OSCILLOSCOPES

The oscilloscope, or the *scope*, is an important tool in engineering. The oscilloscope displays a graph of an electrical signal on a screen. In its basic operational mode, the oscilloscope graphs instantaneous signal values versus time. Displayed waveforms have three basic components: Y, the vertical or amplitude component; X, the horizontal or time component; Z, the signal brightness or intensity. Single channel and multi-channel oscilloscopes are available. The most popular is a two-channel instrument un which a single trace display with channel multiplexing is available. In this case not only instantaneous signal values versus time, but also amplitude waveform component versus the other, can be observed.

Oscilloscopes are used in physics, electronics, instrumentation and measurements, communications, control, mechanical engineering, and many other areas where nonelectrical signal can be converted into electrical signals. The graphical display allows a user to determine many signal parameters, such as:

- Voltage and time values
- Frequency, period, and rise and fall times
- Phase shift
- Noise level, jitter
- Frequency ratio of two signals
- Calculated Fourier spectrum
- Calculated statistical parameters
- Calculated mathematical functions of signals, such as the integral, derivative, sum, difference, and product

Two major types of oscilloscopes have emerged over the last decade: analog and digital. Within these two categories, a number of operational modes can be distinguished. There are real-time data acquisition and display scopes, real-time acquisition and equivalent or transformed-time display scopes, and random data acquisition and random display scopes. A typical analog scope directly acquires signal and displays them on the screen in real time. An analog sampling scope can operate in real-time and low signal frequencies, and in equivalent time at high frequencies. A digital scope can operate in real-time or in equivalent time to acquire signals, but the display shows the reconstructed signal in the equivalent-time mode, which allows for great reduction of the display unit speed, which in turn achieves great reduction of the scope cost. Currently, the major oscilloscope manufacturers, such as Agilent Technologies, Tektronix, and LeCroy, do not list analog scopes in their catalogs but many analog scopes have been used recently and will be used in the near future. The digital scopes, also called digitizing or digital storage oscilloscopes, are considerably more powerful and flexible for signal inspection and analysis. Signal digitization has opened unlimited possibilities for signal storage and processing.

ANALOG SCOPES

Analog scopes without sampling acquire and display waves in real time. The most critical part of the analog oscilloscope is a cathode ray tube (*CRT*), whose maximum speed of wave tracing limits the speed of the entire scope. Figure 1 shows the simplified structure of a CRT. The beam of electrons generated by the cathode is directed towards the fluorescent screen by a set of electrodes. The beam makes a bright spot on the screen at a position controlled by the voltages applied to the vertical and horizontal deflection plates. The tube can have a single or a double beam system. The latter has two separate beam-forming and deflection structures. The tube shown in Fig. 1 employs a two-stage electron acceleration process. The electrons emitted from the cathode are formed into the beam, whose density is controlled by the cylindrical electrode. Later, the beam is focused and deflected, passing through the vertical and horizontal deflection plates. Final acceleration, called post-deflection acceleration (which is necessary to produce a visible spot on the screen), is achieved by applying very high voltage, at least several kilovolts, to a distributed electrode located inside the tube between the deflection plates and the screen. The inner surface of the screen is covered with a phosphor, which emits visual radiation on being bombarded by electrons. The length of time during which the phosphor emits radiation until its level decays to 10% of the initial value is called the persistence. Several types of phosphor inner coatings are applied in CRTs. The most popular phosphor, P 31, exhibiting high luminance and reasonable persistence of about 32 ms (1), is found in most CRTs.

In analog scopes, an image of a non-repetitive signal fades quickly or slowly, depending upon the tube persistence. Fast single-shot events may not be registered by a classical CRT whose screen directly reacts to the electron current delivered to it. In order to enhance the quality of writing, micro-channel plate CRTs are used in some analog scopes (3). Inside the tube, an array of hollow glass fibers is located. The fibers internally coated with a semiconductor, multiply the number of electrons through secondary emission when activated by adequately accelerated electron beam. The beam deflection can be affected by the proximity of power supplies, especially transformers, and chokes. To avoid interference, the tubes and potentially interfering components are well shielded.

The block diagram of a typical analog scope in shown in Fig. 2. The vertical channels, A and B, include input coupling circuits, attenuators, pre-amplifiers, delay line, and differential output amplifiers driving the vertical plates of the CRT, as shown in Fig. 3. Quite often, voltage or current probes are connected to the inputs to provide better interfacing with the tested circuits. The horizontal section of the oscilloscope is composed of triggering unit with its coupling circuits, trigger shaping unit, trigger level control, and trigger holdoff units; a sweep generator, which defines the main time base of the scope; and a differential output amplifier driving the horizontal deflection plates of the tube (Fig. 4). The main sweep generator can be supported by a fast time-base unit triggered at a preselected level to expand desired parts of the tested waves. Figure 5 illustrates typical waveforms of analog scopes. Two time

J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*.

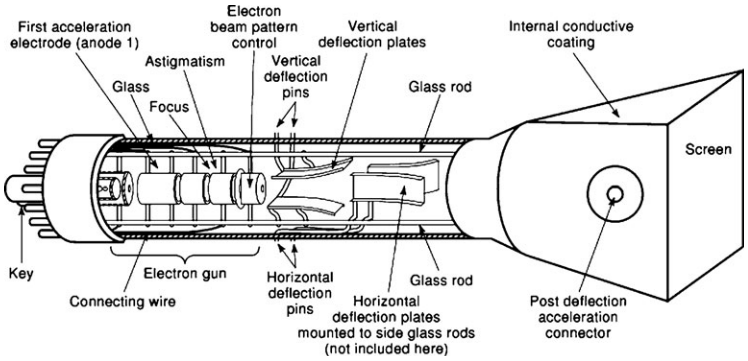

Figure 1. Internal structure of a CRT.

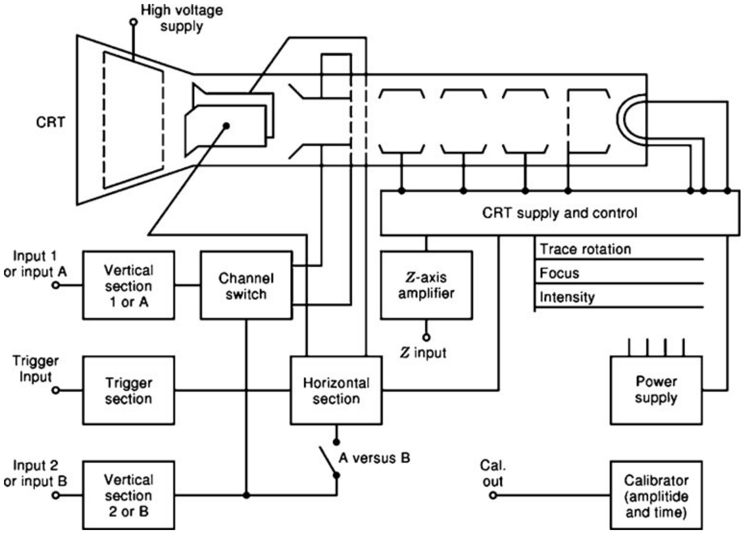

Figure 2. General diagram of an analog oscilloscope.

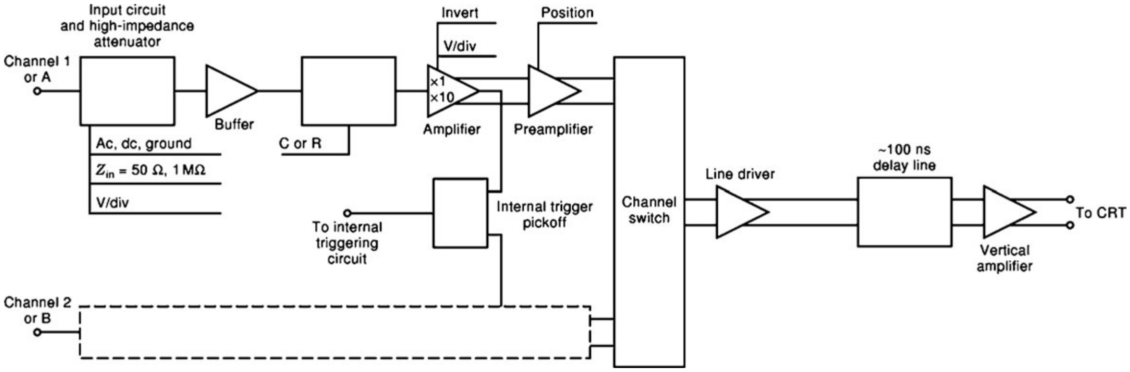

Figure 3. Vertical channel of an analog oscilloscope.

bases are activated to show distinguished sections of the signals under test with the help of the fast ramp, which is called the delayed time base. The waves observed on the tube screen are delayed in relation to the input signals due to the action of the delay lines forming parts of the vertical amplifier. In this way the trigger and the time-base circuit delays and nonlinearities are compensated to create good conditions for tests of the wave leading edges without introducing distortions. Figure 5 also shows internally generated triggering pulses initiated by the input signal of channel 1 or 2.

To stabilize the horizontal wave position on the screen, the trigger level is selected within the frame of the vertical span of the incoming waves. At the same time an auxiliary system called *holdoff* has to be adjusted to make the time-base generator insensitive to excessively frequent triggering. If more than one channel is used and a single-trace tube is applied, then a channel switch can direct only one channel to the screen at a time for the duration of the time base, especially at high rates of the time base (alternating mode). At lower time base rates small segments of the individual channels can be displayed one by one (chopped mode). The waves for both modes of the display are shown in Fig. 6. Multichannel data acquisition allows one to perform basic hardware arithmetic operations on signals, such as addition and subtraction. The process of subtraction,

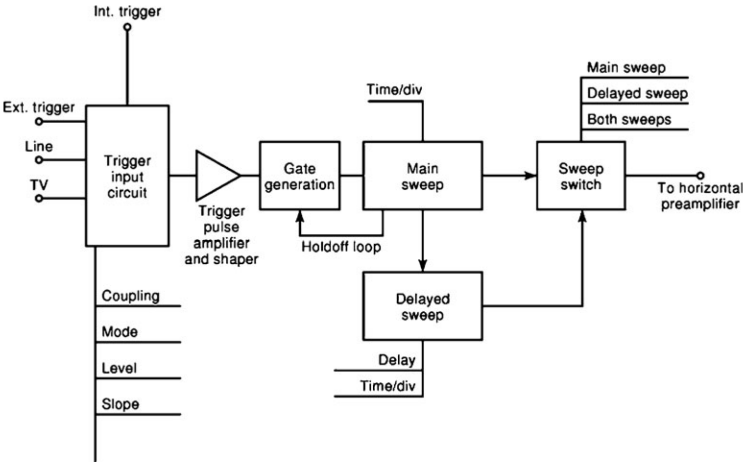

Figure 4. Horizontal channel of an analog oscilloscope.

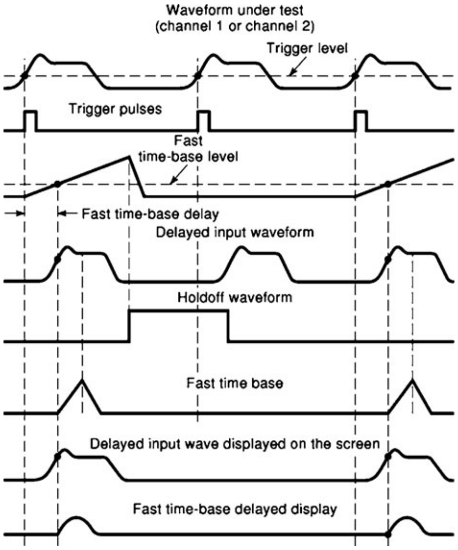

Figure 5. Waveforms in an analog oscilloscope.

which can disclose a differential signal component, is corrupted by interchannel interference due to the common ground pathways and nonideal channel isolation of the channel switch. Many analog oscilloscopes have internal amplitude calibrators, which help check the scope amplitude calibration and verify or adjust the compensation of the voltage probes.

SAMPLING SCOPES

Typical real-time analog oscilloscopes have operating bandwidths up to several hundred megahertz. The limits are mainly imposed by the CRT writing speed. One of the means to reduce the speed of observed waves has been the time transformation by means of coherent sampling. The method can be only applied to repetitive waveforms. A basic set of waveforms for a sampling scope is shown in Fig. 7; the scope block diagram is depicted in Fig. 8. The signal under test applied to the input is delayed by a broadband transmission line, and then sampled by very narrow pulses in a sampling gate. If the repetition frequency is less than several hundred kilohertz, which is the maximum repetition frequency of the trigger circuitry, a single sample is taken from each pulse of a frame defined by the time base. For higher repetition rates the trigger circuits divide the frequency so that every *n*th one sample is taken from a single pulse of a repetitive wave. When the samples are taken, they are stretched, amplified, and memorized in a sample-and-hold circuit. Later, the samples are applied to low-frequency vertical amplifiers driving the tube. The sampling scope system uses a track-and-hold feature that enables the scope to process the small samples formed by the differences between the two consecutive values of the sampled signal. Generation of subsequent sampling pulses is achieved by comparison of two fully synchronized time bases. One of them is a fast time base, and the other is a staircase signal. The horizontal channel provides the timing of all samples. It also delivers trigger signal to the sampling pulse generator and to the time bases. Sampling oscilloscopes can operate up to frequencies above 70 GHz of an equivalent bandwidth, which corresponds to the rise time of 5 ps. Both, vertical and horizontal channels of such scopes have been digitized and new generations of sampling scopes have been available for the last few years (12).

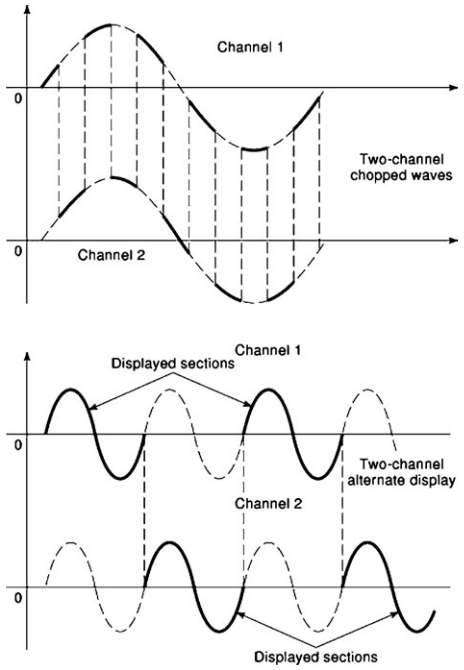

Figure 6. Modes of display of an analog oscilloscope.

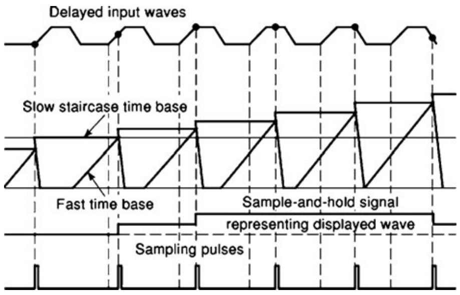

Figure 7. Time transformation in an analog sampling scope.

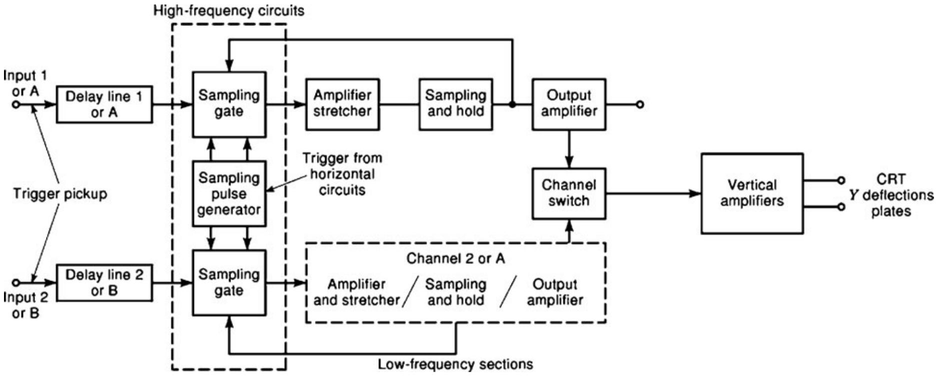

Figure 8. Vertical system of a coherent sampling oscilloscope.

They are applied not only in the typical scope measurements but also in time-domain reflectometry (*TDR*).

DIGITAL SCOPES

Digital oscilloscopes have overcome many disadvantages of analog scopes, especially the necessity for using long persistence CRTs and delay lines. A digital scope display can be adjusted after wave acquisition and storage. The input circuitry of a typical digital scope does not differ from that of analog scope. After preliminary attenuation or amplification, analog signals are sampled and digitized. The digitized samples are stored in a memory. The display receives the reconstructed analog samples of vertical and horizontal information through digital-to-analog converters. The process of data display is delayed and stretched in time, so the samples of the signal are displayed at a slower rate than they are acquired. Three major types of digitizers are applied in digital scopes:

- Real-time digitizers operating at high sampling and conversion rates, which can capture non-periodic short transient processes.
- Coherent sampling digitizers working in the same way as the sampling oscilloscopes with time transformation described before. The analog-to-digital conversion is applied to much slower waves after the sampling and time transformation. In this approach, a pretrigger pulse is required; it is obtained either from the tested signal, or from a separate source whose output wave follows the trigger.
- Random interleaved sampling digitizers, which sample repetitive signals in a pseudorandom manner. Amplitude and timing data are digitized and memorized in corresponding memories and later displayed to follow the stored timing sequence.

All three digitizers can equally well acquire periodic signals. In the last two approaches, only a single sample can be taken during the input signal cycle, especially at low frequencies of very short input pulses. The real-time signal capture capability of most digital scopes is limited by the maximum sampling rate, which is directly associated with the maximum speed of the analog-to-digital converters. The inherent storage capability of digital scopes, especially the possibility of storing long records of a number of channels, allows for processing the signals applying complex mathematical operation, including Fourier analysis and statistical functions (5). When the oscilloscope calculates the fast Fourier transform (*FFT*) of the input signal, the frequency spectrum can be displayed separately from the time-domain signal image. A typical block diagram of a two-channel digital storage scope (*DSO*) is shown in Fig. 9. The channels acquire and digitize the signals independently, and then the digital signals are accumulated and processed according to the chosen function. In the simplest case, the digitized signals are retrieved from the memory, converted back into their analog forms by the digital-to-analog converters, and displayed. The reduced speed of the signal display processes eliminates the need for high-frequency CRTs. Many scope displays utilize liquid crystal display tubes (*LCD*), which are directly controlled by addressing the picture elements (pixels) of a display matrix. Analog scopes with CRTs can update their pictures about 10^5 times per second. Time changes in the signals are then recorded immediately. The display process of a typical digital storage scope is usually a memory reconstruction of the acquired samples taken from many periods, so the entire image can be acquired only 5 to 10 times per second. High quality of the picture display of analog scopes requires rather high frequency of image updates. Such update frequencies are not available when the signal is not repeated frequently. Some digital storage scopes with high-speed digitizers and processors, and with smart display algorithms, update their displays by creating high-quality analog persistence images over a broad range of signal frequencies. The number of samples displayed on the screen is fixed independently of the time-base settings, which leads to changes of the sampling rates for different time bases. In order to reproduce periodic waves, taking five to ten samples per period of the highest harmonic is regarded as the minimum to preserve sufficient signal details. The Nyquist sampling rate is too low to reconstruct periodic signals in all cases, especially when the signals are sampled near zero crossings. Major features of the digital storage scopes can be summarized as follows:

- Large amounts of pretrigger information can be acquired without delay lines.
- Single or repetitive waves can be stored permanently.
- Computer or printer interfacing to store or print more data can be easily achieved.
- One may reliably capture unpredictable events.
- One may reliably capture glitches shorter than the resolution time by means of peak detectors.
- Within the memory capacity, there is no dead time between acquired events.
- Measurements can be automated.
- Currently acquired waves can be compared with reference waves.
- Wave tolerance tests are possible, including go-no-go tests.
- Acquired waves can be processed mathematically, including statistical operations.
- Finite resolution and a small number of display sweeps per second cam mask the time distribution of waveforms.
- The limited number of samples and the constant sample intensity commonly used in displaying simple repetitive waves can distort composite repetitive signals, including waves of various speeds.

TECHNICAL PARAMETERS AND LIMITATIONS

This section describes basic parameters of the oscilloscopes to help select the right one for an application. In the selection process, the scope parameters must be related to the waves under test. The major specifications of analog scopes are number of channels, bandwidth, voltage sensitivity, maximum time-base speed, amplitude noise, time jitter, and overall accuracy. From these parameters other scope features can be derived. For digital scopes, the same set of parameters is also important but maximum sampling rate, vertical and horizontal resolutions, and memory length should be considered.

Number of Channels

Common-purpose single-channel scopes are not very popular in measurement laboratories. If the number of channels is greater than one, the interchannel interference becomes important and a high common-mode rejection ratio (*CMRR*) is desired. For example, if CMRR = 40dB, then with one channel receiving a signal of 1 V and the other channel receiving a signal of 10 mV, the lower amplitude channel will measure the amplitude with an error of about 10%, which is well above scope error specifications.

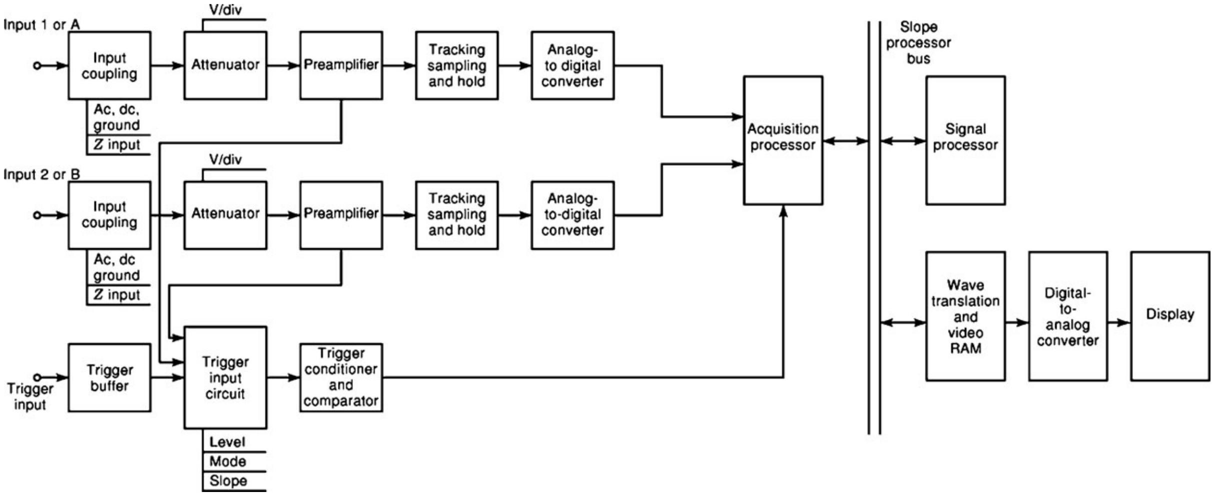

Figure 9. General block diagram of a digital oscilloscope.

Bandwidth

The bandwidth (*BW*) is usually defined as the frequency range between the dc and the frequency at which a sinusoidal signal amplitude observed on the screen is reduced 3 dB in relation to the value at dc or low frequencies. The input sinusoidal signal is supplied from a source having very low internal resistance, normally 50 ohms. The bandwidth of an analog scope is primarily determined by the frequency response parameters of its vertical amplification channel, including attenuators and the tube or other display. The magnitude response error introduced by the frequency limitations is shown in Table 1. The frequency response bandwidth relates to an equivalent time-domain parameter, namely, the risetime, usually considered as the time the step response changes between 10% and 90% of the steady-state level. For the simplest frequency response approximation, the relationship between the risetime and the bandwidth is as follows:

Table 1.

Signal Freq. for 3 dB BW (MHz)	Error (%)
0.1	1
0.2	2
0.5	11
1.0	29

$$T_B = \frac{0.35}{BW}$$

For instance, for a 100 MHZ scope the rise time is 3.5 ns. This leads to time-domain measurement error, whose effects can be corrected for using the following expression:

$$T_T = \sqrt{T_B^2 + T_R^2}$$

where T_T actual risetime
T_0 measured risetime
T_R scope's own risetime

Table 2 shows the time-domain error calculated without corrections.

Table 2.

$T_R{}^a$(ns)	T_T(ns)	T_0(ns)	Error (%)
3.5	1	3.6	260
3.5	2	4	100
3.5	5	6.1	22
3.5	10	10.6	6
3.5	20	20.3	1.5

[a] BW 100 MHz.

Both tables suggest that in order to maintain reasonable measurement accuracy, the scope should be at least several times faster than the fastest tested wave. Frequency-domain or time-domain speed limitations of digital scopes are additionally imposed by the sampler sampling speed and the analog-to-digital (*ACD*) converter speed. The sampler includes the sample-and-hold unit, whose sampling pulse width determines the fastest change that can be captured and later converted in the ADC. Majority of digital scopes use flash or parallel analog-to-digital converters. With ideal sampling pulses, the sampling rate should be several times greater than the expected maximum frequency of the tested signals. The sampling rate also determines the scope horizontal resolution.

Vertical Sensitivity

This parameter expresses the scope ability to accommodate small signals as well as large signals within the same space of the screen. Typical ranges of scope sensitivities are between several millivolts per division and 20 volts per division. The sensitivity range is a compromise between the user's desired values and the technical limitations imposed by the noise level of the scope amplifiers and the maximum available attenuation of high-frequency compensated attenuators.

Amplitude Noise Level

The scope noise mainly includes the broadband noise generated by the input stages of the scope and by the source resistance. The observed noise levels are usually on the order of 1 mV. Bandwidth reduction decreases the noise level and allows increasing the scope sensitivity. In digital scopes, the input analog amplifiers introduce their noise, thus degrading the resolution of the ADC conversion process. For example, 1 mV noise on a 1 V signal limits the resolution of the conversion to less than 12 bits.

Time Jitter

Time jitter, or jitter, is caused by threshold instabilities in triggering and time-base circuits. The jitter is observed on the screen as a spread of vertical parts of the tested signals. In digital scopes, the clock jitter adds its component to this time-domain instability [8]. The levels of jitter are on the order of picoseconds for fast sampling scopes, and on the order of nanoseconds for low-frequency scopes.

Accuracy

The inaccuracy of a scope is mainly caused by vertical and horizontal calibration and reading errors. The reading errors of digital scopes, with built-in digital amplitude and time meters, are negligible in comparison with calibration errors of amplifiers, voltage attenuators, and input resistors. The total amplitude error can reach several percent, but the dc voltage error can be as low as one percent. The time-base errors in digital scopes are comparable with the errors of digital counters, which are below 0.1% (7), while the time-base errors in analog scopes are usually 2% to 5%. The process of selecting a scope is primarily determined by the information about the waves under test: their shapes, repetitivity, frequency and amplitude, drift, and speed. Additional conditions that should be considered are the length of the record, possibility of test automation, signal statistics, and wave storage. The scope capabilities and parameters should be also chosen with regard to future applications and affordability.

OSCILLOSCOPE PROBES

Almost all standard oscilloscopes use different voltage probes to connect to a circuit or a device under test, chosen to minimize the effects of the scope input impedance and electromagnetic interference. Some probes convert a nonelectrical quantity or another electrical quantity, such as current, into a voltage, which is measured by the scope. Two major types of voltage probes are used. The first type is a passive probe, which yields high input resistance and low input capacitance but introduces significant signal attenuation, usually ten times. The second type is an active probe, which does not attenuate the signal but provides high input resistance and low input capacitance. Unfortunately, the supply voltage required for active probe devices also introduces undesired noise and offset. Active probes usually employ field effect transistors and broad-band operational amplifiers (13). A typical voltage probe has two input terminals: a ground terminal and a signal terminal. In many cases, tests of differential signals cannot be done by means of two-channel differential measurement, due to the limitations of the CMRR. For these tests, differential active probes, which have very high CMRR, are recommended.

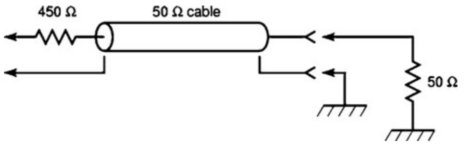

Figure 10. Low-impedance passive probe.

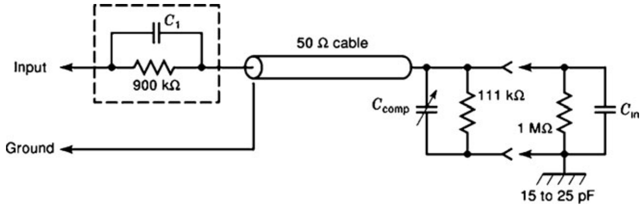

Figure 11. Passive probe, 1 MΩ input resistance.

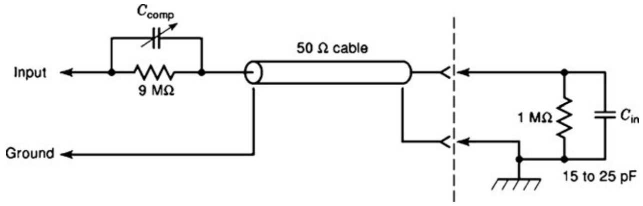

Figure 12. Passive probe, 10 MΩ input resistance.

Passive Probes

Passive probes include low-impedance resistive voltage divider probes and compensated high-impedance voltage divider probes. There are also high-impedance probes with a very large voltage division factor, which are used in high-voltage measurements. Figure 10 shows a low-impedance passive probe. This type of probe has very low capacitive loading and wide bandwidth. It can be used in testing low-impedance circuits. High-impedance passive probes are shown in Figs. 11 and 12. In both cases, the probes require compensation before the measurement process starts. The compensation is performed by observing a standard square wave signal generated by the scope calibrator. The effects of the pulse compensation on the square wave and the sine wave are shown in Fig. 13. High-voltage probes have similar structure to that in Fig. 13. The series resistor is of much higher value and larger physical size, to withstand voltages higher than 500 V. A high-voltage probe circuit is shown in Fig. 14.

The parameters of passive probes are:

- Voltage attenuation (e.g., 10× or 1×)
- Bandwidth for 50 Ω source resistance
- Maximum input voltage (e.g., 500 V)
- Input resistance (e.g., 1 MΩ)
- Input capacitance (e.g., 2 pF)

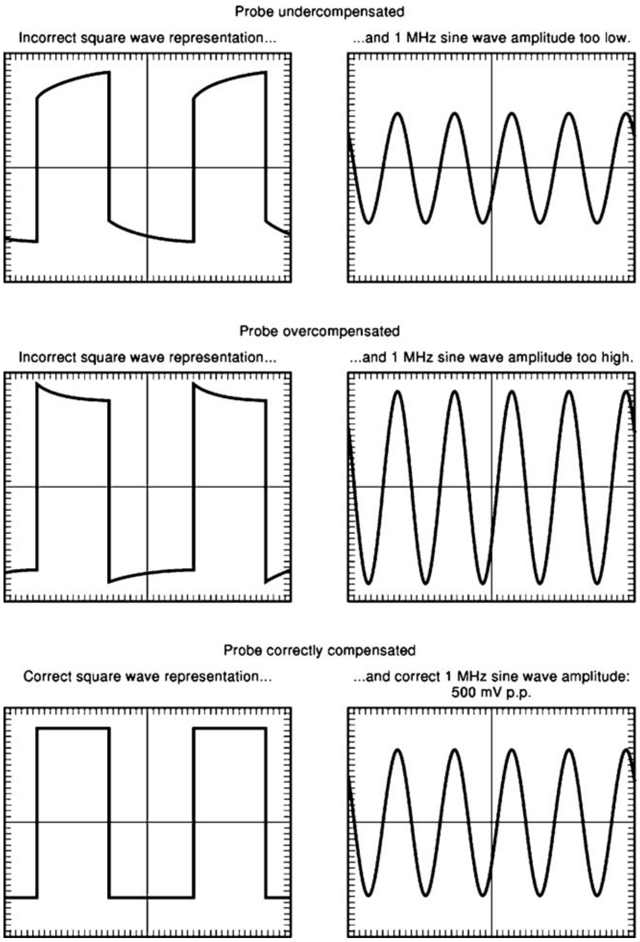

Figure 13. Compensated probe waveforms.

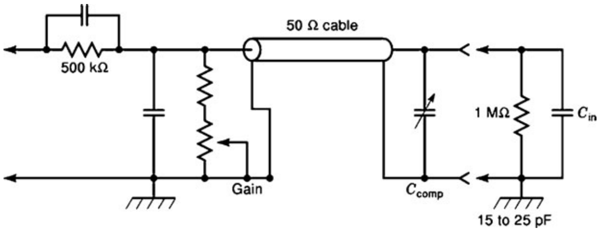

Figure 14. High-input-resistance high-voltage probe.

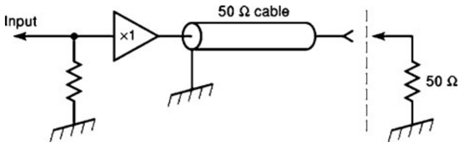

Figure 15. Diagram of an active probe.

Active Probes

Figure 15 is a diagram of an active probe with a single input. A differential probe is shown in Fig. 16. Both probes have very large input resistance, broad band, and no attenuation. The differential probe also has high CMRR, greater than 60 dB.

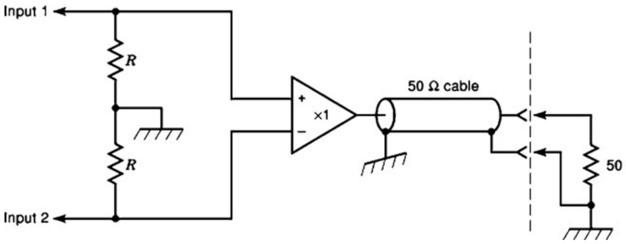

Figure 16. Differential probe.

OSCILLOSCOPE MEASUREMENTS

Scopes can measure the following basic quantities:

- Voltage
- Current (with a current probe)
- Frequency and time, including period, time delay, pulse width, and duty factor
- Phase shift
- Rise and fall times
- Amplitude modulation index
- Jitter
- Eye diagram to evaluate quality of communication signals

Voltage

Voltage measurements are elementary tests done with oscilloscopes. Dc voltages are measured by observing the level shift of the horizontal line on the screen when the input of the scope is dc coupled to the source. The screen graticule and the vertical sensitivity setting indicate the amount of shift. Modern scopes have internal digital voltmeters indicating numerical values of the beam position and the positions of the different markers. Ac voltages, in older scopes, are measured in terms of the voltage differences, which are calculated with the aid of the graticule. In modern scopes, the marked levels are measured digitally and displayed numerically on the screen.

Current

Current measurement requires the use of current-to-voltage converting devices, such as Hall effect sensors for dc currents, current transformers clamping sensors for ac currents, or combinations of both. The Hall effect current sensors are supplied from the scope or from a separate power supply, which also incorporates additional amplifiers.

Frequency and Time

With older scopes, the time-domain parameters can be measured using the screen reading in relation to the current time-bas setting. Modern scopes, especially digital, have digital readout and they display the time- domain parameters with reference markers. Rise and fall times are measured with the help of horizontal levels marked at 10% and 90%. Figure 17 illustrates the way the risetime is evaluated.

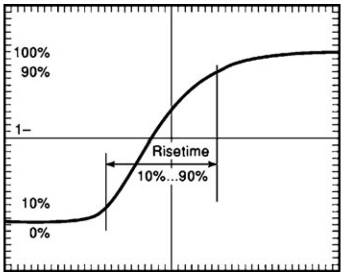

Figure 17. Measurement of the risetime.

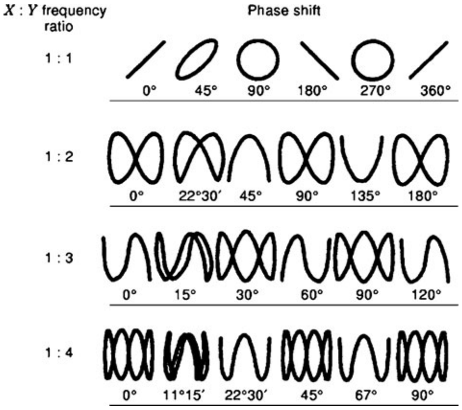

Figure 18. Phase measurement applying *XY* display.

Phase Shift

The phase shift between two waves is the amount of time, expressed in degrees, that passes between the beginnings or other selected points of the two waves. The phase shift is thus obtained from two time measurements in which the relative position and the period of the waves are found and phase angles are calculated. Another method, which can be used only for coherent sinusoidal signals, involves the *XY* display mode. One signal is applied to the horizontal channel, the other to the vertical channel. The *XY* patterns displayed on the screen are called Lissajous graphs, and from the shape of the pattern the phase shift and frequency can be determined. Figure 18 shows different Lissajous patterns.

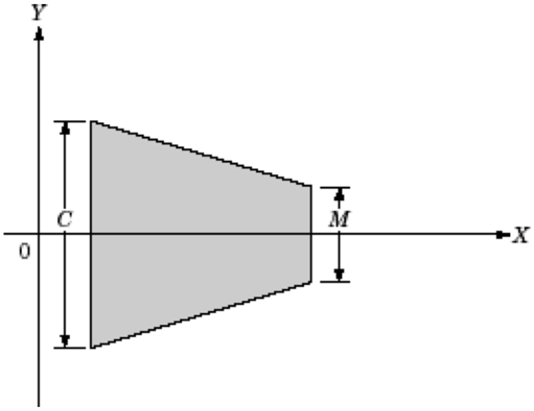

Figure 20. Measurement of the modulation depth (index) applying *XY* display.

Amplitude Modulation Index

Figure 19 shows a time-domain AM wave displayed on the screen while the external triggering of the scope is synchronized by means of a modulating lower frequency wave. The modulation index is calculated as a ration of *M* to *C*. It is also possible to display the *XY* pattern in which the modulated wave is applied to the scope vertical system, and the modulating signal is applied to the horizontal system. Figure 20 shows a typical AM wave pattern for this method.

Eye Diagram

The eye diagram is a very useful visual method, which is often applied in digital communication systems, to evalu-

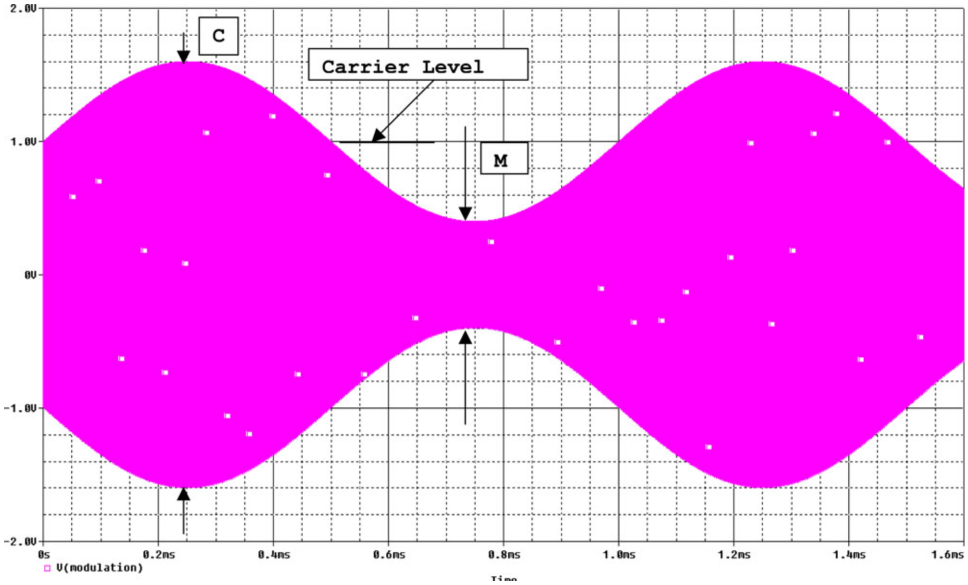

Figure 19. Time-domain measurement of the AM modulation depth (index).

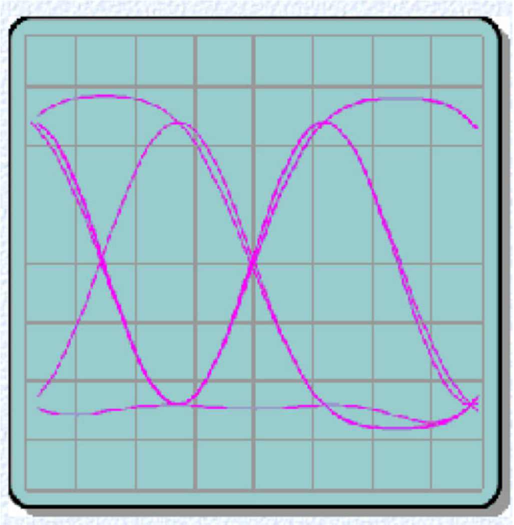

Figure 21. Eye diagram.

ate quality of the information data. The vertical channel of the scope displays the demodulated and filtered bipolar symbol stream but the horizontal channel is triggered at every symbol period or every multiple of the symbol period (Fig. 21). Thanks to the screen persistence the consecutive symbols of various durations can be observed, and amplitude and time domain distortions evaluated.

PROGRAMMABILITY OF OSCILLOSCOPES

Most modern digital scopes can be controlled by computers. The computer provides more flexibility in storing data, and in programming and controlling experiments. Advance interfacing techniques involve applications of GPIB or IEE-488 cards and connections controlled by the dedicated software, like VEE of Agilent Technologies or LAB VIEW of National Instruments (10, 11).

BIBLIOGRAPHY

1. D. A. Helfrick and W. D. Cooper *Modern Electronic Instrumentation and Measurement Techniques*, Prentice-Hall, 1990.
2. Advances in Oscilloscope Technology, LeCroy, White Paper, http://www.lecroy.com
3. *TDS 210 and TDS 220 Digital Real-Time Oscilloscopes*, 070-8483-02, Beaverton, OR: Tektronix, 1997.
4. User's and Service Guide, 3000 Series Oscilloscopes, Agilent Technologies, http://www.agilent.com
5. A. White, Low-Cost, 100-MHz Digitizing Oscilloscopes, *Hewlett-Packard J.*, **43**(1): 6-11, February 1992.
6. S. Wolf, R. F. M. Smith, *Student Reference Manual for Electronic Instrumentation Laboratories*, Second Edition, Pearson Education, Inc., 2004
7. XYZ of Oscilloscopes, http://www.tektronix.com
8. Measuring Random Jitter on a Digital Sampling Oscilloscope, Application Note: HFAN-04.5.1, Rev 0,08/02, Maxim, http://www.maxim-ic.com.
9. About Oscilloscope http://www.hobbyprojects.com/oscilloscope_tutorial.html.
10. VEE, http://adn.tm.agilent.com/index.cgi?CONTENT_ID=830
11. Shahid F. Khalid,LabWindows/CVI Programming for Beginners, Prentice Hall, http://www.phptr.com, 2000.
12. Digital Serial Analyzer Sampling Oscilloscope, http://www.tektronix.com
13. ABC's of Probes, http://tektronix.com.

ANDREW RUSEK
Oakland University, Rochester, MI