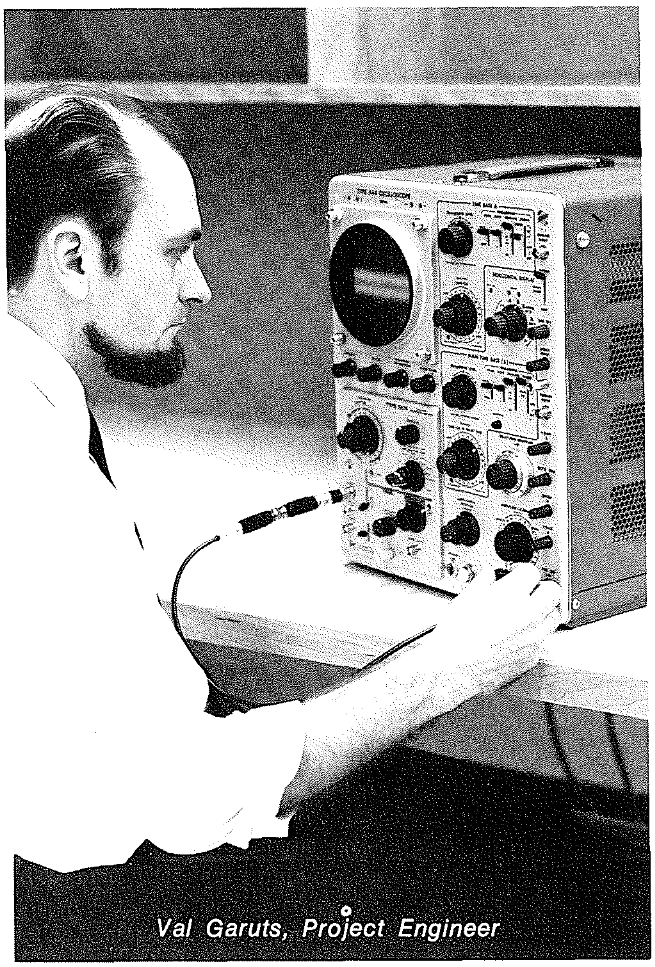
measuring conventional oscilloscope noise

By Val Garuts and Charles Samuel

Noise—random and specific unwanted variations of the trace on a cathode-ray tube (CRT)—is a limiting factor in high-sensitivity measurements with an oscilloscope. The amount of noise visible on a CRT display depends on the oscilloscope's bandwidth, deflection factor setting, the ambient temperature, power line waveform characteristics, and other factors.



Val Garuts, Project Engineer

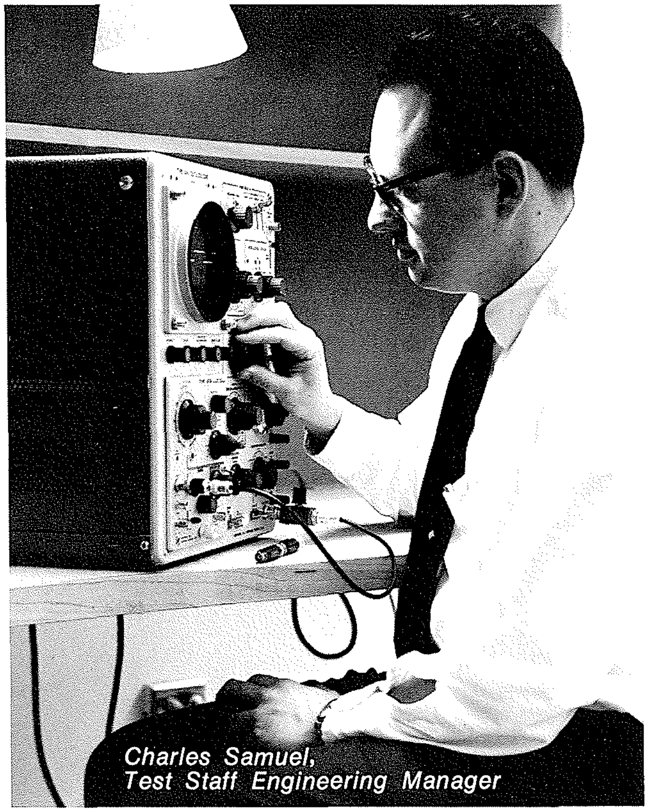
Small amounts of noise usually have little effect on oscilloscope display interpretations. As a result, instruments with less than about 0.2 divisions of noise deflection do not generally have noise performance specified. Instruments with more than 0.2 divisions of noise deflection may have performance areas which are noise limited and thus, a performance specification is required. If the visible noise is much larger than this it may affect measurements made with the oscilloscope.

Three methods to measure and specify noise are presently used on conventional Tektronix instruments:

1. Determine the noise on the display by measuring it at some output point with an RMS voltmeter.
2. Observe the apparent trace width on the CRT.
3. Display a known signal and determine the amount of noise present by tangential measurement (displayed noise).

NOISE MEASURED WITH METER (RMS)

The most repeatable means of measuring noise is with a RMS voltmeter. This method requires access to the signal before it is displayed on the CRT. A calculation is necessary to convert RMS noise to a value corresponding to the CRT observation. The meter *must be* connected to the proper impedance point in the circuit



or the measured noise amplitude will be incorrect. RMS voltmeters are seldom used to describe noise for oscilloscope displays because:

1. Oscilloscope users generally are interested in a specification which can be measured directly from a CRT observation.
2. The complexity of the various sources of noise make it impractical to completely specify noise and difficult to determine where in the circuit to make the measurement.
3. The meter bandwidth will affect the result.
4. Expensive instrumentation is required to verify the specification.

APPARENT TRACE WIDTH

The most convenient method of noise measurement is to determine the peak-to-peak vertical trace width due to noise. Measuring the noise directly at the CRT graticule is also the simplest way to determine the amount of noise present. This requires no extra equipment but is useful only on small amounts of noise deflection where accuracies of ±50% or so are adequate.

Repeatable measurements are difficult to obtain with deflections larger than 0.2 divisions. Different amounts of noise are read at different times and the apparent noise value is changed by ambient lighting and trace intensity. Thus, this method is not adequate for verifying noise performance unless the specification is 0.2 divisions or less. With the apparent trace width method, it is only possible to state that the noise voltage is within a certain value for the time it is observed.

DISPLAYED NOISE

Traditionally, the amplitude of random noise in an amplifier has been stated by an equivalent RMS value of the noise referred to the input. As previously discussed, describing the noise amplitude by stating its RMS value is somewhat unsatisfactory for CRT displays.

Noise interferes with an oscilloscope's usefulness and appears as a visible widening of the trace. This reduces the oscilloscope's ability to display and measure small vertical deflections. A measure of noise-limited resolution may be obtained by noting the vertical signal am-

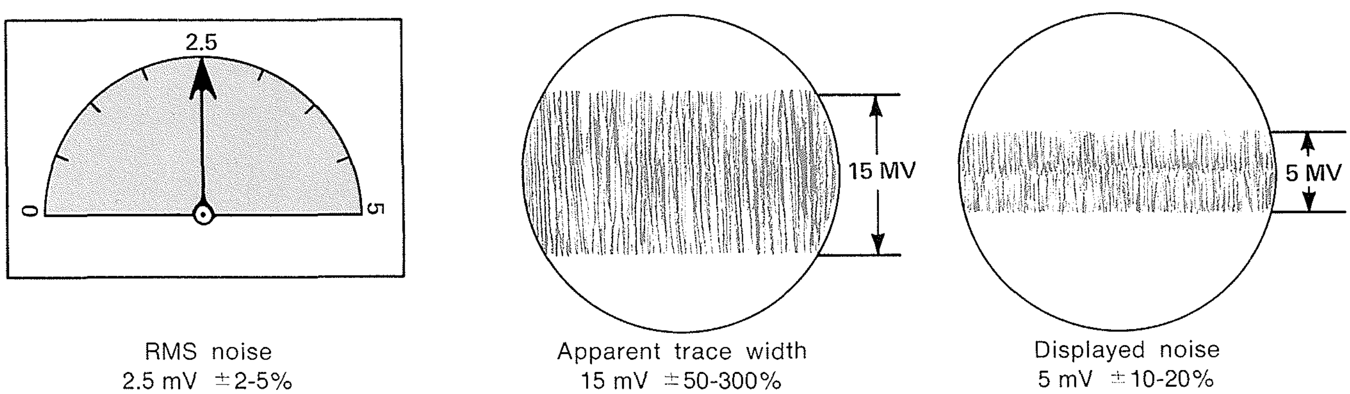


Fig 1. Example illustrating relative amplitudes and accuracies of the three methods used to measure conventional oscilloscope noise at Tektronix.

plitude which will merge two noise traces into one. Noise measured in this manner is defined as displayed noise and is measured by the tangential noise measurement method. This method of stating the noise is more meaningful than the RMS value, since it more closely approximates the actual effect of noise interfering with measurements. It is also much more repeatable than just observing the trace width.

TANGENTIAL NOISE MEASUREMENT

This method is useful with all noise-limited instruments (apparent trace width of 0.2 division or greater). The equipment required is listed below:

1. A squarewave generator, with an internal or external variable attenuator, to produce a frequency 1/10 or less the bandwidth of the oscilloscope.
2. A precision (e.g., ±1%) 100X attenuator.
3. Necessary terminations, cables, etc.

By following the steps below, the displayed noise is easily measured.

1. Set up equipment as in fig 2.
2. Adjust the oscilloscope sweep controls for a free running sweep at about 0.2 ms/div. Adjust the oscilloscope intensity control for comfortable viewing; also adjust the focus and astigmatism concontrols if necessary. The setting of the CRT controls is not particularly critical. Any intensity which produces comfortable viewing may be used and sweep time can have any value that does not produce flicker.

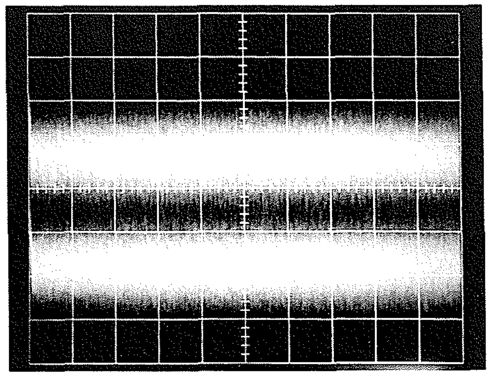


Fig 3. Initial setup for tangential noise measurement.

3. Set the oscilloscope vertical volts/division to the deflection factor where the noise is to be measured, and apply the signal from the test setup shown in fig 2. Adjust the squarewave amplitude so two bands of noise can be observed on the CRT, see fig 3.
4. Reduce the squarewave amplitude till the two noise bands merge (the point where the darker band between the noise bands just vanishes), see fig 4. The final amplitude adjustment should be made slowly, since the observer may adapt to the pattern and tend to observe a residual dark band where none is observable a few seconds later. A total adjustment time of 1 minute is typical.
5. Remove the 100X attenuator from the squarewave path, change the oscilloscope deflection to

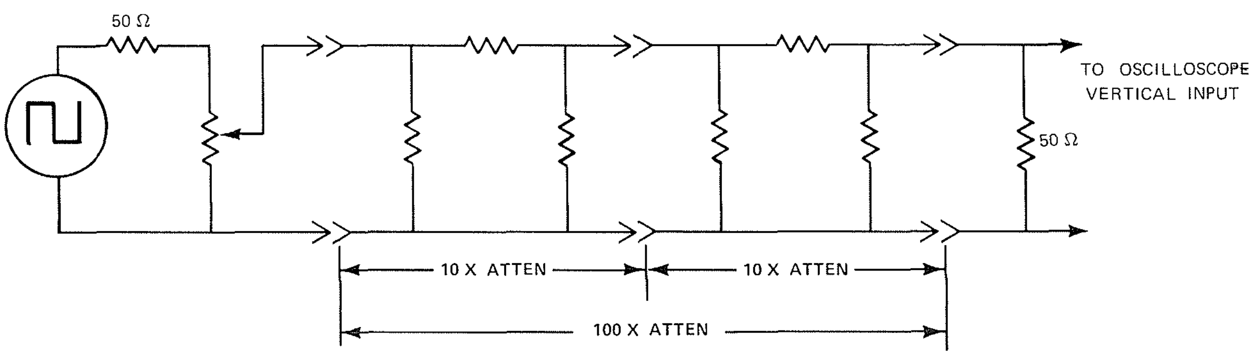


Fig 2. Equipment setup for measuring displayed noise.

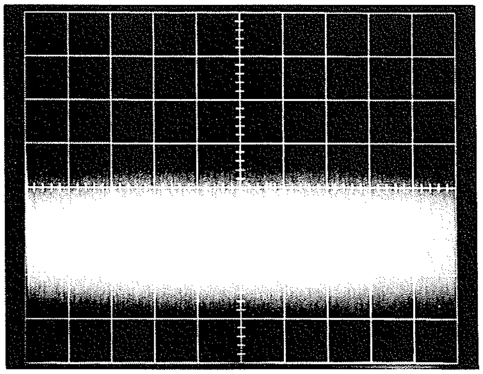


Fig 4. Final Adjustment. Dark band between the noise bands has just vanished.

a suitable value, and measure the squarewave amplitude. Divide this amplitude by 100 to obtain the amplitude of the displayed noise.

RELATIONSHIP TO RMS VALUE

For the very common case of a Gaussian noise amplitude distribution (e.g., thermal resistance noise), tangentially measured displayed noise has a simple relationship to RMS noise: displayed noise ≈2X RMS noise. A common situation where these relationships do not hold is for essentially Gaussian noise mixed with a comparable amount of single-frequency signal (i.e., hum).

ACCURACY AND REPEATABILITY

The repeatability of the tangential method is relatively unchanged by changes in trace intensity or ambient lighting. The measurement accuracy depends primarily on the user's ability to detect small differences in the brightness of two adjacent regions. This difference threshold depends upon the absolute brightness of the regions, the brightness relative to background, the closeness of the regions (rate of change of brightness with dimension), the absolute angular size, and other factors. Under optimal conditions, brightness differences as small as 2% can be seen; a 50% brightness difference is always easily perceived. Experiments indicate a 20% brightness difference may be perceived by most operators since conditions such as size, absolute brightness, and relative brightness are under the operator's control. Statistical analysis of independent measurements indicate that 99% of all observations should lie within 20% of the mean of all observations.

The relationship of the three measurement methods described was determined by experiment. Values were determined for the conversion factors described in the following 2 equations:

Noise measured with a RMS meter X conversion factor 1 = displayed noise.

Displayed noise X conversion factor 2 = apparent peak-to-peak trace width of noise band.

Five observers made measurements on each of 13 Tektronix Type 545B/1A7A Oscilloscopes. They made judgments of the amplitude of the noise band observed, measured the RMS noise with a meter at the signal output connector of the Type 1A7A, and measured the displayed noise by the method just described. These observations were tabulated and the conversion factors were determined. These conversion factors indicated that the following relationships are valid for conventional oscilloscopes:

$$\textbf{Displayed noise} \approx \textbf{2 RMS equivalent noise}$$

$$\textbf{Displayed noise} \approx \frac{\textbf{apparent trace width}}{\textbf{3}}$$

Note that the visible effects of random noise on a CRT display (apparent trace width) is approximately 6 times the RMS noise value.

CONCLUSION

A tangential noise measurement requires a minimum amount of equipment and offers an accuracy of approximately ±20%. The mean of 5 observations should be accurate to ±10%, provided a particular observer has no fixed bias. In comparison, the accuracy of the apparent trace width measurements may vary several hundred percent. The RMS meter is slightly more accurate than the displayed noise technique but requires more care and additional equipment to make an accurate measurement. As a result of these conclusions, all new Tektronix conventional oscilloscopes specify displayed noise performance by the tangential method of measurement discussed.

Al Zimmerman, Program Manager, and George Frye, Project Engineer, confer over a 7T11 Time-Base Unit.

Measuring Jitter with a Sampling Oscilloscope

By Al Zimmerman

COVER—The excellent jitter performance (less than 10 ps) is clearly shown on a randomly sampled fast rise display.

The oscilloscope is a useful tool for measuring time jitter between two different but repetitive events. The **sampling** oscilloscope is particularly well-suited for these measurements because of its extremely fast sweep rates and low internal jitter. Jitter measurement resolution to within a few picoseconds may often be achieved.

Typical examples of time jitter measurements include:

(a) Measuring the inter-period jitter of a repetitive signal source.

(b) Measuring the pretrigger-to-pulse jitter of a pulse generator.

(c) Determining the uncertainty of threshold crossing detectors (comparators) due to noise, etc.

(d) Verifying the oscilloscope's jitter specs.

SOME TERMINOLOGY

"Noise" is the term we shall use to describe a random broadening of the oscilloscope trace in the vertical direction, while "jitter" will be used to describe a random broadening in the horizontal direction. In the sampling oscilloscope, the apparent trace broadening occurs as individual display dots are misplaced along one or both axes.

The causes of noise and jitter are many and varied. Some are truly random, or aperiodic, in nature while others are uniformly periodic. Unless the noise or jitter source is synchronous or very nearly synchronous with the oscilloscope sweep rate (or scanning rate in a sampling oscilloscope), even periodic causes such as hum or RF often *appear* to result in random dot displacements. No matter how many or what the causes are, the result is a statistical distribution of dots along either a vertical or horizontal cross-section of the trace.

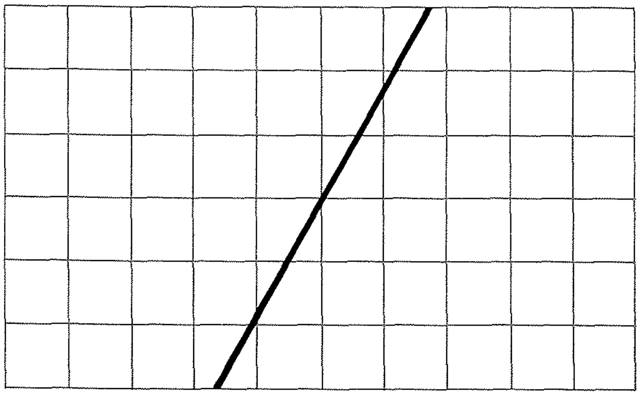
NOISE AND JITTER INTERACTION

When it comes to measuring jitter, a problem arises when noise is also present since these separately-caused effects tend to interact in the display. See drawing 1. *A sloping waveform will suffer both a vertical broadening and a horizontal broadening from either noise or jitter.* While one may always observe noise independently by displaying a horizontal baseline, the analogous operation for a completely independent jitter observation is impossible. In practice, jitter measurements with an oscilloscope must either *reduce the effect* of noise to the point of insignificance in the display *or* the jitter measurement *must be corrected* to remove the effect of noise.

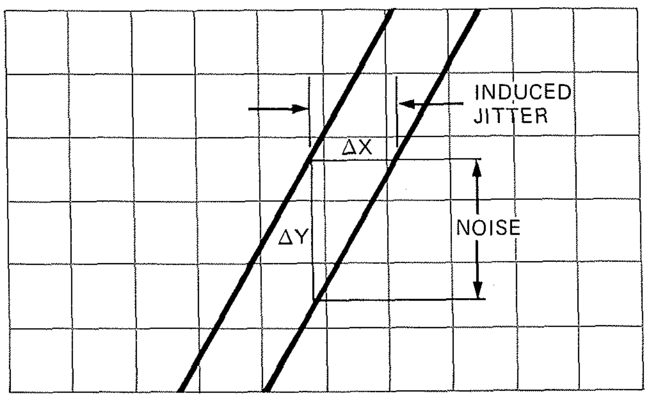
The *first approach* requires a large dV/dt for the input signal relative to vertical volts per division divided by horizontal seconds per division in the oscilloscope display. This produces a steep slope and may provide the required independence of noise and jitter in the display. Either the risetime of the available signal, the risetime of the oscilloscope, or the permissible signal amplitudes may impose the ultimate limit on the dV/dt which may be displayed, however.

It must also be noted that a large signal should be used relative to the inherent noise level of the oscilloscope. *Simply turning up the vertical sensitivity (volts/div) to get a steeper slope does NOT reduce the interactive effect of noise upon jitter.* Anything done to increase the signal-to-noise ratio DOES reduce the effect—at *ANY* sensitivity setting.

The *second approach* to a solution for this problem involves a subtractive correction to the observed jitter based on measurements of waveform slope and noise. Before we describe how to make such a correction, however, we need to look further into the question of how to measure the observed jitter from a noisy, jittery trace.



Drawing 1. No noise.



Drawing 2. Jitter induced by noise.

THE HUMAN FACTOR

A significant problem which plagues both noise and jitter measurements is the subjectivity of display interpretation. Different people find it difficult to agree on the same reading from the oscilloscope screen. The problem is due to the "skirts" on the gaussian or near-gaussian dot distributions encountered. When asked to describe the boundaries or limits of such a distribution, one person will tend toward a peak-to-peak interpretation which includes *all* the dots while another person will discount the more widely scattered dots and consider only the central portion of the distribution. Since most people seem to tend toward the latter interpretation; it is difficult to specify or to describe such a display with much precision.

MEASURING NOISE

In the April '69 issue of TEKSCOPE, a "tangential trace" technique was described for measuring noise displayed on a conventional (non-sampling) oscilloscope. The same technique can be used for measuring noise on a sampling oscilloscope. A typical setup is shown below.

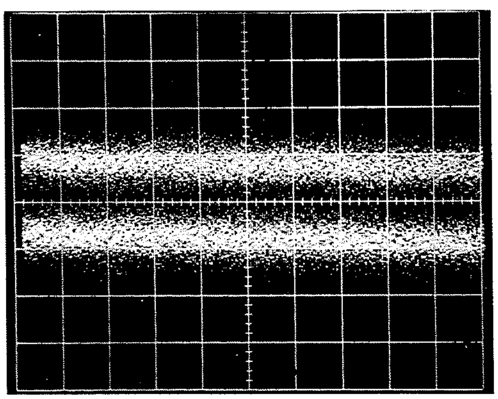


Photo 1. Initial setup for tangential noise measurement.

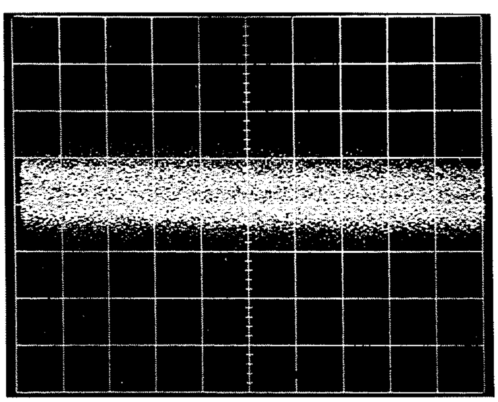


Photo 2. Final adjustment. Dark band between the noise bands has just vanished.

In this technique, two traces are produced by adding a slow squarewave to the vertical signal and adjusting the square-wave amplitude to achieve "tangency" of the two traces. It can be shown for a gaussian distribution, that tangency is achieved when the squarewave value (N_{SW}) is exactly *twice* the RMS noise value.* It can also be shown (see chart 1) that the displayed noise value (N_D) which contains 90% of the dots is approximately *three times* the RMS noise value (N_{RMS}). From these relationships the following statement is derived:

$$N_D \cong 3N_{RMS} = 3/2\ N_{SW}$$

*Garuts, Val., "A Simple Method for Measuring Preamp Noise," Tektronix Engineering Instrument Specification Guidelines.

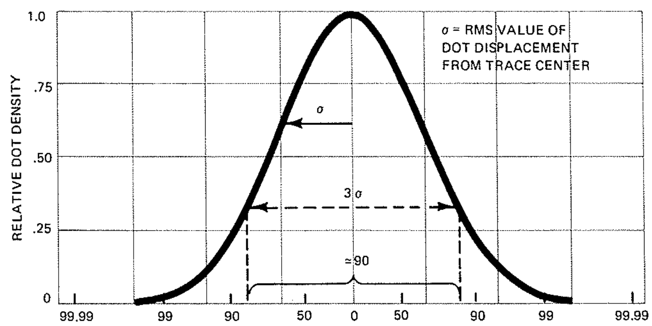
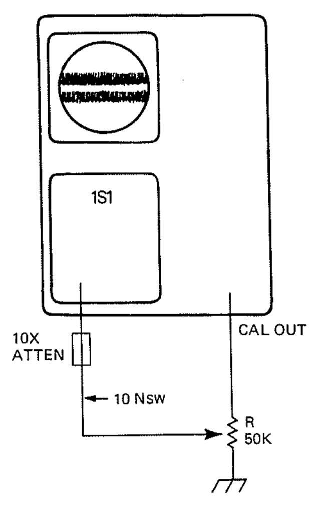


Chart 1. The percentage of dots contained with a cross-section of a trace is approximately 90% (3 σ).

MEASURING NOISE (N_{SW})

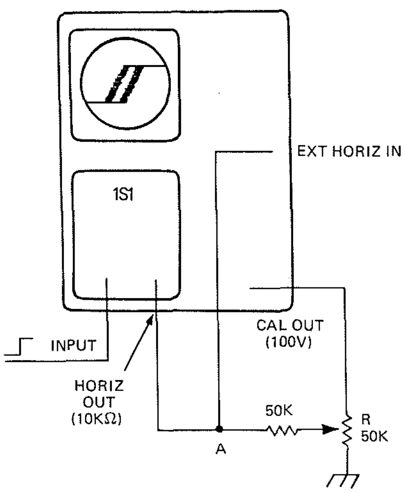


MEASURING JITTER

Several techniques similar to the tangential-trace method for measuring noise have been suggested for measuring the horizontally summed effects of time jitter and and noise which we shall simply call "observed jitter". One of these techniques is shown below (J_{SW}). Here a square wave is added to the slow speed horizontal signal causing the displacement of a fast-rising portion of the display. The square-wave amplitude is again adjusted to achieve tangency, but this time its value must be in terms of the resulting time displacement of the tangent traces. This is most easily done by switching to MANUAL SCAN on the sampling sweep and observing the effective time displacement caused by the square wave alone. The resulting jitter relationships are:

$$J_D \cong 3J_{RMS} = 3/2\ J_{SW}$$

MEASURING JITTER (J_{SW})



CORRECTING FOR NOISE

It must be emphasized that the display-jitter measurement described *includes* a contribution due to vertical noise. If one wishes to describe the *time jitter* independently from the induced contribution from noise, it will be necessary to subtract out this contribution. Thus, noise-corrected time jitter (J_{NC}) may be easily found

$$J_{NC} = \sqrt{J_D^2 - \left(\frac{N_{SW}}{\text{slope}}\right)^2}$$

where the slope is simply $\Delta Y/\Delta X$ of the waveform in the display. All values shown include approximately 90% of the displayed dots along a vertical or horizontal cross-section.

CORRECTING THE MEASUREMENT

Since the jitter introduced by the oscilloscope itself (J_O, usually less than 20 ps) may be a significant part of the observed jitter, it may be desired to make a similar subtractive correction for it as well. Oscilloscope jitter may be determined by viewing the triggering event directly and then making a noise correction as described above. The complete formula for time jitter corrected for noise and scope jitter (J) then becomes:

$$J = \sqrt{J_D^2 - \left(\frac{J_{SW}}{\text{slope}}\right)^2 - J_O^2}$$

Using the techniques discussed, the effects of noise and human interpretation may be reduced to allow repeatable jitter measurements to within a few picoseconds with a sampling oscilloscope.

PROCEDURE FOR DETERMINING NOISE AND JITTER

N_{SW}

1. Adjust R for tangency.
2. Remove the 10x attenuator (applying the squarewave signal directly.)
3. Measure the trace separation in volts directly on the screen. (E_{SEP})
4. N_{SW} (in volts) $= \frac{E_{SEP}}{10}$

J_{SW}

1. Adjust R for tangency of the two step transitions.
2. Set 1S1 to MAN SCAN.
3. Measure the squarewave amplitude at A. (E_{TAN})
4. Adjust R for 8 cm deflection.
5. Again measure the squarewave amplitude at A. (E_{8CM})
6. J_{SW} (in seconds) $= \frac{E_{TAN}}{E_{8CM}}$ x (Time/Div) x 8