APPENDIX A

ABC's of Probes – Tektronix, Inc.

This appendix, guest written by the engineering staff of Tektronix, Inc., is a distillation of their booklet, "ABC's of Probes". The complete booklet is available, at no charge, through any Tektronix sales office or call 800-835-9433 ext. 170. For excellent technical background on probe theory see Reference 42.

PART I: UNDERSTANDING PROBES

The vital link in your measurement system

Probes connect the measurement test points in a DUT (device under test) to the inputs of an oscilloscope. Achieving optimized system performance depends on selecting the proper probe for your measurement needs.

Though you could connect a scope and DUT with just a wire, this simplest of connections would not let you realize the full capabilities of your scope. By the same token, a probe that is not right for your application can mean a significant loss in measurement results, plus costly delays and errors.

Why not use a piece of wire?

Good question: There are legitimate reasons for using a piece of wire or, more correctly, two pieces of wire; some low bandwidth scopes and special purpose plug-in amplifiers only provide binding post input terminals, so they offer a convenient means of attaching wires of various lengths.

DC levels associated with battery operated equipment could be measured. Low frequency (audio) signals from the same equipment could also be examined. Some high output transducers could also be monitored. However, this type of connection should be kept away from line-operated equipment for two basic reasons, safety and risk of equipment damage.

Safety: Attachment of hookup wires to line-operated equipment could impose a health hazard, either because the "hot" side of the line itself could be accessed, or because internally generated high voltages could be contacted. In both cases, the hookup wire offers virtually no operator protection, either at the equipment source or at the scope's binding posts.

Risk of Equipment Damage: Two unidentified hookup wires, one signal lead and one ground, could cause havoc in line-operated equipment. If the "ground" wire is attached to **any** elevated signal in line-operated equipment, various degrees of damage will result simply because both the scope and the equipment are (or should be) on the same three-wire outlet system, and short-circuit continuity is completed through one common ground.

Performance Considerations: In addition to the hazards just mentioned, there are two major performance limitations associated with using hookup wires to transfer the signal to the scope: circuit loading and susceptibility to external pickup.

Circuit Loading: This subject will be discussed in detail later, but circuit loading by the test equipment (scope-probe) is a combination of resistance and capacitance. Without the benefit of using an attenuator (10X) probe, the loading on the device under test (DUT) will be 1M ohm (the scope input resistance) and more than 15 picofarad (15pF), which is the typical scope input capacitance plus the stray capacitance of the hookup wire.

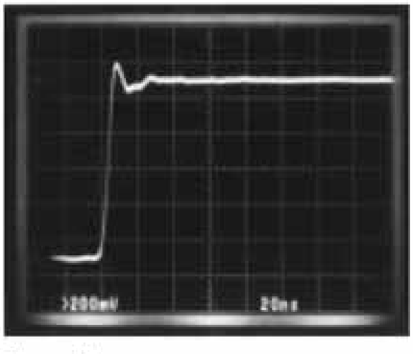

Figure 1-1

Figure 1-1 shows what a "real world" signal from a 500 ohm impedance source looks like when loaded by a 10M ohm, 10 pF probe: the scope-probe system is 300MHz. Observed risetime is 6 nSec.

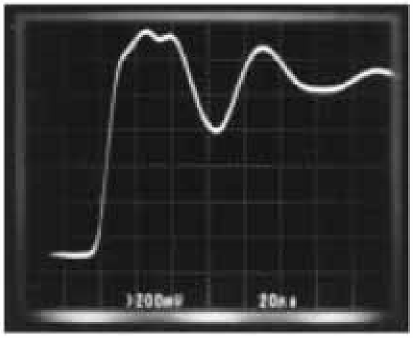

Figure 1-2

Figure 1-2 shows what happens to the same signal when it is accessed by two 2-meter lengths of hookup wire: loading is 1M ohm (the scope input resistance) and about 20 pF (the scope input capacitance, plus the stray capacitance of the wires). Observed risetime has slowed to 10 nSec and the transient response of the system has become unusable.

Susceptibility to External Pickup: An unshielded piece of wire acts as an antenna for the pickup of external fields, such as line frequency interference, electrical noise from fluorescent lamps, radio stations and signals from nearby equipment. These signals are not only injected into the scope along with the wanted signal, but can also be injected into the device under test (DUT) itself.

The source impedance of the DUT has a major effect on the level of interference signals developed in the wire. A very low source impedance would tend to shunt any induced voltages to ground, but high frequency signals could still appear at the scope input and mask the wanted signal. The answer, of course, is to use a probe which, in addition to its other features, provides coaxial shielding of the center conductor and virtual elimination of external field pickup.

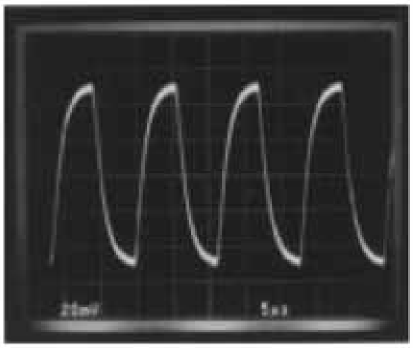

Figure 1-3

Figure 1-3 shows what a low level signal from a high impedance source (100mV from 100K ohm) looks like when accessed by a 300MHz scope-probe system. Loading is 10M ohm and 10 pF. This is a true representation of the signal, except that probe resistive loading has reduced the amplitude by about 1%: the observed high frequency noise is part of the signal at the high impedance test point and would normally be removed by using the BW (bandwidth) limit button on the scope. (See Figure 1-4.)

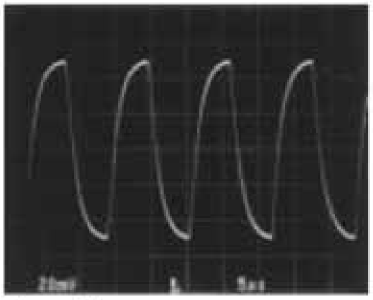

Figure 1-4

If we look at the same test point with our pieces of wire, two things happen. The amplitude drops due to the increased resistive and capacitive loading, and noise is added to the signal because the hookup wire is completely unshielded. (See Figure 1-5)

Most of the observed noise is line frequency interference from fluorescent lamps in the test area.

Probably the most annoying effect of using hookup wire to observe high frequency signals is its unpredictability. Any touching or rearrangement of the leads can produce different and nonrepeatable effects on the observed display.

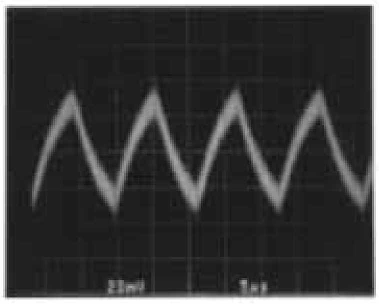

Figure 1-5

Benefits of using probes

Not all probes are alike and, for any specific application, there is no one ideal probe; but they share common features and functions that are often taken for granted.

Probes are convenient. They bring a scope's vertical amplifier to a circuit. Without a probe, you would either need to pick up a scope and attach it to a circuit, or pick up the circuit and attach it to the scope. Properly used, probes are convenient, flexible and safe extensions of a scope.

Probes provide a solid mechanical connection. A probe tip, whether it's a clip or a fine solid point, makes contact at just the place you want to examine.

Probes help minimize loading. To a certain extent, all probes load the DUT—the source of the signal you are measuring. Still, probes offer the best means of making the connections needed. A simple piece of wire, as we have just seen, would severely load the DUT; in fact, the DUT might stop functioning altogether.

Probes are designed to minimize loading. Passive, non-attenuating 1X probes offer the highest capacitive loading of any probe type—even these, however, are designed to keep loading as low as possible.

Probes protect a signal from external interference. A wire connection, as described earlier, in addition to loading the circuit, would act as an antenna and pick up stray signals such as 60Hz power, CBers, radio and TV stations. The scope would display these stray signals as well as the signal of interest from the DUT.

Probes extend a scope's signal amplitude-handling ability. Besides reducing capacitive and resistive loading, a standard passive 10X (ten times attenuation) probe extends the on-screen viewability of signal amplitudes by a factor of ten.

A typical scope minimum sensitivity is 5V/division. Assuming an eight-division vertical graticule, a 1X probe (or a direct connection) would allow on-screen viewing of 40V p-p maximum. The standard 10X passive probe provides 400V p-p viewing. Following the same line, a 100X probe should allow 4kV on-screen viewing. However, most 100X probes are rated at 1.5kV to limit power dissipation in the probe itself.

Check the specs. Bandwidth is the probe specification most users look at first, but plenty of other features also help to determine which probe is right for your application. Circuit loading, signal aberrations, probe dynamic range, probe dimensions, environmental degradation and ground-path effects will all impact the probe selection process, as discussed in the pages that follow.

By giving due consideration to probe characteristics that your application requires, you will achieve successful measurements and derive full benefit from the instrument capabilities you have at hand.

How probes affect your measurements

Probes affect your measurements by loading the circuit you are examining. The loading effect is generally stated in terms of impedance at some specific frequency, and is made up of a combination of resistance and capacitance.

Source Impedance. Obviously, source impedance will have a large impact on the net affect of any specific probe loading. For example, a device under test with a near zero output impedance would not be affected in terms of amplitude or risetime to any significant degree by the use of a typical 10X passive probe. However, the same probe connected to a high impedance test point, such as the collector of a transistor, could affect the signal in terms of risetime and amplitude.

Capacitive Loading. To illustrate this effect, let's take a pulse generator with a very fast risetime. If the initial risetime was assumed to be zero ($t_r = 0$), the output tr of the generator would be limited by the associated resistance and capacitance of the generator. This integration network produces an output rise time equal to 2.2 RC. This limitation is derived from the universal time-constant curve of a capacitor.

Figure 1-6 shows the effect of internal source resistance and capacitance on the equivalent circuit. At no time can the output risetime be faster than 2.2 RC or 2.2 nSec.

If a typical probe is used to measure this signal, the probe's specified input capacitance and resistance is added to the circuit as shown in Figure 1-7.

Because the probe's 10M ohm resistance is much greater than the generator's 50 ohm output resistance, it can be ignored.

Figure 1-8 shows the equivalent circuit of the generator and probe, appling the 2.2 RC formula again. The actual risetime has slowed from 2.2 n Sec. to 3.4 nSec.

Percentage change in risetime due to the added probe tip capacitance:

$$\% \text{ change } \frac{tr_2 - tr_1}{tr_1} \text{ X } 100 = \frac{3.4 - 2.2}{2.2} \text{ X } 100 = 55\%$$

Another way of estimating the affect of probe tip capacitance on a source is to take the ratio of probe tip capacitance (marked on the probe compensation box) to the known or estimated source capacitance.

Using the same values:

$$\frac{C_{\text{probe tip}}}{C_1} \text{ X } 100 = \frac{11\text{pF}}{20\text{pF}} \text{ X } 100 = 55\%$$

To summarize, any added capacitance slows the source risetime when using high impedance passive probes. In general, the greater the attenuation ratio, the lower the tip capacitance. Here are some examples:

Probe	Attenuation	Tip Capacitance
Tektronix P6101A	X1	54 pF
Tektronix P6105A	X10	11.2 pF
Tektronix P6007	X100	2 pF

Capacitive Loading: Sinewave. When probing continuous wave (CW) signals, the probe's capacitive reactance at the operating frequency must be taken into account.

The total impedance, as seen at the probe tip, is designated Rp and is a function of frequency. In addition to the capacitive and resistive elements, designed-in inductive elements serve to offset the pure capacitive loading to some degree.

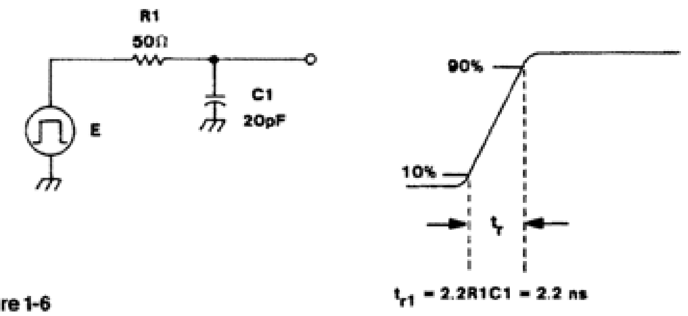

Figure 1-6

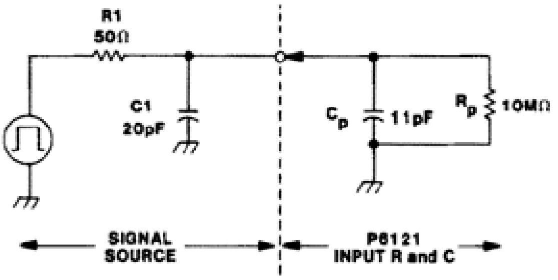

Figure 1-7

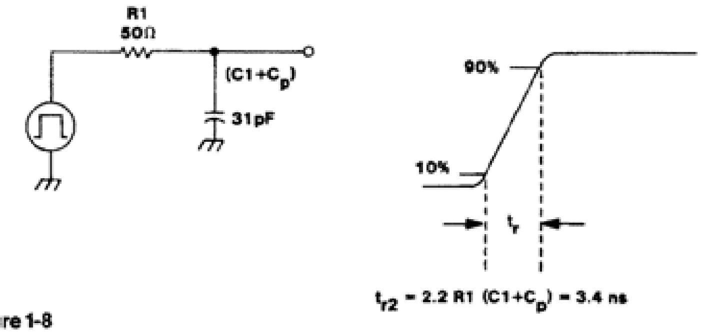

Figure 1-8

Curves showing typical input impedance vs frequency, or typical Xp and Rp vs frequency are included in most Tektronix probe instruction manuals. Figure 1-9A shows the typical input impedance and phase relationship vs frequency of the Tektronix P6203 Active Probe. Note that the 10 KΩ input impedance is maintained to almost 10 MHz by careful design of the associated resistive, capacitive and inductive elements.

Figure 1-9B shows a plot of Xp and Rp vs frequency for a typical 10 MΩ passive probe. The dotted line (Xp) shows capacitive reactance vs frequency. The total loading is again offset by careful design of the associated R, C and L elements.

If you do not have ready access to the information and need a worst-case guide to probe loading, use the following formula:

$$Xp = \frac{1}{2\pi FC}$$

Xp = Capacitive reactance (ohms)
F = Operating frequency
C = Probe tip capacitance (marked on the probe body or compensation box.)

For example, a standard passive 10M ohm probe with a tip capacitance of 11 pF will have a capacitive reactance (Xp) of about 290 ohm at 50MHz.

Depending, of course, on the source impedance, this loading could have a major effect on the

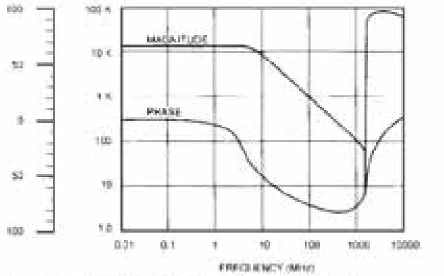

Figure 1-9A. Typical Input Impedance vs Frequency for the Tektronix P6203 Active Probe

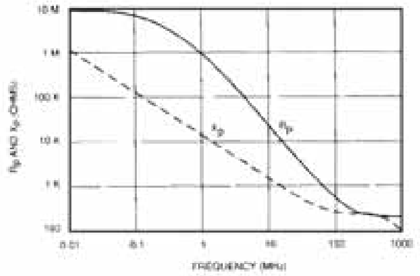

Figure 1-9B. Xp and Rp vs Frequency for a Typical 10 MΩ Passive Probe

signal amplitude (by simple divider action), and even on the operation of the circuit itself.

Resistive Loading. For all practical purposes, a 10X, 10M ohm passive probe has little effect on today's circuitry in terms of resistive loading, however, they do carry a trade-off in terms of relatively high capacitive loading as we have previously discussed.

Low Z Passive Probes. A "Low Z" passive probe offers very low tip capacitance at the expense of relatively high resistive loading. A typical 10X "50 ohm" probe has an input C of about 1 pF and a resistive loading of 500 ohm; Figure 1-10 shows the circuit and equivalent model of this type of probe.

This configuration forms a high frequency 10X voltage divider because, from transmission line theory, all that the 450 ohm tip resistor "sees" looking into the cable is a pure 50 ohm resistance, no C or L component. No low frequency compensation is necessary because it is not a capacitive divider. Low Z probes are typically high bandwidth (up to 3.5GHz and risetimes to 100 pS) and are best suited for making risetime and transit-time measurements. They can, however, affect the pulse amplitude by simple resistive divider action between the source and the load (probe). Because of its resistive loading effects, this type of probe performs best on 50 ohm or lower impedance circuits under test.

Note also that these probes operate into 50 ohm scope inputs only. They are typically teamed up with fast (500MHz to 1GHz) real time scopes or with scopes employing the sampling principle.

Bias-Offset Probes. A Bias/Offset probe is a special kind of Low Z design with the capability of providing a variable bias or offset voltage at the probe tip.

Bias/Offset probes like the Tektronix P6230 or P6231 are useful for probing high speed ECL circuitry, where resistive loading could upset the operating point. These special probes are fully described in Part 3; under Advanced Probing Techniques.

The Best of Both Worlds. From the foregoing, it can be seen that the totally "non-invasive" probe does not exist. However, one type of probe comes close—the active probe.

Active probes are discussed in the Tutorial section, but in general, they provide low resistance loading (10M ohm) with very low capacitive loading (1 to 2 pF). They do have trade-offs in terms of limited dynamic range, but under the right conditions, do indeed offer the best of both worlds.

Bandwidth. Bandwidth is the point on an amplitude versus frequency curve where the measurement system is down 3dB from a starting (reference) level. Figure 1-11 shows a typical response curve of an oscilloscope system.

Scope vertical amplifiers are designed for a Gaussian roll-off at the high end (a discussion of Gaussian response is beyond the scope of this primer). With this type of response, risetime is approximately related to bandwidth by the following equation:

$$\text{Tr} = \frac{.35}{\text{BW}} \qquad \text{or, for convenience:}$$

$$\text{Risetime (nanoseconds)} = \frac{350}{\text{Bandwidth (MHz)}}$$

It is important to note that the measurement system is −3dB (30%) down in amplitude at the specified bandwidth limit.

Figure 1-12 shows an expanded portion of the −3dB area. The horizontal scale shows the input frequency derating factor necessary to obtain accuracies better than 30% for a specific bandwidth scope. For example, with no derating, a "100MHz" scope will have up to a 30% amplitude error at 100MHz (1.0 on the graph). If this scope is to have an amplitude accuracy better than 3%, the input frequency must be limited to about 30MHz (100MHz X .3).

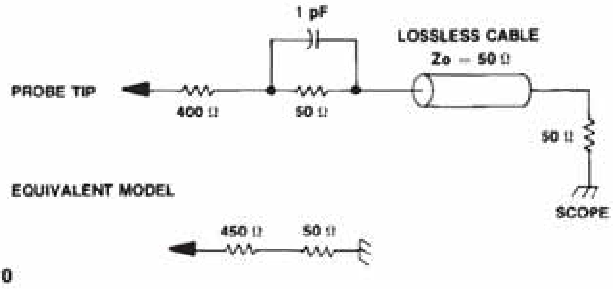

Figure 1-10

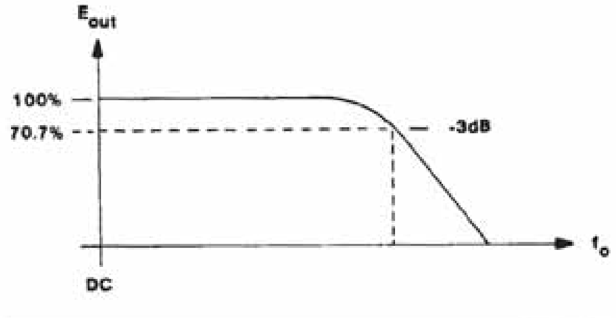

Figure 1-11

For making amplitude measurements within 3% at a specific frequency, choose a scope with at least four times the specified bandwidth as a general rule of thumb.

Probe Bandwidth. All probes are ranked by bandwidth. In this respect, they are like scopes or other amplifiers that are ranked by bandwidth. In these cases we apply the square root of the sum of the squares formula to obtain the "system risetime." This formula states that:

$\text{Risetime system} = \sqrt{\text{Tr}^2 \text{ displayed} - \text{Tr}^2 \text{ source}}$

Passive probes do not follow this rule and should not be included in the square root of the sum of the squares formula.

Tektronix provides a probe bandwidth ranking system that specifies "the bandwidth (frequency range) in which the probe performs within its specified limits. These limits include: total abberrations, risetime and swept bandwidth."

Both the source and the measurement system shall be specified when checking probe specifications (see Test Methods, this page).

In general, a Tektronix "100MHz" probe provides 100MHz performance (−3dB) when used on a compatible 100MHz scope. In other words, it provides full scope bandwidth **at the probe tip.**

However, not all probe/scope systems can follow this general rule. Refer to the sidebar, "Scope Bandwidth at the Probe Tip?."

Figure 1-13 shows examples of Tektronix scopes and their recommended passive probes.

Test Methods: As with all specifications, matching test methods must be employed to obtain specified performance. In the case of bandwidth and risetime measurements, it is essential to connect the probe to a properly terminated source. Tektronix specifies a 50 ohm source terminated in 50 ohm, making this a 25 ohm source impedance. Furthermore, the probe must be connected to the source via a proper probe tip to BNC adaptor. (Figure 1-14).

Figure 1-14 shows an equivalent circuit of a typical setup. The displayed risetime should be a 3.5 nSec or faster.

Figure 1-15 shows an equivalent circuit of a typical passive probe connected to a source.

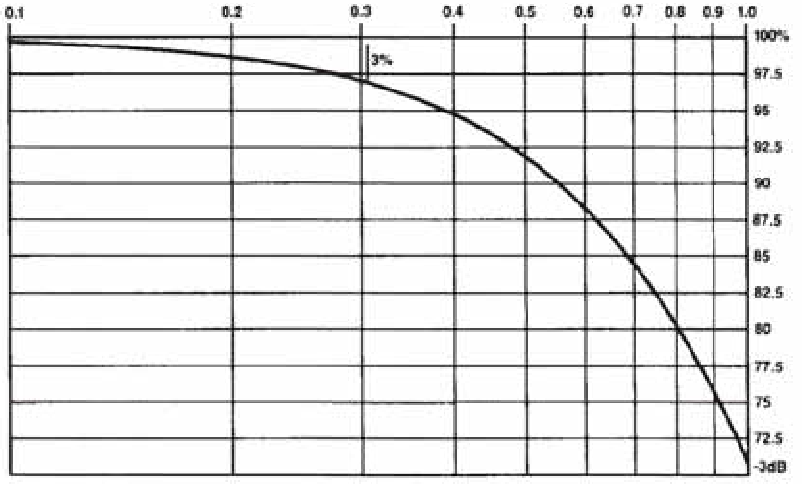

Figure 1-12

SCOPE	BW (1 MΩ input)	PROBE	BW	SYSTEM
2235	100	P6109	150	100
2245A	100	P6109	150	100
2246A	100	P6109	150	100
2445B	150	P6133 Opt 25	150	150
485	350	P6106A	250	250
2465B	400	P6137	400	400
2467B	400	P6137	400	400

Figure 1-13

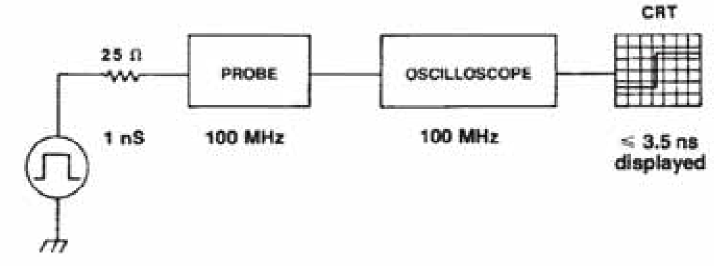

Figure 1-14

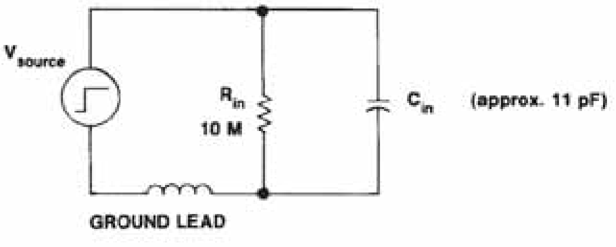

Figure 1-15

Scope Bandwidth at the Probe Tip ?

Most manufacturers of general-purpose oscilloscopes that include standard accessory probes in the package, promise and deliver the advertised scope bandwidth **at the probe tip.**

For example, the Tektronix 2465B 400 MHz Portable Oscilloscope and its standard accessory P6137 Passive Probes deliver 400 MHz (−3db) at the probe tip.

However, not all high performance scopes can offer this feature, even when used with their recommended passive probes. For example, the Tektronix 11A32 400 MHz plug-in has a system bandwidth of 300 MHz when used with its recommended P6134 passive probe. This is simply because even the highest impedance passive probes are limited to about 300 to 350 MHz, while still meeting their other specifications.

It is important to note that the above performance is only obtainable under strictly controlled, and industry recognized conditions; which states that the signal must originate from a 50 Ω back-terminated source (25 Ω), and that the probe must be connected to the source by means of a probe tip to BNC (for other) adaptor.

This method ensures the shortest ground path and necessary low impedance to drive the probe's input capacitance, and to provide the specified bandwidth at the signal acquisition point, the probe tip.

Real-world signals rarely originate from 25 Ω sources, so less than optimum transient response and bandwidth should be expected when measuring higher impedance circuits.

How ground leads affect measurements

A ground lead is a wire that provides a local ground-return path when you are measuring any signal. An inadequate ground lead (one that is too long or too high in inductance) can reduce the fidelity of the high frequency portion of the displayed signal.

What grounding system to use. When making **any** measurement, some form of ground path is required to make a basic two-terminal connection to the DUT. If you want to check the presence or absence of signals from low-frequency equipment, **and** if the equipment is line-powered and plugged into the same outlet system as the scope, then the common 3-wire ground system provides the signal ground return. However, this indirect route adds inductance in the signal path—it can also produce ringing and noise on the displayed signal and is not recommended.

When making any kind of absolute measurement, such as amplitude, risetime or time delay measurements, you should use the shortest grounding path possible, consistent with the need to move the probe among adjacent test points. The ultimate grounding system is an in-circuit ECB (etched circuit board) to probe tip adaptor. Tektronix can supply these for either miniature, compact or subminiature probe configurations.

Figure 1-15 shows an equivalent circuit of a typical passive probe connected to a source. The ground lead L and C_{in} form a series resonant circuit with only 10M ohm for damping. When hit with a pulse, it will ring. Also, excessive L in the ground lead will limit the changing current to C_{in}, limiting the risetime.

Without going into the mathematics, an 11pF passive probe with a 6-inch ground lead will ring at about 140MHz when excited by a fast pulse. As the ring frequency increases, it tends to get outside the passband of the scope and is greatly attenuated. So to increase the ring frequency, use the shortest ground lead possible and use a probe with the lowest input C.

Probe Ground Lead Effects. The effect of inappropriate grounding methods can be demonstrated several ways. Figs. 1-16A, B and C show the effect of a 12-inch ground lead when used on various bandwidth scopes.

In Figure 1-16A, the display on the 15MHz scope looks OK because the ringing abberations are beyond the passband of the instrument and are greatly attenuated. Figs. 1-16B and C show what the same signal looks like on 50MHz and 100MHz scopes.

Even with the shortest ground lead, the probe-DUT interface has the **potential** to ring. The potential to ring depends on the **speed** of the step function. The ability to **see** the resultant ringing oscillation depends on the scope system bandwidth.

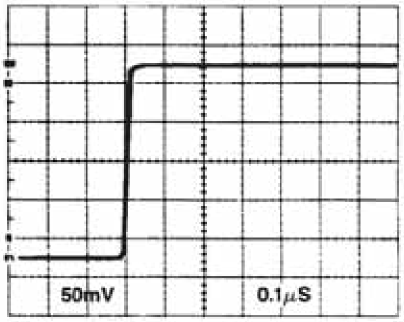

Figure 1-16A

Scope BW = 15MHz
Ground lead 12 inches

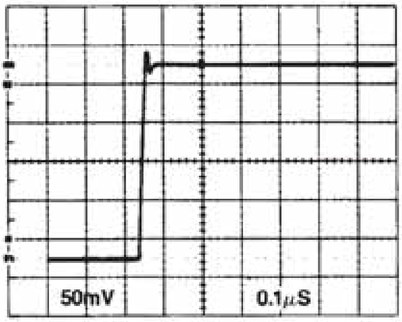

Figure 1-16B

Scope BW = 50MHz
Ground lead 12 inches

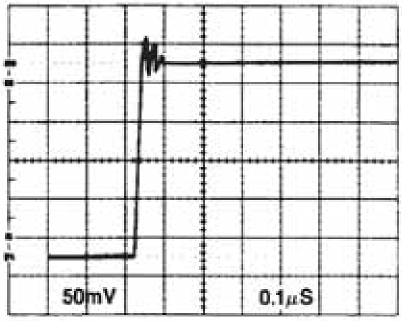

Figure 1-16C

Scope BW = 100MHz
Ground lead 12 inches

Figs. 1-17A through F show the effects of various grounding methods and ground lead lengths on the display of a very fast pulse. This is the most critical way of looking at ground lead effects: we used a fast pulse, with a risetime of about 70 pico seconds and a fast (400 MHz) scope with a matching P6137 probe.

Fig. 1-17A shows the input pulse under the most optimum conditions when using 50 ohm coax cable. Scope: the Tektronix 2465B with 50 ohm input and 50 ohm cable from a 50 ohm source. Displayed risetime is < 1 nSec.

Fig. 1-17B shows the same signal when using the scope-probe combination under the most optimum conditions. A BNC to probe adaptor or an in-circuit test jack provides a coaxial ground that surrounds the probe ground ring. This sytem provides the shortest probe ground connection available. Displayed risetime is < 1nSec.

Figures 1-17C through E show the effects of longer ground leads on the displayed signal. Fig. 1-17C shows the effect of a short semi-flexible ground connection, called a "Z" lead. Finally, Fig. 1-17F shows what happens when no probe ground lead is used.

How probe design affects your measurements

Probes are available in a variety of sizes, shapes and functions, but they do share several main features: a probe head, coaxial cable and either a compensation box or a termination.

The probe head contains the signal-sensing circuitry. This circuitry may be passive (such as a 9-M ohm resistor shunted by an 11 pF capacitor in a passive voltage probe or a 125-turn transformer secondary in a current probe); or active (such as a source follower or Hall generator) in a current probe or active voltage probe.

The coaxial cable couples the probe head output to the termination. Cable types vary with probe types.

The termination has two functions:

- to terminate the cable in its characteristic impedance.
- to match the input impedance of the scope.

The termination may be passive or active circuitry. For easy connection to various test points, many probes feature interchangeable tips and ground leads.

A unique feature of most Tektronix probes is the Tektronix-patented coaxial cable that has a resistance-wire center conductor. This distributed resistance suppresses ringing caused by impedance mismatches between the cable and its terminations when you're viewing fast pulses on wideband scopes.

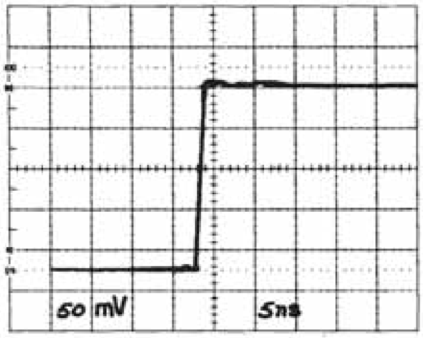

Figure 1-17A

50 ohm Source/Cable/2465B/50 ohm input

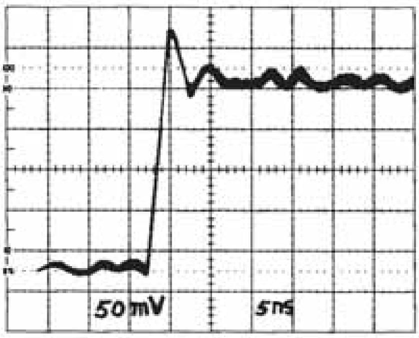

Figure 1-17C

P6137 - Probe/Z Ground Tr = 1.5 nS

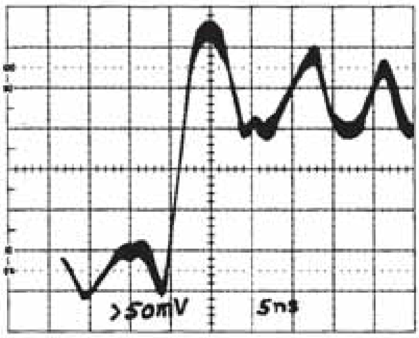

Figure 1-17E

P6137 - Probe/6" Gnd Lead Tr = 4 nS

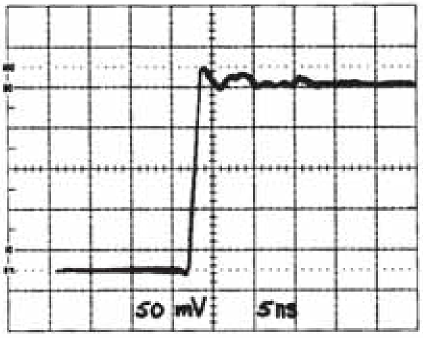

Figure 1-17B

P6137-BNC/Probe Adaptor Tr = < 1nS

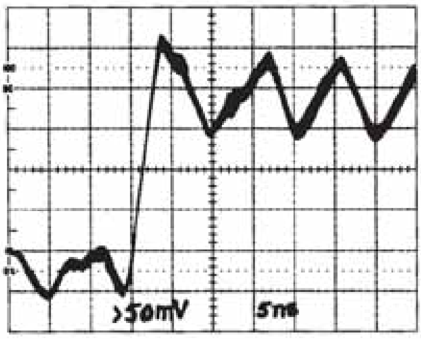

Figure 1-17D

P6137 - Probe/3" Gnd Lead Tr = 4 nS

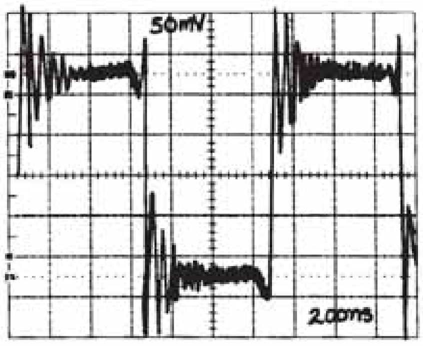

Figure 1-17F

No Ground Lead

PART II: EFFECTS OF PROBE COMPENSATION — UNDERSTANDING PROBES

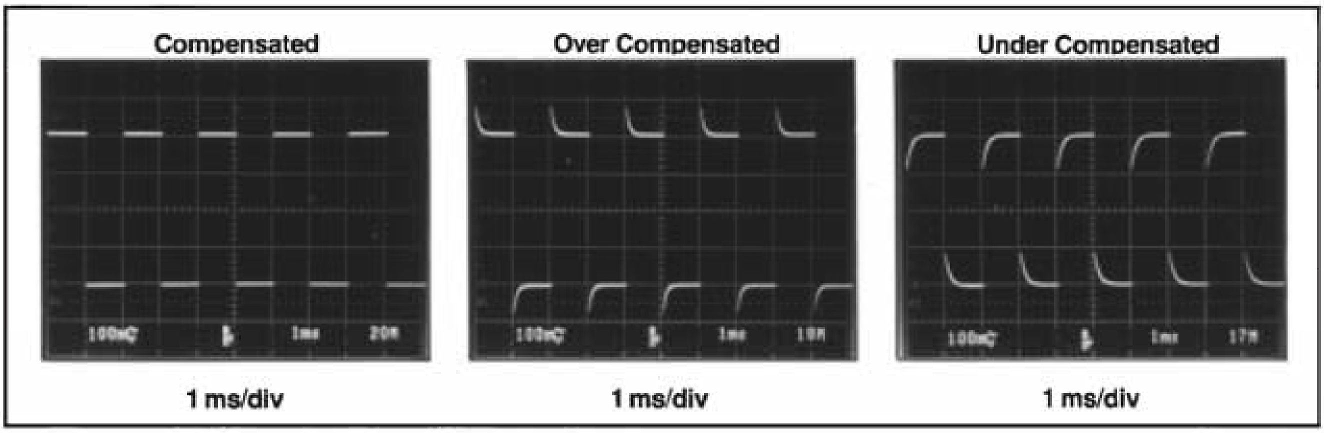

Figure 2-1. Shows the display associated with correctly and incorrectly compensated probes.

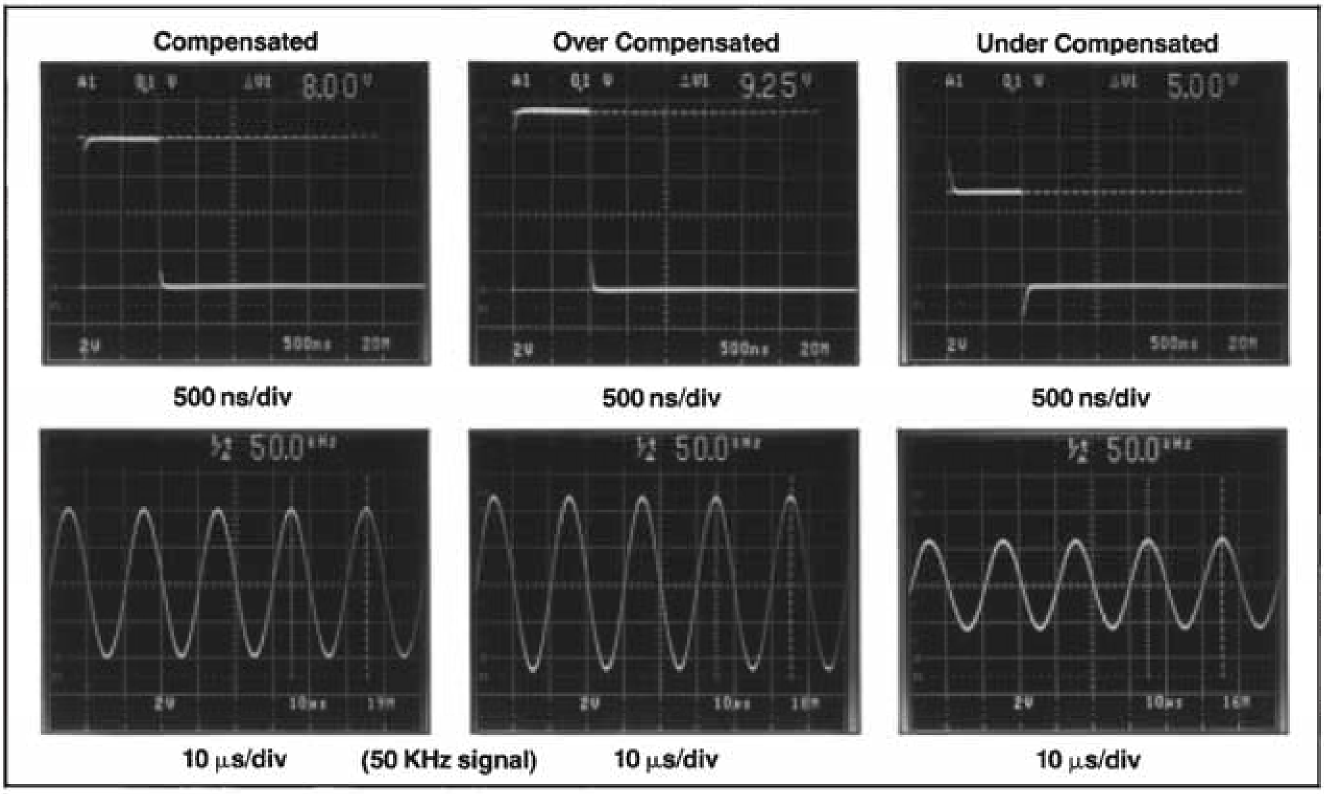

Figure 2-2. Shows the effects on faster pulses and sinewaves when an incorrectly compensated probe is used. Note that the much faster sweep rates used to correctly view these waveforms does not warn the user of an adjustment problem.

Tips on using probes

Compensating the probe. The most common mistake in making scope measurements is forgetting to compensate the probe. Improperly compensated probes can distort the waveforms displayed on the scope. The probe should be compensated as it will be used when you make the measurement.

The basic low frequency compensation (L.F. comp.) procedure is simple:

- Connect the probe tip to the scope CALIBRATOR (refer to Scope Calibrator Outputs.)
- Switch the channel 1 input coupling to dc.
- Turn on the scope and move the CH1 VOLTS/DIV switch to produce about four divisions of vertical display.
- Set the sweep rate to 1mSec/div. (for line-driven calibrators see Scope Calibrators Outputs.)
- Use a non-metalic alignment tool to turn the compensation adjust until the tops and bottoms of the square-wave are flat.

PART III: ADVANCED PROBING TECHNIQUES

Introduction:

In Part III we will examine some of the more advanced probing techniques associated with accessing high frequency and complex signals, such as fast ECL, waveforms offset from ground, and true differential signals.

Most of the techniques to be described follow recommended practices outlined throughout this Booklet, and to a large extent involve proper grounding techniques.

Workers in the audio and relatively low frequency fields may wonder what all the fuss is about, and may comment "I don't have any of these problems," or "I can't see any difference when I use different ground lead lengths, or even when I leave the ground lead completely off?"

In order to see abberrations caused by poor grounding techniques, two conditions must exist:

1. The scope system bandwidth must be great enough to handle the high frequency content existing at the probe tip.
2. The input signal must contain enough high frequency information (fast risetime) in order to cause ringing and aberrations due to poor grounding techniques.

To illustrate these points, a 20 MHz scope was used to access a 1.7 nS pulse by using a standard passive probe with a 6" ground lead.

NOTE: A fast scope can be made into a slow scope simply by pushing the Bandwidth Limit (B/W Limit) button ?.

We used a 350 MHz scope with a 20 MHz B/W Limit function.

Figure 3-1 shows the resultant clean displayed pulse with a risetime of about 20 nS (17.5 MHz).

This display does not represent conditions actually existing at the probe tip, because the 20 MHz measurement system cannot "see" what's really happening.

Figure 3-2 shows what the probe tip signal really looks like when a 350 MHz scope is used under the same conditions (B/W Limit off).

The observed risetime has improved to about 2 nS, but we have serious problems with ringing and aberrations, caused by incorrect grounding techniques.

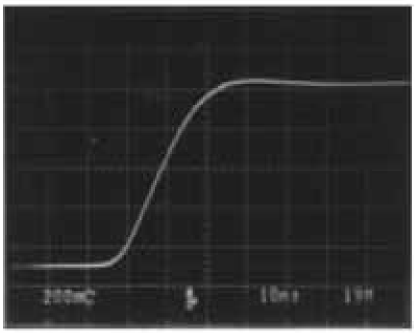

Figure 3-1. Resultant clean, but incorrect display caused by inadequate scope system bandwidth.

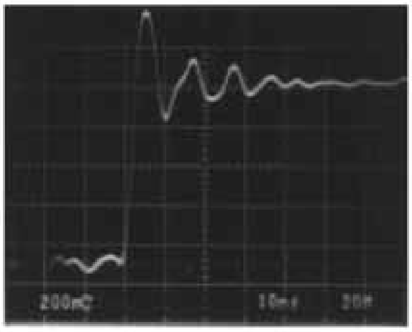

Figure 3-2. The same input signal as shown in figure 3-1, but accessed by a 350 MHz system bandwidth scope (same 6" ground lead).

The problem can now be seen because the scope system bandwidth is great enough to pass and display all the frequency content existing at the probe tip.

To further stress the points about high frequency content and scope system bandwidth, let's assume an input pulse with a risetime of about 20 nS. If the signal is accessed by the same probe /6" ground lead /350 MHz system, it would look very much like the display in figure 3-1.

There would be no frequency content higher than 17.5 MHz (20 nS Tr). The 6" ground lead would not ring, and would therefore be the correct choice for accessing this relatively slow signal.

In the following sections we discuss how to recognize signal acquisition problems, and how to avoid them.

Techniques for probing ECL, high speed 50 Ω environments, and accessing true differential signals are also discussed.

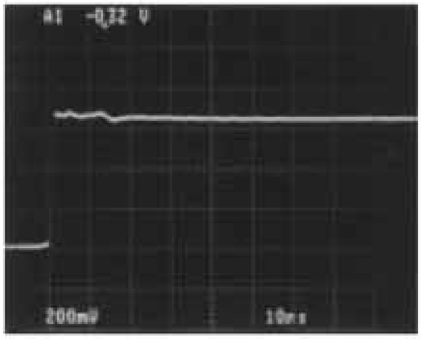

Figure 3-3. 1 nS Tr pulse accessed via an ECB to Probe Tip Adaptor (test point)

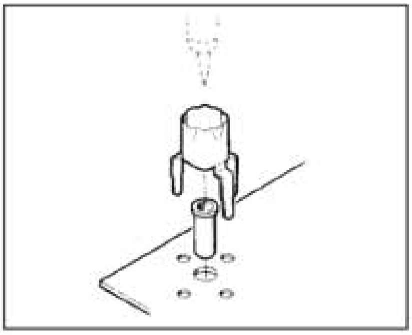

Figure 3-4. Typical ECB to Probe Tip Adaptor installation

Probe Ground Lead Effects. In Part I we discussed the basic need for probe grounding, and showed several different ways of looking at the effects of correct, and incorrect probe grounding.

In this section, we will expand upon these techniques and show how to identify problem areas.

When a probe (high Z, low Z, passive or active) is connected to the circuit under test via an ECB to Probe Tip Adaptor (test point), the coaxial environment existing at the probe tip is extended through the adaptor to the signal pick-off point, and to the ECB ground plane (or device ground).

Figure 3-3 shows what a typical 1 nS Tr pulse looks like when a suitable probe is connected to the circuit via an ECB to Probe Tip Adaptor.

Figure 3-4 shows a typical ECB to Probe Tip Adaptor (test point) installation.

These test points are available in three sizes to accept miniature, compact or sub-miniature series probes.

If a flexible ground lead is used in place of the ECB to Probe Tip Adaptor, the 1 nS Tr input step (with high frequency content up to 350 MHz) will cause the ground lead to ring at a frequency determined by the ground lead inductance and the probe tip and source capacitance.

Figure 3-5 shows the effect of using a 6" ground lead to make the ground connection.

The ring frequency for the 6" ground lead/probe tip C combination is 87.5 MHz. This signal is injected in series with the wanted signal and appears at the probe tip, as shown in figure 3-6.

Unfortunately, the problem is not this simple.

The probe's coaxial environment has been disrupted at the signal acquisition point by ground lead inductance, and is no longer correctly terminated (for high speed signal acquisition).

This abrupt transition leaves the probe's outer shield susceptible to ring frequency injection (the ground lead inductance is in series with the outer braid)

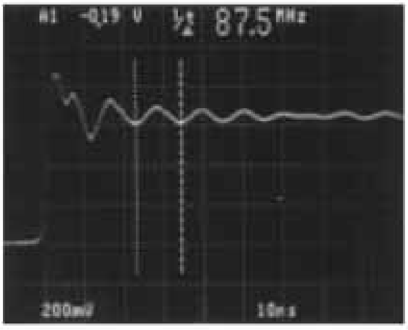

Figure 3-5. Effect of a 6" ground lead on a 1 nS Tr input step.

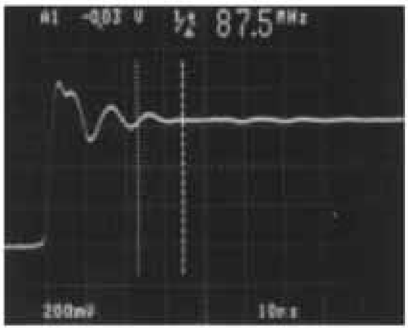

Figure 3-7. The same setup as in figure 3-5, except that the probe cable has been repositioned, and a hand has been placed over part of the probe cable.

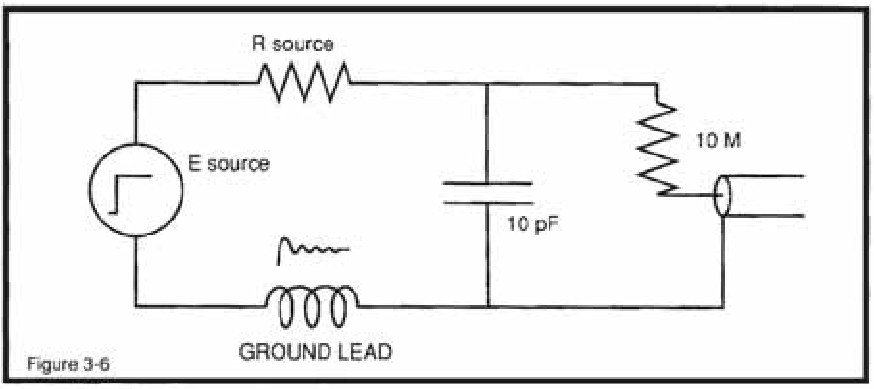

Figure 3-6. Equivalent circuit, ground lead inductance (excess inductance).

The now unterminated probe cable system develops reflections, which intermix with the ring frequency and the signal to produce a multitude of problems and unpredictable results.

Herein lies the key to the identification of ground lead problems.

Figure 3-7 shows exactly the same setup as in figure 3-5, except that the probe cable has been moved, and a hand has been placed over part of the probe cable.

KEY: If touching or moving the probe cable produces changes in the display, you have a probe grounding problem.

A correctly grounded (terminated) probe should be completely insensitive to cable positioning or touch.

Ground Lead Length. All things being equal, the shortest ground lead produces the highest ring frequency.

If the lead is very short, the ring frequency might be high enough to be outside the passband of the scope, and/or the input frequency content may not be high enough to stimulate the ground lead's resonant circuit.

In all cases, the shortest ground lead should be used, consistant with the need for probe mobility.

If possible, use 3" or shorter ground leads, such as the Low Impedance Contact (Z Lead). These are supplied with the Tektronix P613X and P623X family or probes.

One final note. The correct probe grounding method depends on the signal's high frequency content, the scope system bandwidth, and the need for mobility between test points.

A 12" ground lead may be perfect for many lower frequency applications. It will provide you with extra mobility, and nothing will be gained by using shorter leads.

If in doubt, apply the cable touch test outlined previously.

Ground Loop Noise Injection. Another form of signal distortion can be caused by signal injection into the grounding system.

This can be caused by unwanted current flow in the ground loop existing between the common scope and test circuit power line grounds, and the probe ground lead and cable.

Normally, all these points are, or should be at zero volts, and no ground current will flow.

However, if the scope and test circuit are on different building system grounds, there could be small voltage differences, or noise on one of the building ground systems.

The resulting current flow (at line frequency or noise frequency) will develop a voltage drop across the probe cable's outer shield, and be injected into the scope in series with the desired signal.

Inductive Pickup in Ground Loops. Noise can enter a common ground system by induction into long 50 Ω signal acquisition cables, or into standard probe cables.

Proximity to power lines or other current-carrying conductors can induce current flow in the probe's outer cable, or in standard 50 Ω coax. The circuit is completed through the building system common ground.

Prevention of Ground Loop Noise Problems. Keep all signal acquisition probes and/or cables away from sources of potential interference.

Verify the integrity of the building system ground.

If the problem persists, open the ground loop:

1. By using a Ground Isolation Monitor like the Tektronix A6901.
2. By using a power line isolation transformer on either the test circuit or on the scope.
3. By using an Isolation Amplifier like the Tektronix A6902B.
4. By using differential probes (see Differential Measurements).

NOTE: Never defeat the safety 3-wire ground system on either the scope or on the test circuit.

Do not "float" the scope, except by using an approved isolation transformer, or preferably, by using the Tektronix A6901 Ground Isolation Monitor.

The A6901 automatically reconnects the ground if scope ground voltages exceed ± 40 V.

Induced Noise in Probe Ground Leads. The typical probe ground lead resembles a single-turn loop antenna when it is connected to the test circuit.

The relatively low impedance of the test circuit can couple any induced voltages into the probe, as shown in figure 3-8.

High speed logic circuits can produce significant electro-magnetic (radiated) noise at close quarters.

If the probe ground lead is positioned too close to certain areas on the board, interference signals could be picked up by the loop antenna formed by the probe ground lead, and mix with the probe tip signal.

Question: Is this what my signal really looks like?

Moving the probe ground lead around will help identify the problem.

If the **noise level** changes, you have a ground lead induced noise problem.

A more positive way of identification is to disconnect the probe from the signal source and clip the ground lead to the probe tip.

Now use the probe/ground lead as a loop antenna and search the board for radiated noise.

Figure 3-9 shows what can be found on a logic board, **with the probe tip shorted to the ground lead.**

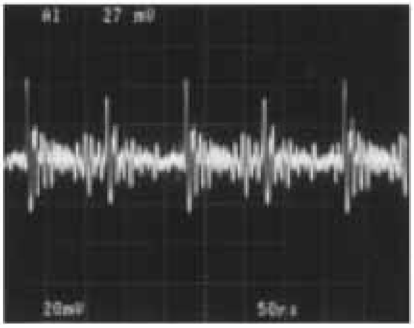

Figure 3-9. Induced noise in the probe ground loop (tip shorted to the ground clip).

This is radiated noise, induced in the single-turn loop and fed to the probe tip.

The significance of any induced or injected noise increases with reduced working signal levels, because the signal to noise ratio will be degraded. This is especially true with ECL, where signal levels are 1 V or less.

Prevention: If possible, use an ECB to Probe Tip Adaptor (test point). If not, use a Z Lead or short flexible ground lead.

Also, bunch the ground lead together to make the loop area as small as possible.

Bias Offset Probes. A Bias/Offset probe is a special kind of Low Z design with the capability of providing a variable bias or offset voltage at the probe tip.

Bias/Offset probes like the Tektronix P6230 and P6231 are useful for probing high speed ECL circuitry, where resistive loading could upset the operating point.

They are also useful for probing higher amplitude signals (up to ± 5 V), where resistive loading could affect the DC level at some point on the waveform.

Bias/Offset probes are designed with a tip resistance of 450 Ω (10X). When these probes are connected into a 50 Ω environment, this loading results in a 10% reduction in peak to peak source amplitude. This round-figure loading is more convenient to handle than that produced by a standard 500 Ω (10 X) Low Z probe, which would work out at 9.09% under the same conditions.

It is important to note that bias/offset probes always present a 450 Ω resistive load to the source, regardless of the bias/offset voltage selected.

The difference between bias/offset and standard Low Z probes lies in their ability to null current flow **at some specific and selectable point** on the input waveform (within ± 5 V).

To see how bias/offset probes work, let's take a typical 10 × 500 Ω Low Z probe and connect it in the circuit shown in figure 3-10.

By taking a current flow approach we find that at one point on the waveform the source voltage is − 4 V, therefore the load current will be;

$$I = ER - 4/Rs + Rp + R\,scope - 4/550 = 7.27\ \text{mA.}$$

Therefore the voltage drop across the 50 Ω source resistance (Rs) will be;

$$E = IR = 7.27 \times 10^{-3} \times 50 = 0.363\ \text{V}$$

And the measured pulse amplitude will be −4 −0.363 = 3.637 V (E dut), or about 9% down from its unloaded state.

If we substitute the 500 Ω Low Z probe with a 450 Ω bias/offset probe, the circuit will look like figure 3-11.

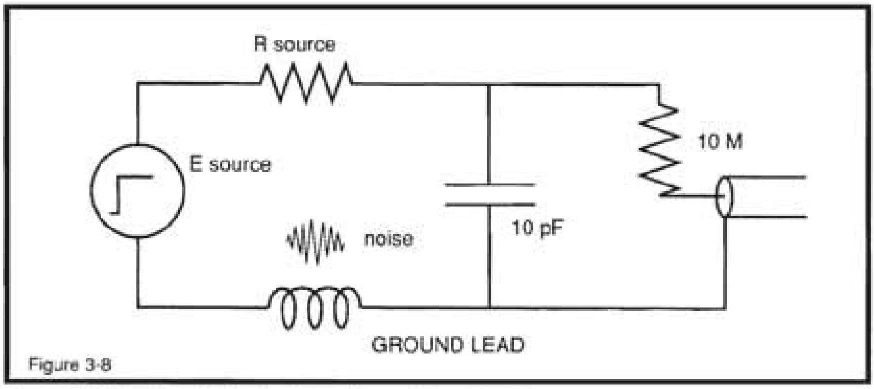

Figure 3-8

Figure 3-8. Equivalent Circuit. Ground Lead Induced Noise.

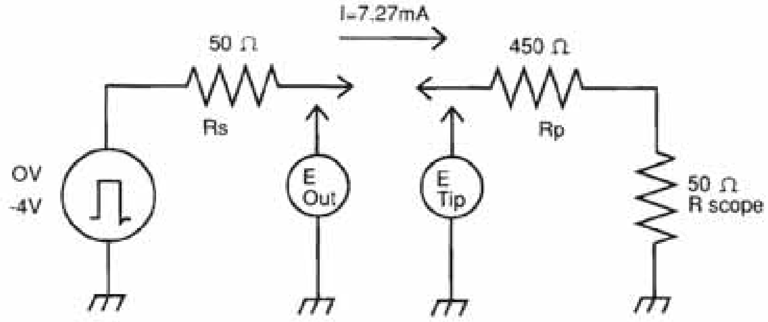

Figure 3-10

Figure 3-10. Low Z 10X 500 Ω probe connected to a 50 Ω source.

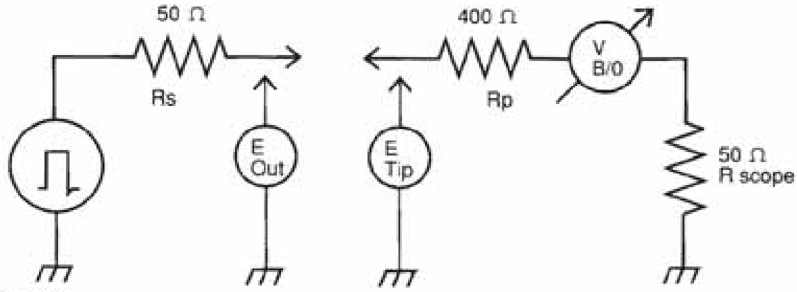

Figure 3-11

Figure 3-11. A 450 Ω Bias/Offset probe connected to a 50 Ω source.

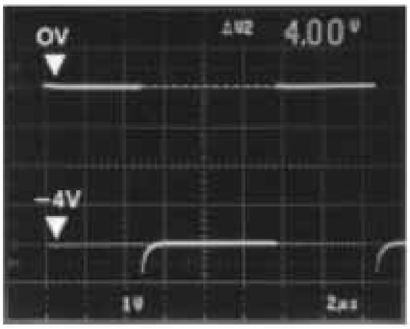

Figure 3-12. Unloaded negative-going 4 V pulse acquired by a 10 M Ω probe.

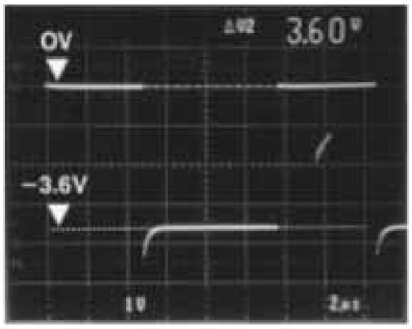

Figure 3-13. Effect of connecting a 450 Ω Bias/Offset probe (offset = 0 V). Minus level has been reduced by 10%.

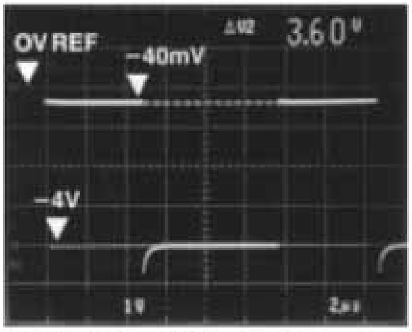

Figure 3-14. Bias/Offset adjusted for −4 V. Signal current at the −4 V level is zero. Current flow at ground level is maximum. Peak to peak amplitude remains the same (10% down).

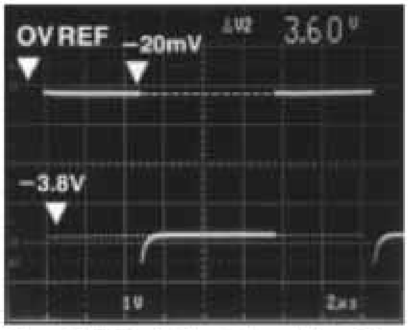

Figure 3-15. Bias/Offset adjusted for −2 V. Load current distributed between the negative and positive-going swings. Peak to peak amplitude remains the same (10% down).

With the bias/offset adjusted for 0 V, the effect on the circuit will be similiar to a 500 Ω Low Z probe, except for the small resistive change.

Figure 3-12 shows the source waveform acquired by a 10 M Ω probe.

Figure 3-13 shows the effect on the waveform when the 450 Ω probe is added.

As expected, the pulse amplitude has reduced from −4 V to 3.60 V, or exactly 10% down.

Figure 3-14 shows the effect of adjusting the offset to −4 V. The −4 V bias opposes the signal at the −4 V level and results in zero current flow, and the source is effectively unloaded **at this point.**

However, when the signal returns to ground level, there is a 4 V differential between the top of the pulse and the bias/offset source. Current will flow, and Ohms Law will dictate that the top of the pulse will go negative by −40 mV (10%).

Sometimes it is desirable to adjust the offset mid-way between the peak to peak excursions. This distributes the effect of resistive loading between the two voltage swings.

Figure 3-15 shows the effect of adjusting the bias/offset to −2 V. Current flow will be the same for both signal swings, and they will be equally down by 5%, for a total of 10%.

Summary:

1. Bias/Offset probes can be adjusted (within ± 5 V) to provide zero resistive (effective) loading at one selected point on the input waveform.
2. Bias/Offset probes can be used to simulate the effect of pull-up or pull-down voltages (within ± 5 V) on the circuit under test (voltage source impedance is 450 Ω).
3. Bias/Offset probes always present a total resistive load of 450 Ω, and reduce the peak to peak amplitude of 50 Ω sources by 10%.
4. For simplicity, we have ignored the effects of capacitive loading. Typically, Bias/Offset probes have less than 2 pF tip C.

Bias/Offset probes like the Tektronix P6230 or P6231 have bandwidths to 1.5 GHz, 450 Ω input R, and 1.3 pF (P6230), or 1.6 pF (P6231) input C.

They provide offset voltages of ± 5 V DC, and function with 1 M Ω or 50 Ω input systems (P6231, 50 Ω only).

The P6230 obtains operating power, either from the scope itself, or from the Tektronix 1101A or 1102 Power Supply.

The P6231 is designed to operate with the Tektronix 11000 Series scopes, and obtains operating power and bias/offset from the scope. Offset is selectable from the mainframe touch screen.

Differential Probing Techniques. Accessing small signals elevated from ground, either at an AC level or a combination of AC and DC, requires the use of differential probes and a differential amplifier system.

One of the problems associated with differential measurements is the maintenance of high common mode rejection ratio (CMRR) at high common mode frequencies.

Poor common mode performance allows a significant portion of the common (elevated) voltage to appear across the differential probe's inputs. If the common mode voltage is pure DC, the result may only be a displayed baseline shift. However, if the common mode voltage is AC, or a combination of AC and DC, a significant portion may appear across the differential input and will mix with the desired signal.

Figure 3-16 shows the basic items necessary to make a differential measurement.

In this example two similar but un-matched passive probes are used. The probe ground leads are usually either removed or clipped together. They are **never** connected to the elevated DUT (device under test).

CMRR depends upon accurate matching of the probe-pair's electrical characteristics, including cable length. System CMRR can be no better than the differential amplifier's specifications, and in all cases, CMRR degrades as a function of frequency.

Figure 3-17 shows a simplified diagram of a DUT with a pulsed output of 1 V p-p floating on a 5 V p-p 20 MHz sinewave.

CMRR at 20 MHz is a poor 10:1 because of the un-matched probes.

Observed signal. (referred to probe input) = 1 V p-p pulse + (5 V p-p sine/10) = 1 V p-p pulse + 0.5 V p-p sine.

Figure 3-18a shows what the displayed waveform might look like under the conditions shown in figure 3-17.

In comparison, figures 3-18b and 3-18c show what the displayed signal might look like at CMRR's of 100:1 and 1000:1.

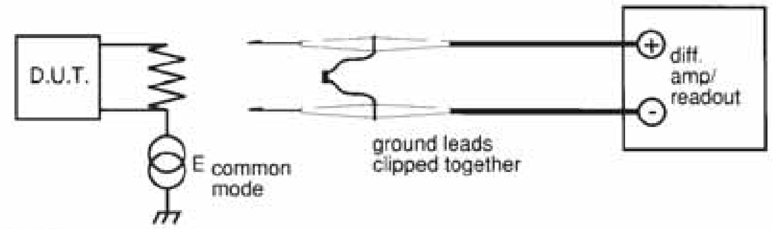

Figure 3-16

Figure 3-16. Basic connections to a device under test to make a differential measurement.

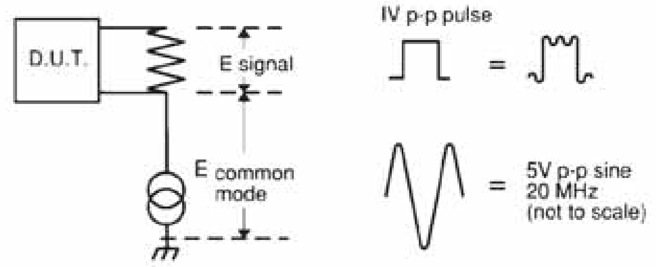

Figure 3-17

Figure 3-17. Simplified diagram. Elevated DUT. Common mode rejection is 10:1 at 20 MHz.

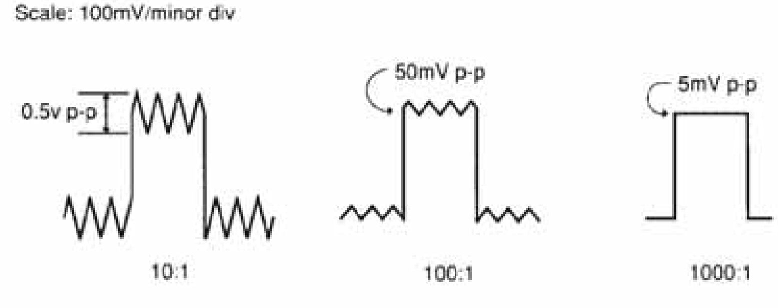

Figure 3-18

Figures 3-18, a, b and c. Displayed waveforms from the circuit shown in figure 3-17 at CMRR's of 10:1, 100:1 and 1000:1.