Keysight Technologies

Understanding Oscilloscope Probe Correction

Application Note

KEYSIGHT
TECHNOLOGIES
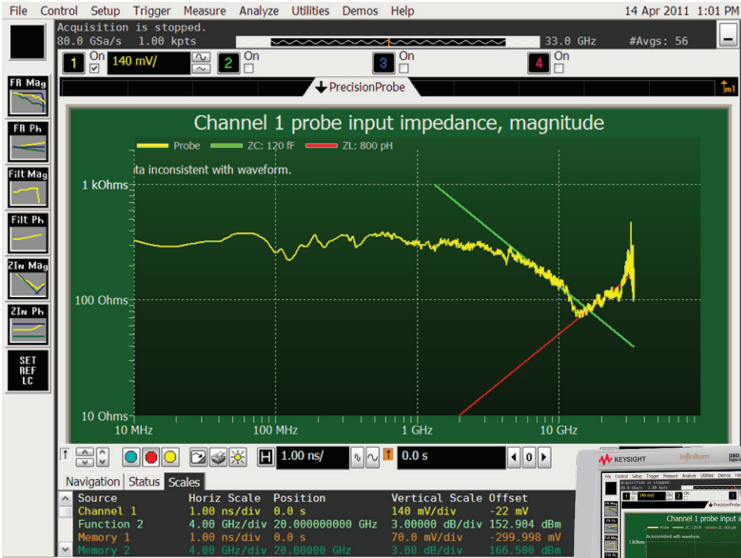
Introduction

A "probe" can be thought of as any device used to transmit a voltage signal from a DUT (device under test) to an oscilloscope; this includes 50 ohm cables, active probes, passive probes, differential probes, wire leads and ground extensions, etc. Probes are used to deliver signals to an oscilloscope from the device and are inherently lossy, plus their characteristics vary from probe to probe. The characteristics can depend on frequency, temperature, manufacturing variations, connection methods, and of course damage. For the purpose of this paper, the probes considered are active and passive probes.

As oscilloscopes continue to achieve higher bandwidths, the cables used are becoming the bandwidth bottleneck of the systems. To keep up with the increasing bandwidth needs of their customers, oscilloscope vendors now invest in high end semiconductor chips on probes as well as their oscilloscopes. However, even with high bandwidth technology, probes remain lossy and probe vendors use digital signal processing techniques to ensure a flat frequency response and less loss. The evolution of various methods and techniques of probe correction have followed scopes' path toward feature-richness and sophistication. The advantage of digital signal processing is that it provides more flexibility over hardware implementations, and with modern microprocessors in oscilloscopes, present very little impact on update rate performance.

The terms "calibration" and "correction" can be used interchangeably, however normal nomenclature is that calibration tends to represent the process of setting up a correction, which is then applied to a signal once calibration is completed. To understand and characterize scope probes, it's important to understand that any circuit with a probe attached effectively becomes a new circuit that includes the probe and probe accessories. VSource represents a circuit signal with no probe connected, VIn represents a new signal with the probe's effect included (the voltage at the probe's tip), and VOut represents the signal as passed through the probe. An understanding of these signals is essential to any discussion of probe correction.

DC Correction Methods

The most common correction method for probes is the DC adjustment, which entails the adjustment of probe gain and probe offset. Probe gain correction simply adjusts the scope's scaling factors of the signal displayed on screen to properly match the correct DC values. In other words, the instrument forces V_{Source} and V_{Out} to match (at DC only) by scaling the vertical axis (voltage) accordingly. In Keysight Technologies, Inc. oscilloscopes the DC voltage source ("probe comp" or "cal out") has a source impedance of 0 ohms, so $V_{Source} = V_{In}$ (probe loading does not affect this circuit.

It's important to note that this scaling can be greater or less than one (gain or attenuation); for example, a 10:1 passive probe must be scaled up by 10, and many active probes must be scaled down. Typically a given probe will not have exactly nominal gain characteristics due to manufacturing variability (a 10:1 passive probe might actually be 9.85:1, for instance). Probe offset variation stems from similar manufacturing differences and simply represents the output of the probe when it measures a signal of 0 V. The instrument subtracts the offset from future measurements after probe calibration to ensure this case is true.

These DC corrections represent a very simple straight line, $y = mx + b$ situation; to determine gain and offset coefficients the user connects a given probe to the instrument, with its tip, or input, connected to an instrument output (typically known as "probe comp"). Once the calibration is initiated, the instrument outputs known DC voltages and compares these values to the scope input after the signals pass through the probe. While only two points are technically required to determine the gain and offset coefficients, most instruments collect more than that. These coefficients don't typically drift much with time; performing probe DC calibrations several times a year is enough.
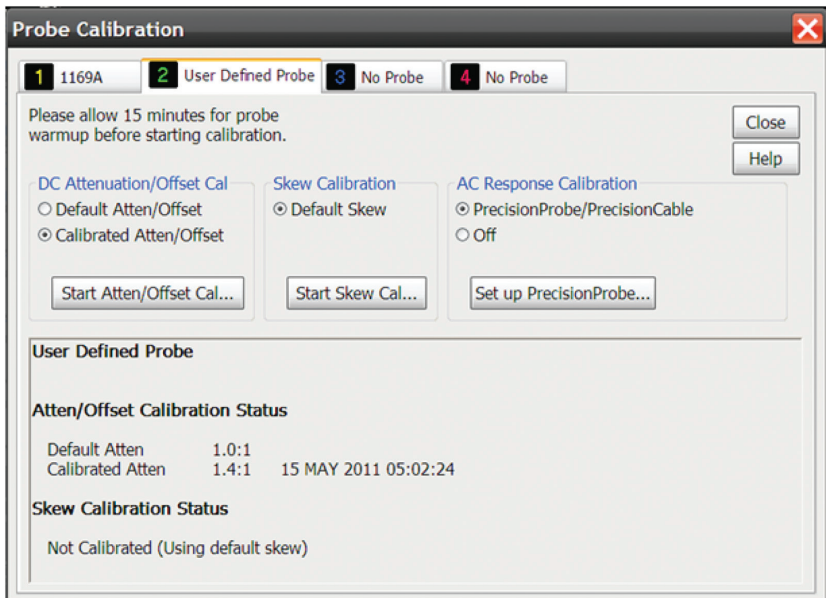

Figure 2. Calibration menu as part of the Keysight 90000 X-Series oscilloscope

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AC Correction Methods

As oscilloscope performance increases to multi-GHz levels, the use of DC correction methods becomes less reliable, since many probe characteristics are strong functions of frequency, particularly at higher bandwidths. The term "AC correction" refers to correction schemes that vary with frequency and that attempt to adjust a probe's characteristics to be in line with those of an "ideal probe." An ideal probe is one that has a flat frequency response up to its bandwidth (-3dB point, or the point at which the signal level is attenuated by the probe to 71% of the original signal), and that minimally loads the circuit to which it is connected. The loading of a probe is a complex impedance, and ideally would be infinite, since in that case it would have no effect on the DUT circuit whatsoever. Unfortunately probe manufacturers are limited by the realities of physics, and a number of other real-world constraints which lead to deviations from the ideal.

AC correction methods require understanding some key terms:

V_{Src} - The signal at the probe point before the probe is connected which would be the signal at the probe point if an ideal probe with infinite input impedance were connected

V_{In} - The signal at the probe point while the signal is being loaded by the probe. Probe loading is caused by the input impedance of the probe making a voltage divider with the source impedance of the circuit being measured.

V_{Out} - The signal that is output from the probe

V_{out}/V_{in} Correction - The signal at the output of the probe is an accurate representation of the signal that currently exists, as it is being probed

V_{out}/V_{Src} Correction – The signal at the output of the probe depicts the signal before it was probed or V_{Src}
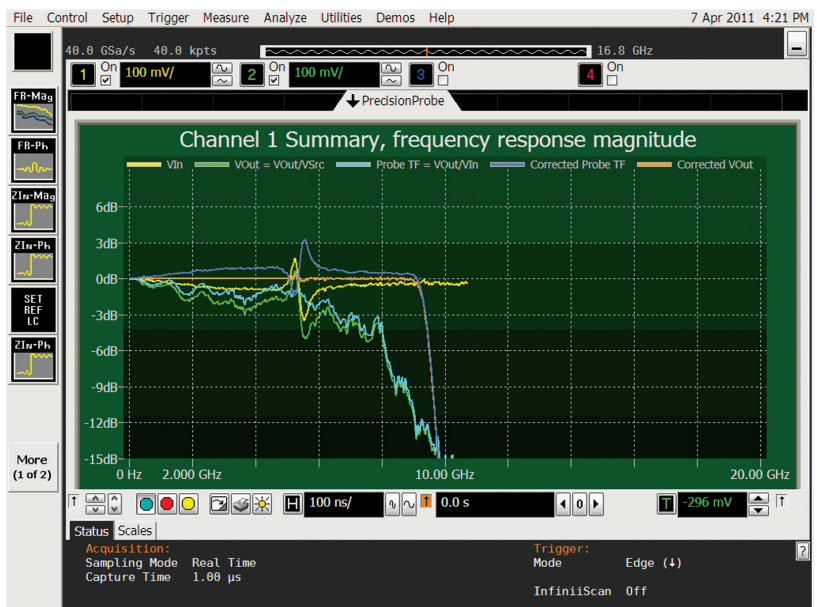

Figure 3. Frequency response of a probe as measured by PrecisionProbe.

AC Correction Methods

To correct for an oscilloscope's frequency response vendors must use some ratio of input to output. Which input to use V_{In} or V_{Source}, has been a matter of debate between scope vendors for some time. Using V_{Source} has the advantage of representing the probed signal as if no probe were connected and thus no probe loading. The negatives of using V_{Source}, however, are that it requires knowledge or assumption of the DUT source impedance. Scope vendors that use V_{Source} to determine probe response typically assume 25 ohm differential impedance—this assumption may or may not be accurate, depending on the particular DUT. DUT impedance is very difficult to measure and is not typically quantified or even understood by probe users. Keysight oscilloscopes and probes use the V_{In} method to determine probe response, and include the loading effects of the probe.
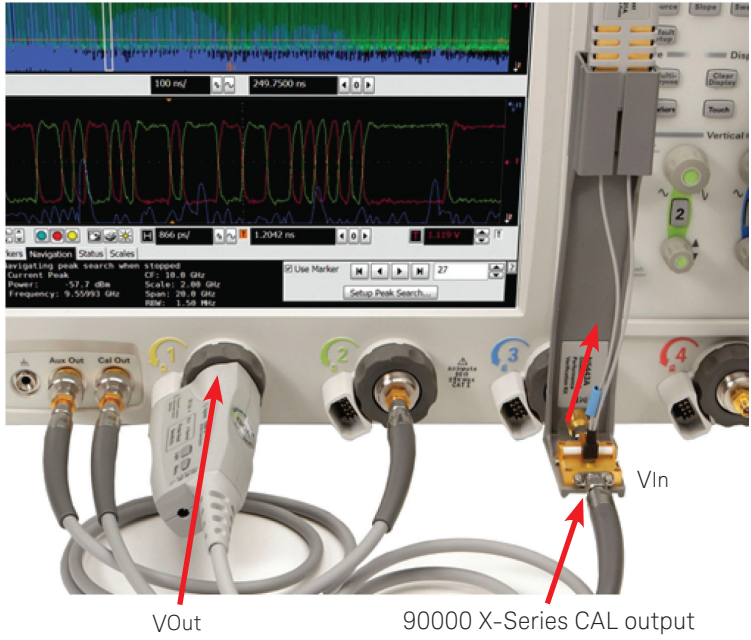

VOut   90000 X-Series CAL output

VIn

Figure 4. VOut as defined to the oscilloscope

Vin (probe)

Vin (to scope)
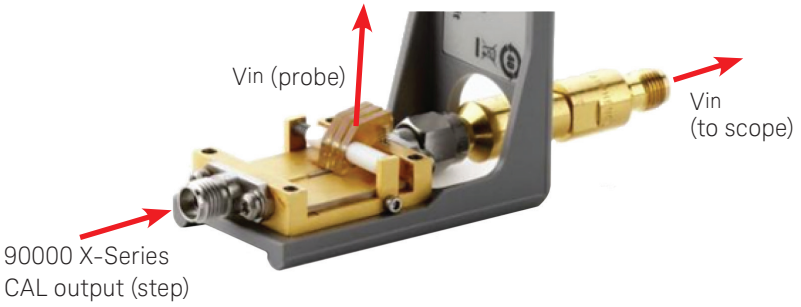
90000 X-Series CAL output (step)

Figure 5. Depiction of VIn/VOut as connected to the InfiniiMax III Performance Verification kit

AC Correction Methods

For high frequency probing, all oscilloscope vendors apply a frequency dependent, "nominal" or factory correction scheme to their high-performance probing solutions. To determine the correction that will be applied to an individual probe the probe needs to be characterized. During the development of the probes and oscilloscope, the vendor measures some set of devices very accurately, averages their characteristics, and creates a correction filter that represents the average probe and scope system. This same nominal correction is applied regardless of probe serial number or condition. An exception to the rule is the InfiniiMax III probe amplifier, which uses custom s-parameter files for each individual amplifier. Keysight measures the S-parameters (parameters that completely describe the electrical behavior of linear networks, used commonly in the RF world) of each InfiniiMax III probe amplifier using a vector network analyzer, and stores these parameters in the memory of the probe itself. When the probe is connected to an instrument it shares these parameters and the instrument assembles the proper correction on-the-fly. This form of correction leads to significantly increased accuracy over a nominal correction, without requiring any additional inconvenience to the scope user.

With the exception of the InfiniiMax III probing system, a correction method corrects for systematic design and manufacturing variations, but not drifting or random variations. To take advantage of this method of correction a scope user only needs to ensure the instrument configuration of their probe system is accurate; the rest is typically automatic, and there are no disadvantages to utilizing this form of correction if it is available.

Aside from factory calibration drift, there are a number of other factors that can drastically change a probe's behavior that are impossible to capture and correct for at the factory. A very significant amount of probe variation occurs at the probe tip, where the probe makes contact with the DUT. Some scope users build their own custom probes, which obviously aren't factory corrected. For other probes or probe heads it is impossible or inconvenient to include S-parameter data from the factory. For these cases an even more accurate correction/calibration process is required.

User-Controlled AC Correction Methods

To avoid the variation that occurs with using models for correction and ensure an accurate compensation, users need a method to analyze the probes themselves and then correct for frequency response themselves. Previosly this could only be done by measuring each individual component of the probing system with a vector signal analyzer (VNA) and then using waveform transformation software to compensate for the probing system. While effective, this method requires significant knowledge of the measurement equipment and the transformation software. With the development and release of PrecisionProbe, Keysight is now pioneering this correction method in the form of the N2809A Precision Probe software and hardware kit. This product enables the scope user to perform a very accurate tip-to-scope AC calibration of a probing system without any additional instrumentation, and only a few probe fixtures and cables. The scope performs this calibration by outputting a fast edge (<15pS on the Keysight 90000 X-Series) to completely characterize V_{Source}, V_{In}, and V_{Out} (which includes probe loading characteristics), and combining this measured information into a custom correction filter for a given probing setup.
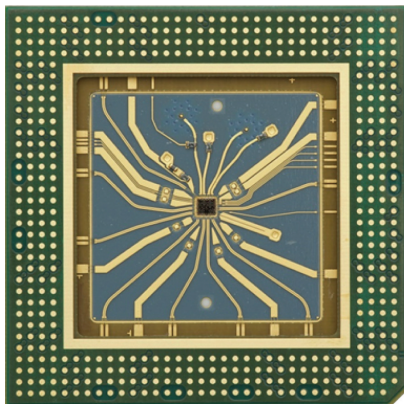
PrecisionProbe software characterizes and compensates custom probes in less than five minutes using only an Infiniium oscilloscope. PrecisionProbe characterizes the probe's frequency response (either V_{Out}/V_{In} or V_{Out}/V_{Src}) and then creates a custom filter that is loaded in oscilloscope hardware to perfectly flatten the frequency response of the probe. Loss on the probes is then compensated for and higher bandwidth on the oscilloscope can be achieved. In addition to measuring the frequency response (both magnitude and phase), PrecisionProbe provides impedance plots generated in the AC calibration process which can also help engineers to develop an intuition about their probes.
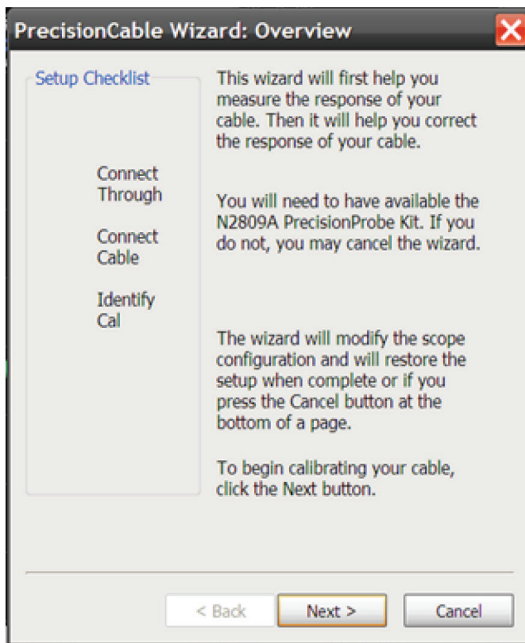

Figure 6. Keysight's custom calibration edge is enabled by the multi chip module and Keysight's custom Indium Phosphide technology.

Figure 7. PrecisionProbe provides an easy wizard to characterize and compensate for probes
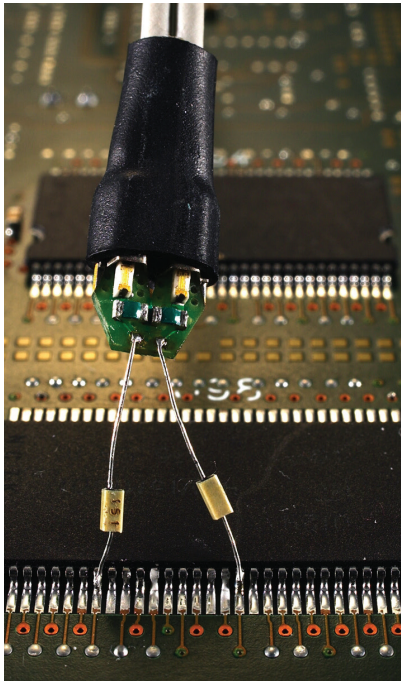
User-Controlled AC Correction Methods

There are several specific situations that clearly illustrate the utility of custom AC corrections. Since so much probe variation can occur at the probe tip, it is essential that users of probe accessories, such as Keysight's long-wire ZIF solution (N5425A probe head with N5426A probe tips) keep wire lengths as short as possible and in the correct orientation; otherwise the factory correction method applied leads to a less accurate measurement, since it may correspond to a slightly different geometric configuration. Clearly the more the user alters the probe accessory the more it will vary from the nominal correction applied by the test vendor and the more error will be introduced in the measurement. Precision Probe or any other custom AC calibration software allows the user to choose the probe geometry that works best for their situation—whether that means making the wires longer or shorter, or spaced more narrowly or wider—and calibrate the system to that geometry in order to obtain very accurate measurement results.

Figure 9. Long-wire ZIF tip

Figure 8. Notice the differences in the frequency response magnitude after the PrecisionProbe correction.

Probe Correction Pitfalls

However there are several pitfalls that you must avoid when considering probe correction methods, and these apply to all correction methods; DC, AC, and user-AC. The most important is the idea that probe correction can somehow fix a low-quality probe. Low-quality probes will often have very non-flat frequency responses; correcting valleys and peaks in a probe's response at frequencies much lower than the bandwidth of the probe leads to significantly more noise. Also, poorly designed probes often have terrible loading characteristics. Probe correction CANNOT remove the effects of this probe when connected to a DUT; it can only hide or alter what is displayed on the instrument. For the best-quality measurement that impacts a DUT minimally, probe users should select probes with the highest input impedance at the frequencies of concern. It is also wise to avoid haphazardly boosting bandwidth unless measuring a repetitive signal that can be averaged. Boosting the bandwidth of certain probes can lead to very noisy results.

With certain probe response definitions and resulting correction schemes, it's possible for a scope to present waveforms on screen with faster rise times than the actual signal. For example, if using a V_{Out}/V_{Source} definition of probe response, it is possible for V_{In} to be peaked significantly and still yield a flat response. In this case, higher frequency content is amplified relative to other frequencies as the signal passes through the probe. This effectively gives the higher frequency content more "weight" in the content of a fast edge, which makes it look faster than it really is. Some users like to see that their DUT edges are fast, but they must realize their probe system is not quite telling the truth in a case like this. The same effect can show rise times slower than reality as well, for instance if V_{In} was attenuated at higher frequencies instead of peaked. The final pitfall to be considered is the trade off of noise versus bandwidth. PrecisionProbe is correcting for probe loss and non-linearity in the frequency response by using digital signal processing boosting. To understand DSP boosting, first remember that a signal can be broken down into its numerous frequency components. Using software you can amplify the higher frequency components of the signal. If you look at figure 11, the red trace represents a typical oscilloscope frequency response.
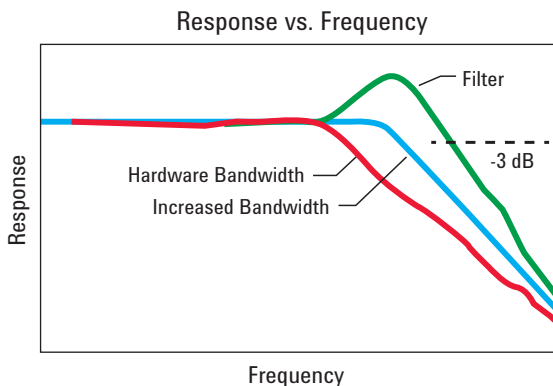

Figure 10. The effect of bandwidth-enhancement on noise

Conclusion

Probe correction methods can be quite complex, and as probe and scope users demand higher performance their complexity will only grow. In general, to get the highest measurement accuracy users should always take advantage of DC corrections by regularly performing DC calibrations on their probes. Also, taking advantage of factory AC correction methods costs nothing in terms of user convenience and yields significant accuracy improvements. Users with more advanced probing needs should consider a user-AC calibration system such as Keysight's Precision Probe to make better measurements and tame their probing complexities. Understanding the various options regarding probe correction and their nuances ensures probe users obtain the highest measurement fidelity.
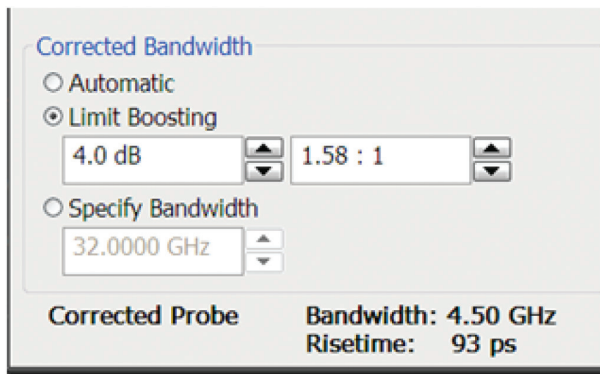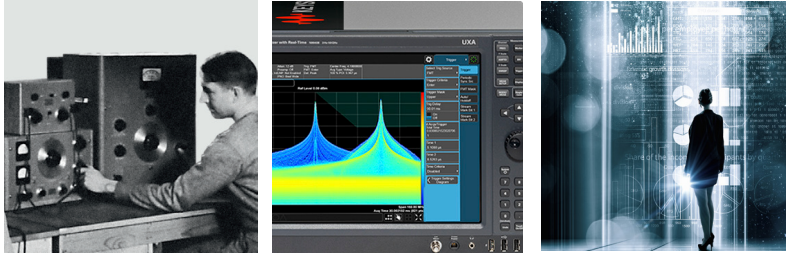

Figure 11. PrecisionProbe provides the ability to make the tradeoff between higher bandwidth and higher noise

Calibration Accuracy	DC Calibration	Factory AC Calibration	Factory S-Parameter AC Calibration	Precision Probe Calibration
Probe Amplifiers	*	**	***	***
Probe Heads	*	**	Not Available	***
Probe Tip Wires	*	Not Possible	Not Possible	***
Custom User Probes	*	Not Possible	Not Possible	***
Cables and 50 ohm Solutions	N/A	**	Not Available	***

How do different probes benefit from the various calibration/correction methods?

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