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Oscilloscope Voltage Measurement

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Jerry Murphy
Hewlett-Packard

19.1 Introduction

Engineers, scientists, and other technical professionals around the world depend on oscilloscopes as one of the primary voltage measuring instruments. This is an unusual situation because the oscilloscope is not the most accurate voltage measuring instrument usually available in the lab. It is the graphical nature of the oscilloscope that makes it so valued as a measurement instrument—not its measurement accuracy.

The oscilloscope is an instrument that presents a graphical display of its input voltage as a function of time. It displays voltage waveforms that cannot easily be described by numerical methods. For example, the output of a battery can be completely described by its output voltage and current. However, the output of more complex signal source needs additional information such as frequency, duty cycle, peak-to-peak amplitude, overshoot, preshoot, rise time, fall time, and more to be completely described. The oscilloscope, with its graphical presentation of complex waveforms, is ideally suited to this task. It is often described as the “screwdriver of the electronic engineer” because the oscilloscope is the most fundamental tool that technical professionals apply to the problem of trying to understand the details of the operation of their electronic circuit or device. So, what is an oscilloscope?

The oscilloscope is an electronic instrument that presents a high-fidelity graphical display of the rapidly changing voltage at its input terminals.

The most frequently used display mode is voltage versus time. This is not the only display that could be used, nor is it the display that is best suited for all situations. For example, the oscilloscope could be called on to produce a display of two changing voltages plotted one against the other, such as a Lissajous display. To accurately display rapidly changing signals, the oscilloscope is a high-bandwidth device. This means that it must be capable of displaying the high-order harmonics of the signal being applied to its input terminals in order to correctly display that signal.
19.2 Oscilloscope Block Diagram

The oscilloscope contains four basic circuit blocks: the vertical amplifier, the time base, the trigger, and the display. This section treats each of these in a high-level overview. Many textbooks exist that cover the details of the design and construction of each of these blocks in detail [1]. This discussion will cover these blocks in enough detail so that readers can construct their own mental model of how their operation affects the application of the oscilloscope for their voltage measurement application. Most readers of this book have a mental model of the operation of the automatic transmission of an automobile that is sufficient for its successful operation but not sufficient for the overhaul or redesign of that component. It is the goal of this section to instill that level of understanding in the operation of the oscilloscope. Those readers who desire a deeper understanding will get their needs met in later sections.

Of the four basic blocks of the oscilloscope, the most visible of these blocks is the display with its cathode-ray tube (CRT). This is the component in the oscilloscope that produces the graphical display of the input voltage, and it is the component with which the user has the most contact. Figure 19.1 shows that the input signal is applied to the vertical axis of a CRT. This is the correct model for an analog oscilloscope, but it is overly simplified in the case of the digital oscilloscope. The important thing to learn from this diagram is that the input signal will be operated on by the oscilloscope's vertical axis circuits so that it can be displayed by the CRT. The differences between the analog and digital oscilloscope are covered in sections to follow.

The vertical amplifier conditions the input signal so that it can be displayed on the CRT. The vertical amplifier provides controls of volts per division, position, and coupling, allowing the user to obtain the desired display. The amplifier must have a high enough bandwidth to ensure that all of the significant frequency components of the input signal reach the CRT.

The trigger is responsible for starting the display at the same point on the input signal every time the display is refreshed. It is the stable display of a complex waveform that allows the user of an oscilloscope to make judgments about that waveform and its implications as to the operation of the device under test.

The final piece of the simplified block diagram is the time base. This circuit block is also known as the horizontal system in some literature. The time base is the part of the oscilloscope that causes the input signal to appear on the CRT display over time.

FIGURE 19.1 Simplified oscilloscope block diagram that applies to either analog or digital oscilloscopes. In the case of the digital oscilloscope, the vertical amplifier block will include the ADC and high-speed waveform memory. For the analog scope, the vertical block will include delay lines with their associated drivers and a power amplifier to drive the CRT plates.
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19.3 Oscilloscope as a Voltage Measurement Instrument

The oscilloscope's vertical axis requires a wide-bandwidth amplifier and its time base is capable of displaying events that are as short as a few nanoseconds apart indicates that the oscilloscope can display rapidly changing voltages. Voltmeters, on the other hand, are designed to give their operator a numeric readout of steady-state or slowly changing voltages. Voltmeters are not well suited for displaying voltages that are changing levels very quickly. It is better understood by the examination of the operation of a voltmeter as compared to that of an oscilloscope. T o use the oscilloscope, one must first calibrate the magnetic field produced by current flowing through a coil to move the pointer against the force of a spring. It is nearly linear deflection of the voltmeter pointer is calibrated by applying known standard voltages to its input. Therefore, if a constant voltage is applied to the coil, the pointer will move to a point where the magnetic force being produced by the current flowing in its coil is balanced by the force of the spring. If the input voltage is slowly changing, the pointer will follow the changing voltage. It is mechanical deflection system limits the ability of this measurement device to the measurement of steady-state or very low-frequency changes in the voltage at its input terminals. Higher frequency voltmeters depend on some type of conversion technique to change higher frequencies to a dc signal that can be applied to the meter's deflection coil. For example, a diode is used to rectify ac voltages to produce a dc voltage that corresponds to the average value of the ac voltage at the input terminals.

The digital voltmeter is very much like the analog meter except that the mechanical displacement of the pointer is replaced with a digital readout of the input signal. In the case of the digital voltmeter, the input signal is applied to an analog-to-digital converter (ADC) where it is compared to a reference voltage and digitized. The digital value of the input signal is then displayed in an numerical display. The ADC techniques applied to voltmeters are designed to produce very accurate displays of the same signals that were previously measured with analog meters. The value of a digital voltmeter is its improved measurement accuracy as compared to that of its analog predecessors.

The oscilloscope will display a horizontal line displaced vertically from its zero-voltage level when a constant or dc voltage is applied to its input terminals. The magnitude of this deflection of the oscilloscope's beam vertically from the point where it was operating with no input being applied is how the oscilloscope indicates the magnitude of the dc level at its input terminals. Most oscilloscopes have a graticule as a part of their display, and the vertical axis of the scope is calibrated in volts per division of the graticule. As one can imagine, this is not a very informative display of a dc level, and perhaps a voltmeter with its numeric readout is better suited for such applications.

There is more to the scope-voltmeter comparison than is obvious from the previous discussion. The oscilloscope is based on a wide-bandwidth data-acquisition system is the major difference between these two measurement instruments. The oscilloscope is designed to produce a high-frequency display of rapidly changing signals. It is puts additional constraints on the design of the oscilloscope's vertical system that are not required in the voltmeter. The most significant of these constraints is that of a constant group delay. It is a rather complex topic that is usually covered in network analysis texts. It can be easily understood if one realizes the effect of group delay on a complex input signal.

Figure 19.2 shows such a signal. The amplitude of this signal is a dc level, and the rising edge is made up of a series of high-frequency components. Each of these high-frequency components is a sine wave of specific amplitude and frequency. A another example of a complex signal is a square wave with a frequency of 10 MHz. The signal is made up of a series of odd harmonics of that fundamental frequency. These harmonics are sine
waves of frequencies of 10, 30, 50, 70 MHz, etc. So, the oscilloscope must pass all of these high-frequency components to the display with little or no distortion. Group delay is the measure of the propagation time of each component through the vertical system. A constant group delay means that each of these components will take the same amount of time to propagate through the vertical system to the CRT, independent of their frequencies. If the higher order harmonics take more or less time to reach the scope’s deflection system than the lower harmonics, the resulting display will be a distorted representation of the input signal. Group delay (in seconds) is calculated by taking the first derivative of phase versus-frequency response (in radians/(1/s) of an amplifier). If the amplifier has a linearly increasing phase shift with frequency, the first derivative of its phase response will be a horizontal line corresponding to the slope of the phase plot (in seconds). Amplifier systems that have a constant group delay are known as Gaussian amplifiers. They have this name because their pass band shape resembles that of the bell curve of a Gaussian distribution function (Figure 19.3). One would think that the oscilloscope’s vertical amplifier should have a flat frequency response, but this is not the case because such amplifiers have nonconstant group delay [1].

**FIGURE 19.2** A typical complex waveform. The waveform is described by measurements of its amplitude, of set, rise time, fall time, overshoot, preshoot, and droop.

**FIGURE 19.3** The Gaussian frequency response of the oscilloscope’s vertical system, which is not flat in its pass band. Amplitude measurements made at frequencies greater than 20% of the scope’s bandwidth will be in error.
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The oscilloscope's bandwidth specification is based on the frequency where the vertical deflection will be \(-3\) dB (0.707) of the input signal. This means that if a constant 1 V sine wave is applied to the oscilloscope's input and the signal's frequency is adjusted to higher and higher frequencies, the oscilloscope's bandwidth will be that frequency where its display of the input signal has been reduced to be 0.707 V. Noticeable errors in amplitude measurements will start at 20% of the scope's bandwidth. The oscilloscope's error-free display of complex waveforms gives it poor voltage accuracy. For the measurement of dc and single-frequency signals such as sine waves, other instruments can produce more accurate measurements.

Conclusion: The voltmeter makes the most accurate measurements of voltages that are dc, slowly changing, or can be converted to a dc analog of their ac content. The oscilloscope is not the most accurate voltage measurement instrument, but it is well suited to measurements of voltages that are changing very rapidly as a function of time. Oscilloscopes are the instrument of choice for observing and characterizing these complex voltages.

19.3.1 Analog or Digital

The world of oscilloscopes is divided into two general categories: analog and digital. The first oscilloscopes were analog. These products are based on the direct-view vector cathode-ray tube (DVVCRT or CRT for short). The analog oscilloscope applies the input signal to the vertical deflection plates of the CRT where it causes the deflection of a beam of high-energy electrons moving toward the phosphor-coated faceplate. The electron beam generates a lighted spot where it strikes the phosphor. The intensity of the light is directly related to the density of the electrons hitting a given area of the phosphor. Because this analog operation is not based on any digitizing techniques, most people have little trouble creating a very accurate and simple mental model in their minds of its operation.

The analog oscilloscope produces a display of the input signal that is bright and easy to see under most conditions. It can also contain as many as 16 shades of gray-scale information. This means that an event that occurs less frequently will appear at a lower intensity in the display than another event that occurs more frequently. The oscilloscope does not produce a continuous display of the input signal. It is blind during retrace and trigger hold-off times. Because the display depends on the production of visible light from the phosphor being excited by an electron beam, the display must be refreshed frequently. This makes the analog oscilloscope a low-dead-time display system that can follow rapidly changing signals. Also, there is little lag time in front-panel control settings.

The analog oscilloscope is not without its shortcomings. The strength of the analog oscilloscope is its CRT, but this is also the source of its weaknesses. The biggest problem with analog scopes is their dependence on a display that is constantly being refreshed. This means that these scopes do not have any waveform storage. If the input signal fails to repeat frequently, the display will simply be aash of light when the beam sweeps by the phosphor. If the signal's repetition rate falls below 100 Hz, the display will flicker annoyingly. Figure 19.4 shows a plot of the range of an input signal's repetition frequency range from a single-shot event to the full bandwidth of a scope versus the scope's sweep speeds. The result is a map of the scope's operational area. Figure 19.4 shows that the analog oscilloscope fails to map onto the full range of possible input signals and sweep speeds.

Another problem of the analog oscilloscope is its inability to display information ahead of its trigger. This is a problem in applications where the only suitable trigger is at the end of the event of interest. Another limitation of analog scopes is their timing accuracy. The time base of the analog scope is based on the nonlinearity of a voltage ramp. There are other sources of errors in the analog oscilloscope's horizontal axis, but the sweep nonlinearity is the major contributor. This results in these scopes having a timing accuracy of typically \(\pm 3\)% of their full-scale setting. Therefore, if the time base is set to 100 ns/div, in order to view a 100 ns wide pulse, the full scale will be 1000 ns or 1 \(\mu\)s. The accuracy of this pulse width measurement will be \(\pm 30\) ns or \(\pm 30\)% of the pulse width!
The operating range of the analog oscilloscope. The operating range is a plot of input signal repetition rate from the lower limit of single-shot to the full bandwidth of the scope plotted against sweep speed. The shaded area is the area where the analog oscilloscope will produce a usable display.

The digital oscilloscope or digital storage oscilloscope (DSO) differs from its analog counterpart in that the input signal is converted to digital data and therefore it can be managed by an embedded microprocessor. The waveform data can have correction factors applied to remove errors in the scope's acquisition system and can then be stored, measured, and/or displayed. The input signal is converted from analog to digital and manipulations are performed on it by a microprocessor results in people not having a good mental model of the digital oscilloscope's operation. It is not would not be a problem except for the fact that the waveform digitizing process is not totally free from errors, and a lack of a correct mental model of the scope's operation on the part of its user can increase the odds of a measurement error. To make matters worse, various manufacturers of these products make conflicting claims, making it easy to propagate incorrect mental models of the digital scope's operation. It is the intention of this presentation to give the information needed to create a mental model of the operation of these devices that enable the user to perform error-free measurements with ease.

The DSO offers many advantages over its analog counterpart. First is accuracy. The voltage measurement accuracy of the digital oscilloscope is better than that of an analog scope because the microprocessor can apply correction factors to the data to correct for errors in the calibration of the scope's vertical system. Timing accuracy of a digital oscilloscope is an order of magnitude better than that of an analog scope. The digital scope can store the waveform data for comparison to other test results or uploading to a computer for analysis or project documentation. The digital oscilloscope does not depend on the input signal being continuously updated to produce an easily viewable display. A single-shot event is displayed at the same brightness level as a signal that repeats in time periods corresponding to the full bandwidth of the scope.

The disadvantages of the digital oscilloscope are its more complex operation, aliasing, and display performance. The analog-to-digital conversion process is used to convert the input signal into a series of discrete values, or samples, uniformly spaced in time, which can be stored in memory. Voltage resolution is determined by the total number of codes that can be produced. A larger number permit a smoother and more accurate reproduction of the input waveform but increase both the cost and difficulty in achieving a high sample frequency. Most digital oscilloscopes provide 8-bit resolution in their ADC. As the ADC's sampling speed is increased, the samples will be closer together, resulting in smaller gaps in the waveform record.
All digital scopes are capable of producing an aliased display. Some models are more prone to this problem than others, but even the best will alias under the right conditions. An alias is a lower-frequency false reproduction of the input signal resulting from undersampling, that is, sampling less than the Nyquist frequency. The display of the digital scope is based on computer display technology. The display is a raster scan display with a resolution of 500 lines, less than half the resolution of an analog scope's display. This is not a problem in most applications. It could become a factor where very complex waveforms, such as those found in TV systems, are being analyzed. Many digital scopes have display systems that exhibit large dead or blind times. Scopes based on a single CPU will be able to display their waveform data only after the CPU has finished all of its operations. The display is unresponsive to front-panel control inputs as well as not being able to follow changes in the input signal.

Table 19.1 shows that both analog and digital oscilloscopes have relative advantages and disadvantages. All the major producers of oscilloscopes are pushing the development of digital scopes in an attempt to overcome their disadvantages. A few manufacturers produce scopes that are both analog and digital. These products appear to have the best of both worlds; however, they have penalties with respect to both cost and complexity of operation.

Digital systems place additional demands on the oscilloscope that exceed the capabilities of the analog scope. For example, of en, in digital electronic systems, there is a need to view fast events that occur at very slow or infrequent rates. Figure 19.4 shows that these events fail to be viewable on analog scopes. Another common problem with digital systems is the location of trigger events. Of en, the only usable trigger is available at the end of the event being viewed. A digital scope can only display events that occur at or after a trigger event. The rapid growth of digital electronics in the late 1990s is being attributed to the lowering of the cost of single-chip microcontrollers. These devices, which contain a complete microprocessor on one integrated circuit, are responsible for the “electronics everywhere” phenomenon, where mechanical devices are becoming electronic as well as those devices that were previously electrical in nature. In 1996, Hewlett-Packard introduced a class of oscilloscope designed to meet the unique needs of the microcontroller-based applications. This class of oscilloscope is known as the mixed-signal oscilloscope or MSO [2].

<table>
<thead>
<tr>
<th>TABLE 19.1</th>
<th>Comparison of Analog and Digital Oscilloscopes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Operation</strong></td>
<td><strong>Analog Oscilloscope</strong></td>
</tr>
<tr>
<td>Front-panel controls</td>
<td>Simple</td>
</tr>
<tr>
<td>Display</td>
<td>Direct access knobs</td>
</tr>
<tr>
<td>Gray scales</td>
<td>Real-time vector</td>
</tr>
<tr>
<td>Horizontal resolution</td>
<td>&gt;16</td>
</tr>
<tr>
<td>Dead time</td>
<td>&gt;1000 lines</td>
</tr>
<tr>
<td>Aliasing</td>
<td>Short</td>
</tr>
<tr>
<td>Aliasing</td>
<td>No</td>
</tr>
<tr>
<td>Voltage accuracy</td>
<td>±3% of full scale</td>
</tr>
<tr>
<td>Timing accuracy</td>
<td>±3% of full scale</td>
</tr>
<tr>
<td>Single-shot capture</td>
<td>None</td>
</tr>
<tr>
<td>Glitch capture</td>
<td>Limited</td>
</tr>
<tr>
<td>Waveform storage</td>
<td>None</td>
</tr>
<tr>
<td>Pretrigger viewing</td>
<td>None</td>
</tr>
<tr>
<td>Data out to a computer</td>
<td>No</td>
</tr>
</tbody>
</table>
19.4 Voltage Measurements

Voltage measurements are usually based on comparisons of the waveform display to the oscilloscope's graticule. Measurements are made by counting the number of graticule lines between the end points of the desired measurement and then multiplying that number by the sensitivity setting. This is the only measurement available to most analog scope users, and it is still used by those performing troubleshooting with their digital scope as a time-saving step. (Some late-model analog oscilloscopes incorporate cursors to enhance their measurement ability.) For example, a waveform that is 4.5 divisions high at a vertical sensitivity of 100 mV/div would be 450 mV high.

Switching the scope's coupling between ac and dc modes will produce a vertical shift in the waveform's position that is a measurement of its dc component. This technique can be applied to either analog or digital scopes. Simply note the magnitude of the change in waveform position and multiply by the channel's sensitivity.

Additional measurements can be performed with an analog oscilloscope, but they usually require more skill on the part of the operator. For example, if the operator can determine the location of the top and base of a complex waveform, its amplitude can be measured. Measurements based on percentages can be made using the scope's vernier to scale the waveform so that its top and bottom are five divisions apart. Each division represents 20% of the amplitude of the waveform being studied. The use of the vernier, which results in the channel being uncalibrated, prevents performance of voltage measurements. Many analog scopes have a red light to warn the operator that the scope is uncalibrated when in vernier mode.

The digital oscilloscope contains an embedded microprocessor that automates the measurement. This measurement automation is based on a histogramming technique, where a histogram of all the voltage levels in the waveform is taken from the oscilloscope's waveform data. The histogram is a plot of the voltage levels in the waveform plotted against the number of samples found at each voltage level. Figure 19.5 shows the histogramming technique being applied to the voltage measurements of complex waveforms.

![Histogram](image)

**FIGURE 19.5** Voltage histograms as applied by a digital oscilloscope. The complex waveform is measured by the use of the voltage histogram. This histogram is a plot of each voltage level in the display and the number of data points at that level.
19.5 Understanding the Specifications

The oscilloscope's vertical accuracy is one place that a person's mental model of the scope's operation can lead to measurement trouble. For example, the oscilloscope's vertical axis has a frequency response that is not flat across its pass band. However, as noted earlier, the scope has a Gaussian frequency response to produce the most accurate picture of complex signals. The input to the oscilloscope's acquisition system is means that the oscilloscope's accuracy speciation of $\pm 3\%$ is a dc-only speciation. If one were to attempt to measure the amplitude of a signal whose frequency is equal to the bandwidth of the scope, one would have to add another 29.3% to the error term, for a total error of $\pm 32.3\%$. The is true for both analog and digital oscilloscopes. The limitation can be overcome by carefully measuring the frequency response of the oscilloscope's vertical channels. One will need to repeat this process every time the scope is serviced or calibrated, because the various high-frequency adjustments that may need to be made in the scope's vertical axis will affect the scope's frequency response. One is probably asking, why don't the manufacturers do this for me? The answer is twofold. The first is cost, and the second is that this is not the primary application of an oscilloscope. There are other instruments that are much better suited to the measurement of high-frequency signals. The spectrum analyzer would be this author's first choice.

Additionally, the vertical accuracy is a full-scale speciation. The input to the oscilloscope is at 1 V/div, the full-scale value is typically 8 V. The measurement error for a scope with a $\pm 3\%$ speciation under these conditions will be $\pm 0.24$ V. If the signal being measured is only 1 V high, the resulting measurement will be $\pm 24\%$ of reading. Check the manual for the scope being used, as some manufacturers will specify full-scale as being 10 or even 10.2 divisions. The will increase the error term because the full-scale term is larger.

In digital oscilloscopes, the vertical accuracy is often expressed as a series of terms. These attempt to describe the analog and digital operations the scope performs on the input signal. Terms might include digitizing resolution, gain, and of set (sometimes called as position). They might also be called out as single- and dual-cursor accuracies. The single-cursor accuracy is a sum of all three terms. In the dual-cursor case, where the voltage measurement is made between two voltage cursors, the of set term will cancel out, leaving only the digitizing resolution and gain errors. For example, the Hewlett-Packard model 54603B has a single-cursor accuracy speciation of $\pm 1.2\%$ of full scale, $\pm 0.5\%$ of position value, and a dual-cursor speciation of $\pm 0.4\%$ of full scale.

Hint: Always try to make the voltage measurements on the largest possible vertical and widest possible display of the signal.

The horizontal accuracy speciations of analog and digital scopes are very different; however, both are based on a full-scale value. In the analog scope, many manufacturers limit accuracy speciations to only the center eight divisions of their display. The input to the oscilloscope is means that a measurement of a signal that starts or ends in either the first or ninth division will be even more error prone than stated in the scope's speciation. To the best of this author's knowledge, this limitation does not apply to digital scopes. The horizontal speciation of digital scopes are expressed as a series of terms. These might include the crystal accuracy, horizontal display resolution, and trigger placement resolution. These can be listed as cursor accuracy. For example, the Hewlett-Packard model 54603B has a horizontal cursor accuracy speciation of $\pm 0.01\% \pm 0.2\%$ full-scale $\pm 200$ ps. In this example, the first term is the crystal accuracy, the second is the display resolution (500 lines), and the final term is twice the trigger placement error. By comparing the analog and digital scopes' horizontal speciations, it can be seen that in either case, the measurement is more accurate if it can be made at full screen. The digital scope is more accurate than its analog counterpart.

Digital scopes also have acquisition system specifications. Here is another place where the operator's mental model of the operation of a digital scope can produce measurement errors. All manufacturers of digital scopes specify the maximum sampling speed of their scope's acquisition system.
as well as its memory depth and number of bits. The scope’s maximum sampling speed does not apply to all sweep speeds; only memory depth and number of bits applies to all sweep speeds. The scope’s maximum sampling speed applies only to its fastest sweep speeds.

The complexity of the digital scope results from the problem of having to sample the input. There is more to be considered than Nyquist’s sampling theorem in the operation of a digital scope. For example, how does the scope’s maximum sampling rate relate to the smallest time interval that the scope can capture and display? A scope that samples at 100 M Sa/s takes a sample every 10 ns; therefore, in principle, it cannot display any event that is less than 10 ns wide because that event will fall between the samples. In practice, however, this limit can—under certain circumstances—be extended. If the scope is operating in an “equivalent time” or “random repetitive” mode and if the signal is repetitive, even if very infrequently, the scope will be able to capture any event that is within its vertical system bandwidth. Figure 19.6 shows an infrequently occurring pulse that is 25 ns wide embedded into a data stream being captured and displayed on an oscilloscope with a maximum sampling speed of 20 M Sa/s (sampling interval of 50 ns). Figure 19.6b shows this pulse at a faster sweep speed. An analog scope would produce a similar display of this event, with the infrequent

![Figure 19.6](image-url)

**FIGURE 19.6** An infrequently occurring event as displayed on a digital oscilloscope with random repetitive sampling: (a) the event embedded in a pulse train, and (b) shows the same event at a faster sweep speed. The fact that the waveform baseline is unbroken under the narrow pulse indicates that it does not occur in every sweep. The width of this pulse is less than half the scope’s sampling period in (b). Both traces are from a Hewlett-Packard model 54603B dual-channel 60 M Hz scope.
event being displayed at a lower intensity than the rest of the trace. Notice that the infrequent event
does not break the baseline of the trace.

The correct mental model of the digital scope's ability to capture signals needs to be based on the
scope's bandwidth, operating modes, and timing resolution. It is the timing resolution that tells the
operator how closely spaced the samples can be in the scope's data record.

The most common flaw in many mental models of the operation of a digital scope is related to its
maximum sampling speed specification. As noted, the maximum sampling speed specification applies
only to the scope's fastest sweep speeds. Some scope manufacturers will use a multiplex A/D system
that operates at its maximum sampling speed only in single-channel mode. The scope's memory depth
determines its sampling speed at the sweep speed being used for any specified measurement. The scope's
memory depth is always equal to the scope's horizontal full-scale setting. For scopes with no screen
memory, this is 10x the time base setting. If the scope has screen memory, this must be taken into
account. For example, assume that one has two scopes with a maximum sampling speed of 100 M Sa/s.
One scope has a memory depth of 5 K points and the other only 1 K. At a sweep speed of 1 μs per divi-
sion, both scopes will be able to store data into their memory at their full sampling speed, and each will
be storing 100 data points per division, for a total of 1000 data points being stored. The scope with the
5 K memory will have a data point in one of every 500 memory locations, and the scope with the 1 K
memory will have only one point in every memory location. If one reduces the sweep speed to 5 μs/div,
the deeper memory scope will now fill every one of its memory locations with data points separated by
10 ns. The scope with only 1 K of memory would produce a display only two divisions wide if its sampling
speed is not reduced. Scope designers believe that scope users expect to see a full-length sweep at
every sweep speed. Therefore, the 1 K scope must reduce its sampling speed to one sample every 50 ns,
or 20 M Samples/s, to be able to fill its memory with a full sweep width of data. The 5:1 ratio of sampling
speeds between these two scopes will be maintained as their time bases are set to longer and longer
sweeps. For example, at 1 s/div, the 5 K scope will be sampling at 500 samples per second, while the 1 K
scope will be sampling at only 100 samples/s. One can determine a scope's sampling speed for any spe-
cific time base setting from Equation 19.1:

\[
S \text{ (samples/second)} = \frac{\text{Memory depth (samples)}}{\text{Full-scale time base (seconds)}}
\]

(19.1)

or the scope's maximum sampling speed, whichever is less.

One must look closely at the application to determine if a specific scope is best suited to that applica-
tion. As a rule, the deeper the memory, the faster the scope will be able to sample the signal at any given
time base setting. Memory depth is not free. High-speed memory required to be able to store the data
out of the scope's A/D is costly, and deeper memory takes longer to fill, thus reducing the scope's display
update rate. Most scopes that provide memory depths of 20 K or more will also give the user a memory
depth selection control so that the user can select between fast and deep. (In 1996, Hewlett-Packard Co.
introduced two scopes based on an acquisition technology known as MegaZoom (TM) [2] that removes
the need for a memory depth control.) A correct mental model for the sampling speed of a digital scope
is based on Equation 19.1 and not just on the scope's maximum performance specifications.

Some digital oscilloscopes offer a special sampling mode known as peak detection. Peak detection
is a special mode that has the effect of extending the scope's sampling speed to longer time records.
The special mode can reduce the possibility of an aliased display. The performance of this special
mode is specified as the minimum pulse width that the peak detection system can capture. There are
several peak detection systems being used by the various manufacturers. Tektronix has an analog-
based peak detection system in some of its models, while Hewlett-Packard has a digital system in
all of its models. Both systems perform as advertised, and they should be evaluated in the lab to see
FIGURE 19.7 Peak detection. T is special mode has the effect of increasing the scope's sampling speed at time base settings where it would be decimated. In operation, each memory location contains either the maximum or minimum value of the waveform at that location in time. (a) A series of 300 ns wide pulses being captured at a slow sweep speed and (b) the same setup with peak detection disabled. These narrow pulses would appear as intermittent pulses if the scope could be seen in operation with peak detection disabled.

which system best meets one's needs. There is a downside to peak detection systems and that is that they display high-frequency noise that might not be within the bandwidth of the system under test. Figure 19.7 shows a narrow pulse being captured by peak detection and being missed when the peak detection is off.

What effect does display dead time have on the oscilloscope's voltage measurement capabilities? Display dead time applies to both analog and digital oscilloscopes, and it is that time when the oscilloscope is not capturing the input signal. This is also a very important consideration in the operation of a digital scope because it determines the scope's ability to respond to front-panel control commands and to follow changing waveforms. A digital scope that produces an incorrect display of an amplitude-modulated signal is not following this rapidly changing signal because its display update rate is too low. Sampling speed is not related to display update rate or dead time. Display dead time is a function of the scope's ability to process the waveform data from its A/D and plot it on the display. Every major oscilloscope manufacturer has been working on this problem. Tektronix offers a special mode on some of its products known as InstaVu (TM) [3]. This special mode allows these scopes to process up
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![Oscilloscope Display](image)

**FIGURE 19.8** Display dead time. The time that an oscilloscope is blind to the input signal has an effect on the scope's ability to correctly display rapidly changing signals: (a) an amplitude-modulated signal with a high-speed display and (b) the same signal with the dead time increased by the use of hold-off.

to 400,000 waveforms per second to their display. Hewlett-Packard has developed a multiple parallel processor technology [4] in the HP 54600 series of benchtop scopes that provides a high-speed, low-dead-time display in a low-cost instrument. These instruments can plot 1,500,000 points/s to their display, and they have no dead time at their slower sweep speeds. LeCroy has been applying the PowerPC as an embedded processor for its scopes to increase display throughput. There are other special modes being produced by other vendors, so be sure to understand what these can do before selecting an oscilloscope. Figure 19.8 shows the effect of display update rate on a rapidly changing waveform. An amplitude-modulated signal is displayed with a high-speed display and with the display speed reduced by the use of hold-off.

**19.5.1 Triggering**

The trigger of the oscilloscope has no direct effect on the scope's ability to measure a voltage except that the trigger does enable the oscilloscope to produce a stable display of the voltage of interest. Reference [5] presents a thorough discussion of this subject.
Conclusion: The mental model that oscilloscope users have created in their minds of the oscilloscope’s operation can be helpful in reducing measurement errors. If the operator’s mental model is based on the following facts, measurement errors can be minimized:

- Oscilloscopes have a frequency response that affects measurement accuracy.
- Digital scopes are more accurate than analog scopes.
- Analog scopes do not have continuous displays.
- Oscilloscope accuracy specifications always contain a percent of full-scale term.
- Measurements should be made at the largest possible deflection in order to minimize errors.
- Maximum sampling speed is available only at the scope’s fastest sweep speeds.
- Deeper memory depth allows faster sampling at more sweep speeds.
- All digital scopes can produce aliases, some more than others.
- Display dead time is an important characteristic of digital scopes that is often not specified.
- Display dead time affects measurement accuracy because it can cause a distorted display.
- The scope with the highest maximum sampling speed specification might not be the most accurate or have the lowest display dead time.
- The operator must have some knowledge of the signals being measured to be able to make the best possible measurements.

The person who has the mental model of the oscilloscope that takes these factors into account will be able to purchase the scope that is best suited to his or her application and not spend too much money on unnecessary additional performance. In addition, that person will be able to make measurements that are up to the full accuracy capabilities of the scope.

19.6 Selecting the Oscilloscope

There are 10 points to consider when selecting an oscilloscope. The author has published a thorough discussion of these points [6], and they are summarized as follows:

1. Analog or digital? There are a few places where the analog scope might be the best choice, and the reader can make an informed selection based on the information presented here.

2. How much bandwidth? This is a place where the person selecting an oscilloscope can save money by not purchasing more bandwidth than is needed. When analog oscilloscopes were the only choice, many people were forced to purchase more bandwidth than they needed because they needed to view infrequent or low repetition signals. High-bandwidth analog scopes had brighter CRTs so that they were able to display high-frequency signals at very fast time base settings. At a sweep speed of 5 ns/div, the phosphor is being energized by the electron beam for 50 ns, so the electron beam had to be very high energy to produce a visible trace. This situation does not apply to digital scopes. Now, one needs to be concerned only with the bandwidth required to make the measurement. Figure 19.9 shows the effect of oscilloscope bandwidth on the display of a 50 MHz square wave.

The oscilloscope’s bandwidth should be >2× the fundamental highest frequency signal to be measured.

The bandwidth of the scope’s vertical system can affect the scope’s ability to correctly display narrow pulses and to make time interval measurements. Because of the scope’s Gaussian frequency response, one can determine its ability to correctly display a transient event in terms of rise time with Equation 18.2:

\[
\text{rise time} = \frac{0.35}{\text{BW}}
\]  

Therefore, a 100 MHz scope will have a rise time of 3.5 ns. This means that if the scope were to have a signal at its input with zero rise time edges, it would be displayed with 3.5 ns edges. This will affect
FIGURE 19.9  

The effect of the scope's bandwidth is shown in this set of waveforms. The same 50 MHz square wave is shown as it was displayed on different bandwidth scopes: (a) 500 MHz bandwidth, (b) 250 MHz bandwidth, (c) 100 MHz bandwidth.

(continued)
The 19.9 (continued) The same 50 MHz square wave is shown as it was displayed on different bandwidth scopes: (d) 60 MHz bandwidth, and (e) 20 MHz bandwidth. Notice that the 100 MHz scope produced a usable display although it was missing the high-frequency details of the 500 MHz display. The reason that the 100 MHz scope looks so good is the fact that its bandwidth is slightly greater than 100 MHz. Its performance, which is not specified on any data sheet, is something to look for in any evaluation.

The scope's measurements in two ways. First are narrow pulses. Figure 19.10 shows the same 5 ns wide pulse being displayed on oscilloscopes of 500 and 60 MHz bandwidths, and the effect of the lower bandwidth on this event that is closest to the rise time of the slower scope is apparent.

The second is fast time interval measurements. A measurement of signal rise time is an example. The observed rise time on the scope's display is according to Equation 19.3:

$$t_{\text{observed}} = \left(t_{\text{signal}}^2 + t_{\text{scope}}^2\right)^{1/2}$$

(19.3)

If a 10 ns rise time were to be measured with a 100 MHz scope, one would obtain a measurement of 10.6 ns based on Equation 19.3. The scope would have made this measurement with a 6% reading error before any other factors, such as time base accuracy, are considered.

The scope's rise time should be at least no more than 1/5 of the shortest time interval to be measured. For time interval measurements, this should be >1/10.
3. How many channels? Most oscilloscopes in use today are dual-channel models. In addition, there are models described as being 2+2 and four channels. This is one time where 2+2 is not equal to 4. These 2+2 models have limited features on two of their channels and cost less than 4-channel models. Most oscilloscope suppliers will hold the 4-channel description only for models with four full-featured channels, but users should be sure to check that the model under consideration so as to be sure if it is a 4- or 2+2 model. Either of the four channel classes is useful for applications involving the testing and development of digital-based systems where the relationship of several signals must be observed.

Hewlett-Packard introduced a new class of oscilloscopes that is tailored for the applications involving both analog and digital technologies and mixed-signal systems. The MSO [3] provides two scope channels and 16 logic channels so that it can display both the analog and digital operations of a mixed-signal system on its display.

4. What sampling speed? Do not simply pick the scope with the highest banner specification. One needs to ask, what is the sampling speed at the sweep speeds that my application is most likely to require? As observed in Equation 19.1, the scope's sampling speed is a function of memory depth and full-scale time base setting. If waveforms are mostly repetitive, one can save money by selecting an oscilloscope that provides equivalent time or random repetitive sampling.
5. How much memory? As previously discussed, memory depth and sampling speed are related. The memory depth required depends on the time span needed to measure and the time resolution required. The longer the time span to be captured and the finer the resolution required, the more memory one will need. High-speed waveform memory is expensive. It takes time to process a longer memory, so the display will have more dead time in a long memory scope than a shallow memory model. All the suppliers of deep memory scopes provide a memory depth control. They provide this control so that the user can choose between a high-speed display and deep memory for the application at hand. Hewlett-Packard introduced MegaZoom (TM) technology [7] in 1996; it produces a high-speed low-dead-time display with deep memory all the time.

6. Triggering? All scope manufacturers are adding new triggering features to their products. These features are important because they allow for triggering on very specific events. They can be a valuable troubleshooting tool because it will let the user prove whether a suspected condition exists or not. Extra triggering features add complexity to the scope's user interface; so be sure to try them out to make sure that they can be applied.

7. Trustworthy display? Three factors critically affect a scope’s ability to display the unknown and complex signals that are encountered in oscilloscope applications. If the user loses confidence in the scope’s ability to correctly display what is going on at its probe tip, productivity will take a real hit. These are display update rate, dead time, and aliasing.

   Because all digital scopes operate on sampled data, they are subject to aliasing. An alias is a false reconstruction of the signal caused by undersampling the original. An alias will always be displayed as a lower frequency than the actual signal. Some vendors employ proprietary techniques to minimize the likelihood of this problem occurring. Be sure to test any scope being considered for purchase on your worse-case signal to see if it produces a correct or aliased display. Do not simply test it with a single-shot signal that will be captured at the scope’s fastest sweep speed because this will fail to test the scope’s ability to correctly display signals that require slower sweep speeds.

8. Analysis functions? Digital oscilloscopes with their embedded microprocessors have the ability to perform mathematical operations that can give additional insight into waveforms. These operations include addition, subtraction, multiplication, integration, and differentiation. An FFT can be a powerful tool, but do not be misled into thinking that it is a replacement for a spectrum analyzer. Be sure to check the implementation of these features in any scope being considered. For example, does the Fast Fourier Transform (FFT) provide a selection of window functions? Are these analysis functions implemented with a control system that only their designer could apply?

9. Computer I/O? Most of the digital scopes on the market today can be interfaced to a PC. Most of the scope manufacturers also provide some software that simplifies the task of making the scope and PC work together. Trace images can be incorporated into documents such as PC Paintbrush (.pcx), tagged image file format (.tif), Joint Photographic Expert Group (.jpg) files. Waveform data can be transferred to spreadsheet applications for additional analysis. Some scope models are supplied with a disk drive that can store either waveform data or trace images.

10. Try it out? Now, one has the information to narrow oscilloscope selection to a few models based on bandwidth, sampling speed, memory depth, and budget requirements. Contact the scope vendors (Table 19.2) and ask for an evaluation unit. While the evaluation unit is in the lab, look for the following characteristics:

   a. Control panel responsiveness: Does the scope respond quickly to inputs or does it have to think about it for a while?

   b. Control panel layout: Are the various functions clearly labeled? Does the user have to refer to the manual even for simple things?

   c. Display speed: Turn on a couple of automatic measurements and check that the display speed remains fast enough to follow changing signals.

   d. Aliasing: Does the scope produce an alias when the time base is reduced from fast to slow sweep speeds? How does the display look for the toughest signal?
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<table>
<thead>
<tr>
<th>Vendor</th>
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</tr>
</thead>
<tbody>
<tr>
<td>B&amp;K Precision, 6460 W. Cortland St., Chicago, IL 60635</td>
<td>Analog and digital scopes and Metrix scopes in France</td>
<td><a href="http://bkprecision.com">http://bkprecision.com</a></td>
</tr>
<tr>
<td>Boonton Electronics Corp., 25 Estmans Road, P.O. Box 465, Parsippany, NJ 07054-0465</td>
<td>US importer for Metrix analog, mixed analog, and digital scopes from France</td>
<td><a href="http://www.boonton.com">http://www.boonton.com</a></td>
</tr>
<tr>
<td>Fluke, P.O. Box 9090, Everett, WA 98206-9090</td>
<td>Handheld, battery-powered scopes (ScopeMeter), analog scopes, and CombiScopes(R)</td>
<td><a href="http://www.fluke.com">http://www.fluke.com</a></td>
</tr>
<tr>
<td>Gould, Roebuck Road, Hainault, Ilford, Essex IG6 3U E, England</td>
<td>200 MHz DSO products</td>
<td><a href="http://www.gould.co.uk">http://www.gould.co.uk</a></td>
</tr>
<tr>
<td>Hewlett-Packard Co., Test &amp; Measurement, Mail Stop 5ILSJ, P.O. Box 58199, Santa Clara, CA 95052-9952</td>
<td>A broad line of oscilloscopes and the MSO for technical professionals</td>
<td><a href="http://www.tmo.hp.com/tmo/pia">http://www.tmo.hp.com/tmo/pia</a> search on “oscilloscopes”</td>
</tr>
<tr>
<td>LeCroy Corp., 700 Chestnut Ridge Road, Chestnut Ridge, NY 10977</td>
<td>Deep memory oscilloscopes for the lab</td>
<td><a href="http://www.lecroy.com">http://www.lecroy.com</a></td>
</tr>
<tr>
<td>Tektronix, Inc., Corporate Of ces, 26600 SW Parkway, P.O. Box 1000, Watsonville, OR 97070-1000</td>
<td>The broad line oscilloscope supplier with products ranging from handheld to high-performance lab scopes</td>
<td><a href="http://www.tek.com/measurement">http://www.tek.com/measurement</a> search on “oscilloscopes”</td>
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<tr>
<td>Yokogawa Corp. of America, Corporate Of ces, Newman, GA, 1-800-258-2552</td>
<td>Digital oscilloscopes for the lab</td>
<td><a href="http://www.yca.com">http://www.yca.com</a></td>
</tr>
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The oscilloscope is undergoing a period of rapid change. The major manufacturers of oscilloscopes are no longer producing analog models, and the digital models are evolving rapidly. There is confusion in the oscilloscope marketplace because of the rapid pace of this change. Hopefully, this discussion will prove valuable to the user in selecting and applying oscilloscopes in the lab in the years to come.

References