# FINAL PUBLISHABLE REPORT

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| RMG: - | | |

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# 1 Overview

Most instruments used in real industrial settings operate under dynamic conditions, where signals of complex waveforms vary with time and therefore require calibration in such dynamic conditions (dynamic measurements). This gave rise to the need for a new traceability scale for current and voltage waveforms based on measurements using digital instruments (digital measurements), namely digitisers. To achieve the required accuracy, this new digital traceability chain was implemented and verified using a quantum standard for electrical measurements, achieving the objectives of the project. This will enable dynamic measurement of current and voltage waveforms for many different applications.

# 2 Need

Alternating Current (AC) voltage and current measurements have been related to corresponding Direct Current (DC) values using transfer techniques mainly based on thermal converters for more than 60 years at NMIs and at high-level calibration laboratories. Thermal converters (conductors heated by an electric current) are able to provide accuracy at the 1 μV/V level, and for some specific voltages and frequencies even better accuracy at the 0.1 μV/V level but are limited to providing Root Mean Square (RMS) values of sinusoidal waveforms with low harmonic content. Substitution methods already developed in comparison experiments between AC Quantum Voltage Standards (ACQVS) and digital electrical instruments using thermal converters proved to be unsuitable in the presence of dynamic signals because they can only provide RMS values.

It was therefore necessary to establish a traceability chain, with adequate measurement methods, equipment, and algorithms, from SI quantum units to digital dynamic electrical measurement equipment in a clear way for uptake by NMIs, calibration and testing laboratories, as well as industry and research organisations. This traceability chain was validated and was demonstrated to enable the transformation from analogue to digital AC voltage and current measurements, not only for pure sine wave signals, but also for more complex (or dynamic) signals. The basis for this approach was established through a coordinated effort amongst European NMIs.

# 3 Objectives

This project focused on the development of metrological capacity for the transition from analogue to digital measurements for AC voltage and current to enable operation under dynamic conditions.

The specific objectives are:

1. To define the digitiser requirements and metrological grade electrical parameters for digital electrical measurements for AC voltage and current, including identifying the traceability and performance requirements related to the use of AC quantum voltage standards.
2. To develop measurement systems employing digital techniques for use at NMIs and calibration laboratories to achieve a practical realisation of step-up and step-down procedures (scaling) for electrical current and voltage, beginning with a Josephson standard as the fundamental reference.
3. To develop publicly available methods, algorithms and software for the traceability chain of dynamic measurements, including data processing and uncertainty estimation, for use by NMIs and calibration laboratories. The methods should facilitate the quick integration of future improvements.
4. To validate the complete system of digital measurement of AC voltage and current, including passive coaxial current and voltage devices, algorithms, and software. To use the validated system as the basis to define the protocol for a future intercomparison of digital AC voltage and current standards between European NMIs.
5. For each participant, to develop an individual strategy for the long-term operation of the capacity developed, including regulatory support, research collaborations, quality schemes and accreditation. This should include the development of a strategy for offering calibration services from the established facilities to their own country and neighbouring countries. The individual strategies should be discussed within the consortium and with other EURAMET NMIs/DIs, to ensure that a coordinated and optimised approach to the development of traceability in this field is developed for Europe as a whole.

# 4 Results

The project was structured over five objectives. In the following the project results are presented in relation to the planned objectives.

## 4.1 Objective 1: Definition of the digitiser requirements and metrological grade electrical parameters for digital electrical measurements for AC voltage and current

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)*

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

PJVS is very suitable for DC static tests of digitisers' gain, integral non-linearity (INL), dynamic non-linearity (DNL), and for dynamic tests using the fast-settling features of PJVS.

*Josephson Arbitrary Waveform Synthesizer (JAWS)*

In JAWS, RF excitation of the array is performed by periodic streams of pulses instead of sinewaves. 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. Recently developed JAWS can produce rms voltages up to 3 V for frequencies up to 1 MHz.

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

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

| Parameter | Programmable Josephson Voltage Standard (PJVS) | Josephson Arbitrary Waveform Synthesizer (JAWS) |
|---|---|---|
| Voltage Range | ±10 V, 7 V rms | 1 V rms (PTB)<br>3 V rms (NIST) |
| Frequency | DC to 100 kHz* | DC to 1 MHz |
| Accuracy | DC: ±10 V, $\Delta V/V_{10V} = 1\times10^{-10}$<br>AC: $\Delta V/V = 5\times10^{-7}$ @ V ≤ 7.1 V rms, ≤ 1 kHz, 1 min meas. time**<br>Limit of calibrator, otherwise $1\times10^{-8}$ | 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 a common clock and trigger. The 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.

The table below 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) |
| 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

Based also on the existing equipment available to the project partners, the conclusion is that the following 3 digitisers would be of the highest interest to be validated. 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 not of interest for testing, comparison of results, or gathering experience.

The project succeeded in meeting the objective by defining digitiser requirements and metrological grade parameters for digital measurements of AC voltage and current. In the above table all parameters of the digitiser and the use of quantum voltage standards, suitable for their testing, are given.

## 4.2 Objective 2: Development of measurement systems employing digital techniques for use at NMIs and calibration laboratories

The basic idea in planning this objective was to build up new knowledge for a quantum-based digital scaling starting from the current state of development among the participating NMIs. To that aim, the preparation of a document summarizing the state-of-the-art of scaling techniques of all partners was set as the first step. The document "Overview of scaling methods in use" prepared by INRIM in collaboration with all partners provides an exhaustive overview of techniques in use in participants' labs, as well as systematic knowledge of the devices and techniques used by NMIs and DIs for scaling both voltage and current and, to some extent, their motivation in the needs of other organizations (e.g., industry). This survey of the most used techniques for the extension of measurement ranges contributed to a classification of the range requirements in the main applications. The uncertainties of the different solutions were also analysed. The two main sections are voltage and current, and since they necessarily involve different measurement methods; upscaling and downscaling were then considered for both, to highlight specific issues with measurements at small and high values of the range. It wasfurther noticed that up/downscaling may be somewhat arguable with currents, due to the "shift" of the typical reference point down to a very low value within the range (10 mA, typically), leaving little room for the downscaling interval, but keep the same structure as with voltage, for uniformity and clarity.

Overall, nine NMIs and DIs, including the main institutes in Europe, contributed to this analysis: FER, INRIM, CEM, Metrosert, PTB, TUBITAK, IPQ, NPL. The report provided an inclusive synopsis of the scaling methodologies in use. In particular, quite noticeably, in all institutes involved only techniques based on classical thermal standards are used on a regular basis for AC measurements of voltage and currents and over all ranges, with just a few laboratories having started research on digitally based methods. Exceptions exist when lower accuracy calibrations are considered. The methods developed for scaling are built around the thermal converter, to extend its operating range. To that aim, solutions used by different institutes vary. Exploiting the capability of a commercial muti-range commercial semiconductor thermal converter (Fluke 792A) is a viable option, provided a suitable calibration service is available, as does GUM with PTB. Otherwise, the exploitation of converters with increasing but partly overlapping ranges, makes it possible to implement a voltage step-up procedure, as done for instance by PTB, CEM, IPQ, NPL and INRIM.

However, resistive techniques are the most widely used for voltage scaling, with resistive dividers in step-down setups as done, e.g., by FER, Metrosert, CEM and NPL; with range extenders in step-up procedures, as in the case of: PTB, TUBITAK, GUM, IPQ, INRIM. Solutions based on active circuits and dedicated amplifiers were adopted in a few cases. With regard to ranges, the lowest value is typically down to a millivolt, but it can be as high as hundreds of millivolts for some institutes. Greater uniformity is observed in high values, always upper bounded to one kilovolt. Uncertainties vary significantly with value and signal frequency: best results reported, close to 1 kHz and 1 V, are some µV/V (CEM, NPL) and below 1 µV/V (INRIM); at the lower and upper boundaries and frequencies above 100 kHz, figures in excess of 100 µV/V are typical (TUBITAK, PTB). For current scaling, thermal converters are generally used in voltage mode, with two possibilities to implement current-voltage conversion: shunts used, for instance, by FER, PTB, Metrosert; or transconductance amplifiers, adopted, e.g., by INRIM and CEM. In current calibrations the lowest frequency value of 10 Hz is the same in all laboratories whereas the highest frequency is generally 10 kHz (FER, GUM, Metrosert), but can be as high as 100 kHz in some cases (NPL, IPQ). Measurement range extends from about 10 µA up to 20 A typically, with the exception of CEM that reports 100 A and PTB that goes up to 160 A. Uncertainties vary from about 20 µA/A, close to 10 mA and with frequencies around 1 kHz, up to several hundred µA/A at the upper range values.

Though limited in application and mainly limited to research, digital techniques already tested by some participants (mainly PTB and Metrosert) existed and were considered as starting point for the objective. The document (available on the project webpage) "Guidelines on the development of scaling systems employing digital techniques for use at NMIs and calibration laboratories for the practical realisation of step-up and step-down procedures and scaling of electrical current and voltage" summarized the outcomes of this analysis, arguing that the adoption of intrinsically digital techniques for scaling the electrical standards of voltage and current has proven very successful for DC signals with Josephson standards and allows further improving DC ratio measurement though correction of the residual nonlinearity, and raising interest in their application also to the AC and, more generally, to time-dependent regimes. Then research on this topic was considered with some interesting results published (e.g., digitally traceable: transformers, amplifiers, voltage dividers…) involving scaling of both voltage and current based on digital methods. From the analysis of the solutions adopted, methods based on digital techniques for practical realisation of step-up and step-down procedures were devised through the integration of high accuracy ADCs available in modern precision DVM along with traditional scaling, specifically divider-based methods, which offered the best solution to exploit digital techniques for scaling quantum standards.

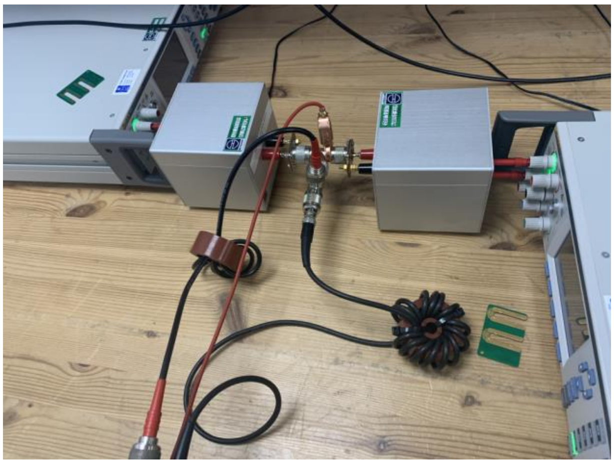

*Fig. 4.2.1: Metrosert measurement setup used for digital-based mixed analog/digital scaling of voltage*

Most of the later investigations within DIG-AC project followed this criterion. Based on these results, a set of the most suited ranges for digital techniques for scaling with quantum traceability was also defined at this stage after discussion with all partners, as: 10 mA to 1 A; 10 mV to 100 V; both up to 1 kHz.

In the course of a detailed study of specific issues in digital scaling, the following activities were undertaken:

- INRIM studied the effect of staircase signals present at the output of Programmable Josephson Standards on voltage scaling using the selected digital techniques, showing the contribution of divider impedance on sampler and the effects of staircase signals on sigma-delta converters.
- CEM studied the effect of digitiser's instabilities with time, temperature, frequency, considering in particular the input impedance for the loading effect on dividers and shunts at higher frequencies as well as a digital counterpart of thermal-converter-based step up of shunts using a calibrated combination of shunt and quantum-traceable digitiser to obtain a complete set of shunts-digitisers calibrations up to the highest current.
- Metrosert with FER characterised the phase displacement of dividers and shunts within the selected ranges in systems with a digital voltmeter for fast sampling, phase compensated and guarded voltage dividers, coaxial current shunts.
- Metrosert with FER studied the application of fast simultaneous sampling of two voltages using two digital voltmeters for direct digital determination of a voltage ratio, as a way to cancel digitiser's errors.
- TUBITAK defined dividers for voltage calibration and evaluated their performance by measurements of the dividers for dynamic digital metrology aspects.

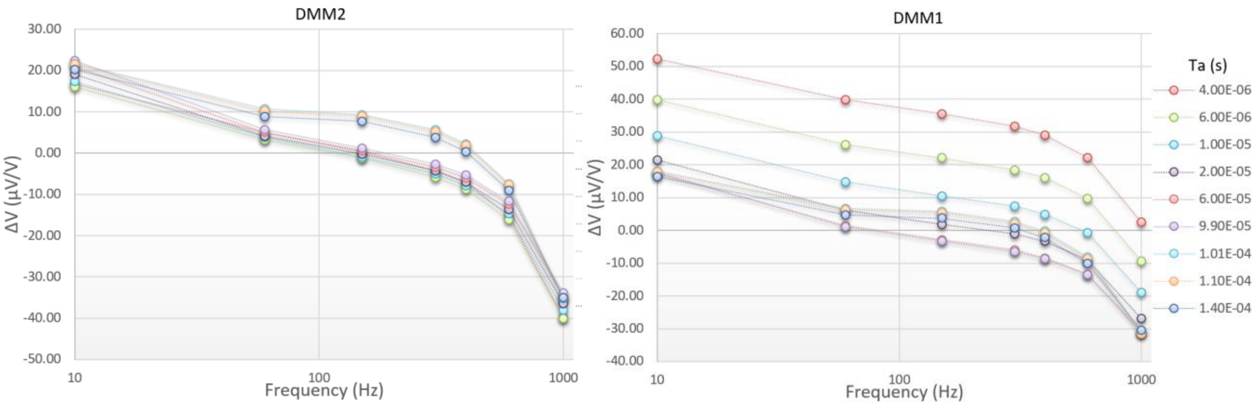


*Fig. 4.2.2: Frequency response of two different digitisers Keysight 3458A for different aperture times* ($T_a$)

Finally, INRIM together with all partners considered the selected solution with DVM and resistive divider integration to outline an optimal system integration configuration suitable to application in NMIs and calibration laboratories, with limited costs and minimal additional hardware. This work was published as a guideline providing an integrated approach to scaling, digital techniques and quantum standards by combining digitisers with voltage dividers and current shunts ("Guidelines on the development of scaling systems employing digital techniques for use at NMIs and calibration laboratories for the practical realisation of step-up and step-down procedures and scaling of electrical current and voltage").

To conclude, it is now generally accepted that electrical metrology will face in the future the expanding needs of a digital world. The results from this project objective provided a fundamental tool to coordinate the future developments for a digital-ready and quantum accurate European metrological network in scaling quantities over a wide range of values.

The objective then was fully achieved. Toward meeting the objective, the following were achieved by project partners:

- A comprehensive overview of the methods in use among the participating NMIs was carried out. This allowed to understand the know-how of partners, their needs and provide a reference for the design of the new digital setup with reduced costs and minimal additional hardware, set by the project tasks.
- A detailed knowledge and discussion on recent research involving scaling of both voltage and current based on digital methods, which was used to select the most suitable solutions for all participating NMIs and calibration laboratories.
- The selection of the most suitable operating ranges for upscaling and downscaling of an AC quantum standard were considered. An interval of operating values was defined, depending on the signal frequency, to provide the targeted viable digital calibration solutions for end-users e.g., device manufacturers and semiconductor industry.
- The development of a complete method based on digital techniques for practical realisation of step-up and step-down procedures was accomplished. The method is implemented with DVM and resistive dividers that are generally available and widely used by NMIs and calibration laboratories.
- Issues in interfacing digitisers in dynamic voltage scaling and in the measurement and scaling of currents were investigated and optimal system configurations suitable for applications at NMIs and calibration laboratories were defined. The analysis provides a reliable support for the estimation of uncertainties in digital-based scaling system, by considering contribution specific to the digital realm.
- Guidelines were produced providing an integrated approach to scaling, digital techniques and quantum standards by combining digitisers with voltage dividers and current shunts. The published guide summarizes the knowledge advancements attained within this project in the field of scaling AC electrical signals to extend digital techniques over the relevant ranges of calibrations and traceability to quantum standards of AC signals. It is to be regarded as a starting point toward final targeted objective, since further work is needed to determine the complete uncertainty budget and define the ultimate limitations of calibrations that join the power of digital techniques with the traceability to fundamental constant provided by quantum standards. The results reported in there, however, provide

a fundamental tool to coordinate the future developments for a digital-ready and quantum accurate European metrological network.

All documents mentioned previously, prepared for the project in accomplishment of Objective 2 are freely available at the DIG-AC website: https://digac.gum.gov.pl/.

## 4.3 Objective 3: Development of publicly available methods, algorithms and software for the traceability chain of dynamic measurements

Dynamic measurements are necessary based on sampling and data processing. Data processing includes the measured values and the uncertainty evaluation. To obtain the measured values and uncertainties adequate and validate algorithms most be used. For both data acquisition and processing a developed software is fundamental. A collaborative work for a common software was fundamental for its development. The open and common use of the methods, algorithms and software has the great advantage that the improvements developed for any user can be quickly integrated within other users.

To meet the objective, first a general theory on errors and uncertainties was formulated. Then, existing software was used, and new software was developed for testing and validation of algorithms. Subsequent work focused on the testing and validation of selected algorithms and presented successful validation of several algorithms used in processing of sampled data.

*Errors and uncertainties of a general quantity estimating algorithm*

TUBITAK in collaboration with GUM, CMI, CEM, JV, IPQ and UMA formulated uncertainties and validation of algorithms to support development of software for testing of algorithms. Output quantities $O_i$ are related to input quantities $I_i$ by a general function $f$. An algorithm $A$ estimates output quantities $O_i'$ based on the input quantities $I_i$ . Algorithm adds unknown error $\varepsilon_A$ . The algorithm error is a function of input quantities. The algorithm error manifests as a bias of the output quantities and the estimated quantities differ from the true value of output quantities.

This description can be extended to a case with uncertainties. Every input quantity has an unknown error $\varepsilon_{Ii}$ , that is represented by uncertainty of the input quantity $u(I_i)$. In calculations, the uncertainty is often represented by a probability distribution function (PDF) $g_{Ii}(\xi_i)$. Uncertainties of output quantities are related to input quantities and its uncertainties by function $f$. Thus, the uncertainty of output quantities calculated by algorithm $A$ is a function of input quantities, its uncertainties, and algorithm error. Because of the PDFs of input quantities, the error of the algorithm will variate according to PDF $g_\varepsilon(\xi)$. The error of the algorithm can be obtained exactly only if both input and output quantities and uncertainties are known. Using $A$, one can calculate $O_i'$ from $I_i$ and obtain $\varepsilon$. Another possibility is to know the inverse function $f^{-1}$. In the case of a real measurement, neither the true values of all input quantities $X_i$, inverse function $f^{-1}$ nor the true values of output quantities $Y_i$ are precisely known and the value of the error $\varepsilon$ cannot be obtained.

However, the algorithm error can be estimated for another set of input and output quantities $\tilde{X}_i$ , $\tilde{Y}_i$ , that are near to the actually measured quantities. Based on the assumption that the error of the algorithm is changing linearly and only a little with little change of quantities, it can be assumed $\varepsilon \approx \tilde{\varepsilon}$. Thus, first output quantities $Y_i$ are calculated using $A$ and measured values $X_i$ . Next, the values of the $\tilde{Y}_i$ are selected to be as near as possible to $Y_i$. Using $A^{-1}$, the input quantities $\tilde{X}_i$ are obtained, and using $A$ the error of the algorithm $\tilde{\varepsilon}$ is calculated. The method is graphically described in Figure 4.3.1.

$$\begin{tikzcd} X_i \arrow[r, bend left, "A"] & Y_i' \arrow[d] & \\ \tilde{X}_i \arrow[dr, bend right, "A"'] & \tilde{Y}_i \arrow[l, bend right, "A^{-1}"'] \arrow[dr] & \\ & \tilde{Y}_i' \arrow[r] & \tilde{\varepsilon} \end{tikzcd}$$

*Fig. 4.3.1: Method for estimation of algorithm error. Quantities in blue are obtained by measurement. Quantities in red are simulated.*

The described method was used to estimate algorithm errors and algorithm uncertainties, as described in following sections. The application of the method is time consuming, especially if the Monte Carlo method has to be used. Therefore, a new software named QWTBvar was developed.

*Software for calculation and propagation of uncertainties*

A common situation in the data processing of sampled signal is the estimation of multiple quantities using the same record. The user is interested in the amplitude and the phase of the main signal component, in a spectrum and stability of these quantities during multiple records. For the case of evaluating a property of a digitiser, spurious free dynamic ratio (SFDR), total harmonic distortion (THD) and effective number of bits (ENOB) are important quantities.

Algorithms exists for all of these quantities, but it is a complex task to learn how to use every single algorithm. Q-Wave toolbox (QWTB) was developed to help with this situation. It is a software toolbox written in M-code and is running in Matlab or GNU Octave. It aims for aggregation of high-quality algorithms required for data processing of sampled measurements. QWTB consist of data processing algorithms from different sources, unifying application interface and graphical user interface. However, it was not tailored for actual metrological measurements with various transducers, digitisers and other hardware. Therefore, during development of TWM (TracePQM Wattmeter) an extension of the QWTB interface was formulated. TWM is a transparent, metrology grade measurement system for traceable measurement of Power and Power Quality (PQ) parameters. TWM defined name space for quantities needed for transducers, errors of connecting transducers to digitisers. During the TracePQM project, new versions of algorithms were developed capable of using the defined quantities.

The estimation of algorithm errors was not solved successfully in QWTB nor in the TWM extension. Therefore, CMI in collaboration with GUM, IPQ and CEM developed a new software, QWTB variator, abbreviated as **QWTBvar.** This is a system that can:

- variate input quantities or its uncertainties,
- calculate errors of output quantities to the nominal values,
- plot dependence of output quantities on the varied input quantities or its uncertainties,
- create lookup table of uncertainties of output quantities,
- interpolate the lookup table for quick estimation of uncertainties.

QWTBvar is a complex tool. The documentation to the software was described in the “Report on the integrated software for data processing and uncertainty estimation of dynamic measurements, including related methods and algorithms”. Several examples have been included for easy user uptake.

*Comparison of two algorithms*

CMI, CEM and IPQ used the QWTBvar to compare two algorithms for estimation of Total Harmonic Distortion (THD). The two selected algorithms were TWM-THDWFFT and TWM-MFSF. The TWM-THDWFFT algorithm was designed for calculation of the harmonics and THD of the non-coherently sampled signal. It uses windowed FFT to detect the harmonic amplitudes, which limits the achievable accuracy of the harmonics detection due to the window scalloping effect. TWM-MFSF is an algorithm for estimating the frequency, amplitude, and phase of the fundamental and harmonic components in a waveform. Amplitudes and phases of harmonic components are adjusted to find minimal sum of squared differences between the sampled signal and the multiharmonic model.

To compare both algorithms, first a simulated signal was constructed. Next both algorithms were used to calculate THD value. Both results were then compared.

Generally, the value of THD calculated using THDFFT algorithm showed a small offset, compared to the results of the MFSF algorithm. The uncertainties were mostly covering the error of the THD for both methods. However, the WFFT algorithm does not implement MCM uncertainties correctly and only uncertainties calculated by GUF were relevant. The uncertainties were affected by the noise and increased linearly with increasing noise. The value of THD calculated using THDFFT showed a variation on the signal frequency, which was expected due to principles of the implemented Discrete Fourier Transformation. The MFSF was not affected by signal frequency because of the implemented fitting method. Figure 4.3.2 shows the dependence of calculated THD value on the simulated THD value of the signal with uncertainties calculated using GUF.

The errors were very small for both methods. The most interesting fact is zero or small dependence of MFSF uncertainty on the THD value.

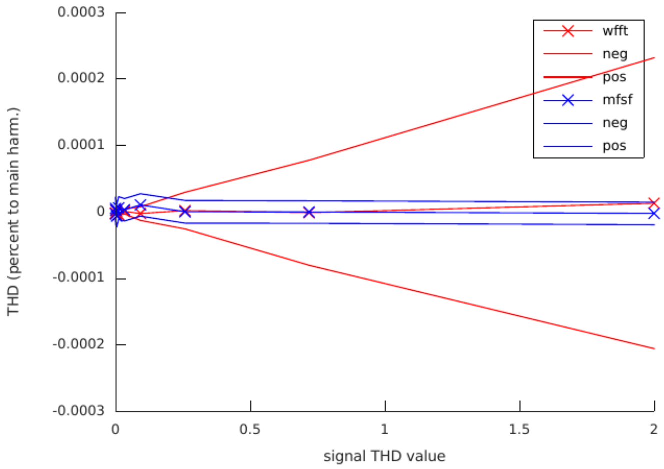


*Fig. 4.3.2: Comparison of two algorithms calculating THD value. Red lines show algorithm TWM-THDWFFT, blue lines represent results of algorithm TWM-MFSF.*

The algorithm comparison showed several things. Both algorithms calculated GUF uncertainties correctly, i.e., the uncertainty is greater than the error of the algorithm, for at least 95 % of results. The MFSF algorithm errors were much smaller than the WFFT algorithm ones. Because uncertainties were greater than the errors originated in the algorithm, the calculation was considered validated.

*SFDR algorithm validation and uncertainty estimation*

IPQ in collaboration with CMI used the Spurious Free Dynamic Range algorithm to estimate purity of the spectrum of sampled waveform. An algorithm process validation was performed to verify and quantify any systematic error introduced by the SFDR algorithm, its dependence on input quantities values and the application of the QWTB function to estimate the uncertainty of the SFDR output value as a function of the uncertainty variation of the input quantity introducing disturbances.

The validation process was based on the application of the algorithm to a simulated sampled data generated from a sine wave signal. The algorithm error was calculated as the difference between the SFDR value calculated by the algorithm and the theoretical value calculated from the simulated input signal applied. First, a set of simulations was conducted to observe the dependence of the algorithm error as a function of input quantities values: frequency of the fundamental component, frequency of spurious components, spurious amplitude related to amplitude of fundamental and random noise in sampled input values. Then, an amount of uncertainty was added to the sampled values and the effect in the algorithm output value and the related uncertainty value estimated (using Monte Carlo method) was observed. These results were compared with the SFDR algorithm error and its standard deviation obtained in previous tests. Finally, the algorithm was applied to a simulated non-coherently sampled signal, and its error was calculated as function of the input quantities values.

For a coherently sampled signal and with the acquisition quantities used (sample frequency, number of samples) and in the range of input quantities tested, it was possible to confirm that the SFDR algorithm does not input any relevant systematic error in the calculation of the SFDR value, being this is limited to a maximum relative value of $6\times10^{-9}$. The presence of noise in signal originates the variation of the algorithm output value with larger scattering than the noise value, as it can be seen by the maximum and minimum values obtained from 1000 runs of the algorithm and from the standard deviation values which were one order of magnitude greater than the noise value. The mean values of the SFDR relative error obtained were around 2 orders of magnitude lower than the corresponding standard deviation values.

The algorithm was also run with a rectangular window instead of the default Blackman window. The results obtained from the standard deviation were between 21 % and 27 % lower which confirms that the use of windows in coherent sampling increases the influence of noise in the standard deviation of the FFT results. Figure 4.3.3 shows results for 1 kHz and $1\times10^{-6}$ V of noise amplitude.

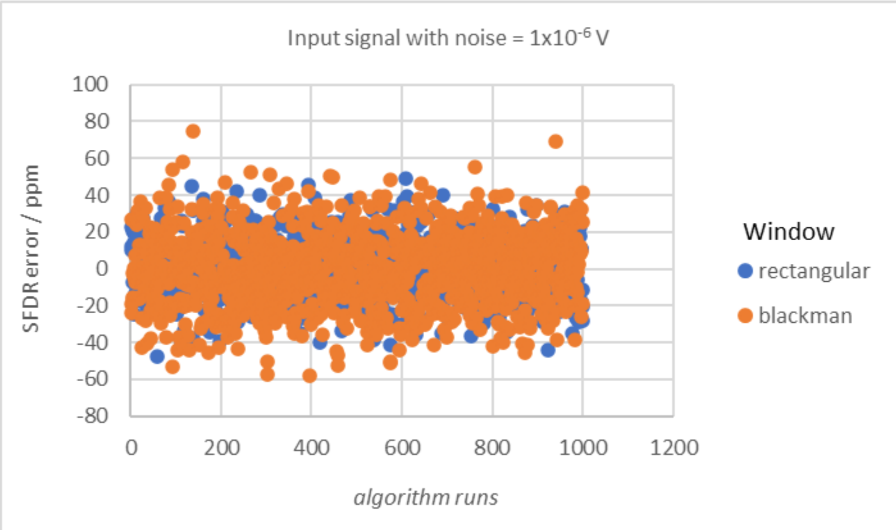


*Figure 4.3.3: SFDR error of the algorithm output from a simulated signal of 1 kHz, SFDR −80 dB, spurious component at $1.5 \cdot f_0$ and sampled values with $1\text{x}10^{-6}$ V of random noise.*

For the next batch of tests, each sampled value of the simulated signal, (with SFDR = −80 dB (relative to carrier) and $f_s = 1.5{\cdot}f_0$) was attributed by an uncertainty with values of $1\times10^{-6}$ V, $1\times10^{-5}$ V and $1\times10^{-4}$ V. The output uncertainty values covered the residual relative error of the SFDR value estimation.

To estimate the performance of the algorithm with non-coherent sampling, a deviation of 10 µHz/Hz in the fundamental frequency to the simulated test signal was introduced. It was observed that the SFDR relative error depended on the input quantities of the signal: SFDR, fundamental frequency and non-harmonic component. For the range of signal quantities tested, without considering the results of the spurious frequency, the largest error found was 210 ppm for a signal with SFDR of −40 dB and with a spurious frequency equal to 4.5 multiples of the fundamental frequency. For signals with a spurious frequency $f_s = 1.1 \cdot f_0$ and SFDR = −80 dB and SFDR = −90 dB, the absolute value of the SFDR error increases exponentially with the decrease of the fundamental frequency value. See Figure 4.3.4.

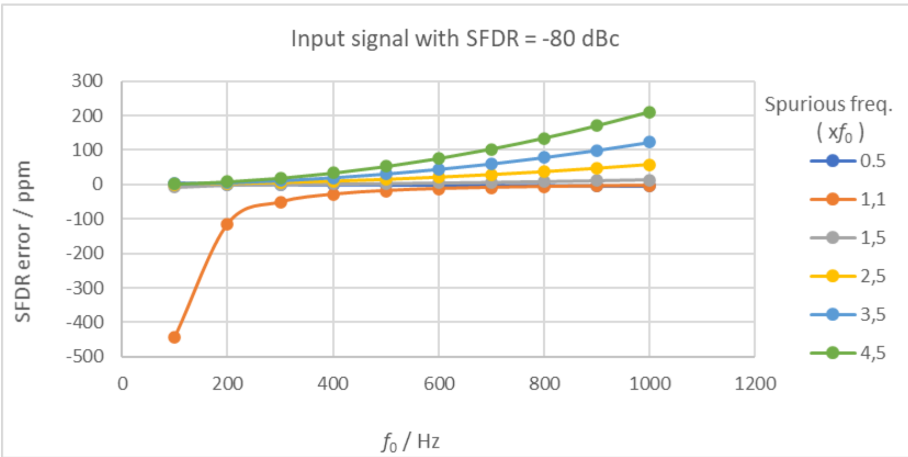


*Fig. 4.3.4: SFDR error of the algorithm output from a simulated signal with SFDR −80 dB and non-coherently sampled values by the introduction of a relative deviation in fundamental frequency of 10 µHz/Hz.*

A Blackman-Harris window with stronger leakage reduction than Blackman window was experimentally tested for signals with $f_s = 1.1 \cdot f_0$. The results presented in Figures 4.3.5 and 4.3.6 showed that for low frequencies the algorithm error is strongly reduced. For higher frequencies (>500 Hz), the absolute error increased slightly.

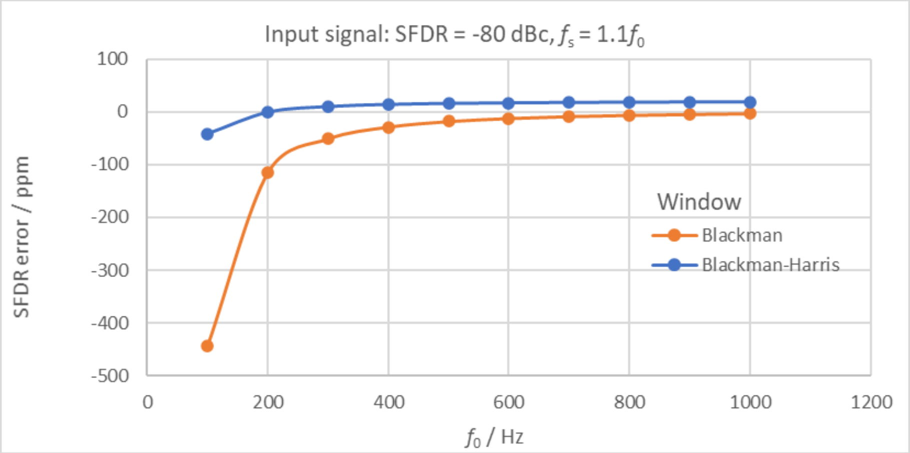


*Fig. 4.3.5: SFDR error of the algorithm output using different window from a non-coherently sampled signal of SFDR −80 dB and $f_s = 1.1 \cdot f_0$.*

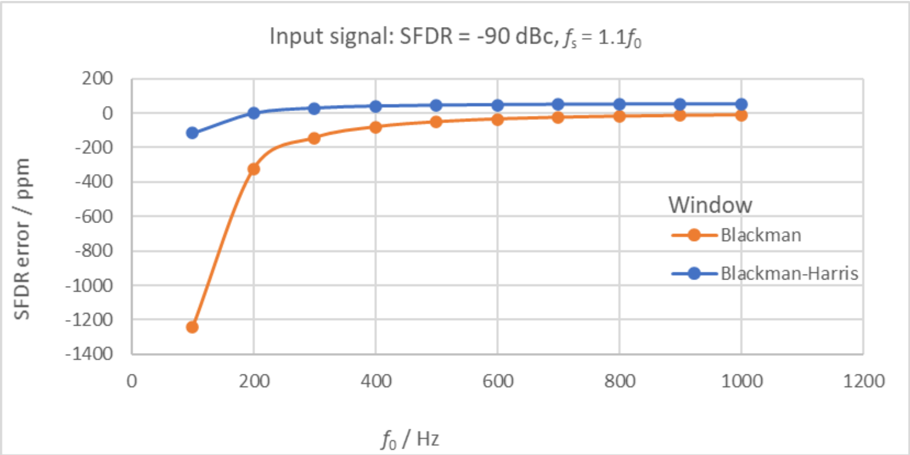


*Fig. 4.3.6: SFDR error of the algorithm output using different window from the non-coherently sampled signal of SFDR −90 dB and fs = 1.1 · $f_0$.*

The overall conclusion is the SFDR algorithm presents a residual systematic error (the maximum relative error found was $6 \times 10^{-9}$) for a coherent sampling of sine wave signal in the frequency range tested (100 Hz to 1 kHz), with non-harmonic components from 0.5 to 4.5 multiple of the main frequency and to SFDR values from −40 dB to −140 dB. The algorithm output shows dependence on the random noise value present in the sampled signal:

- with standard deviation values within one order of magnitude greater than the random noise.
- with the standard deviation of the result covered by two orders of magnitude the relative error of the SFDR estimation.

The uncertainty added to each sampled value was processed and generated an uncertainty estimation which was in agreement with the observed algorithm dependence on random noise. The application of SFDR algorithm to non-coherently sampled signal generated results with significant systematic error which depends on the signal parameter values frequency, non-harmonic component present and SFDR value. Error values reached hundreds of ppm for non-harmonic component equal or greater than 0.5 times the fundamental frequency. Errors reached up to 0.12 % as was observed in the worst case for a signal with a non-harmonic component close to the fundamental. The type of used window had a strong influence on the error obtained and was effective in reducing significantly the algorithm error. For signals with SFDR values equal or below

−100 dB, the algorithm was not working properly, generating output errors with values too high to be considered acceptable, reaching the relative value of -24 %.

*INL-DNL algorithm validation and uncertainty estimation*

Integral non-linearity (INL) and differential non-linearity (DNL) were used by CEM and CMI to measure the performance of analog-to-digital (ADC) converters. These measurements were performed after offset and gain errors have been compensated. INL represents the deviation between the ideal input threshold value and the measured threshold level of a certain output code. As DNL is calculated from INL, in this study only INL was researched.

The INL-DNL algorithm included in QWTB uses the sine-wave histogram method to locate code transitions and then calculate INL and DNL values. An overdriven sinewave function is used as input for ADC. ADC transform this signal to discrete values. The number of samples in each code are counted and a histogram is built. As only a finite number of records is possible, the histogram shape is always different to ideal histogram shape, even if there is no INL and DNL error. Therefore, the algorithm has an inherent error when INL and DNL are calculated.

The way to estimate error and uncertainty of the algorithm is to input a known solution and compare the differences between algorithm solution and input solution when some variables were changed. Regarding the aim of quick estimation of the uncertainty, the problem is reduced to two cases:

1. Input noise is small: algorithm errors are quantized, and just a maximum uncertainty can be provided since the mean of the error is not zero and varies abruptly.
2. Input noise is big: uncertainty prevails over algorithm error and an uncertainty can be provided since the mean of the error is zero.

It is clear that the input quantity number of bits is a fixed value. Also, the number of samples was considered as a fixed value with no uncertainty. Experimentally it was proven that the influence of the overdrive is small if this is known with enough accuracy, and that the value of the INL was not important for the calculation of the maximum uncertainty. Therefore, just the noise (uncertainty of the input signal) was considered as the only uncertainty source in this study.

As an example of result, Figure 4.3.7 shows the calculated uncertainty for a 10 bits ADC, for different noises and sampling to signal frequency ratio $f_s$ / $f_i$ for one cycle (m = 1), and a fixed overdrive of 1 V (R = 4 V). The two cases were identified. The points shown represent calculated values and lines represent the fitting of these points. For both zones, INL uncertainty fits quite well into the following equation:

$$u(INL) = C\sqrt{\frac{\sigma}{m}\frac{f_\mathrm{i}}{f_\mathrm{s}}(2^N - 1)}$$

Where in zone 1:

$$C = C_1 = \sqrt{\frac{m}{\sigma}\frac{f_\mathrm{i}}{f_\mathrm{s}}}\left(1.162 + \frac{1.155}{R/2}O_\mathrm{v}\right)$$

And in zone 2:

$$C = C_2 = 0.1131 + 0.0822\frac{2O_\mathrm{v}}{R}$$

Note that $C_2$ is just a constant with an overdrive correction. Note also that in zone 1 uncertainty is independent of noise and that it can be written also as a constant with an overdrive correction too. With these equations the uncertainty of zone 2 can be calculated with high accuracy. Although they provide the maximum uncertainty in this zone it fits very well to the uncertainty of most of the codes. For zone 1 equations provide an upper limit of the uncertainty since it is impossible to provide a general case. This upper limit is currently very conservative, especially close to the boundaries of the two zones when *m* is high. The limit between zone 1 and 2 (noise) can be calculated approximately making equal $C_1$ = $C_2$ for *m* = 1.

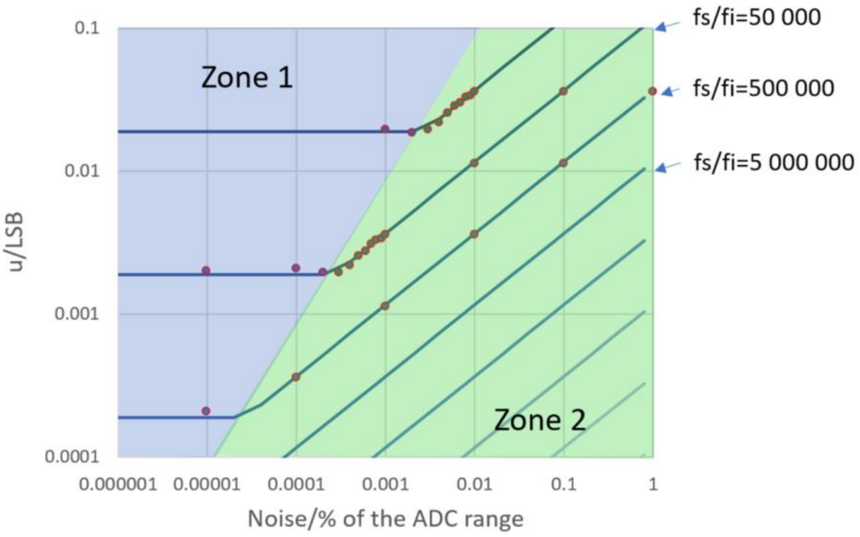


*Fig. 4.3.7: Uncertainty (y axis) vs. noise (x axis, as percentage of the range) for different sampling frequency and input signal frequency ratios. Points indicate calculated values, and lines fitted values. Two zones were identified depending on noise.*

The algorithm INL-DNL was used extensively for different cases and parameters during this study and its output was compared to an independent ideal output. The results were always satisfactory, so the algorithm is considered as validated.

As a result of the work developed the objective has been achieved developing a publicly available methods, algorithms and software for the traceability chain of dynamic measurements, including data processing and uncertainty estimation, for use by NMIs and calibration laboratories.

## 4.4 Objective 4: Validation of the complete system, including passive coaxial current and voltage devices, algorithms, and software

The work undertaken in work package 4 involved a coordinated effort from all project partners to bring together the results of the characterisation of many components of the proposed new digital traceability chain in order to make recommendations for the future implementation in European NMIs. The partners performed many measurements and analyses to validate the proposed new traceability chain for AC voltage and current. Josephson voltage standards (programmable and pulse-driven) were used to characterise the performance of three types of digitisers over a range of operating parameters. Josephson standards were also utilised to characterise current shunts and voltage dividers and their use in combination with digitisers.

Software and algorithms were applied to typical measurement configurations and their suitability for use in the measurement of AC voltage and current was assessed. The main conclusions of this work have been published in J Ireland et al 2023 Meas. Sci. Technol. 34 015003. These results are briefly summarised below noting which partner was responsible for each contribution. The output of this work package required close collaboration between all partners in order to ensure that many parameters and configurations of the system were tested and analysed. The different facilities and expertise available at each NMI meant that a large range of investigations were carried out, with the results combined and discussed by all partners leading to a successful outcome. This work could not have been done by a single NMI working alone.

Measurements of the static gain stability of the Keysight 3458A by TUBITAK showed long term stability suitable for use as a transfer standard. Use of this digitiser to sample at PJVS waveform at the maximum sample frequency of 100 kHz was demonstrated by NPL. The effect of temperature on this instrument was found by CEM to be significant only below 100 µs aperture time where correction must be made if using the instrument at a different temperature. In work performed by CMI, the Fluke 8588A demonstrated gain stability that reaches an optimum at around 0.03 s sample time. In measurements at PTB, the dynamic performance of the NI5922 revealed a larger variation in gain, up to 25 µV/V for a few minutes integration time. To use it as a transfer standard the integration time needs to be increased e.g., to one hour and the gain drift needs to be compensated by regular Josephson-based calibrations. In addition, the non-linearity of the device needs to be measured and compensated, which is challenging but possible.

Measurements at FER and PTB showed that the DC resistance of resistive dividers can be determined using a Josephson standard with an uncertainty of 0.1 µΩ/Ω, while using the same system at AC enabled current measurements with an uncertainty of 0.3 µA/A.

Traceability for current measurements using a digitiser and current shunt characterized as a single unit performed by Metrosert and GUM showed good agreement with thermal methods. This shows sufficient performance for use in addition to thermal methods at frequencies up to 1 kHz. Initial study by CEM, PTB and FER of the use of multi-tone waveforms showed promising potential for further reducing measurement time via the application of several frequencies at once with no loss of accuracy. The use of complex waveforms is very useful for analysis of dynamic measurements.

Uncertainty analysis methods were developed by CMI and CEM to accommodate the non-ideal performance of system components. An example of the use of this method to measure THD has shown that this analysis method is a valid and useful tool for determining the measurement time required to achieve lowest uncertainty, reducing the use of unnecessarily long measurements which do not reduce the uncertainty past the limiting value.

The above promising results are expected to lead to the integration of these digital methods into NMI traceability chains and will, in the longer term, replace thermal-based methods.

A comparison of the proposed new digital method with the existing thermal based method was carried out and a report comparing the two methods was submitted by TUBITAK. This confirmed how fast, flexible and comprehensive the digital method is compared to the thermal method for measuring AC voltage. The only advantage of the thermal method is its applicability to a wider frequency range, up to 1 MHz, while the digital method only provides comparable accuracy to the thermal method up to frequencies of several kHz’s using the existing technology. Current shunts and voltage dividers are still calibrated at highest level of accuracy by using the thermal method. Therefore, the new method should be recommended whenever its uncertainty is sufficient to measure AC voltage.

A report evaluating the advantages and disadvantages of digitisers in the traceability chain was also prepared by GUM. This concluded that the use of digitisers has several advantages, as described above but several disadvantages must be mitigated. This includes the fact that when the measured signal contains harmonics a large number of samples must be used which has the effect of reducing the integration time (aperture) and causes decrease of measurement accuracy. Careful attention must also be given to synchronising the source to the digitiser or selecting an appropriate window function otherwise spectral leakage will lead to a large measurement error. For non-stationary signals, advanced wavelet algorithms (wavelet analysis) are required. This requires a more complex process to estimate the uncertainty budget and therefore a high level of specialist technical knowledge is required by the user.

All partners agreed on a protocol for a future intercomparison of AC voltage and current standards between European NMIs. This intercomparison uses a travelling standard based on a digitiser that will be sent to participating institutes. In conjunction with the individual NMI strategies developed in work package 5, this future intercomparison will enable the adoption across Europe of the new traceability route developed in this project. The timetable and pilot laboratory for the intercomparison will be established in the near future as part of the ongoing work in this area described in the document “Agreed individual strategies and coordinated strategic plan for the long-term development of FER, CEM, CMI, IPQ, JV, GUM, Metrosert, NPL, INRIM, PTB and TUBITAK research capability in digital traceability chain for AC voltage and current metrology”.

In summary, the objective was achieved, with all components of the proposed system characterised and the main results and conclusions published in a journal article. In addition, two reports were produced on the advantages of the new method and a comparison to thermal methods. Finally, a protocol for a future intercomparison has been agreed for follow on work after this project. This will ensure that the output of this project will be utilised across European NMIs in the future.

## 4.5 Objective 5: Strategies for the long-term operation of the capacity developed and development of traceability for Europe as a whole

Each participant developed an individual strategy for the long-term operation (5 years) of the capacity developed, including regulatory support, research collaborations, quality schemes and accreditation. This includes the development of a strategy for offering calibration services from the established facilities to their own country and neighbouring countries. The individual strategies were discussed within the consortium and with other EURAMET NMIs/DIs, to ensure that a coordinated and optimized approach to the development of traceability in this field is developed for Europe as a whole.

All participants are confident that the achievements within the project are adequate to provide traceability via digital methods and calibration service in due time. Some specifics can be summarized as follows:

- The participants agree that they will continue to implement digital traceability chains for future voltage and current metrology. This undertaking seems to be correlated in most cases with a progressively replacement of thermal transfer standards which requires much more measurement time and are only valid for the calibration of rms values.
- Most NMI participants want to further continue with characterization of analog-to-digital converters even though the project started with a selection of available digitisers for the digital traceability chain. The reason is that a metrology digitiser with wide bandwidth is missing. Two different digitisers were selected within the project for more specific scaling investigations, a Keysight 3458A and a National Instruments PXI 5922 card. While the Keysight instrument is very good at low frequency it is limited in bandwidth. The PXI card provides a sufficiently large bandwidth, but stability and linearity are weak.
- Coordinated development of the European research and measurement infrastructure for underpinning new power and energy traceability from the early beginning is e.g., ensured by the on-going JRP 19RPT01 Quantum Power.
- Coordinated development of the European research and measurement infrastructure on impedance bridges is e.g., ensured by the JRP 18SIB07 GIQS and follow-on activities.
- Regarding the present state of advancement of quantum voltage metrology, programmable Josephson voltage standards (PJVS) cannot be considered as a routine technique in calibration services for several NMIs. Some NMIs are presently setting such PJVS while others are still in the situation where purchase and setup of a PJVS based system is the main target of the plan, which was initiated by the JRP 14RPT01 ACQ-PRO. The advantage of PJVS is that these systems are now available up to the 10 V level. This makes it possible to use PJVS also as a replacement for old arrays capable of generating DC voltages only. Many institutes consider this opportunity as a convenient solution that will allow in the future to provide DC calibrations with the same quantum standard, with advantages from the technical and economical point of view. He-free system are now regarded by most as the best choice for cooling Josephson arrays in the future and the setup of a cryocooled system is part of many plans. Conversely, JAWS are at the front end of research, even more complex and much more expensive, then most NMIs don't foresee a JAWS system as a possible development, at least in the mid-term horizon.
- Further joint activities are organized within the EURAMET TC-EM SC LF and SC DC&QM. In addition, project partners are also well linked to the EMN for quantum technologies to keep in touch with stakeholders.

A draft “Protocol for a future intercomparison of digital AC voltage and current standards between European National Metrology Institutes (NMIs)” will be submitted to EURAMET. The planned intercomparison will ensure a future collaboration / guest working in this specific area, and besides partners of the project other EURAMET NMIs/DIs will be informed for possible involvement. Finally, the comparison protocol will also include detailed uncertainty calculations for the establishment of appropriate quality schemes and accreditation.

Finally, a successful proof-of-principle study has already been carried out within the frame of this project (an abstract has been submitted to CPEM 2022). Furthermore, the standards for such an intercomparison are widespread, they are available in most NMIs, and they can easily be replaced if better ones are on disposal.

The intercomparison proposed consists of the measurement of AC voltage and current for different frequencies, voltage/current amplitudes and single/combined waveforms.

Specifically, the quantity to be reported will be the relative calibration error of the travelling standard when measuring current and when measuring voltage, defined as the difference between the measured quantity by the travelling standard and the quantity applied to it, and divided by the applied current/voltage. The calibration error will be expressed in µV/V and µA/A, respectively-

The current travelling standard will be a digitiser Keysight 3458A, working in DCV mode, together with a 20-mA current shunt. The same Keysight 3458A digitiser working in DCV mode together with a 4 V resistive voltage divider (RVD) is chosen as voltage travelling standard. A laptop with the software to be used and connectors will be also provided.

The equipment that will be transferred during the intercomparison is shown in the Figure 4.5.1.


*Fig. 4.5.1: Components transferred in the intercomparison: digitiser, current shunt and RVD.*

In summary, the objective was achieved and individual strategies for the long-term operation (5 years) of the capacity development were defined by all partners. Furthermore, for the planned intercomparison first measurements with the defined set-up were done, showing promising results which will be published at conference CPEM 2022.

# 5 Impact

Information on the project was shared with the European metrology community via engagements with the EURAMET Technical Committee for Electricity and Magnetism (TC-EM), and with its Subcommittee Low Frequency (SC LF). Project partners promoted project outputs to broader scientific and academic audiences at the 2020 and 2022 Conference on Precision Electromagnetic Measurements (CPEM), the 23rd (2019), 24th (2020) and 25th (2022) IMEKO TC 4 International Symposiums, and CROLAB Conference (2020 and 2022). User communities were targeted with additional presentations to Mars-Energo and KB-5 from Russia, the Talinn University of Technology, and the Accredited Laboratories Association of Portugal.

*Impact on industrial and other user communities*

The availability of traceable digital dynamic measurements of current and voltage waveforms will provide an entirely new measurement capability for industry. This will allow, for the first time, the measurement of time varying signals and spectral information, replacing the existing RMS value calibrations provided by NMIs until now. This will improve the characterisation of devices and instruments in a wide range of industries including power and energy, healthcare, sensors, instrumentation and advanced manufacturing. In this project, stakeholders from a range of industrial sectors from across Europe provided direct input to the development and strategy for digital traceability. They will also have the opportunity to make early use of the new systems via collaboration with project partners after the end of this project.

*Impact on the metrology and scientific communities*

Since electrical measurements, and in particular electrical waveform measurements, are an enabling technology for up to 70 % of NMI measurement and calibration activities, the establishment of a digital traceability chain will lead to improved measurement capability in many areas, a reduction of uncertainties, a shortening of time required for calibrations, and an increase in recalibration intervals. This will lead to cost savings at NMIs and the ability to offer new calibration services based on the improved characterisation of electrical waveforms. This project resulted in the establishment of capability at all of the project partners and the knowledge of the more experienced institutes has been disseminated throughout and built on by the consortium.

*Impact on relevant standards*

The project has already been presented at the EURAMET TC-EM Contact Persons Meeting held in Cavtat, Croatia in September 2018 and at the EURAMET TC-EM SC Low Frequency Experts Meeting in Ljubljana, Slovenia in May 2019. The final results were presented at the EURAMET TC-EM Contact Persons Meeting in

October 2022, held in Sofia, Bulgaria. A Good Practice Guide was prepared in the project on dynamic digital voltage and current measurements, which is to be used as the basis for a future EURAMET calibration guide; it is available online. The consortium will also disseminate the outcomes of this project to IEEE, which is responsible for drafting standards related to current and voltage waveforms.

*Longer-term economic, social and environmental impacts*

In the long term, the adoption of digital traceability and the availability of dynamic measurements will have far reaching impact across a wide section of industries (e.g., healthcare, defence, advanced manufacturing, instrumentation, aerospace and civil engineering) because sampled electrical measurement is an essential enabling technology across all sectors. These industries are expected to benefit from improved characterisation, lower uncertainties and improved design of devices and instruments, providing long term economic advantage. Furthermore, the improved characterisation of devices and instruments will enable the development of a wide range of sensors which is envisaged to lead to, for example, improved healthcare related sensing.

# 6 List of publications

1. Yolanda Alvarez Sanmamed, José Ramón Salinas, Javier Díaz de Aguilar, Francisco García-Lagos, Raul Caballero: "Temperature influence on the frequency response of the Keysight 3458A digital multimeter", 23rd IMEKO TC 4 International Symposium, Xi'an, China, September 17-20, 2019. https://www.imeko.org/publications/tc4-2019/IMEKO-TC4-2019-042.pdf
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8. Javier Díaz de Aguilar, Yolanda A. Sanmamed, David Peral, Martin Šíra, Damir Ilić, Witold Rzodkiewicz, Patryk Bruszewski, Grzegorz Sadkowski, Andrea Sosso, Vitor Cabral, Luís Ribeiro, Helge Malmbekk, Andrei Pokatilov, Jane Ireland, Patrick Reuvekamp, Jonathan Williams, Ralf Behr, Jonas Herick, Tezgül Coşkun Öztürk, Mehedin Arifoviç, Naylan Kanatoğlu, José Ramón Salinas: “Good Practice Guide on traceability of digital dynamic measurements of AC voltage and current”, https://doi.org/10.5281/zenodo.7092107
9. Jane Ireland, Patrick G. Reuvekamp, Jonathan M. Williams, David Peral, Javier Díaz de Aguilar, Yolanda A. Sanmamed, Martin Šıra, Stanislav Mašlán, Witold Rzodkiewicz, Patryk Bruszewski, Grzegorz Sadkowski, Andrea Sosso, Vitor Cabral, Helge Malmbekk, Andrei Pokatilov, Jonas Herick, Ralf Behr, Tezgül Coşkun Öztürk, Mehedin Arifoviç, Damir Ilić: “A method for using Josephson voltage standards for direct characterization of high performance digitizers to establish AC voltage and current traceability to SI”, Measurement Science and Technology, vol. 34, no. 1, 2022, 015003 (17 pp). https://doi.org/10.1088/1361-6501/ac9542

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

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Any partner on the project.