horizontal system causes the horizontal time base to move the glowing dot across the screen from left to right within a specific time interval. Many sweeps in rapid sequence cause the movement of the glowing dot to blend into a solid line. At higher speeds, the dot may sweep across the screen up to 500,000 times each second.

Together, the horizontal sweeping action and the vertical deflection action traces a graph of the signal on the screen. The trigger is necessary to stabilize a repeating signal. It ensures that the sweep begins at the same point of a repeating signal, resulting in a clear picture as shown in Figure 7.

![UnTriggered Display](image1) ![Triggered Display](image2)

**Figure 7: Triggering Stabilizes a Repeating Waveform**

In conclusion, to use an analog oscilloscope, you need to adjust three basic settings to accommodate an incoming signal:

- The attenuation or amplification of the signal. Use the volts/div control to adjust the amplitude of the signal before it is applied to the vertical deflection plates.
- The time base. Use the sec/div control to set the amount of time per division represented horizontally across the screen.
- The triggering of the oscilloscope. Use the trigger level to stabilize a repeating signal, as well as triggering on a single event.

Also, adjusting the focus and intensity controls enables you to create a sharp, visible display.

**Digital Oscilloscopes**

Some of the systems that make up digital oscilloscopes are the same as those in analog oscilloscopes; however, digital oscilloscopes contain additional data processing systems. (See Figure 8.) With the added systems, the digital oscilloscope collects data for the entire waveform and then displays it. When you attach a digital oscilloscope probe to a circuit, the vertical system adjusts the amplitude of the signal, just as in the analog oscilloscope.

Next, the analog-to-digital converter (ADC) in the acquisition system samples the signal at discrete points in time and converts the signal's voltage at these points to digital values called sample points. The horizontal system's
sample clock determines how often the ADC takes a sample. The rate at which the clock "ticks" is called the sample rate and is measured in samples per second.

The sample points from the ADC are stored in memory as waveform points. More than one sample point may make up one waveform point. Together, the waveform points make up one waveform record. The number of waveform points used to make a waveform record is called the record length. The trigger system determines the start and stop points of the record. The display receives these record points after being stored in memory.

Depending on the capabilities of your oscilloscope, additional processing of the sample points may take place, enhancing the display. Pretrigger may be available, allowing you to see events before the trigger point.

Figure 8: Digital Oscilloscope Block Diagram

Fundamentally, with a digital oscilloscope as with an analog oscilloscope, you need to adjust the vertical, horizontal, and trigger settings to take a measurement.
Sampling Methods

The sampling method tells the digital oscilloscope how to collect sample points. For slowly changing signals, a digital oscilloscope easily collects more than enough sample points to construct an accurate picture. However, for faster signals, (how fast depends on the oscilloscope’s maximum sample rate) the oscilloscope cannot collect enough samples. The digital oscilloscope can do two things:

- It can collect a few sample points of the signal in a single pass (in real-time sampling mode) and then use interpolation. Interpolation is a processing technique to estimate what the waveform looks like based on a few points.

- It can build a picture of the waveform over time, as long as the signal repeats itself (equivalent-time sampling mode).

Real-Time Sampling with Interpolation

Digital oscilloscopes use real-time sampling as the standard sampling method. In real-time sampling, the oscilloscope collects as many samples as it can as the signal occurs. (See Figure 9.) For single-shot or transient signals you must use real time sampling.

![Waveform Constructed with Sample Points](image)

Figure 9: Real-time Sampling

Digital oscilloscopes use interpolation to display signals that are so fast that the oscilloscope can only collect a few sample points. Interpolation "connects the dots."

Linear interpolation simply connects sample points with straight lines. Sine interpolation (or sin x over x interpolation) connects sample points with curves. (See Figure 10.) Sin x over x interpolation is a mathematical process similar to the "oversampling" used in compact disc players. With sine interpolation, points are calculated to fill in the time between the real samples. Using this process, a signal that is sampled only a few times in each cycle can be accurately displayed or, in the case of the compact disc player, accurately played back.
Equivalent-Time Sampling

Some digital oscilloscopes can use equivalent-time sampling to capture very fast repeating signals. Equivalent-time sampling constructs a picture of a repetitive signal by capturing a little bit of information from each repetition. (See Figure 11.) You see the waveform slowly build up like a string of lights going on one-by-one. With sequential sampling the points appear from left to right in sequence; with random sampling the points appear randomly along the waveform.

Figure 11: Equivalent-time Sampling
Acquisition

Acquisition is the process of sampling the analog input signal, converting it into digital data, and assembling it into waveform record. The oscilloscope creates a digital representation of the input signal by sampling the voltage level of the signal at regular time intervals (Figure 2-4).

![Waveform Diagram](https://via.placeholder.com/150)

**Figure 2-4:** Acquisition: Input Analog Signal, Sample, and Digitize

The sampled points are stored in memory along with corresponding timing information. You can use this digital representation of the signal for display, measurements, or further processing.

You specify how the digitizing oscilloscope acquires data points and assembles them into the waveform record.

**Sampling and Digitizing**

The trigger point marks time zero in a waveform record. All record points before the trigger event make up the pretrigger portion of the waveform record. Every record point after the trigger event is part of the posttrigger portion. All timing measurements in the waveform record are made relative to that trigger event.

Each time it takes a sample, the oscilloscope digitizer produces a numeric representation of the signal. The number of samples may be larger than the number of points in your waveform record. In fact, the oscilloscope may take several samples for each record point (Figure 2-5).

![Sampling Diagram](https://via.placeholder.com/150)

**Figure 2-5:** Several Points May be Acquired for Each Point Used
The digitizer can use the extra samples to perform additional processing, such as averaging or looking for minimum and maximum values.

The digitizing oscilloscope creates a waveform record containing a user-specified number of data points. Each record point represents a certain voltage level that occurs a determined amount of time from the trigger event.

**Record Length**

The number of points that make up the waveform record is defined by the record length. You can set the record length in the Horizontal menu. The digitizing oscilloscope provides record lengths of 500, 1,000, 2,500, 5,000, and 15,000 points.

You can order option 1M that provides a maximum record length of 50,000 points. That option is available only at the time of original purchase; it cannot be installed later.

**Sampling Methods**

Sampling is the process of converting the analog input signal to digital data for display and processing. The two general methods of sampling are real-time and equivalent-time.

**Real-Time Sampling**—In real-time sampling, the oscilloscope digitizes all the points it acquires after one trigger event (see Figure 2-6). Use real-time sampling to capture single-shot or transient events.

Two factors that affect real-time sampling on the digitizing oscilloscope are interleaving and interpolation.

*Interleaving* refers to the ability of the digitizing oscilloscope to attain higher digitizing speeds by combining the efforts of several digitizers. For example, if you want to digitize on all channels at one time (four on the TDS 540 and two on the TDS 520), each of those channels can digitize at a maximum real-time speed of 250 Megasamples/second (per channel).

If you use two channels, the TDS 540 oscilloscope can combine the efforts of two digitizers to each channel and acquire at 500 Megasamples/second (per channel).
If you focus on only one channel at the maximum possible real-time rate, the TDS 520 oscilloscope can acquire at 500 Megasamples/second using both its digitizers, while the TDS 540 oscilloscope can combine all four digitizers and acquire at 1 Gigasample/second.

Depending on how many channels you are using and the speed of the time base, at some point the digitizing oscilloscope will not be able to get enough samples to create a waveform record. (See the discussion on page 2-10 for more details about when that happens.) At that point, the digitizing oscilloscope will create the waveform record in one of two ways depending on whether you have limited the oscilloscope to real-time sampling or enabled equivalent-time sampling (you make that choice in the Acquisition menu).

If you have restricted it to real-time sampling, the digitizing oscilloscope uses a process called interpolation to create the intervening points in the waveform record. There are two options for interpolation: linear or $\sin(x)/x$.

Linear interpolation computes record points between actual acquired samples by using a straight line fit. It assumes all the interpolated points fall in their appropriate point in time on that straight line. Linear interpolation is useful for many waveforms such as pulse trains.

$\sin(x)/x$ interpolation computes record points using a curve fit between the actual values acquired. It assumes all the interpolated points fall along that curve. That is particularly useful when acquiring more rounded waveforms such as sine waves. Actually, it is appropriate for general use, although it may introduce some overshoot or undershoot in signals with fast rise times.

**NOTE**

When using either type of interpolation, you may wish to set the display style so that the real samples are displayed intensified relative to the interpolated samples. The instructions under Display Style on page 3-31 explain how to turn on intensified samples.

**Equivalent-Time Sampling**—The digitizing oscilloscope only uses equivalent-time sampling if you have enabled the equivalent-time option in the Acquisition menu and the oscilloscope is not able to get enough samples with which to create a waveform record.

In equivalent-time (ET) sampling the oscilloscope acquires samples over many repetitions of the event (Figure 2-7). It should only be used on repetitive signals.
The oscilloscope takes a few samples with each trigger event and eventually constructs a waveform record using the samples from multiple acquisitions. That feature lets you accurately acquire signals with frequencies much higher than the digitizing oscilloscope real-time bandwidth.

The digitizing oscilloscope uses a type of equivalent-time sampling called random equivalent-time sampling. Although the samples are taken sequentially in time, they are random with respect to the trigger. That is because the oscilloscope sample clock runs asynchronously with respect to the input signal and the signal trigger. The oscilloscope takes samples independent of the trigger position and displays them based on the time difference between the sample and the trigger.

Selecting Sampling Mode

The sampling speeds and the number of channels you choose affect the mode the digitizing oscilloscope uses to sample waveforms. Basically, if the time base is 200 ns or slower, the digitizing oscilloscope uses real-time sampling for creating waveform records.

When the time base is faster than 50 ns, the digitizing oscilloscope creates waveform records using equivalent-time sampling or interpolation. For speeds between 200 ns and 20 ns, the digitizing oscilloscope creates waveform records differently depending on the number of input channels and type of oscilloscope you are using (see Table 2-1).
Acquisition Controls for Digital Oscilloscopes

Digital oscilloscopes have settings that let you control how the acquisition system processes a signal. Look over the acquisition options on your digital oscilloscope while you read this description. Figure 35 shows you an example of an acquisition menu.

![Image of Acquisition Menu](image)

**Figure 35: Example of an Acquisition Menu**

### Acquisition Modes

Acquisition modes control how waveform points are produced from sample points. Recall from the first section that sample points are the digital values that come directly out of the Analog-to-Digital-Converter (ADC). The time between sample points is called the sample interval. Waveform points are the digital values that are stored in memory and displayed to form the waveform. The time value difference between waveform points is called the waveform interval. The sample interval and the waveform interval may be but need not be the same. This fact leads to the existence of several different acquisition modes in which one waveform point is made up from several sequentially acquired sample points. Additionally, waveform points can be created from a composite of sample points taken from multiple acquisitions, which leads to another set of acquisition modes. A description of the most commonly used acquisition modes follows.

- **Sample Mode:** This is the simplest acquisition mode. The oscilloscope creates a waveform point by saving one sample point during each waveform interval.
- **Peak Detect Mode**: The oscilloscope saves the minimum and maximum value sample points taken during two waveform intervals and uses these samples as the two corresponding waveform points. Digital oscilloscopes with peak detect mode run the ADC at a fast sample rate, even at very slow time base settings (long waveform interval), and are able to capture fast signal changes that would occur between the waveform points if in sample mode. Peak detect mode is particularly useful for seeing narrow pulses spaced far apart in time.

- **Hi Res Mode**: Like peak detect, hi res mode is a way of getting more information in cases when the ADC can sample faster than the time base setting requires. In this case, multiple samples taken within one waveform interval are averaged together to produce one waveform point. The result is a decrease in noise and an improvement in resolution for low speed signals.

- **Envelope Mode**: Envelope mode is similar to peak detect mode. However, in envelope mode, the minimum and maximum waveform points from multiple acquisitions are combined to form a waveform that shows min/max changes over time. Peak detect mode is usually used to acquire the records that are combined to form the envelope waveform.

- **Average Mode**: In average mode, the oscilloscope saves one sample point during each waveform interval as in sample mode. However, waveform points from consecutive acquisitions are then averaged together to produce the final displayed waveform. Average mode reduces noise without loss of bandwidth but requires a repeating signal.

### Stopping and Starting the Acquisition System

One of the greatest advantages of digital oscilloscopes is their ability to store waveforms for later viewing. To this end, there are usually one or more buttons on the front panel that allow you to stop and start the acquisition system so you can analyze waveforms at your leisure. Additionally, you may want the oscilloscope to automatically stop acquiring after one acquisition is complete or after one set of records has been turned into an envelope or average waveform. This feature is commonly called single sweep or single sequence and its controls are usually found either with the other acquisition controls or with the trigger controls.

### Sampling Methods

In digital oscilloscopes that can use either real-time sampling or equivalent-time sampling as described on page 10, the acquisition controls will allow you to choose which one to use for acquiring signals. Note that this choice makes no difference for slow time base settings and only has an effect when the ADC cannot sample fast enough to fill the record with waveform points in one pass.
Acquisition Modes

The acquisition system has several options for converting analog data into digital form. The Acquisition menu lets you determine the acquisition mode, whether or not to permit equivalent time sampling, and how to start and stop acquisitions.

Description of Modes

The digitizing oscilloscope supports five acquisition modes:

- Sample
- Peak Detect
- Hi Res
- Envelope
- Average

The Sample, Peak Detect, and Hi Res modes operate in real-time on a single trigger event, provided the digitizing oscilloscope can acquire enough samples for each trigger event. Envelope and Average modes operate on multiple acquisitions. The digitizing oscilloscope averages or envelopes several waveforms on a point-by-point basis.

Figure 3-1 illustrates the different modes and lists the benefits of each. It will help you select the appropriate mode for your application.

Sample Mode

In Sample mode, the oscilloscope creates a record point by saving the first sample (of perhaps many) during each acquisition interval. (An acquisition interval is the time covered by the waveform record divided by the record length.) This is the default mode.

Peak Detect Mode

Peak Detect mode alternates between saving the highest sample in one acquisition interval and lowest sample in the next acquisition interval. That mode only works with real-time, non-interpolated sampling.

If you set the time base so fast that it requires real-time interpolation or equivalent-time sampling, the mode automatically changes from Peak Detect to Sample, although the menu selection will not change.
Acquisition Modes

Single Waveform Acquisition

<table>
<thead>
<tr>
<th>Interval</th>
<th>Sample</th>
<th>Acquisition Mode</th>
<th>Displayed Record Points</th>
<th>Waveform Drawn on CRT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Uses first sample in interval
- Use for fastest acquisition rate
- This is the default mode.

Peak Detect

- Uses highest and lowest samples in two intervals
- Use to reveal aliasing and for pitch detection
- Provides the benefits of enveloping with the speed of a single acquisition.

Hi Res

- Calculates average of all samples in interval
- Use to reduce apparent noise
- Provides the benefits of averaging with the speed of a single acquisition.

Multiple Waveform Acquisitions

Three Acquisitions from One Source

<table>
<thead>
<tr>
<th>Acquisition 1</th>
<th>Acquisition Mode</th>
<th>Waveform Drawn on CRT</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Envelope</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Uses Peak Detect Mode for Each Acquisition
- Finds highest and lowest record points over many acquisitions
- Use to reveal variations in the signal across time.

Uses Sample Mode for Each Acquisition

- Calculates average value for each record point over many acquisitions
- Use to reduce apparent noise in a repetitive signal.

Figure 3-1: How the Acquisition Modes Work
Hi Res Mode

In Hi Res mode, the digitizing oscilloscope averages all samples taken during an acquisition interval to create a record point. That average results in a higher-resolution, lower-bandwidth waveform.

This mode only works with real-time, non-interpolated sampling. If you set the time base so fast that it requires real-time interpolation or equivalent-time sampling, the mode automatically becomes Sample, although the menu selection will not change.

A key advantage of Hi Res is its potential for increasing resolution regardless of the input signal. Table 3-1 and the equations shown below illustrate how you can obtain up to 15 significant bits with Hi res mode. Note that the resolution improvements are limited to speeds slower than 400 ns/div. Also, resolutions above 15 bits are not allowed by internal hardware and computation limitations.

\[ S_i = \text{Sampling Interval for TDS 500} = 4 \text{ ns} \]
\[ \Delta t = \text{Sample Interval} = \frac{\text{Time/Div}}{\text{Number Of Points/Div}} = \frac{5 \mu s/\text{Div}}{50 \text{ Points/Div}} = 100 \text{ ns} \]
\[ N_{d} = \text{Number of points per decimation interval} = \frac{\Delta t}{S_i} = 25 \]
\[ \text{Resolution Enhancement (bits)} = 0.5 \times \text{LOG}_2(N_{d}) \approx 2 \text{ extra bits} \]

<table>
<thead>
<tr>
<th>Time Base Speed</th>
<th>Bits of Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>400 ns and faster</td>
<td>8 bits</td>
</tr>
<tr>
<td>1 \mu s to 4 \mu s</td>
<td>7 bits</td>
</tr>
<tr>
<td>5 \mu s to 10 \mu s</td>
<td>10 bits</td>
</tr>
<tr>
<td>20 \mu s to 60 \mu s</td>
<td>11 bits</td>
</tr>
<tr>
<td>100 \mu s to 200 \mu s</td>
<td>12 bits</td>
</tr>
<tr>
<td>500 \mu s</td>
<td>13 bits</td>
</tr>
<tr>
<td>1 ms to 2 ms</td>
<td>14 bits</td>
</tr>
<tr>
<td>5 ms and slower</td>
<td>15 bits</td>
</tr>
</tbody>
</table>

Envelope Mode

Envelope mode lets you acquire and display a waveform record that shows the extremes in variation over several acquisitions. You specify the number of acquisitions over which to accumulate the data. The oscilloscope saves the highest and lowest values in two adjacent intervals similar to the Peak Detect mode. But Envelope mode, unlike Peak Detect, gathers peaks over many trigger events.
After each trigger event, the oscilloscope acquires data and then compares the min/max values from the current acquisition with those stored from previous acquisitions. The final display shows the most extreme values for all the acquisitions for each point in the waveform record.

**Average Mode**

Average mode lets you acquire and display a waveform record that is the averaged result of several acquisitions. This mode reduces random noise. The oscilloscope acquires data after each trigger event using Sample mode. It then averages the record point from the current acquisition with those stored from previous acquisitions.

**Acquisition Readout**

The acquisition readout at the top of the display (Figure 3-2) shows the state of the acquisition system (running or stopped). The "running" state shows the number rate and acquisition mode. The "stopped" state shows the number of acquisitions acquired since the last stop or major change.

![Acquisition Readout](image)

*Figure 3-2: Acquisition Menu and Readout*

**Operation**

To bring up the acquisition menu (Figure 3-2) press SHIFT ACQUIRE MENU.