Comparison of the Josephson Voltage Standards of the KRISS and the BIPM

(part of the ongoing BIPM key comparison BIPM.EM-K10.b)

S. Solve, R. Chayramy and M. Stock
Bureau International des Poids et Mesures
Pavillon de Breteuil
F- 92312 Sèvres Cedex, France

K-T. Kim, W. Song, M-S Kim, and Y. Chong
Korea Research Institute of Standards and Science
1 Doryong-Dong, Yuseong-Gu
Daejeon 305-340, Rep. of Korea

Comparison of the Josephson Voltage Standards of the KRISS and the BIPM

(part of the ongoing BIPM key comparison BIPM.EM-K10.b)

S. Solve, R. Chayramy and M. Stock
Bureau International des Poids et Mesures
Pavillon de Breteuil
F- 92312 Sèvres Cedex, France

K-T Kim, W. Song, M-S Kim, and Y. Chong
Korea Research Institute of Standards and Science
1 Doryong-Dong, Yuseong-Gu
Daejeon 305-340, Rep. of Korea

1. Introduction

In 2004, the BIPM sent a questionnaire to the national metrology laboratories to propose a new type of comparison, where a stable reference voltage produced across the BIPM Josephson array is measured using the laboratories' Josephson array voltage standards (JAVS). This scheme allows a direct comparison with the routine measurement technique used for calibrations in the laboratories, requiring only the BIPM array (not both arrays) to maintain a perfectly stable output during the measurements. This article describes the comparison of the BIPM 10 V standard with that of the Korea Research Institute of Standards and Science (KRISS), Republic of Korea, carried out at KRISS in February 2008.

2. Comparison equipment

2.1 The BIPM JAVS

The part of the BIPM JAVS used in this comparison comprises the cryoprobe with a PTB 10 V SIS array (S/N JK50/11), the microwave equipment and the bias source for the array. The Gunn diode frequency was stabilized using an EIP 578B counter, and an ETL/Advantest stabiliser. To visualize the array characteristic, while keeping the array floating from ground, an optical isolation amplifier was placed between the array and the oscilloscope; during the measurements, the array was disconnected from this instrument. To verify the step stability, an HP 34401A digital voltmeter (DVM) was used to measure the voltage between the array voltage bias leads. The total series resistance of the measurement leads was 4 Ω, and the mean value of the thermal electromotive forces (EMFs) was found to be 140 nV, which is typically what we have in the BIPM's laboratory. The leakage resistance between the measurement leads is 5×10^{11} Ω; it should be noted that this value does not take into account the leakage due to the DVM and the optional external filter that can be used during this comparison.

2.2 The KRISS JAVS

Description of the KRISS JAVS

- Type of array: 10 V SIS, manufactured by IPHT(s/n 1469-2);
- Detector: Keithley 2182, used on the 10 mV range (without any filter);
- Bias source: Homemade source based on a PTB design;
- Oscilloscope: A Tektronix 7603 oscilloscope is used to visualise the steps and to adjust the RF power level at the beginning of a series;
- Software: Homemade under Visual Basic © environment;
- Frequency source stabilizer: Counter EIP 578B with locking of the frequency to the external 10 MHz reference and a stability better than ±1 Hz during the period of the comparison. The KRISS array is irradiated at a frequency around 75 GHz;
- The 10 MHz reference signal for the counter is provided by a synthetiser HP3325A which is itself referred to the 10 MHz signal coming from the reference clock.
- Thermal EMF (including array connections): approximately 500 – 600 nV, varies with liquid He level in reservoir;

- Total impedance of the two array measurement leads: 40 Ω or 80 Ω; this resistance includes the series resistance of a filter inserted in the two measurement leads (possible choice between two different filters).
- Leakage resistance of measurement leads: 1×10^{12} Ω.

3. Grounding configuration

The grounding configuration of the two JAVS has an important impact on the final result because it influences the dispersion of the measurement results used to calculate the final comparison result. Many different configurations were tried and are described in the Appendix A. Despite our efforts, we did not find an ideal configuration for two main reasons:

1- Part of the BIPM equipment (RF setup) was powered by the 240 V supply from the standard electricity distribution of the shielded room but the DC bias current source was powered by the 110 V from the isolated line also used to bias the KRISS JAVS.

2- The KRISS JAVS was connected to two different current sources: the scope was powered through an isolated line (isolation transformer), while the RF equipment was referred to the standard power distribution of the shielded room.

The best compromise was found to be the following: the BIPM DC bias source was referred to the KRISS DC bias source (G) and both RF sources were referred to the shielded room electricity supply (110 V for the KRISS and 240 V for the BIPM). The shielding of all the equipment was referred to G, as well as the KRISS dewar.

4. Comparison procedures: Option B scheme

The two different comparison types (options A and B) were carried out during the time allotted to the exercise. We started with an option B protocol where the KRISS JAVS was used to measure the BIPM array voltage as if it were a Zener voltage standard. It was followed by a comparison following the procedure of option A (see Appendix A).

The preliminary measurements carried out from 25 to 28 February lead to a relative voltage difference of: $(U_{\mathrm{KRISS}} - U_{\mathrm{BIPM}}) / U_{\mathrm{BIPM}} = +1.7 \times 10^{-10}$ with a relative standard Type A uncertainty of $u_{\mathrm{A}} / U_{\mathrm{BIPM}} = 0.8 \times 10^{-10}$. However, during the series of measurements, some defects coming from bad grounding connections, ground loops and leakage resistance were identified. Many different experiments (carried out on these three initial days) were carried out to improve the grounding of the two JVS.

The two arrays were connected in series-opposition via a KRISS thermal shunt. A KRISS low thermal-EMF switch allowed to open or close the circuit, to perform the detector polarity reversal, and to change the position of the detector from the negative polarity of the JAVS (when the two JAVS positive polarity are connected together) to the opposite polarity (when the two JAVS negative polarity are joined).

During the measurements, the KRISS array is disconnected from its bias source which is battery operated and floating from ground. The BIPM array was operated on batteries and was thus floating from ground during the step adjustment sequence, and was then disconnected from its bias source during the data acquisition process. During the comparison, the polarities of the two arrays as well as the detector input were reversed.

4.1 Description of the measurements (also See Appendix A)

The following is a brief description of the procedure used by the KRISS to obtain a single measurement of the voltage of the BIPM array. The voltage difference is measured with a nanovoltmeter Keithley 2182A controlled by a homebuilt program developed in Visual Basic©, whereas an HP 3458A is used to visually monitor the array voltage. Eight sets of 10 readings integrated over 20 powerline cycles each (NPLC=20) are taken, four sets in the positive polarity of the bias of the two arrays (U+), and four in the negative polarity (U-). For each polarity, two sets are acquired for the two polarities of the detector (D+ and D-). These measurements follow the scheme: U+D+, U+D- , U-D-, U-D+, U-D+, U-D-, U+D-,U+D+. For each set, the program acquires 10 readings of the voltage difference measured by the detector. These data are transferred to the computer via an optic fiber connection. The complete series of measurements takes about ten minutes when there is no array instability. The readings are stored in an ASCII datafile which is then imported into an Excel spreadsheet where the value attributed to the BIPM standard is calculated. The nanovoltmeter gain correction factor and linearity correction are included into the calculations.

The differences between the values measured by the KRISS and the theoretical value of the BIPM array voltage during the comparison are plotted in Fig. 1.

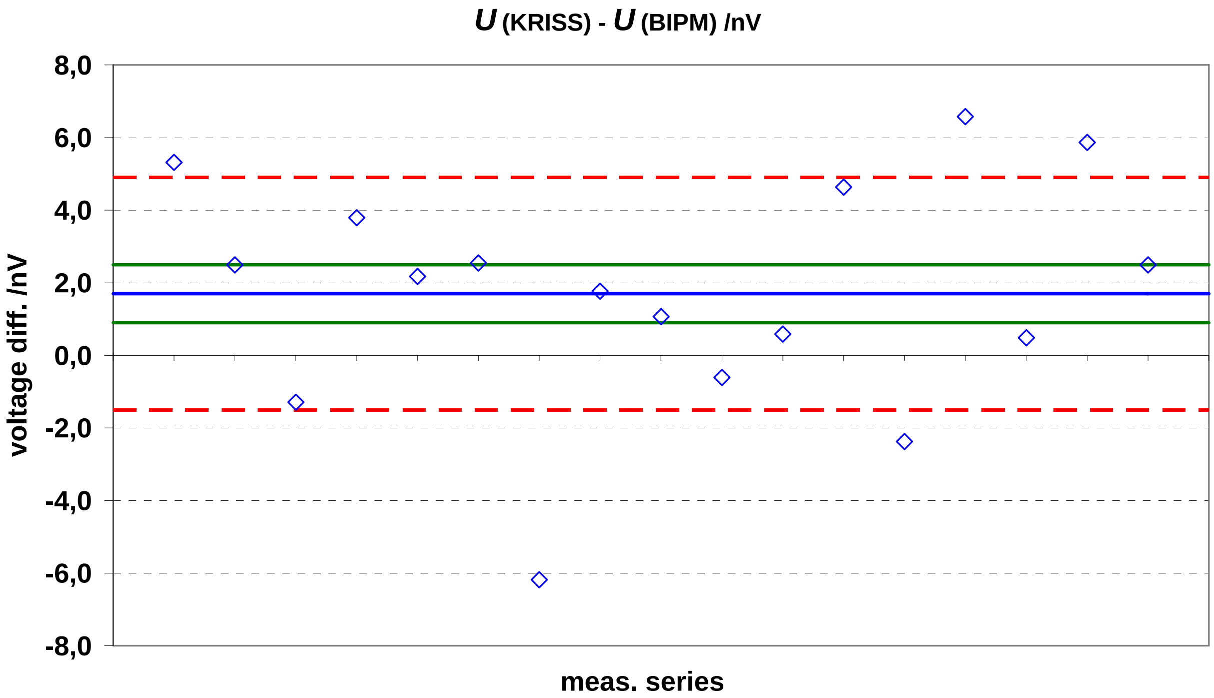

Fig. 1. Differences between the measured values and the theoretical value of the BIPM array voltage (option B). The solid lines (––––) are the standard deviation of the mean, and the dotted lines (– – –) are the standard deviation of the single measurements.

4. 2 Uncertainties and results

The sources of Type B uncertainty (Table 1a and 1b) are: the absolute value of the frequency measured by the EIP counters (i.e., frequency offset), the measurement leakage resistance, the repeatability of the thermal emfs in the reversing switch and the detector gain and non-linearity. Most of the effects of the frequency stability are already contained in the Type A uncertainty. As both array polarities were reversed during the measurements, the effect of the residual thermal EMFs (i.e., non-linear drift) is also already contained in the Type A uncertainty of the measurements.

The standard Type A uncertainty of the mean is 0.8 nV.

BIPM uncertainties components	Type	Contribution / nV
Frequency (*)	B	0.2
Leakage resistance	B	0.1
Detector	B	n.a.
Total Type B unc.		**0.15**

Table 1a. BIPM estimated Type B standard uncertainty components.

(*) As both systems were referred to the same 10 MHz frequency reference, only a Type B uncertainty of the EIP frequency counter is included.

KRISS Type B uncertainties components	At 10 V
Microwave freq. (1 Hz/75 GHz)	0.13 nV
Probe leakage (DWG) (0.3 Ω/10 GΩ @ 0.5 min)	0.3 nV
Circuit Leakage (See Appendix B)	0.8 nV
Rev. Sw. Thermal Repeatability	0.3 nV
Digital nanovoltmeter (**) (0.01 mV reading w/Keithley 2182)	0.3 nV
RSS Type B	**1.0 nV**

Table 1b. KRISS estimated Type B standard uncertainty components.

(**) As the KRISS array was biased on different steps and as the detector gain and linearity were taken into account, a large part of the detector uncertainty is already contained in the Type A uncertainty of the measurements. This component only expresses the effect of the uncertainty of the detector non-linearity correction.

The result, expressed as the relative difference between the values that would be attributed to the 10 V Josephson array standard by the KRISS (U_{KRISS}) and its theoretical value (U_{BIPM}) is:

$$\mathbf{(U_{KRISS} - U_{BIPM}) / U_{BIPM} = +1.7 \times 10^{-10}} \textbf{ and}$$

$$\mathbf{u_c / U_{BIPM} = 1.3 \times 10^{-10}}$$

where u_c is the relative combined standard uncertainty.

5. Comparison procedures: Option A scheme

As the participant was able to bias its array on a selected step and to quickly recover it in the opposite polarity, it was decided to move to an option A comparison where the BIPM measures the participant's JAVS with its own measurement chain. The measurements were performed on 29 February and 1 March.

The BIPM equipment consists of an EM model N1a analog nanovoltmeter 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 switch. The equipment includes a voltage divider to prevent the detector from overload if both systems are no more on the selected steps.

5.1 Organisation of the measurements

After the BIPM equipment has been set up and sufficiently stable conditions have been found with the participant's standard connected to the BIPM measurement system, the following procedure was applied by the BIPM software to acquire the measurement points:

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 cancel out any detector offset error and thermo-electromotive forces.

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.

5. 2 Uncertainties and results

The computation of the data obtained during these two days gives a relative voltage difference of:

$$(U_{\mathrm{KRISS}} - U_{\mathrm{BIPM}}) / U_{\mathrm{BIPM}} = +3.5 \times 10^{-10}$$

with a total relative combined standard uncertainties of

$$u_{\mathrm{c}} / U_{\mathrm{BIPM}} = 1.15 \times 10^{-10}$$

The differences between the values measured by the KRISS and the theoretical value of the BIPM array voltage during the exercise are plotted in Fig. 2

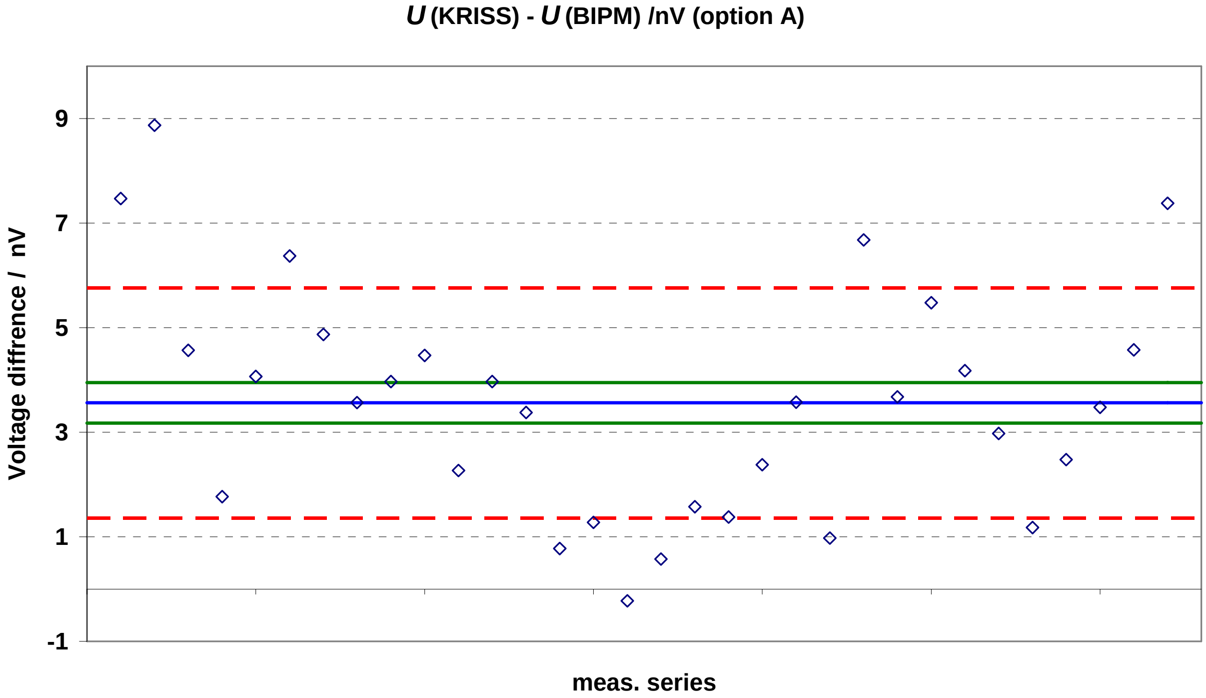

Fig. 2. Differences between the measured values and the theoretical value of the BIPM array voltage (option A). The solid lines (––––) are the standard deviation of the mean, and the dotted lines (– – –) are the standard deviation of the single measurements.

The budget for the uncertainty of the voltage difference measured with the BIPM equipment (option A) is given in Table 2:

Uncertainty component	Type	BIPM Contribution / nV	KRISS Contribution / nV
Detector Calibration [1]	A	0.05	n.a.
Standard deviation of the mean of the results [2]	A	0.81	n.a.
Microwave frequency [3]	B	0.20	0.13
Leakage resistance of the meas. leads	B	0.10	0.80 (See Appendix B)

Table 2. Estimated standard uncertainty components for the option A comparison.

([1]) 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. This component is thus negligible.

([2]) this component includes the noise in the measurement loop (u_L = 7 x 10^{-10} V) where the BIPM detector noise of u_D = 2 x 10^{-10} V is also comprised.

([3]) 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.

6. Discussion and conclusion

The results of the comparison demonstrate the ability of the KRISS in 10 V measurements. This comparison allowed the laboratory to study different problems, and to improve the measurement conditions. Furthermore, all the conditions required to carry out the two options comparisons protocols were met and the final results are presented in Fig 3.

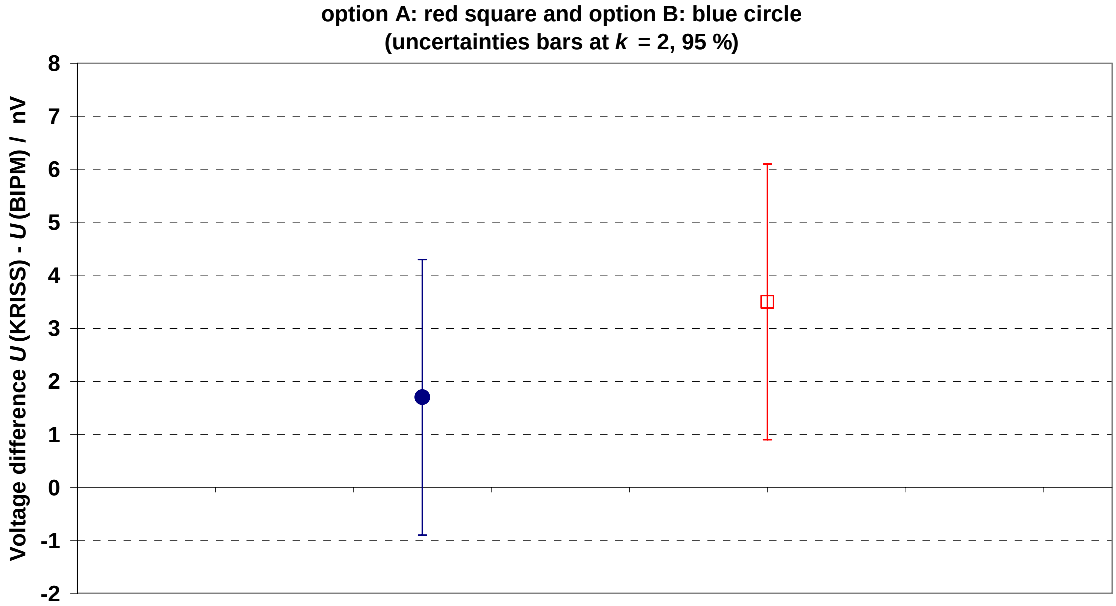

Fig 3 : Option A (red square) and option B (blue circle) final results at k = 2 (level of confidence of 95 %).

This comparison is the eleventh of a new series (started in September 2004) where the host laboratory uses its own Josephson equipment to measure the voltage of the BIPM array, considered as the transfer instrument. The main feature of this new measurement technique is that it requires only the BIPM array, not both arrays, to maintain a perfectly stable and reproducible 10 V output during the measurements.

The final result of the comparison is the option B:

$$(U_{\mathrm{KRISS}} - U_{\mathrm{BIPM}}) / U_{\mathrm{BIPM}} = +1.7 \times 10^{-10} \text{ and}$$

$$u_{\mathrm{c}} / U_{\mathrm{BIPM}} = 1.3 \times 10^{-10}$$

where u_{c} is the relative combined standard uncertainty.

However, as the participating laboratory was able to stay on a selected step and to recover it quickly after a polarity reversal, we switched to an option A scheme where the BIPM uses its measurement chain to measure the voltage provided by the KRISS JVS. This configuration was possible as the complete BIPM equipment was brought to KRISS to carry out a Zener comparison at the same time. We also decided to switch to this comparison scheme to see if we could improve the option B final results. The results of this comparison scheme showed a repeatable difference $U_{\mathrm{KRISS}} -$

U_{BIPM} = +3.5 nV within an expanded combined standard uncertainty of 2.3 nV. Despite the time spent to find the origin of this repeatable difference, we couldn't find a measurement configuration which could ameliorate the result. However we are convinced that a bad leakage path to ground is responsible for this "offset".

DISCLAIMER

Certain commercial equipment, instruments or materials are identified in this paper in order to adequacy specify the environmental and experimental procedures. Such identification does not imply recommendation or endorsement by the BIPM, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

Appendix A

This appendix describes the measurements in a chronological manner.

22 February 2008

After having assembled the BIPM equipment (with an Hypres array), we had some difficulties to lock the RF frequency on the BIPM system. After checking the level of the 10 MHz reference signal of the EIP, we found the amplitude was too large (5 V peak to peak) compared to a recommended value of the manufacturer (Phasemetrix recommends a typical 1 V peak to peak reference signal). We decided to operate a Low Frequencies Generator (referred to the standard signal) to decrease the level of the 10 MHz reference of the two systems to 1 V peak to peak.

Checking for the continuity of the grounding line between the two JAVS, we found a leakage current on the KRISS RF equipment: the ETL stabiliser power supply consists of a double DC output source. To provide the + and – 15 V required, the + of one source was connected to the – of the second one, to the common point and to the guard. The leakage current was flowing between these two last points. The solution was found in disconnecting the common from the guard input.

23 February 2008

We tried to operate the BIPM array at the frequency at which the KRISS JAVS was operated, 75.015 GHz. The BIPM array wasn't found to be as stable as it is usually. We identified bad propagation conditions of the RF along the array. We didn't manage to carry out a single measurement because of strong interference between the two systems. We tested different grounding configurations and inserted a BIPM LC filter between the two arrays. There was no effect on the stability of the voltage measurement difference.

25 February 2008

The backup BIPM array (10 V SIS PTB array S/N JK-50/11) was mounted on the BIPM probe. Stable steps were found at 72.950 GHz with the array biased with the DC bias source on batteries. However, it was impossible to find proper conditions to monitor the voltage across the BIPM array. Fortunately, the steps were so stable that we could stay on a particular step once the bias was disconnected and the step position could be clearly identified on the scope.

The BIPM low thermal EMF switch was initially installed between the two standards. As it had to be installed after the KRISS switch, its role was redundant. Furthermore the KRISS spade terminals were too large to be safely adapted on the BIPM switch. We finally replaced the later one with a simple thermal shunt.

KRISS is operating an intermediate filter box on the measurement leads of the array. Different type of filters can thus be used. It was decided to install the filter with the largest line resistance (80 Ω in total including the line resistance of the measurement leads).

26 February 2008

A compromise among the groundings connection problems was found and the first acceptable comparison results were obtained on that day. The grounding connection was the following:

1- Both RF equipments are referred to the grounding of the EIPs power supply; Note that on the BIPM system, a physical electrical isolation exists between the RF source and the probe. It consists of a Mylar © film inserted on the WR12 waveguide flanges between the source and the waveguide to the array. The two flanges are connected using Nylon © screws;

2- The KRISS JAVS as well as the BIPM JAVS are powered from the same isolation transformer. The KRISS dewar is the only one to be referred to the ground of the JAVS.

27 February 2008

On the different series of measurements carried out on that day, we found that the standard deviation of 10 successive points acquired in a single polarity could vary from 10 nV up to 100 nV. A strong BIPM LC filter was unsuccessfully installed between the two JAVS. However, we decided to use the analog filter on the nanovoltmeter for all the acquisitions. We haven't found any explanation for that large discrepancy except that the noise was probably coming from the supply[1] or from any interference between the

[1] We clearly saw the environnement noise level changing during the day.

two systems due to the large value of the line resistance filter on the KRISS JAVS measurement leads.

28 February 2008

As the conditions were getting worse, a complete review of the equipment was done and the reason was found in a broken measurement wire inside its insulation. The linearity of the detector was also checked using the BIPM array (cf. Fig. 2). The results confirm the correction factors used since the beginning of the comparison.

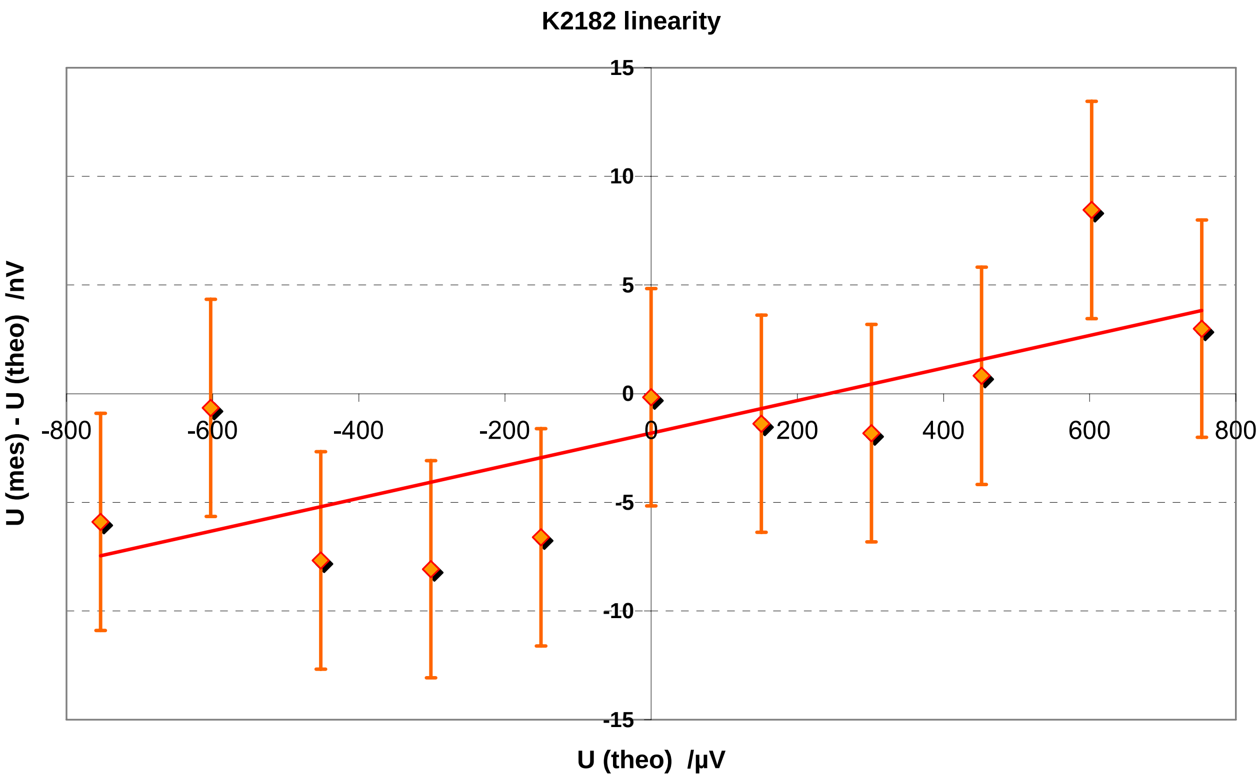

Fig 2 : Linearity check of the digital nanovoltmeter operated during the comparison.

29 February 2008

As the KRISS array was very stable and the same step could be easily recovered in both arrays polarities, it was decided to replace the digital nanovoltmeter with an EM N11 analog detector. A Fluke 867B multimeter was reading the isolated output of the N11 and the data sent to the *RS232-C* port of the computer via an optical fiber.

It was also decided to remove the HP3458A which monitors the voltage across the array once the KRISS array was adjusted on the selected step. This instrument is sometimes responsible for bringing some noise in the system.

None of these modifications improved significantly the noise level of the setup.

It was then decided to move to an option A comparison protocol. We managed to obtain some series of measurement points in very satisfactory stability conditions. From the results, we saw that systematically $U_{\mathrm{BIPM}} - U_{\mathrm{KRISS}} < 0$ within a standard deviation twice lower than for the option B comparison. That would mean that either the voltage provided by the BIPM standard is higher than its theoretical value, either the KRISS standard provides a lower value than expected.

It is important to note that despite the fact that we couldn't operate both arrays at the same RF frequency, we could always diminish the expected voltage difference by adjusting the value of the KRISS 10 MHz EIP reference signal via a synthesiser (referred to the 10 MHz issued from the reference clock).

For instance while the BIPM array was biased at 72.860 GHz (n= 66373) and the KRISS array was biased at 75.013 GHz (n= 66468), the theoretical voltage difference $U_{\mathrm{BIPM}} - U_{\mathrm{KRISS}}$ was 2.696 µV. By changing the 10 MHz reference of the KRISS EIP counter from 10 to 9.9999973 MHz, the voltage difference was decreased to 3.522 nV.

In order to detect any leakage effect in the measurement loop, it was decided to insert a 1 kΩ resistor between the two positive outputs of the arrays (the detector is installed between the two negative potential leads), with the positive polarity connected on the BIPM array side. We never managed to carry out a satisfactory measurement: the stability of both arrays was satisfactory but we identified an offset which was evolving during the data acquisition process. The 1 kΩ resistor was changed to a 250 Ω resistor and three points were acquired. The voltage difference was $U_{\mathrm{BIPM}} - U_{\mathrm{KRISS}}$ = - 187 nV with a standard deviation of 63 nV. The voltage drop and noise can probably be explained by a strong leakage effect.

01 March 2008

To detect if the KRISS JAVS line resistance of the filter was partly responsible for the bad leakage effect, this resistance value was changed from 80 Ω to 40 Ω. We didn't see any real change with this improvement.

To try to change the leakage path to ground, we then tried different detector positions between the two JVS and different system grounding configurations. Note that both arrays were floating from ground for all the measurements carried out before.

1- The detector was set between the two positive polarities of the JVS, the two negative leads being connected together and the positive input of the detector on the BIPM array side.

2- The detector was set between the two negative polarities of the JVS, the two positive leads being connected together and the positive input of the detector on the BIPM array side.

3- The detector was disposed between the two positive polarities of the JVS, the two negative leads being connected together and the positive entry of the detector on the BIPM array side. The negative KRISS array polarity was forced to ground.

4- The detector was placed between the two positive polarities of the JVS, the two negative leads being connected together and the positive entry of the detector on the BIPM array side. The negative BIPM array polarity was grounded.

The three first configurations gave some results similar to those obtained the days before. However the last configuration gave, over 5 successive points, a difference of

$U_{\mathrm{BIPM}} - U_{\mathrm{KRISS}} =$ 34 nV within a standard deviation of the mean of 6 nV.

Appendix B Leakage effect

The leakage effect in the direct comparison can be explained with the following diagram.

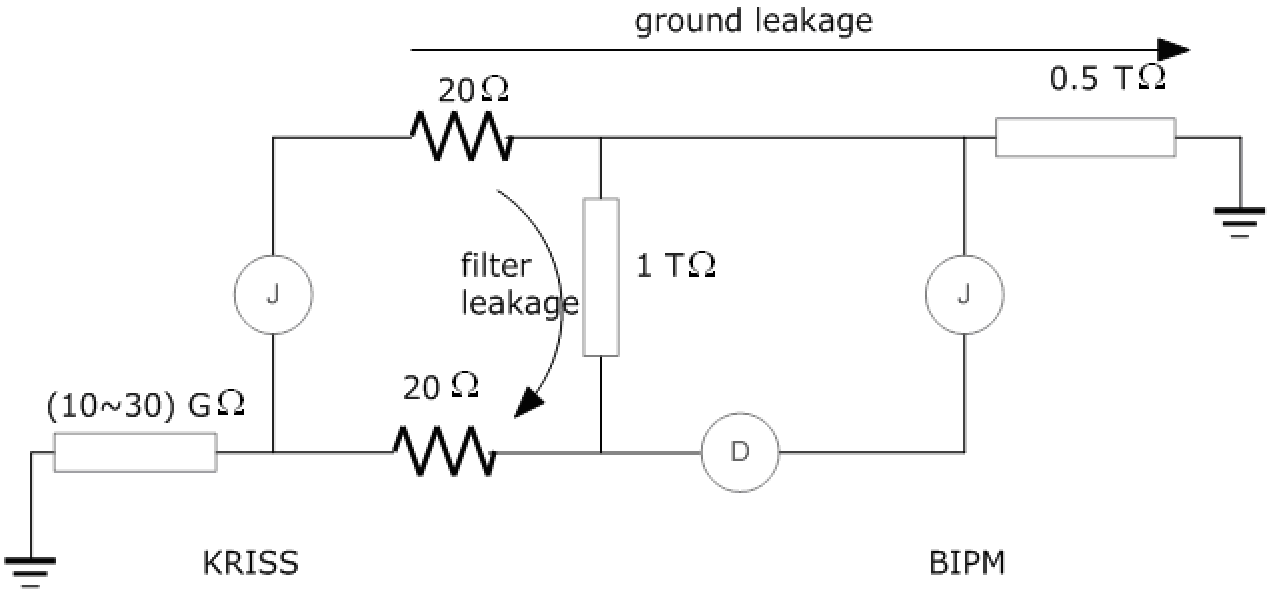

Fig. Josephson ground leakage effect through KRISS filter upper resistor (*R*) and self leakage effect through two resistors (2*R*). *R* is usually 20 Ω but some experiments, a resistor of 40 Ω was used.

There are two different possible leakage paths. Both of them act in the same direction and cause the measurement result to be higher than the theoretical value :

(1) filter leakage error 10 V (40 Ω/1 TΩ) = 0.4 nV,

(2) ground leakage error 10 V (20 Ω/0.5 TΩ) = 0.4 nV.

The total error 0.8 nV (if we take *R*=20 Ω) to 1.6 nV (if we take *R*=40 Ω) agrees with the 1.7 nV the comparison result. It should be noted that the ground leakage part is not necessarily associated with the volt representation at KRISS, because it can only happen when the grounds of the two JVS are connected.