On-site comparison of Josephson arrays

Technical protocol for BIPM.EM-K10.a & b option A 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) at the level of 1.018 V and 10 V 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. 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).

2. Purpose

The purpose of the comparison described in this protocol is to link the voltage reference of the "name of laboratory (NMI), country"[1], to that of the pilot (BIPM) in the framework of the BIPM.EM-K10 key comparisons.

The measurements will be made at nominal voltages "1.018 V or 10 V" at the "laboratory" between "dates".

This protocol follows the rules of the "Measurement comparisons in the CIPM MRA" and the "CCEM Guidelines for Planning, Organizing, Conducting and Reporting Key, Supplementary and Pilot Comparisons". These documents can be downloaded as *pdf* files from:
http://www.bipm.org/en/cipm-mra/cipm-mra-documents/ and
http://www.bipm.org/en/committees/cc/ccem/publications-cc.html

Technical changes to this protocol need to be approved by the CCEM comparison support group.

3. The travelling standard

The travelling standard is the BIPM Josephson array voltage standard, which is composed of the cryoprobe with a 10 V SIS array, microwave equipment and a bias source for the array. To visualize the array characteristic, while keeping the array floating from the ground, an optical isolation amplifier is placed between the array and the oscilloscope. During the measurements, the array is disconnected from its bias source and from the oscilloscope. The series resistance of both precision measurement leads is less than 4 Ω, and the value of the thermal electromotive forces (EMFs) is less than 100 nV. The leakage resistance between the precision measurement leads is typically 5 to 7×10^{11} Ω and is usually checked on-site. This operation is done with a megaohmeter while the array is not yet mounted on the probe. To verify the step stability, a digital voltmeter is used to measure the voltage across the array using a separate set of leads.

4. The option A

The BIPM offers two variants for performing on-site JAVS keys comparisons. In the one considered here, option A, the BIPM uses its equipment to measure the voltage provided by the participant's JAVS. The BIPM equipment consists of an EM model analog nanovoltmeter (N1a or N11) whose output is connected, via an optically-coupled isolation amplifier, to a pen recorder and a digital voltmeter (DVM) which is connected to a computer.

This computer is used to monitor measurements, acquire data and calculate results. Low thermal electromotive force switches are used for critical switching, such as polarity reversal of the detector input. The connection of both arrays in series opposition is also controlled by a low thermal electromotive force switch. The equipment includes a voltage divider to prevent the detector from overload if both systems are no more on the selected steps.

5. Organisation of the measurements

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[1] Words in orange color between quotation marks are variable.

After the BIPM equipment has been set up and sufficiently stable conditions have been found on both standards (*ie* stability of the voltage arrays when the measurement loop is closed), the participant's standard is connected to the BIPM measurement system.

Ten measurement points are acquired according to the following procedure:

1- Positive array polarity and reverse position of the detector;
2- Data acquisition;
3- Positive array polarity and normal position of the detector;
4- Data acquisition;
5- Negative array polarity and reverse position of the detector;
6- Data acquisition;
7- Negative array polarity and normal position of the detector;
8- Data acquisition;
9- Negative array polarity and reverse position of the detector;
10- Data acquisition
11- Negative array polarity and normal position of the detector;
12- Data acquisition;
13- Positive array polarity and reverse position of the detector;
14- Data acquisition;
15- Positive array polarity and normal position of the detector;
16- Data acquisition;

The reversal of the detector polarity is done to compensate the non unity gain of the isolation amplifier placed in between the analogue detector output and the DVM input. This operation will also cancel out the thermo-electromotive forces at the level of the detector.

Each "data acquisition" step consists of 10 preliminary points followed by 30 measurement points. Each of these should not differ from the mean of the preliminary points by more than twice their standard deviation, otherwise the data are rejected and the acquisition is restarted. The "data acquisition" sequence lasts 25 s and is basically the time period during which both arrays are to stay on the selected step. The total measurement time (including polarity reversals and data acquisition) is approximately 5 minutes.

This procedure is repeated ten times. The standard deviation of the mean of these points will be considered as the type A uncertainty.

If the measured voltage difference is repeatable within an acceptable standard deviation (depending on the type of the detector), this will be published as the comparison result.
Experience has shown that most direct comparisons of Josephson standards have helped reveal measurement problems such as those associated with leakage resistance, ground loops, etc. If such problems are identified and corrected within the week allotted for the comparison and this leads to a significantly better comparison result, the CCEM has decided, that the new result can be published in the KCDB as if it were the result of a subsequent bilateral comparison.
However in such cases, both results will appear in the tabular form in the BIPM Key Comparison Database (Appendix B of the KCDB: http://kcdb.bipm.org) but only the second result will be plotted on the graph.

6. Connections and compatibility requirements

- The output voltage of the participant's array has to be connected to the BIPM equipment (in series opposition with the BIPM array) using two 5 mm spade terminals.
- The BIPM probe itself is designed to fit with a PNEUROP NW50 flange type. It requires a clear diameter of 45 mm (Cf. Figure 1) extending all the way down to the helium bath.
- The laboratory is expected to provide a helium dewar fitted with this type of flange.
  For any other type of flange, please contact the pilot to check if an adapter is required.
- The BIPM array probe is inserted through a matching NW50 sliding flange so that a wide range of dewar neck lengths can be accommodated. However, the minimum immersion depth into the liquid helium is 160 mm.
- A 10 MHz reference signal must be provided by the "laboratory".

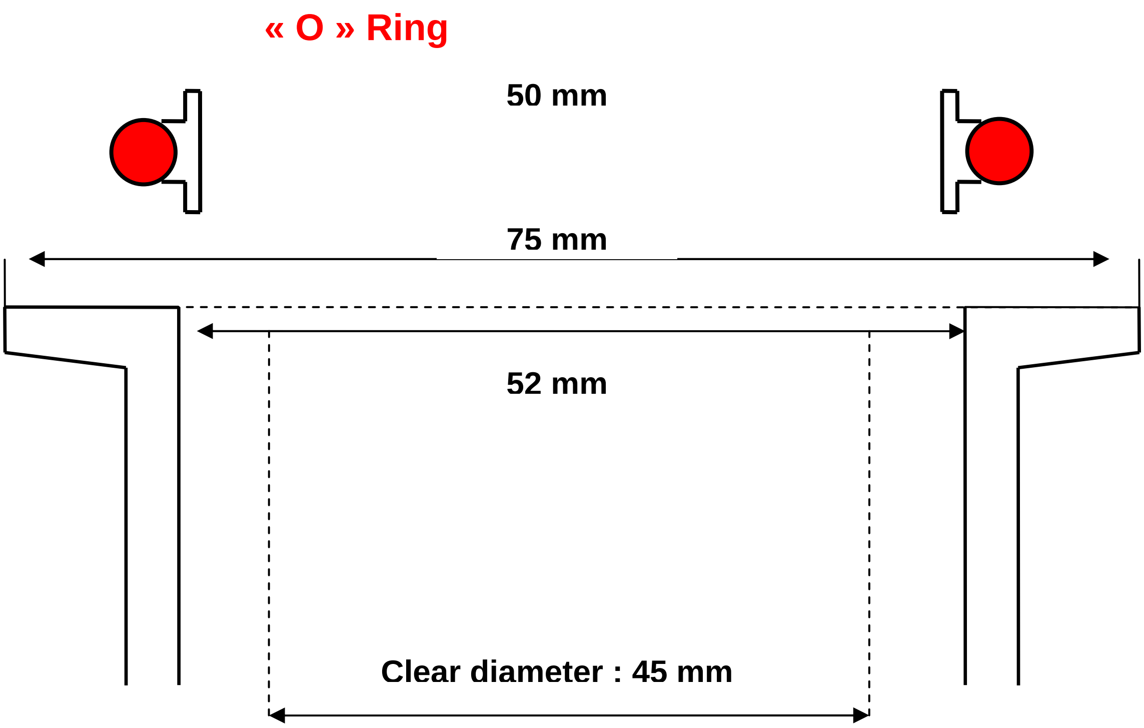

Fig 1. PNEUROP NW50 Flange Type.

7. Participant's measurement report

The "laboratory" report must be sent to the BIPM within one month from the completion of the measurements.

This report must contain:

1- A short description of the equipment and procedure used to operate the JAVS.

2 -An uncertainty budget stating the different sources of uncertainty and their values; examples are:

- realisation of the volt representation based on K_{J-90} (uncertainties related to the equipment required to operate the array);
- leakage resistance;
- thermal electromotive forces;
- effects of electromagnetic interference.
- …

A typical budget for the relative uncertainty of the voltage difference measured with the BIPM equipment, for 1 V and 10 V, is given in Table 1:

Uncertainty component	Type	Relative Contribution
Detector Calibration [a]	A	1.11×10^{-11}
Standard deviation of the mean of the results [b]	A	To be determined during the exercise
Microwave frequency [c]	B	3.0×10^{-12}
Leakage resistance of the meas. leads [d]	B	2.5×10^{-12}

Table 1: Typical relative uncertainty components (k=1) for the voltage difference measurement with the BIPM equipment, for comparisons at 1 V and 10 V.

([a]) The BIPM "detector" is corrected for its gain and non-linearity and the comparison is carried out for a voltage difference between the two quantum standards close to zero. The component is given for a voltage difference of 800 nV in this example.
([b]) This component includes the BIPM detector noise $u_r = 2.3 \times 10^{-10}$ nV and the noise in the measurement loop ($u_r = 8.6 \times 10^{-10}$ nV).
([c]) As both systems are referred to the same 10 MHz frequency reference and most of the effects of the frequency stability are already contained in the Type A uncertainty, only a Type B uncertainty for systematic errors of the EIP frequency measurement is included.

([d]) The leakage resistance uncertainty is calculated for typical values of the resistance of measurement leads (r = 4 Ω) and their insulation resistance ($R_L = 5 \times 10^{11}$ Ω). This result is the worst case as all the leakage current is considered flowing through the 4 Ω of the measurement leads.

8. Draft A Comparison Report

As pilot laboratory, BIPM will write the comparison report and this includes the items mentioned in the former paragraph.

The result is expressed as the relative voltage difference between the BIPM Josephson array (V_{BIPM}) and the "laboratory"'s JAVS ($V_{\text{“laboratory”}}$):

$$(V_{\text{“laboratory”}} - V_{\text{BIPM}}) / V_{\text{BIPM}}$$

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

The Draft A report will be sent to the "laboratory" for discussion and approval, normally within two months after completion of the comparison. Upon approval by the participant, it becomes the Draft B report.

As in all key comparisons in the series BIPM.EM-K10.a and BIPM.EM-K10.b, the key comparison reference value will be the voltage value of the BIPM Josephson standard.

9. Impact of the Comparison Result on CMCs

Following the recommendation of the CCEM (25^{th} in April 2007), the BIPM as the pilot laboratory should prepare an executive report that should consist of a compilation of short reports from the participant. The short report should list the CMCs that the participant should expect to be supported by the comparison and describe the measures that will be taken if any of these CMCs are not supported. If any participant does not provide such a report to the pilot laboratory, the pilot laboratory should include a statement in the executive report. Unlike the main report of the comparison, the distribution of the executive report is to be limited to the participant and the members of the WGRMO (Minutes of the 25^{th} CCEM – Appendix E4 - § 4 –p60).

10. Final report

The Draft B report will be submitted to the chairman of the CCEM – WGLF for final approval. If case of unresolved disagreements between the participants concerning the analysis and interpretation of the results the issue will be reported to the *CCEM support group for BIPM Josephson comparisons* who will then seek to settle it.
The final report will be submitted to the KCDB manager for inclusion in the KCDB.

11. Share of costs

The BIPM covers the travel expenses for the BIPM staff and the cost of the transport of the equipment to the NMI. The NMI is engaged to arrange and pay for the accommodation of the staff and for the transport of the equipment back to the BIPM not later than two weeks after the end of the comparison.

12. Contact persons

Pilot Laboratory

Dr. Stéphane SOLVE
Bureau international des poids et mesures (BIPM)
Pavillon de Breteuil
F 92312 Sèvres Cedex France
Tel.: + 33 1 45 07 70 26
Fax.: + 33 1 45 07 62 62
stephane.solve@bipm.org

Participant

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

13. Revision History

Version number	Date of Issue/Review	Summary of change
Draft 1	06/02/07 to 02/04/07	First version of the document : BIPM internal review
Draft 2	02/04/07 to 20/07/07	Review from the *CCEM support group for BIPM Josephson comparisons*
Ver 1.0	25/07/2007	Final version V1.0
Ver 2.0	04/09/2008	Revision of the uncertainty budget and insertion in **§ 8**
Ver 2.1	07/01/2009	Revision of the document layout
Ver 2.2	15/01/2010	Annual Review of the protocol
Ver 2.3	09/07/2010	Clarification of the uncertainty budget
Ver 3.0	16/04/2012	Table 1: Increase of uncertainty due to leakage resistance from 2.5 to 8 parts in 10^{12} and addition of related comment Inclusion of charging policy, paragraph 11 Attribution of QMS identifier: BIPM/ELEC-T-14, V3.0
Ver 3.1	25/10/2013	Unc. budget harmonization with the one presented in BIPM/ELEC-T-01, V3.2
Ver 3.2	23/09/2015	Link to the BIPM website updated (section 2). Precision added in §11