Maximizing the Measurement Accuracy of Digitized Signals

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Abstract—Analysis of digitized waveforms requires an understanding of the limitations of the acquisition hardware, an understanding of how digital sampling interacts with the waveform shape, and an understanding of how the desired measurements are influenced by the sampling operation. By paying attention to these considerations and following some general guidelines an acquisition system can be tuned to get the most accurate results for each type of measurement. This paper provides guidelines for obtaining the best measurement results for digitized waveforms by highlighting the interactions between the waveform to be acquired, the acquisition system capturing the waveform, and the measurements desired.

I. INTRODUCTION

There are many factors present in the digitization process and the analysis of captured waveform records. This paper describes the roles played by the acquisition hardware and the analysis algorithms in providing measurements of digitized signals. Some simple guidelines are presented to assist in maximizing the performance of the hardware and analysis algorithms for particular measurements.

Measurement accuracy begins with the accuracy of the data acquisition hardware. Manufacturers specify the accuracy of the hardware for particular settings and the resolution of voltages for various ranges. Do not to confuse the accuracy and resolution of the instrument with the accuracy and resolution of a measurement performed on acquired waveforms. When performing repeated measurements using data acquisition hardware the goal is to perform accurate measurements with sufficient resolution. The terms accuracy, precision and resolution are often used to describe measurements. Sometimes these terms are used interchangeably but they have very different meanings and roles in measurements.

Resolution The smallest change or increment that a measuring instrument can detect
Precision The repeatability of a measurement of a fixed quantity across a number of measurements
Accuracy The correctness of a measurement when compared to the measurement of a known value

When most engineers consider data acquisition of analog signals the first thing that comes to mind is the Nyquist frequency. The Nyquist criteria states that an analog signal must be sampled at twice the maximum frequency of interest for accurate reconstruction of the signal from the sampled information. While this is sufficient for spectral analysis of the signal, it is not sufficient for most measurements. Some waveform measurements, i.e. rise time, may require sampling at 100 or more times the Nyquist frequency.

This paper will explore 4 topics so that users can maximize measurement accuracy.

- Data Acquisition Hardware
- Analysis Algorithms
- Sources of Measurement Error
- Measurement Guidelines

II. OVERVIEW OF DATA ACQUISITION HARDWARE

Data acquisition of analog signals requires conversion to a digital representation. This is performed by an analog to digital converter (ADC) circuit. When the signal is converted to a digital representation it is coerced into a finite number of bits [1]. The number of bits in the ADC determines the resolution for single acquisitions of the digitized signal. The resolution can be improved using averaging when there is a Gaussian distribution of noise in the analog signal. Most acquisition instrumentation supports multiple voltage ranges for acquiring analog signals. These ranges are scaled within the instrument to allow the full range of the ADC to be used.

A. Sampling and Decimation

To perform a capture of an analog signal the ADC is clocked at regular intervals. Each clock results in a digital representation of the analog signal at a point in time. This process is referred to as sampling. In most high performance acquisition instrumentation the sampling at the ADC happens at the maximum clock rate of the instrument. This simplifies the timing of the ADC and provides the most stable time domain representation of the digitized data. The typical acquisition system uses a low pass filter set at ½ the maximum sample rate to limit the bandwidth of signals entering the ADC. This assures that the Nyquist frequency will not be exceeded.

The instrumentation hardware contains memory for holding the sample data. To allow the capture of slow signals and to
make efficient use of the sample memory, the samples may be
decimated. Decimation is the process of discarding samples
that fall between adjacent locations in the sample memory, Fig
1. This reduces the effective sample rate to the interval between
adjacent locations in the sample memory. The Nyquist
frequency is always based on the interval between locations in
sample memory.

Instrumentation can either begin sampling based on a
trigger event or perform continuous sampling. In
instrumentation that synchronizes sampling with the trigger
event, it is not possible to see information prior to the trigger
event and the signal will need to be delayed so the trigger event
can be sampled. When an instrument performs continuous
sampling, the trigger event is asynchronous to the sampled
data. In continuous sampling it will be possible to see
information prior to the trigger event. Since the sampled data is
asynchronous to the trigger event, the instrument must save
information to indicate the relationship of the trigger event to
the sampled data.

In real time sampling the analog input is sampled at a
regular rate and the resulting samples are placed in sample
memory. The resulting waveform record represents an
occurrence of the analog signal in response to a single trigger
event. The maximum sample rate in real time sampling is
limited by the maximum continuous conversion rate of the
ADC and the minimum write cycle time of the sample
memory. Real time sampling can initiate based on a trigger
event or can be performed continuously.

B. Equivalent Time Sampling

Equivalent time sampling (ETS) is a method to address the
hardware limitations of the instrumentation acquisition system.
Using ETS, the analog input is sampled for multiple
occurrences of the trigger event. For each occurrence of the
trigger, the analog signal is sampled and placed in sample
memory, but unlike real time sampling the samples are not
placed in adjacent memory locations. The sample memory is
subdivided to introduce additional time slots between the real
time samples. These time slots represent delta times between
the occurrence of the trigger event and the \( n \)th occurrence of the
sample clock. There are two methods, random and sequential,
used to determine the time slot and the resulting memory
location in which to place samples for each occurrence of the
trigger event [2], Fig 2. Since multiple trigger events are used
to acquire the waveform ETS requires a repeating input signal.

Random ETS sampling is used in instruments that perform
continuous sampling. In these systems the circuitry used to
capture the timing between the asynchronous trigger event and
the first sample is used to determine the delta time. This
method is random because the additional time slots may be
filled in any order due to the asynchronous trigger event. This
method is also nondeterministic for the number of triggers that
will be required to completely fill the sample memory.

Sequential ETS sampling adds a delta time interval to the
onset of acquisition for each trigger event. This time delay is
incremented each time the trigger occurs so that the additional
time slots are filled in order. This method cannot be used with
continuous sampling since it requires synchronization of the
delta time with the trigger event.

C. Triggering and Signal Acquisition

Triggering is used to ensure a repeatable acquisition of the
analog signal. This will minimize temporal variations in the
acquired waveform record. Triggering allows the specification
of one or more events of interest in the analog signal. Data
acquisition instruments have various types of triggering to
simplify the configuration of the trigger event. Examples of
trigger types are; edge, pulse width, glitch, pattern, and state. In
many data acquisition systems the trigger circuitry has much
higher bandwidth than the acquisition channels. This high
bandwidth makes the trigger circuitry very susceptible to noise.
The trigger circuitry usually incorporates hysteresis to
minimize false triggers.

The instrumentation’s acquisition system normally supports
multiple acquisitions modes. Examples of acquisition modes
are; single, average, envelope, high resolution, and peak. Some
of these modes require retriggering the acquisition system and
performing multiple acquisitions. The hardware, or sometimes
the software driver, combines information from the multiple
acquisitions to provide a single record.
Average and high resolution acquisition modes can be used to reduce the effects of noise in the waveform record. Both modes average samples but do so in different ways. Average acquisition mode averages samples from multiple acquisitions. The user can specify the number of acquisitions to capture for the average. High resolution acquisition mode runs the ADC at the maximum sample rate and averages the samples between intervals of updating the sample memory. These samples would normally be discarded by decimation. High resolution acquisition has an advantage since it can be used with a single occurrence of a trigger event. The number of samples available for averaging is dependent on the number of decimated samples. High resolution mode works best for slow signals where the acquisition system is performing more decimation between waveform points.

Peak and envelope acquisition modes are used to determine the maximum and minimum for sample points in the waveform record. Envelope mode performs peak acquisitions across a user-defined number of retriggered acquisitions. These acquisition modes provide two captured waveform records; one with maximum values the other with minimum values.

III. ANALYSIS ALGORITHMS

Algorithms are used to process the signal samples to determine information about the signal. The algorithms may process sampled information in real time, or may operate on a captured waveform record. These algorithms may be used to determine waveform frequency, rise time, duty cycle and various other signal properties. The Interchangeable Virtual Instrument Foundation (IVI) scope standard defines 20 measurements for waveforms [3]. Most measurements are made with respect to 1 or more thresholds. The thresholds serve as voltage markers when performing the analysis algorithm. These thresholds are based on percentages of some characteristic of the waveform.

Most instrumentation measurement algorithms use percentages of the steady state levels of the acquired signal to calculate the voltage thresholds. In IVI these steady state levels are referred to as Voltage High (VH) and Voltage Low (VL). It is important that the waveform contain sufficient information for an accurate determination of these levels. If no steady state level is found for either VH or VL the Max or Min value is used. VH and VL are used to determine a Voltage Range (VR) for the waveform. After the determination of VR, 3 percentages are used to define low (TrLow), mid (TrMid) and high (TrHigh) measurement thresholds, Fig 3.

$$VR = VH - VL$$

$$TrHigh = (VR \times PercentHigh) + VL$$

$$TrMid = (VR \times PercentMid) + VL$$

$$TrLow = (VR \times PercentLow) + VL$$

A. Voltage Analysis Algorithms

Histograms are very useful as a first pass at determining steady state values for an acquired sample set. Steady state values will appear as peaks in the histogram. Some algorithms use a threshold within the histogram to determine a steady state value for VH and VL, for example if a bin in the histogram contains more than 5% of the samples. This method is reasonable if there are a sufficient number of samples within a cycle of the acquired waveform.

Other algorithms determine the steady state voltage by finding the edges in the waveform and ignoring some percentage of samples on either side of the edge. The number of samples ignored will be based on the number of samples between successive edges. If the deviation of the remaining samples between the edges is below some percentage, then either the mean or average can be used for VH or VL. Some algorithms use a similar method but only process a percentage of samples centered between the edges.

Other voltage analysis algorithms are not concerned with determining steady state values but deal with continuously changing voltages or statistical analysis. Examples of these are determining the maximum or minimum voltage, RMS voltage, standard deviation, and average voltage. The accuracy for these measurement algorithms, with the exception of RMS voltage, is mostly affected by signal noise in the waveform record. The accuracy of an RMS voltage measurement is greatly affected by the number of samples within a cycle of a signal.

B. Time Analysis Algorithms

The Fast Fourier Transform, FFT, is a technique for determining the frequency spectrum of a waveform. The component of the spectrum with the greatest magnitude is the fundamental frequency of the waveform. The FFT algorithm returns an array of frequencies that is the same size as the number of points in the waveform record. This and the sampling frequency limit the resolution of the frequency components of the FFT. Frequency components that lie between the bins in the FFT will appear across multiple bins. The resolution can be improved by using larger waveform records at a tradeoff of increased processing time in the FFT algorithm. The FFT can provide frequency results for waveform records that contain one or more cycles of a waveform.
Edge detection is a process for determining the locations in a waveform record where the signal passes through a threshold. An edge detection algorithm examines the values in the waveform record and compares the value to a threshold. This process can determine the location in the record where the edge occurs and the direction of the signal transition through the threshold. Some edge detection algorithms incorporate hysteresis to minimize the detection of false edges due to noise on the signal, Fig. 4. This is typical for single threshold edge detection algorithms. Other algorithms require that the signal pass through all 3 measurement thresholds to be seen as a valid edge. Even when all 3 thresholds are used, the edge is said to occur when the mid threshold is crossed. The accuracy of an edge detection algorithm is related to the noise on the signal, the number of points that occur around the threshold, and the algorithm used to interpolate the threshold crossing.

IV. SOURCES OF MEASUREMENT ERROR

There are many sources that can contribute to the measurement accuracy of digitized signals. The sources can be hardware related, environmental, or a side effect of the digitization process.

Measurement accuracy starts with the linearity of the data acquisition hardware. The hardware must be linear across all required frequencies and voltage ranges. The most common sources of error in data acquisition hardware are clock and trigger jitter [1]. Clock jitter manifests itself as temporal error between samples. Trigger jitter is seen as temporal error between multiple acquisitions. In both cases the error is usually not significant unless sampling near the maximum real time capability of the hardware or using ETS mode. In ETS mode the jitter will impact the accuracy of the delta time delay and may cause errors as the sample bins are filled.

Noise captured as part of the sampled signal can have an impact on measurement accuracy. There are noise sources in acquisition instrumentation, such as wideband noise in the analog front end and quantization noise from the ADC. In most cases these noise levels are below a threshold that will affect the accuracy of measurements performed on the acquired waveform. Environmental noise sources can have a significant impact on the accuracy of measurements. Examples of environmental noise are; radiated noise from adjacent instrumentation, and noise from lighting and power lines. Care must be taken to minimize these sources by using shielded interconnects and proper grounding. Most acquisition instrumentation incorporates analog or digital filtering techniques to help remove environmental noise.

The setup of the acquisition instrument plays a significant role in measurement accuracy. As was stated earlier, usually the Nyquist frequency is insufficient when sampling the analog signal. The analysis of rise time, RMS voltage, and phase relationships will require 100 or more samples per cycle. If fewer samples per cycle are used, the measurements will have errors due to the interpolation of threshold locations and the quantization of voltages.

Another source of measurement error is aliasing of frequencies that are beyond the Nyquist frequency [4]. These aliased frequencies may be due to high frequency noise that is below the cutoff of the lowpass filter in the acquisition hardware. They may also be present due to mistakes in the setup of the acquisition system based on decimation of samples. For example, if the acquisition system is configured to sample at a rate of 25us, sampling of a 50kHz signal will produce a sampled waveform that appears to have a frequency of 10kHz, Fig 5.

V. MEASUREMENT GUIDELINES

Some knowledge of the expected result is necessary to maximize the accuracy of a measurement. For example to maximize the accuracy of a max voltage measurement it is necessary to know the approximate frequency of the signal and the expected voltage. This helps to determine the voltage range, sampling rate and the number of samples to ensure that sufficient samples are acquired around the peak of the signal.

A. Voltage Measurements

The accuracy of a voltage measurement starts with selecting the correct voltage range for the acquisition of the signal. Since all values will be quantized to discrete values by the ADC it is important to maximize the scaled input signal across as much of the full range of the ADC as possible without clipping the signal. For example, if the acquisition system uses an 8 bit ADC, this allows 256 quantization levels. If a 10V range is used to measure a 1V signal, 90% of the range of the
ADC is unused. This means there are only 25 values that can be used to represent the acquired signal, Fig 6. The result is that voltage measurements, for a single acquisition, have at best a resolution of 40mV or an accuracy of approximately 4%.

Min, Max, High and Low measurements are dependent on the placement of the samples within the waveform. For nearly all waveform types, the accuracy of these measurements is based on the relationship of the sample and the waveform peak. In practice it is very difficult to align the sample of the acquisition with the peak of a waveform. This is because the frequency of the waveform may not be an integral multiple of the sample clock of the acquisition system. To increase the accuracy of voltage measurements it is best to sample the waveform for a small number of cycles, usually less than 10 and capture a large number of points per cycle. The number of points to acquire per cycle is based on the number of bits of resolution in the ADC and the shape of the waveform.

The maximum accuracy for voltage measurements is achieved by:

- Full scale voltage range equal to peak to peak voltage of waveform
- 2x ADCql samples per cycle *
- Use average acquisition mode for at least 10 acquisitions
- Capture multiple cycles in the waveform record

* ADCql is the number of possible quantization levels for the ADC.

If the width of the ADC is 10 then ~211 points should be captured per cycle. The guideline of capturing multiple cycles in the waveform record is only valid if the algorithms used to calculate voltage measurements will use sample data across multiple cycles in the waveform record. Some measurement algorithms are limited to only using the first complete cycle when performing their analysis. The guideline of capturing 2x the number of ADCql samples per cycle is usually sufficient for min, max, high and low voltage measurements of most waveforms. In most cases acquiring more samples per cycle will only increase measurement error due to noise.

The accuracy of an RMS measurement is based on the number of acquired points within a cycle of the waveform. The goal in sampling is to approach the curve of the continuously varying waveform. This goal is limited by the quantization of the waveform by the ADC. Most of the guidelines for voltage measurements also apply to RMS measurements. To help approach the curve of the waveform the high resolution acquisition mode of the hardware should be used and at least 10 cycles of the waveform should be captured in the waveform record. This will maximize the accuracy of an algorithm that calculates RMS voltage across all complete cycles in the waveform record.

The IVI specification defines overshoot as the difference between the maximum voltage and voltage high. Preshoot is defined with respect to the minimum voltage and voltage low. The accuracy of these measurements is based on an accurate determination of voltage high and voltage low. It is also critical to acquire a good value for the maximum and minimum voltage. In the case of preshoot and overshoot, the maximum and minimum values of interest are associated with the transitions, edges, of the signal. Since these measurements are typically made on square or pulse waveforms it is important to acquire sufficient samples before, during and after the transition of the signal. If the preshoot and overshoot is not cyclical, it may be difficult to get an accurate measurement due to the real time sampling limitations of the acquisition hardware. If the preshoot and overshoot are cyclical ETS mode should be used. In either case the goal in setting up the acquisition system is to capture, if possible, at least 10 samples during the transition of the signal. This should result in sufficient samples for the overshoot and/or preshoot since sampling occurs on regular intervals. The captured waveform record should contain a complete cycle or at least 500 samples on either side of the transition during the steady state level of the waveform. The transition should be centered in the waveform record. These settings will ensure an accurate determination of VH, VL, maximum and minimum.

B. Time Measurements

The accuracy of time measurements is directly related to the ability of the analysis algorithms to determine the point in time when a threshold is crossed. The measurement guidelines for time measurements are more focused on the number of samples that occur during the transition of a signal and the time between samples. It is still necessary to incorporate the guidelines for VH and VL determination since these voltages are required for proper setting of the thresholds used for time measurements. In measurements that require accurate determination of edges in a waveform, there is always a tradeoff of oversampling vs. noise.

As was covered in the algorithms section, there are two algorithmic techniques for determining frequency and period; FFTs and edge detection. Each technique has different acquisition requirements to maximize the accuracy of the resulting measurement. If the waveform is complex, i.e. is modulated or has nonharmonic frequency components, then FFT analysis must be used. For these waveform types the algorithms normally used for edge detection will fail to give accurate results.
The sample rate and number of points in the waveform record determine the frequency resolution of an FFT algorithm.

\[
\text{Resolution} = \frac{f_s}{N}
\] (5)

Where \( f_s \) is the sample frequency and \( N \) is the number of samples.

When using FFTs for frequency and period measurements a general guideline is to acquire 10,000 or more points at the maximum sample rate that is a close multiple at least 2x greater than the frequency to be measured.

Frequency and period measurements using edge detection algorithms may provide better resolution than FFTs when the acquisition hardware has finite steps for choosing record length and sample rate. When performing a frequency or period measurement with an edge detection algorithm it is important to capture sufficient samples around the signal transitions and to capture multiple cycles. These algorithms usually perform an average measurement across all complete cycles in the waveform record. The acquisition settings for performing edge based frequency and period measurements start with the guidelines for voltage measurements. If the frequency to be measured is near the maximum real time capability of the instrumentation, ETS mode should be used.

Pulse width and duty cycle measurements have similar guidelines to those for edge based frequency and period measurements. For pulse width measurements of narrow pulses, it may be necessary to acquire a record where the record length, is twice the pulse width. If this is the case the trigger should be set so the pulse is centered in the waveform record and ETS mode should be used.

The accuracy of rise and fall time measurements is directly related to the number of samples acquired during the signal transition. If the signal has a fast linear transition over the range of the measurement, then the guidelines for preshoot and overshoot measurements will result in an accurate rise or fall time measurement. The only additional requirement is to center the proper edge for the measurement. If the signal has a slow transition or is nonlinear, then the number of samples during the transition must be increased and it may be necessary to increase the sample frequency. There are no hard and fast rules for this. The goal is to capture as many points as possible during the nonlinear portion of the waveform to minimize the error in the algorithms that perform threshold interpolation.

VI. SUMMARY

There are many factors present in the digitization process and the analysis of waveform records. Many of these factors limit the accuracy of measurements on digitized waveform records. There is no single solution to the problem of selecting acquisition settings. The optimum acquisition settings are based on the hardware, the type of analog signal, and the desired measurement. By following a few simple guidelines it is possible to tune the acquisition system and maximize the accuracy of measurements on digitized signals.

REFERENCES