INTRODUCTION

Since the introduction of the first oscilloscope in 1946, Tektronix has maintained a leadership position in the development of high performance signal acquisition and measurement technology.

In the early '50s Tektronix introduced the modular oscilloscope, providing a degree of flexibility and adaptability never before available.

In 1960 Tektronix made it possible to measure signals over 100 MHz with the introduction of the first analog sampling oscilloscope.

Today, Tektronix continues this leadership tradition by utilizing an innovative sampling technique to achieve oscilloscope bandwidths up to 40 GHz.

All digitizing oscilloscopes sample their input in some fashion. As a result, all digitizing oscilloscopes could be called "sampling oscilloscopes". However, this term has come to mean instruments which sample their input signals prior to any amplification or attenuation by a method called sequential sampling. It is this type of sampler that we will focus on in this primer.

Our purpose here is to review the basic sampling methods and architectures, and to focus on the particular benefits and tradeoffs of sequential sampling oscilloscopes, in particular the Tektronix 11800 Series Digital Sampling Oscilloscopes.

SAMPLING CONCEPTS

What is Sampling?

Sampling is the process of converting a portion of an input signal into a number of discrete electrical values for the purpose of storage, processing, and/or display. The magnitude of each sampled point is equal to the amplitude of the input signal at the instant in time in which the signal is sampled.

Sampling is like taking snapshots. Each snapshot corresponds to a specific point in time on the waveform. These snapshots can then be arranged in the appropriate order in time so as to reconstruct the input signal.

In a digital oscilloscope, an array of sampled points is reconstructed on a CRT, with the measured amplitude on the vertical axis and time on the horizontal axis (Figure 1). The input waveform appears as a series of dots on the screen.
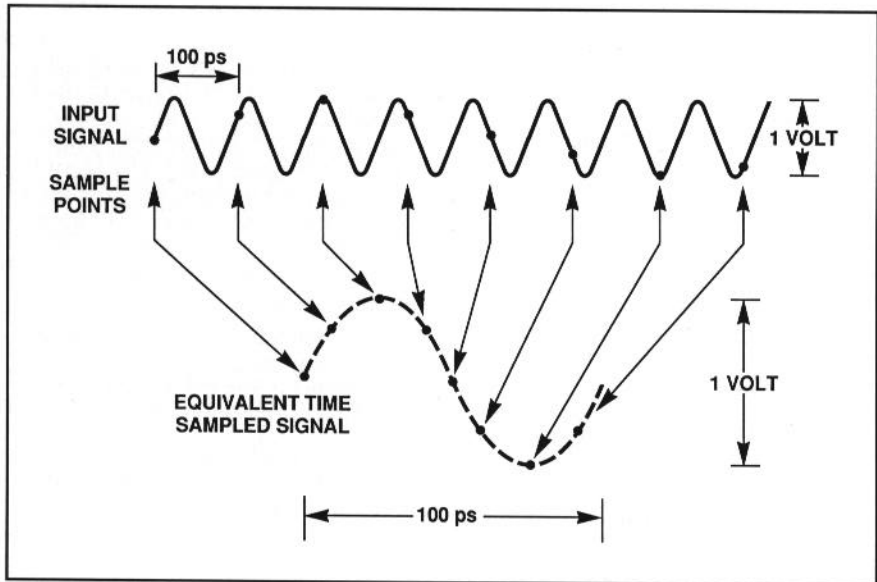
SAMPLING OSCILLOSCOPE TECHNIQUES

Figure 1. *Basic Sampling*. Sampled points are connected by interpolation to produce a continuous waveform.
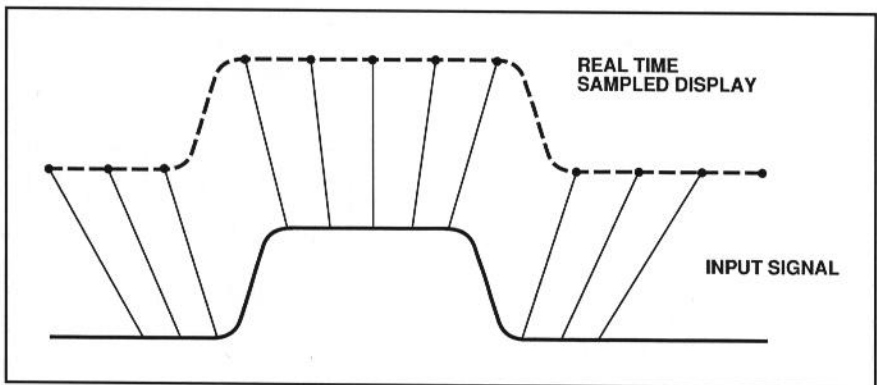

Figure 2. In order to capture this 10 ns pulse in real-time, the sample rate must be high enough to accurately define the edges.

If the dots are widely spaced and difficult to interpret as a waveform, the dots can be connected by a process called interpolation. Interpolation connects the dots with lines, or vectors. A number of interpolation methods are available which can be used to produce an accurate representation of a continuous input signal.

Sampling Methods

Although there are a number of different implementations of sampling technology, today's digital oscilloscopes utilize only two basic sampling methods: real time sampling and

equivalent time sampling. Equivalent time sampling can be divided further, into two sub-categories: random and sequential. Each method has distinct advantages depending on the kind of measurements being made.

Real Time Sampling

In real time sampling, the digitizer (or sampler) operates at maximum speed to acquire as many points as possible in one sweep. Therefore, real time sampling is intended for capturing single shot or transient events (Figure 2).

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Real time sampling presents the greatest challenge for digital oscilloscopes because of the sample rate needed to accurately digitize high-frequency transient events. These events occur only once, and must be sampled in the same time frame that they occur. If the sample rate isn't fast enough, high-frequency components can "fold down" into a lower frequency, causing aliasing in the display.

In order to accurately represent a signal and avoid aliasing, Nyquist theory says that the signal must be sampled at least twice as fast as its highest frequency component. A signal with frequency components as high as 500 MHz, for example, would require a sample rate of at least 1 gigasample/second to accurately represent it.

Real time sampling is further complicated by the high speed memory required to store the waveform once it is digitized.

Measurement systems such as the Tektronix DSA 600 Series Digitizing Signal Analyzers, with sample rates to 2 GS/s and bandwidths to 1 GHz, have been optimized for capturing very fast single shot and transient events. These systems have the ability to sample input signals as fast as once every 500 picoseconds.

Equivalent Time Sampling

Equivalent time digitizers take advantage of the fact that most naturally occurring and man made events are repetitive. Therefore, samples may be acquired over many repetitions of the signal, with one or more samples taken on each repetition. This allows the oscilloscope to accurately capture signals whose frequency components are much higher than the scope's sample rate.

There are two types of equivalent time sampling methods in use today, random equivalent time sampling and sequential equivalent time sampling. Each has its advantages. Random equivalent time sampling allows display of the input signal prior to the trigger point, without the use of a delay line. Sequential equivalent time sampling provides much greater time resolution and accuracy. Both require that the input signal be repetitive.

Random Equivalent Time Sampling

Random equivalent time sampling is the most common method of sampling employed in today's digital oscilloscopes. Random equivalent time

digitizers utilize an internal clock that runs asynchronously with respect to the input signal and the signal trigger (Figure 3). Samples are taken continuously, independent of the trigger position, and are displayed based on the time difference between the sample and the trigger.

Although samples are taken sequentially in time, they are random with respect to the trigger — hence the name "random" equivalent time sampling.

The ability to acquire and display samples prior to the trigger point is the key advantage of this sampling technique. Random samplers advance the trigger point and allow viewing of the leading edge of an input signal. It acts like a pretrigger generator, and so eliminates the need for external pretrigger signals or delay lines.

This is particularly valuable in fault detection applications, where leading edge viewing lets the engineer see the cause of the fault.

Advanced digitizing oscilloscopes like the Tektronix 11400 Series use random sampling to provide capture of up to 8 repetitive signals at once,

with extensive pretrigger viewing and 10 ps horizontal resolution.

Depending on the sample rate and the time window of the display, random sampling offers another important benefit — it allows more than one sample to be acquired per triggered event.

Here's how it works. As the sweep speed is decreased so that the time window of the display becomes longer, more samples per trigger may be acquired. At some point, the timebase can be slowed down to the point where the digitizer becomes a real time sampler. It captures the entire waveform from a single trigger.

However, the converse is also true. As the sweep speed is increased the acquisition window narrows, until the digitizer cannot sample on every trigger. It takes longer and longer for the random sampler to fill out the waveform at faster sweep speeds.

It is at these fast sweep speeds where very precise timing measurements are often made, and where the extraordinary time resolution of the sequential equivalent time sampler is most beneficial.
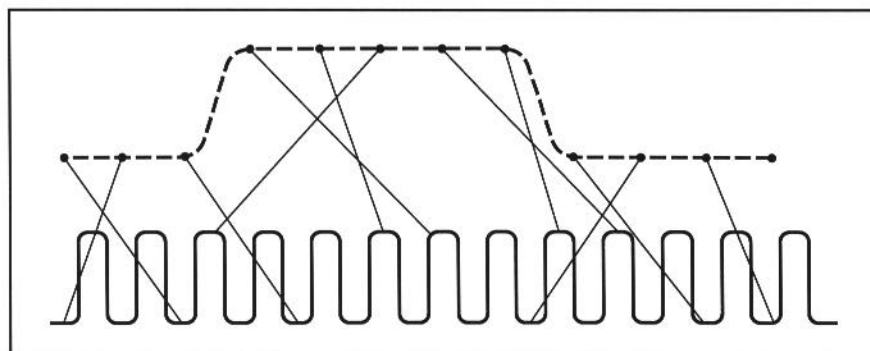

Figure 3. In random equivalent-time sampling, the sampling clock runs asynchronously with the input signal and the trigger.
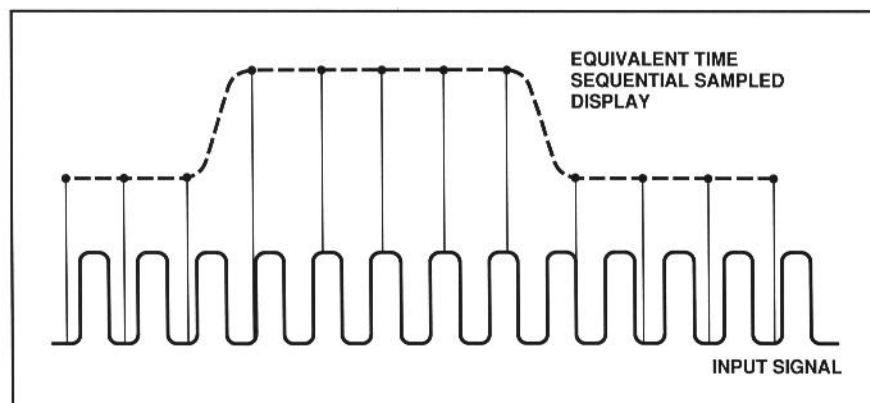

Figure 4. In sequential equivalent-time sampling, a single sample is taken for each recognized trigger after a time delay which is incremented after each cycle.

Sequential Equivalent Time Sampling

The sequential equivalent time sampler acquires one sample per trigger (Figure 4), independent of the time/div setting (sweep speed). When a trigger is detected, a sample is taken after a very short, but well defined, delay. When the next trigger occurs, a small time increment — "delta t" — is added to this delay and the digitizer takes another sample. This process is repeated many times, with "delta t" added to each previous acquisition, until the time window is filled.

Technologically speaking, it is easier to generate a very short, very precise "delta t" than it is to accurately measure the vertical and horizontal positions of a sample relative to the trigger point, as required by random samplers. State of the art sequential sampling oscilloscopes like the Tektronix 11800 Series can generate precise delay times as small as 10 femto-seconds. This precisely measured delay is what gives sequential samplers their unmatched time resolution.

[It should be noted, however, that within the limits imposed by current technology, the 11800's useable resolution is less than the sample interval. Noise in the horizontal and vertical systems create trigger uncertainty which results in time jitter.]

Since, with sequential sampling, the sample is taken after the trigger level is detected, the trigger point cannot be displayed without an analog delay line, which may, in turn, reduce the bandwidth of the instrument. If an external pretrigger can be supplied, bandwidth will not be affected.

Sampling Oscilloscope vs. Digital Storage Oscilloscope Architectures

Now let's see how the different sampling methods are utilized in digital storage and sampling oscilloscope architectures. Each architecture is characterized by distinct sampling and display functions. It is these differences that determine their suitability for a given task.

As we mentioned in the introduction, all digitizing oscilloscopes sample their input in some fashion. As a result, all digitizing oscilloscopes could be called "sampling oscilloscopes". This term, however, has come to designate instruments which sample their input signals prior to any amplification or attenuation.

How does this differ from the way a digital storage scope samples an input? In the digital storage oscilloscope, the input signal first encounters an attenuator/amplifier circuit, in which gain and offset are adjustable (Figure 5). The output of the amplifier is then digitized by real-time or random equivalent time sampling, or both. When random sampling is used the scope can provide flexible pretrigger capabilities.

The attenuator/amplifier circuit protects the scope's other internal circuits from overload. Therefore, the attenuator/amplifier must operate at the full bandwidth of the instrument. High performance scopes with this architecture — such as the 11400 Series and DSA 600 Series — are available with bandwidths to 1 GHz.

By contrast, the architecture of sampling oscilloscope reverses the position of the attenuator/amplifier and the sampling bridge (Figure 6). The input signal is sampled before any attenuation or amplification is performed. A low bandwidth amplifier can then be utilized after the sampling bridge because the signal has already been converted to a lower frequency by the sampling gate. This results in a much higher bandwidth instrument. Sequential sampling oscilloscopes — like the 11800 Series — are available with bandwidths to 40 GHz.

The tradeoff for this high bandwidth, however, is that the sampling oscilloscope's dynamic range is severely limited. Since there is no attenuator/amplifier in front of the sampling gate, there is no facility to scale the input. The sampling bridge must be able to handle the full dynamic range of the input at all times. Therefore the dynamic range of most sampling scopes is limited to about 1 V peak-to-peak. Digital storage oscilloscopes, on the other hand, can handle 50 to 100 volts.

In addition, protection diodes cannot be placed in front of the sampling bridge as this would limit the bandwidth. This reduces the safe input voltage for a sampling scope to about 3 V, as compared to 500 V available on other scopes.
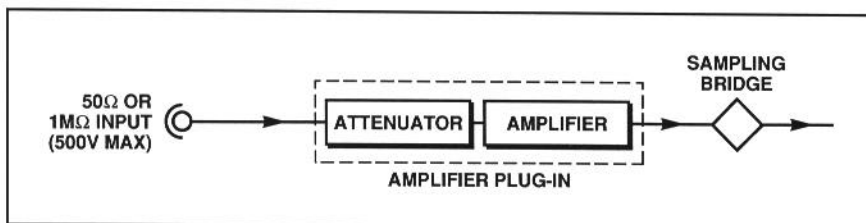
Figure 5. In the conventional DSO, the signal is amplified/attenuated before it is sampled and digitized.
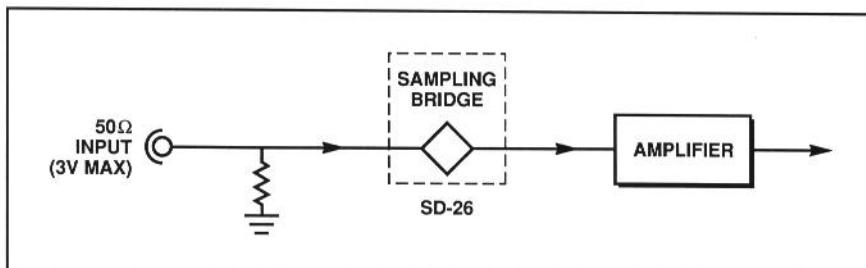
Figure 6. In the sampling scope, the signal is sampled prior to amplification.

Understanding the tradeoffs of dynamic range and safe input voltage will let you take advantage of the high bandwidth and timing resolution of the sampling oscilloscope (Table 1).

GLOSSARY OF TERMS

Display Window — The time window represented within the horizontal limits of an oscilloscope's display graticule. See Time Window.

Dot — A displayed point indicating the horizontal and vertical components of a sample. One dot usually represents one sample.

Dot Density — The number of dots per horizontal division (also called sample density).

Equivalent time — The time scale represented in the display of a sampling oscilloscope operating in the equivalent-time sampling mode.

Equivalent-time Sampling — A sampling technique in which a representative waveform is created with a series of samples taken from identical repetitive waveforms.

Leading Edge Viewing — The ability to observe signal characteristics prior to a trigger event.

Pre-trigger — An auxiliary trigger event that occurs before the main trigger in order to allow leading edge viewing and measurement.

Random Equivalent Time Sampling — An equivalent time sampling technique in which the samples are taken independently of the signal trigger time. Sample position is determined by measuring the time difference between the sample event and the trigger event.

Real Time Sampling — A sampling process in which all samples are taken in a single cycle of the digitizing system. The event is captured and displayed in the same time frame in which it occurs.

Sampling — The process of converting a portion of an input signal into a discrete electrical value for the purpose of storage, processing, and/or display.

Sampling Bridge — The electronic circuit that samples and stores a discrete representative value for a portion of an input signal.

Sampling Oscilloscope — An oscilloscope characterized by an architecture which samples the input signal prior to amplification or attenuation. Sampling oscilloscopes have much higher bandwidth than conventional oscilloscopes, but have a lower input dynamic range and a lower safe input voltage.

Sequential Equivalent-Time Sampling — An equivalent-time sampling technique in which one sample is taken for each triggered event. Samples are taken sequentially after a delay time which is incremented on each sample cycle.

Trigger — An electrical event which causes an oscilloscope to begin the process of waveform acquisition.

Table 1. The Sequential Sampling Oscilloscope vs. the Convential DSO

SEQUENTIAL SAMPLER	CONVENTIONAL DSO
• Very High Bandwidth (Up to 40 GHz with the 11800 Series)	• Bandwidth Limited (Maximum of 1 GHz)
• Very High Timing Resolution (to 10 femto-seconds)	• Lower Timing Resolution (to 10 ps)
• Faster Sweep Speeds (to 1 ps/div)	• Slower Sweep Speeds
• Limited Leading Edge Viewing Capability with Pretrigger or Delay Lines	• Flexible Leading Edge Viewing and Pretrigger Capabilities
• Narrow Dynamic Range — Amplifiers/ Attenuators Condition Signal *After* Acquisition	• Wide Dynamic Range — Amplifiers/ Attenuators Condition Signal *Before* Acquisition
• One Sample Taken per Trigger Independent of Time/div Setting	• Variable Number of Samples Taken per Trigger from >1 to <1
• Signal Must be Repetitive	• Signal may be Repetitive or Single Shot (Single-shot capability is limited to high-performance instruments)

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