Hello everyone, my name is Jae-yong Chang and I am the product manager for oscilloscope probes and accessories in Agilent Technologies. Thanks for joining the Test & Measurement World, EDN web cast seminar today.

Today we’re going to talk about scope probing. Probing is critical to making quality oscilloscope measurements, and often the probe is the first link in the oscilloscope measurement chain. Selecting the right probe for your application and how you use the probe is the first step toward reliable measurements. In this web cast, I will present you six useful tips in making better scope probing.
Here is the list of six hints on scope probing we will be learning about today.
One of the questions most of you might have asked when selecting scope probe is when to choose passive probe and when to choose active probe. This passive probe on the picture is the probe that many of you use with your scope and is shipped with the most of low to mid-range oscilloscopes today. The probe tip R is typically 9 Mohm which gives a 10:1 divider ratio with the scope’s 1Mohm input resistance. The probe tip is followed by a cable which in this case is a high-impedance cable. A termination box or probe interface at the end of the probe cable connects to the input of the oscilloscope.

A rule of thumb is that for general-purpose mid-to-low-frequency (less than 500-MHz) measurements, high-impedance passive probes are good choices.
#1 : Passive or Active probe?

Conventional single-ended active probe

If you have a scope with more than 500 MHz of bandwidth, you are probably using an active probe today… or should be. Here’s the diagram of a conventional single-ended active probe. This active probe differs from the passive probes in that the probe tip contains an active amplifier that amplifies in-coming signals, drives a 50 ohm cable and which is then connected to the 50 ohm input of oscilloscope. They typically cost more than passive probe and are limited in measuring a couple tens of volts for this high bandwidth active probe but they significantly reduce capacitive loading to achieve fast signal measurements with much better signal fidelity.
To see how active probe plays out better in measuring fast signal, here I took two measurements using a 1-GHz bandwidth scope measuring a signal that has a 1-ns rise time. On the left, a 600-MHz passive probe was used to measure this signal. On the right, a 1.5-GHz single-ended active probe was used to measure the same signal. The blue trace shows the signal before it was probed and is the same in both cases. The yellow trace shows the signal after it was probed, which is the same as the input to the probe. The green trace shows the measured signal, or the output of the probe.

A passive probe on the left loads the signal down with its input inductance and capacitance (yellow trace). The probed signal’s rise time becomes 1.9 ns, partly due to the probe’s loading effect, but also due to its limited 600-MHz bandwidth in measuring a 350-MHz signal (0.35/1 ns = 350 MHz). The inductive and capacitive effects of the passive probe also cause overshoot and fluctuation effects in the probe output (green trace).

On the other hand, we can see that the signal is virtually unaffected when we attach an 1.5 GHz active probe to the DUT. The signal’s characteristics after being probed (yellow trace) are nearly identical to its un-probed characteristics (blue trace). In addition, the rise time of the signal is unaffected by the probe being maintained at 1 ns. Also, the active probe’s output (green trace) matches the probed signal (yellow trace) and measures the expected 1-ns rise time. You can see that active probe gives you much accurate insight into measuring fast signals.
#1 : Passive or active probe?

Comparing high-impedance passive probe and active probe

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<thead>
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<th>High Impedance Passive Probe</th>
<th>Single-ended Active Probe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power requirement</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Loading</td>
<td>Heavy capacitive loading and low resistive loading</td>
<td>Best overall combination of resistive and capacitive loading</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>up to 600MHz</td>
<td>up to 13GHz</td>
</tr>
<tr>
<td>Applications</td>
<td>General purpose mid-to-low frequency measurements</td>
<td>High-frequency applications</td>
</tr>
<tr>
<td>Ruggedness</td>
<td>Very rugged</td>
<td>Less rugged</td>
</tr>
<tr>
<td>Max input voltage (10:1)</td>
<td>~ 300V</td>
<td>~ 40V</td>
</tr>
<tr>
<td>Typical Prices</td>
<td>$100-$500</td>
<td>&gt;$1k</td>
</tr>
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</table>

Key differences between passive and active probes are summarized in the table. One obvious distinction between two probes is that active probe requires probe power while passive probe does not. Many of today’s modern active probes offer an automatic probe interface that gives an intelligent communication and power link between probe and oscilloscope that eliminates a need for external power supply to the active probe.

Passive probes are more rugged and inexpensive, offering wide dynamic range (greater than 300 V) and high input resistance. However, they impose heavier capacitive loading and offer lower bandwidths than active probes or low-impedance (z0) passive probes. All in all, high-impedance passive probes are a great choice for general-purpose debugging and troubleshooting on most analog or digital circuits.

For high-frequency applications (greater than 600 MHz) that requires accurate measurements across a broad frequency range, active probes are the way to go. They cost more than passive probe and their input voltage is limited, but because of their significantly lower capacitive loading, they give you more accurate insight into fast signals, as we have seen in the previous slide.


Here we show a diagram of the circuit under test and the probe that is used to look at the desired waveform.

In an ideal world, a scope probe would be a non-intrusive (having infinite input resistance, zero capacitance and zero inductance) wire attached to the circuit of interest and it would provide an exact replica of the signal being measured, not distorting the original waveform.

But in the real world, the probe becomes the part of the measurement and it introduces loading to the circuit. This resistive, capacitive and inductive components on the probe can change the response of the circuit under test, depending on how much the probe loads the circuit. It is important to understand the electrical behavior of the probe that can affect the measurement results and the operation of the circuit.
Here is a simple method to check how much the probe loads your circuit. We call it double probing.

First, connect one probe to the circuit under test or a known step signal and the other end to the scope’s input. Watch the trace on the scope screen, save the trace and recall it on the screen so that the trace remains on the screen for a comparison. Then, using another probe of the same kind, connect to the same point and see how the original trace changes over the double probing.

Here on the scope screen, blue trace is the signal measured with a single probe, and as you double probe the signal (yellow trace) signal is loaded by the second probe. Here you see the rise time of the signal is slowed down with the probing. You can see how much of probe loading there is by double probing your signal.
You may need to make adjustments to your probing or consider using a probe with lower loading to make a better measurement. For this experiment I used a special fixture what we call 50-ohm feedthrough fixture shown on the picture. One end of the fixture is connected to the scope input and the other end of fixture is connected to the BNC cable hooked up to a signal source and the fixture maintains accurate 50ohm so that it does not affect the signal characteristics. It allows you to probe the 50 ohm signal easily, not necessarily stripping off the BNC cable.

In this example, the circuit ground is probed with a long 18 cm (7”) ground lead in the upper case. In the lower case, the same signal is probed with a much shorter spring-loaded ground lead. As you see, shortening the ground lead did the trick. The ringing on the probed signal (purple trace) went away with the shorter ground lead. The source of the ringing is the LC circuit formed by the probe’s internal capacitance and the ground lead. So if at all possible, it is good to use just as short a ground lead as possible to minimize the ringing on top of your waveform.
Here are a few recommendations to minimize probe loading and to achieve better measurement.

• I did not mention about the resistive loading effects previously. But the resistive loading of the circuit can affect the measured amplitude of the signal as well as change the DC offset or bias level. This will most likely occur with low impedance resistor divider probes. Choose a probe whose input resistance is at least 10x higher than the source resistance of the signal to avoid excessive resistive loading.

• Choose a probe that exceeds the signal bandwidth by 5x. For example, to measure 1 nsec edge we looked at in the previous page whose signal bandwidth is 350 MHz (≈0.35/1nsec), use a 1.5 GHz bandwidth probe applying the 5x multiplier.

• Minimize the probe tip capacitance. Capacitive loading affects delay in waveform, rise time and bandwidth of the measurement.

• Use as short a ground lead as possible (ground wire inductance = 1nH/mm)
#3 : Compensate probe before use

If your probe calibration signal looks like either of this,

![Compensate your probe!](image)

Most probes are designed to match the inputs of specific oscilloscope models. However, there are slight variations from scope to scope and even between different input channels in the same scope. Make sure you check the probe compensation when you first connect a probe to an oscilloscope input because it may have been adjusted previously to match a different input.
So, what is the probe compensation?

Common 10:1 high-impedance passive probes utilize a resistor-capacitor, RC voltage divider to obtain 10:1 voltage attenuation ratio. Most passive probes have built-in compensation RC divider networks. Probe compensation is the process of adjusting the RC divider (variable capacitor, C comp, in this case) on the probe so the probe maintains its attenuation ratio over the probe’s rated bandwidth.
#3 : Compensate probe before use

1. Make sure that the probe’s input capacitance lies within the probe’s compensation range.

<table>
<thead>
<tr>
<th>Infiniium 8000 scope’s input characteristics</th>
<th>10073C probe’s characteristics</th>
</tr>
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<tbody>
<tr>
<td>Input impedance</td>
<td>1 MΩ ± 1% (13 pF typical) 50 Ω ± 1.5%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Model</th>
<th>Cable length</th>
<th>Attenuation</th>
<th>Typical scope bandwidth</th>
<th>Compensates 1 MΩ oscilloscope input</th>
</tr>
</thead>
<tbody>
<tr>
<td>10073C</td>
<td>1.5 m</td>
<td>10:1</td>
<td>500 MHz</td>
<td>1 MΩ, 6-15 pF</td>
</tr>
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</table>

2. Viewing the square wave reference signal, make the proper adjustments on the probe using a small screw driver so that the square waves on the scope screen look “square”.

Before you proceed to compensate the probe for the scope, make sure that the scope’s input capacitance falls within the probe’s compensation range. Most scope and probe vendors specify the scope’s input characteristics and probe’s variable compensation range in the data sheet or manual. For example, Agilent’s 8000 Series oscilloscope’s input characteristics show that at 1 Mohm input it exhibits 13 pF of typical input capacitance. And the probe you’re going to use with this scope has 6-15pF of compensation range. You can see that the scope’s input capacitance lies within the probe’s compensation range so that the probe can be properly compensated for the scope input channel.

Most scopes have a square wave reference signal available on the front panel to use for compensating the probe. You can attach the probe tip to the probe compensation terminal and connect the probe to an input of the scope. Viewing the square wave reference signal, make the proper adjustments on the probe using a small screw driver so that the square waves on the scope screen look square.
You can have either overshoot or undershoot on the square wave when the low-frequency adjustment is not properly made. This will result in high-frequency inaccuracies in your measurements. It’s very important to make sure this compensation capacitor is correctly adjusted so that the square wave on the scope’s reference signal look square.
In recent years, engineers working on battery-powered devices like this mobile phone or ICs have demanded higher-sensitivity current measurement to help them ensure the current consumption of their devices is within acceptable limits.

Typical current measurement requires breaking the circuit, putting a small resistor in series with the circuit, measuring the voltage across the resistor and dividing the voltage measurement by the resistor value to derive the current value.

Using a clamp-on current probe with an oscilloscope is an easier way to make current measurement that does not necessitate breaking the circuit. But this process gets tricky as the current levels fall into the low milliampere range or below. Let’s look at some measurement tips in making low currents with a scope and a clamp on AC/DC current probe.
A modern AC/DC current probe such as Agilent’s 100-MHz current probe is capable of measuring ~5 mA of AC or DC current with less than 3% accuracy which is very good. On the other hand, the baseline noise of a typical midrange oscilloscope measured at its most sensitive V/div setting is approximately 2-3mVpp. The current probe is designed to output 0.1 V per one ampere current input. In other words, the oscilloscope’s inherent 2-mVpp vertical noise can be a significant source of error if you are measuring less than 20 mA of current, as the current signal is buried in the scope noise.

As the current level decreases, the oscilloscope’s inherent vertical noise becomes a dominant issue. When you are measuring low-level signals, measurement system noise may degrade your actual signal measurement accuracy. Since oscilloscopes are broadband measurement instruments, the higher the bandwidth of the oscilloscope, the higher the vertical noise will be. You need to carefully evaluate the oscilloscope’s noise characteristics before you make low current measurements.
#4: Low current measurement tips

**Helpful tips**

1. Use a scope with 1mV/div minimum vertical resolution.
2. Set the scope to the BW limit filter on the scope, high resolution mode or averaging mode to reduce scope’s noise or turn on

- Normal mode – 25mApp
- High res mode – 3mApp
- 8x averaging mode – 800uApp

The first recommendation for making low level current measurements is to use a scope with low minimum vertical resolution such as 1mV/div. With modern digital oscilloscopes, there are a number of possible approaches to minimize the scope’s vertical noise.

* Bandwidth limit filter – Most digital oscilloscopes offer bandwidth limit filters that can improve vertical resolution by filtering out unwanted high frequency noise from input waveforms and by decreasing the noise bandwidth.

* High-resolution acquisition mode – Most digital oscilloscopes offer 8 bits of vertical resolution in normal acquisition mode. High-resolution mode on some oscilloscope offers much higher vertical resolution, typically up to 12-16 bits, which reduces vertical noise and increases vertical resolution, as the scope averages adjacent data points from one trigger.

* Averaging mode – When the signal is periodic or DC, you can use averaging mode to reduce the oscilloscope’s vertical noise. Averaging mode takes multiple acquisitions of a periodic waveform and creates a running average to reduce random noise. The noise reduction effect is larger than with any of the methods above as you select a greater number of averages.
#4 : Low current measurement tips

**Helpful tips**

3. Demagnetize (or degauss) and adjust offset zero control before making “every” measurement on the AC/DC current probe.

Now that you figure out how to lower the oscilloscope’s vertical noise with one of the techniques above, let’s take a look at how to improve accuracy and sensitivity of a clamp-on current probe.

There are two useful tips for using this type of current probe:

To ensure accurate measurement of low-level current, you need to eliminate residual magnetism built up on the current probe by demagnetizing (or degaussing) the magnetic core. Just as you would remove undesired magnetic field built up within a CRT display to improve picture quality, you can degauss or demagnetize a current probe to remove any residual magnetization. If a measurement is made while the probe core is magnetized, an offset voltage proportional to the residual magnetism can occur and induce measurement error. It is especially important to demagnetize the magnetic core whenever you connect the probe to power on/off switching or excessive input current. In addition, you can correct a probe’s undesired voltage offset or temperature drift using the zero adjustment or offset adjustment control on the probe.
A current probe measures the magnetic field generated by the current flowing through the jaw of a probe head. Current probes generate voltage output proportional to the input current. If you are measuring DC or low-frequency AC signals of small amplitude, you can increase the measurement sensitivity on the probe by winding several turns of the conductor under test around the probe. The signal is multiplied by the number of turns around the probe. For example, if a conductor is wrapped around the probe 5 times and the oscilloscope shows a reading of 25 mA, the actual current flow is 25 mA divided by 5, or 5 mA. You can improve the sensitivity or resolution of the current probe by a factor of 5 in this case.
Scope users often need to make floating measurements where neither point of the measurement is at earth ground potential. For example, suppose you measure a voltage drop across the input and output of a series voltage regulator U1. Either the voltage in or out pin of the regulator is not referenced to ground. This kind of measurement is called floating measurement.

A standard oscilloscope measurement where the probe is attached to a signal point and the probe tip ground lead is attached to circuit ground is actually a measurement of signal difference between the test point and earth ground. Most scopes have their signal ground terminals (or outer shells of the BNC interface) connected to the protective earth ground system. This is done so that all signals applied to the scope have a common connection point. Basically all scope measurements are with respect to “earth” ground. Connecting the ground connector to any of the floating points essentially pulls down the probed point to the earth ground, which often causes spikes or malfunctions on the circuit. How do you get around this floating measurement problem?
There are some methods in making floating measurements. Many customers use an isolation transformer or disconnecting power line ground to connect to a scope and keep the scope floating. Using an isolation transformer or cutting off the ground tab of power line are very unsafe methods as they cause safety issues. Using a battery powered oscilloscope can be an alternative but it should not be used to measure >30V safety voltage.

A popular yet undesirable solution to the need for a floating measurement is the “Channel 1 – Channel 2” technique using two single-ended passive probes and a scope’s built-in math function. Most digital oscilloscopes have a subtract mode where the two input channels can be electrically subtracted to give the difference in a differential signal. For decent results, each probe used should be matched and compensated before using it. In this method, the common mode rejection ratio is typically limited to less than 20dB (10:1). If the common mode signal on each probe is very large and differential signal is much smaller, any gain difference between the two sides will significantly alter their "differential" or “Channel 1 – Channel 2” result. A good sanity check here would be to double probe the same signal and see what the “Channel 1 – Channel 2” shows them.
For making safe, accurate floating measurements with any oscilloscope using a high-voltage differential probe is a much better solution. A high-voltage differential probe is supposed to measure high differential voltage or floating signal with high common mode rejection ratio, by converting floating signals into a low voltage ground referenced signal that can be safely fed to a ground referenced scope. We recommend you to use a differential probe with sufficient dynamic range, bandwidth and common mode rejection capability for your application to make safe and accurate floating measurements.
The performance of a probe is highly affected by the probe connection. • Probes form a resonant circuit where they connect to the device.

If you have to add wires to the tip of a probe to make a measurement in a tight environment, put a resistor at the tip to damp the resonance of the added wire.

The last probing tip I would introduce you today is with respect to the probe resonance damping. As the speeds in your design increase, you may notice more overshoot, ringing, and other perturbations when using an oscilloscope probe. Basically any probes form a resonant circuit where they connect to the device because of capacitive and inductive components on the probe we discussed earlier. If this resonance frequency is within the bandwidth of the oscilloscope probe you are using, it will be difficult to know if the measured perturbations on the trace are due to your circuit or the probe.

If you have to add wires, grabbers, or hook tip kind of accessories to the probe tip to make a measurement in a tight, hard-to-reach environment, we recommend you to put a resistor at the tip to damp the resonance of the added accessories. The probe tip damp resistor can be used for passive probe or active probe. This probe’s damped accessories give a flexible use model that maintains low input capacitance and inductance and flat frequency response through its specified bandwidth. Many of Agilent’s high speed active probe systems use this damped accessory technology for better performance.
Here is a real world example of how damping resistor can play out in your measurement. Here I used a 4-GHz single-ended active probe.

The input impedance of the 4 GHz active probe with an undamped 5cm lead wire finds it’s resonant frequency at approximately 750MHz, at which time the input impedance drops to approximately 15Ω. Looking at the impedance measurement of the 4GHz probe with a properly damped 5cm lead wire accessory, we see that the input impedance doesn’t resonate low. It never goes below the value of the damping resistor.
Looking at the transmitted frequency response of the undamped probe, we can see that the Vin-measured is significantly “dinged” at the resonant frequency. Also, Vout is peaked-up at this same resonant frequency. The resulting calculation of Vout/Vin-measured (transmitted frequency response) shows tremendous peaking at the resonant frequency, and the overall –3dB bandwidth of the 4GHz probe with a 5cm lead wire is approximately 1.5GHz.

Now with properly damped probe, you get a flat response over the entire frequency range, eliminating the in-band resonance and signal fidelity problem and shows you desirable bandwidth characteristics.
Now if you compare two probes in time domain, with a 1ns input risetime signal, both 4 GHz probes (damped and undamped) do a very good job of measuring this signal because 1 nsec edge (or 350 MHz signal bandwidth) is fairly low bandwidth relative to the 4 GHz probe bandwidth.
With a 100ps risetime signal, 10x faster than 1nsec, you can see that not only is the undamped probe beginning to load and alter the input signal, but the measured output signal begins to show significant ringing. This is due to the resonance of the probe connection. Now with the properly damped probe, both the input and output signal look virtually identical.
As we crank up the clock frequency to 250MHz, the distortion caused by the undamped probe connection really begins to look ugly. Again, is this distortion real? If you were viewing this clock as an eye-diagram, you would interpret the “eye” to be almost entirely closed. The measurement with the properly damped probe maintains signal fidelity. However, you can begin to see the bandwidth limitation problem as evidenced by the slower edge speeds on the measured output signal.
As we increase the clock speed to 500MHz, you can see that the ringing caused by the resonance begins to compound onto itself, and we end up with a very distorted waveform. By using the damping resistor probe accessory we maintain signal fidelity. However, in both cases, our 5cm connection has caused a decrease in bandwidth and risetime. A 5cm connection will result in a probe system bandwidth of approximately 1.5GHz, regardless of the specified bandwidth of the probe and the vendor.
Summary

- Hint #1 – Passive or active probe? Consider pros and cons of each.
- Hint #2 – Double probe to check the probe loading. Minimize the probe tip capacitance and inductance.
- Hint #3 – Probe compensation needs to be checked before each use.
- Hint #4 -- Low current measurement tips – Lower the scope noise and improve probe accuracy and sensitivity.
- Hint #5 -- Make safe floating measurements with differential probes.
- Hint #6 – Probes for a resonant circuit. Damp the resonance by putting a resistor at the tip of the probe.

For more information about Agilent’s scope probes and accessories, visit www.agilent.com/find/scope_probes

Now we have looked over all the six tips in making better scope probing. First we looked at pros and cons of each passive and active probes. And a way to quickly check your probe loading by double probing and I introduced some recommendations to minimize probe tip capacitance and inductance to lower the loading effects. Probe compensation needs to be checked before each use of a probe. And I introduced some measurement tips to lower scope noise and improve probe accuracy and sensitivity. To make safe and reliable floating measurement I recommend to use a differential probe. Lastly for damping the probe resonance, you may want to put a resistor at the tip of the probe.