

ADVANCED MODULAR OSCILLOSCOPES AND DIGITIZERS OPTMIZED FOR ACCELERATOR APPLICATIONS

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Abstract

Modular oscilloscopes and digitizers, including those with embedded EPICS IOCs, provide powerful off-the-shelf solutions for accelerator controls and beamline data acquisition applications requiring fast sampling, high resolution and/or tight multi-channel synchronization. This presentation discusses features and capabilities of EPICS and non-EPICS LXI, VXI, PXI/cPCI and PCI oscilloscopes and digitizers as they specifically relate to accelerator and beamline applications. Modular oscilloscopes and digitizers with on-board DSP and FPGAs provide the advanced waveform acquisition and analysis capabilities of benchtop instruments with the size and channel-density advantages of modular instruments. Instruments with on-board processing, such as those from ZTEC Instruments, enable real-time waveform math and waveform parameter analysis. Advanced triggering and multiple acquisition modes are other features found on some of today’s advanced modular instruments. Furthermore, instruments with embedded EPICS IOCs save users the time and money of developing their own EPICS drivers and display panels.

ACCELERATOR REQUIREMENTS FOR OSCILLOSCOPES & DIGITIZERS

Accelerator applications often challenge instrumentation manufacturers. In addition to requiring low noise and distortion during data acquisition, responsive remote instrument control and fast screen update rates are important for many machine control applications. And because large amounts of data are often captured, it becomes important to reduce the data to include only the desired information and download the information as quickly as possible so that the instrument is ready for the next acquisition.

Furthermore, it is frequently necessary to tightly synchronize many channels of data acquisition and multiple triggers across numerous instruments and across multiple chassis that may be separated by significant physical distances.

Because of the demanding technical requirements of accelerator applications, it is often necessary for engineers to develop their own custom products to meet specific requirements. However, developing custom instruments adds significant costs and time to most projects. Because of this, engineers and experimenters prefer to purchase off-the-shelf solutions whenever possible.

ATTRIBUTES OF ADVANCED MODULAR SCOPES & DIGITIZERS

Advanced instrument functionality that was traditionally found only on benchtop instruments is now available on modular instruments in PXI/cPCI, PCI, LXI and VXI formats. For oscilloscopes and digitizers, this functionality includes input signal conditioning, multiple acquisition modes, advanced triggering, on-board waveform math and analysis and much more. Figure 1 illustrates some of these ‘benchtop’ functions as they exist in ZTEC modular instruments.

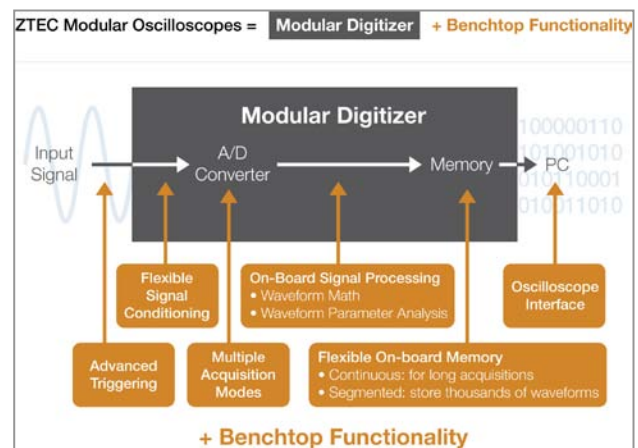


Figure 1: Benchtop functionality

Triggering

Going beyond simple rising/falling edge triggers, advanced modular oscilloscopes and digitizers add the ability to trigger on complex signal conditions, from multiple sources, just like their benchtop counterparts. For example, pulse width triggers can be configured to occur only on pulses that meet certain conditions – e.g., greater than or less than a user-defined pulse width, or inside/outside a specified range of pulse widths.

Pattern triggers are used to acquire waveforms when a user-defined pattern becomes true or false. The pattern is a combination of HIGH/LOW states on a combination of one or more input channels and/or backplane triggers like those found on PXI and VXI. For example, an instrument could be set to trigger and acquire data when Input 1 is HIGH, Input 2 is LOW and Input 3 is HIGH. See Figure 2.



Figure 2: Example of a pattern trigger

Glitch triggers look for glitches in a waveform as short as 250ps in duration and capture data when the glitch occurs. This is a valuable trigger when monitoring waveforms over long periods and is important to find out how often abnormal events occur. See Figure 3 below.



Figure 3: Example of a glitch trigger

Triggers can also be cascaded and the number of events can be counted; combining to define extremely specific trigger events. For example, the instrument could be configured to trigger on the fourth occurrence of event 'B' (e.g., a rising edge on Input 2), only after event 'A' occurs (e.g., a pattern of LOW on Input 1, HIGH on Input 3 and HIGH on Input 4).

Acquisition Modes

Similar to the discussion on triggering, some of today's advanced modular oscilloscope and digitizers have the same advanced acquisition modes that are commonly found on benchtop instruments. Beyond the default normal acquisition mode where a single waveform is captured and saved to memory, advanced acquisition modes provide options for decreasing noise, over-sampling, and other techniques that instrument operators can use to capture data in a manner more useful for a given application.

Scalar average mode takes waveform points from a user-defined number of consecutive acquisitions and averages them together (see Figure 4).

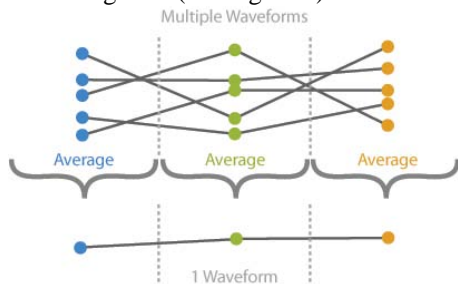


Figure 4: Scalar average mode

Averaging waveforms reduces the effects of random noise and increases measurement resolution. In contrast to

scalar averaging, a high resolution acquisition mode averages a number of adjacent points in a single over-sampled acquisition, resulting in a single, higher resolution waveform (see Figure 5). With both scalar averaging and high resolution modes, the result is a single waveform with lower random noise and improved accuracy, as compared to a waveform from a normal acquisition.

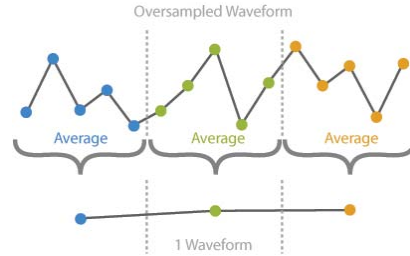


Figure 5: High resolution mode

Envelope and peak detect acquisition modes result in two waveforms that represent the maximum and minimum waveform points from either a single over-sampled acquisition (peak detect mode), or from multiple acquisitions (envelope mode). See Figures 6 and 7. These acquisition modes are useful for signals such as amplitude modulated signals, where it may not be necessary to capture all the data in every acquisition, but it is important to see the envelope of the waveform(s).

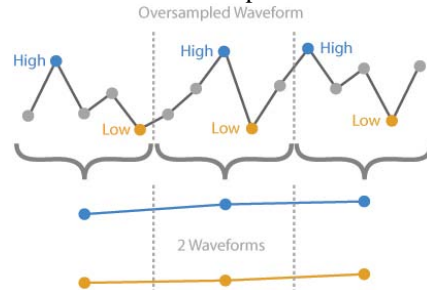


Figure 6: Peak detect mode (single acquisition)

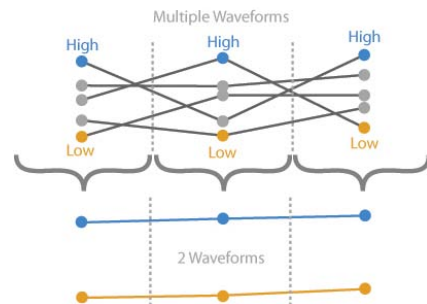


Figure 7: Envelope mode (multiple acquisitions)

Like benchtop oscilloscopes, some of today's modular oscilloscopes and digitizers have an equivalent-time acquisition mode. In equivalent-time acquisition mode, waveforms are sampled at the maximum real-time sampling rate of the instrument's analog-to-digital converters (ADCs). Each real-time acquisition fills in some points in the resultant equivalent time waveform. After many acquisitions, the equivalent time waveform fills in and appears as if it were acquired at a much faster

sampling rate. For example, on the ZTEC Instruments' ZT4610 series of oscilloscopes, the maximum real-time sampling rate is 4 GS/s; in equivalent time acquisition mode the resulting waveform has an effective sampling rate of up to 400 G/s.

High Performance Data Acquisition

Today's most advanced modular oscilloscopes and digitizers meet the demanding data acquisition requirements of accelerator beamline and control applications by offering higher ADC resolution, faster sampling, less noise and more memory than benchtop oscilloscopes.

With very few exceptions, benchtop oscilloscopes have 8-bit ADCs. 8-bit ADCs provide a maximum of 2^8 , or 256 digitization levels across the full scale input range. In other words, under perfect conditions, an oscilloscope with a 10V full scale range has vertical (voltage) resolution of 10V/256, or ~39mV. Contrast that with modular oscilloscopes and digitizers that are commonly found with 12, 14 and 16-bit ADC resolution (and occasionally even more). A 16-bit ADC has 65,536 digitization levels. This represents a voltage resolution of ~153µV across a 10V full scale range, under perfect conditions.

Fast sampling is also an important aspect of waveform monitoring and data acquisition at accelerators. Often it is necessary to accurately capture very fast events. Today's 8-bit modular oscilloscopes have maximum real-time sampling rates of 4 GS/s (250ps sample spacing). High resolution instruments (those with more than 8-bit ADC resolution) typically have lower maximum real-time sampling rates as vertical resolution increases. Figure 8 shows the vertical resolution and the maximum sampling rate of ZTEC Instruments' high-resolution instruments.

| Series | Resolution | Max Sampling |
|--------|------------|--------------------|
| ZT4420 | 12-bit | 1 GS/s (1 ns) |
| ZT4440 | 14-bit | 800 MS/s (1.25 ns) |
| ZT410 | 16-bit | 400 MS/s (2.5 ns) |

Figure 8: Resolution and maximum sampling rate of ZTEC Instruments' high resolution oscilloscopes

High vertical resolution/accuracy, combined with low noise is a common need for waveform monitoring and data acquisition applications at accelerators. Oftentimes signals from beamline detectors and other instruments are very small and may be superimposed on top of larger signals. Clearly it is not practical to accurately characterize a signal that is a few millivolts in amplitude, riding on top of a much larger signal, if you only have 39mV of resolution (i.e., 8-bit ADC, 10V range). To capture signals such as these, it is clearly advantageous to use high-resolution instrumentation.

Noise and distortion are critical instrument attributes when measuring any signal, especially signals with small amplitudes. It is important for the instruments to have as little internal noise and as little signal distortion as

possible. Noise and distortion in oscilloscopes and digitizers are typically characterized by the following measures:

- Signal-to-Noise Ration (SNR)
- Total Harmonic Distortion (THD)
- Signal-to-Noise + Distortion (SINAD)
- Effective Number of Bits (ENOB) = $(\text{SINAD} - 1.76) / 6.02$
- Spurious-Freed Dynamic Range (SFDR)

ZTEC Instruments' ZT4440-DP series of modular digitizers have been optimized to minimize noise and distortion, making them ideal for many accelerator applications where small signals accurately captured, sometimes superimposed on top of larger signals. Figure 9 shows the frequency response of a 10.7 MHz signal captured on the ZT4440-DP (14-bit) PXI modular digitizer. The ZT4440-DP has the following characteristics:

- SNR = 65.1 dBc
- THD = -86.7 dBc
- SINAD = 65.0 dBc
- SFDR = 81.5 dBc

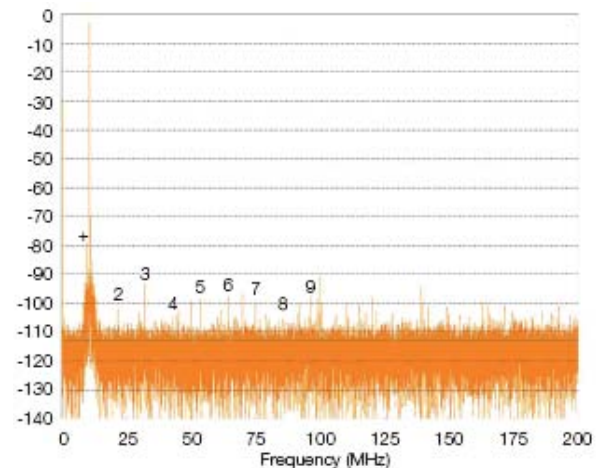


Figure 9: Frequency response of 10.7 MHz signal captured on ZTEC Instruments' 14-bit ZT4440-DP digitizer

On-Board Signal Analysis

On-board signal analysis is another key differentiator between basic modular digitizers and more advanced modular oscilloscopes. On-board signal processing and data reduction reduces data transfer time and speeds up data acquisition rates and analysis times. Instead of acquiring waveform data and then downloading it from the card to software such as MATLAB® for additional analysis, advanced modular instruments perform the math and analysis on-board the instrument, in real-time, without having to download the entire waveform.

On-board data analysis is especially important with today's long-memory instruments. With acquisition memory lengths of hundreds of millions of data points and longer, it can be very time consuming to download

every waveform from every channel, even with very fast data buses like PCI and PCI express. For most applications, it is much faster to use on-board processing to extract the desired information from the signal and reduce the data before transferring it to a PC than it is to simply download every data point that is captured.

For example, let's assume that an event is used to trigger the oscilloscope. The trigger event indicates that a pulse will occur sometime within the next 1ms, but the exact time of its occurrence within the 1ms window is unknown. The user of the oscilloscope only needs to know two bits of information: 1) when the event started relative to the trigger event and 2) the area under the pulse. If the instrument samples at 1 GS/s for 1ms, one million data points are captured. Instead of transferring all one million data points to a PC for analysis, an oscilloscope or digitizer with built-in processing can calculate the rising edge of the pulse, perform an integration of the pulse, and transfer the results of these two calculations to a PC. The amount of data transferred in this case, using on-board processing, is much less and the time required for data transfer is also less than if the entire waveform had to be transferred to a PC. These time savings are particularly significant when there are multiple instruments sharing a single bus, e.g., the PCI bus on the backplane of a PXI chassis.

ZTEC Instruments' M-Class oscilloscopes and digitizers use on-board FPGAs and DSP to perform waveform math and calculate over forty waveform parameters. On-board waveform math includes algebraic functions, integration, differentiation, Fast Fourier Transforms (FFTs), histograms, parameter trending, limit/mask testing, and others. Waveform parameters related to voltage and time are also automatically calculated. Figures 10 and 11 show some of the voltage and time parameters calculated.

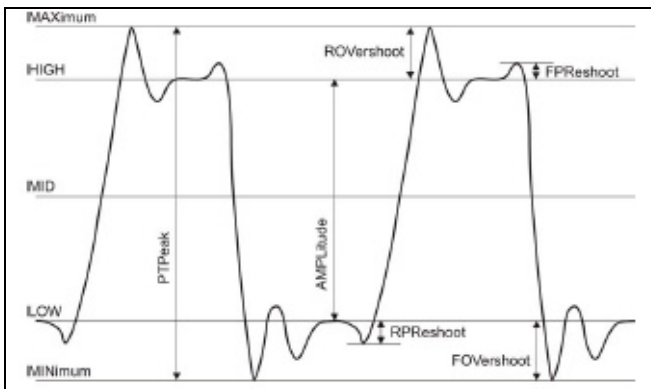


Figure 10: Some vertical-axis measurements

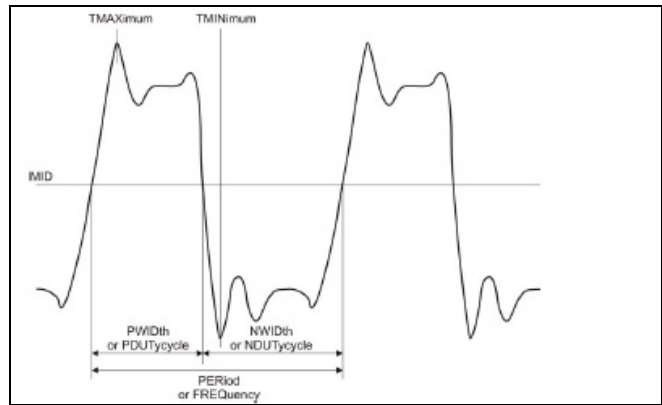


Figure 11: Some horizontal-axis measurements

EMBEDDED EPICS FOR ACCELERATOR APPLICATIONS

ZTEC Instruments became the first manufacturer to embed Experimental Physics and Industrial Control System (EPICS) in a high performance oscilloscope when it introduced its first EPICS oscilloscopes in 2008. Today, several series of ZTEC EPICS oscilloscopes are available, off-the-shelf, designed to meet the different oscilloscope/digitizer requirements of the accelerator community. This includes high speed applications and high resolution applications. High speed EPICS oscilloscopes are available with up to 1 GHz analog bandwidth, 4 GS/s, 8-bit resolution. High-resolution EPICS oscilloscopes with up to 14 bits of resolution are available as shown in Figure 12.

| <u>Series</u> | <u>Resolution</u> | <u>Max real-time sampling rate</u> | <u>Analog bandwidth</u> |
|---------------|-------------------|------------------------------------|-------------------------|
| ZT4610 | 8 bit | 4 GS/s | 1 GHz |
| ZT4210 | 8 bit | 1 GS/s | 300 MHz |
| ZT4420 | 12 bit | 1 GS/s | 300 MHz |
| ZT4430 | 13 bit | 500 MS/s | 300 MHz |
| ZT4440 | 14 bit | 800 MS/s | 300 MHz |

Figure 12: ZTEC Instruments' EPICS oscilloscopes

ZTEC's EPICS oscilloscopes have process variables (PVs) supporting all instrument functions. With roughly 900 PVs, the EPICS oscilloscopes may be controlled and monitored completely via EPICS and Channel Access (CA). Users of the EPICS oscilloscopes can modify the PV database file of each oscilloscope to better fit their application requirements. For example, the PV prefix can be modified to meet local PV naming conventions. Also, it is clearly necessary to modify the PV prefixes anytime more than one EPICS oscilloscope is on a single network so that each instrument has unique PV names. The PV database file can also be modified to include specialized forward links (FLNKs) and fanout PVs to perform special EPICS functions in a system.

By providing the free EDM and MEDM panels for the EPICS oscilloscopes, ZTEC's EPICS oscilloscopes are a complete EPICS-based solution for advanced data acquisition, data analysis and waveform monitoring.

Providing a high performance out-of-the-box solution saves users the development time and costs associated with securing their own software resources to write drivers for other off-the-shelf instruments. Figure 13 shows two EDM panels. The top panel includes basic vertical and horizontal scale control as well as real-time display of the input channel 1 waveform. The bottom panel shows waveform parameters calculated automatically on-board the instrument.

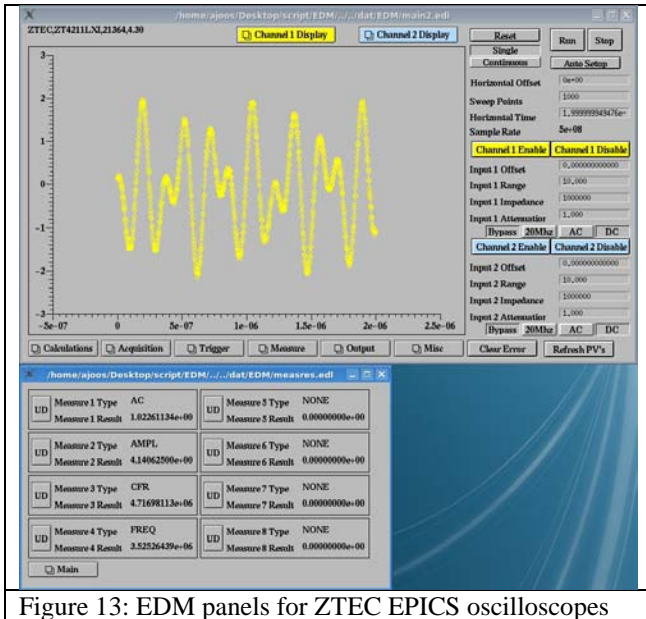


Figure 13: EDM panels for ZTEC EPICS oscilloscopes

MULTI-INSTRUMENT TIMING & SYNCHRONIZATION

Timing and synchronization of multiple instruments in a system is critically important in many accelerator applications. Depending on the measurement platform being used (e.g., PXI, cPCI, LXI) there are different ways to tightly synchronize multiple instruments over short and long distances.

PXI systems provide multiple triggers on the chassis backplane. The most accurate trigger is the PXI_STAR trigger. The PXI_STAR trigger consists of 13 propagation-matched triggers that extend from the star trigger slot (adjacent to the system slot) to the first 13 peripheral slots directly to the left of the star trigger slot. Each of the 13 trigger lines are matched to within 1 ns of propagation delay and the delay from the trigger slot to each of the peripheral slots may not exceed 5ns. In addition to tightly synchronizing multiple instruments in a single chassis, the PXI_STAR trigger may also be daisy-chained to other chassis, extending the ability to highly synchronize instruments across multiple chassis.

Accelerators around the world are now using Micro-Research Finland’s event generator (EVG) and event receiver (EVR) system to provide master timing signals via fiber optic cables across large distances at accelerators. ZTEC Instruments is currently developing a solution where ZTEC’s oscilloscopes are integrated with

Micro-Research Finland’s cPCI EVRs. The solution consists of a PXI or cPCI chassis, ZTEC EPICS IOC code loaded onto an embedded PXI or cPCI controller, multiple ZTEC PXI oscilloscopes (which are compatible with cPCI) and Micro-Research Finland’s cPCI EVRs.

The LXI instrumentation standard, with which ZTEC Instruments’ EPICS scopes comply, include hardware triggers for synchronizing multiple instruments. Using the eight LVDS LXI hardware trigger lines, instruments may be connected together in a daisy-chain or star configuration. Figure 14 shows the two configurations. Propagation delay between two instruments will depend on the length of the cable. While the LXI standard does not specify maximum delay times between instruments, in practice, trigger delays between instruments are very short, when trigger cables are kept to ~1m or less.

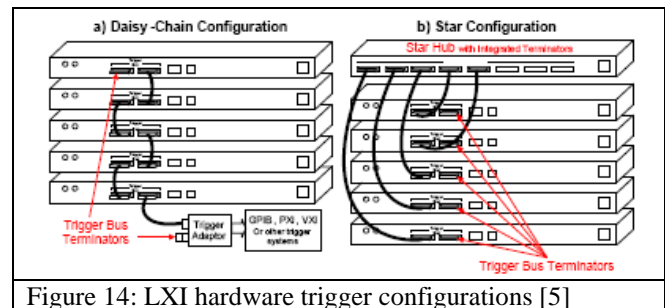


Figure 14: LXI hardware trigger configurations [5]

CONCLUSION

Today’s off-the-shelf modular oscilloscopes and digitizers are becoming more and more advanced and are able to meet many of the demanding requirements of accelerator applications. In addition to the high channel density offered by modular instrumentation, today’s most advanced modular instruments include advanced triggering and acquisition modes and on-board waveform math and analysis. Additionally, ZTEC Instruments EPICS oscilloscopes and digitizers offer an out-of-the-box solution for users who need a high performance waveform capture, analysis and monitoring. Modular instrumentation also provides a number of methods for tightly synchronizing multiple instruments and multiple chassis.

REFERENCES

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