FINAL PUBLISHABLE REPORT

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1 Overview

Quantum effects play a fundamental role in the redefinition of the SI electrical units, allowing their direct realisation. Currently, most NMIs and some industrial laboratories possess a quantum standard but these needed to be improved and their metrological applications extended to other voltage levels and frequencies, so that their use can also be extended to industrial calibration laboratories and further levels of the traceability chain.

This project tackled that problem by providing European National Metrology Institutes (NMIs) the access to AC quantum voltage standards, therefore contributing to spread the capacity to countries or regions in Europe where access to these facilities was limited. The project also established the basis for the future collaboration between metrology institutes working on AC quantum voltage standards.

2 Need

At the beginning of this project, infrastructure and level of knowledge presented a barrier for most of the NMIs to develop their own AC quantum voltage standards, the consequence being that only a few institutes in Europe had access to these standards and the technological gap between NMIs was increasing. Furthermore, existing AC quantum voltage standards systems are complicated to construct and operate. As a consequence, only a few NMIs in Europe had the capability to operate and conduct research in this technical area, Traceability to AC quantum voltage standards could only be provided by a few NMIs and the dimension of the European research capacity on AC quantum voltage metrology was not large enough to keep up with the societal challenges associated with energy, environment and health. In addition, when raising the profile of basic scientific metrology, knowledge and technology transfer into industry and pre-/co-normative research, not even the most established institutes in Europe were able to exploit the full potential of their AC quantum voltage standards. The European research capacity in AC quantum voltage metrology needed therefore to be improved.

3 Objectives

The overall objective of the project was to develop the European measurement and research capacity. The specific scientific and technological objectives of the project were to:

- Transfer experience and expertise in different and specific technologies to enable the integration, operation and modification of AC quantum voltage standards. The purpose is not only to provide the infrastructure but also the capacity to improve the measurement technology through continuing research and development
- To design a new practical AC quantum voltage infrastructure accessible to all NMIs, which is easy to implement and operate, maintaining the potential research capacity. The design should be for a consolidated AC quantum voltage standard based on the knowledge acquired in previous research projects, where different types of approaches were followed.
- To produce a Good Practice Guide on the use of AC quantum voltage standards including guidance on development and validation of measurement methods for different specialised applications.
- To establish the basis for future cooperation between European NMIs working on AC quantum voltage standards research and the further propagation of their use.
- To create an individual strategy for the long-term development of the research capability in AC quantum voltage metrology for each NMI/DI partner developing capability in project. Individual strategies will include priorities for collaborations with the research community in the respective country, the establishment of appropriate quality schemes and accreditation. The future plans will consider the possible cooperation of some NMIs to build and use shared AC quantum infrastructures depending on the particular needs of each country.

4 Results

4.1 Transfer of experience and expertise in different and specific technologies to enable the integration, operation and modification of AC quantum voltage standards.

Relevance to the project needs and objectives

All project activities contributed to the transfer of experience and expertise but two were specifically programed aiming this objective: Workshop on quantum based voltage measurements and development of research capability on AC quantum voltage measurement systems. These activities were planned because most of the institutes developing capacity did not have practical knowledge of the available quantum voltage standards, the problems associated with its integration and operation and practical application. These were necessary for the active contribution of all partners on the other project's objectives, and to provide the less experienced NMIs the expertise and practical knowledge to develop AC quantum voltage standards and to develop measurements systems that can be reasonably developed in less experienced participant NMIs.

Work undertaken

Workshops on quantum voltage measurements

A one week workshop at PTB was programed during the first month of the project. PTB capacity building facilities for AC quantum measurements are unique in Europe and only comparable to NIST and NMIJ (National Metrology Institute of Japan). Other half day workshop was held at NPL for the occasion of the midterm meeting, which covered practical operation of the new design. Finally half a day was held at INRIM related with different types of cryocoolers, (Helium free refrigeration system), operation of quantum voltage standards requires as low temperature as 6 K.

Workshop at PTB
An introduction and an overview of different aspects of Josephson voltage standards used for AC applications were given on the first day. The programme included two talks on the different types of Josephson voltage standards i.e. the programmable Josephson voltage standard (PJVS) and the pulse-driven voltage standard usually called Josephson Arbitrary Waveform Synthesiser (JAWS).

To make the differences between the two systems clearer, the talks were succeeded by a laboratory tour. Figure 1 shows graphically the difference between PJVS and JAWS. Knowing the differences between the two systems was fundamental for new design (Objective 2) and strategy plans (Objective 5).

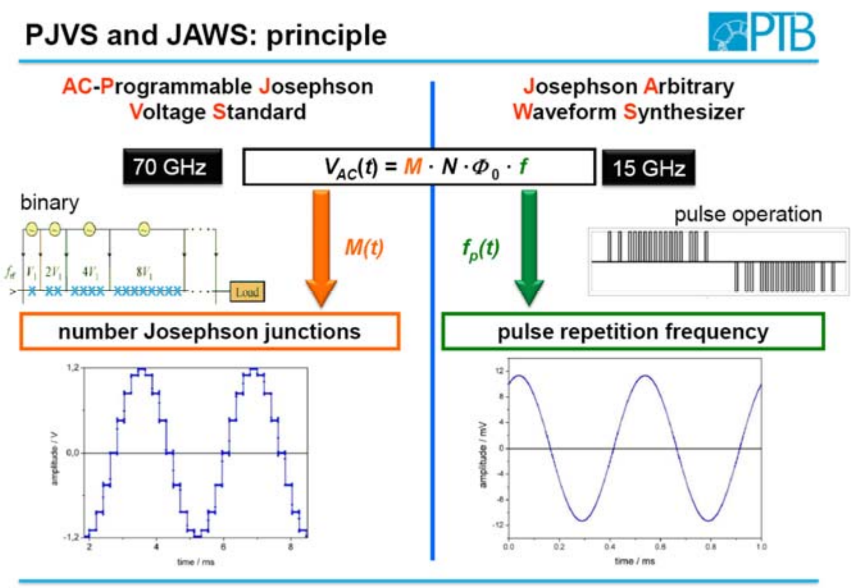

Figure 1. Differences between PJVS and JAWS.

Two talks on cryocoolers were also given on i) basics of cryocoolers in voltage metrology and ii) using a JAWS system inside a cryocooler, with special attention paid to the sampling mounting, directly on the cold head or concentrated on a “top loading” system.

These talks were followed by an overview on Josephson standards for power measurements

A final talk on different instrumentation was given which initiated an intensive discussion about availability of instruments and costs. All presentations have been discussed considering the situation and needs of the participants. Finally, two demonstrations on cooling down Josephson arrays in dewars and in cryocoolers were given.

The workshop included also hands-on training with three parallel sessions. The participants were divided into three subgroups of 3 - 4 people. Each group spent two hours at each of the three systems presented:

1) Sampling (AC Quantum Voltmeter)
2) Supracon (Supracon commercial system)
3) RMS & TC measurements (combined PJVS+JAWS)

After the hands-on training sessions a discussion on all systems was held. This general discussion was aimed at sharing ideas and questions between the groups discussing the situation and needs of the participants related to the presented systems. This took into account the availability of a complete standard or the required instruments, the range of calibration covered and the costs for it.

In addition, three parallel training sessions took place. The group was divided again into three subgroups of 3-4 people. These small groups allowed for a hands-on training within a two-hour section designated for each system. Three systems have been presented, namely:

1) JAWS (pulse-driven Josephson system)
2) JAWS bridge (Impedance bridge based on two JAWS)
3) PJVS bridge (Impedance bridge based on two PJVS)

A discussion on all systems was held after the practical training, which aimed at sharing ideas and questions between the groups discussing the situation and needs of the participants related to the presented systems. This also took into account the availability of a complete standard or the required instruments, the range of calibration covered and the costs for it.

Development of research capability on AC quantum voltage measurement systems

Twelve research visits to PTB and NPL took place in periods extending from a few weeks to several months with the aim of developing capability on quantum based AC experiments All participants were very interested in gaining experience in running.

Below are some of the research activities performed:

Study on the use of a programmable Josephson system (PJVS) for the calibration of a voltmeter.

The main task involved characterising the properties of several difference amplifiers (DAs), which record the difference between a Digital to Analog Converter (DAC) and a step-wise approximated sine wave from the PJVS. The characterisation of the DAs was used to determine the uncertainty in transferring the PJVS value to the voltmeter, using the DAC as a real time calibrated transfer standard. The results of this research were presented at CPEM 2018. Figure 2 shows the results for three different Das.

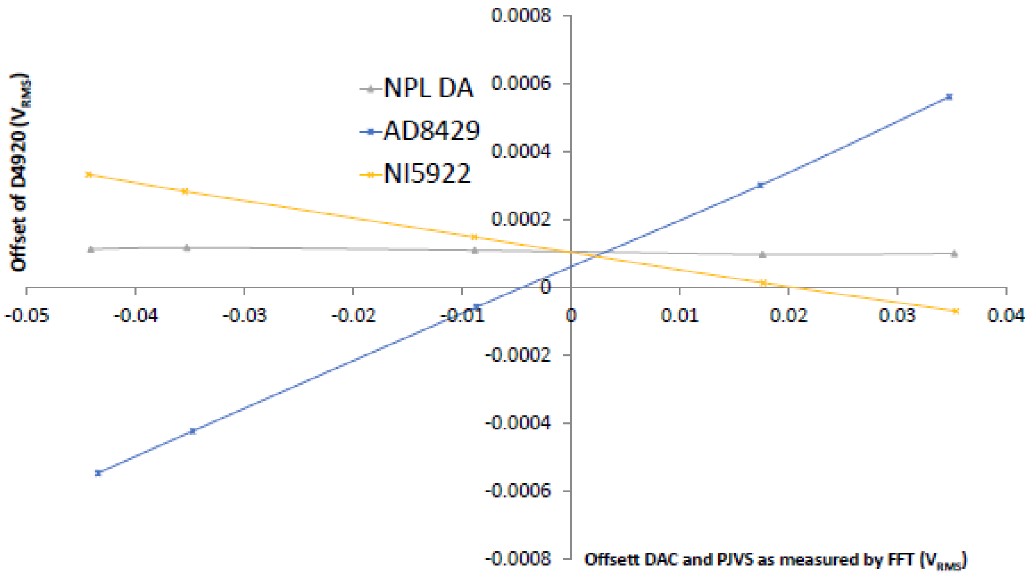

Figure 2 - Offset between Datron 4920 reading and PJVS + DA reading.

Quantum calibration of an AC source

An AC quantum voltmeter was used as standard to calibrate directly an AC source. Different parameters of the configuration of the setup (e.g. sampling rate, number of periods averaged, number of deleted points in the step transitions) were studied to observe the repeatability and/or reproducibility of the results, along its work range of voltage and frequency. Figure 3 shows the sample rate influence on the calibration error.

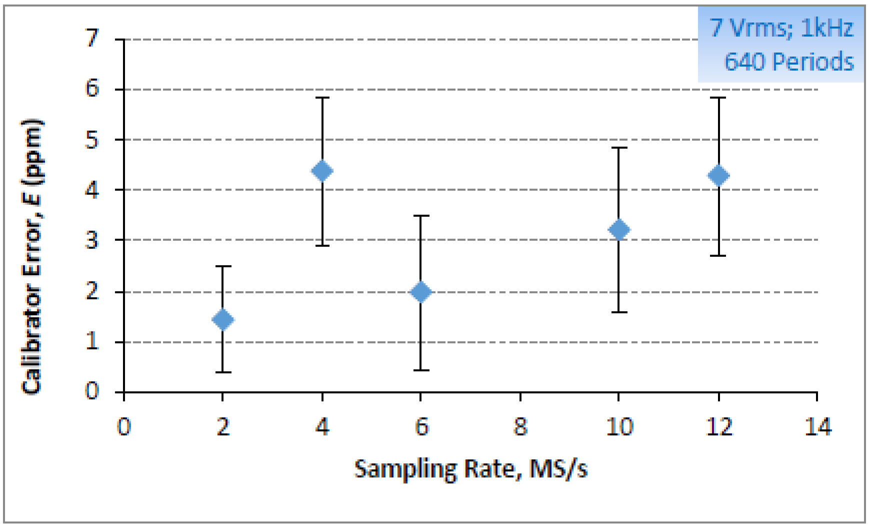

Figure 3 - Calibrator Error as function of Sampling Rate.

Application of Josephson Arbitrary Waveform System (JAWS) for the calibration of digitizers

A special waveform has been prepared with the aim of calibrating several parameters of digitizers at once. The waveform was designed to exploit unique abilities of JAWS and it was sampled by the selected digitizer. Multiple properties of the digitizer have been evaluated. The results of this research have been submitted for peer review publication. Figure 4 shows the waveform generated by the JAWS.

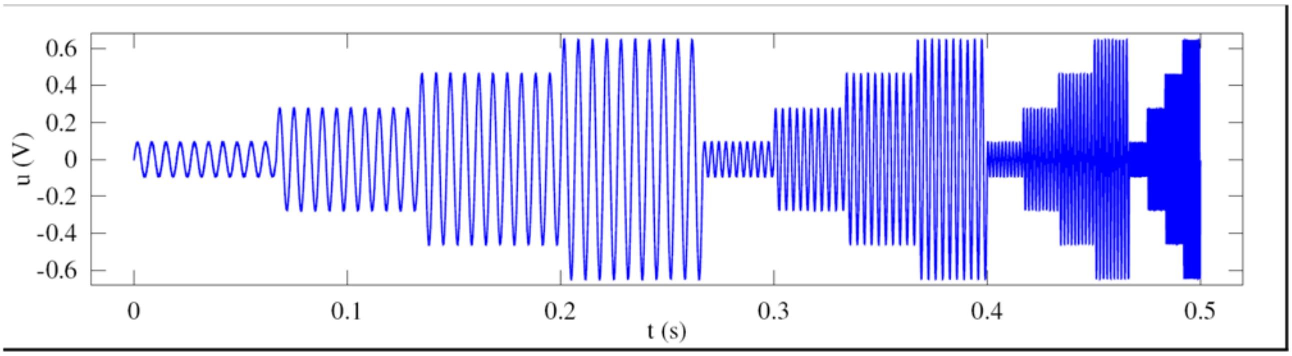

Figure 4 - Waveform generated by JAWS to calibrate digitizers.

Frequency response of Analog–to-Digital Converters (ADC)

This experiment used the PTB Josephson Array Waveform Synthesizer (JAWS) as it is the only quantum voltage standard able to produce waveforms at high frequencies. The PJVS is limited to the frequency range 1 kHz to 5 kHz. The results of this research have been submitted for peer review publication. Figure 5 shows the frequency response for an integrating ADC at different integration times. The frequency variation at different aperture time has been obtained. The applications of the corrections from the frequency response will improve the dynamic measurements using ADCs especially when low time apertures are necessary when sampling higher frequency signals.

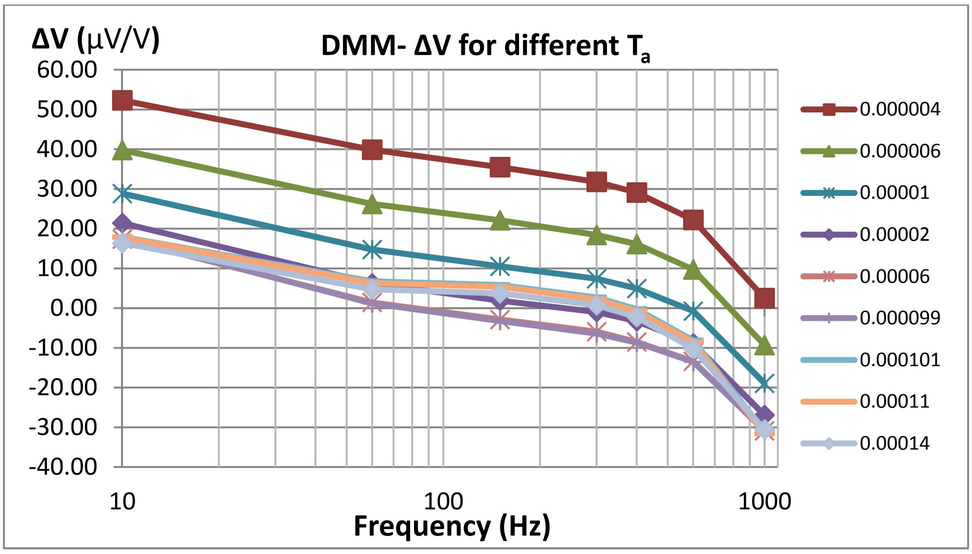

Figure 5 - Gain dependence with frequency and aperture time.

Summary of the key results and conclusions

This objective was achieved. Less experienced NMIs had the possibility to visit institutes with much more advanced AC quantum facilities and knowledge (NPL and PTB) and to carry out research activities at those institutes. This enabled all institutes to participate in the revision of the Good practice guide and the new design of a practical AC quantum voltage infrastructure.

The research activities carried out under this objective lead to a strengthening of connections between scientists all over Europe and helped to:

- Transfer experience and expertise in different specific technologies to enable the integration, operation and modification of AC quantum voltage standards.
- Establish the basis for future cooperation between European NMIs working on AC quantum voltage standards research.

- Create an individual strategy for the long-term development of the research capability in AC quantum voltage metrology for each partner developing capability in project.

4.2 Design of a new practical AC quantum voltage infrastructure accessible to all NMIs, which is easy to implement and operate, maintaining the potential research capacity

Relevance to the project needs and objectives

Current AC quantum voltage standards are difficult to integrate and operate. Therefore, a new system easier to develop and operate would facilitate the integration of AC quantum voltage standards in most NMIs.

In addition to this, the development of the necessary software is cumbersome. It was fundamental to define common software requirements in order to facilitate the collaboration between NMIs in and to facilitate the quick integration of new improvements and modification. The use of common software will increase the capacity of the European NMIs as a whole.

Work undertaken

A configuration has been designed for a new general AC quantum voltage standard which included the best choices of equipment, Josephson junction arrays, voltage waveforms and sampling parameters. It brought together the experience of NMIs who have been conducting research in this area over several years. This design of quantum voltage standard was intended to serve the interest of a range of institutes involved in precision AC metrology and the metrology community in general. It was designed to underpin the calibration uncertainties regularly required to deliver state of the art measurement services.

To validate the system a comparison between BIPM, NPL and PTB has taken place using a BIPM travelling standard. The results of this comparison have shown the difficulty of a back-to-back comparison of AC quantum Voltage Standards and have shown that further research is needed to design a comparison procedure to validate AC quantum standards, as it was already successfully done in DC quantum metrology.

A description of common software requirements has been documented.

New design description.

Figure 6 shows a diagram of the new configuration following with a detailed description of the different components and operation of the system.

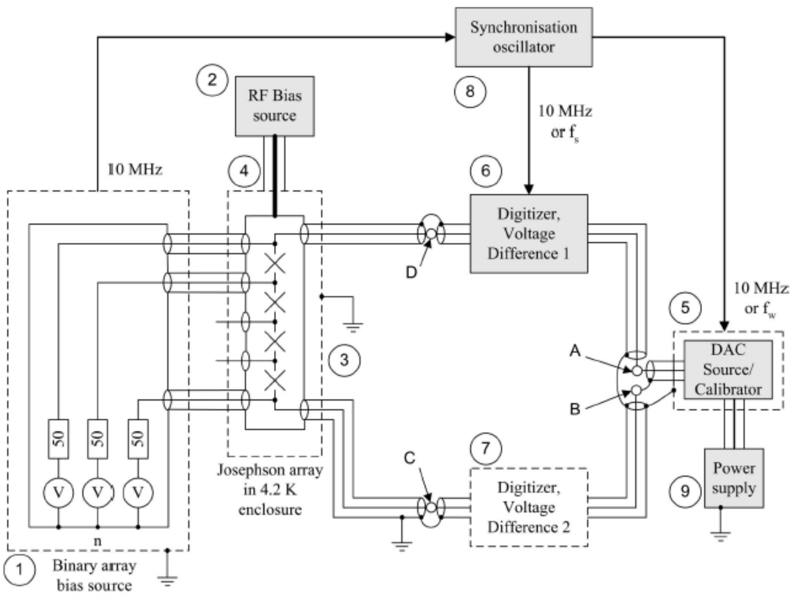

Figure 6. Schematic diagram of the new design.

The stable DAC source or calibrator (5) generates a smooth sine wave with the same period and amplitude as the step-wise waveform from the Josephson waveform synthesizer (JWS). The Josephson array high frequency bias is supplied by the RF bias source (2), operating at 20 GHz or 70 GHz, depending on the type of Josephson array. The DAC source or calibrator is frequency-locked to the Josephson synthesizer using a synchronization oscillator (8) operating at 10 MHz or the synthesis frequency, f_w depending on the type of voltage source. The difference voltage between the DAC source and the Josephson synthesizer is measured using the digitizer (6) at the high potential terminals. There is an option of using a second digitizer (7) at the low potential terminals. The digitizer (6) is synchronized from the oscillator using either a 10 MHz frequency or the sampling frequency of the Josephson synthesizer, depending on the model of the digitizer. The second digitizer (7) is synchronized in a similar way.

The connection scheme for the DAC source or calibrator (5) depends on the quality of the associated power supply (9). The high potential terminal of the DAC source or calibrator is connected to the digitizer (6) at node A. If the second digitizer (7) is not used, then the low potential terminal of the DAC source or calibrator is directly connected to the low potential terminal of the Josephson array via nodes B and C. As a consequence, any common-mode current from the DAC source or calibrator power supply will flow into the low potential terminal of the Josephson array, C, and can affect the accuracy of the quantized voltage. Note that this problem is not solved by using a single digitizer in the low potential connection between nodes B and C instead. Due to the low output impedance of the source, the common-mode current from the power supply will now flow through the high potential connection to the Josephson array via nodes A and D. There are two solutions:

- The DAC source can be powered with a supply having a common-mode current of less than 1 μA or a calibrator with low common-mode current can be used.
- The common-mode current can be diverted to a safe route (note that a common-mode current of this kind comes from a high impedance so needs to have a path to return it to its source). For this solution, node B has to be connected to the measurement system screen (represented by the coaxial cables) at the source output. The second digitizer (7) is then also required to isolate the low potential terminal of the Josephson array from the measurement system screen.

The digitizer (6) measures a voltage difference but at an elevated potential equal to the amplitude of the voltage waveform being generated. It therefore requires a high common-mode rejection ratio (CMRR) if the output of the DAC source or calibrator is to be calibrated accurately against the Josephson reference. For example, an accuracy of 1 part in 10^6 on amplitude requires a CMRR of 120 dB. Alternatively, if the digitizer has an internal guard which is effective at the frequency of the waveform being synthesized, then this guard can be driven by the source by making a connection between the guard and node A (this will have a negligible loading effect on the source).
It is essential that the data collected by the digitizers is correctly synchronized and that voltages associated with Josephson array transients are eliminated to the required uncertainty level. If an integrating voltmeter, such as a model 3458A is used, then normally the integration time of the voltmeter is set to be slightly less than the duration of a JWS sample interval and the voltmeter trigger delay adjusted to avoid the transients. If a high speed digitizer, such as a National Instruments model 5922 is used, then many samples for a given JWS sample are acquired and selected samples are eliminated to avoid the Josephson array transients.

Common software description

The common software for the AC quantum voltage infrastructures, involves monitoring and control of the AC quantum voltage standard (and automation of the measurements taken by the system under calibration (including RMS and direct sampling).The requirements were identified based on the experience with PTB and NPL systems and on the experience of developing metrology grade software in CMI. Following a summary of the common software description, the requirements can be divided into main two parts.

- Measurement system - requirements based on hardware of the standard and on common operations, such as calibrations and maintenance.
- Good coding practice - requirements based on a set of informal rules that the software development community has learned over time which can help improve the quality of software.

Due to large hardware differences, the requirements are also specified according the measurement system.

- Programmable Josephson System (PJVS) used either as a voltage generator or a voltmeter.

- Josephson Arbitrary Waveform System (JAWS).

Requirements based on the Measurement system

Common software should be able to operate a hardware commonly used in metrological laboratories. Microwave source, bias sources and null meter should be able to operate with hardware commonly used in metrological laboratories, and to carry out specific tasks and operate the whole system as a unit, rather than doing only simple operations with measurement devices. Examples of specific tasks are the measurement of the properties of the chip, the check of the stability of devices under test or the maintenance of the system.

Requirements based on the Good coding practice

Documentation is the key for any software being developed and the software should be thoroughly checked and reviewed.
Using the common software in calibrations, it must be possible to verify if it calculates results correctly. This could be achieved by implementing simulation of measurement devices with predefined "measured" values and checking that the software gives the same result as calculated externally.

The common software was designed to be modular. Because the measurement system evolves (components are added, removed or changed), one needs an easy way to add, remove or change parts of the software without affecting the rest. This was a key requirement for the future use of the software.

The common software needed to be used with a variety of measurement devices. For example, as a null meter several digitizers can be used. However the same actions are required with the device: setup the device, start the sampling, acquire samples. With hardware abstraction layer it is easy to change the software to use different devices for the same operation. An abstraction layer between operations and tasks enhances modularity and simplifies creation of new tasks for the case of implementation of new measurement methods.

Whole software should be open source, or at least source code should be accessible to end-users. Typically a metrological software of primary standards have to be modified to fit current hardware or methods of use. Also end-user require the possibility to check all calculations are correct otherwise the traceability of the system cannot be assured.

For every programming language a set of good programming recommendations can be found. For example good variable naming reduces the effort needed to read and understand source code, and National Instruments provide this recommendation for Labview at http://www.ni.com/white-paper/5560/en/#toc5.

Figure 7 shows the configuration of the common software.

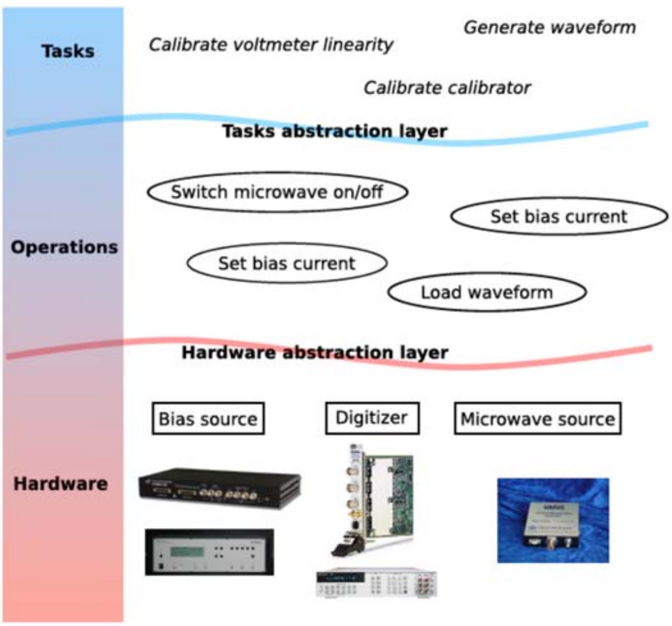

Figure 7 – General scheme of common software.

Validation

The overall aim of the validation was to establish equivalence between the new design of quantum standard for alternating voltage based on the Josephson effect and a second system with comparable measurement uncertainty. The full performance of a quantum system can only be realized by direct comparison with a second quantum system to eliminate uncertainties associated with transfer standards. A direct comparison of the new design was a crucial step in validating the apparatus and method and will enable international acceptance of the system as a source of traceability for SI voltage. The *Bureau International des Poids et Mesures* (BIPM) was chosen as a collaborator for the validation experiment as they have recently established a transportable system for the purposes of international comparison.

Two validation exercises of the new design were carried out, one at the PTB and one at the NPL. Both institutes have AC quantum voltage standards which closely align with the new design using binary-divided arrays of Josephson junctions. In both cases a commercially available precision AC source, was used as a transfer standard. The output of this source has a low level of harmonic distortion and a relative short term stability of a few parts in 10^6.

PTB results

The validation exercise at PTB was carried out in August 2017. The measurements were carried out for sine waves corresponding to RMS values of 0,829 V, 1V and 6.5 V. A sine wave frequency of 62,5 Hz was used. A frequency of 125 Hz was only applied for further investigations of the quantum systems. Two synthesizers acted as transfer standard – a Fluke 5700 calibrator and an Aivon DualDAC 2. At the beginning of the exercise the influence of interferences and ground loops were aggravating factors leading to an increase of the measured voltage differences. Finally, these problems were solved and the measurement agreements for the Fluke 5700 were 0.2 µV/V at 1V and 0.3 µV/V at 6.5 V. The measurement result for the Aivon DualDAC 2 was 0.93 µV/V at 0.829 V. As the amplitude and frequency stability of the Aivon source is excellent a much better difference was expected prior the comparison. This difference was found to happen due to small glitches within the sine wave and different sampling windows of the two quantum systems. Figure 8 shows the results of the BIPM-PTB comparison.

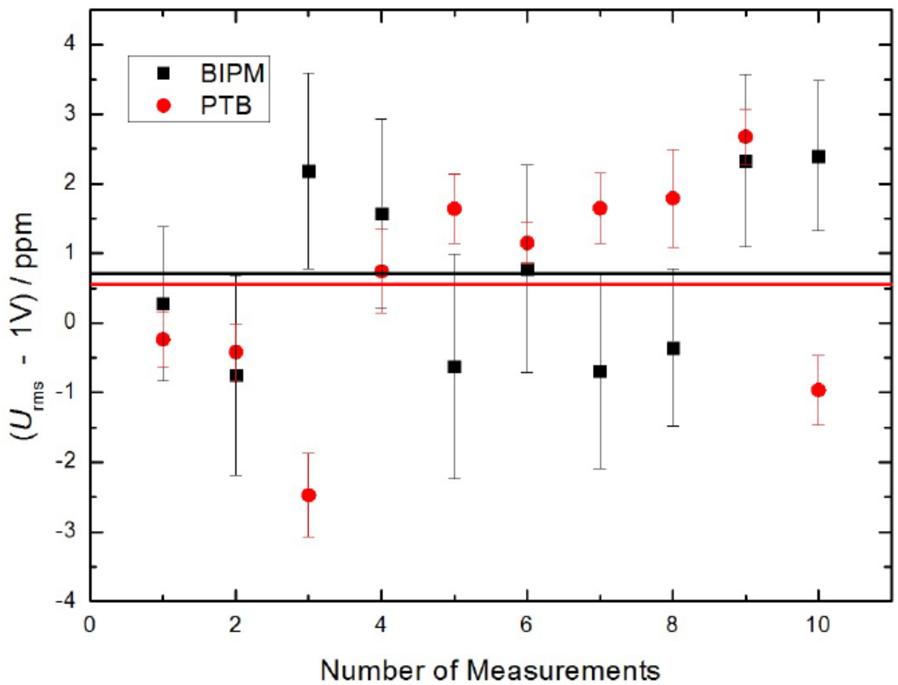

Figure 8 - Summary of PTB-BIPM comparison results.

NPL results

The validation exercise at NPL was carried out in early 2018. All measurements were carried out for a sine wave amplitude of 1V corresponding to an RMS value of 0.71 V. Three sine wave frequencies of 78.3 Hz, 156.3 Hz and 312.5 Hz were used. For each frequency, a series of measurements of the source amplitude were made by the BIPM using their reference system followed by a series of measurements using the NPL reference system. A series of measurements typically lasted approximately an hour. The differences between the BIPM and the NPL measurements vary with sine wave frequency and are of the order of a few 1 µV/V. Figure 9 shows the results of the BIPM-NPL comparison.

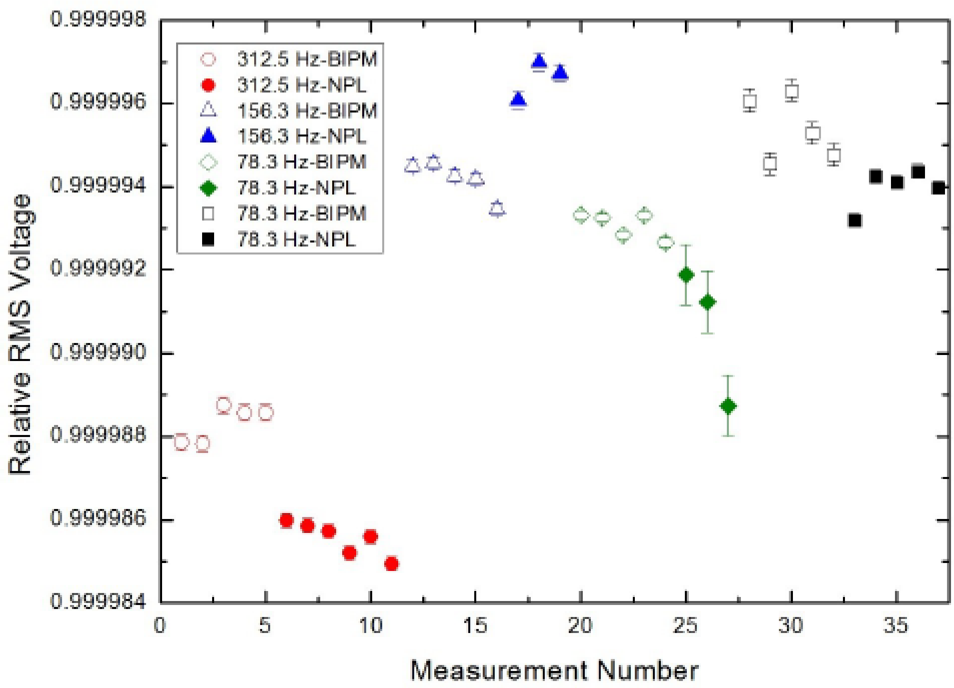

Figure 9 - Summary of NPL-BIPM comparison results.

Summary of the key results and conclusions

This objective was achieved. A reference design of AC quantum voltage standard for adoption by NMIs has been created and verified by comparison with a quantum standard of similar performance developed by BIPM. The reference design contains all the elements required to reproduce a system suitable for top level measurements of AC voltage directly traceable to the Josephson effect. Two validation exercises carried out at NPL and at PTB have demonstrated that the reference design is capable of achieving measurement uncertainties at the 1 µV/V level.

The commons software requirement to facilitate the integration and collaboration within NMIs have been described.

4.3 Good Practice Guide on the use of AC quantum voltage standards including guidance on development and validation of measurement methods for different specialised applications

Relevance to the project needs and objectives

To support the propagation of Quantum Voltage standards, a Good Practice Guide (GPG) is necessary to facilitate NMIs and laboratories who wish to invest in the development of a quantum standard for alternating voltage based on the Josephson Effect. This GPG should give detailed description of the components required to construct a practical system as well as information on measurement techniques, uncertainty estimation, software tools and safe operation of cryogenic equipment, supported by a comprehensive list of references to material already published in scientific literature.

Work undertaken

Josephson junction arrays have been used as primary standard for voltage metrology for over 30 years. A number of review articles have been written which summarize the main aspects of the design of junction arrays and their associated measurement systems to form a practical quantum standard of voltage. The development of non-hysteretic junctions paved the way for quantum metrology of dynamic voltages using either programmable arrays of Josephson junctions arranged in a binary sequence or linear arrays of Josephson junctions with a pulse train bias. A GPG which gives a detailed description of the components and systems required to realize a practical AC quantum voltage standard has been prepared. It refers extensively to material already available in scientific literature and complements this with practical details and illustrations.

The guide has been organised into three parts: systems, ii) practical application and iii) software. An appendices with safety rules in cryogenics have been included.

The following topics have been studied in relation to systems:

- Binary-divided arrays
- Pulse-driven arrays
- Description of a general system easier to integrate and operate
- Cryocoolers in voltage metrology

In relation to applications, the following topics have been studied:

- A standard voltmeter referenced to an AC Josephson standard
- AC Voltage measurements using PJVS and differential sampling
- Procedure for calibration ac-dc transfer standards using AC quantum voltage standards
- Calibrating voltmeters with PJVS
- Procedure for metrology grade characterization of analog-to-digital converters frequency response using ac quantum voltage standards
- Calibration of thermal converters, voltmeters and AC sources

In relation with the software, the following topics have been studied:

- Array characterization and optimization
- Binary array waveform synthesis
- Binary array waveform synthesis. Source voltages
- Null detector data collection and processing
- Device control
- System control, automated measurements and calibrations
- Interoperability of software components
- Data storage: content and format
- Data analysis, measurement parameters, measurement uncertainty

In relation with safety rules in cryogenics:

- Generalities
- Security risks
    - Levels of oxygen

- Cold burn hazards
- Collective protection devices
- Clothing and personal protective equipment
- Rules of conduct for the use of cryogenic liquids
- Transfer of cryogenic liquids
- Storage of Dewar or tanks containing cryogenic liquids
- Transport and lifting of Dewar or tanks containing cryogenic liquids
- In the event of an accident, spillage, emergency, natural disaster, evacuation
- Work alone
- Interference with other workers in the same room
- Normative and bibliographic references

Summary of the key results and conclusions

This objective was achieved. The guide has been prepared by the partners and to facilitate uptake of this work, the guide has been made available on the project website (http://www.acqpro.cmi.cz). The users are free to share, copy and redistribute the Good Practice Guide if appropriate credit is given. To increase the impact the guide have been submitted to the TC-EM to be considered a TC-EM document. The guide is also available on “ResearchGate”, a social networking site for scientists and researchers to share papers, ask and answer questions, and find collaborators. It is the largest academic social network in terms of active users. During its first month of publication have had near two hundred readers.

4.4 Establishment of the basis for future cooperation between European NMIs working on AC quantum voltage standards research and the further propagation of their use. For this, a Web pages and training course will also be used.

Relevance to the project needs and objectives

A working group on AC quantum voltage standards was necessary that would work in close collaboration with the relevant existent technical groups and committees, specifically with the EURAMET TC-EM: on “DC & Quantum Metrology”, “Low Frequency” and “Power and Energy”. The objective of the Working Group (WG) for AC Quantum Voltage standard Development and Cooperation should be to establish the basis for the European cooperation on AC voltage quantum standards and coordinate European NMIs working on AC quantum voltage standards, supporting propagation of their use in research and application. The group should assist all institutes but especially new and/or emerging, in the development of a national metrological capabilities on AC voltage quantum standards.

Work undertaken

The working group has been created and the terms of reference for the working group have been prepared as follows:

Scope

The “AC Quantum Voltage standard Development and Cooperation” Group has been established to:

- Integrate individual strategies of each NMI/DI for the long-term development of the research capability in AC quantum voltage metrology, bridging the gap between the less-and more-advanced NMIs and DIs.
- Promote and support cooperation to build a sustainable metrology infrastructure including the access to shared AC quantum infrastructures in order to achieve concentration and the synergetic and efficient use of competences and resources as well as the fulfillment of the particular needs of each country.

- Share metrological expertise between established member institutes and new or emerging EURAMET Members, at the same time consolidating the existing measurement capabilities in the participating institutes.
- Promote the development in the countries of the new and emerging EURAMET Members by increasing cooperation and collaboration on AC Quantum voltage standards.

<u>Tasks</u>

The general tasks of the group are to:

- Promote, coordinate and set priorities for collaborations for participating institutes in the field of quantum AC voltage standards
- Provide an official place and suitable means for the discussion of all the thematic related to cooperation and development of quantum AC voltage standards, both within the participants and potentially with other EURAMET NMIs/DIs.
- Raise awareness of metrologists and, more generally, of stakeholders on Group activities by means of a broad impact strategy that may include: presentations at the relevant TCs and sub-committees, conferences, as well as communications to a broader audience by means of webpages and social media.
- Propose appropriate research activities and targeted initiative for foreign researchers hosting (e.g. RMGs), to develop the research potential among the less experienced EURAMET members (for example through EMPIR RPT JRPs), facilitating access to EU structural and other funds, and engagement with EMPIR.
- Ensure a coordinated and optimized approach to the development of traceability to quantum AC voltage standards for Europe as a whole.
- Supervise the establishment of appropriate quality schemes and accreditation. On the long-term, all strategies are expected to include the offering of calibration services, in individually-run or shared facilities, both within each country and addressed to neighboring countries.
- Keep an updated metrology quantum AC voltage standards capacity map and identify national, regional and European priority needs and to establish an action plan based on this map and elaborate prospections of EU NMIs/DIs needs/plans for AC quantum voltage standards (polls, questionnaires..)
- Facilitate collaborations and the joint use of facilities and enable the efficient use of available resources.
- Stimulate, identify the need and start training activities (e.g web-based training courses) and comparisons,
- Collaborate with TC-EM subcommittees, specifically with EURAMET TC-EM-“DC &Quantum Metrology”, EURAMET TC-EM-“Low Frequency”, EURAMET TC-EM-“Power and Energy”, on the group tasks.

Organisation

- This working group (WG) is composed by members that have been selected according to the following rules:
  - at least 4 experts with specific know-how in DC Voltage & Quantum Metrology, as required for DC & Quantum Metrology” Subcommittee membership
  - at least 2 experts with specific know-how in Power and Energy, as required for Power and Energy EURAMET TC-EM Subcommittee membership

- at least 2 experts with specific know-how in AC/DC and Low Frequency, as required for Low Frequency EURAMET TC-EM membership
- at least 1 expert with specific know-how in Fabrication Technology
- preferably 1 expert in the relevant fields from BIPM

— The number of WG members must not be lower than 10 nor exceed 15.

— Representatives from involved organizations may be invited to the meetings and the activities.

— The WG is chaired by a Convener, proposed by the Members of the group. The Convener is appointed for a term of two years. The Working Group is entitled to organize its internal operations according to the needs of the Working Group.

— The WG will meet on a regular basis (typically once a year, in correspondence to TC-EM Subcommittees meetings or main conferences). Meetings and contacts can be arranged also via teleconferencing.

Activities

At the first meeting held by teleconference on 4 April 2018 the following actions were taken:

— Constitution of the group

— Approval of the terms of reference

— Election of the group convener

Proposal as a working group of the TC-EM

- The group was proposed as a working group of the TC-EM
- The chairperson of the TC-EM that the network on quantum technologies can change the structure of the TC.EM and subcommittees. An asked the working group to remind on stand-by, or go through the proposal so it will be discussed in the next meeting of the working group for Strategy plans.

A second meeting was held as a CPEM 2018 satellite meeting. This meeting was also open to all interested in AC quantum standards. It was decided to go ahead with the proposal to be a TC-EM working group.

Summary of the key results and conclusions

This objective was achieved. The working group has been stablished. The first members were selected. The terms of reference have been approved. The convener for the first two years was elected. The group have been proposed as a working group of the TC-EM. The decision will be taken during the next meeting of the Strategy planning working group to be held in Croatia on September 2018.

4.5 Creation of individual strategies for the long-term development of the research capability in AC quantum voltage metrology for each NMI/DI partner developing capability in project.

Relevance to the project needs and objectives

One of the long term research objectives of EURAMET is to make AC quantum voltage standards the basic for AC metrology. To achieve this, it is necessary that the NMIs establish their individual strategic plans for the development of AC quantum voltage standards.

Work undertaken

With the knowledge acquired in the project, NMIs developing capabilities in the field have prepared these individual strategic plans covering at least the next five years. The strategies consider the development of either individual or collaborative quantum standards, or even an agreement to the future use of other NMI standards. In addition, a strategy for the NMIs to offer calibration services in in their own country and neighboring countries within quality schemes and accreditation that will ensure a coordinated appropriate development of traceability in the field of AC quantum voltage metrology in Europe.

Each individual plan includes: i) the selected AC Voltage Standard(s) to be implemented: Programmable Josephson Voltage Standard (PJVS), and/or Josephson Arbitrary Waveform Synthesizer (JAWS); ii) priorities for collaborations with the research community in the NMI country or with neighboring NMIs for the establishment of the AC quantum voltage standard; iii) future applications of AC Voltage Standard; iv) establishment of appropriate quality schemes and accreditation to ensure a coordinated development of traceability in this field in Europe; v) expected individual contribution to the improvement of CMCs for the next five years; vi) Gantt chart presenting the planning of the individual strategies.

In consideration of the cooperative approach, the individual strategies, were previously discussed with the other participant Institutes, to ensure a coordinated development of the European research and measurement infrastructure from the early beginning. Finally, all the individual strategies were revised by INRIM, PTB and NPL.

Summary of the key results and conclusions

This objective was achieved. All partners have prepared the short and long term strategies for AC quantum standards development. According with this strategies in a few years most of the NMIs will have AC quantum standards, providing direct traceability to the new future SI definition.

5 Impact

The results of this project were presented at 7 conferences and submitted for publication as two peer-reviewed papers. The project was presented to EURAMET Technical Committee for Electricity and Magnetism (TC-EM) and a Good Practice Guide on the operation of AC quantum voltage standards which was written by the consortium was submitted to TC-EM to be considered as a TC-EM document. Three articles aimed at general public and calibration laboratories were published in journals EspacoQ and Revista Medições e Ensaios.

The training material used in the first workshop was collected, assembled and, after agreement for guarding the intellectual property rights of the partners, it was published on the project public website so that it is accessible to any interested party.

The project website contains all information and output documents that could be released publicly. In addition, a project page was created on ResearchGate to increase the visibility and ensure the documents are available for longer. An overview of the publically available material was sent to metrological technical committees of all Regional Metrology Organisations.

Impact on industrial and other user communities

During the project, a pioneering intercomparison of PJVS has been arranged among BIPM, PTB and NPL. This intercomparison took place from 2017 to 2018 and it was beneficial for BIPM to establish the comparison protocol, given the three different designs used. Such a protocol is a prerequisite for key comparisons of AC voltage using quantum systems and thanks to this activity a key comparison can be started and traceability initiated. Comparisons are a main prerequisite for the use of AC quantum voltage standards in accredited laboratories and industry, and therefore this activity will have worldwide impact.

Results of the project were discussed with and presented to BIPM, Supracon AG and eszAG.

Impact on the metrology and scientific communities

With the knowledge acquired in the project, 9 NMIs developing capabilities in the field have prepared individual strategies for the development of the research capabilities in AC quantum voltage metrology. These strategies are the result of activities carried out within this project and cover at least the next five years. The strategies considered the development of either individual or collaborative quantum standards, or an agreement to the future use of other NMI standards. In addition, the strategies included a plan for calibration services in the established facilities which will comply with quality schemes and accreditation and will ensure a coordinated appropriate development of traceability in the field of AC quantum voltage metrology in Europe. The individual strategies were discussed within the consortium, to ensure a coordinated development of the European research and measurement infrastructure from the early beginning. According with these strategies in a few years most of the NMIs that participated in this project will have AC quantum standards, providing direct traceability to the new future SI definition.

Training material on AC quantum voltage systems and measurement methods were collated and made publically available. This material is being used as teaching material at the Department of Physical Electronics, Masaryk University, in Brno. The course on Low temperature physics, which is using this material is attended by many students every year.

AC quantum standards cannot be driven without a software. However, contrary to expensive hardware or know-how, software can be often easily transferred to other institutes thus decreasing time to acquire the new device. This can be usually done only if the software is open-source because some modification of the source code is almost always required. INRIM developed an open source software for operation of PJVS, which allows future improvements. This initiative has the potential to save other institutes significant time that otherwise would be spent in the development of software for ACQVS.

Impact on relevant standards

Two papers have been submitted for publication in peer-reviewed journals which address the issues of present standards for calibration of analogue to digital converters, namely IEEE Std. 1057-2017 and IEEE Std. 1241-2010. The problems of aperture time, stability of digitizer and uncertainties were studied in detail and are advancement compared to the actual standards.

A new group was formed and was proposed as a working group of EURAMET TC-EM. This group will be crucial for sharing and developing knowledge on AC voltage quantum standards after the end of the project and therefore will contribute to the establishment of a basis for a future European cooperation on the area. Because of the knowledge gained in this project, even less experienced NMIs were able to join this group.

Longer-term economic, social and environmental impacts

ACQVS have become the primary standards in the field of electrical power. Therefore, the acquisition of ACQVS by the less experienced NMIs which participated in this project will have a long term impact on CMCs related to power measurement, which are required for development of smart grids. This will lead to a decrease in the wasting of electrical power, which in turn will have direct economic and environmental impact.

6 List of publications

Javier Díaz de Aguilar, Raúl Caballero, Yolanda A. Sanmamed, Martin Šíra, Patryk Bruszewski, Andrea Sosso, Vitor Cabral, Luís Ribeiro, Helge Malmbekk, Jonathan M. Williams, Ralf Behr, Oliver Kieler, Recep Orhan, Grégoire Bonfait, Good practice guide on the operation of AC quantum voltage standards, ISBN: 978-80-905619-2-2, 2018.

7 Contact details

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