Activity A1.3.3

Deliverable D2: Report on the best quantum-based system verification approach for testing digitisers to provide digital traceability chain for AC voltage and current

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1. Objectives

This report identifies the best available references/standards and the most appropriate approach for testing the digitisers to provide digital traceability chain for AC voltage and current. It is based on the 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*.) and other activities in *Task 1.3: Plan for verification of the digitisers*, and will provide input to activities A4.1.1, A4.1.2 and A4.2.2. in *WP4: Validation of the new traceability chain*.

2. List of the Test Parameters of Digitizers for Voltage Measurements

Most common specifications used to define digitisers for voltage measurements are given here as reminder, and are as follows:

- Input Range
- Input Impedance
- Dynamic Range/Resolution
- Frequency Response/Bandwidth
- Sample Rate
- Accuracy / Uncertainty
- Synchronization/Trigger Capabilities
- Internal Memory Size
- Software Compatibility/Drivers
- Common Mode Rejection Ability (CMRR)

Resolution, sample rate, memory size and software compatibility are rather design parameters used by manufacturer to specify product. On the other hand, input range, input impedance, dynamic range and frequency response are critical when digitisers are used to measure ac voltage. These specifications are expressed by various parameters which should be tested in order to determine how digitiser is suitable for ac measurements. In the table below, specifications and parameters related to are listed. Parameters describing step response of the digitisers are omitted.

Specification	Test Parameter
Input Range	• Static Offset • Static Gain • Static Gain Drift (Temperature) • Integral non-linearity (INL) • Differential non-linearity (DNL) • Static Gain Stability
Input Impedance	• Input Impedance

Specification	Test Parameter
Dynamic Range	• Signal-to-noise ratio with distortion/ Effective number of bits SINAD/ENOB • Total Harmonic Distortion (THD) • Spurious Free Dynamic Range (SFDR)
Frequency Response	• Bandwidth • Dynamic gain, Flatness • Dynamic gain, Level dependence • Dynamic gain, Stability • CMRR • Crosstalk (for 2-ch digitisers):
Synchronization/Trigger Capabilities	• Phase (for 2-ch digitisers)

3. Test Methods for Digitiser Parameters

Reference [1] extensively describes methods for the testing of the digitiser parameters. Similar methodology is presented in [2] aiming testing of ADCs which are critical part of each digitiser. In the table below, parameters list, related tests and their citing in [1] and [2] are presented.

Specification	Parameter	Test Method
Input Range	Static Offset	[1], 6.1, p. 83 [2], 7.4.1, p. 44
	Static Gain	[1], 6.1, p. 83 [2], 7.4.1, p. 44
	Static Gain Drift (Temperature)	Perform static gain test at different environmental temperatures
	Integral non-linearity (INL)	[1], 7.1.2, p. 85 [2], 8.2.1, p. 46
	Differential non-linearity (DNL)	[1], 7.3.2, p. 86 [2], 8.4.1, p. 47
	Static Gain Stability	Repeat static gain test during a specific period
Impedance	Input Impedance	[1], Chapter 5.1, p. 81 [2], Chapter 7.2.1, p. 44
Dynamic Range	SINAD/ENOB	[1], Chapter 8.1, p. 105 [2], Chapter 9.2, p. 65
	Total Harmonic Distortion (THD)	[1], Chapter 7.7, p. 91 [2], Chapter 8.8, p. 51
	Spurious Free Dynamic Range (SFDR)	[1], Chapter 8.8, p. 112 [2], Chapter 8.8.2, p. 56

Specification	Parameter	Test Method
Frequency Response	Bandwidth	[1], Chapter 10.1, p. 127 [2], Chapter 11.1, p. 76
	Dynamic gain, Flatness	[1], Chapter 10.2, p. 127 [2], Chapter 11.2, p. 78
	Dynamic gain, Level dependence	[1], Chapter 10.3, p. 128 [2], Chapter 11.3, p. 78
	Dynamic gain, Stability	Repeat dynamic gain test during a specific period
	CMRR	[1], Chapter 15.2, p. 140 [2], Chapter 14.4.2, p. 96
	Crosstalk (for 2-ch digitisers):	[1], Chapter 11.1, p. 133
Synchronization/Trigger Capabilities	Phase	

Test methodology referred in [1] and [2] is based on the classical electronic instrumentation. However developments and increased use of high resolution modern digitisers in metrology requires even more accurate testing. For example, linearity of a 28-bit digitiser is specified below 0.1 ppm (ppm – parts per million), and no any electronic instruments today can provide such accuracy.

On the other hand, the development of quantum standards has made it possible to overcome such problems and increase their use in the testing of modern digital technology.

4. Using Quantum Voltage Standards in Digitiser Testing

Quantum voltage standards are intrinsic standards, based on Josephson Effect, and generate voltages that are defined only by fundamental constants (namely *e* and *h*). They have been used and constantly improved over the last 40 years, and greatly increased the accuracy of the electrical measurements. Early Josephson standards, also named conventional, are suitable only for dc voltage measurements due to hysteretic behaviour of their junctions. However, recent improvements of the arrays led to the new types of quantum standards which can be used for ac measurements, as well: Programmable Josephson Voltage Standard (PJVS) and pulse driven, also known as Josephson Arbitrary Waveform Synthesizer (JAWS).

Programmable Josephson Voltage Standard

PJVS are based on using binary-divided arrays of damped Josephson junctions which can produce stable dc voltages, or step-wise ac waveforms. As the steps of the generated waveform are intrinsic, quantum voltages, PJVS is an ideal digital-to-analogue converter (DAC) [3]. Accuracy of rms value and frequency range of PJVS is limited due to the transition time between steps, as well due to the transients. Recent developed PJVSs can produce dc voltages up to 10 V amplitude, and 7 V rms ac step-wise ac waveforms used up to several kilohertz by differential sampling [4], and possibly up to 100 kHz by sub-sampling [5].

PJVS is very suitable for dc static tests of the digitisers like gain, INL, DNL, and for dynamic tests using fast settling features of PJVS [6-10].

Josephson Arbitrary Waveform Synthesizer (JAWS)

In JAWS, RF excitation of the array is performed by periodic streams of pulses instead of sine-waves [10]. The time integral of each junction's voltage pulse is quantized in units of *h*/2*e*. So, the arrays behave as perfect pulse quantisers and can generate arbitrary voltage waveforms that are accurate and predictable. Recent developed JAWS can produce rms voltages up to 3 V for the frequencies up to 1 MHz.

As JAWS can produce complex signals it is very suitable for dynamic tests and frequency response of the digitisers up to 1 MHz [15]. In addition JAWS can be used for testing static parameters of the digitisers with statistical method (histogram). Furthermore, it still can be used as dc reference for calibration of the static parameters of the digitisers.

State of the art of PJVS and JAWS are summarized in table below:

Parameter	Programmable Josephson Voltage Standard (PJVS) [10, 11]	Josephson Arbitrary Waveform Synthesizer (JAWS) [13, 14]
Voltage Range	±10 V, 7 V rms	1 V rms (PTB) 3 V rms (NIST)
Frequency	DC to 100 kHz*	dc to 1 MHz
Accuracy	DC: ±10 V, $\Delta V/V_{10V} = 1\times10^{-10}$ AC: $\Delta V/V = 5\times10^{-7}$ @ V ≤ 7.1 V rms, ≤ 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

* differential sampling up to 10 kHz and sub-sampling up to 100 kHz
** Fluke 5720A ACV calibration

Both standards can be synchronized with digitisers to have common clock and trigger. Input impedance of the tested digitisers should be high enough in order to not disturb output of the quantum standards. Most of the digitisers recommended for evaluation have 1 MΩ of the input impedance so they are suitable for direct connection to both quantum standards. For digitisers with lower input impedances some kind of buffer or impedance matching circuit may be necessary.

Table bellow provides a cross-section of the parameters of the digitiser and the quantum voltage standards suitable for their testing. Rows marked with yellow colour show parameters which need to be measured due to the calculation of uncertainty. Rows marked with green colour show parameters which need to be measured for the determination of corrections that will be applied on the measured values.

Parameter	PJVS	JAWS
Static Offset	√	√ (2)
Static Gain	√	√ (2)
Static Gain Drift (Temperature)	√	√ (2)
Integral non-linearity (INL)	√	√ (2)
Differential non-linearity (DNL)	√	√ (2)
Static Gain Stability	√	√ (2)

Parameter	PJVS	JAWS
SINAD/ENOB	√ (1)	√
Total Harmonic Distortion (THD)	√ (1)	√
Spurious Free Dynamic Range (SFDR)	√ (1)	√
Bandwidth	√ (1)	√
Dynamic gain, Flatness	√ (1)	√
Dynamic gain, Level dependence	√ (1)	√
Dynamic gain, Stability	√ (1)	√
CMRR	√ (1)	√
Crosstalk (for 2-ch digitisers)	√ (1)	√

(1) up to 100 kHz using sub-sampling technique
(2) either in dc mode or using statistical method

5. Conclusion

In section 4 the last table gives the information about the **parameters of the digitiser and the quantum voltage standards suitable for their testing**. Important rows are marked with **yellow** colour, meaning that these parameters need to be measured due to the calculation of uncertainty, while rows marked with **green** colour pointed parameters which need to be measured for the determination of corrections that will be applied on the measured values. Both these groups of parameters are important and have priority in the plans for verification. However, it does not mean that other parameters cannot be measured, as appropriate, or are of interest for testing, comparison of results, or gathering experience.

Based also on the (i) recommendation given in section 8 of the deliverable D1, (ii) existing equipment available to the partners nowadays, and (iii) that new digitiser Fluke 8588A came just recently on the market and possibly would be important for NMIs, DIs and calibration laboratories, the conclusion of the partners is that the following 3 digitisers would be of the highest interest to be validate in WP4. These are:

1. National Instruments 5922
2. Keysight (Agilent, HP) 3458A
3. Fluke 8588A

However, it does not mean that other digitisers cannot be tested and validated, as appropriate, or are of interest for testing, comparison of results, or gathering experience.

6. References

[1] IEEE Standard for Digitizing Waveform Recorders

[2] IEEE Standard for Terminology and Test Methods for Analog-to-Digital Converters

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