Activity A1.2.7

Deliverable D1: Report on the selection of three digitisers and their parameters that meet the necessary requirements for digital traceability chain. This will include the performance related to the requirements of using AC quantum voltage standards.

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1. AC Voltage, Basic Requirements

AC Voltage in LF field is defined to be in the range of 1 mV – 1000 V at a single frequency in the band of 10 Hz – 1 MHz. Best specification of the state of the art electronic instruments (thermal converters not considered) widely used for AC voltage measurements are 24 μV/V (Fluke 5790A), and 43 μV/V (Fluke 5720A). In order to provide traceability for this range using a digitizer, it is necessary to have basic specifications as:

Range*: 100 mV – 1 Vrms @ DC – 1 MHz
Uncertainty: ≤ 25 μV/V @ 1 V, 1 kHz

*For higher voltages (up to 1000 V), digitizer will be combined with suitable dividers developed in the scope of QuADC and other projects. For measurements at low voltages (1-100 mV) digitizer alone or combined with special amplifiers can be used.

2. Parameters Used in the Selection of Digitizers for Voltage Measurements

Basic parameters required to specify digitizers used for voltage measurements are listed below.

Input Range

Input range, or vertical range, is the peak-to-peak voltage span that a digitizer can measure at the input connector. The simplest interface is to have a single input with a fixed input range matching the ADC of the digitizer. Single fixed input range shifts design work from the digitizer manufacturer (general purpose design) to the end user who needs to care for correct amplification/attenuation by himself (metrology purpose design).

Input Impedance

Input Impedance is defined as the effective resistance and capacitance seen at the input to the digitizer. In general, the higher the input impedance of the digitizer, the less the digitizer will disturb (load) the signal (device) being measured.

Dynamic Range/Resolution

The dynamic range is defined as the ratio between the largest and smallest values that a digitizer can reliably measure. Resolution determines the dynamic range of the digitizer. However, all real digitizers introduce some noise and distortion reducing the ideal number of quantized levels. Effective number of bits (ENOB) is a quality measure of the dynamic performance of a digitizer. ENOB specifies the resolution of an ideal ADC that would have the same resolution as the digitizer being specified.

Frequency Response/Bandwidth

Bandwidth describes the highest frequency sine wave that can be digitized with attenuation to 70.7 percent of its original amplitude, also known as the -3 dB point. For sine waves, a bandwidth of greater four to five times the maximum frequency is generally adequate.

Sample Rate

Sample rate is the rate at which the analog-to-digital converter (ADC) in the digitizer is clocked to digitize the incoming signal. According to the Nyquist theorem, to avoid aliasing, the sample rate of a digitizer needs to be at least twice as fast as the highest frequency component in the signal being measured. To accurately digitize the incoming signal, it is recommended the digitizer's real-time sample rate should be at least three to four times the digitizer's bandwidth.

Accuracy / Uncertainty

Accuracy is the total error with which the digitizer can convert a known voltage, including the effects of quantization error, gain error, offset error, and nonlinearities. Accuracy of digitizers is often specified in time domain and includes static parameters as Gain, Offset, INL and DNL.

Synchronization/Trigger Capabilities

Triggers synchronize data acquisition with external events. Effective use of a digitizer requires great flexibility in device triggering. If digitizer contains more than one channel or multiple single-channel digitizers are used, they should be able to share common triggers and a common clock.

Internal Memory Size

Memory size is important in determining the amount of time a digitizer can sample an analog waveform without interruption. Memory, sample rate and acquisition time of a digitizer are related as:
Acquisition Memory = Time Span x Required Sample Rate.
Other way to increase uninterrupted acquisition is to use digitizers with fast bus technology like PCI Express and PXI Express which are able to sustain multi-GS/s rates.

Larger memory lets sample at a high rate for a longer period of time to capture more points. More points in signal processing enable averaging which results in lower noise and improved resolution.

Software Compatibility/Drivers

Digitizers should include driver software that supports user operating system and programming language, especially LabView, LabWindows, Matlab and other common software used in metrology applications.

Common Mode Rejection Ability (CMRR)

Common-Mode Rejection Ratio (CMRR) is a measure of the capability of an instrument to reject a signal that is common to both input leads. CMRR in dB is defined by CMMR = 20log (Differential Gain / Common Mode Gain). It decreases as frequency of the signal increases. Higher CMRRs are preferable.

In table below, optimum parameters for a digitizer to be used for AC voltage measurements (as given above) are summarized.

Parameter	Value
Input Range	1 Vrms
Input Impedance	≥1 MΩ
Resolution	≥20 Bits
Bandwidth	5 MHz
Sample Rate	15 MS/s
Accuracy (Uncertainty)	0,0025 %
Trigger/Clock	Ext Trigger, Ext Clock
Internal Memory	≥1 MB
CMRR	≥100 dB
Software	LabView, LabWindows …

3. List of Available Digitizers

Manufacturer	Model	Resolution	Sample rate	Platform
Keysight (Agilent/HP)	3458A	28-Bit (DCV)	150 kS/s (DCV)	Standalone
National Instruments	5922	24-Bit (Max)	15 MS/s (Max)	PXI
Applicos	WFD22	22-Bit	1 MS/s	ATX
Zurich Instruments	MF-DIG	16-24-Bit	60 MS/s	Standalone*
Adlink	PXI-9527	24-Bit	432 kS/s	PXI
Keithley	DMM7510	18-Bit	1 MS/s	Standalone
Spectrum GmbH	MX.4963	16-Bit	50 MS/s	PXI
Astronix Test Systems	PXIe-1803	16-Bit	180 Ms/s	PXIe
VXInstruments	PXD€721x	16-Bit	100 Ms/s	PXIe

*Option to ZI Lock-in Amplifier

4. List of the Test Parameters of Digitizers for Voltage

Parameter	Test	Test System
Input Range	• Static Offset • Static Gain • Static Gain Drift (Temperature) • Integral non-linearity (INL) • Differential non-linearity (DNL) • Static Gain Stability	PJVS (Static) JAWS (Histogram)
Input Impedance	• Input Impedance	Impedance Analyzer
Dynamic Range	• Signal-to-noise ratio with distortion/ Effective number of bits SINAD/ENOB • Total Harmonic Distortion (THD) • Spurious Free Dynamic Range (SFDR)	JAWS
Frequency Response	• Bandwidth • Dynamic gain, Flatness • Dynamic gain, Level dependence • Dynamic gain, Stability • CMRR • Crosstalk (for 2-ch digitizers):	JAWS PJVS (≤100 kHz)
Synchronization/Trigger Capabilities	• Phase (for 2-ch digitizers)	JAWS

5. State of the Art Quantum Voltage Standards

Parameter	Programmable Josephson Voltage Standard (PJVS)	Josephson Arbitrary Waveform Synthesizer (JAWS)
Voltage Range	±10 V, 7 Vrms	1 Vrms (PTB) 3 Vrms (NIST)
Frequency	DC – 100 kHz*	DC - 1 MHz
Accuracy	DC: ±10 V, $\Delta V/V_{10V} = 1\times10^{-10}$ AC: $\Delta V/V = 5\times10^{-7}$ @ V ≤ 7.1 Vrms ≤ 1 kHz, 1 min meas. time** Limit of calibrator, otherwise 1×10^{-8}	Best; 12 nV/V @ 250 Hz
SFDR	-	120 dBc
Synchronization	Yes	Yes
Advantages	• Relatively high output • Suitable for differential sampling	• Arbitrary signals • Very high signal purity • Suitable as Synthesizer
Drawbacks	• ACrms not calculable	

* differential sampling up to 10 kHz and sub-sampling up to 100 kHz

** Fluke 5720A ACV calibration

6. Test Methods for Digitizers Parameters

Parameter	Test	Method
Input Range	Static Offset	[1], 6.1, pg 83 [2], 7.4.1 pg 44
	Static Gain	[1], 6.1, pg 83 [2], 7.4.1 pg 44
	Static Gain Drift (Temperature)	Perform static gain test at different environmental temperatures
	Integral non-linearity (INL)	[1], 7.1.2, pg 85 [2], 8.2.1 pg 46
	Differential non-linearity (DNL)	[1], 7.3.2, pg 86 [2], 8.4.1 pg 47
	Static Gain Stability	Repeat static gain test during a specific period*
Impedance	Input Impedance	[1], Chapter 5.1, pg 81 [2], Chapter 7.2.1 pg 44
Dynamic Range	SINAD/ENOB	[1], Chapter 8.1, pg 105 [2], Chapter 9.2, pg 65
	Total Harmonic Distortion (THD)	[1], Chapter 7.7, pg 91 [2], Chapter 8.8, pg 51
	Spurious Free Dynamic Range (SFDR)	[1], Chapter 8.8, pg 112 [2], Chapter 8.8.2, pg 56
Frequency Response	Bandwidth	[1], Chapter 10.1, pg 127 [2], Chapter 11.1, pg 76
	Dynamic gain, Flatness	[1], Chapter 10.2, pg 127 [2], Chapter 11.2, pg 78
	Dynamic gain, Level dependence	[1], Chapter 10.3, pg 128 [2], Chapter 11.3, pg 78
	Dynamic gain, Stability	Repeat dynamic gain test during a specific period*
	CMRR	[1], Chapter 15.2, pg 140 [2], Chapter 14.4.2, pg 96
	Crosstalk (for 2-ch digitizers):	[1], Chapter 11.1, pg 133
Synchronization/Trigger Capabilities		

References:

[1] IEEE Standard for Digitizing Waveform Recorders
[2] IEEE Standard for Terminology and Test Methods for Analog-to-Digital Converters

7. Digitizer Evaluation

Model	Input Range	Input Impedance	Resolution	Bandwidth	Sample Rate	Trigger/Clock	Internal Memory	Software	Other
Adlink PXI-9527	Selectable: ±(0.3–40) V	50Ω/1MΩ	24 Bit	130 kHz	432 kS/s (24Bit)	Ext Trigger PXI Clock	2048 S	LabView	PXI, 2 ch
Applicos WFD22	Selectable: ±(0.4–10) V	1MΩ	22 Bit	1 MHz	1 MS/s	Ext Trigger Ext Clock	32 MS	LabView	ATX
Applicos WFD20	Selectable: ±(0.5–8) V	1MΩ	20 Bit	2 MHz	2 MS/s	Ext Trigger Ext Clock	4 MS	LabView	ATX
Applicos WFD16	Selectable: ±(0.5–8) V	50Ω/1MΩ	16 Bit	100 MHz	180 MS/s	Ext Trigger Ext Clock	8 MS	LabView	ATX
Astronix PXIe-1803	Selectable: ±(0.5–30) V	50Ω/1MΩ	16 Bit	175 MHz	180 MS/s	Ext Trigger Ext Clock	64 MS	LabView	PXIe, 2 ch
Keithley DMM7510	Selectable: ±(0.1–1000) V	10GΩ/10MΩ	18 Bit	600 kHz	1 MS/s	Ext Trigger Ext Clock	8 MS	LabView	Standalone
Keysigth 3458A	Selectable: ±(0.1–1000) V	10GΩ	28 Bit	150 kHz	1 MS/s	Ext Trigger Ext Clock(m)	48 kS	LabView	Standalone
Nat.Instruments 5922	Selectable: ±(2, 10) V	50Ω/1MΩ	24 Bit	6 MHz	15 MS/s	Ext Trigger Ext Clock	64 MS/ch	LabView	PXI, 2 ch
Nat.Instruments 9225	300 V	1MΩ	24 Bit	25 kHz	50 kS/s	--	--	LabView	NI CompactRio
Spectrum MX.4963	Selectable: ±(0.2 – 10) V	50Ω/1MΩ	16 Bit	30 MHz	50 MS/s	Ext Trigger Ext Clock	64 MS/ch	LabView	Standalone, 4 ch
Tasler LTT24	Selectable: ±(0.3 – 50) V	50Ω/1MΩ	24 Bit	1.7 MHz	4 MS/s	Ext Trigger Ext Clock	32 MS/ch	LabView	Standalone, 4 ch
VXInstruments PXD€721x	Selectable: ±(0.25–60) V	50Ω/1MΩ	16 Bit	100 MHz	100 MS/s	Ext Trigger PXI Clock	2 MS	LabView	PXIe, 2 ch
Zurich Instr. MF-DIG	Selectable: ±(0.001–3) V	50Ω/1MΩ	24 Bit	7 MHz	60 MS/s	Ext Trigger Ext Clock	2.5 MS/ch	LabView	Standalone 2 ch

Useful notes for selection of the digitizers:

Resolution – Sample rate

Two most important specifications of the digitizer are resolution and sample rate. While resolution determines the precision of the amplitude measurements, sample rate determines the bandwidth. These two parameters are not independent, increasing the resolution causes decreasing the bandwidth. In the case both specifications cannot be satisfied, depending on the application tradeoffs can be made. Digitizers for measurement of low distorted AC voltage can be adjusted to sample at a rate only slightly higher than twice the frequency of the signal. On the other hand, for measurement of the distorted signals (harmonics) sample rate should be set to twice of the largest frequency component of the interest.

Accuracy – Resolution

Resolution and Accuracy are terms that are often interchanged when the performance of a digitizer is discussed. Resolution does not imply but only indicates what the theoretical accuracy can be.
The accuracy of the digitizer determines how close the actual digital output is to the theoretically expected digital output for a given analog input. In other words, how close a digitizer comes to meeting its theoretical resolution. If specified by manufacturer accuracy of a digitizer is often defined in time domain, where specifications are static (DC). Despite these figures still can be used at low frequencies (up to several kilohertz, depending on the bandwidth of the digitizer), accuracy at higher frequencies should be related to dynamic parameters.

Resolution – Dynamic range

High-resolution digitizer is preferred when small signals are measured. As an example; with a vertical range of 1 V, the 8 bit digitizer cannot ideally resolve voltage differences smaller than 3.92 mV; while a 16 bit digitizer, with 65656 discrete levels, can ideally resolve voltage differences as small as 15 μV.
Digitizers intended to be used in the scope of this project should have minimum 10:1 dynamic ratio. If such a digitizer with full scale of 1 V is used to measure Fluke 5720A calibrator whose AC voltage specification at 100 mV @ 1 kHz is 135 μV/V, targeted error is $135 \times 10^{-6} \times 100$ mV = 13.5 μV. In that case digitizer needs to resolve 13.5 μV out of 1 V, which would require 17 bit ENOB. This probably will not be enough if digitizer does not have also the good noise floor.

Measurement Conditions – Dynamic range

It is very important to match the amplitude of the test signal to digitizer range. For example, if 1.4 V is applied to a 3 V & 16 Bit digitizer, loss in ENOB will be 1 bit. For the best accuracy, amplitude of the reference system should be equal or higher than digitizer range. The similar situation is when digitizer is going to be used with auxiliary equipment like shunts, dividers or external amplifiers; for best accuracy the range in which the auxiliary equipment will be used should match the digitizer range.

ADC Architecture

Digitizers based on integrating analog-to-digital converters (IADC) provide high resolution with good noise rejection. The main disadvantage is they are slow, and can be used at low frequencies (up to hundreds Hz), making them ideal for LF power applications. On the other hand Delta-Sigma (ΔΣ) type ADCs provides high resolution with relatively wide bandwidth. It is possible to combine different types of digitizers to cover frequency band of interest.

Isolation and CMR

Common mode rejection of the digitizer gets important when used to measure outputs of shunts or voltage dividers. When high CMR is required digitizer with differential inputs or platform powered with battery is recommended.

8. Recommendation of the Digitizers for Evaluation

According to the parameters of the digitizers specified by their manufacturers, we can classify them into 3 groups:

1. National Instruments 5922, Tasler LTT24, Applicos WFD20/22, Zurich Inst. MF-DIG. This group has the best resolution – bandwidth performances and seems to be most suitable for evaluation during the project.

2. Astronix PXIe-1803, Applicos WFD16, VXInstruments PXD€721x, Spectrum MX.4963 This group has fair resolution and large bandwidth. Those digitizers whose bandwidth can be traded for resolution may be interesting for evaluation.

3. Keysigth 3458A, Keithley 7510. These digitizers are ideal for low frequency applications. Although extensively studied for almost three decades (3458A) it is desirable to have it included for evaluation during the project.