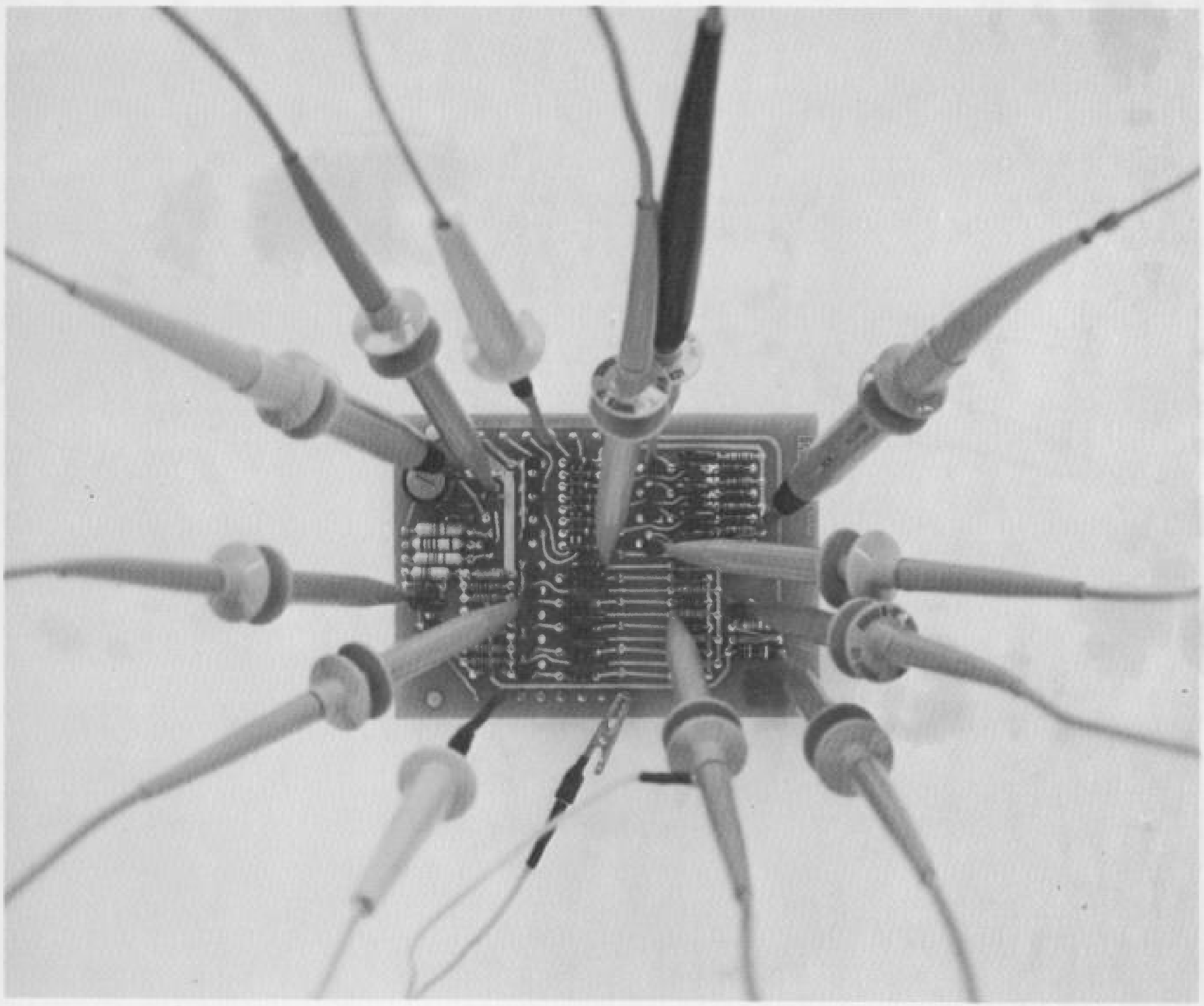
APPLICATION NOTE 152

PROBING IN PERSPECTIVE



HEWLETT hp PACKARD

OSCILLOSCOPE SYSTEMS

APPLICATION NOTE 152

PROBING IN PERSPECTIVE

by

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INTRODUCTION

For many years, oscilloscopes have been the chief test and analysis instruments used by electronic engineers and technicians. In recent years, new techniques and components have extended oscilloscope measurement capabilities to many new applications. However, the oscilloscope is a useful measurement instrument only if the test signal can be accurately coupled to the amplifiers. In many applications, the voltage probe is the only practical method to pick-off and apply the signal. With the increased bandwidths in today's scopes, one probe cannot be used for all measurements. This application note provides an approach that will allow you to select the best probe for most commonly encountered oscilloscope measurement situations. Major areas covered are:

(a) How to select the most accurate scope/probe for a particular measurement.

(b) How to quickly evaluate a given scope/probe for its adequacy in a particular measurement situation.

(c) How to quickly estimate errors caused by the probe.

Almost any probe/scope combination can be used to view a waveform. However, making accurate measurements requires careful attention to proper probe selection.

Since all probes inherently create some error, the objective is to select a probe that reduces the error to an acceptable (or known) level. Proper probe selection increases the confidence you can put into oscilloscope measurements. Part of your confidence comes from knowing your scope, but the right probe determines whether or not the full accuracy potential of your oscilloscope is realized.

SIGNAL SOURCE LOADING

The ideal probe couples an exact replica of the test signal to an oscilloscope input without disturbing the source. Of course, no input system is ideal; therefore we can only attempt to minimize the undesirable effects of resistive and capacitive loading. Oscilloscope inputs may be characterized as a resistance shunted by some capacitance as shown in figure 1.

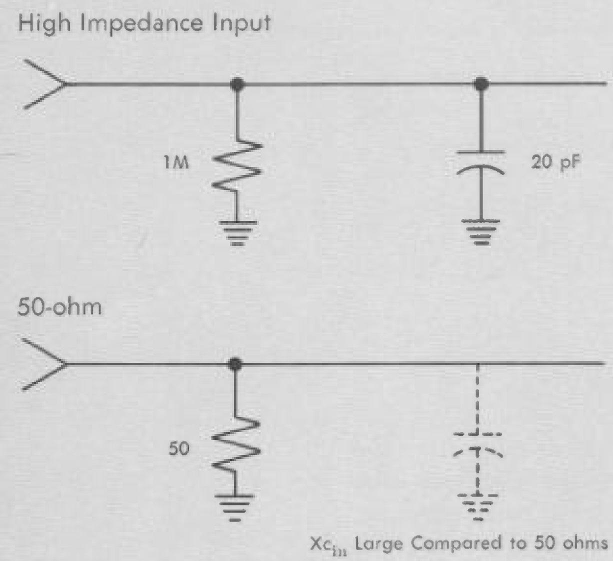


Figure 1. Typical Oscilloscope Inputs

When a probe is added to the scope input, the probe/scope combination may still be represented by an equivalent R and a shunt C. Values and tolerances for R, C, and the division ratio are normally specified in the probe data sheet. These values can be used to estimate loading effects of the probe/scope input system.

RESISTIVE LOADING

If the input resistance of the probe/scope combination is the same order of magnitude as that of the signal source, significant measurement errors will result because of resistive loading. Some possible effects of resistive loading are:

1. CW amplitude attenuation.
2. Pulse amplitude attenuation.
3. Additional current drawn from the signal source may force a circuit into saturation or nonlinear operation.
4. The circuit under test may stop operating.

Figure 2. Equivalent Circuit of a Resistive Load.

Referring to figure 2, the amplitude measurement error caused by resistive loading may be computed from the expression:

$$\text{Percent error} = \frac{R_g}{R_g + R_{in}} \times 100,$$

where:

R_g = SIGNAL SOURCE RESISTANCE

R_{in} = PROBE/SCOPE INPUT RESISTANCE

One rule-of-thumb to keep resistive loading errors below 1% is to select a probe/scope that has an R_{in} that is at least 100 times greater than the source impedance.

CAPACITIVE LOADING

Most oscilloscopes have some capacitance in shunt with their input resistance. This capacitance causes measurement errors that are frequency variable. The input capacitance of an oscilloscope requires careful attention to probe selection if these errors are to be minimized. Some problems that become increasingly evident as the input shunt capacitance increases are:

1. CW amplitude attenuation.
2. CW phase shift.
3. Induced pulse perturbations.
4. Inaccurate pulse rise time measurements.
5. Inaccurate propagation delay measurements.
6. Excessive source loading.
7. Abnormal circuit operation.

At high frequencies, the oscilloscope input behaves like a low pass filter which shunts the high frequency information to ground and significantly reduces the oscilloscope input impedance. For example, at 30 MHz the X_c for 20 pF is 265 ohms, while at 100 MHz it drops to 80 ohms. As will be shown in later sections, many measurements, especially phase shift and pulse rise time, are more adversely affected by input capacitance than by resistive loading. The capacitive reactance of an oscilloscope input varies as a function of frequency as shown in figure 3 for input capacitances of 1, 10, and 100 pF. An equivalent circuit of a capacitive load is shown in Figure 4.

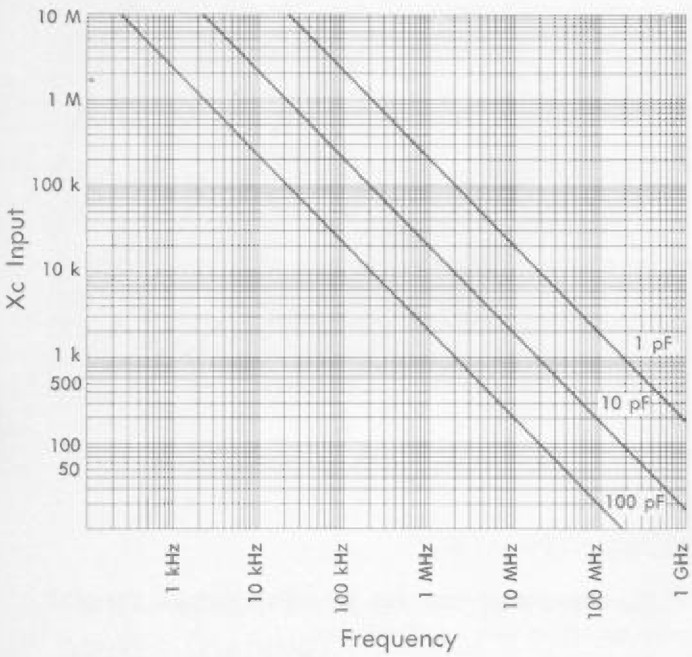
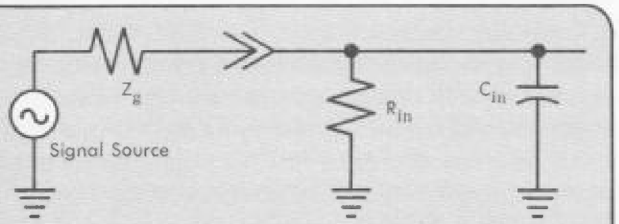


Figure 3. Capacitive Reactance as a Function of Frequency.



Z_g = Source Impedance

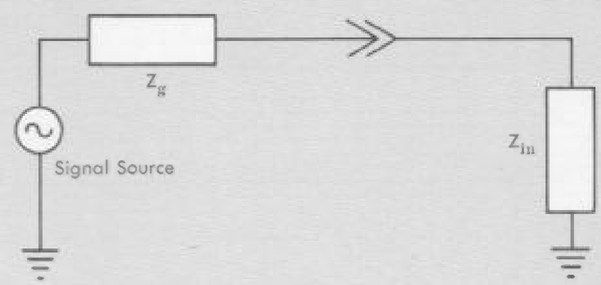
R_{in} = Input Resistance

C_{in} = Input Capacitance

Figure 4. Equivalent Circuit of a Capacitive Load.

COMBINED EFFECTS OF RESISTIVE AND CAPACITIVE LOADING

Since Z_{in} consists of the parallel combination of R_{in} and X_c, neither can be neglected if both are of the same order of magnitude. Input impedance for the simplified circuit in Figure 5 is calculated by the expression:



$$Z_{in} = \frac{R_{in} \quad Xc_{in}}{\sqrt{R^2_{in} + Xc_{in}^2}}, \text{ where } Xc_{in} = \frac{1}{2\pi \quad fC_{in}}$$

Z_g = Source Impedance

Z_{in} = Input Impedance

Figure 5. Input Impedance Equivalent Circuit.

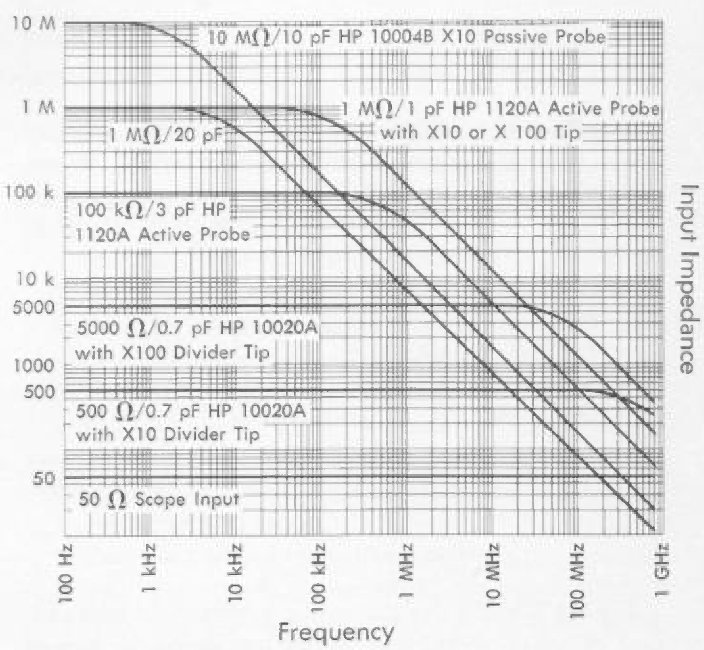


Figure 6. Probe/Scope Input Impedance Changes as a Function of Frequency.

It can be seen from the previous expression that Z_{in} cannot be higher than the smaller of R_{in} or X_c but can be significantly lower than either. And as frequency increases, $X_{c\ in}$ can drop significantly below the input R. The input impedance of some probe/scope combinations and how they vary with frequency is shown in figure 6.

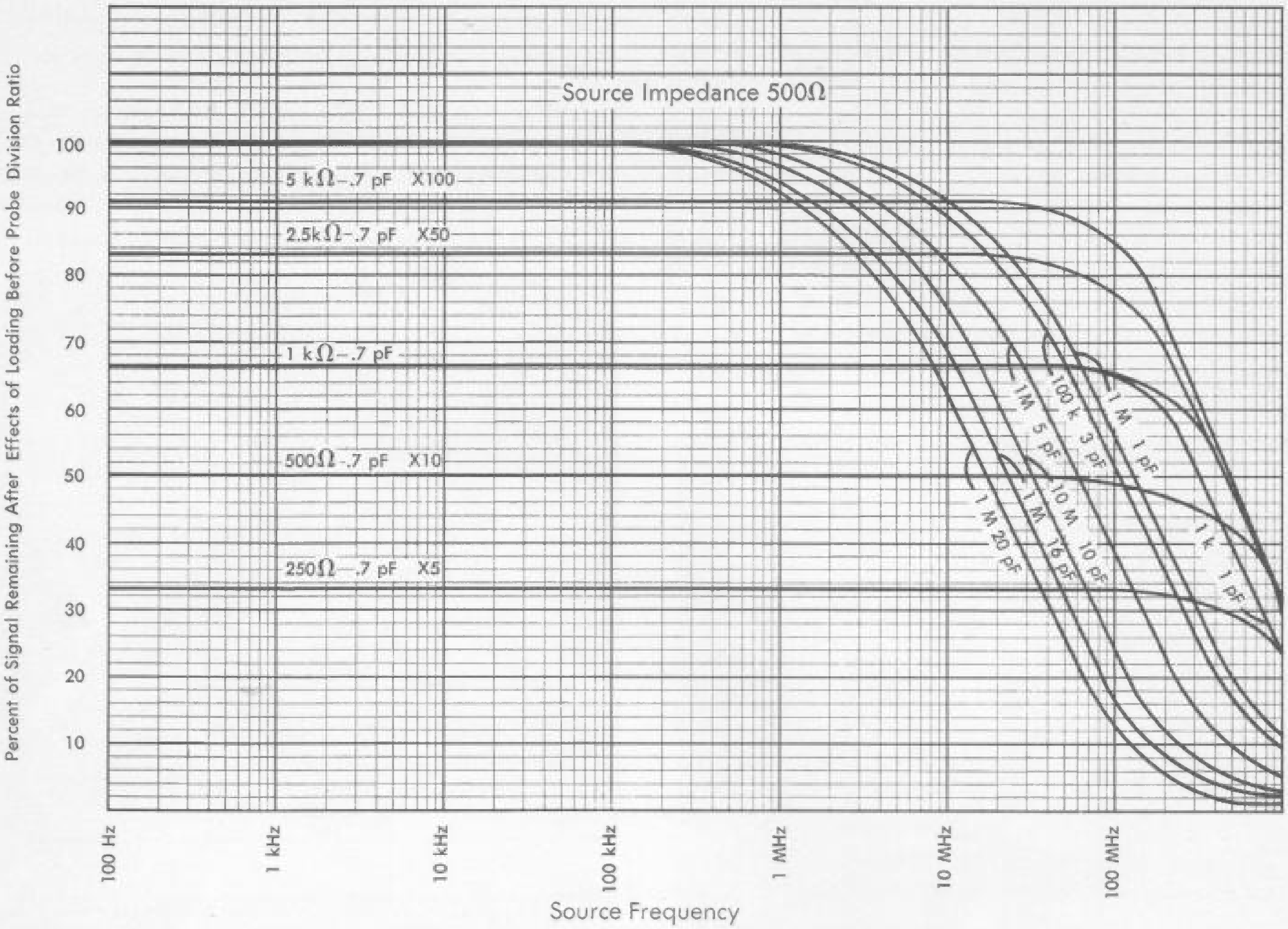


Figure 7. Probe Loading Effects for Source Impedance of 500 ohms.

Signal loss from loading effects caused by probe/scope can be expressed as a function of Z_{in} source impedance, and frequency.

$$\text{PERCENT SIGNAL LOSS} = \frac{Z_{in}}{Z_{in} + Z_g} \times 100,$$

$$\text{where } Z_{in} = \frac{R_{in} \quad X_{c\,in}}{\sqrt{R^2_{in} + X^2_{c_{in}}}} \quad \text{and} \quad X_{c_{in}} = \frac{1}{2\pi f\ C_{in}}$$

Figures 7 and 8 use the above equations to plot percent of signal remaining versus frequency for source impedances of 500 and 5000 ohms and are useful for making quick evaluations of CW amplitude errors caused by the loading of various commonly used probes. The break in these curves occurs at frequencies where capacitive loading first becomes significant. While these curves do show source loading they do not indicate the constant signal attenuation resulting from the probe division ratio.

An example of how the curves in figures 7 and 8 may be effectively used follows:

Assume that a selection between two probes must be made for a CW amplitude measurement from a 500 ohm source. Probe 1 is 10 megohm, 10 pF, 10:1 division ratio; Probe 2 is 500 ohms, 0.7 pF, 10:1 division ratio. The problem is to determine which probe to use for a 50 MHz CW amplitude measurement. Figure 7 shows that for source frequencies above approximately 33 MHz, Probe 2 (500Ω/0.7pF) causes less source loading than Probe 1 and therefore provides a more accurate measurement solution. Conversely, for frequencies below 33 MHz, Probe 1 (10 MΩ/10 pF creates less loading. The input impedance of Probe 2 is lower than Probe 1 at dc, is higher than Probe 1 for frequencies above 33 MHz, and relatively constant over a broad frequency range. The relatively high input capacitance of Probe 1 causes its input impedance to rapidly decrease with increasing source frequency.

The significant point to remember from this example is that because of the effects of input capacitance, probes with high values of input resistance can be much less accurate than probes with a much lower input resistance.

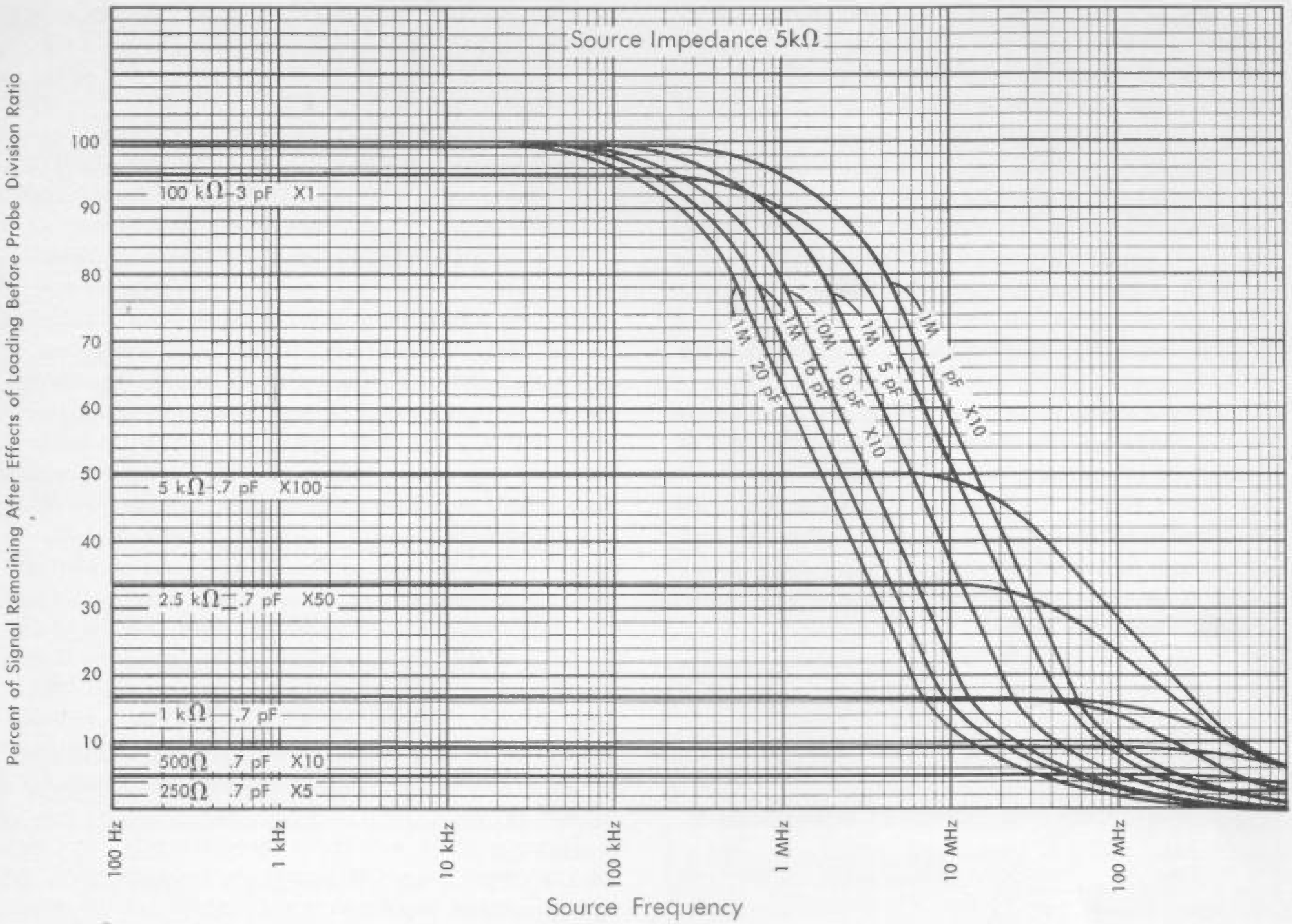


Figure 8. Probe Loading Effects for Source Impedance of 5 k ohms.

SIGNAL LOSS (PROBE DIVISION RATIO vs. SOURCE LOADING)

It is important to recognize the distinction between signal loss caused by variable loading and signal loss caused by the constant probe division ratio. Both combine to reduce the signal level available for display. However, the probe division ratio is specified as constant* within a certain percentage over a stated frequency range and is therefore easily accounted for. Loading losses, on the other hand, depend on source impedance and frequency and are not easily estimated. Loading degrades accuracy and reduces the signal voltage at the input while the probe division ratio only reduces the signal input voltage by a known constant factor.

COMMONLY AVAILABLE PROBES

Voltage probes may be grouped according to their ability to minimize resistive, capacitive, or both types of loading. It is useful to classify probes into three groups since each group has unique capabilities and limitations. They are: Group I, high resistance; Group II, miniature passive divider; and Group III, active. These groups along with their major features are presented below. Table 1 lists typical probes aavilable from various manufacturers.

Group I: High Resistance Probes

1. Minimize resistive loading.
2. Input impedance is high at dc, but due to high input capacitance (see figure 7), falls off rapidly with increasing frequency.
3. Input capacitance can be reduced somewhat if high division ratios (100:1) are practical (this depends on the test signal level and scope vertical amplifier sensitivity).
4. High dynamic range.
5. Best used where capacitive loading is not a critical factor; for example, pulse amplitude measurements or when the source impedance is known to be in the 50-ohm region.
6. Can be typically used with signals up to several hundred volts.

Group II: Miniature Passive Divider Probes

1. Lowest input capacitance available in a probe.
2. Used mainly when resistive loading is not a major consideration.
3. Fastest rise time available.

*Probe division ratio is constant to within a few percent only if the probe is properly compensated so that its RC time constant matches the scope input RC time constant.

4. Divider ratios ranging from 1:1 to 100:1 depending on divider tip.

5. Maximum input voltage not as high as Group I.

6. Best used for fast rise time measurements, phase shift measurements, and high frequency measurements if some resistive loading is acceptable.

7. Source loading is relatively high at dc but remains constant over a broad frequency range, thus loading is easy to predict (see figure 7).

Group III: Active Probes

1. Offer negligible resistive loading.

2. Less capacitive loading than Group I and more than Group II.

3. Limited dynamic range. By using divider tips, dynamic range may be extended to as much as plus or minus 50 V. Offset is commonly available.

4. Offers highest R and lowest C of all probe types without reducing the input signal. Excellent for high frequency, low level signals.

5. The best general-purpose probing device within its dynamic range.

6. Some disadvantages are: larger size (not convenient for very dense circuits); slightly higher pulse perturbations than passive probes.

Table 1. Typical Probes Available Commercially

Group	Model or Type No.	R	C (pF)	Division Ratio	Hi Z Input	50Ω Input	Type	Mfr. (see notes)
I	10004B	10MΩ	10	10	X		Passive	HP
	1124A	10MΩ	10	10		X	Active	HP
	P6007	10MΩ	25	100	X		Passive	Tek
	4290B	10MΩ	11	10	X		Passive	Dumont
	4292B	10MΩ	11	100	X		Passive	Dumont
	7994B	10MΩ	7	10	X		Passive	Dumont
	10000A	10MΩ	9	10	X		Passive	Dumont
II	P6048	1kΩ	1	10	X		Passive	Tek
	10020A	250Ω	0.7	5		X	Passive	HP
	10020A	500Ω	0.7	10		X	Passive	HP
	10020A	1kΩ	0.7	20		X	Passive	HP
	10020A	2.5kΩ	0.7	50		X	Passive	HP
	10020A	5kΩ	0.7	100		X	Passive	HP
III	P6045	10MΩ	5.5	1	X	X	Active	Tek
	P6045	10MΩ	2.5	10	X	X	Active	Tek
	P6045	10MΩ	1.8	100	X	X	Active	Tek
	1120A	100kΩ	<3	1		X	Active	HP
	1120A	1MΩ	<1	10		X	Active	HP
	1120A	1MΩ	<1	100		X	Active	HP

Notes
1. HP = Hewlett-Packard Co.
2. Tek = Tektronix, Inc.
3. Refer to manufacturers' data sheets for latest specifications.

AMPLITUDE MEASUREMENTS

This section describes how to make more accurate waveform amplitude measurements by selecting the optimum probe for an application and how to estimate the errors introduced by the probe. Both the displayed signal amplitude and the resulting measurement error depend on the cumulative effect of the following factors:

1. Source frequency, if CW.
2. Repetition rate, if pulse.
3. Probe/scope input impedance.
4. Source impedance.
5. Oscilloscope amplifier bandwidth and sensitivity.
6. Probe compensation and division ratio.

Now, here's an explanation of the effects of these six factors.

The source frequency determines the input impedance of the probe/oscilloscope. If the input impedance is not extremely large relative to the source impedance, there will be an error in the CW amplitude measurement. If a probe from group II (low R, low C) is selected, this error remains relatively constant over a frequency range extending from dc to over 100 MHz. If a probe from Group I is selected (high R, high C) the loading error changes with frequency and is relatively difficult to estimate. It is also quite possible that as the frequency of the source increases, the input impedance of the Group II probe will overtake the Group I probe and allow a more accurate measurement. Therefore, the key to making an accurate CW amplitude measurement is to select the probe/scope combination which has the highest input impedance at the **frequency of the source.**

Accurate pulse amplitude measurements pose less of a problem than CW amplitude measurements. An accurate pulse amplitude measurement can be made with almost no concern for the input capacitance of the system. The only exception is when the R_{in} C_{in} product of the input system is greater than about 1/5 of the pulse width. The pulse must be present long enough (i.e., wide enough) to charge the input capacitance to the 100% amplitude level. The main concern when making pulse amplitude measurements is that R_{in} be large relative to the source impedance.

An error can be introduced by the scope since the vertical amplifier response changes as a function of frequency. A point to remember is that errors introduced by the amplifier rolloff can usually be neglected if the bandwidth is about five times greater than the input signal frequency.

The probe compensation should be checked and adjusted prior to any measurement. If not indicated on the probe, the division ratio can be obtained from a data sheet or operating note.

The following example will help you select a probe to minimize the amplitude errors discussed in this section.

EXAMPLE:

Signal frequency = 35 MHz
Source impedance = 500 ohms
Signal amplitude = 1V p-p

Neglecting vertical amplifier rolloff errors, which of the following probes most accurately couples the signal to the oscilloscope?

1. 10 megohm/10pF, 10:1 (HP 10004B).
2. 100 k ohm/3 pF, 1:1 (HP 1120A).
3. 1 megohm/1 pF, 10:1 (HP 1120A with 10:1 divider tip).
4. 500 ohm/0.7 pF, 10:1 (HP 10020A with 10:1 divider tip).
5. 5 k ohm/0.7 pF, 100:1 (HP 10020A with 100:1 divider tip).

Intuitively, the 10 megohm/10 pF probe appears to be the best selection since the high input resistance produces the lowest resistive loading for a 500 ohm source. However, intuition is not always correct. The relative accuracy of each probe is listed in table 2.

Table 2. Relative Probe Accuracy

Probe	Percent of signal remaining after loading effects	Scope input voltage after probe div ratio
1	48%	48 mV
2	76%	760 mV
3	78%	78 mV
4	50%	50 mV
5	89%	8.9 mV

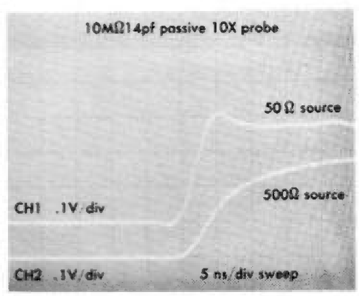
Note from figure 7 that the 500 ohm/0.7 pF Probe 4 has significant resistive loading but the impedance remains a constant 500 ohms from dc to approximately 100 MHz. Although the dc resistive loading is high with this probe, it is easy to allow for by simply doubling the voltage reading for all frequencies to 100 MHz with the 500-ohm source.

The most accurate probe is this example is the 5 k ohm/0.7 pF, 100:1 divider, Probe 5, with only 11% signal loss including resistive and capacitive loading.

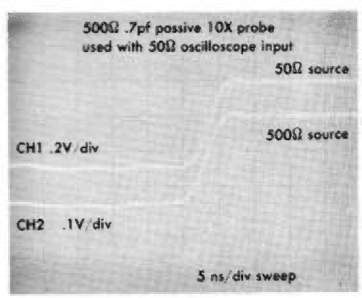
Notice that selecting a probe with a resistance higher than 5000 ohms does not increase the amplitude measurement accuracy since input capacitance also increases, which increases capacitive loading. The best probe provides the optimum trade-off between resistive and capacitive loading for a particular source impedance and frequency. Even though the source frequency in this example is only 35 MHz, and five probes were considered, the loading error was still 11% using a very low shunt capacitance (0.7 pF) probe which points out the need to be aware of the problems that even 1 pF of capacitance can cause. While this is especially true for frequencies exceeding 50 MHz, significant accuracy problems can occur below 50 MHz.

SENSITIVITY/LOADING TRADE OFF

While the 5000 ohm/0.7 pF probe minimized the loading error, the 100:1 divider ratio reduced the input voltage to the oscilloscope to only 8.9 mV. This means that for a vertical amplifier with a deflection factor of 10 mV/div, less than one centimeter of input signal would be displayed. To minimize reading errors, it is always more accurate to display several divisions of signal. If the signal amplitude in the previous example were 250 mV instead of 1 V, the measurement would be much more difficult. Assuming it would be possible to trigger properly, there would be a large error resulting from readout accuracy because the signal would only be 2 mm high. If a different probe were selected with a lower division ratio to overcome the scope sensitivity problem, the loading error would increase. A choice must then be made between loading errors and reading errors because of insufficient signal display on screen. For example, Probe 2 (100 k ohm, 3 pF, 1:1, active) would allow a full-screen display of the 250 mV div. But the amplitude error from loading effects signal, assuming a vertical deflection factor of 20 mV/div would be 24%.



Displayed risetime when using 10MΩ 14pf probe depends on source impedance.



Displayed risetime when using 500Ω .7pf probe on 50Ω input is essentially independent of source impedance.

General Probe Selection Rules for Amplitude Measurements

1. If you have a choice, select a minimum impedance source. For example: emitter-to-base impedance of a transistor is generally lower than the collector-to-base impedance.

2. Select a probe with the highest possible Z_{in} at the frequency of interest. When measuring pulse amplitude, capacitance is not as important as R_{in} being high relative to the source impedance. While probe capacitance distorts pulse shape, the flat portion of the pulse top (maximum amplitude) can be used to make an accurate amplitude measurement since it contains low frequency information. Conversely, if the pulse width is short compared to the measurement system rise time, input capacitance can introduce errors since the source cannot fully charge the input capacitance during its on time. This problem increases with increasing source impedance.

3. When source impedance is unknown, the probe with the highest Z_{in} usually yields the greatest accuracy. However, for frequencies above 10 MHz, high probe capacitance can reduce accuracy more than high probe resistance can help.

4. If the source voltage is totally unknown, it is wise to start with a 100:1 divider probe to reduce the possibility of damaging the probe. This will also indicate whether or not there is enough signal available to capitalize on the relatively low capacitance of a 100:1 divider probe. If the source voltage level is too low for a 10:1 divider probe, then use of an active probe is advisable.

PULSE RISE TIME MEASUREMENTS

Pulse rise time measurements are one of the most frequent and challenging measurements for an oscilloscope. Since there are few alternative measurement devices for making pulse rise time measurements, accuracy of the over-all measuring system is especially important. Conditions affecting pulse rise time measurement accuracy are:

1. **Source Impedance.** Should be as low as possible to reduce charging resistance of the probe/scope input capacitance.
2. **Probe Rise Time.** Should be short relative to the signal rise time since the observed rise time can generally be approximated as the vector sum of the combined risetimes of the parts of a system.
3. **Input R and C of Probe/Scope Combination.** Both R and C should be as small as possible.
4. **Oscilloscope Rise Time.** Should be at least twice as fast as the signal to be measured if errors are to be kept below 10%.
5. **Signal Source Termination.** Signal source should be terminated with an impedance that closely matches the source impedance if reflections and perturbations are to be kept to a minimum. For example, a 50-ohm source does not operate cleanly into a 1 megohm/20 pF input. A feedthru termination in shunt with a 1-megohm input can reduce the displayed rise time which reduces the observed error when working with high impedance inputs, but still leaves reflections from the 20 pF input capacitance.
6. **Maximum Acceptable Source Resistive Loading.** When the source resistance is much greater than 50 ohms, the displayed rise time error can be reduced by increasing the resistive loading of the source.
7. **Signal Amplitude.** If this is small in relation to the oscilloscope vertical amplifier deflection factor, less flexibility remains for using divider probes.
8. **Vertical Amplifier Deflection Factor.** In combination with the signal amplitude, this can be a limiting factor in selecting a probe.

The observed rise time can be approximated as a function of all the rise times in the system:

$$t_{ob} = \sqrt{t^2_{probe} + t^2_{scope} + t^2_{g} + t^2_{input}\,RC}$$

WHERE: t_{ob} = Observed rise time.
t_{probe} = Specified probe rise time.
t_{scope} = Specified scope rise time.
t_{input} RC = Rise time of probe/scope input system.
t_g = Actual rise time of signal generator.

The observed rise time is accurate if all the other rise times in the above equation except t_g equal zero. Since these rise times cannot be zero, the observed rise time will always have some error. Other than selecting a fast oscilloscope, the only variable that can be controlled is t_{input}RC.

t_{input}RC is the key to accurate rise time measurements. What is t_{input}RC? Figure 9 shows that input capacitance is charged through the parallel combination or R_g and R_{in}. The signal generator may therefore be characterized as an equivalent resistance, $R_{charging}$, which charges the input capacitance.

WHERE: $R_{charging} = \dfrac{R_g\ R_{in}}{R_g + R_{in}}$

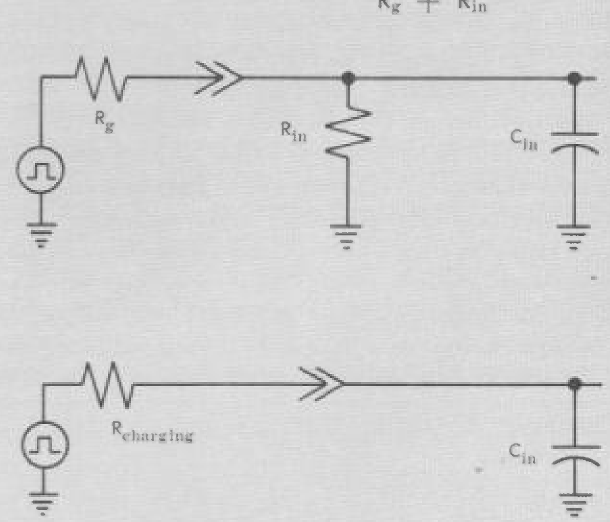


Figure 9. Equivalent Circuits for Rise Time Calculations

It can be shown that the rise time of the RC network in figure 9B is approximately 2.2($R_{charging}$) (C_{input}) which is t_{input}RC. Both $R_{charging}$ and C_{input} should be as small as possible to optimize the accuracy of the risetime measurement. There are two ways to minimize t_{input}RC. The first way is to minimize $R_{charging}$. Since $R_{charging}$ is the parallel combination of $R_{generator}$ and R_{input}, if either value is large, the other should be kept small. If both are large, then $R_{charging}$ will of necessity be large and accuracy will be degraded. Therefore, remember to minimize either.

1) $R_{generator}$

or

2) R_{input}

It is preferable to minimize $R_{generator}$ as this will also minimize the resistive loading and allow a more ac-accurate amplitude measurement. When $R_{generator}$ is high (500 ohms or more), some resistive loading will be unavoidable if the most accurate rise time measurement is desired. In this case, select the lowest R_{input} that the circuit can tolerate without actually overloading the circuit. This is the most difficult rise time measurement situation because some resistive loading is mandatory if $R_{charging}$ is to be minimized. A resistive divider probe set (such as HP 10020A) with several divider tips is very convenient for optimizing the trade-offs of this measurement.

The second way to minimize t_{input} RC is to minimize C_{input}. This is best accomplished by using a 50-ohm oscilloscope input which has effectively zero input capacitance. However, if 50 ohms causes too much resistive loading for the circuit, a probe can be added to the input to increase the input resistance to as high as 1 M ohm. There will be a slight increase in the C_{in} value when the R_{in} value is raised by a probe.

EXAMPLE:

From the following probes, select the one that is most accurate for measuring rise time from a source impedance of 500 ohms.

1. 10 megohm/10 pF, 10:1 (HP 10004B).
2. 100 k ohm/3 pF, 1:1 (HP 1120A).
3. 1 megohm/1 pF, 10:1 (HP 1120A with 10:1 divider tip).
4. 1 k ohm/0.7 pF, 20:1 (HP 10020A with 20:1 divider tip).
5. 5 k ohm/0.7 pF, 100:1 (HP 10020A with 100:1 divider tip).

Key Equations

$$R_{charging} = \frac{R_g \; R_{in}}{R_g + R_{in}}, \text{ Where } R_g = \text{Source Resistance}$$

$$t_{input}\,RC = 2.2\, R_{charging}\, C_{in}$$

$$t_{observed} = \sqrt{t^2_g + t^2_{scope} + t^2_{probe} + t^2_{input}\,RC}$$

$$\text{Percent of Resistive Loading} = \left(\frac{R_g}{R_{in} + R_g}\right) \times 100$$

The source will saturate if resistive loading exceeds 30%. This example covers many of the trade-offs and considerations necessary for selecting the best probe to make an accurate transition time measurement. Table 3 summarizes the probe loading effects.

Table 3. Calculated Probe Loading from a 500 ohm source.

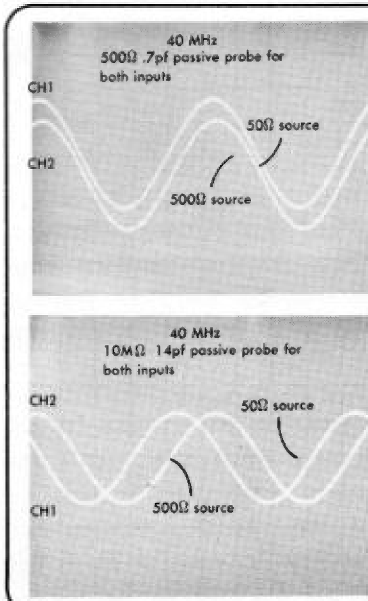
Probe	R	$2.2\,R_{ch}\,C_{in} = t_{input}$	% Signal Loss Caused by Resistive Loading	Probe Div Ratio	Specified t_r of probe only (25 ohm source)
1. 10 MΩ/ 10 pF	500	11 ns	0%	10:1	2.5 ns
2. 100 kΩ/ 3 pF	500	3.3 ns	0.5%	1:1 (Active)	0.75 ns
3. 1 MΩ/ 1 pF	500	1.1 ns	0.05%	10:1 (Active)	0.75 ns
4. 1 kΩ/ 0.7 pF	333	0.514 ns	33%	20:1	0.5 ns
5. 5 kΩ/ 0.7 pF	455	0.7 ns	9.1%	100:1	0.5 ns

The results in table 3 indicate that Probe 4 (1 k ohm/0.7 pF 20:1 passive divider) is the fastest, but it fails the acceptable resistive loading criterion of 30% signal loss. The reason this probe is so much faster is because $R_{charging}$ is the lowest and the input C is very low. The next fastest which meets the loading criteria is Probe 5 (5 k ohm/0.7 pF 100:1 divider) with only 9.1% resistive loading. The choice of this probe would depend on whether or not there is sufficient signal remaining after the 100:1 division ratio to present an acceptable display on the CRT. If not, then the next choice would be Probe 3 (1 M ohm/1 pF, active), which is only slightly slower than the 100:1 divider probe.

GENERAL RULES FOR RISE TIME MEASUREMENTS

1. Always try to probe the lowest impedance point that contains the waveform of interest.

2. The fastest input system will generally have the lowest R_{in} and C_{in}. (This rule is limited only by the maximum resistive loading that the source can tolerate).



The probes can introduce phase shift if both probes do not see the same source impedance. The phase shift is minimized by using probes with low input R and C. See fig. 10 for set up.

MINIMIZE PHASE SHIFT

When two identical probes are used to measure phase relationships, gross errors can result if the source impedance seen by each probe is different. The following equation helps to explain why this is true:

$$\phi = -90 + \tan^{-1}\left[X_{C_{in}}\left(\frac{1}{R_{in}} + \frac{1}{R_g}\right)\right]$$

Where: ϕ = phase shift caused by probe/scope input
If $\frac{R_{in}}{R_g} > 10$, the previous expression simplifies to:

$$\phi \cong -\tan^{-1}\left(\frac{R_g}{X_c}\right) \quad \text{where } X_c = \frac{1}{2\pi f C_{in}}$$

Ideally the phase shift, ϕ, should be zero or at least minimized.

Referring to the preceding equations, it can be easily shown that the phase shift introduced by the probe/scope input will be minimized by following these rules:

1. X_c should be as large as possible or C_{in} should be as small as possible.
2. R_{in} should be as small as possible.
3. R_g should be as small as possible.

You may recall that these phase measurement rules are identical with the rules for making accurate rise time measurements. A limit to Rule 2 is that R_{in} should be kept as small as possible consistent with maximum acceptable circuit loading. Consider the following phase shift example (see figure 10).

EXAMPLE:

The input signal is generated by a 500 ohm, 30 MHz source and the amplifier output impedance is 2 k ohms. Assume that two 10 megohm/10 pF divider probes are used to couple both the input phase reference and output signal to the oscilloscope and that the amplifier under test has no phase shift. Since $\frac{R_{in}}{R_g} > 10$, the simplified phase shift equation given earlier applies. The input probe will couple a signal that is phase-shifted from the source by:

$$\phi_{in} = -\tan^{-1}\left(\frac{R_g}{X_c}\right) = -\tan^{-1}\left(\frac{50}{541}\right) = -\tan^{-1} 0.094 = -5^\circ$$

The output probe will couple a signal that is phase-shifted from the source by:

$$\phi \text{ out} = -\tan^{-1}\left(\frac{R_g}{X_c}\right) = -\tan^{-1}\left(\frac{2000}{541}\right)$$

$$= -\tan^{-1} 3.77 = -75^\circ$$

Displayed phase shift is:

$$\phi_{out} - \phi_{in} = -70^\circ$$

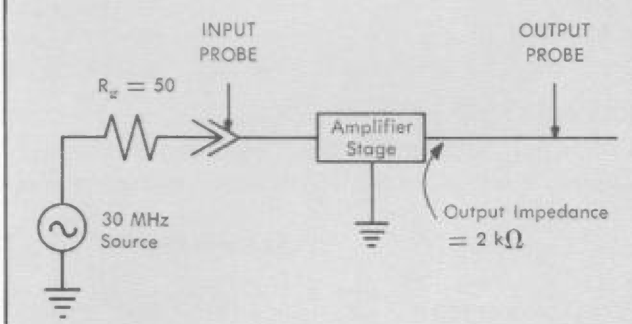


Figure 10. Phase Shift Measurement

The phase shift of -70° as displayed on a dual channel oscilloscope was introduced solely by the probe/scope input. If the output impedance of the amplifier were the same as the signal generator input impedance, no phase shift error would have resulted; however, this is seldom the case in actual practice. When the input and output impedances are unknown, accurate measurements can still be made by using probes that have low R_{in} and C_{in}.

We will now substitute two 50 ohm/0.7 pF probes (HP 10020A) for the two 10 megohm/10 pF probes. Since R_{in} is small compared to the amplifier output impedance, the rigorous equation is required to determine phase shift.

Input probe phase shift:

$$\phi_{in} = -90 + \tan^{-1}\left[7550\left(\frac{1}{50} + \frac{1}{50}\right)\right]$$

$$\cong -90^\circ + 89^\circ\, 49' = 0^\circ$$

Output probe phase shift:

$$\phi\ out = -90 + \tan^{-1}\left[7550\left(\frac{1}{2000} + \frac{1}{50}\right)\right]$$

$$\cong 90^\circ + 89^\circ\, 37' = 0^\circ$$

Displayed phase shift:

$$\phi\ out - \phi\ in \cong 0^\circ$$

The probes have contributed negligible phase shift but have produced considerable resistive loading in the case of the 50 ohm probe across the 2000 ohm amplifier output impedance.

So far it is clear that neither probe that we have used in this example represents a logical choice for this phase shift measurement. The 10 megohm/10 pF, 10:1 divider probe introduced 75° phase shift error and the 50 ohm/0.7 pF, 1:1 passive probe which had zero phase shift caused 98% signal loss from resistive loading.

A probe with more than 50 ohms input resistance and an input capacitance of 0.7 pF would provide a satisfactory compromise between phase error and resistive loading. Such a probe would be the HP 10020A with a 50:1 divider tip which has 2.5 k ohm/0.7 pF input parameters.

Input probe phase shift:

$$\phi_{in} = -90 + \tan^{-1}\left[7550\left(\frac{1}{50} + \frac{1}{50}\right)\right]$$

$$\cong -90^\circ + 89^\circ\, 49' = 0^\circ$$

Output probe phase shift:

$$\phi\ out = -90 + \tan^{-1}\left[7550\left(\frac{1}{2.5\ k} + \frac{1}{2\ k}\right)\right]$$

$$\cong -90^\circ + 82^\circ = -8^\circ$$

Displayed phase shift:

$$\phi\ out - \phi\ in \cong -8^\circ$$

Signal loss from resistive loading =

$$1 - \frac{R_{in}}{R_{in} + R_g} = 1 - \frac{2.5\ k}{2.5k + 2\ k} = 44\%$$

If the 44% resistive loading is not acceptable, further trade-offs must be made between lower resistive loading and higher phase shift errors. Table 4 lists the results that would be produced by several probes.

Table 4. Calculated Phase Shift Errors Introduced by Probes

Probe $R_{in}\ C_{in}$	Phase Error $\phi_2 - \phi_1$	Resistive Loading % signal loss
10 MΩ/10 pF	75°	0
1.0 MΩ/3 pF	47.4°	0
5 kΩ/0.7 pF	27.8°	28.6%
2.5 kΩ/0.7 pF	8°	44%
50 Ω/0.7 pF	0	98%

PHASE SHIFT MEASUREMENT SUMMARY

1. Phase shift error is negligible if the source impedances for the two probes are equal. In this case any set of identical probes would be satisfactory for the measurement.
2. As the difference between input and output source impedance increases, the selection of probes becomes increasingly important.
3. The phase shift error is minimized by selecting the probe with the lowest R_{in} that a circuit can tolerate and with the lowest possible C_{in}.

THE 50-OHM INPUT VERSUS THE "HIGH IMPEDANCE" INPUT

In recent years there has been much controversy over the merits and demerits of these two types of oscilloscope inputs. They key issue in making a comparison is input impedance versus frequency. The "high impedance" input is only high impedance for frequencies below approximately 1 MHz. Above 1 MHz the shunt capacitance takes over and there is a fair amount of uncertainty as to what the input impedance actually is. The 50-ohm input starts out with low impedance but has essentially a constant input impedance over the oscilloscope vertical amplifier bandwidth, and virtually eliminates the effects of capacitive loading. These input characteristics dictate the applications for which each input is best suited and the choice of probe to do the job.

BENEFITS OF "HIGH IMPEDANCE" SCOPE INPUTS

1. Passive probes can be used where high input resistance is required. No need for an active probe unless signal levels are small relative to vertical sensitivity.
2. Can tolerate much greater input voltages than a 50 ohm input.
3. Can be used with high voltage probes.

PROBLEMS OF "HIGH IMPEDANCE" SCOPE INPUTS

1. Capacitive loading is much higher than with 50-ohm inputs.
2. Input impedance is highly variable with frequency.
3. There is a tendency to have confidence that there is no loading because R is high, when in fact capacitive loading is extremely high.
4. Does not offer a good termination for fast 50-ohm signal sources. Even when a 50-ohm termination is used to shunt the high input resistance the VSWR caused by the remaining capacitance is very high.

BENEFITS OF 50-OHM OSCILLOSCOPE INPUT

1. Minimizes input capacitance and the problems that it causes.
2. Presents a perfect termination for high speed 50-ohm sources. Minimizes pulse shape distortion, VSWR, reflections.
3. When an appropriate probe is added to the 50-ohm input, the input impedance can be considerably higher than that of a "high impedance" input scope. The source frequency for which this is true depends on the particular probe selected.

PROBLEMS WITH 50-OHM INPUT

1. Limited maximum input voltage. Typically the maximum voltage which can be applied directly is less than ± 10V.
2. Requires a probe to increase the input resistance:
   (a) Passive probes can be used to increase the input resistance to 5 kΩ if 100X division ratios can be used.
   (b) Active probes are generally required to increase the input resistance to the 100 kΩ to 10 MΩ area. Active probes are expensive but generally offer a more flexible general purpose probing solution.
   (c) 50-ohm inputs are not compatible with high voltage probes.
3. Does not have ac coupling for signal input.

To summarize, the 50-ohm input offers superior measurement capability in many situations but it cannot be considered to be a very general purpose solution because a probe is required to increase the input resistance and ac coupling is not available without an active probe.

The high impedance oscilloscope input is much more general purpose but is generally not as capable for making accurate high speed pulse measurements, phase shift measurements, and high frequency amplitude measurements, even when a probe has been carefully selected.

While the benefits of each type of oscilloscope input are well understood, the oscilloscope user has until very recently been asked to choose one or the other input system. Now input systems are available which offer "the best of both worlds." For example the Hewlett-Packard 1808A 75 MHz vertical amplifier plug-in has an input attenuator which allows one to select either a 50-ohm input or a 1 M ohm/12 pF input. This type of flexibility permits the oscilloscope user to select the optimum input for all of his probing needs. Other HP instruments offering the selectable 50-ohm or high impedance inputs are: Model 1805A 100 MHz vertical amplifier plug-in and Model 1710A 150 MHz portable oscilloscope.

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OSCILLOSCOPE SYSTEMS

For More Information, Call Your Local HP Sales Office or, in U.S. East (201) 265-5000. Midwest (312) 677-0400. South (404) 436-6181. West (213) 877-1282. Or, Write: Hewlett-Packard, 1501 Page Mill Road, Palo Alto, California 94304. In Europe, Post Office Box 85, CH-1217 Meyrin 2, Geneva, Switzerland. In Japan, YHP, 1-59-1, Yoyogi, Shibuya-Ku, Tokyo, 151.

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