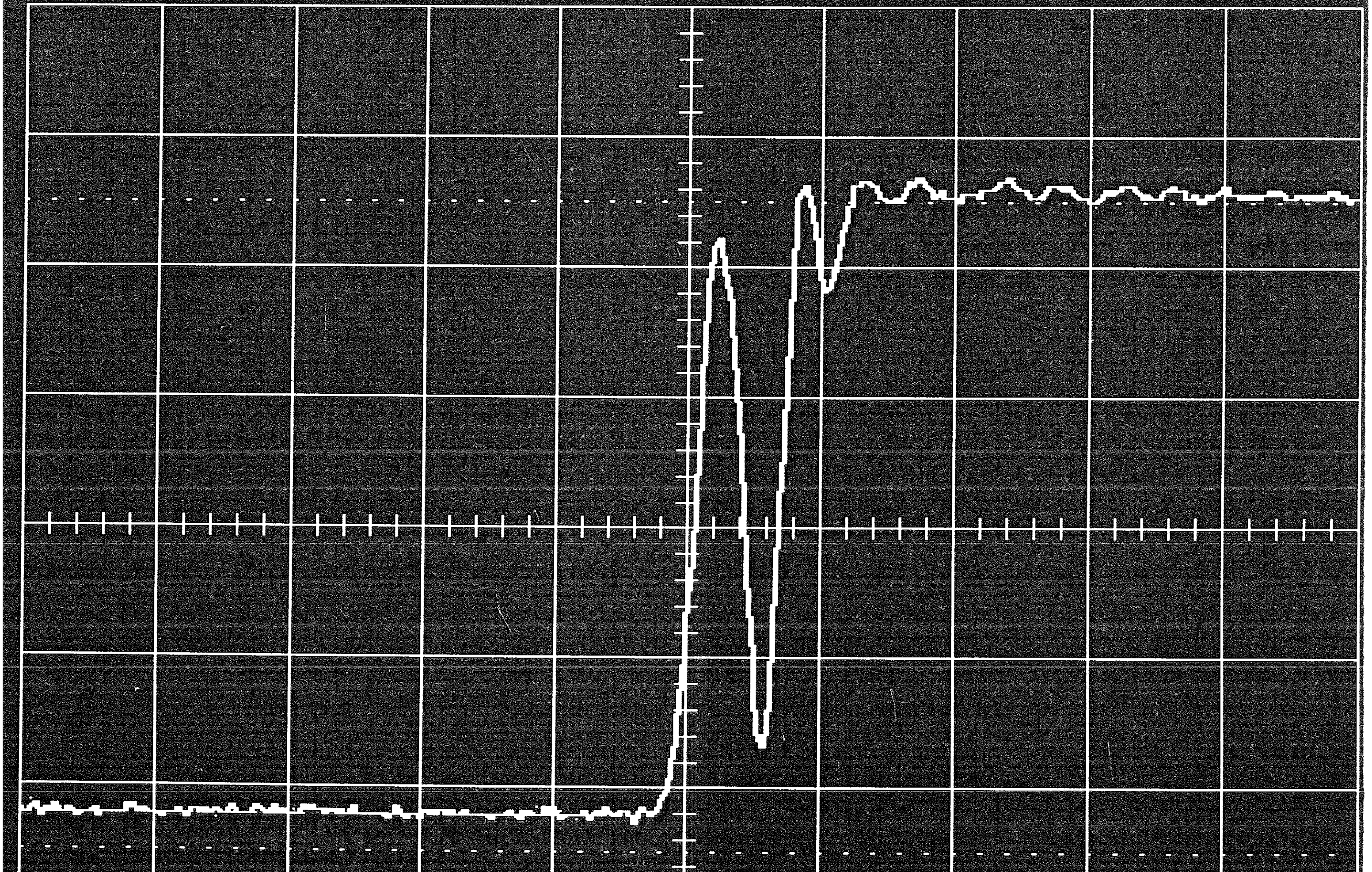
APPLICATION
NOTE ITI 015

LeCroy

Characterizing High-Speed Circuits



CHARACTERIZING HIGH SPEED CIRCUITS

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Summary

With the latest fast TTL and CMOS technologies, sub-nanosecond edges have become a reality. For that reason, it is now important to use good technique for circuit design and board layout. Traditionally, engineers have relied on the analog oscilloscope as their primary tool for circuit testing. Unfortunately, these instruments have limited bandwidth (typically 400 MHz) and they are rapidly becoming inappropriate for testing modern logic signals. The higher frequencies associated with fast logic have created a need for faster test instrumentation. This application note discusses some circuit characterization problems, and how LeCroy's latest wide bandwidth digital oscilloscopes can help provide solutions.

I. CHOOSING THE RIGHT OSCILLOSCOPE

A. High Frequency Single Shot Signals

Digital oscilloscopes use an analog-to-digital converter (ADC) to digitize waveforms at a certain sampling rate. There are two classes of oscilloscopes: Single Shot and Repetitive. While the Single Shot oscilloscope is generally more versatile, it requires high speed ADCs and fast memories. These technologies are expensive to implement and, as a consequence, the single shot oscilloscope carries a high price tag.

A typical Single Shot instrument is shown in figure 1. The input waveform is first sampled, using a fast Sample & Hold (S/H). It is then digitized by the ADC, and stored in memory. This type of oscilloscope can be used to record Single Shot events, (e.g. Power Supply turn-on phenomena) provided they are sampled at an appropriate rate. See the discussion below on Bandwidth and Sample Rate.

B. High Frequency Repetitive Signals

It is not always necessary to acquire signals in one (single-shot) acquisition. Since the majority of electronic signals are repetitive, it is possible to reconstruct them by acquiring them repetitively with a slower ADC, and then interleaving the individual acquisitions. This requires very good timing resolution, which is normally provided by an internal time-to-digital converter. Since the ADCs and memory are slower, Repetitive Sampling oscilloscopes are less expensive than Single-Shot instruments. Two techniques are used for repetitive sampling: Random Interleaved Sampling (RIS) and Sequential Sampling (SEQ). Block diagrams for both are shown in figures 2a and 2b.

Random Interleaved Sampling takes advantage of the fact that the trigger signal and the sample clock are asynchronous. For each acquisition, the time from the sample clock to the trigger time is measured very precisely. This information is used to create a composite waveform from many separate aquisitions, with a very high effective sample rate. For example, with a high resolution (<10 ps) time-to-digital converter, equivalent sample rates of 20 GS/s can be achieved. An important advantage of RIS is that it allows full pre-trigger acquisition. LeCroy scopes employ RIS whenever repetitive waveform acquisition is required.

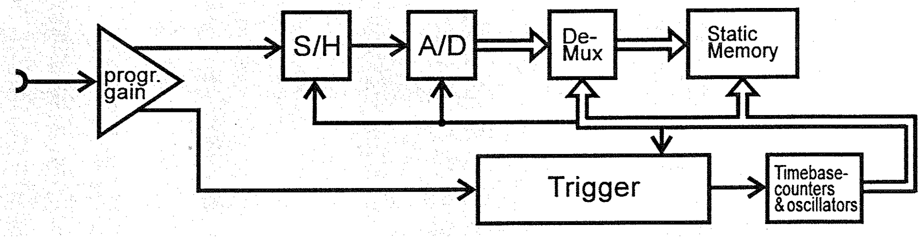


Figure 1: Block Diagram of a Single Shot Sampler. The sample rate is typically > 4 to 10 times the Bandwidth.

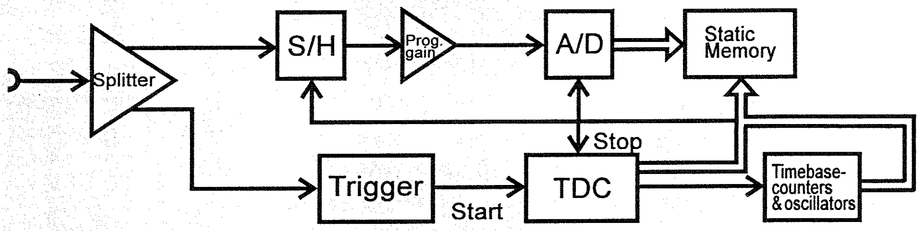


Figure 2a: Block Diagram of a RIS Sampler. The bandwidth is typically much greater than the sample rate.

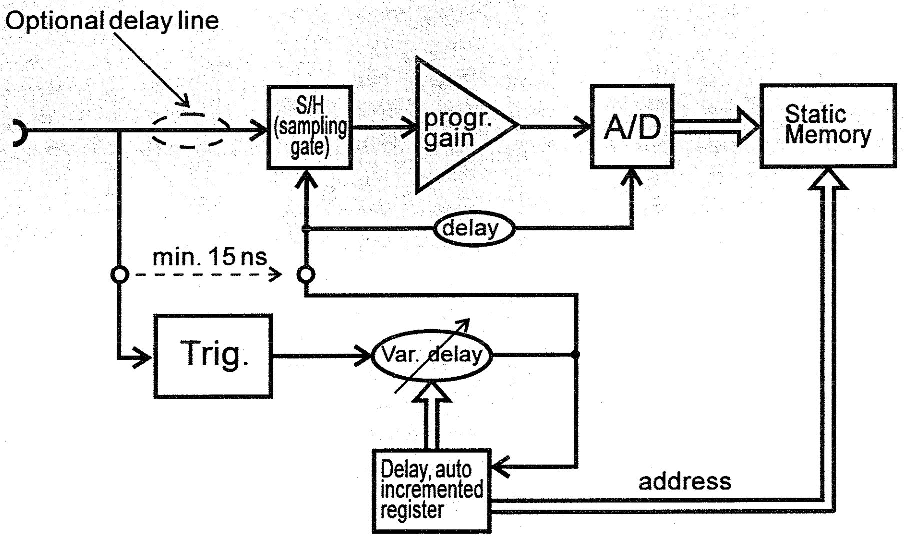


Figure 2b: Block Diagram of a SEQ Sampler

In contrast, SEQ sampling operates by adding incrementally longer delays to the sample clock, for each acquisition of the repetitive signal. This method is typically used in very high bandwidth (>10 GHz) oscilloscopes. While yielding very fine time resolution, it cannot capture pre-trigger information. (Some sequential oscilloscopes use short delay lines to provide a limited pre-trigger view.)

II. BANDWIDTH - HOW MUCH IS ENOUGH?

Bandwidth determines the ability of an oscilloscope to capture a fast signal (or signal detail) without substantially filtering it. Using an oscilloscope that has insufficient bandwidth will reduce the signal's high-frequency content. High frequency signal amplitudes will be reduced and pulse edges will be slowed down.

But how much bandwidth is enough? In the case of fast pulses, we are particularly concerned with errors caused on risetime and falltime measurements. An oscilloscope has a finite risetime, determined by the following equation:

$$\text{Bandwidth (MHz)} = 350/\text{Risetime (ns)}$$

A 350 MHz oscilloscope thus has a risetime of 1 nanosecond. Using such an instrument to acquire a signal with 1 nanosecond edges, will result in 1.4 nanosecond edges on the viewed waveform. This corresponds to a 40% measurement error!

In a further example three different oscilloscopes were studied, LeCroy's 9414, 9310 and 9324. These scopes have bandwidths of 150 MHz, 300 MHz and 1 GHz respectively. Pulses with various rise times were captured and measured using each oscilloscope. The risetime errors for each measurement are graphed in Figure 3.

Figure 3 shows that for risetimes of 2 or 3 ns, the 150 and 300 MHz oscilloscopes introduce significant (more than 10%) errors. The 1 GHz oscilloscope makes accurate measurements even in the 1 ns range.

A useful measure of oscilloscopes' pulse response is the Usable Risetime Response (URR). The URR is defined as the input risetime for which the oscilloscope overestimates rise times by 5%. For signals with slower rise times the oscilloscope makes an accurate measurement. For signals that have faster rise times, the instrument will cause significant distortion.

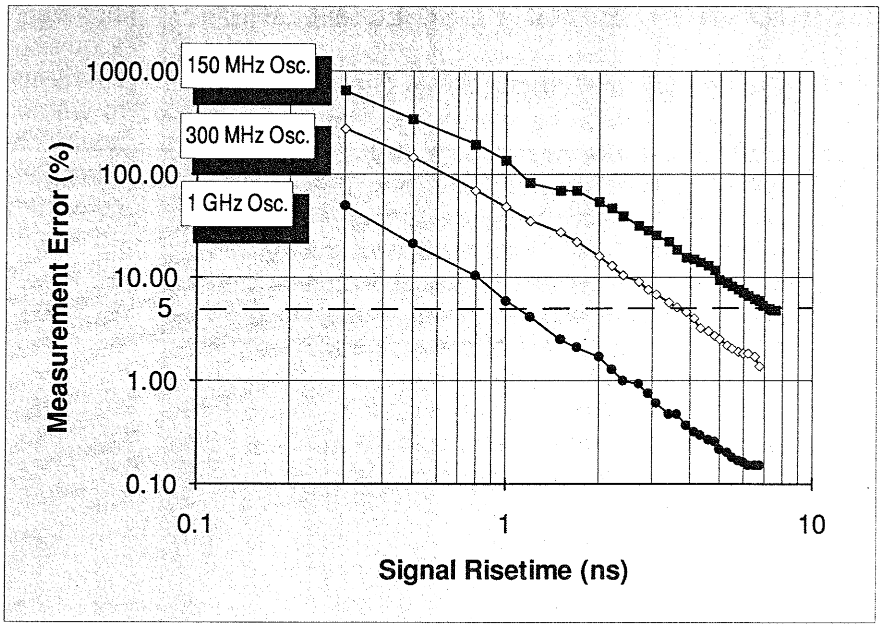


Figure 3: Risetime Response of Various Oscilloscopes.

The URR is shown for each of the oscilloscopes in Table 1, below.

Oscilloscope bandwidth	URR (ns)	Signal Bandwidth (MHz)
1 GHz	1.1	318
300 MHz	3.6	97
150 MHz	7.3	48

Table 1: Usable Risetime Response

For accurate measurements, it is advisable to ensure the following relationship between the bandwidth of an input signal and the bandwidth of the oscilloscope used:

$$\text{Bandwidth}_{oscilloscope} \cong 3 \times \text{Bandwidth}_{signal}$$

Note that this relationship only applies to instruments that have a flat frequency response. This is the case for the LeCroy instruments shown in figure 3. In practice, it is found that instruments with flat frequency response also make faster risetime measurements than oscilloscopes that have complex ("peaked") frequency response. In the case of peaked response, the rule of thumb above will require a 4x or even a 5x coefficient.

III. SAMPLE RATE CONSIDERATIONS

An oscilloscope's sample rate also sets a limit on the fastest signal that it can capture. The sample rate must be at least twice as fast as the highest frequencies present in the signal (Nyquist criterion). For precise measurements, however, the sample rate should be at least 4 to 10 times faster than the frequencies measured. Sampling too slowly will result in poor horizontal resolution. Under-sampling a signal can even cause aliasing, which completely distorts displayed waveforms. A typical under-sampled signal is shown in figure 4.

Thus, an oscilloscope's bandwidth and sampling rate each affect the measured signal in different ways. Fast circuits should therefore be analyzed using a scope with wide bandwidth and high sampling rate. Logic signals with sub-nanosecond edges would require an oscilloscope with 5 GS/s sampling rate and at least 1 GHz analog bandwidth. Such a device would certainly be expensive to produce.

As an alternative, a good laboratory might be equipped with a pair of scopes. One would be a wide band RIS instrument for repetitive signals, and the other a single shot device with slightly lower bandwidth. This combination will be far more affordable than the fast sampling, wide bandwidth oscilloscope described above.

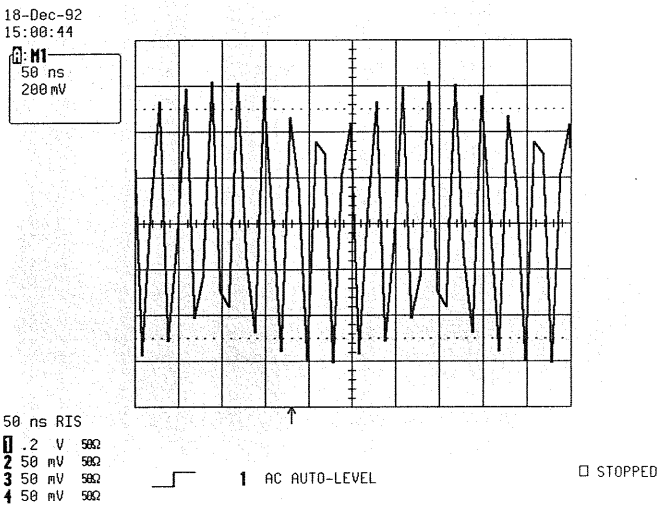


Figure 4: A Sample Rate Limited Waveform

IV. FAST PULSE MEASUREMENTS

Risetime: As shown above, the risetime of a signal is accurately measured as long as its value is within an oscilloscope's Usable Risetime Response. Risetimes are typically measured from the 10% to the 90% point on the waveform. According to IEEE Standard 181-1977 this is defined in terms of the full swing of the waveform, even if there is an inflection point on the leading edge. In the very fastest circuits, it is standard to measure the 20% to 80% risetime. This makes the risetime specification insensitive to inflections near the top of the pulse.

Overshoot: Measurement of signal overshoot requires proper attention to the bandwidth of the oscilloscope used. In addition, the overshoot of the oscilloscope itself is important to consider. For input pulses, where the risetime of the signal is approaching the limit of the oscilloscope, overshoot larger than 5% is not uncommon.

Making Measurements in the presence of Noise: In some cases, it is necessary to characterize a circuit under adverse conditions. This may occur early in the product design, when the issues of shielding and layout have not yet been fully addressed. Alternatively, circuit layout may make good grounding technique difficult. In either case, the noise present can dramatically mask the measurement. See Figure 5.

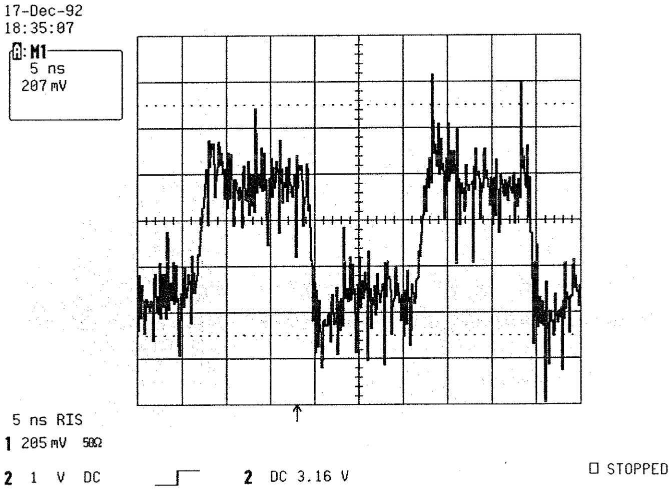


Figure 5: A Noisy Waveform

Because noise is usually very wideband, using a wider bandwidth oscilloscope generally reveals more noise. A simple solution to this problem is to filter the signal. This, however, can compromise measurement accuracy by reducing bandwidth. Another solution is to average the waveform over time. The noise, which is random, is averaged to zero. Thus, for example, LeCroy's Continuous

Averaging function provides noise rejection without any compromise in bandwidth. A further benefit of averaging is that the resulting averaged waveform has a greater dynamic range than a single waveform. This can be very useful when measuring small effects, like overshoot on large signals.

Figure 6 shows the effect of averaging the noisy waveform shown earlier.

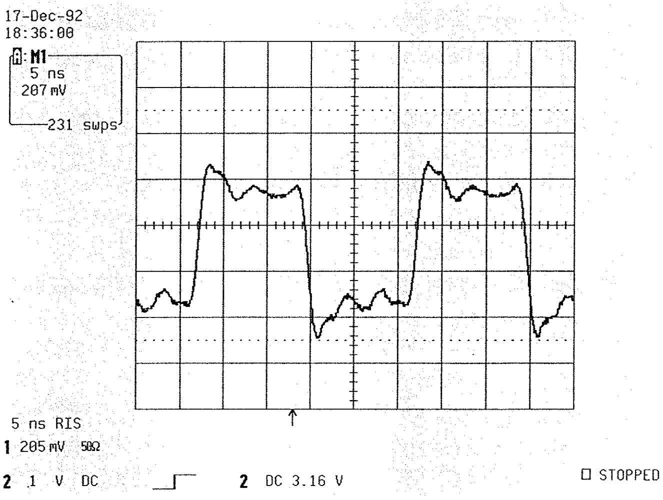


Figure 6: Noise Removed Through Averaging

V. SUBTLE PROBLEMS IN FAST ELECTRONICS

Today's digital ICs become faster with each new release. Technologies like FAST TTL, CMOS FACT, BiCMOS, ECL, etc. offer toggle frequencies up to hundreds of MHz. To support these switching speeds, transition times of less than one nanosecond are required. As a reference, Table 2 gives the maximum toggle frequency, and rise/fall times associated with the most important logic families.

When designing with these fast techologies, it is insufficient to think of gates as simple switches. Devices operating at such speeds exhibit many "analog" characteristics. These characteristics, which severely affect circuit performance, may occur at frequencies between 3 and 10 times the toggle rate. Transition times and edge effects can also have catastrophic consequences on circuit performance. A user who does not concern himself with these effects may encounter many problems! These include glitches, race conditions, ground bouncing, oscillations, reflections due to bad bus terminations, clock skew, metastable states, crosstalk and more. The following section presents a few real life examples illustrating the analog nature of today's digital signals, and some of the problems which can be encountered in circuit board debugging.

Logic Family	Logic Type	Max. Toggle Rate (MHz)	Rise/Fall Times (ns)
TTL	Standard (S)	30	10
	Low Power (LS)	30	10
	High Speed (F)	70	4
CMOS	Standard	10	20
	High Speed (HC)	40	8
	Advanced (FACT,etc.)	150	<1
BiCMOS	Standard (BCT)	70	2
	Advanced (ABT)	200	1
ECL		300	0.8
ECLinPS		2000	0.3

Table 2: Toggle Speeds for Various Logic Families

A. Bus Reflections

Example 1. Parasitic Capacitance in a Transmission Line

The first example shows the effect of a 5 pF parasitic capacitance on the integrity of an ECLinPS pulse. The schematic diagram of the circuit under test is shown in figure 7 while figures 8, 9 and 10 show the signal, as seen at point A, by instruments with 150, 300 and 1000 MHz bandwidth respectively.

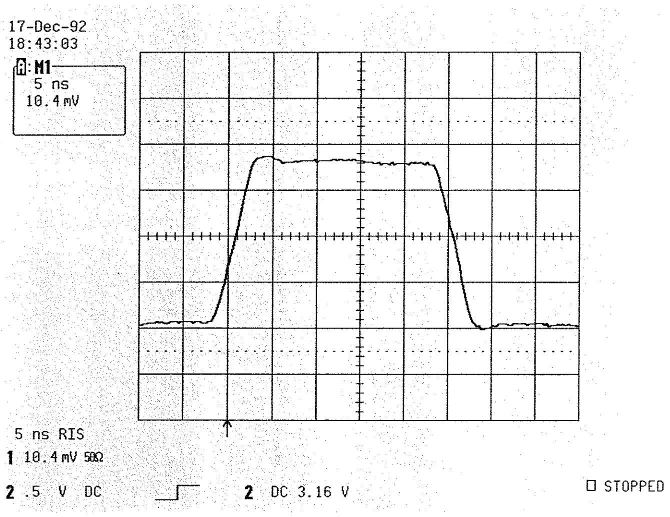


Figure 8: Pulse measured with 150 MHz Bandwidth

The pulse viewed with the 150 MHz oscilloscope appears to be very clean and relatively free of noise. The signal has a rise time of 2 ns and a fall time of 3 ns. Both edges appear to be smooth although a small amount of overshoot can be seen on the leading edge.

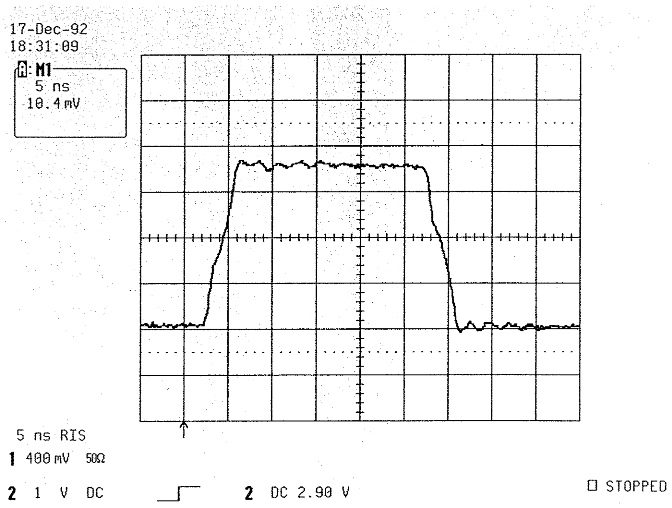


Figure 9: Pulse Measured with 300 MHz Bandwidth

When viewed with a 300 MHz oscilloscope, the pulse looks a little different. While the edge rates have not appreciably changed, there is a significant inflection in both edges. It is also evident that there is significant noise present.

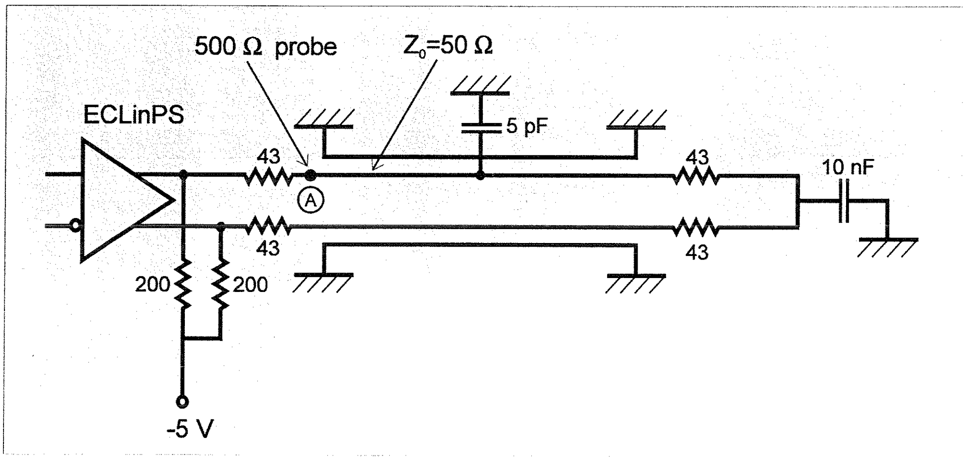


Figure 7: Schematic Diagram of the Circuit Under Test

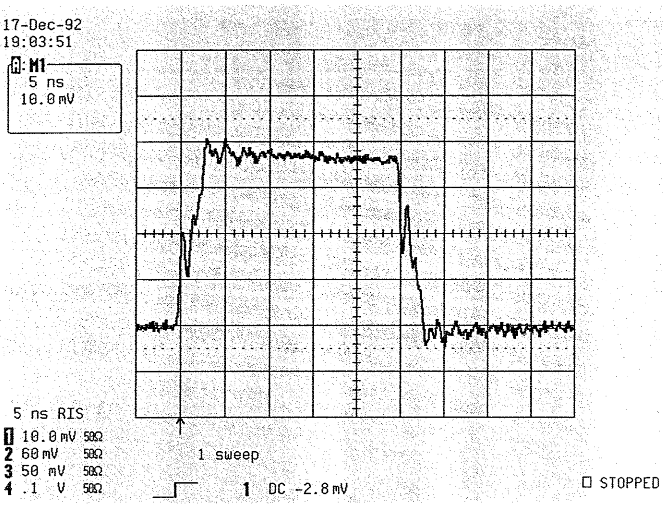


Figure 10: Pulse Measured with 1000 MHz Bandwidth

When viewed with the 1 GHz oscilloscope the anomalies in the signal are dramatic. The two small peaks at the beginning and at the end of the pulse are reflections produced by the 5 pF capacitance. These peaks actually alter the rise and fall time of the main pulse and affect the switching time of the following stage. Even worse, they can generate a double firing or a metastable state in the following stage. While the reflections are apparent with a scope having 1 GHz bandwidth, they are only subtle effects when viewed with a 300 MHz oscilloscope, and are completely hidden from the 150 MHz instrument.

Example 2: PCB Bus Termination

The second example shows the possible effect of a poor Printed Circuit Board (PCB) bus termination. To illustrate the importance of using an oscilloscope of adequate bandwidth, a poorly terminated 10 cm bus was observed. The results of the measurement are shown in figures 11 and 12, taken respectively with a 300 MHz and a 1 GHz oscilloscope.

Figure 11 shows an almost smooth risetime and does not indicate that the circuit under test has any significant problems.

Figure 12 clearly shows the reflections produced by the incorrectly terminated bus. The first reflection is big enough to exceed the logic threshold of the following circuit, and can therefore produce double firing. Earlier generations of digital logic were immune to such narrow glitches, but the reflections would certainly cause problems in fast logic. Good bus termination not only avoids this problem, but also reduces unwanted electromagnetic emission and crosstalk. Proper measurement technique is vital for debugging these types of design problems.

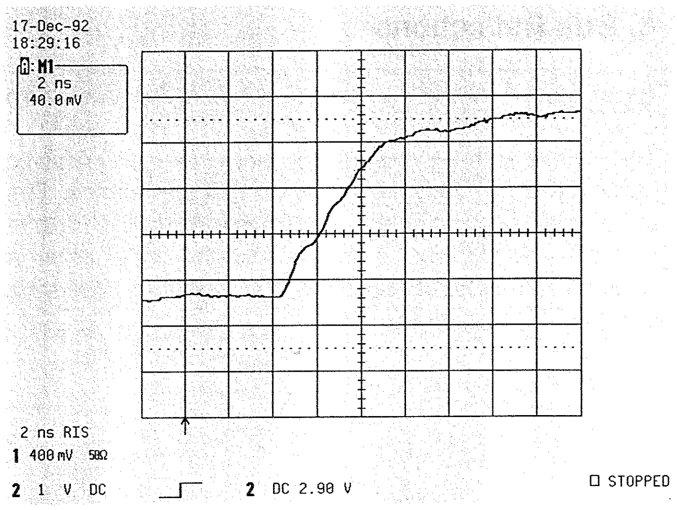


Figure 11: Reflections are Hidden @ 300 MHz...

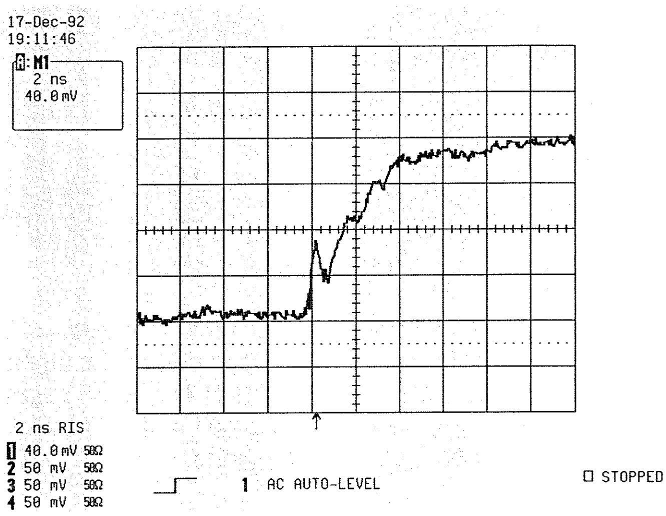
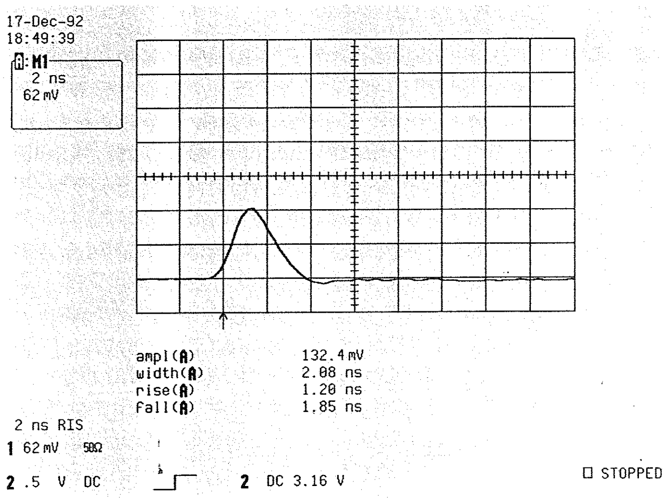


Figure 12: ...But are Visible @ 1 GHz

B. Crosstalk

The fast edges of modern logic devices can often propagate through the parasitic capacitance between a pair of PCB tracks. This effect, known as crosstalk, can have catastrophic effects. In severe cases, crosstalk produces glitches large enough to cross the logic threshold of some circuits. They may cause unpredictable failures such as unwanted logic pulses in a data path or, more subtly, timing errors that result in device misfiring. Detection of glitches, and accurate measurements of their amplitudes and widths, is therefore of major importance.

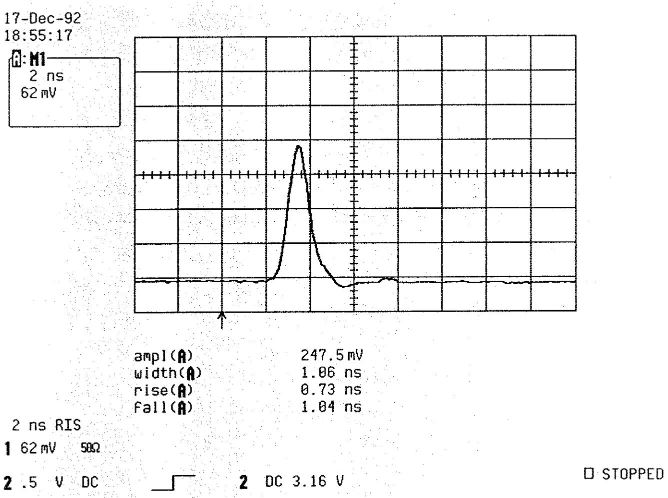
Figures 13, 14 and 15 show an example of how the apparent glitch amplitude can be altered by instrument bandwidth. The glitch shown in this example is produced by the output of a two input AND gate. The cause of the glitch is incorrect timing of the two input signals due to jitter produced by crosstalk. Figures 13 and 14 may lead the test engineer to feel that the glitch observed has insufficient amplitude to produce failures in the circuit. Only the 1 GHz bandwidth oscilloscope, figure 15, shows the problem to be worse than expected.



```
17-Dec-92
18:49:39
A:M1
 2 ns
62 mV

ampl(A)      132.4 mV
width(A)     2.08 ns
rise(A)      1.20 ns
fall(A)      1.85 ns
2 ns RIS
1 62 mV  50Ω
2 .5  V  DC        2  DC 3.16 V        □ STOPPED
```

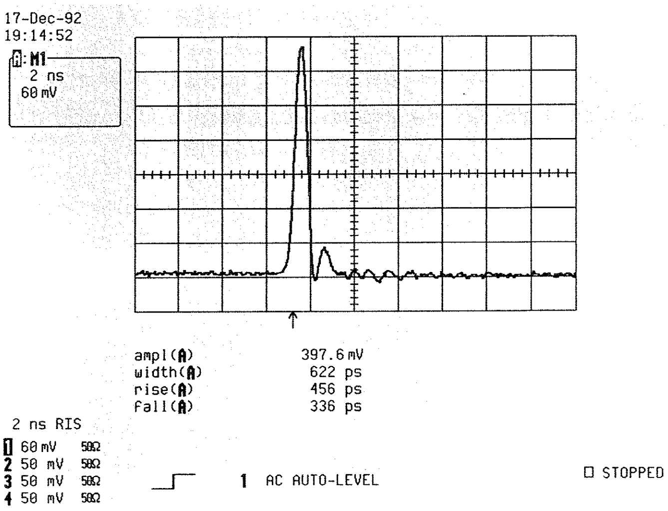
Figure 13: Glitch Viewed with 150 MHz Bandwidth



```
17-Dec-92
18:55:17
A:M1
 2 ns
62 mV

ampl(A)      247.5 mV
width(A)     1.06 ns
rise(A)      0.73 ns
fall(A)      1.04 ns
2 ns RIS
1 62 mV  50Ω
2 .5  V  DC        2  DC 3.16 V        □ STOPPED
```

Figure 14: Glitch Viewed with 300 MHz Bandwidth



```
17-Dec-92
19:14:52
A:M1
 2 ns
60 mV

ampl(A)      397.6 mV
width(A)      622 ps
rise(A)       456 ps
fall(A)       336 ps
2 ns RIS
1 60 mV  50Ω
2 50 mV  50Ω
3 50 mV  50Ω
4 50 mV  50Ω       1  AC AUTO-LEVEL        □ STOPPED
```

Figure 15: Glitch Viewed with 1 GHz Bandwidth

C. Edge Effects

Assume that the glitch shown in the previous figures is inadvertently applied to an AND gate at the same time as another pulse arrives at its other input. In such a case, there is a significant chance that the following circuitry would be sensitive to negative transitions and, as a result, catastrophic failure would occur. Figures 16 and 17 show what the user would see if he were monitoring the output of the AND gate, using scopes with 150 MHz and 300 MHz. Again, no major problem is detected. Figure 17 shows an inflection in the edge, although it appears to be too small to cause serious problems. When the signal is viewed with the 1 GHz oscilloscope the real magnitude of the problem becomes apparent. Figure 18 shows the true size of the inflection largely hidden by the other instruments.

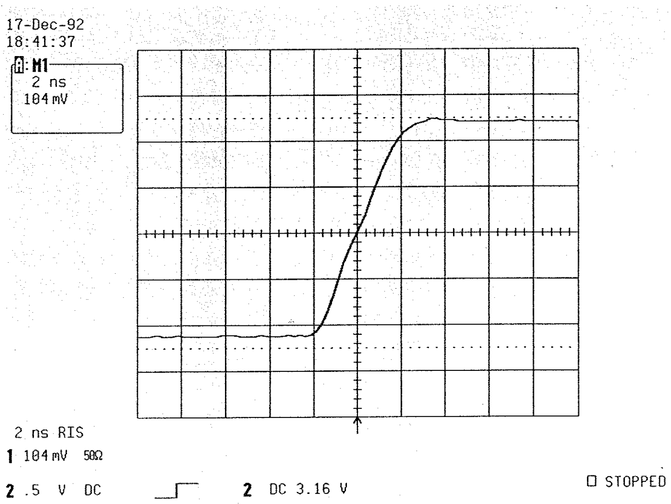


Figure 16: Edge Glitch Obscured by 150 MHz Scope

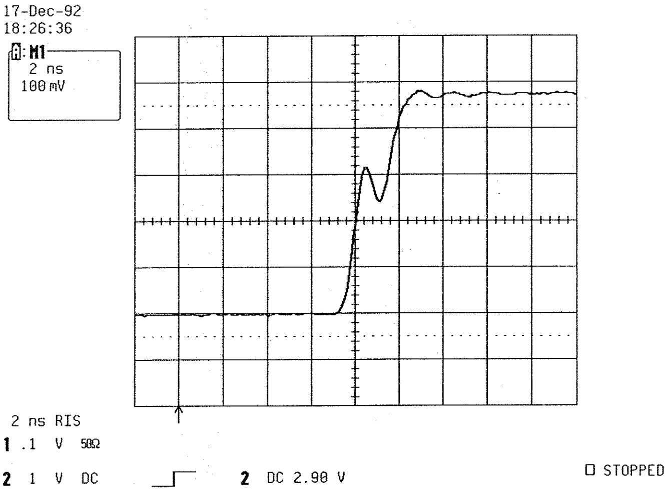


Figure 17: Edge Glitch Barely Visible at 300 MHz Bandwidth

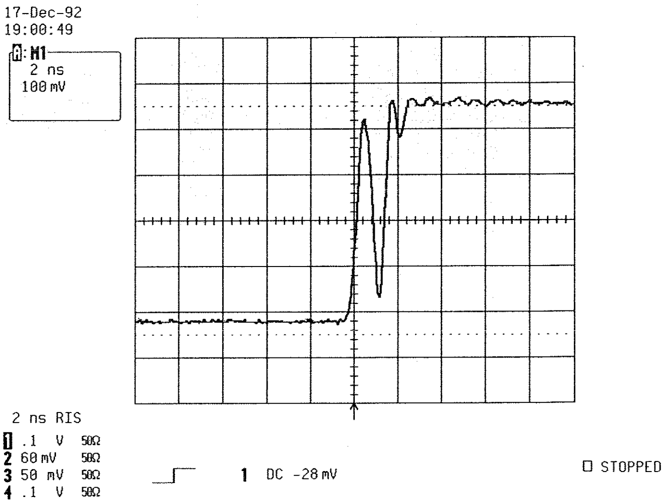


Figure 18: Edge Glitch Clearly Visible at 1 GHz Bandwidth

VI. PROBES AND PROBING

In high frequency circuit characterization the proper use of probes is crucial. The simple act of probing a high frequency circuit can significantly alter the characteristics of the circuit itself. For each type of measurement it is important to choose the right probe and also to use good grounding technique. (Ground leads should be kept as short as possible and, whenever possible, a spring clip ground pin should be used.)

There are three factors which are important when selecting a probe: its bandwidth, resistance and its capacitance. The effects of probe bandwidth are obvious: the composite oscilloscope/probe bandwidth is degraded.

Low Impedance Passive Probes offer very high bandwidth (typically several GHz). They also feature very low capacitance. Due to their low impedance, however, (typically 500 Ω) they present a significant load to the circuit under test. This resistive loading results in loss of signal amplitude. This may be a problem when using TTL with 1 kΩ pull-up resistors, or CMOS which is not capable of sourcing the current required. It is usually not a problem when using ECL.

High Impedance Passive Probes present much lower circuit loading. They also present significant capacitance. This can be a major bandwidth degrading factor, resulting in signal distortion. For example, the capacitance of a 10 MΩ probe is typically around 15 pF. This means that with a 1 kΩ source impedance, bandwidth degradation would limit rise time measurements to the order of 33 ns. HiZ probes are generally restricted to applications where signal frequency is less than 50 MHz.

A high performance approach to circuit probing is the use of an active probe. These have bipolar or field-effect devices in the probe tip, which act as the input stage of a buffer amplifier. These active probes provide high bandwidth, high impedance and low capacitance but they are more expensive, and may be sensitive to damage due to over voltage abuse.

For more details on probes and probing, see LeCroy Application Note ITI 016 "Probes and Probing."

VII. CONCLUSION

Modern digital circuits operate at such high speeds that they must be treated with proper analog technique. In particular, attention to layout and termination issues is crucial. In order to correctly test and debug modern circuits it is particularly important to use test instrumentation that preserves signal fidelity. In particular, engineers should avoid the use of oscilloscopes that have inadequate bandwidth. Low bandwidth instruments can easily mask important problems which may lead to unpredictable and unreliable designs.

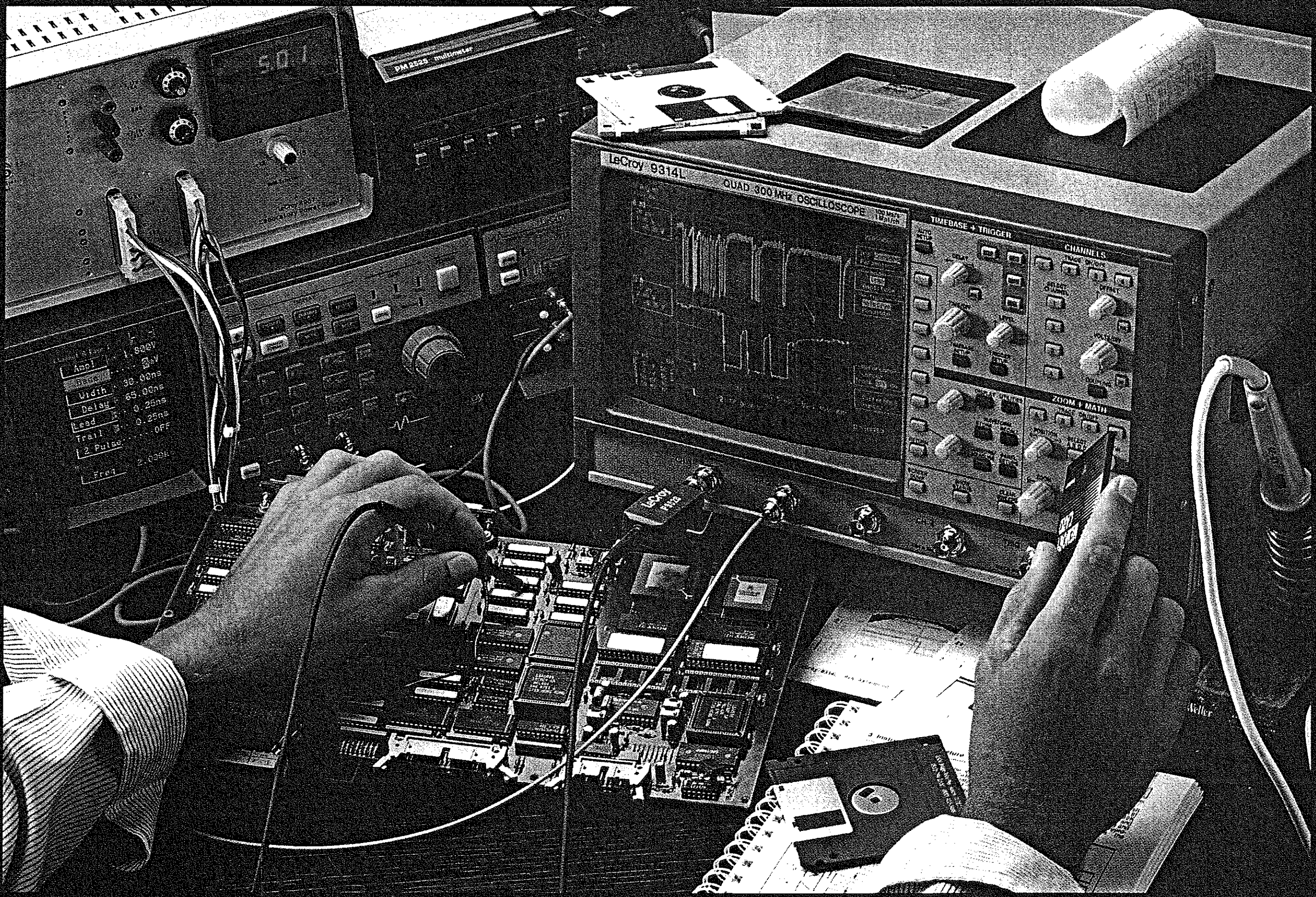
Other application notes available from LeCroy

a. Application notes for the 9400 and the 9300 series oscilloscopes

ITI 003	The 9400 Oscilloscope in Ultrasonics
ITI 004	Reprint from POWER Magazine: Vibration Analysis Now Works on Reciprocating Engines
ITI 007	Single-shot Bandwidth as a Function of Memory Length in Digital Oscilloscopes
ITI 008	Benefits of Long Memories in Digital Oscilloscopes
ITI 009	How to Trigger on the Most Elusive Events
ITI 011	Enhanced Resolution for the LeCroy 9420/24/50 Oscilloscopes
ITI 012	Troubleshooting and Monitoring TV Signals With LeCroy 9420/24/50
ITI 013B	Benefits of Digital Oscilloscopes in Communications
ITI 014	Benefits of Digital Oscilloscopes in Power Supply Design and Test
ITI 016	Probes and Probing

b. Miscellaneous application notes

AN-005	The Hows and Whys of Arbitrary Function Generators
AN-16	Dynamic Range considerations for ADC's
AN-2004	Dynamic Performance Testing of High-Speed Transient Recorders
AN-2005	Digitizer Performance through Visual Methods
AN-2012	Modular Waveform Digitizers for Medical Ultrasound Applications
AN-2018	Digital Signal Processing
CSD-001	Principles of Digital Waveform Recording
CSD-002	Fundamentals of A to D Conversion
CSD-003	Fundamentals of Aliasing
CSD-004	Understanding Effective Bits



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