Comparison of the Josephson Voltage Standards of the NMC, A*STAR and the BIPM
(part of the ongoing BIPM key comparisons BIPM.EM-K10.a and BIPM.EM-K10.b)

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

Yinzhu Zhou, Jinni Lee, and Sze Wey Chua
Electromagnetic Metrology Department
National Metrology Centre, A*STAR
1 Science Park Drive, 118221, Republic of Singapore
Abstract. A comparison of the 10 V and 1 V Josephson array voltage standard of the Bureau International des Poids et Mesures (BIPM) was made with that of the National Metrology Centre (NMC), A*STAR, Singapore, in September 2010. For this exercise, option B of the comparison protocol was applied for the two voltages. The BIPM provided a reference voltage for measurement by the NMC, A*STAR using its Josephson standard with its own measuring device (option B of the comparison protocol). The BIPM array is floating from ground.

The final results are in very good agreement within the combined relative standard uncertainty of 9.6 parts in $10^{11}$ and 0.9 parts in $10^9$ for the nominal voltages of 10 V and 1.018 V respectively.

1. Introduction

In the framework of CIPM MRA key comparisons, the BIPM performed a direct key comparison of Josephson voltage standards (JVS) with the National Metrology Centre (NMC), A*STAR, Singapore, in September 2010.

This comparison followed option B of the technical protocol for BIPM.EM-K10.a and BIPM.EM-K10.b comparisons whereby the BIPM ships its JVS to the participating laboratory to perform an on-site Josephson comparison.
For option B, the BIPM only provides a reference voltage for measurement by the participating laboratory using its Josephson standard with its own measuring device. The BIPM array is floating from the ground.

This article describes the technical details of the experiments which were carried out to achieve the final result of the comparison.

2. Comparison equipment

2.1 The BIPM JVS

The BIPM JVS used in this comparison comprises the cryoprobe with a Hypres 10 V SIS array (S/N: 2538F-3), 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. An optical isolation amplifier was placed between the array and the oscilloscope to visualize the array I-V characteristics, while keeping the array floating from ground. During the measurements, the array was disconnected from this instrument. An HP 34401A digital voltmeter (DVM) was inserted between the array voltage measurement leads to measure the voltage to periodically verify the voltage step stability. The DVM was removed during the measurement sessions. The measurements were carried out without monitoring the voltage across the BIPM JVS. The series resistance of the measurement leads was less than 4 Ω in total. The leakage resistance between the measurement leads was greater than $7 \times 10^{10}$ Ω for the BIPM JVS.

2.2 The NMC, A*STAR JVS

The NMC, A*STAR JVS is based on a Hypres SIS 10 V array. During the course of the comparison, the array was operated with a critical current of 75 µA. The system was biased by the VMetrix JVS1002 and connected to the EIP 578B where the external 10 MHz was referenced to the Caesium clock standard. A standard oscilloscope, Insek GOS-6103, used for monitoring I-V curves took its output from the JVS1002. An IOtech bus isolator 488 was used for isolating the GPIB connections to the laptop computer controlling the system.

Other details of the NMC, A*STAR JVS are as follows:

- Precision measurement leads resistance: 15 Ω
- Leakage resistance between the precision measurement leads: $2.6 \times 10^{11}$ Ω
- Josephson junction array: Hypres 10 V SN2626B6
- Null detector: Agilent 34420A SN:US36000320; range: 1 mV
• Bias source: VMetrix JVS1002 / JVS 501
• Software: NISTVolt for Windows, version 2.2.10.

The value of the thermal electromotive forces (EMFs) between the two JVS was found to be 620 nV – 650 nV (cf. Fig. 1).

![Graph](image)

**Fig.1:** Example of the short term evolution of the thermal EMFs for the complete measurement loop during the comparison over 6 consecutive measurements during a period of 50 minutes.

3. Comparison procedures - Option B at the 10 V level

3.1 *Operating set-up for the preliminary measurements*

The measurement loop was arranged in such a way that both positive polarities of the arrays were connected together and the nanovoltmeter was placed between the two negative polarities of the arrays. The “High” of the nanovoltmeter was connected to the BIPM array. The following is a brief description of the procedure used by NMC, A*STAR to obtain a single measurement of the voltage of the BIPM array.

During the comparison, the BIPM current bias source was adjusted to manually select the same step after each polarity reversal. The NISTVolt program, written in Visual Basic® was used to bias the NMC, A*STAR JVS to 10 V, to monitor the detector and record the data. The detector was a digital nanovoltmeter (HP34420A on the 10 mV range).
Four sets of 10 data, each of which is the mean of 5 consecutive readings at 10 powerline cycles (NPLC=10) were taken, one set in the positive polarity of the bias of the two arrays, one in the negative polarity, a second set in the positive polarity of the bias of the two arrays, and a second set in the negative polarity. The measurement followed the scheme: +, -, +, -. The recorded data were transferred to the computer through a GPIB interface. The complete series of measurements (+, -, +, -) took about 8 minutes when there was no array instability.

From the readings, the software calculates the values attributed to the BIPM standard for each polarity and using the so called ‘Thermal drift model’ calculates a final result. The final result and the intermediately calculated voltages are stored in an ASCII data file. The readings of the nanovoltmeter were not corrected for the gain error of the 10 mV range.

After each polarity reversal 10 seconds were allowed to elapse before beginning the data acquisition in order to avoid the larger effects of filter capacitor discharge.

### 3.2 First measurements result

After the BIPM equipment was set up and sufficiently stable conditions were found, the JVS was connected to the NMC, A*STAR’s measurement system and nine measurements were acquired following the procedure applied by NMC, A*STAR to calibrate Zener voltage standards.

The result was \( \frac{U_{\text{NMC}} - U_{\text{BIPM}}}{U_{\text{BIPM}}} = -39 \times 10^{-10} \).

The experimental standard deviation of the mean was 6.28 nV, or \( 6.3 \times 10^{-10} \) in relative terms.

Although this difference is significant, this comparison result validated the CMCs of the laboratory. However, this result is one order of magnitude greater than expected from the direct comparison of two JVS. As will be shown, a systematic error is assumed to offset this result and within the week allotted to the comparison, different experiments were carried out in order to achieve the lowest voltage difference between the two JVS.

The stability achieved with the two pieces of apparatus was very satisfactory, even when they were connected together and many different measurement configurations were tested. The details of these test measurements are described in the Appendix A.
Regardless of the measurement configuration, the NMC, A*STAR JVS array was always disconnected from its bias source, which is itself referred to a virtual ground (different to the ground of the laboratory).

The BIPM array was operated using batteries during the step adjustment sequence, and was then disconnected from its bias source during the data acquisition process. The reference ground of the chassis of the instruments that constitute the BIPM JVS was connected to the NMC, A*STAR JVS potential reference point. The two arrays were connected in series-opposition via a dedicated NMC, A*STAR switch.

In this comparison scheme (option “B”), the NMC, A*STAR JVS measurement set-up was used to measure the BIPM array voltage as if it were a Zener voltage standard. During the comparison, only the biases of the two arrays were reversed (no mechanical switch reversal). This operation was carried out electronically on the NMC, A*STAR JVS and manually on the BIPM JVS. The polarity reversal was typically completed within less than 10 s.

3.2 Description of the subsequent measurements (See also Appendix A)

Operating set-ups for the best measurements

In order to determine the reason for the systematic error of the preliminary measurements, different measurement set-ups were tried and the subsequent intermediate results were computed to obtain the final result.

The 36 individual measurements (cf. Fig 2) used for the computation of the final result have been performed in the following configurations:

Set-up 1:

The initial NMC, A*STAR measurement loop was modified in the following way: a short circuited digital detector was connected to the IEEE bus of the NMC, A*STAR measurement set-up. It acted as an artificial device to avoid any error from the software. The nanovoltmeter that measured the voltage difference between the two JVS was moved to a second IEEE bus line and its settings as well as the readings were recorded with the BIPM Labview© dedicated software:

Four sets of 10 readings at 10 powerline cycles (NPLC=10) were taken, one set in the positive polarity of the bias of the two arrays, two sets in the negative polarity, and a fourth set in the positive polarity. The measurement followed the scheme: +, -, -, + and took about 5 minutes.
The gain of the 1 mV range was measured using the BIPM JVS and a correction factor of 3.2 ppm was applied to the readings before the calculation of the result (cf. Appendix A).

A fine adjustment of the voltage provided by the digital to analogue converter (DAC) of the NMC, A*STAR JVS bias source was undertaken using NISTVolt.

18 Measurements were performed on 25 September 2010:

- Points #1 to #6: both arrays were biased at the frequency $f = 74.074$ GHz. The two pieces of JVS equipment were powered from a single plug located outside the screened room and the IEEE bus isolator was disconnected from the NMC, A*STAR measurement set-up.

- Points #7 to #9: The complete equipment set-up was powered through an isolation transformer in the screened room.

- Points #10 to #12: the RF frequency of both JVS was changed to $f = 74.078$ GHz.

- Points #13 to #15: The analogue filter of the nanovoltmeter was activated. As a consequence, a decrease of the noise by a factor of 2 or 3 was observed.

- Points #16 to #18: Both RF biasing signals were changed to $f = 74.18$ GHz and 3 measurements were performed with the analogue filter of the nanovoltmeter ON.

15 Measurements were performed on 27 September 2010:

- Points #19 to #21: Both RF biasing signals were changed to $f = 74.17$ GHz and 3 measurements were performed without any filter on the nanovoltmeter.

- Points #22 to #24: 3 measurements were carried out for the same frequency but with the detector’s filter activated.

- Points #25 to #27: Both RF biasing signals were moved to $f = 74.074$ GHz and 3 measurements were performed without any filter on the nanovoltmeter.

- Points #28 to #30: 3 measurements were carried out for the same frequency but with the detector’s filter activated.

At this point, the software was modified in order to:

a) systematically remove the 5 first readings of each set;
b) replace the “RESET” command sent to the DVM at the beginning of each set by a “CLS” command;

c) the DVM was forced on its 1 mV range (it was previously in Auto Range).

- Points #31 to #33: 3 measurements were carried out for the same frequency but with the detector’s filter activated.

Set-up 2:

The measurement set-up was modified for the last 3 measurements on 27 September. The HP34420A nanovoltmeter was controlled by the software module of NISTVolt dedicated to direct comparisons of JVS. This is different from the module dedicated to Zener measurements. Another HP34420A nanovoltmeter was placed across the voltage biasing leads of the BIPM JVS to check the stability of its voltage output.

Fig. 2: Individual results retained to calculate the final result at the level of 10 V: diamonds represent the measurements obtained on 25 September with set-up 1, squares, the measurements obtained on 27 September with set-up 1 and circles, the measurements obtained on 27 September with set-up 2. The solid
line represents the mean value, the dashed lines (— —) represent the experimental standard deviation, and the dotted lines (···) are the experimental standard deviation of the mean.

The final result is computed as the simple mean of the 36 individual measurements and the Type A uncertainty is calculated as the standard deviation of the mean of the individual results. 

\[
\frac{U_{\text{NMC}} - U_{\text{BIPM}}}{U_{\text{BIPM}}} = 4.2 \times 10^{-11} \quad \text{and} \quad \frac{u_A}{U_{\text{BIPM}}} = 7.1 \times 10^{-11},
\]

where \( u_A \) is the Type A uncertainty.

As will be demonstrated, this significant improvement from the preliminary measurement is mainly due to the 12 ppm error on the 10 mV range of the detector when operating the module of the NISTVolt program dedicated to calibrate Zener standards.

4. Comparison procedures - Option B at the 1.018 V level

No preliminary measurements were carried out at this voltage level.

Both arrays were set to \( f = 74.074 \) GHz and the BIPM JVS was adjusted to the Shapiro step number 6646 corresponding to a theoretical voltage of \( U = 1017985.8184 \) µV. The NMC, A*STAR JVS was biased to within a few steps of the same voltage.

Eight consecutive measurements were performed using direct comparison set-up 1, then the measurement configuration was changed to set-up 2 and a further 6 measurements were performed. All the measurements are presented on Figure 3.

![Figure 3](image)

**Fig. 3:** Differences between the measured values and the theoretical value of the BIPM array voltage at the level of 1 V. The squares represent the measurements obtained on 27 September with set-up 1 and the
circles, the measurements obtained on 27 September with set-up 2. The solid line represents the mean value, 
the dashed lines (— — —) represent the experimental standard deviation, and dotted lines (· · ·) are the 
experimental standard deviation of the mean.

The final result is calculated as the simple mean of the 14 individual measurements and the Type A uncertainty is calculated as the standard deviation of the mean of the individual results. 
\[
\frac{U_{\text{NMC}} - U_{\text{BIPM}}}{U_{\text{BIPM}}} = 1.8 \times 10^{-9} \quad \text{and} \quad \frac{u_A}{U_{\text{BIPM}}} = 8.6 \times 10^{-10},
\]
where \(u_A\) is the Type A uncertainty.

5. Uncertainties and results

5.1 Type B uncertainty components

The sources of Type B uncertainty (Table 1) are: the frequency accuracy of the Gunn diodes, the leakage currents, and the detector gain and linearity. Most of the effects of detector noise and 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) and electromagnetic interferences are also already contained in the Type A uncertainty of the measurements. Uncertainty components related to RF power rectification and sloped Shapiro voltage steps are considered negligible as no such physical effect was observed.

<table>
<thead>
<tr>
<th>Source</th>
<th>Type</th>
<th>Relative uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>BIPM</td>
</tr>
<tr>
<td>Frequency noise and offset (A)</td>
<td>B</td>
<td>(2 \times 10^{-12})</td>
</tr>
<tr>
<td>Leakage resistance (B)</td>
<td>B</td>
<td>(5 \times 10^{-11})</td>
</tr>
<tr>
<td>Detector (C)</td>
<td>B</td>
<td>(1.6 \times 10^{-11})</td>
</tr>
<tr>
<td>Total (RSS)</td>
<td>B</td>
<td>(5 \times 10^{-11})</td>
</tr>
</tbody>
</table>

**Table 1.** Estimated Type B relative standard uncertainty components.
Only a Type B uncertainty from the frequency measured by the EIP is included, as both systems are referred to the same 10 MHz frequency reference. The frequency reference used for the comparison is traceable to the Caesium clock standard.

BIPM JVS: It has been demonstrated on many occasions that the EIP-578B is a very good frequency locker and the frequency accuracy can reach 0.1 Hz. Assuming a rectangular distribution, the uncertainty on the offset of the frequency can be calculated from the formula: 
\[ u_f = \left( \frac{1}{\sqrt{3}} \right) \times U \times (0.1/74) \times 10^{-9}. \]

NMC, A*STAR JVS: The stability of the EIP-578B was taken as ± 1 Hz, assuming a normal distribution. The uncertainty of the frequency contribution is calculated as 
\[ u_f = U \times (1/74) \times 10^{-9}. \]

Assuming a rectangular statistical distribution, the uncertainty contribution of the leakage resistance \( R_L \) can be calculated from the formula: 
\[ u_L = \left( \frac{1}{\sqrt{3}} \right) \times U \times \left( \frac{r}{R_L} \right), \]
where \( r \) is the series resistance of the measurement leads. The values attributed to the resistances were measured during the comparison exercise on both JVS.

A large proportion of the detector uncertainty is already included in the Type A uncertainty of the measurements. This component only expresses the effect of the uncertainty of the detector non-linearity correction. The uncertainty due to the DVM gain and linearity errors was estimated by calibrating the 1 mV range of the detector with the BIPM JVS. The results are given in Appendix A. The uncertainty on the gain is calculated from the uncertainty on the least squares fit for a voltage value of 0.6 mV which is equal to \( u = 1.6 \times 10^{-11} \) V.

5.2 Results at 10 V.

The result using Option B, expressed as the relative difference between the values that would be attributed to the 10 V Josephson array standard by NMC, A*STAR (\( U_{NMC} \)) and its theoretical value (\( U_{BIPM} \)) is:
\[ \frac{(U_{NMC} - U_{BIPM})}{U_{BIPM}} = 4.2 \times 10^{-11} \text{ and } \frac{u_c}{U_{BIPM}} = 9.6 \times 10^{-11} \]
where \( u_c \) is the combined standard uncertainty.
5.3 Results at 1.018 V.

The result using Option B, expressed as the relative difference between the values that would be attributed to the 1.018 V Josephson array standard by NMC, A*STAR ($U_{NMC}$) and its theoretical value ($U_{BIPM}$) is:

$\frac{(U_{NMC} - U_{BIPM})}{U_{BIPM}} = 1.82 \times 10^{-9}$ and $u_c / U_{BIPM} = 0.9 \times 10^{-9}$

where $u_c$ is the combined standard uncertainty.

6. Discussion and conclusion

The preliminary measurements demonstrated NMC, A*STAR’s ability to perform accurate and precise automatic measurements at 1.018 V and 10 V.

During the subsequent scientific exercise, experiments were carried out on various parts of the whole system and, in particular, on the assembly of both JVS and on using different measurement set-ups in order to identify the reason for the existing systematic error when using NISTVolt Zener calibration software version 2.2.7 (or 2.2.10) and, to determine some critical parameters on the measurement set-up.

In the initial set-up, problems were encountered with automatically setting the bias of the NMC, A*STAR JVS to a null voltage between both systems that was lower than 3 mV, with values typically at 5 mV. Hence, the initial set-up was undertaken in the 10mV range of the DVM. We found a 12 ppm gain error of the null meter on its 10 mV range. The gain error could explain the systematic error that was observed in the initial results.

Therefore, a separate function of NISTVolt that is dedicated to comparisons of JVS was used to manually control the bias. Using that function, both systems could remain stable within a few steps (below 1 mV). The following result was achieved at the 10 V level:

$(U_{NMC} - U_{BIPM}) = -1.7 \times 10^{-10} \text{ V}$ within a Type A uncertainty $u_A = 2.2 \times 10^{-9} \text{ V}$.

This matches the result recorded using the BIPM software.

This comparison allowed both the BIPM and NMC, A*STAR to improve the characterization and robustness of their equipment and measurement set-ups.
We believe that the final result at the 1.018 V level could have been significantly improved if more time had been available.

During the time allotted to the comparison, the NMC, A*STAR bias source was identified as a weak component (probably with respect to its DAC) in the measurement set-up when trying to achieve a direct comparison of JVS at the relative level of 1 part in $10^{11}$.

The great advantage of operating an analogue detector to measure the voltage difference between two JVS is the considerable improvement in the sensitivity of the measurement. The methodology used in this comparison exercise was sufficiently accurate to identify the equipment in the measurement set-up which was not operating at 100%.
References


DISCLAIMER

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

This appendix describes the comparison measurements in chronological order.

22 September 2010

After having assembled the BIPM equipment, the BIPM array (Hypres S/N 2538F-3) was cooled down and a suitable critical current (80 µA) was obtained. The RF Gunn source was mounted on the probe and adjusted to the same frequency at which NMC, A*STAR operated its array (74.074 GHz). We found adequately stable conditions for the voltage provided by the array.

23 September 2010

During the voltage adjustment of the arrays the JVS systems were grounded to two different potential reference points. The BIPM array was floating from these grounds once the adjustments were made. The shielding of the measurement leads and equipment were grounded to the NMC, A*STAR potential reference point which was the potential reference of the biasing source (VMetrix JVS 1002).

Note: The NMC, A*STAR probe and Dewar are automatically referred to the virtual ground provided by the bias source. The BIPM probe and Dewar are isolated from any potential reference but they can be referred to a common reference point if this brings stability into the measurement loop.

The positive poles of the two quantum standards were connected together and the detector was inserted in between the negative poles, the high side of the detector was connected to the BIPM JVS side. The JVS were directly connected through a low thermal electromotive forces switch in such a way that the polarity reversals of both standards did not have to be carried out at the same time.

The measurements were performed using the Zener calibration software from NISTVolt for Windows (version 2.2.10). Each measurement point was computed from four sets of 10 data each being the mean of 5 consecutive readings at 10 powerline cycles (NPLC=10). One set was measured in the positive polarity of the bias of the two arrays, one in the negative polarity, a second set in the positive polarity of the bias of the two arrays, and a second set in the negative polarity. The measurement followed the scheme: +, -, +, -. The recorded data were transferred to the computer through a GPIB interface. From the readings, the software calculates the values attributed to the BIPM standard for each polarity and, using the
so called ‘Thermal Drift Model’, calculates a final result. The final result and the intermediate calculated voltages are stored in an ASCII data file.

However, each of the two (+,-) series were considered as one measurement point.

Some adjustments had to be performed on the connections before carrying out the first series of measurements.

1) Six different isolation transformers could be used to power different instruments of the NMC, A*STAR measurement set-up. We decided to power all the instrumentation of both JVS from the same isolation transformer.

2) The NMC, A*STAR RF equipment was originally forced to the virtual ground and we decided to remove this connection.

3) A 10 MHz signal issued from the same frequency reference was provided to the JVS by two different physical lines. We decided to use only one line and to connect the two EIP counters using a coaxial “T”.

The JVS were found to be more stable without grounding the BIPM Dewar. Under these conditions, we carried out a series of preliminary measurements which gave a repeatable voltage difference between the two systems of 39 nV with a standard deviation of the mean of 7 nV. It was obvious that a systematic error was responsible for this result. Therefore, we performed different experiments and measurement set-up configurations in order to identify the origin of this error. We also noticed that each of the two (+,-) series were significantly different from the final measurement point calculated using the ‘Thermal drift model’.

The experiments performed are listed in the following:

1) The switch (Guideline 9145) used to open and close the circuit was replaced by the BIPM low thermal EMFs switch.

2) The BIPM Dewar was grounded.

3) A 1 kΩ resistance was added on one side of the BIPM array leading to a significant voltage difference shift in the measurement (100 nV on the positive side and 20 nV on the negative side) compared to the 40 nV obtained usually. This experiment showed that the distribution of the leakage current in the measurement set-up was very sensitive.

4) At this point, we assumed that a leakage was the origin of the offset. We thus performed a measurement series at three different voltages. The results are presented in Table A1:
Table A1: Results of the measurements of the voltage difference between the two JVS at different nominal voltages.

<table>
<thead>
<tr>
<th>Nominal Voltage/V</th>
<th>$U(\text{NMC}) - U(\text{BIPM})/\text{nV}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-0.8</td>
</tr>
<tr>
<td>5</td>
<td>+6</td>
</tr>
<tr>
<td>10</td>
<td>-50</td>
</tr>
</tbody>
</table>

The results could be due to a leakage path to the ground in between the two JVS, however, the leakage resistance could not be determined from the results.

5) We decided to measure the leakage resistance of the measurement leads of both JVS and the results were as expected for the two JVS.

6) The nanovoltmeter HP34420A was replaced by a Keithley 2182A but no improvement in the measurements was observed.

24 September 2010

Another experiment was conducted to confirm if a leakage effect could explain the voltage offset. We decided to bias both arrays using the same biasing source. This methodology was originally applied in the bilateral comparison between NIST and NRC in 2007 [1] and was successfully applied to determine sources of error in a BIPM.EM-K10.b comparison [2]. We performed the experiment using both methods: at first the NMC, A*STAR biasing source was operated to bias both arrays and in a second run the BIPM source was selected to bias both arrays (cf. Fig A1). The measurements were carried out in both configurations and the JVS showed an agreement within 2 nV with a standard deviation of the mean of 3 nV. This cross-check demonstrated that there was no major leakage of any of the quantum standards. Furthermore the nanovoltmeter that measured the voltage difference controlled through an IEEE bus line, its settings and the readings, were recorded with the BIPM Labview© dedicated software.
**Fig. A1:** Schematic of the measurement set-up used to analyze any major leakage effect on the JVS. When Array 1 is set to a voltage by the bias source B and when the detector D is short-circuited by S, Array 2 is set to the same voltage as Array 1 within a few steps.

7) After checking the position of the phase and the neutral of the main supply on each piece of measurement equipment, we discovered the scope chassis on the BIPM JVS was not properly powered. This problem was fixed.

Using the same measurement set-up the NISTVolt automation program for Zeners was used instead of the BIPM software to perform the measurements and to calculate the voltage difference (#15 to #20). The systematic error was still observed.

At this stage, a decision was made to power all the equipment from outside the screened room using the same 240 V plug. This operation did not result in an improvement (#21 to #26). Measurements #27 to #31 were performed by inserting a filter at different locations in the measurement set-up (capacitor across the input of the nanovoltmeter and BIPM LC filter inserted in between the two JVS). The two last measurements of this series were carried out in the initial configuration where both systems were powered from the isolation transformer inside the Faraday cage. At the end of 24 September, the NMC, A*STAR Dewar was opened to the atmosphere so that the two Dewars had the same configuration.

**25 September 2010**

The configuration of the mains was checked again. The power was supplied from an isolation transformer with 120 V between the phase and the ground and between the neutral and the ground from inside the screened room. We decided to perform additional measurements with both JVS powered from an isolation transformer outside the Faraday cage with 240 V between the phase and the neutral and almost 1 V between the neutral and the ground (#32 to #44).
A number of slight changes were performed within this configuration:

1) Removal of the IEEE bus isolator on the NMC, A*STAR JVS.
2) The computer which ran the measurement process was powered from batteries.
3) The connection of the BIPM Dewar and the scope chassis to the ground were removed.
4) The NISTVolt software version was changed from 2.10 to 2.7.

None of these modifications resulted in an improvement. The offset was still observed. We noticed that the automatic Zener calibration function was unable to bias the NMC, A*STAR JVS so that both JVS remained below 1 mV. This was due to large step jumps on the NMC, A*STAR’s array at the instant of detaching bias.

5) The initial NMC, A*STAR measurement loop was modified in the following way. A short circuited digital detector was connected to the IEEE bus NMC, A*STAR measurement set-up. It acted as an artificial device to avoid any error from the software. The nanovoltmeter that measured the voltage difference between the two JVS was moved to a second IEEE bus line and its settings as well as the readings were recorded using the BIPM Labview® software.

Four sets of 10 readings at 10 powerline cycles each (NPLC=10) were taken, one set in the positive polarity of the bias of the two arrays, two sets in the negative polarity, and a third set in the positive polarity. The measurement followed the scheme: +, -, -, + and took about 5 minutes.

A gain of the 1 mV range was measured using the BIPM JVS and a correction factor of 3.2 ppm (cf. Fig A2) was applied to the readings before calculating the result.
**Fig. A2:** Linearity of the HP34420A SN:US36000320: The blue curve represents a Least Square adjustment of the blue points. The uncertainty on the Least Squares fit does not appear as negligible.

18 measurements were performed in this configuration, leading to a relative voltage difference of:

\[
\frac{U_{NMC} - U_{BIPM}}{U_{BIPM}} = 0.16 \times 10^{-10} \text{ and } u_A / U_{BIPM} = 0.7 \times 10^{-10} \]

where \(u_A\) is the Type A uncertainty.

27 September 2010

On 27 September, 15 measurements were repeated using the same measurement set-up but with various RF frequencies and either with or without the nanovoltmeter’s analogue filter engaged. The mean of the results obtained is:

\[
\frac{U_{NMC} - U_{BIPM}}{U_{BIPM}} = 0.86 \times 10^{-10} \text{ and } u_A / U_{BIPM} = 1.46 \times 10^{-10} \]

where \(u_A\) is the Type A uncertainty.
The measurement set-up was then modified to use the NISTVolt module dedicated to direct comparison of JVS. Three measurements were carried out in this configuration and very good agreement was found between the two JVS using this software.

28 September 2010

Measurements were carried out at the 1.018 V level in order to perform a BIPM.EM-K10.a comparison. NISTVolt software for Zener calibration was used and confirmed the presence of an offset of -9 nV.

The measurements taken into consideration for the calculation of the final result at the level of 1.018 V are listed in the following:

- 5 measurements were performed using the NISTVolt software module dedicated to direct JVS comparisons.
- 8 measurements were carried out using the BIPM Labview module to run the measurements.

Measurements at the 1.018 V and 10 V levels with a new set-up (set-up #3):

The option A measurement chain was set-up to measure the voltage difference between the two JVS. This set-up allows the BIPM to use its equipment to measure the voltage provided by the participant’s JVS. The BIPM equipment consists of an EM model N1a analogue nanovoltmeter which has its output connected, via an optically-coupled isolation amplifier, to a pen recorder and a digital voltmeter (DVM) which is connected to a computer.

The computer was used to monitor measurements, acquire data and calculate results. Low thermal electromotive force switches were used for critical switching, such as polarity reversal of the detector input. The connection of both arrays in series opposition was also controlled by a low thermal switch. The equipment included a voltage divider to prevent the detector from overload if both systems were not on the selected steps.

Comment: An EM N11 was borrowed from the NMC, A*STAR to replace the N1a in the measurement chain. This allowed a saving in space and weight during transportation of the equipment.

Even though it was difficult to precisely select a step on the NMC, A*STAR JVS, the stability of both JVS was good enough to consider the use of the analogue detector to measure the voltage difference. As a consequence, the BIPM array was adjusted to the same step as the NMC, A*STAR JVS after each polarity reversal. However, this exercise cannot be considered as an
option A comparison and the corresponding measurements cannot be included in the calculation of the final result.

The procedure consisted of the following: both arrays were biased from their respective sources, then the NMC, A*STAR bias source was disconnected first. The two JVS were connected (i.e. the short on the nanovoltmeter was removed). The BIPM array was adjusted to match that of the NMC, A*STAR and its bias source was disconnected. We waited for 10 s to 15 s before running the data acquisition. The voltage generated by both arrays was thus always identical within a few steps from the nominal value, although this was not a critical issue because both JVS were biased to the same frequency. Nevertheless, this experiment could not be considered as having followed an option A comparison protocol and therefore the results were not taken into account for the calculation of the final result.

Comment: the NMC, A*STAR bias source is gradually disconnected from its array via an optoisolator. The gradually increasing impedance of the optoisolator should greatly reduce step jumps when the bias is disconnected from the array. However, we noticed that each time the source was disconnected from the array, it always jumped by a few steps.

This experiment was carried out to find the systematic error that appeared when using the automatic configuration for Zener calibrations.

8 measurements were carried out at the 1.018 V level on the 3 µV range of the detector and position 3 of the filter. The result showed very good agreement between the two systems:

\[
\frac{U_{\text{NMC}} - U_{\text{BIPM}}}{U_{\text{BIPM}}} = -0.78 \times 10^{-9} \quad \text{and} \quad \frac{u_A}{U_{\text{BIPM}}} = 0.43 \times 10^{-9} \quad \text{where} \quad u_A \text{ is the Type A.}
\]

A total of 9 measurements were performed with this set-up at the level of 10 V leading to the following result:

\[
\frac{U_{\text{NMC}} - U_{\text{BIPM}}}{U_{\text{BIPM}}} = -2.97 \times 10^{-10} \quad \text{and} \quad \frac{u_A}{U_{\text{BIPM}}} = 0.47 \times 10^{-10} \quad \text{where} \quad u_A \text{ is the Type A.}
\]

This result shows a satisfactory agreement and confirmed the very good quality of the two standards.

29 September 2010

From the results obtained on 28 September, it was obvious that an offset of 3 nV existed in this configuration. Furthermore, it was impossible to perform a measurement on the 3 µV range of the EM-N11 nanovoltmeter because of the level of noise in the set-up.
The BIPM Dewar was disconnected from the ground and we managed to perform 5 measurements on the 3 µV range using filter position 3 of the detector:

\[(U_{NMC} - U_{BIPM}) / U_{BIPM} = + 15 \times 10^{-10} \text{ and } u_A / U_{BIPM} = 0.44 \times 10^{-10}\] where \(u_A\) is the Type A.

The offset of 15 nV disappeared when the BIPM Dewar was re-connected to the ground. However, after performing 5 new measurements on the 3 µV range using filter position 3, the 3 nV offset was still observed.

We decided to replace the NMC, A*STAR bias source (JVS1002) with a JBS-501 model and we performed 10 measurements that gave the following satisfactory result:

\[(U_{NMC} - U_{BIPM}) / U_{BIPM} = + 0.27 \times 10^{-10} \text{ and } u_A / U_{BIPM} = 0.64 \times 10^{-10}\] where \(u_A\) is the Type A.