Scanning A/D Converters, Waveform Digitizers, and Oscilloscopes

Scanning A/Ds, waveform digitizers and oscilloscopes all digitize analog signals. In all three instrument types, the purpose is to capture all significant details (i.e., frequency components) of the input waveform so that information can be extracted. These instruments differ in how performance parameters are optimized, the depth of user control over the data acquisition process, and the level of information output.

Scanning A/Ds are used to economically automate measurement of static (i.e., slowly changing) parameters, such as temperature, pressure, and strain. They are optimized for high absolute accuracy (at DC and low frequencies), high-resolution, and low-cost-per-channel. Users have low-level control over how data is collected, and the level of information output is correspondingly low.

Digitizers and oscilloscopes both digitize dynamic(i.e., rapidly changing) analog signals.In fact, the heart of an oscilloscope is a relatively low-resolution, high-speed digitizer—perfectly adequate for visual interpretation of fast transients and high-frequency waveforms. Oscilloscopes are used primarily to measure waveform parameters. They give users limited control over how data is captured, but many traditional parameters—such as rise time, fall time and pulse width—are available at the push of a button.

Waveform digitizers capture raw time data for further processing, usually in a host computer, but sometimes in the digitizer itself. This architecture allows a much more detailed analysis of the waveform than is possible using an oscilloscope—computers can make practical use of high-resolution measurements, and post-processing possibilities are unlimited. As a result, digitizers have (compared to oscilloscopes) higher resolution, and while output may be processed, parameters are seldom extracted directly.

Compared to scanning A/Ds with high absolute accuracy at DC, digitizers are optimized for relative measurements throughout the frequency range and across channels. Because waveform digitizers convert rapidly changing (or high-frequency) signals compared to scanning A/Ds, sample rates are higher, and they usually have a separate A/D for each channel, which greatly increases the cost-per-channel. The resolution of waveform digitizers is usually less than that of scanning A/Ds for reasons of economy and application.

Choosing a Scanning A/D

Scanning A/Ds economically automate collection of relatively static voltage and resistance values from diverse physical locations. Normally, these voltage or resistance values are from transducers sensing slowly-changing parameters, such as temperature, static pressure or strain.

In its simplest form, a scanning A/D consists of a multiplexer, a voltmeter, and a system controller or computer. The system controller sequentially closes the multiplexer switches, records the corresponding voltmeter reading, and moves on to the next switch position. Data is not recorded simultaneously, but the scan rate is usually fast enough so data can be considered correlated for most purposes. (Note: the HP E1413C has an option which provides simultaneous sample and hold for correlating the measurements.) Scanning A/Ds are optimized for absolute accuracy at DC and low frequency. Junctions are compensated for thermal effects, the system is calibrated at DC, and the low-frequency common mode rejection ratio is high. While today's scanning A/Ds are conceptually simple, they have evolved into sophisticated instruments, highly optimized for low-sample-rate data acquisition. They are fast, accurate, and provide both complete signal conditioning and high-level instrument functions.

HP E1413C 64-Channel Scanning A/D Converter

The HP E1413C Scanning A/D converters define the state-of-the-art in both functionality and performance. One C-size single-slot module contains a 64-channel multiplexer, an A/D converter, multiplexer control, a 64 k Sample FIFO, on-board DSP, auto-calibration, and a current value table.

Primary performance specifications are 16 bits of resolution at a 100kHz scan rate, with 0.01% of reading accuracy over as many as 64 active channels. Continuous data acquisition is possible in many applications. With a 64-kSample FIFO memory, up to 1000 readings per channel can be accumulated before transferring data to the host. Because the FIFO is a dual-ported memory (simultaneously transferring data in and out), it is consumed only while the data acquisition rate is greater than the rate of data transfer to the host. On-board functions, such as real-time units conversion, limit testing, and averaging provide higher level measurement results when needed. Optional signal conditioning plug-ins (SCPs) provide everything to interface with industry-standard sensors such as thermocouples, thermistors, RTDs, and strain gages.

HP E1313A 32-Channel Scanning A/D Converter

The HP E1313A is a B-size, three-slot functional equivalent of the HP E1413C. Option 001 provides a total of 64 channels in 4 slots. It is a cost-effective alternative for applications requiring no more than 256 channels in a B-size mainframe.

HP E1414A Pressure Scanning A/D

The HP E1414A pressure scanning A/D converter is used in conjunction with the Model 8400 Pressure Scanner from Pressure Systems Incorporated (PSI). It provides up to 512 channels of highly accurate pressure data acquisition. A/D sample rates are 20 kReadings/s in the random address mode and 50 kReadings/ s in the parallel address mode.

Choosing a Waveform Digitizer

Waveform digitizers are used to capture a wide variety of dynamic signals for processing in a computer. They are used in many applications, but most uses are for transient signals, IF/ base-band signals, or noise and vibration signals. Digitizers provide low-level control over the data acquisition process. Digitization of a waveform often includes several steps: signal conditioning, conversion control (e.g., trigger), A/D conversion, data storage, and data processing. Hewlett-Packard's VXI waveform digitizers combine several of these functions into a single module, depending on the intended applications. While all digitizers convert analog signals to a time series of amplitude samples, several factors—such as how data is conditioned and sample rate—depend on how the data will ultimately be used. Digitizers are optimized for analyzing captured data in either the time domain or the frequency domain. Complicating matters somewhat, digitizers optimized for time domain analysis can be used for some frequency domain applications and, likewise, digitizers optimized for the frequency domain can be used for some time domain applications. The following brief tutorials will help you understand how digitizers are optimized for each domain, and how that optimization affects performance in the non-optimized domain. The tutorials are followed by a more in-depth comparison of HP VXI digitizers.

Aliasing

Aliasing occurs when a signal is under-sampled. The most familiar example of aliasing is the "wagon wheel effect" in an old western movie. Wheels sometimes appear to be turning backwards because the series of still photographs (i.e., samples) making up the film arbitrarily catch the spokes in a position approaching the position of the spokes in the previous photograph. The effect is novel in a movie, but catastrophic if you are acquiring data. Analogous to the wagon wheel, an under-sampled waveform provides a distorted "picture" of the actual events. Visualizing the effects of aliasing is even easier in the frequency domain, although less intuitive. Consider a signal with two frequency components: one less than half the sampling frequency(f1), and one slightly higher than the sampling frequency (f2). The digitized output after sampling would contain at least one additional component at (f2-fs) (1) with the amplitude of the original signal f2. When aliasing is allowed to occur, new signals seemingly appear out of nowhere!

The Cure

There is only one cure for aliasing— using a sample rate at least twice the frequency of the highest frequency component in the signal (2). Digitizers used primarily to capture data for analysis in the time domain solve the aliasing problem by providing a five-fold safety margin. Sample rates are often 10x the highest expected frequency component of the signal to be analyzed. By sampling at a 10x rate, even components five times the frequency of the desired signal are properly sampled.

Digitizers optimized for wideband frequency domain applications are constrained by the need for higher amplitude resolution. One of the principal advantages of working in the frequency domain is detection of extremely small frequency components in the presence of large signals. Users normally want a wide dynamic range (i.e., lots of bits!). Sample rate is traded off for amplitude resolution or number of bits for economic reasons. Therefore, digitizers for frequency domain applications sample at a rate only slightly higher than twice the frequency of the highest desired frequency component in the signal

At first, this seems to be an adequate solution. But consider the frequency domain example of aliasing. Suppose the desired signal was f1. To get the highest resolution possible, the sampling frequency is set to slightly more than twice f1. In this example, f2 is "out-of-band" energy, since the frequency band of interest is only that of frequencies up to half the sample rate. Now consider the output. The signal of interest f1is digitized as desired, but the "out-of-band" energy at f2 is also digitized and now appears at f2-fs— within the band of interest. Having a non-existent frequency component suddenly appear in the band of interest is clearly unacceptable!

In this case, the aliasing problem is solved using a steep roll-off “anti-aliasing" filter to eliminate the out-of-band energy before the signal is digitized. Now the A/D digitizes only the desired band of frequencies—at reasonable cost, and with the desired high-amplitude resolution. So why not use this same technique in the time domain? Many digitizers optimized for the frequency domain use Chebyshev filters for alias protection because of their excellent (i.e., easily corrected) frequency domain characteristics. Unfortunately, the price normally paid for this excellence is degradation of the time domain performance. When Chebyshev filters are used, waveforms with fast rise times can experience serious ringing. Digitizers optimized for the time domain normally use Bessel filters.

It is possible to have both the frequency domain excellence of the Chebyshev filters and excellent time domain performance. Correction algorithms can be used to remove the ringing effects of the anti-aliasing filters in the digitized waveform. This feature has been implemented on the HP E1430A and HP E1437A.

Effective Bits and Usable Dynamic Range

By themselves, small signals are not particularly difficult to digitize, since signal conditioning amplifiers on the input can boost signal levels to well within the range of the A/D. The real test of a digitizer is how accurately it can detect and convert small signals in the presence of much larger signals on the input. Noise and (especially) distortion can seriously limit a digitizer's performance when an input signal contains frequency components with dramatically different amplitudes.

Two different approaches are used to quantify the performance of a digitizer: effective bits (1) and dynamic range. As the name suggests, effective bits are the number of usable bits think of it as the number of bits a perfect digitizer would need to give the same performance. Dynamic range is simply the ratio, expressed in dBs, of the largest and smallest signals that can be reliably measured at the same time. Both effective bits and dynamic range include the effect of all limiting deterministic and random signals— quantization error, differential nonlinearity, harmonic distortion, aperture uncertainty, spurious responses, and random noise.

Noise

Noise is defined as unwanted disturbances superimposed upon a useful signal (2). It can be induced from external sources, or arise naturally from thermal effects in circuit components (random noise). Fifty- or sixty-hertz noise from power lines is probably the most troublesome induced noise. It can be controlled by carefully managing the cabling to the digitizer and by selecting a digitizer with a high common mode rejection ratio (CMRR).

Random noise is a limiting factor when measuring transients. Not much can be done to reduce random noise when digitizing one-time events, except to limit the bandwidth of the digitizer to a minimum needed to accurately capture all details (i.e., frequency components) of the input signal. The bandwidth is usually reduced using low-pass filters or by transforming (FFT) the data into the frequency domain for spectral analysis. If the signal is repetitive, the picture is much brighter. Noise can be reduced by time averaging in the time domain or linear and RMS averaging in the frequency domain. If a trigger signal is available, time or linear averaging can be used to reduce the RMS value of the noise by the square root of the number of averages. In the frequency domain, non-synchronous averaging of power spectra will reduce the standard deviation of the noise around its RMS value.

Regardless of the method used, reducing noise is beneficial only when spurs and distortion levels remain below the averaged noise floor.

Distortion

Distortion is troublesome because there is little a user can do except to buy a low-distortion digitizer with lots of headroom on each input range. Distortion results from non-linearities in the digitizer circuitry, and exists at some level in even the best digitizers. Some types of distortion rise quickly through the noise floor even when slight overloads occur. Digitizers optimized for the frequency domain often allow 2 to 3 dB of headroom above the maximum input level to avoid this condition. A 1 volt digitizer that develops significant distortion at 1.05 volts must be used very carefully at 1 volt.

Arm and Trigger Flexibility

All digitizers give a high degree of control over the data acquisition process. However, there is an area of subtle difference between digitizers optimized for the time or frequency domain. In the simplest mode, digitizers optimized for time domain applications can be programmed to record a user-specified number of readings, with the first reading coinciding exactly with the triggering event. This allows users to precisely measure the time between the triggering event and any sample. With frequency-domain digitizers, a user-selected block of samples is measured, beginning with the first sample clock cycle after the triggering event. This method introduces an uncertainty Of t'(i.e., the period of one sample clock cycle) between the triggering event and the first sample in time-domain measurements.

In frequency-domain measurements, the effect of the sampling delay is to introduce a slight phase ramp in the measurement data. Good digitizers that are optimized for frequency domain measurements measure this delay and correct the phase ramp.

Both time and frequency domain optimized digitizers have a variable sample rate and usually accept signals from external sampling clocks. Time-domain digitizers vary the sample clock speed directly to change the sample rate. Most digitizers optimized for frequency domain applications have an internal clock that samples at a constant rate and then decimates the data to obtain lower rates (e.g., discards nine consecutive readings and keep the tenth to effectively reduce the sample rate to a tenth of its original value). Digitizers optimized for time domain applications allow an arbitrary number of samples to be specified for each event.

With frequency domain digitizers, a predetermined number of readings (i.e., a block of data) will be taken, beginning with the next sample clock pulse when an event occurs. Blocks are usually 76.0 binary multiples and sub-multiples of 1024 (driven by FFT requirements), but some digitizers offer completely user-selectable block sizes.

All digitizers have at least one characteristic in common—when arm and trigger conditions are satisfied, they take a predetermined number of samples. A block of samples can be triggered by another module in the VXI system, a level on an input channel, or an input from the external trigger port.

Often, pre- and post-event (or trigger) samples are taken to capture the waveform both before and after the event. When pre-event data is being acquired, the A/D continuously feeds data into a circular buffer. When the event signal is received, a user-specific number of pre-event samples are concatenated with a user-specified number of post-event samples. Digitizers for both the time or frequency domain both have this capability.

Memory Size and Memory Management

Memory size and memory management are important in determining the amount of time a digitizer can sample an analog waveform without interruption. Having a large memory may "brute force" the issue, but at today's memory prices, it is an acceptable choice. Dual-porting, dual-rate time bases and multiple-segment memory are all memory management techniques that allow memory to be used more effectively.

With dual-ported memories, data can be read from the memory by the host without interrupting the A/D. Typically, blocks of data are transferred from the memory while the A/D simultaneously stores new readings. Dual-ported memories are useful for digitizers acquiring data for analysis in either the frequency or time domain.

Dual-rate time bases are used in digitizers optimized for time-domain analysis to reduce the amount of memory consumed during the pre-event phase of a measurement. In many applications, only a cursory record of the pre-event condition is necessary, so the data is sampled at a low rate. When an arm signal is received, the sample rate is increased for the specified number of post-event readings. The net result is less memory being used than if the digitizer ran constantly at the post-event rate.

Multiple-segment memory is another technique used in time-domain optimized digitizers. In many cases, events of interest in a waveform occur so rapidly that the digitizer does not have time to transfer the data to the host before the next event. Segmenting the memory allows the A/D to digitize and store events in successive memory locations. Transfer to the host is done when it will not interrupt the data acquisition process.

Characteristics of HP Digitizers

Refer to the table for the following discussion on applications versus digitizer.

HP E1429A/B 20 MSa/s Digitizer

Typical applications: transient capture, DAC testing, Research

This simple but powerful two-channel waveform digitizer is an economical choice for traditional time-domain applications including capture of non-repetitive transient signals (single-shot measurements). It provides a selectable sample rate, dual sample rates, extremely flexible triggering, external sample/trigger, and a switch-able 10 Mhz Bessel filter. Use it for frequency- domain applications if 12-bit resolution is adequate, and third-party application software support, such as FFT computations, is not needed.

HP E1432A 16-Channel, 51.2 kSa/s Digitizer with DSP

Typical applications: noise and vibration measurements, structural analysis, modal analysis, rotating machinery analysis

The HP E1432A is HP's premier digitizer for low frequency-domain applications. On board DSP, a 4- to 32-MByte FIFO, and 16 input channels are packed onto a single-slot C-size VXI module.

High-level measurement results are available, in addition to the sampled data normally output from a digitizer. For example, when used in conjunction with the VXI Plug&Play library the digitizer can output complete spectra in the frequency or order domain.

HP E1437A 20 MSa/s Digitizer with DSP

Typical applications: IF digitizer, RF receiver digitizer, DAC testing, focal plane array testing, radar processing, research

The HP E1437A is an ultra-linear digitizer that allows users to accurately characterize signals in both the time (1) and frequency domains with very high resolution. Time-domain measurements, such as the time between pulses, can be measured with up to 18 effective bits of amplitude resolution and picosecond resolution on the time axis. Frequency-domain measurements are made with up to 110 dBFS of distortion-free and spur-free dynamic range. Noise can be reduced by on-board filtering, averaging, or transforming data into the frequency domain in the host computer.

Up to 18 bits of amplitude resolution are possible because of dithering and a unique digital signal processing (DSP) algorithm that reduces deterministic noise—such as spurs and distortion on the fly.

This same extraordinary level of performance is available for time domain measurements by two additional DSP functions: 1) correction algorithms that remove the ringing in time-domain measurements caused by the anti-aliasing filters, and 2) a digital reconstruction filter that recovers all of the information in the original analog waveform—even the values of points between the original sample points! Because all of the original information is present (in a digital format), the output can be re-sampled (in software) at an arbitrarily high sample rate. Time base accuracy and resolution is typically increased three orders of magnitude over traditional digitizers pptimized for the time domain. Note that simple post processing using C functions is required to obtain the time domain performance.

HP E1430A 10 MSa/s Digitizer with DSP

The HP E1430A is a 10 MSa/s version of the HP E1437A. It is a lower priced solution for those applications requiring no more than a 4 MHz bandwidth.

HP E1431A 8-Channel Digitizer

Typical applications: noise and vibration measurements, structural analysis, modal Animation

Most applications for the HP E1431A can be more economically done with the HP E1432A. However, the HP E1431A is more sensitive and has a slightly wider frequency range.

HP E1433A 8-Channel 196kSa/s Digitizer

The HP E1433A module converts data into four domains: time, frequency, revolution, and order. Digitized data can be simple time records, or, the HP E1433A can use the on-board DSP to compute FFTs and power spectrums to provide data in the frequency domain. Also for rotating machinery, this module can measure amplitude as a function of shaft angle, or as multiples of the shaft RPM using order ratio spectrums.

Characteristics of HP Digitizers

	HP E1429 A20 MSa/s Digitizer	**HP E1431A 8-Channel 25.6 kHz Digitizer**	**HP E1432A 16-Channel 51.2kHz Digitizer with DSP**
Primary Application	Time-Domain Analysis	Frequency-Domain Analysis	Frequency-Domain Analysis
Alias Protection	Oversample	Anti-Aliasing Filter (Built-in)	Anti-Aliasing Filter (Built-in)
Resolution	12-bits	16-bits	16-bits
Basic Accuracy	0.5%	1%	1%
Time Base Resolution	50 ns	40 us	20 us
Low-Frequency CMRR	68 dB	65 dB	50 dB
Time-Domain Fidelity	Excellent	Ringing	Ringing
Variable Bandwidth	External Filters	Yes	Yes
2 dB Input Range Headroom	No	Yes	Yes
Trigger	On Eent	Next Sample	Next Sample
Pre-Arm Capture	Yes	Yes	Yes
Memory	512 kSample/ hannel	16 kSample/ Channel	4-32 Mbytes
Dual-Ported Memory	No	Yes	Yes
Dual-Rate Sampling	Yes	No	No
Segmented Memory	Yes	No	No

	HP E1433A 8-Channel 196kSa/s Digitizer	**HP E1430A/E1437A 10/20 Msa/s Digitizer with DSP**
Primary Application	Time, Fequency, Revolution, and Order Domain	Time and Frequency Domain analysis
Alias Protection	Anti-Aliasing Filter(Switchable)	Anti-Aliasing Filter (Built-in)
Resolution	16-bits	23-bits
0.7%	0.7%	+/-0.03 dB
Time Base Resolution	5 us	Picoseconds
Low-Frequency CMRR	70 dB	65 dB at 1 Vcom
Time-Domain Fidelity	Excellent	Excellent
Variable Bandwidth	Yes	Yes
2 dB Input Range Headroom	Yes	1 dB
Trigger	Next Sample	On Event
Pre-Arm Capture	Yes	Yes
Memory	4 to 32 Mbytes	8 Mbytes
Dual-Ported Memory	Yes	Yes
Dual-Rate Sampling	No	No
Segmented Memory	No	No