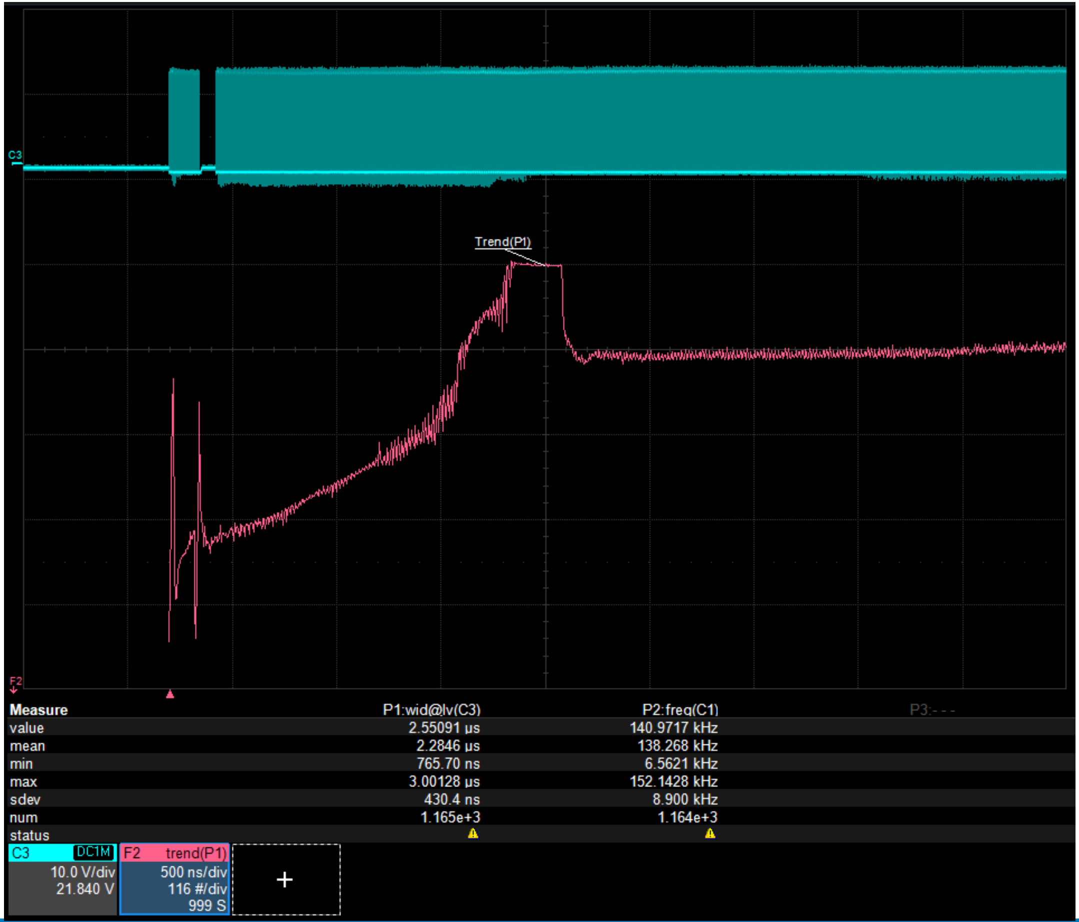
- Synchronous with the source waveform
- Has the same number of samples of the source waveform
  - Can be zoomed and linked (multi-zoom) with source waveform



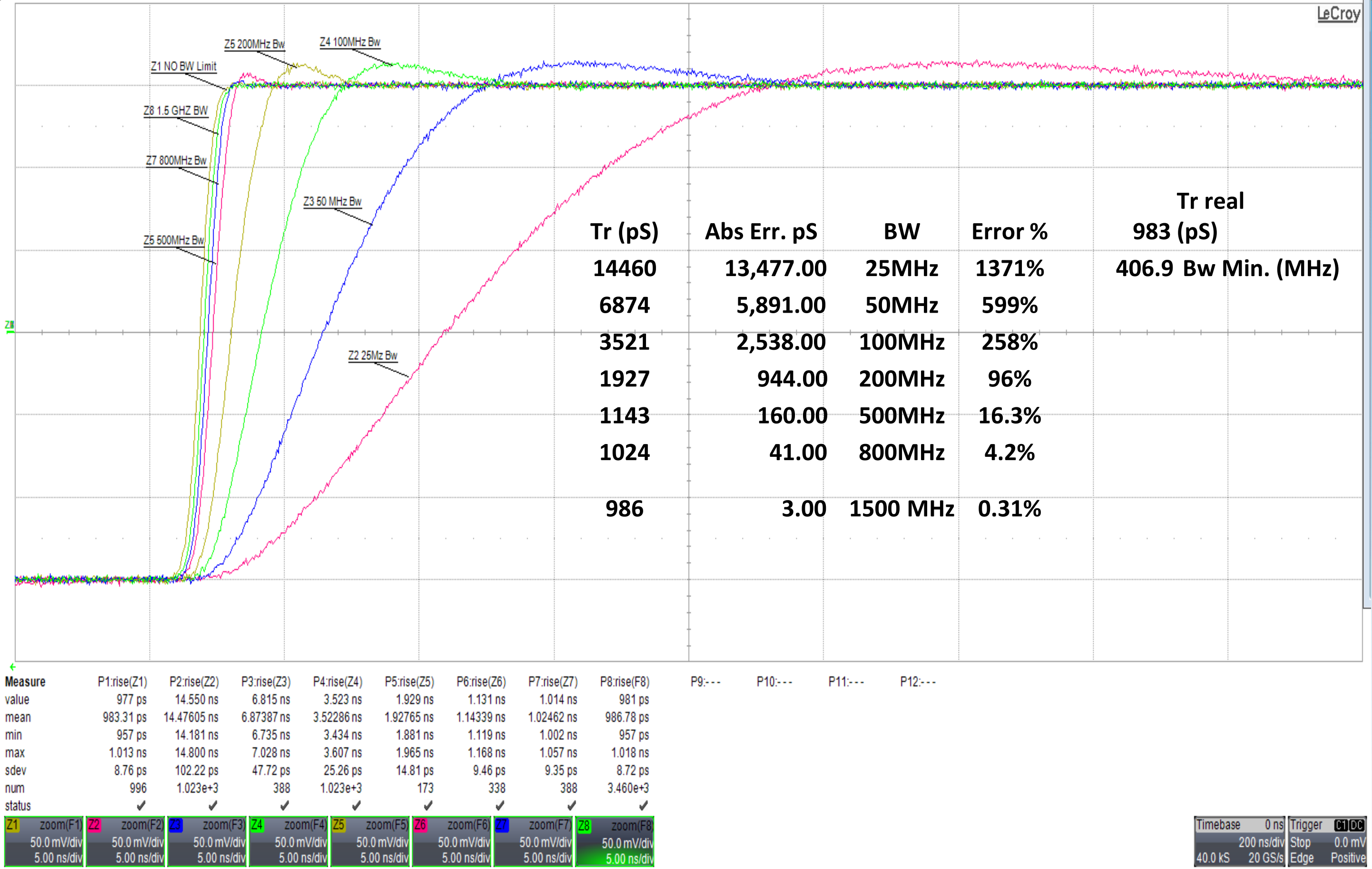
Measure	P1:wid@lv(C3)	P2:npoints(C3)	P3:npoints(F1)
value	2.33639 µs	2.500000e+6	2.500000e+6
mean	2.0826 µs	2.500000e+6	2.500000e+6
min	769.27 ns	2.500000e+6	2.500000e+6
max	2.79579 µs	2.500000e+6	2.500000e+6
sdev	434.1 ns	---	---
num	1.156e+3	1	1
status	⚠	✔	⚠

Trend Function

- One single sample for each measurement, even with multiple acquisitions
  - where there are no measurements then no values
  - not track of possible gaps
  - If there are no gaps, setting the values to trend to the number of measurements will create a visible link to the source waveform
- No link to source waveform behavior
- Horizontal scale is a number, time reference is lost
- Can be used ac chart recorder for accumulating measurement over long period of time



Effect of scope 's BW on Rise Time Measurements



Tr (pS)	Abs Err. pS	BW	Error %
14460	13,477.00	25MHz	1371%
6874	5,891.00	50MHz	599%
3521	2,538.00	100MHz	258%
1927	944.00	200MHz	96%
1143	160.00	500MHz	16.3%
1024	41.00	800MHz	4.2%
986	3.00	1500 MHz	0.31%

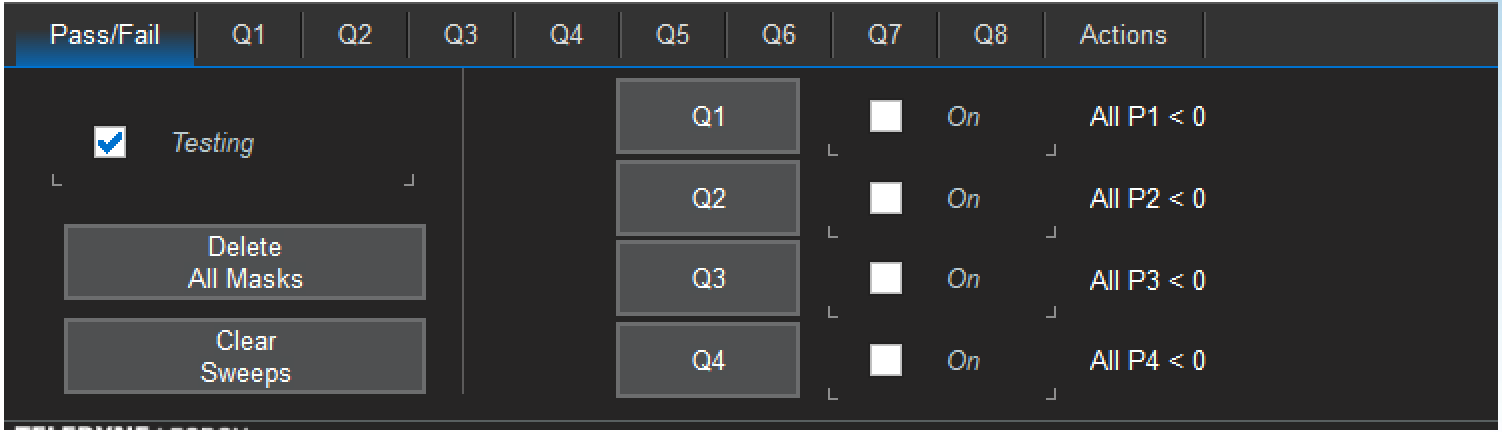
Tr real
983 (pS)
406.9 Bw Min. (MHz)

Measure	P1:rise(Z1)	P2:rise(Z2)	P3:rise(Z3)	P4:rise(Z4)	P5:rise(Z5)	P6:rise(Z6)	P7:rise(Z7)	P8:rise(F8)	P9:- - -	P10:- - -	P11:- - -	P12:- - -
value	977 ps	14.550 ns	6.815 ns	3.523 ns	1.929 ns	1.131 ns	1.014 ns	981 ps				
mean	983.31 ps	14.47605 ns	6.87387 ns	3.52286 ns	1.92765 ns	1.14339 ns	1.02462 ns	986.78 ps				
min	957 ps	14.181 ns	6.735 ns	3.434 ns	1.881 ns	1.119 ns	1.002 ns	957 ps				
max	1.013 ns	14.800 ns	7.028 ns	3.607 ns	1.965 ns	1.168 ns	1.057 ns	1.018 ns				
sdev	8.76 ps	102.22 ps	47.72 ps	25.26 ps	14.81 ps	9.46 ps	9.35 ps	8.72 ps				
num	996	1.023e+3	388	1.023e+3	173	338	388	3.460e+3				
status	✓	✓	✓	✓	✓	✓	✓	✓				

Use Measurement for automated tests

Measurement can be used in Pass-Fail* test

Pass –Fail test is a common standard function in most Digital scope



Up to 8 tests can be defined, which include parameter (measurement) limits, Mask testing, dual parameter compare. Actions can be defined on test Pass or Fail result

*Feature fully covered in the Advanced Scope Seminar