On-site comparison of dc and ac voltages from Josephson arrays

Technical protocol for BIPM.EM-K10 comparisons

1. Introduction

The Mutual Recognition Arrangement (CIPM-MRA) among National Metrology Institutes (NMIs) places particular importance on key comparisons to demonstrate an NMI's ability to measure certain critical quantities. The Consultative Committee for Electricity and Magnetism (CCEM) has identified comparisons of Josephson Array Voltage Standards (JAVS) as key comparisons. These standards are considered as primary voltage standards.

To take advantage of the high accuracy of JAVS, on-site direct comparisons have been carried out by the BIPM since 1991 at the level of 1.018 V, and since 2004 at the level of 10 V. The results are listed in the Key Comparison Database (KCDB) under the identifiers BIPM.EM-K10.a (1.018 V) and BIPM.EM-K10.b (10 V).

In 2015, the BIPM proposed to extend the comparison to alternating (ac) voltages for low frequencies (up to 1 kHz) based on a Programmable Josephson Voltage Standard (PJVS) and differential sampling technique[1], from which the RMS value of the fundamental frequency of a sinusoidal signal (designed as *RMS value* in the document) is measured. The present protocol is based on the results and lessons learnt from several pilot studies conducted with 9 NMIs (CENAM, KRISS, MIKES-VTT, NIST, NMIA, NMIJ, NPL, PTB, and VNIIM), between 2015 and 2021 [1-7] [2]. It offers four different options (two for dc comparisons and two for ac

[1] An extensive bibliography is given in paragraph 12.

[2] The BIPM measurement system includes some of the technologies developed by NMIs during these pilot studies, in particular by NIST, KRISS, NMIA, PTB and VNIIM.

comparisons) depending on the participating laboratory's capabilities and needs. Each completed option during the period allotted to the comparison will lead to a publication in the KCDB.

2. Purpose

The purpose of the comparison described in this protocol is to compare the voltage reference of the participant laboratory with that of the pilot (BIPM) in the framework of the BIPM.EM-K10 key comparisons. The measurements will be performed at the participating laboratory in the presence of two BIPM staff members for a period varying between one week and two weeks depending on the selected options. The related financial cost (equipment shipment, liquid-He consumption, staff travel, living expenses) will be shared between the participant and the BIPM (section 9).

The comparison will consist of a list of exercises selected by the participant:

1- Direct comparison of the participant's JAVS to the BIPM transportable programmable Josephson voltage standard (PJVS)[3] in dc at nominal voltages of 1 V and/or 10 V. Two different options for the comparison at dc are described in sections 4 and 5.

2- Indirect comparisons in ac at 3 different frequencies selected by the participant from the possible values of 10 Hz, 50 Hz, 60 Hz, 62.5 Hz, 100 Hz, 312.5 Hz, 625 Hz, 976.5625 Hz and 1 kHz at one or two different RMS voltages (0.75 V and 7 V) according to the two proposed options and described in detail in sections 4 and 5.

This protocol follows the "Guidelines for CIPM key comparisons" and the "CCEM Guidelines for Planning, Organizing, Conducting and Reporting Key, Supplementary and Pilot Comparisons". The current version of the CCEM document can be downloaded as a *pdf* file from: https://www.bipm.org/utils/common/pdf/CC/CCEM/ccem_guidelines.pdf

[3] The BIPM traveling standard is **no** longer the SIS-based Josephson junctions hysteretic array used for previous BIPM.EM-K10 comparisons.

3. The BIPM traveling standard

The traveling standard is the BIPM programmable Josephson voltage standard (PJVS), which is composed of a cryoprobe that carries “a liquid-helium version of the 10 V SNS NIST programmable array” [8]. The voltage across the array is controlled by a dedicated microwave source and a dedicated bias source. The array must be cooled down to liquid He temperature. The participant shall provide a dewar of liquid He to the BIPM staff for the comparison period: He quantity and dewar flange dimensions will be discussed prior to the comparison.

The PJVS is operated with the embedded NIST software (*iPJVS Core 2021-v1208* or later) and can also be controlled using an external computer equipped with the *NI DataSocket Transfer Protocol*™. The PJVS is electrically floating with no connection to earth potential; this allows the participant to have the low side of its array earthed during the direct comparison of the two quantum voltages. The series resistance of each of the precision measurement leads is 1 Ω, and their leakage resistance to earth is 80 GΩ. These values are checked on-site using a dedicated feature of the *iPJVS Core* software. The value of the thermal electromotive forces (EMFs) measured at the level of the output connection (at the laboratory temperature) is in the range 600-900 nV.

For the ac voltage comparison, the setup is flexible and allows a large number of possibilities for differential sampling, among which the principal ones are:

- The PJVS system uses a single 10 MHz reference for timing and RF bias;
- The stepwise approximated sinewave of the BIPM PJVS can be synchronized to an external signal;
- The BIPM PJVS system can provide to the participant, a synchronization signal of a frequency proportional as that being measured;
- The setup can operate three different samplers (K3458A, NI PXI-5922, F8588A) using specially designed software.

4. The different options to be selected by the participant

The BIPM offers **four** different variants (2 in dc and 2 in ac) for performing the on-site PJVS key comparison and the participant should select a maximum of **two** of them that are in accordance with their measurement capabilities. The four different options are described below and in more detail in section 5.

I. Direct comparison of dc quantum voltages at the level of 1 V and 10 V using the participant's measurement setup. The participant's procedure to measure a secondary voltage standard is applied.

II. Direct comparison of dc quantum voltages at the level of 1 V and 10 V using the BIPM measurement setup (Cf. Fig.1). Previous experience showed that a lower Type A uncertainty can be achieved than in option I.

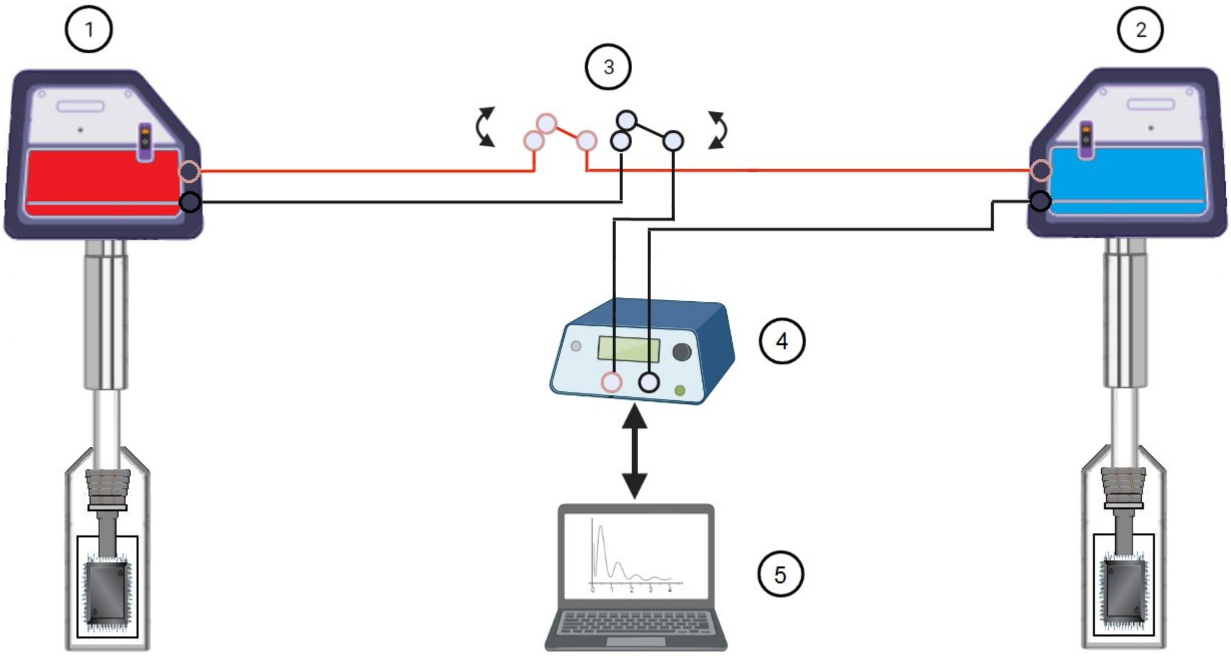

Figure 1: Measurement setup corresponding to option II where ① is the BIPM traveling standard, ② is the participant's measurement standard, ③ is a BIPM's very low thermal EMFs switch to open/close the measurement circuit, ④ is the nanovoltmeter provided by the BIPM and ⑤ is a computer running the BIPM comparison software.

III. Indirect comparison of the RMS value of a sinewave at 3 different frequencies selected by the participant from the following ensemble: 10 Hz, 50 Hz, 60 Hz, 62.5 Hz, 100 Hz, 312.5 Hz, 625 Hz, 976.5625 Hz and 1 kHz, at one or two different RMS voltages

(0.75 V and 7 V). Both the participant's and the BIPM's Josephson-based setups will measure the signal generated by their own ac source. The results will be linked by a full sampling measurement of both source signals carried out by the BIPM sampler (K3458A) and associated full sampling software[4] (Cf. Fig.2).

Remark: the choice of the voltage 0.75 V relies on the benefit of the best metrological capabilities of the 1 V range of the BIPM sampler.

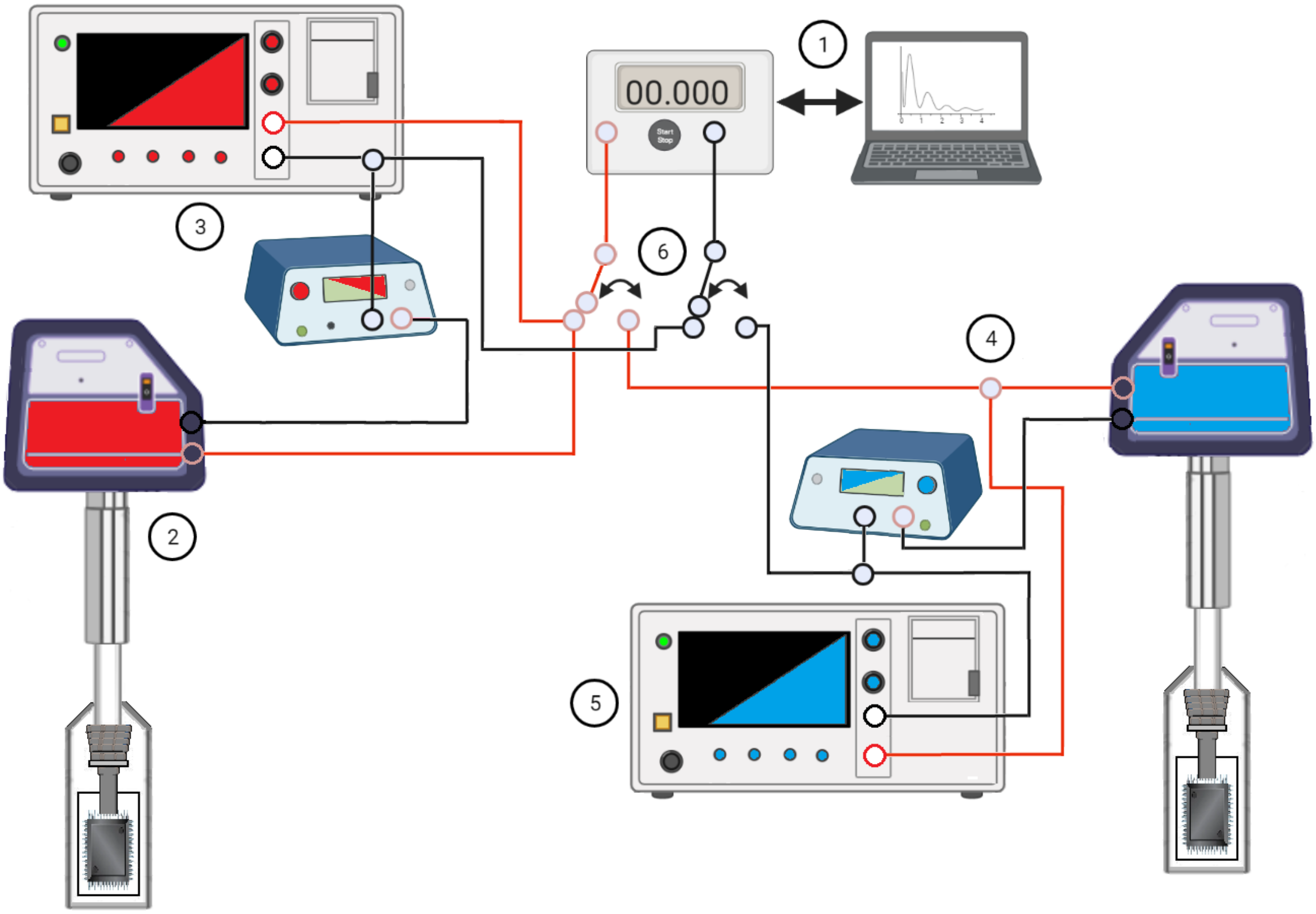

Figure 2: Measurement setup corresponding to option III where ① is the BIPM transfer standard (*sampler and associated full sampling software*), ② is the BIPM differential sampling setup, ③ is the BIPM ac source, ④ is the participant measurement setup, ⑤ is the participant ac source and ⑥ a computer controlled ac coaxial switch to switch the transfer standard between the measurement setups.

Note: This figure shows that the participant setup uses differential sampling with a sampler between the two LOW-terminals of the source and PJVS. This doesn't imply that the participant must comply with this schematic.

[4] *EnergoEtalon* Software developed at VNIIM [9]

IV. Indirect comparison of the RMS value of a sinewave signal generated by a BIPM ac source transfer standard[5] at 3 different frequencies selected by the participant from the following ensemble: 10 Hz, 50 Hz, 60 Hz, 62.5 Hz, 100 Hz, 312.5 Hz, 625 Hz, 976.5625 Hz and 1 kHz, for two different RMS voltages (0.75 V and 7 V) (Cf. Fig.3). The signal generated by the BIPM ac source is measured by the BIPM and the participant alternatively.

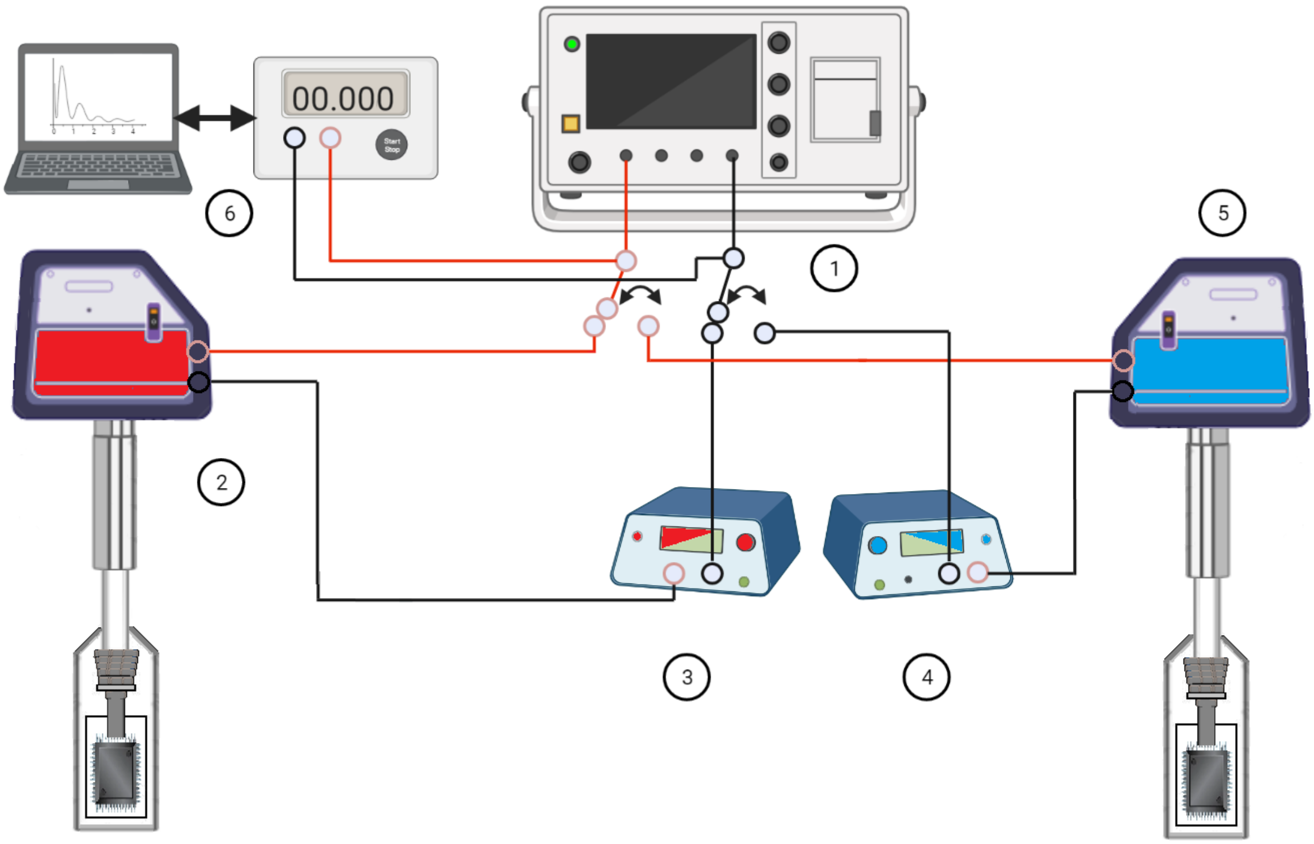

Figure 3: Measurement setup corresponding to the option IV where ① is the BIPM ac source transfer standard associated to a computer controlled symmetric switch to switch the transfer standard between the measurement circuits, ② is the BIPM PJVS, ③ is the BIPM sampler, ④ is the participant sampler, ⑤ is the participant PJVS and ⑥ is a measuring system which records the transfer standard output voltage continuously.

Note: This figure shows that the participant setup uses differential sampling with a sampler between the two LOW-terminals of the source and PJVS. This doesn't imply that the participant must comply with this schematic.

5. Detailed description of each option

In this paragraph, the different options introduced in paragraph 4 are described in more detail.

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[5] *Signal Waveform Generator* developed at CMI [10]

Option I and II: the two PJVSs are programmed to generate a nominally identical dc voltage of 1 V or 10 V. If the frequency of the RF sources **cannot** be adjusted in such a way that the two PJVSs generate identical voltages, the theoretical voltage difference between the two PJVSs is chosen to be the smallest possible. In option I, the voltage difference between the two standards is measured using the participant's dedicated setup and software used to measure secondary voltage standards.

In option II, the BIPM software and digital nanovoltmeter are operated. If the mean value of 10 consecutive measurements and associated Type A uncertainty are of a relative order of a few parts in 10^9 at 1 V or 10^{10} at 10 V, the digital nanovoltmeter is replaced by a BIPM analog nanovoltmeter and a new series of measurements is performed. With this configuration, a relative Type A uncertainty of a few parts in 10^{10} at 1 V or 10^{11} at 10 V is achievable in the best case.

Introduction to options III and IV

In options III and IV, a transfer standard is introduced between the two independent Josephson based measurement setups. Both transfer standards belong to the BIPM.

- In option III, the transfer standard is a sampler (K3458A) connected alternatively in parallel to both ac source outputs. This sampler is associated to a full sampling software designed at the VNIIM [9] to perform a continuous measurement of the RMS value of a sinewave output signal.

- In option IV, the transfer standard is an ac source provided by the BIPM (commercial ac source designed and assembled at CMI - Czech Metrology Institute) [10].

In both options, two BIPM computer controlled switches (BNC connectors type) are installed on the BIPM transfer standards (meter in option III and ac source in option IV) in order to easily switch its input (option III) or output (option IV) between the BIPM measurement setup and the participant's measurement setup; the connection time is reduced to the minimum possible. Furthermore, any physical manipulations and related changes between the two measurement setups are avoided.

The 10 MHz reference signal distributed in the laboratory is used by both setups. In order to avoid any interference, the signal is decoupled between the two setups using isolation transformers provided by the BIPM.

Option III:

The two Josephson based measurement setups are fully independent and each of them measures its own ac source signal. The BIPM meter and associated full sampling software (transfer standard) measures the rms value of the signal of each ac source alternately.

An example of the results obtained is shown in figures 4a and 4b. The difference between the participants, ΔU, will then be calculated as:

$$\Delta U = [U_{\mathrm{LAB.}}(t_1) - U_{\mathrm{FS}}(t_1)] - [U_{\mathrm{BIPM}}(t_2) - U_{\mathrm{FS}}(t_2)],$$ where:

- $U_{\mathrm{LAB.}}(t_1)$ is the mean RMS value measured by the participant's Josephson-based setup during time t_1;
- $U_{\mathrm{FS}}(t_1)$ is the mean RMS value measured by the full sampling software during the same time;
- $U_{\mathrm{BIPM}}(t_2)$ is the mean RMS value measured by the BIPM Josephson-based differential sampling setup during time t_2;
- $U_{\mathrm{FS}}(t_2)$ is the mean RMS value measured by the full sampling software during the same time.

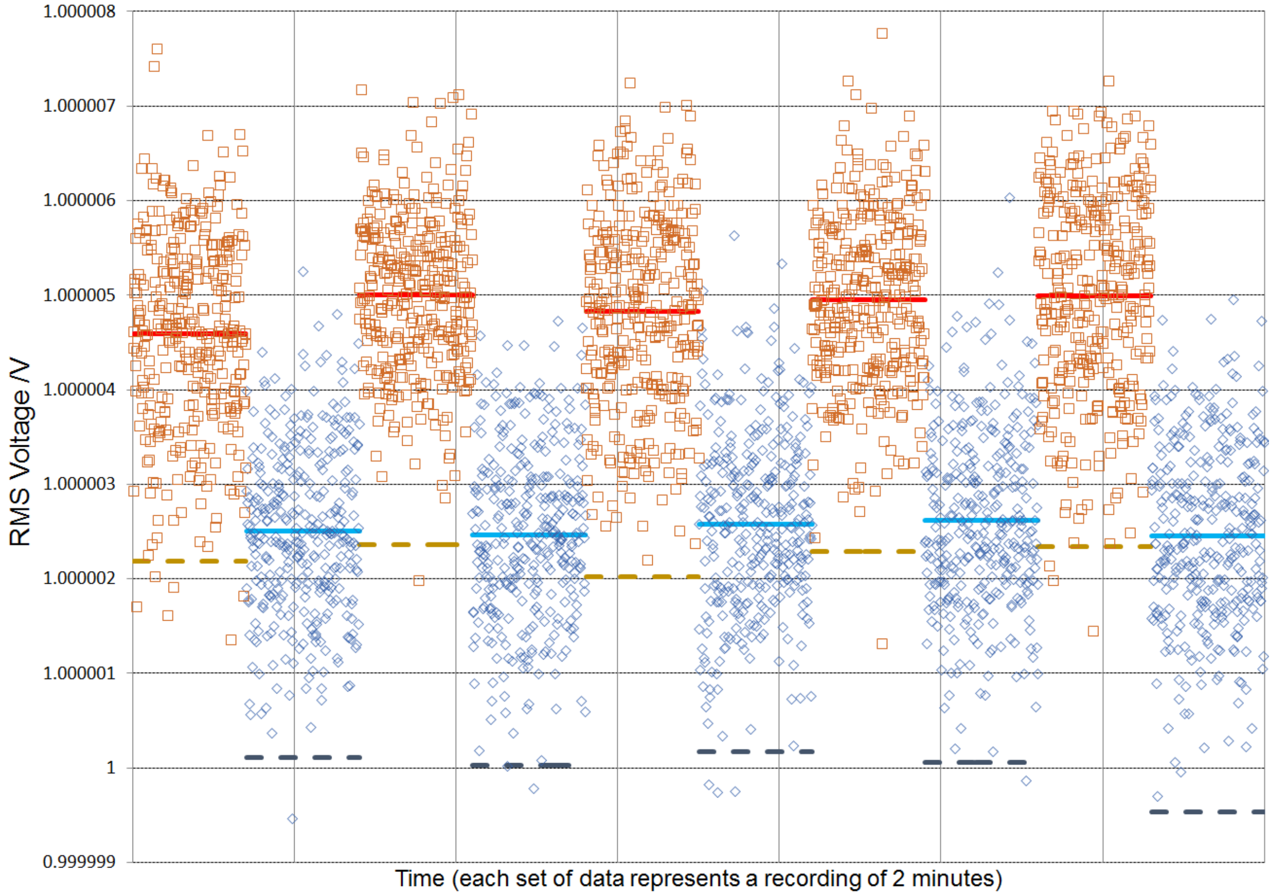

Figure 4a: Results obtained during a pilot study performed with PTB in 2021 for 1 V RMS and 312.5 Hz. The individual points of each data set are the recordings of the BIPM sampler (and VNIIM software) and its mean value is represented by the solid lines. The dashed lines in light colour (orange for PTB and black for the BIPM) are the mean RMS values of the differential sampling obtained over/during the same measurement periods.

<u>Note</u>: In the reported example, the ac sources investigated were of the same type and their drift was negligible over the 30 minutes of the experiment. The commutation time of the transfer standard between the two systems was also negligible since the phase lock of the PJVSs and the signals was never lost. This may not be always the case and would depend on the capabilities of the setup of the participant.

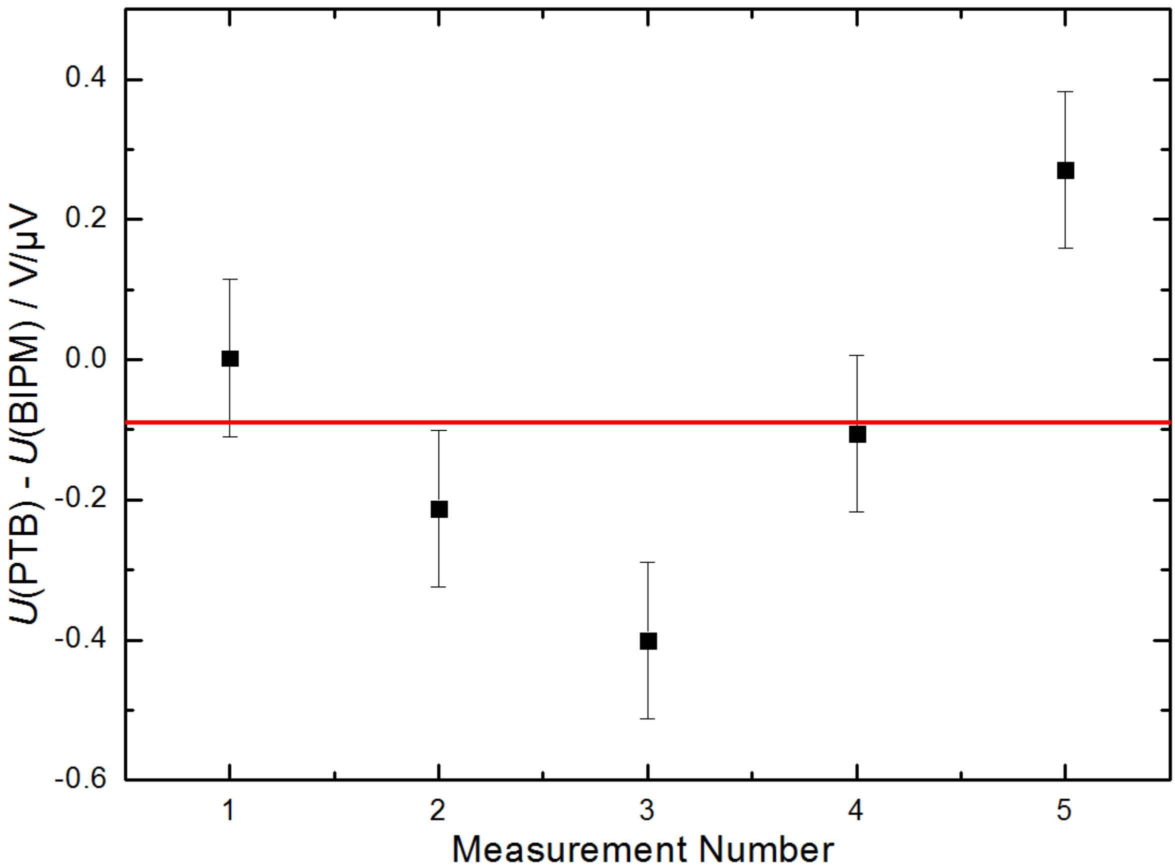

Figure 4b: ΔU calculated from the 5 data sets of Figure 4a providing 5 individual voltage differences between the participant and the BIPM. The straight line in red represents the mean value and the uncertainty bars are the standard deviation of the mean at 1σ.

Option IV:

In option IV, the transfer standard to be measured is the BIPM CMI SWG generator. This source is powered from batteries and is temperature regulated, offering state of the art stability both in voltage amplitude and phase. However, if the participant's setup employs differential sampling relative to a PJVS, it would need to synchronize its PJVS approximated waveform to the ac signal of the transfer standard [7]. This can be performed in two different ways:

1- The transfer standard offers a synchronisation signal that would be used to synchronize the Josephson waveform.

2- A PJVS trigger signal can be used to synchronize the transfer standard ac source signal.

The BIPM PJVS allows different possible synchronization modes [7], developed in collaboration with KRISS, and figure 5 shows option 1.

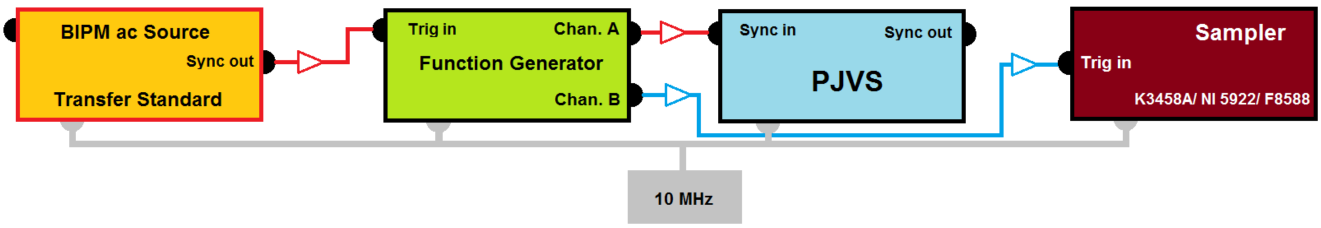

Figure 5: Synchronization signals chart used in the option IV for the BIPM PJVS.

The trigger signal of the ac source is in phase with the sinewave at the output of the source. It triggers a function generator that will produce:

1- A clock signal to synchronize the PJVS approximated sinewave to the ac source sinewave;

2- A trigger signal for the sampler (*K3458A, F8588A, NI - PXI 5922A*).

Remark: The BIPM differential sampling setup can operate different sampler types (Keysight 3458A, NI PXI-5922 and Fluke 8588A) with different differential sampling software. If digital apertures are used in the measurement, an agreement among participants on how to perform an aperture correction may be necessary.

6. Organisation of the measurements

After the BIPM equipment has been set up, the most stable measurement conditions must be identified by looking at the variation of the shape of the quantum voltage steps (quantum margins) as a function of the earthing configurations of the measurement setup.

Remark: It is fundamental to investigate the earthing arrangement of the measurement setups in order to minimize electromagnetic interference from the surroundings but also interference between the systems. This prerequisite cannot be circumvented.

The earthing configuration of the measurement setups is considered acceptable when the statistical dispersion of ten consecutive measurements (i.e. voltage difference between the BIPM and the participant) includes the zero volt difference line with a coverage factor of k=2. This result will be published as the preliminary comparison result.

Experience has shown that most comparisons of Josephson standards have helped reveal measurement problems for example associated with leakage resistance, earth loops, etc., which will typically appear as a systematic error in the measurement results. If such problems are identified and corrected within the time allotted for the comparison and if this leads to a significantly better comparison result, this result will be considered as the final result of the comparison.

However in such cases, both results will appear in the tabular form in the BIPM Key Comparison Database (http://kcdb.bipm.org) but only the second result will be plotted on the graph.

As an example, **Tables 1a, 1b, 1c** present the results relative to the nominal voltage as they would be presented. They are given as examples and are not representative of all possible results. Furthermore, combined uncertainties are presented in the KCDB whereas the following examples only show Type A uncertainties with a coverage factor of k=1.

Note: A maximum of 2 options can be selected by the participant.

Options	KCDB identifier	Nominal Voltage/Frequency	Result / 10^{-9} V
I	BIPM.EM-K10.a	1 V – dc	-1.7 ± 2.6
I	BIPM.EM-K10.b	10 V – dc	2.5 ± 3.3
II	BIPM.EM-K10.a	1 V – dc	0.7 ± 1.1
II	BIPM.EM-K10.b	10 V – dc	0.25 ± 1.30

Table 1a: Example of the results obtained by a participant that selected Option I and II of the comparison protocol. Uncertainties are Type A uncertainties with a coverage factor of k=1.

Options	KCDB identifier	Nominal Voltage/Frequency	Preliminary result / 10^{-6} V	Final result / 10^{-6} V
III	BIPM.EM-K10.c	1 V – 62.5 Hz	0.7 ± 0.7	0.4 ± 0.2
III	BIPM.EM-K10.d	1 V – 312.5 Hz	-1.4 ± 4.0	-0.09 ± 0.12
III	BIPM.EM-K10.e	7 V – 1000 Hz	2.6 ± 2.0	1.25 ± 1.0

Table 1b: Example of the results obtained by a participant that selected Option III of the comparison protocol. Uncertainties are Type A uncertainties with a coverage factor of k=1.

Options	KCDB identifier	Nominal Voltage/Frequency	Preliminary result / 10^{-6} V	Final result / 10^{-6} V
IV	BIPM.EM-K10.c	1 V – 62.5 Hz	0.5 ± 0.5	0.08 ± 0.05
IV	BIPM.EM-K10.d	1 V – 312.5 Hz	-1.3 ± 2.0	-0.12 ± 0.20
IV	BIPM.EM-K10.e	7 V – 1000 Hz	1.6 ± 2.0	0.68 ± 0.70

Table 1c: Example of the results obtained by a participant that selected option IV of the comparison protocol. Uncertainties are Type A uncertainties with a coverage factor of k=1.

7. Participant's measurement report

The participant's measurement report must contain a detailed uncertainty budget stating the method evaluating the different components and their respective values for both the dc voltage measurement and the ac voltage RMS value measurement.

7.1 Uncertainty budget in dc voltage measurement

The following list contains the typical Type B uncertainty components to be considered for measurements of a dc voltage using a Josephson voltage standard:

- realisation of the volt;
- systematic errors of the RF bias frequency source (i.e. frequency offset from the theoretical value);
- detector (linearity);
- leakage resistance;
- thermal electromotive forces (any residual thermal EMFs not contained in the Type A uncertainty);
- effects of electromagnetic interferences.

7.2 Uncertainty budget in ac voltage for the RMS measurement

The following list contains the typical Type B uncertainty components to be considered for measurements of the RMS value of an ac voltage sinewave using a JAVS-based differential sampling technique [7, 11-15]:

- realisation of the volt with the JAVS;
- sampler drift (if not already comprised in the Type A uncertainty);
- sampler gain and integral non-linearity;
- sampler bandwidth;
- drift of the ac transfer standard;
- phase jitter and misalignment of the transfer standard;
- step width/sampler aperture ratio;
- effects of the transients (delay time between step transitions);
- transmission line error and leakage current induced error.

8. Comparison Report and Publication of the results

As pilot laboratory, the BIPM will write the comparison report.

The result will be expressed as the relative difference between the value that would be attributed to the measurand by the participant measurement system ($U_{LAB.}$) and the BIPM's measurement system (U_{BIPM}):

$$(U_{LAB.} - U_{BIPM}) / U_{BIPM}$$

and its relative combined standard uncertainty u_c / U_{BIPM} where u_c is the combined standard uncertainty.

The Draft A report will be sent to the participant for discussion, normally within two months after completion of the comparison.

Upon approval by the participant and the pilot, the report becomes a Draft B report. It is submitted for review by the chairperson of the CCEM Working Group on Low Frequencies (CCEM-WGLF).

Once the Draft B is formally approved, the report becomes a final report that is submitted to the KCDB. The results are published in the BIPM Key Comparison Database (http://kcdb.bipm.org) and the final report is published in the Technical Supplement of *Metrologia*.

9. Cost sharing

The BIPM covers the travel and living expenses for the BIPM staff and the cost of the transport of the equipment from the BIPM to the NMI. The NMI shall pay for the liquid helium consumption, the local hotel accommodation of the staff and for the transport of the equipment from the NMI back to the BIPM, including those costs incurred by the BIPM if it must make some arrangements for the shipment and customs clearance operations.

10. Contact persons

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Participant	name of the contact person “laboratory name” “address” “Country” Tel.: e-mail:

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