Logic Signal Measurements

How to use an oscilloscope to make basic measurements in digital logic circuits

By Robert Ramirez*

If you think digital logic is based on 1s and 0s, you're partially correct. When digital circuits are working logically—as they're supposed to—it's okay to think strictly in terms of 1s and 0s. But when things go wrong (counters don't count, printers don't print, modems don't communicate), you may have to start thinking analog to find the problem and fix it.

Always keep in mind that digital logic is really based on analog signals. Ideally, these signals represent 1s and 0s (fixed high and low states), but in reality are still analog signals. As such, they are subject to all the whims of the analog world, such as attenuation, distortion, noise, propagation delay, and so forth. What looks like a 1 may not really be a good, solid 1 because of amplitude or offset variations that don't meet threshold requirements. A 1 could even be two 1s because of noise-margin violations. Or it could be a 1 at the wrong time, or only sometimes, because of timing-margin violations.

Troubleshooting these "analog-based" digital problems is best done with an oscilloscope. Though any oscilloscope will do for simple problems, to find out what is really going on in marginal logic situations, you need a good scope and some additional measurement tricks.

Good Scope Defined

Bandwidth is the most commonly talked about scope specification. In fact, manufacturers often include it in their scope names. The Tektronix 2246 100-MHz Oscilloscope shown in Fig. 1 is one such example. The bandwidth specification tells you the frequency range of sinusoids that the scope will display without amplitude attenuation. Almost without exception, dc and very low frequencies are implied in the specification. The scope's amplitude measurement accuracy (such as, vertical accuracy = 2%) is guaranteed up to the specified bandwidth, which is commonly fixed at the 3-dB down point, or the point where the amplitude of the displayed signal drops to half what it was within the major portion of the rated bandwidth.

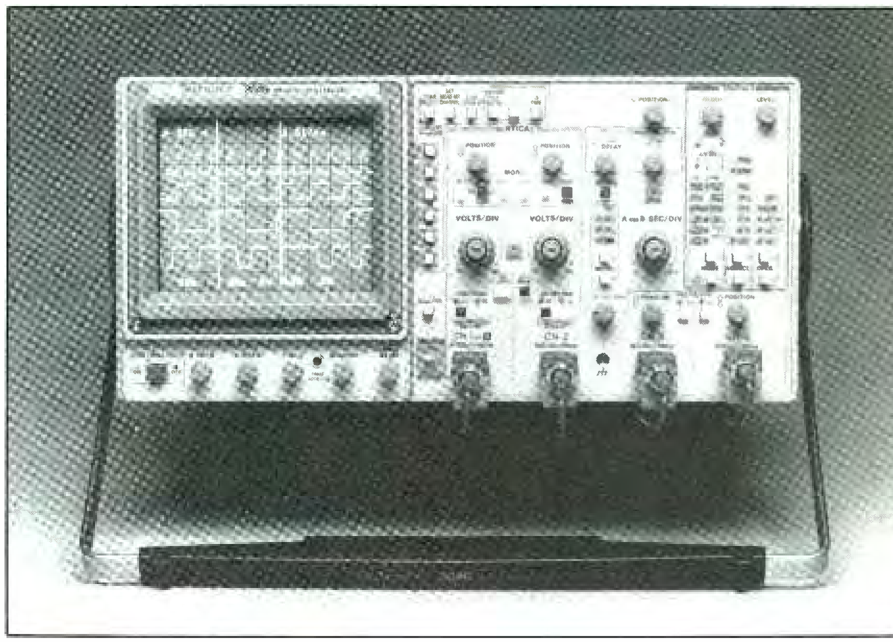

Fig. 1. Modern oscilloscopes provide more bandwidth at lower prices and with more measurement convenience features, such as direct-readout measurement cursors and even pushbutton measurement selections.

Notice the reference to "sinusoid" in talking about bandwidth. By definition, a digital signal is *not* a sinusoid, though it is made up of many sinusoids. All of these sinusoids, except for the fundamental frequency, are of higher-frequency harmonics. For example, Fig. 2(a) shows a 5-MHz clock such as might be used in a personal computer. It has a dc component and a 5-MHz fundamental frequency. These two frequency components are indicated by vertical amplitude lines in the clock spectrum of Fig. 2(b). Notice that there are other components present at odd

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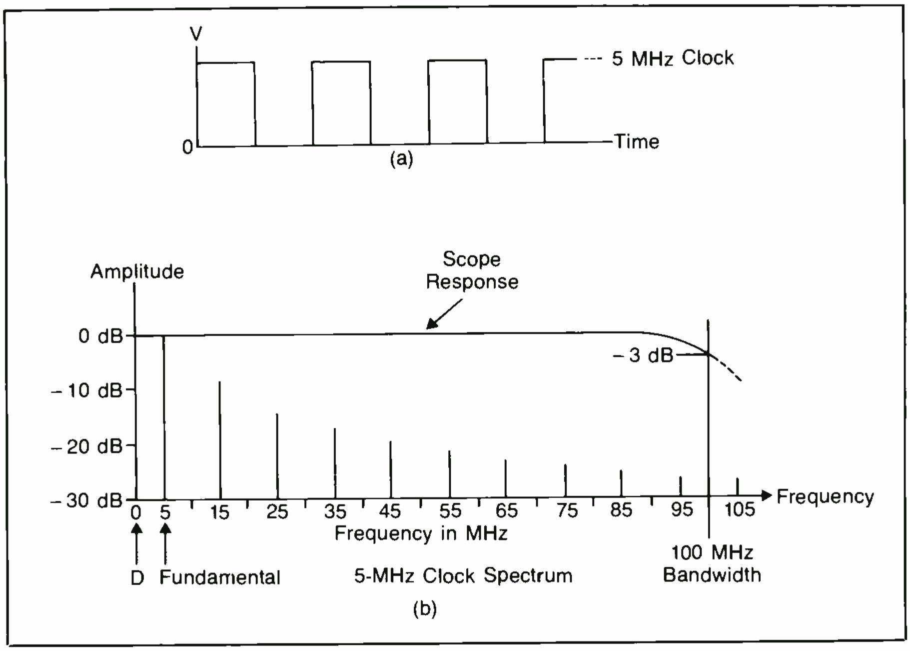


Fig. 2. Digital signals (a) are composed of harmonically related sinusoids (b). Accurate oscilloscope displays require adequate bandwidth to include higher-order harmonics.

multiples of the fundamental (15 MHz, 25 MHz, 35 MHz, etc.) and that their amplitudes diminish with each successively higher multiple.

Higher-order multiples of the clock frequency are the harmonics that give the clock pulses their corners and fast transitions. If you use a scope that has too low a bandwidth, you basically filter out (attenuate) these higher harmonics and their contribution to pulse shape. A higher-bandwidth scope, as indicated by the response curve in Fig. 2(b), preserves more harmonics of the clock signal, or any other nonsinusoidal signal for that matter.

When dealing with digital signals, it is often more convenient to think in terms of scope risetime, rather than bandwidth and signal harmonics. Risetime indicates how fast the scope responds to an ideal voltage step. As a rule, a scope's approximate risetime is related to bandwidth by $T_r = 0.35/BW$, where T_r is risetime and BW is bandwidth in Hertz. Thus, a 100-MHz scope has a 3.5-nanosecond risetime.

Time Measurement Accuracy

Risetime Ratio (Pulse:Scope)	Approximate % Error in Time Measurement
7:1	1
5:1	2
3:1	5.5
2:1	12
1:1	40

Scope T_r = 0.35/scope bandwidth

Also, as a general rule for accurate time measurements, you should use a scope with a risetime that is at least five times greater than the risetime of the pulse you are trying to measure. Thus, a 3.5-nanosecond scope provides best accuracy (less than 2% error) on time measurements up to about 17 nanoseconds. But this can be pushed, as indicated in the Table, if less accuracy can be tolerated.

For accurate measurements, it is important that the bandwidth and risetime specifications be to the *probe tip*. Because this is not always done, some scopes are specified only to the input connector. A high-bandwidth scope is of questionable value if its bandwidth cannot be carried to the probe tip, down to what you are actually measuring. To be able to do this requires probes that are matched to the scope. It is a common measurement error to ignore this important link.

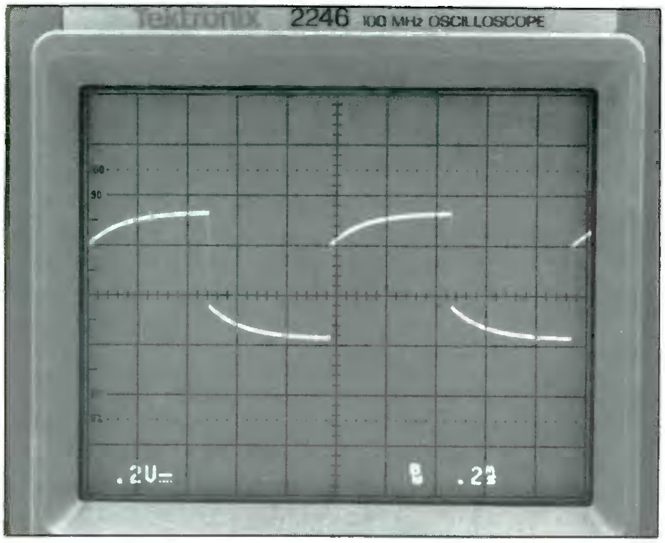
It is also a common measurement error to fail to compensate the probes before making measurements. Compensation is usually done with a screwdriver or twist adjustment on the probe. It must also usually be done at scope settings specified by the manufacturer. The effects of an uncompensated probe are shown in Fig. 3. Using an uncompensated probe can result in amplitude or risetime measurement errors.

Is a 1 a 0 or Two or None?

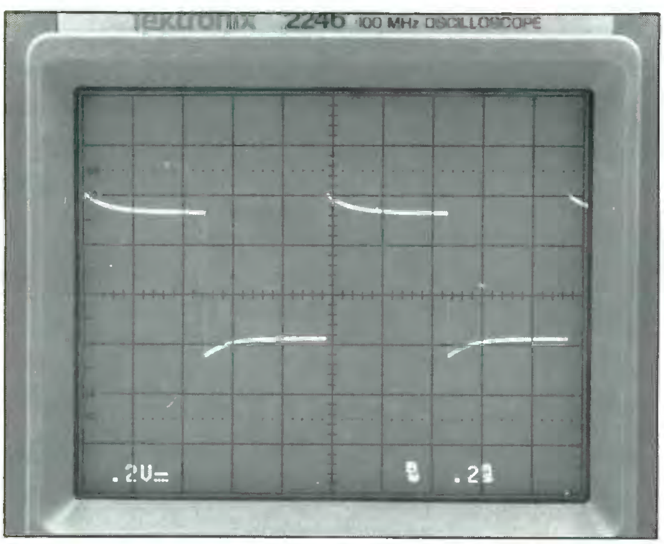
Selecting a good scope is the first step in making measurements. Putting it to proper use is the next step.

For example, in measuring digital signal amplitudes, it is important to recognize the type of signal being dealt with and to use proper scope input coupling. Figure 4 shows three typical signal types—bi-directional (a), uni-directional (b), and uni-directional with offset (c). Without a zero reference, uni-directional signals are indistinguishable from bi-directional signals. So it is important to, first of all, establish a 0-volt baseline on the scope display. This is done with the scope's triggering set to "peak-to-peak auto" and the probe input coupling switch set to ground. The resulting 0-volt display is then vertically positioned to a convenient scale line on the scope screen. Then probe input coupling is switched to the setting (ac or dc) for the signal to be displayed.

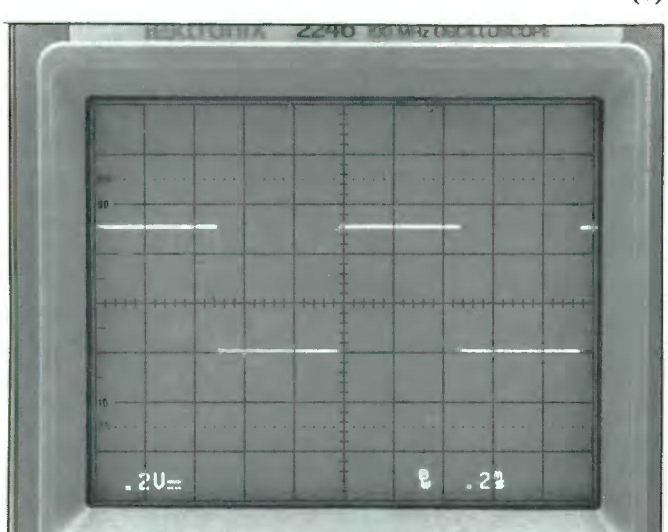
For most logic signals, dc coupling is the best setting. If ac coupling is used, uni-directional signals will have their dc component blocked and will appear as bi-directional signals. Even worse, any amplitude



(a)



(b)



(c)

Fig. 3. Probe compensation is important in measurement accuracy. Undercompensation (a) results in risetime errors; overcompensation (b) results in amplitude errors; proper compensation (c) results in accurate signal display.

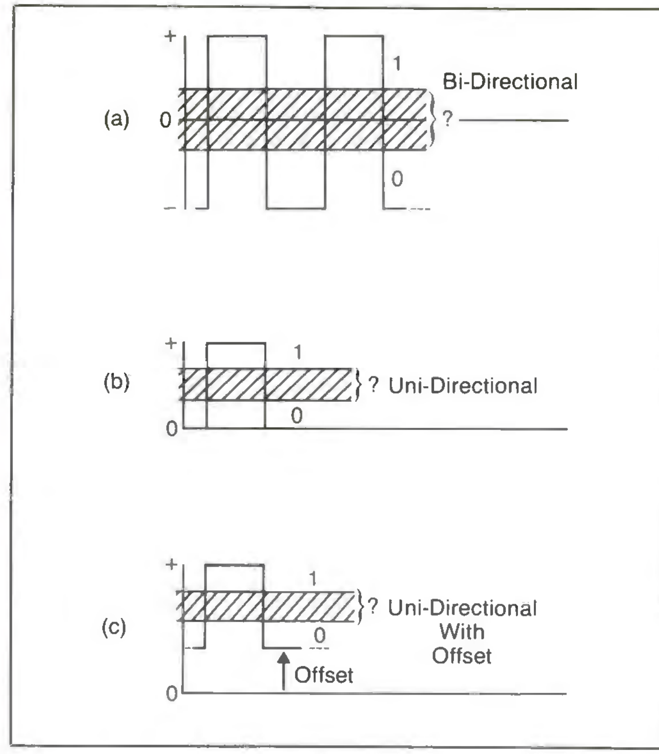


Fig. 4. Three typical types of logic signals. Shaded areas represent bands of indecision, where the signal could be sensed as either a logic 0 or a logic 1.

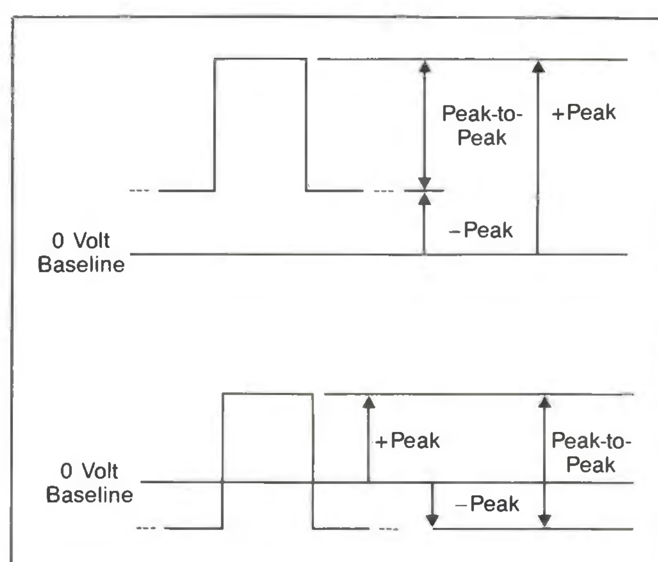


Fig. 5. Definitions of amplitude measurements relative to a 0-volt baseline.

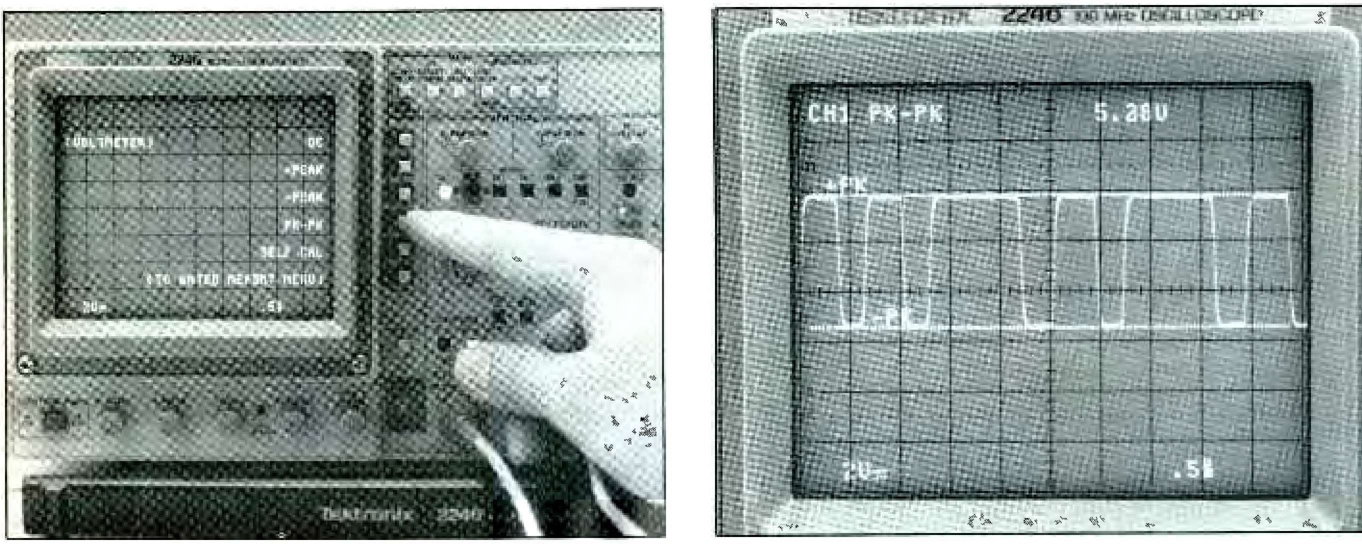


Fig. 6. A modern oscilloscope provides menu selection of measurements (a) and shows results on-screen (b) with readout and automatic cursor placement (dotted lines).

measurements will be ambiguous, since the signal is shifted from its actual dc baseline. Dc coupling, on the other hand, preserves the signal's dc component.

The importance of accurate amplitude measurements is further emphasized by considering the shaded "undecided" zones in Fig. 4. For example, if the logic signal in Fig. 4(a) is being loaded down or attenuated, it may not transition far enough to solidly pass the decision zone and become a solid logic 1 or 0. The signal could look like a valid logic signal, but its low amplitude could result in ambiguous detection of logic levels. In Fig. 4(b), low amplitudes could result in detection as all zeros. In Fig. 4(c), too much offset could result in an all 1s detection.

When troubleshooting logic circuits, it's not enough to just look at the signal and say, "yes it's there." The amplitudes must be measured to ensure that they solidly pass the 1/0 decision levels. Does the signal have sufficient peak-to-peak swing, or +peak, or −peak swing? Is there offset? Should it be there, and if so, is the offset value correct?

The definitions for these measurements are shown in Fig. 5. Typically, the measurements are made by counting divisions from the baseline and multiplying the count by the scope's scale factor readout. Modern oscilloscopes, such as the Tektronix 2246 GPS (General Purpose Scope), simplify this process considerably. As shown in Fig. 6, the 2246 GPS provides pushbutton selection of measurements from an on-screen menu. When a measurement is selected, the 2246 automatically keeps track of where the zero baseline is and makes the selected measurement with a built-in waveform voltmeter. The measurement result is displayed in the on-screen readout and is indicated on the waveform by automatic placement of measurement cursors, —the dotted lines in Fig. 6(b).

The measurement cursors shown in Fig. 6(b) can also be manually positioned on-screen to measure the voltage difference between any two amplitude points. This is useful, for example, in checking digital signal noise margins. By placing the cursors at the logic decision levels, you can easily observe whether noise, amplitude drift or signal aberrations are crossing the threshold and causing false ones or zeros (Fig. 7).

Is It a 1 In Time?

Measurement cursors offer the same convenience in making time mea-

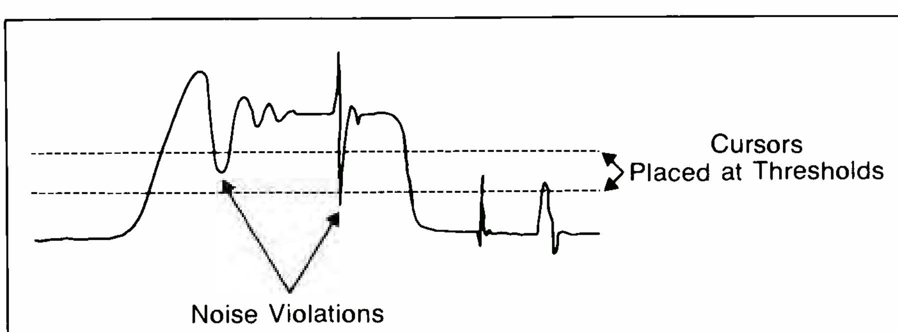


Fig. 7. Cursors can be manually placed for amplitude measurements, or (as shown) can be used as amplitude markers for observing noise violations.

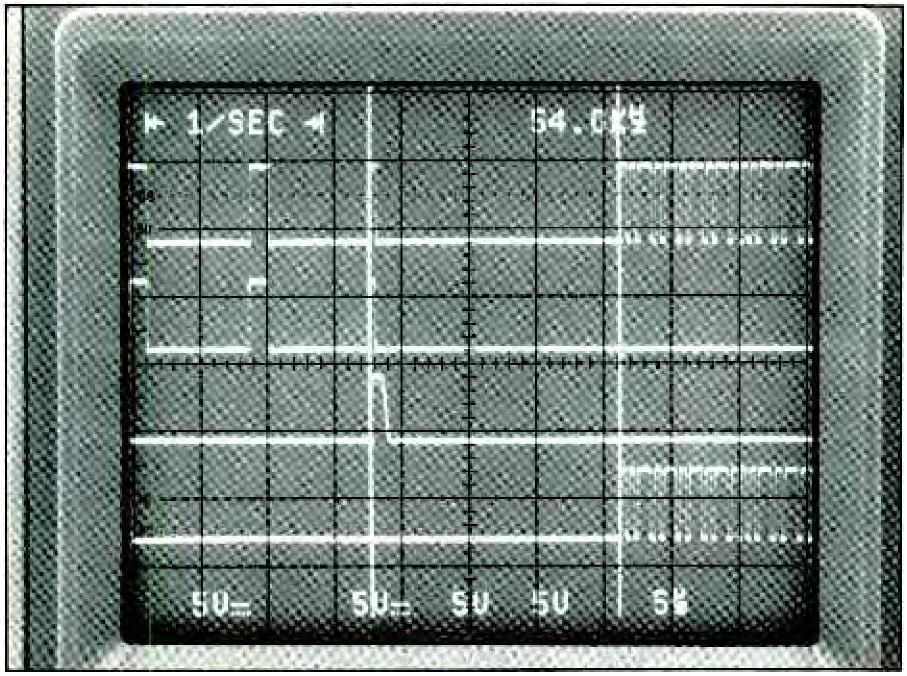


Fig. 8. Cursors can be used in a time measurement mode for checking pulse width, logic line-up (skew) and other timing relationships.

surements. This is shown in Fig. 8, where the cursors have been placed for a timing measurement between logic channels. The measurement result (time between cursors) is shown in the upper right of the display.

It is particularly important to note in Fig. 8 that multiple channels are being displayed. Multi-channel display capability is a necessity for logic signals, since many of the critical timing relationships are between logic channels. A dual-channel scope is needed at minimum for logic signal comparisons. However, a four-channel scope adds convenience by being able to display more signals simultaneously.

Note also in Fig. 8 how the cursors verify the signal edge lineup. A signal edge slightly offset from the cursors would indicate channel skew (time offset) between digital signal lines. For closer observation of skew, it is best to position the suspect signal on the scope's center screen division and select the × 10 horizontal magnification function. This expands the display horizontally by a factor of 10, effectively zooming in on the center of the display. In this expanded mode, you can get a higher resolution measurement of skew and determine whether it exceeds the timing margin specifications of the system on which you are working.

Channel skew is usually the result of mismatched delays in the logic circuits used in each channel path. This could be a design flaw, which can be corrected by buffering faster channels to delay or "de-skew" them. Or excessive skew can be the results of a circuit malfunction causing excessive propagation delay through a gate. These propagation delays—delay time between application of an input signal and appearance of an output response—are relatively simple to measure with a dual-channel scope.

To measure propagation delay, put the scope's channel-1 probe on the gate input and the channel-2 probe on the gate output. Then, in alternate sweep or chopped mode and with triggering set for channel 1, measure the time difference between leading edges on the resulting dual-channel display of the input and output logic pulses.

Other timing measurements you might want to make in troubleshooting a design are pulse width and pulse jitter. Pulse width is critical, since a "1" state must be maintained long enough to be recognized as a 1. This is generally referred to as minimum setup and hold time.

When pressing digital designs for maximum speed, it is easy to get pulse width violations. This can happen, for example, because of a small amount of channel skew at the inputs to an AND gate; the input time offsets can result in an ANDed signal that is too narrow for the next logic stage to recognize.

Even if pulse width is kept longer than the absolute minimum, there can still be occasional violations from pulse or timing jitter. These are generally referred to as timing margin violations. Again, measurement cursors serve as convenient markers for detailed observation of timing margins. The cursors can be placed at the timing limits around a transition. This allows you to easily see occasional jitter or timing drift that violates the margin limits.

Overshoot Kills CMOS

Generally, sufficient logic amplitude and correct logic channel timing relationships will solve most digital circuit problems. However, with today's more sensitive circuits, too much logic swing can be just as bad as not enough.

Overdriving a logic element can cause excessive saturation and extend transistor storage time. This results in pulse stretching, which can cause logic or timing errors or force you to run the circuit at a lower than desired clock rate.

Even if your nominal signal high is

(Continued on page 91)

within circuit amplitude limits, beware of overshoot. Momentary hard saturation caused by pulse overshoot can still extend device storage time.

Overshoot can do even worse things to voltage-sensitive devices. Perhaps you'll have the opportunity to experiment with high-speed CMOS devices. The tendency here is to tweak circuits for the highest slew rate (risetime) pulses possible as part of milking more speed out of the circuit. But fast slew rates often cause overshoot. In CMOS circuits, exceeding logic swing limits with overshoot can result in latchup, which causes the circuit to burn out.

Triggering Tricks

Making any of the above measurements or waveform observations presumes you can get the digital signal displayed on the scope screen. Sometimes that's easy. Sometimes it's not.

When problems arise, it's generally because a stably triggered display cannot be achieved. Signal noise or jitter are causing the trigger point to jump around on the signal. Thus, the signal jumps around on the display.

Most triggering problems can be solved if the scope has some reject modes provided in the triggering section. For example, display drift caused by 60-Hz interference from lights can be eliminated by using a low-frequency reject mode. A high-frequency reject mode is useful for eliminating interference from local radio stations. A noise reject mode emphasizes the peak-to-peak amplitude of the signal coupled to the triggering circuit and improves triggering on signals in the presence of electrical noise.

If your scope does not have these convenience features, you can sometimes emulate them with external filtering. For example, if 60-Hz interference is bothering your measurements, you can build a 60-Hz filter and use it at the channel-1 scope input. You'll need to set the scope for a dual-trace display with triggering on channel 1 and the unfiltered version of the signal fed to channel 2. The filtered channel-1 waveform serves only as a triggering device, and actual measurements must be done on the channel-2 display of the unfiltered version of the waveform.

Such external filtering for a stable trigger signal can get you by in some cases. But it does require building a special filter for your particular needs. It also uses up one of your scope inputs just for triggering purposes. For more widespread measurement needs, it is far more convenient to have a selection of measurement modes and triggering features built into the scope. This allows you to spend more time on your project and less time fiddling with the scope.