# Comparison of the Josephson Voltage Standards of the DMDM and the BIPM

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

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**Abstract**

A comparison of the Josephson array voltage standards of the *Bureau International des Poids et Mesures* (BIPM) and the *Directorate of Measures and Precious Metals* (DMDM), Belgrade, Serbia, was carried out in June 2015 at the level of 10 V. For this exercise, options A and B of the BIPM.EM-K10.b comparison protocol were applied. Option B required the BIPM to provide a reference voltage for measurement by the DMDM using its Josephson standard with its own measuring device. Option A required the DMDM to provide a reference voltage with its Josephson voltage standard for measurement by the BIPM using an *analogue* nanovoltmeter and associated measurement loop. Since no sufficiently stable voltage could be achieved in this configuration, a *digital* detector was used. In all cases the BIPM array was kept floating from ground.

The final results were in good agreement within the combined relative standard uncertainty of 1.5 parts in $10^{10}$ for the nominal voltage of 10 V.

## 1. Introduction

Within the framework of CIPM MRA key comparisons, the BIPM performed a direct Josephson voltage standard (JVS) comparison with the DMDM, Serbia, in June 2015.

The BIPM JVS was shipped to DMDM, where an on-site direct comparison was carried out from 18 June to 24 June 2015. The comparison followed the technical protocols for the options A and B of the BIPM.EM-K10 comparisons. The comparisons involved the BIPM measuring the voltage of the DMDM JVS using its measurement loop where a digital voltmeter was used as a detector for option A and DMDM measuring the voltage of the BIPM transportable JVS using its own measurement chain for option B.

For both protocol options, the BIPM array was kept floating from ground and was biased on the same Shapiro constant voltage step for each polarity. The array remained on a single step during the time frame required for the data acquisition. For convenience, the BIPM array was biased at the same RF frequency with which DMDM operates its quantum voltage standard: $f$=74.90 GHz.

This article describes the technical details of the experiments carried out during the comparison.

## 2. Comparison equipment

### *2.1 The BIPM JVS*

In this comparison the BIPM JVS comprised a 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* stabilizer [1]. An optical isolation amplifier was placed between the array and the oscilloscope to enable the array *I-V* characteristics to be visualized, while the array was kept floating from ground. During the measurements, the array was disconnected from this instrument. The measurements were carried out without monitoring the voltage across the BIPM JVS. The RF biasing frequency is always adjusted to minimize the theoretical voltage difference between the two JVS to zero and in most cases, the BIPM array can operate at the frequency of the participating laboratory.

The series resistance of the measurement leads was 3.65 Ω in total and the value of the thermal electromotive forces (EMFs) was found to be of the order of 400 nV to 500 nV. Their influence was eliminated by polarity reversal of the arrays. The leakage resistance between the measurement leads was greater than $5 \times 10^{11}$ Ω for the BIPM JVS.

### *2.2 The DMDM JVS*

The DMDM JVS is a fully automated system fabricated by *Supracon* – Jena, Germany (S/N: 12). The information presented here is taken from the User Manual of JVS, *Supracon*, September 2012.

The JVS cooled with a cryocooler consists of the following components:

1. Cryoprobe with the 10 V SIS JJ Array Chip (serial number:1996-1) in the pulse tube cooler and the microwave electronics

2. JVS Electronics Unit

3. EIP Source Locking Microwave Counter, Phase Matrix 578 B

4. Keithley nanovoltmeter 2182A (S/N: 1396919)

5. Three-channels polarity reversal switch

6. Sensors for temperature, pressure and humidity

7. Laptop with the suitable software

8. 2 kW Compressor Unit

Other information on the DMDM JVS:

- The microwave electronics consists of a Gunn oscillator with an integrated isolator, a directional coupler, a remote sensor, a voltage controlled attenuator and a power supply, assembled in the rack.
- The three-channel computer-controlled polarity reversal switch, with very low thermal voltages (2 nV to 4 nV) and a resistance of the wiring of 1.5 Ω, according to the manufacturer specifications.

## 3. Comparison procedures - Option B

The option B comparison took place before the option A comparison.

After the BIPM JVS was set up, the array of Josephson junctions was checked for trapped flux. The BIPM array was then successfully biased at the same frequency at which the DMDM operates its quantum voltage standard: $f$ = 74.90 GHz. The BIPM JVS offers a large RF frequency band over which the quantum voltage is stable. This flexibility allows bringing some simplicity in the measurement process as if one of the two arrays jumps during the data acquisition, the effect is independent on the particular array and the software can deal easily with it. Furthermore, as it is possible to adjust the voltage difference between the two arrays to zero within one to three steps, this contributes to limiting the impact of a change in the gain value of the nanovoltmeter during the measurement process.

During the time of the comparison, we met some strong instability of the voltages provided by the JVS for some of the tested grounding configurations. However the array voltages remained very stable once in the best grounding configuration selected. More details on the different evaluated grounding configurations are presented in the following.

### *3.1 Measurement set-up*

The measurements for the option B comparison were carried out with the DMDM *Supracon* JVS and embedded nanovoltmeter and software.

1- We started with the software option: “Zener calibration”. The BIPM JVS was connected to one of the scanner channels (channel C out of three choices available in total) which is part of the DMDM JVS system. In order to cancel out the linear evolution of the thermal EMFs between the array at liquid helium temperature and the top of the probe where the connections are made (room temperature), the polarity reversal must be performed at the level of the JVS (using the bias source). As the DMDM scanner is programmed to perform the reversal of the voltage standard connected to it, we decided to run two consecutive set of measurements: one where the positive voltage output of the BIPM array is presented to the scanner, another one where the negative voltage output of the BIPM array is presented. The combination of the two sets of measurements allows calculating the voltage difference between the two arrays. This procedure is an alternative to the one operated during a previous comparison at INM (Romania) [2].

2- The software offers a second option called “direct comparison”. In this case, the DMDM scanner doesn’t perform any polarity reversal and the JVS voltage output to be compared (BIPM) is directly connected to the selected channel of the scanner. As a consequence of several short circuit measurements on the three different channels of the scanner, we decided to connect the BIPM JVS to channel C (Cf. Appendix A – 20 June 2015)

The gain of the Keithley 2182A nanovoltmeter which measures the voltage difference was measured on a regular basis to correct the readings and also to estimate the uncertainty of the gain (Cf. Figure A1 of Appendix A).

During the measurement process, the BIPM bias source was adjusted manually to the same step after each polarity reversal. This process took a few seconds on the BIPM array while a voltage adjustment after a polarity reversal needed about 50 seconds on the DMDM quantum standard, mainly due to the microwave power adjustment. The microwave source required to be shut down and turned on again to reach a new quantum voltage, after each reversal.

### *3.2 Results of the option B*

#### 3.2.1 Preliminary measurements

The software allows a maximum number of eight individual measurement points in a single file. A preliminary series of 4 points was performed using the software option “Zener calibration”. As everything went smoothly, we carried out 8 more measurements. The preliminary result, calculated as the mean value of these twelve points is: ($U_{DMDM}$ – $U_{BIPM}$) = -2.61 nV with a standard deviation of the mean of 2.38 nV (Fig. 1). This result confirms that the DMDM SIS-junctions-based primary voltage standard offers a very satisfactory metrological reliability.

With respect to the grounding of the measurement loop, it was decided to leave both arrays floating from ground and to equalize the potentials of the chassis of the instrumentation together with the shield of the connection wires by connecting them to the earth potential of the mains power distribution of the laboratory. This potential is by definition the reference potential of the DMDM JVS. This equipotential line had to include the He dewar and probe of the BIPM JVS. When this was not the case, the DMDM array couldn’t reach stable conditions.

After the preliminary measurements were carried out, more grounding configurations were investigated and are presented in the Appendix A of the report. However, the configuration described above was identified to be the best in terms of the lowest electrical noise. The standard deviation of a single data acquisition set (20 consecutive readings at NPLC=1) was at least twice as low as for any other grounding configuration.

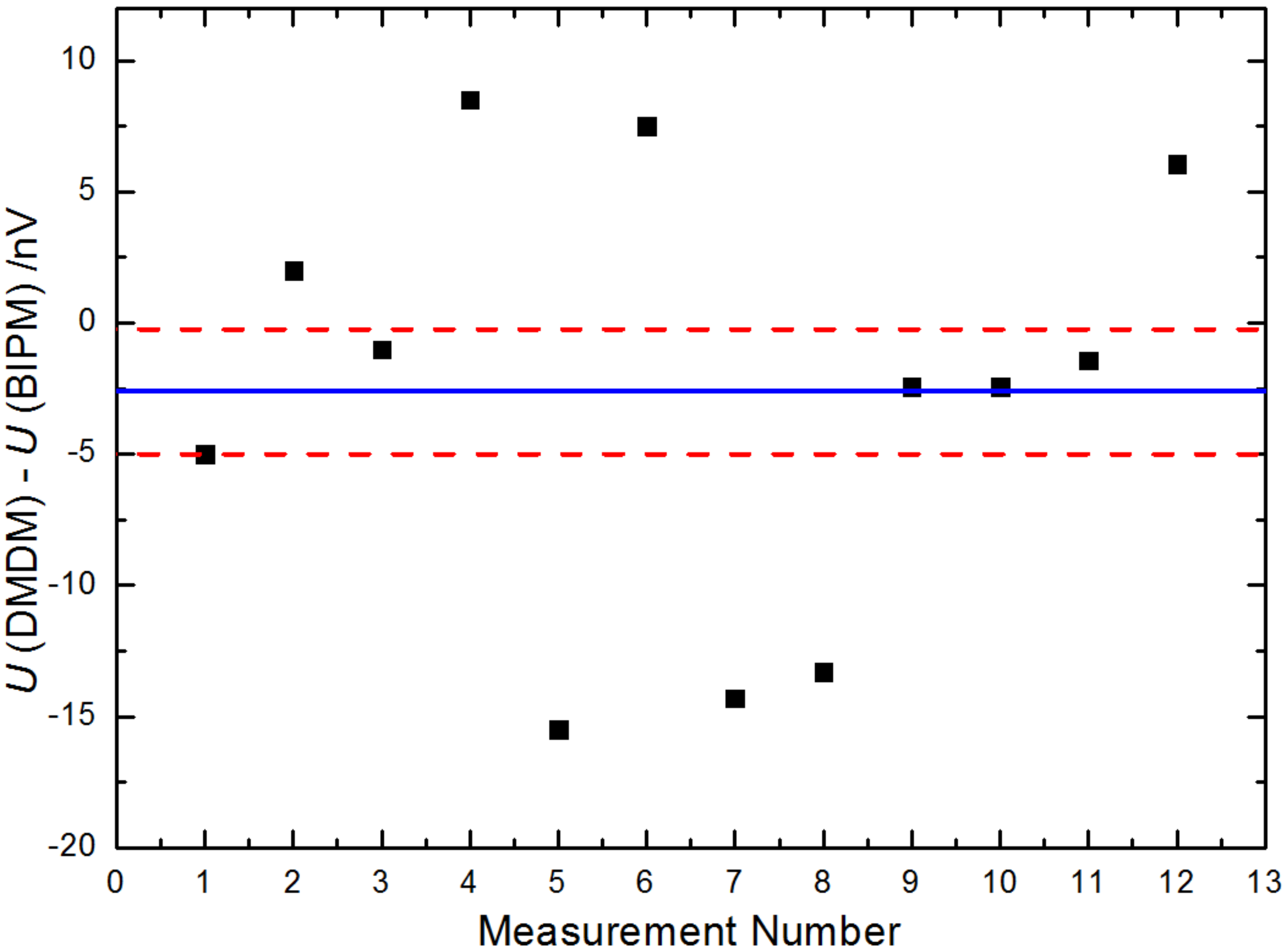


**Fig. 1**: Individual results obtained for the preliminary result of the Option B comparison protocol at the 10 V level. The Type A uncertainty (*k*=1) is represented by the dashed lines underneath and above the mean value represented by the solid blue line at -2.61 nV.

3.2.2 Direct comparison configuration (DMDM software)

The DMDM JVS software offers an option of direct comparison where the polarity reversal is not carried out by the DMDM scanner, but by the BIPM JVS. Within this software option, if the noise level (internal consistency) is larger than a certain level fixed by the manufacturer and which can't be changed by the operator, the measurements are not taken into account by the software and the user is only informed to keep proceeding with the measurement process.

Within different grounding configurations that are extensively described in the Appendix A, the preliminary result couldn't be improved using the direct comparison mode. We suspected the BIPM filter at the output of the measurement leads to introduce some electrical noise in terms of frequency resonance effect. We exchanged the filter with a weaker version which worked well in a past comparison with a *Supracon* JVS [3].

We tried again different grounding configurations and found that the grounding configuration used to obtain the preliminary result was still the best one, once the weaker filter was installed on the BIPM measurement leads.  We carried out 16 measurement points in 2 separate series. The mean value is: ($U_{DMDM}$ – $U_{BIPM}$) = - 0.1 nV with a standard deviation of the mean of 0.74 nV (Cf. Fig. 2).

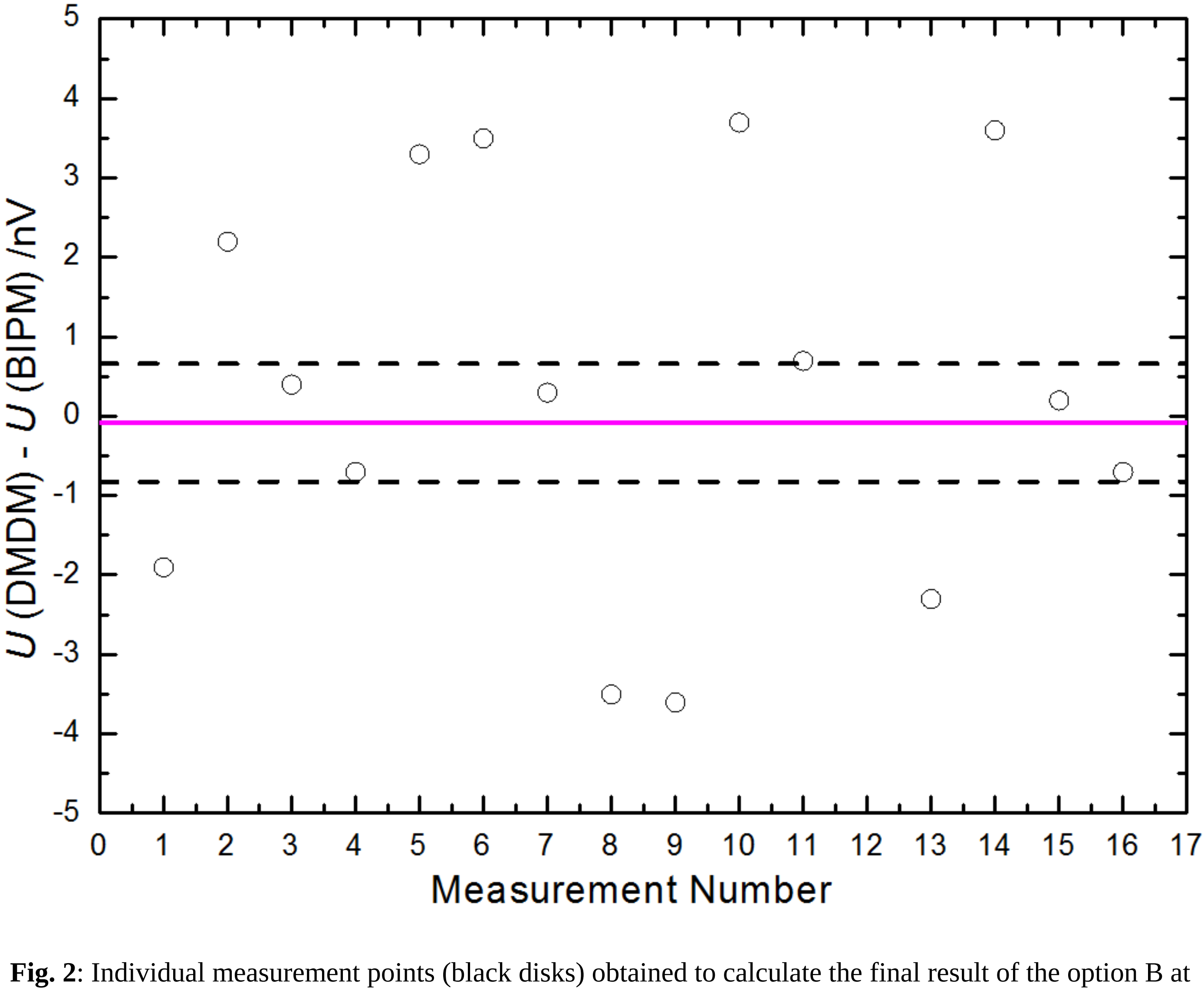


**Fig. 2**: Individual measurement points (black disks) obtained to calculate the final result of the option B at the level of 10 V while using the "direct comparison mode" of DMDM software. The solid line represents the mean value and the dashed lines represent the Type A uncertainty (at $k$=1).

3.2.3 Conclusion

The preliminary result was obtained from the “Zener calibration” mode of the DMDM software where the secondary standard was in fact replaced by the BIPM transportable JVS. It shows that the metrological behavior of the DMDM primary voltage standard and associated measurement setup is very satisfactory and fully supports the related DMDM CMCs.

This preliminary result could be technically improved using the “direct comparison” mode offered by the software with the following actions:

- Several grounding configurations of the measurement setup were investigated to select the one that brings the lowest simple standard deviation of the readings during the data acquisition process. It should be pointed out that some of the grounding configurations introduced such a level of noise that the voltages produced by the arrays were no longer quantized and therefore no measurement could be carried out.

- The 10 mV gain of the nanovoltmeter was carefully monitored as it exhibited a significant offset of the order of 120 ppm and could change by several ppm from one measurement to the next (Cf. Appendix A).

- The BIPM filter installed on the measurement leads is equipped with large inductances (20 mH) that can amplify the electrical noise at some frequencies. This filter was changed to a weaker version equivalent to the one implemented on the DMDM JVS. As a consequence, the amplitude of the coupling interferences clearly decreased between the two quantum standards.

The result obtained from the option B comparison protocol is: $(U_{\mathrm{DMDM}} - U_{\mathrm{BIPM}}) / U_{\mathrm{BIPM}} = -0.1 \times 10^{-10}$ with a relative experimental standard deviation of the mean (Type A uncertainty) of $u_{\mathrm{A}} / U_{\mathrm{BIPM}} = 0.74 \times 10^{-10}$.

## 4. Comparison procedures - Option A

### *4.1 First series of measurements using a digital nanovoltmeter*

As it is specified in the protocol, in order to use an analog detector, both arrays need to remain on the quantized voltage step for at least one minute in each polarity. To investigate on the stability of the measurement setup within the option A configuration, we first inserted a digital voltmeter, an HP34420A on its 10 mV range: if any of the two arrays jumps off from the selected step during the data acquisition, the detector won’t go on overload.

Furthermore, the *Supracon* software offers an arbitrary DC voltage synthesis within two optional intervals (± 2 µV and ± 5 mV). Once the measured voltage exceeds the limits of the voltage settings, the software automatically readjusts the array parameters and the comparison mode is stopped.

No measurements could be performed while the “strong” version of the BIPM filter was installed on the JVS measurement output leads. The DMDM software could not find proper adjustments of the RF power to get Shapiro steps on the array. The BIPM array voltage stability was also strongly affected.

Another try was performed once the option B completed with the new filter (Cf. §3.2.2). Within this configuration we obtained stable steps on both arrays; however the signal recorded on the HP34420A exhibited a significant offset which did not allow to perform a meaningful measurement.

Better stability was found after the HP nanovoltmeter was replaced with a Keithley 2182A nanovoltmeter. Nonetheless, the result exhibited a significant systematic offset the origin of which couldn’t be found during the time allotted to the comparison (Cf. Annex A).

The first result, obtained from 2 series of 8 consecutive measurement points, gave:

$(U_{DMDM} - U_{BIPM}) / U_{BIPM} = - 63 \times 10^{-10}$ with a relative Type A uncertainty $u_A / U_{BIPM} = 33 \times 10^{-10}$.

New series of measurements were carried out with the K2182A with different grounding configurations and after removing the power supplies of the laptops. The systematic error was still of the same amplitude.

Both arrays were not always operating on the same voltage step. To try to explain the observed systematic error, we plot the voltage difference in the positive polarity of the arrays as a function of the step number difference between the two arrays (Cf. Figure 3). The DVM offset was subtracted from all the readings.

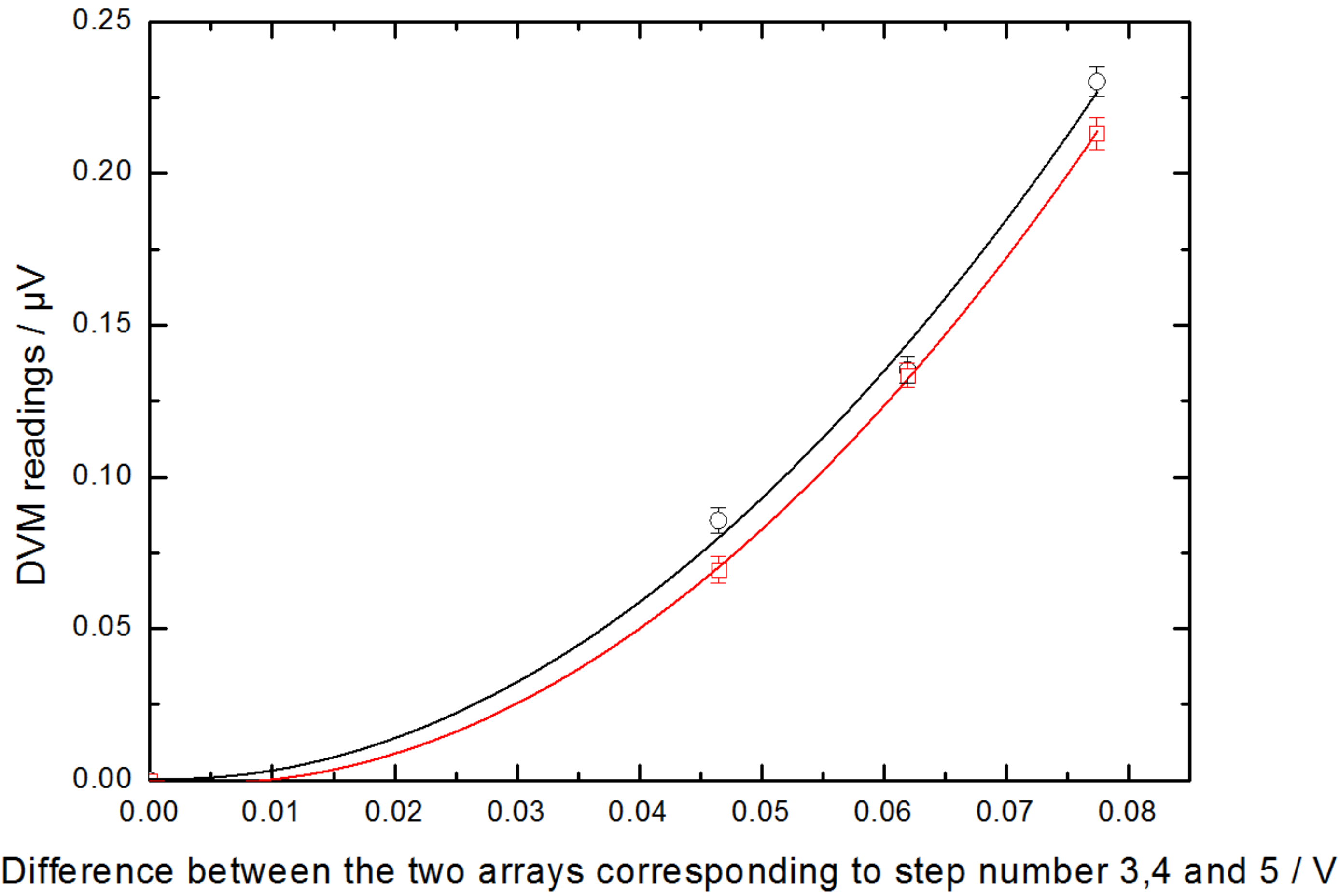


**Fig. 3**: Voltage difference in the positive polarity of the arrays as a function of the step number difference between the two arrays. The first series of measurement is represented with black circles and the second with red squares. A second order polynomial fit is applied to the data. The uncertainty bars represent the standard deviation of the mean of the nanovoltmeter readings for each individual point.

Two additional series of measurements were performed while taking great care in setting both arrays to the same step number in order to record a null voltage on the detector so that the gain error should have no impact. The systematic error was still present and the amplitude of the dispersion still of the same order (Cf. Annex A).

The dependence of the voltage readings on the step number could also be attributed to a difference in the 10 MHz reference signal fed into the two JVS frequency counters and would roughly correspond to a difference of 450 Hz. We investigated this assumption which can explain the “additional” gain error.

However, we tried different combinations of the 10 MHz reference signal to the EIP counters:

- We used a coaxial T connector from a single output of the GPS receiver;
- We used two different outputs of the GPS receiver;
- We used the internal 10 MHz quartz of the BIPM EIP578 frequency counter.

And none of those changes improved the amplitude of the systematic error.

We also tried to evaluate the dependence of the systematic error as a function of the voltage across the array for three points: 0 V, 5 V and 10 V. The initial results (black squares) are presented on Figure 5 and could be interpreted as a consequence of a leakage resistance in the circuit. This conclusion couldn't be confirmed as the subsequent results were not repeatable at 10 V (red disk and green diamond).

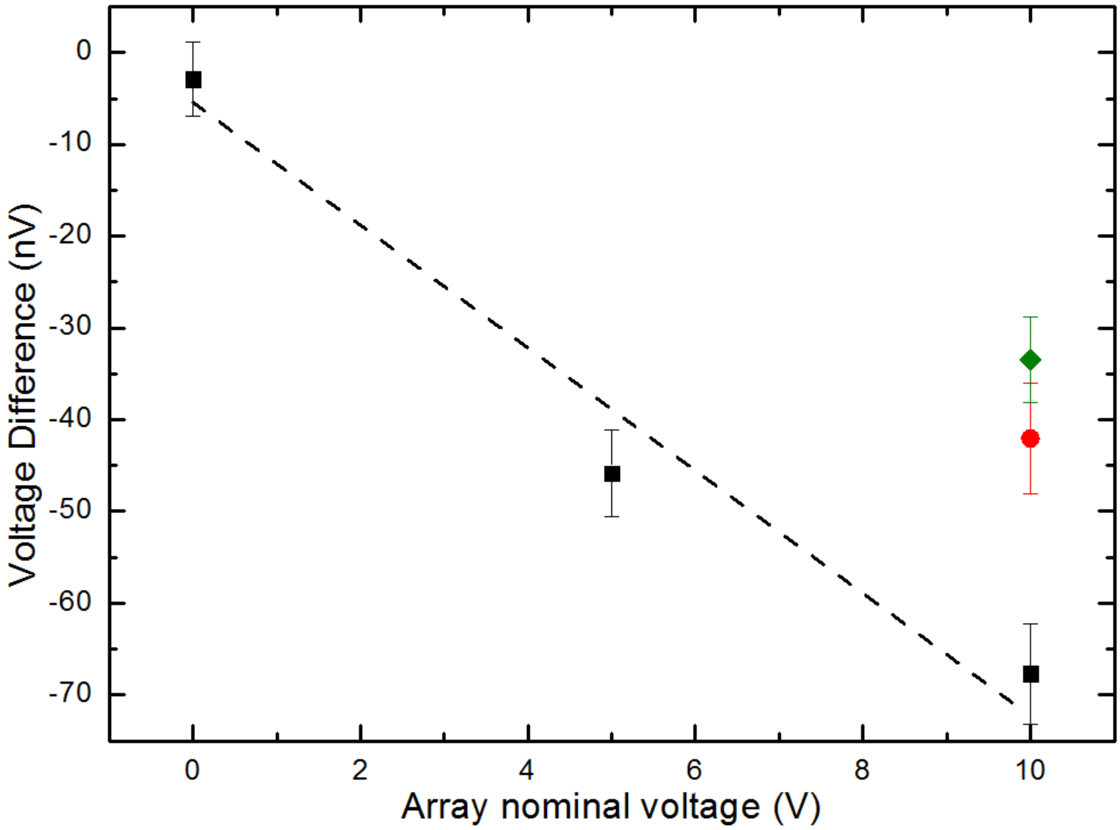


**Fig. 5**: Voltage difference between the two arrays as a function of the nominal voltage. The first series (black squares) seems to indicate a linear dependence which is not confirmed by two repeated measurements at 10 V (red disk and green diamond).

The effect responsible for the systematic error was not clearly identified and the last results lead us to the assumption that it is probably related to a change in the voltage across a parasitic capacitance in the circuit for which the voltage might change depending on its charging state.

### *4.2 Second series of measurements using an analog detector EM-N11*

We couldn't achieve a satisfactory result using a digital voltmeter within the option A of the comparison protocol. However, in the process of trying to identify the origin of the systematic error, we decided to replace the Keithley 2182A digital nanovoltmeter with a EM-N11 analog nanovoltmeter. This requires that both arrays could remain on the same Shapiro step, which was indeed the case. The EM-N11 offers the possibility to monitor an AC signal at its input. A rectified AC signal at the input of the nanovoltmeter could explain the DC offset monitored with a digital nanovoltmeter. No such AC signal was identified but we could clearly see a voltage difference in the two possible positions of the detector (measuring *U*[DMDM]-*U*[BIPM] or the opposite). The mean value of the readings in the two different detector polarities gave the same offset already read on the K2182A.

Since we were coming to the end of the time allotted to the comparison, the experiments were stopped at this point.

## 5. Uncertainties and results

### 5.1. Type B uncertainty components (option B protocol)

The sources of Type B uncertainty (Table 1) are: the frequency accuracy of the BIPM and the DMDM 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. The effect of residual thermal EMFs (*i.e.* non-linear drift) and electromagnetic interferences are also contained in the Type A uncertainty of the measurements because both array polarities were reversed during the measurements. Uncertainty components related to RF power rectification and sloped Shapiro voltage steps are considered negligible because no such behaviour was observed.

| | Type | Relative uncertainty | |
|---|---|---|---|
| | | **BIPM** | **DMDM** |
| Frequency offset (A) | B | $8.0 \times 10^{-13}$ | $13.35 \times 10^{-12}$ |
| Leakage resistance (B) | B | $2.1 \times 10^{-11}$ | $1.73 \times 10^{-11}$ |
| Detector (C) | B | | $1.24 \times 10^{-10}$ |
| Total (RSS) | B | $2.1 \times 10^{-11}$ | $1.26 \times 10^{-10}$ |

**Table 1:** Estimated Type B relative standard uncertainty components (Option B).

(A) As both systems referred to the same 10 MHz frequency reference, only a Type B uncertainty for the frequency measured by the EIP is included. The 10 MHz signal used as the frequency reference for the comparison was produced by a GPS receiver at DMDM.

The BIPM JVS has demonstrated on many occasions that the EIP-578B has a good frequency locking performance and that the accuracy of the frequency can reach 0.1 Hz. The relative uncertainty for the offset of the frequency can be calculated from the formula: $u_f = (0.1/\sqrt{3}) \times (1/75) \times 10^{-9} = 8 \times 10^{-13}$.

(B) If a rectangular statistical distribution is assumed then the relative uncertainty contribution of the leakage resistance $R_L$ can be calculated as: $u_f = (1/\sqrt{3}) \times (r / R_L)$, where $r$ is the series resistance of the measurement leads. For DMDM, the related variables were measured to $r = 3\ \Omega$ and $R_L = 1 \times 10^{11}\ \Omega$. The isolation resistance value includes all the cables from the JVS to the DVM. For BIPM, those parameters are measured to $r = 3.65\ \Omega$ and $R_L = 1 \times 10^{11}\ \Omega$.

(C) For DMDM JVS, a Keithley 2182A served as the null detector, with the correction of (130 ± 2) ppm on its 10 mV range. The uncertainty on the gain has been obtained as the standard deviation of the mean of 33 measurements of the gain performed at different time during the comparison (Cf. Fig A1 of Appendix A). As the array voltage difference was never larger by more than the voltage corresponding to 4 Shapiro steps, (620 µV), when a normal distribution is assumed and the coverage factor is taken as 1, the relative standard uncertainty on the detector can be calculated as $u_d = 1.24 \times 10^{-10}$.

5.2 Result at 10 V (option B)

The result obtained following option B of the protocol, is expressed as the relative difference between the values attributed to the 10 V BIPM JVS) by the DMDM JVS measurement set-up ($U_{\mathrm{DMDM}}$) and by the BIPM($U_{\mathrm{BIPM}}$):

$$(U_{\mathrm{DMDM}} - U_{\mathrm{BIPM}}) / U_{\mathrm{BIPM}} = -0.10 \times 10^{-10} \text{ and } u_c / U_{\mathrm{BIPM}} = 1.46 \times 10^{-10}$$

where $u_c$ is the total combined standard uncertainty and the relative Type A uncertainty is $u_A / U_{\mathrm{BIPM}} = 0.74 \times 10^{-10}$.

This result fully supports the CMCs (Calibration and Measurement Capabilities) of the DMDM.

## 6. Conclusion

The comparison was carried out in the DMDM Electricity Laboratories. The environmental conditions together with our investigations allowed meeting good conditions in the grounding of the measurement loop, essential for the stability of the quantum voltages. The DMDM Josephson Voltage Standard is a commercial system based on a cryocooler cooling equipment. The cryo-pump was installed in the same laboratory but outside the Faraday cage where the JVS was installed. The electrical noise environment was found very satisfactory as in particular, the voltages provided by the two arrays were very stable during the time allotted to the comparison. Both the preliminary result and the final result of the option B are very satisfactory. However, despite a lot of efforts, we couldn't find an explanation for a systematic error ranging from 40 nV to 80 nV within the option A protocol configuration.

## References

[1] Yoshida H., Sakamoto S., *et al*., Circuit Precautions for Stable Operation of Josephson Junction Array Voltage Standard*, IEEE Trans. Instrum. Meas*., 1991, **40**, 305-308.

[2] S. Solve, R. Chayramy, M. Stock, M. Simionescu and L. Cîrneanu, Comparison of the Josephson Voltage Standards of the INM and the BIPM (part of the ongoing BIPM key comparison BIPM.EM-K10.b), *Metrologia*, 2015, **52**, Tech. Suppl., 01009.

[3] S. Solve, R.Chayramy, M. Stock, J. Nicolas and A. Van Teemsche, Comparison of the Josephson Voltage Standards of the SMD and the BIPM (part of the ongoing BIPM key comparison BIPM.EM-K10.b), *Metrologia*, 2010, **47**, Tech. Suppl., 10104.

## 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 DMDM, 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 performed in chronological order.
The DMDM *Supracon* software operated during this comparison was version 2.3.

**18 June 2015:**
Despite the significant number of technical details exchanged for the preparation of the comparison, the liquid helium Serbian company didn't provide a dewar with the proper neck dimensions to fit with the BIPM probe. Fortunately, the company made a significant effort to quickly resolve the issue and a dewar with appropriate dimensions was delivered to DMDM on the 20$^{th}$ of June.

In the meantime we could analyze some aspects of the measurement setup that have a direct impact on the quality of the result in a direct comparison of two JVS:

- Investigations on the mains power supply in order to identify the single source from which the equipment of the two JVSs will be powered and from which the reference potential will be taken. We also checked that the phase and neutral plugs were identical for all the powered equipment;
- Evolution of the gain of the detector operated to measure the voltage difference; Figure A1 presents the evolution of the gain of the DMDM Keithley 2182A over the time of the comparison.

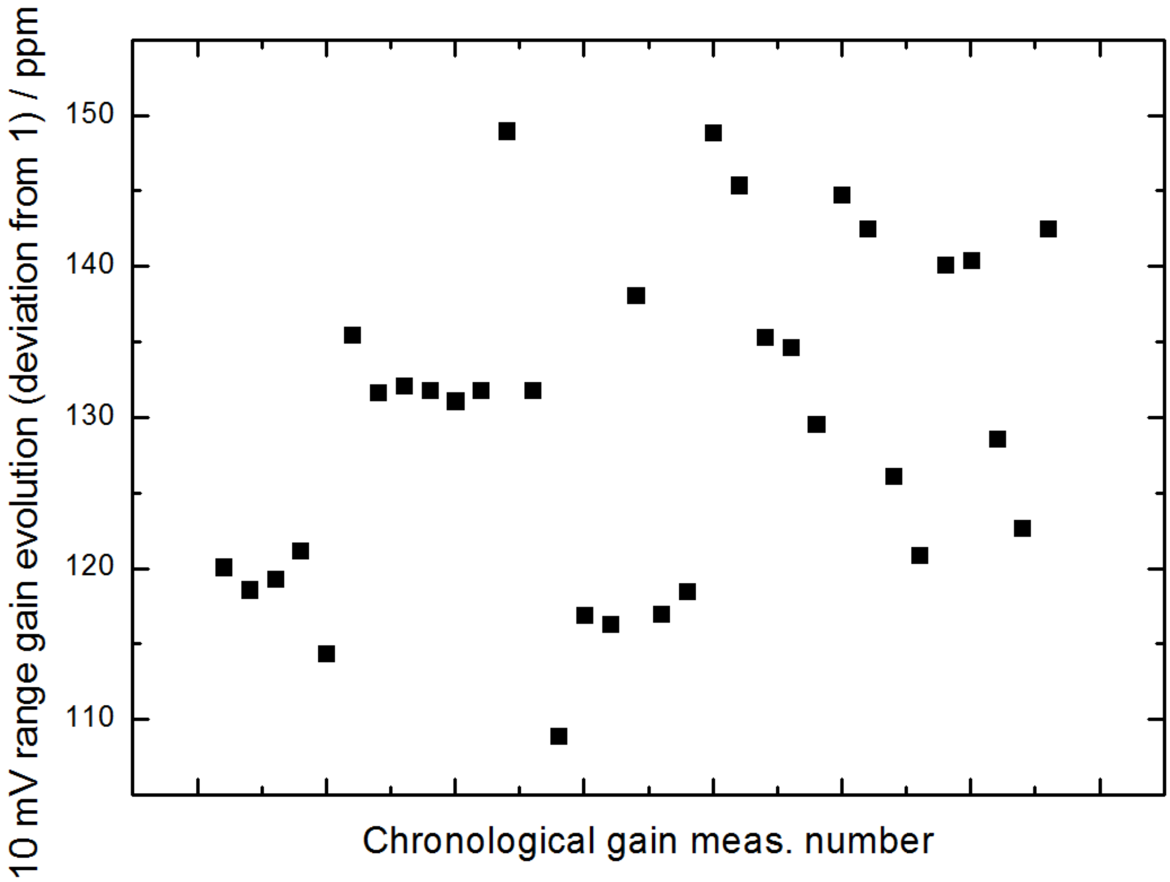


**Fig. A1**: Deviation of the gain correction from unity in ppm corresponding to the 10 mV range of the K2182A operated on the DMDM JVS measurement setup.

- Frequency scan of the DMDM RF source between 74.5 GHz and 75.5 GHz with an increment of 0.1 GHz to identify the frequencies where the DMDM JVS is most stable. This usually corresponds to the lowest RF power level associated with the lowest output resistance of the array biasing source. Figure A2 presents the results of the scan and shows that the region where the array exhibits its best capabilities is in between 74.8 GHz and 75 GHz.

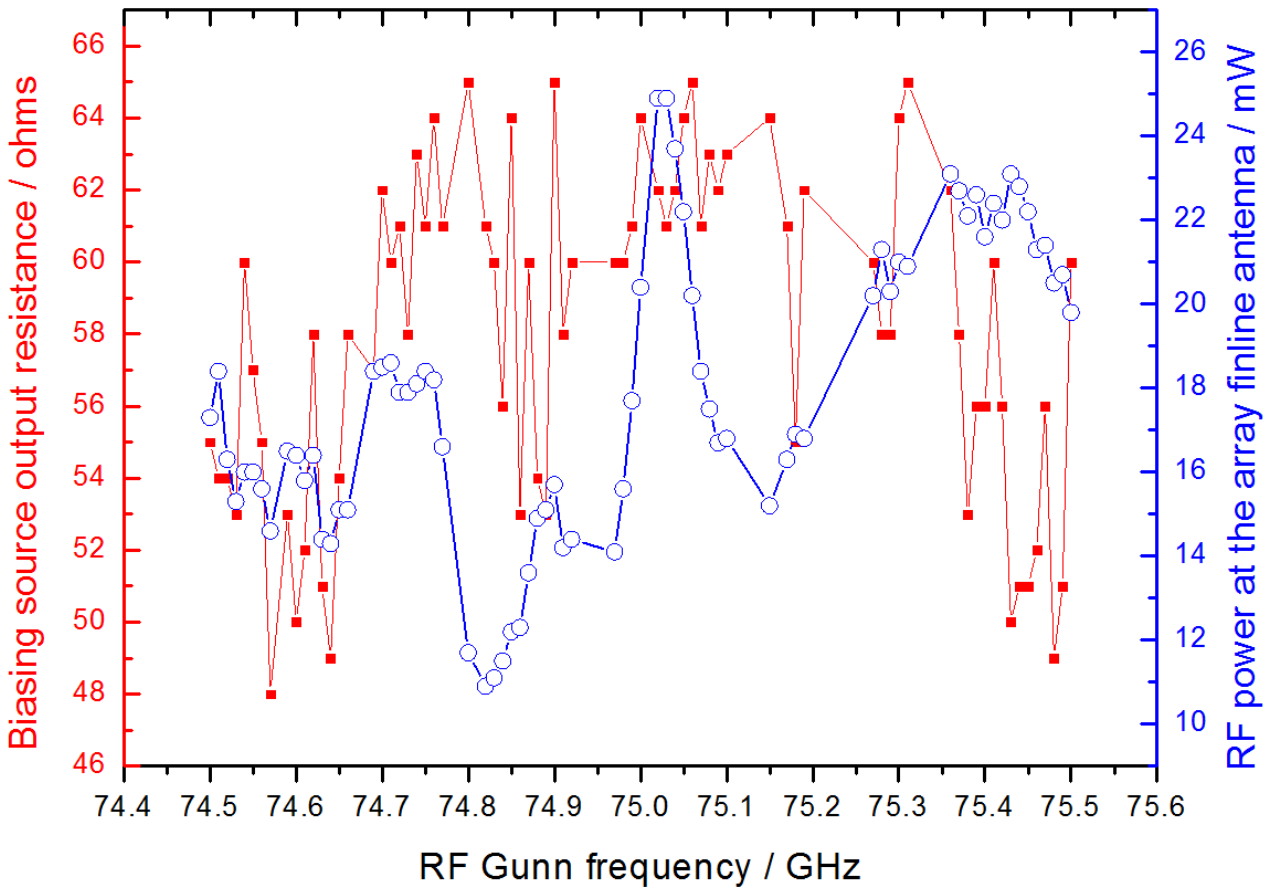


**Fig. A2**: Evolution of the biasing source output resistance and output power at the DMDM array finline antenna to obtain stable Shapiro steps as a function the RF biasing RF source frequency. The optimum parameter corresponds to the lowest output resistance associated with the lowest distributed power level.

We noticed that the embedded *Supracon* software doesn't allow calibrating the gain of a Keithley 2182A nanovoltmeter when the device is designed as an external voltmeter, despite the fact that this device is part of the list of the DVMs normally supported by the software. This is probably due to a bug in the software.

**19 June 2015:**

We performed new calibrations of the gain of the DMDM nanovoltmeter. We sometimes noticed a significant jump of up to 20 ppm in the value of the gain of the 10 mV range from one determination to the next (Cf. Figure A1).

We measured the gain of two more nanovoltmeters (Agilent 34420A and BIPM Keithley 2182A) in order to see if they would exhibit an equivalent spread of the values of the gain of the 10 mV range. No such dispersion could be observed with those two DVMs.

During the 10 mV range gain determination of the DMDM K2182A, we also noticed some frequency fluctuations on the DMDM EIP578P counter. They had a direct impact on the standard deviation of the voltage readings that could reach 300 nV for 10 consecutive readings while the lowest level was of the order of 20 nV. We also noticed that the frequency fluctuations were linked to the data acquisition process.

We tried to identify the source of noise responsible for the fluctuations by:

- Switching the 10 MHz reference signal of the RF source from the GPS receiver to the internal quartz of the EIP frequency counter;
- Using a T-connector from a unique output of the 10 MHz GPS receiver, even if such a connector is not a real splitter;
- Installing an isolation transformer on the 10 MHz line that goes to both JVSs;
- Switching off the BIPM EIP counter;
- Removing the laptop power supply;
- Installing a bus isolator on the IEEE488 line (decoupling the ground);
- Changing the DMDM RF frequency from 74.48 GHz to 74.9 GHz.

None of those actions had an effect on the reduction of the internal consistency. The only action that was efficient on the frequency fluctuations was to remove the coaxial cable bringing the 10 MHz reference signal to the BIPM EIP counter. In addition, the presence of the isolation transformer in between the GPS receiver output and the EIP578B external frequency input was found as a major cause in the gain jumps observed. In the presence of the isolation transformer, the gain of all the DVM tested was increased by 4 ppm to 6 ppm.

In the determination of the following gain values of the DMDM K2182A, we took great care to meet the frequency stability conditions before running a measurement.

**20 June 2015:**

The new helium dewar was received and a suitable critical current ($I_c$=80 µA) together with a stable output voltage at 10 V ($f$=74.9 GHz) were achieved on the first attempt to cool down the BIPM array.

In order to select the best scanner line out of the 3 available on the DMDM JVS system to connect the BIPM array (option B of the comparison protocol), we investigated the residual thermal EMFs on the three lines. All the residual thermal EMFs were far below 10 nV and mostly close to 2 nV. The BIPM array output measurement leads were connected to line C.

The two arrays were set to the same frequency: $f$=74.9 GHz.

The first selected grounding configuration was the following: both arrays were floating. The chassis of all the equipment of the measurement setup were connected to the reference potential. This potential was brought to the BIPM probe and dewar from the shield of the biasing cable. It turned out that the DMDM array couldn't find any stable voltage.

Suitable stability of the DMDM array was obtained as soon as the reference potential was removed from the BIPM probe and dewar. This could be achieved while replacing the BIPM biasing cable with a cable where the shield is not continuous.

Within this configuration, using the Zener software option, the four first points could be performed from which a preliminary result was calculated. In order to cancel out the thermal EMFs along the BIPM probe and as the DMDM scanner reverses automatically the polarity, we carried out 4 consecutive points where the voltage provided by the BIPM array is positive followed by four consecutive points where the BIPM voltage is negative. A series of 8 more measurement points was performed to calculate the preliminary result, starting point of any technical improvement:

$(U_{DMDM} - U_{BIPM}) / U_{BIPM} = -2.61 \times 10^{-10}$ with a relative Type A uncertainty $u_A / U_{BIPM} = 2.38 \times 10^{-10}$.

We switched to the "direct comparison" mode proposed by the software where the scanner doesn't reverse the polarity anymore and where the polarity reversal must be performed at the

level of the biasing source of the array. Eight consecutive points were performed (maximum number of measurements allowed by the software in one series):
$(U_{DMDM} - U_{BIPM}) / U_{BIPM} = -7.4 \times 10^{-10}$ with a relative Type A uncertainty $u_A / U_{BIPM} = 5.4 \times 10^{-10}$, mostly because of an outlier at -35 nV for which no reason to exclude it was found.

**21 June 2015:**

We started the day with the same configuration as we ended the day before. Two series of eight points were performed. One measurement was identified as an outliner and rejected when the BIPM frequency source lost its locking, making the frequency drifting:
$(U_{DMDM} - U_{BIPM}) / U_{BIPM} = 4.46 \times 10^{-10}$ with a relative Type A uncertainty $u_A / U_{BIPM} = 4.03 \times 10^{-10}$,
The gain of the 10 mV range of the DMDM nanovoltmeter was measured before, after and in between each series.

We noticed that the DMDM array needed sometimes 3 RF power scans before finding suitable stable steps, indicating that the level of electrical noise in the measurement loop was significant and could probably been improved.
We changed the grounding configuration: the BIPM probe and dewar were grounded through the shield of the measurement cable all the way from the DMDM chassis reference potential and obtained: $(U_{DMDM} - U_{BIPM}) / U_{BIPM} = 2.47 \times 10^{-10}$ with a relative Type A uncertainty $u_A / U_{BIPM} = 6.5 \times 10^{-10}$.
No clear improvement was observed except that the BIPM array needed more time to be adjusted on the proper step.

We went back to the previous grounding configuration and the frequency of both arrays was changed to $f$=74.48 GHz. The mean value of the 8 points performed in this series was $(U_{DMDM} - U_{BIPM}) / U_{BIPM} = 4.56 \times 10^{-10}$ with a relative Type A uncertainty $u_A / U_{BIPM} = 6.64 \times 10^{-10}$.

We replaced the DMDM 2182A nanovoltmeter with the BIPM one but surprisingly the internal consistency of the readings went above 100 nV and consequently measurements couldn’t be completed. The DMDM 2182A was installed in the measurement setup again and the frequency of both arrays was turned back to $f$=74.9 GHz.

Two sets of 8 measurements points were performed after adding an IEEE488 grounding decoupling device in the loop. The dispersion of the results of the series was not improved and they are respectively:
$(U_{\mathrm{DMDM}} - U_{\mathrm{BIPM}}) / U_{\mathrm{BIPM}} = -16.2 \times 10^{-10}$ with a relative Type A uncertainty $u_{\mathrm{A}} / U_{\mathrm{BIPM}} = 4.5 \times 10^{-10}$ and $(U_{\mathrm{DMDM}} - U_{\mathrm{BIPM}}) / U_{\mathrm{BIPM}} = 0.17 \times 10^{-10}$ with a relative Type A uncertainty $u_{\mathrm{A}} / U_{\mathrm{BIPM}} = 4.79 \times 10^{-10}$.

The IEEE488 bus isolator was removed.

We couldn't complete a measurement series with the low potential side of DMDM array grounded because of the large amplitude of noise in the measurement loop. In addition, we grounded the BIPM probe and dewar through the shield of the connecting wire from the scanner. The power supply of the DMDM laptop was removed.
The simple standard deviation of the DVM readings went down to 50-60 nV after having been previously always very closed to the limit of 100 nV. A related effect could also be noticed on the external consistency of 8 points:
$(U_{\mathrm{DMDM}} - U_{\mathrm{BIPM}}) / U_{\mathrm{BIPM}} = -5.7 \times 10^{-10}$ with a relative Type A uncertainty $u_{\mathrm{A}} / U_{\mathrm{BIPM}} = 1.7 \times 10^{-10}$

We noticed that the improvement in the dispersion of the results was mostly a consequence of the new grounding configuration. The presence of the DMDM power supply had also an impact in the increase of the noise level, but at a lower scale.

**22 June 2015:**

In the following experiments, we tried different configurations of the measurement loop:
- Grounding the BIPM low side of the array while the DMDM array was floating;
- Grounding the DMDM low side of the array while the BIPM array was floating;
- Grounding the BIPM probe and dewar or not.

We couldn't repeat the dispersion level achieved in the last series of the 21st of June. The Type A uncertainty of the 6 series of 8 points carried out within those different conditions was still of the order of 4 nV to 5 nV.

We decided to switch to the option A comparison protocol where the BIPM measurement setup measures the quantum voltage provided by the DMDM array. The first step was to investigate on the best grounding configuration of the measurement loop.

A low thermal EMFs switch was installed to open or close the measurement loop. We quickly noticed that the stability of both arrays was lost within the new setup, as soon as the circuit was closed.

The only grounding configuration where the stability of the voltages was at least partly recovered was the one where the BIPM probe and dewar were grounded from a direct link to the reference potential ("equipment Earth potential") and all the chassis were connected together but not referred to this reference potential. However the stability of the DMDM array wasn't sufficient to perform a measurement.

Remark: The *Supracon* software proposes an option where a quantum voltage can be produced out of the array ("arbitrary voltage"). As long as this voltage remains stable within the selected range (two parameters are available: 2 µV or 5 mV), the software doesn't bias the array again. It should be pointed out that the array is grounded during its biasing operation and is left floating once the stability criterion is met.

We investigated on the size of the quantum voltage step of the DMDM array using a dedicated software option. The step has to be large enough for not being affected by the ambient electrical noise level, which otherwise would make the voltage to jump very often. The steps were found flat over 20 µA which is usually suitable for measurement operations.

We tried to insert a LC PI filter in front of the output of the DMDM array to improve its protection against the ambient noise. This configuration didn't improve the stability of the voltage across the DMDM array.

We decided to switch back to the option B comparison protocol option to experiment the grounding configuration applied during the option A setup. A first series of 8 points was performed with the DMDM array array floating from the reference potential:

$(U_{\mathrm{DMDM}} - U_{\mathrm{BIPM}}) / U_{\mathrm{BIPM}} = 4.5 \times 10^{-10}$ with a relative Type A uncertainty $u_{\mathrm{A}} / U_{\mathrm{BIPM}} = 5.8 \times 10^{-10}$

A second series of 8 points with the low side of the array grounded gave:

$(U_{\mathrm{DMDM}} - U_{\mathrm{BIPM}}) / U_{\mathrm{BIPM}} = -6.2 \times 10^{-10}$ with a relative Type A uncertainty $u_{\mathrm{A}} / U_{\mathrm{BIPM}} = 3.9 \times 10^{-10}$

**23 June 2015:**

At this point, we suspected the filter installed at the output of the BIPM array to amplify by resonance effect some of the AC components of the residual electrical noise in the circuit. We decided to replace it with a lighter version for which the capacitance and inductance values are similar to the one installed at the output of the *Supracon* DMDM JVS.

Once this installation successfully completed without trapping magnetic flux on the BIPM array, a series of 8 points was performed with the low side of the DMDM array connected to the reference potential:

$(U_{\mathrm{DMDM}} - U_{\mathrm{BIPM}}) / U_{\mathrm{BIPM}} = -3.7 \times 10^{-10}$ with a relative Type A uncertainty $u_{\mathrm{A}} / U_{\mathrm{BIPM}} = 0.5 \times 10^{-10}$

The grounding configuration of the measurement setup was identical to the one used the day before.

A second series was performed with the DMDM array floating from the reference potential:

$(U_{\mathrm{DMDM}} - U_{\mathrm{BIPM}}) / U_{\mathrm{BIPM}} = 1.8 \times 10^{-10}$ with a relative Type A uncertainty $u_{\mathrm{A}} / U_{\mathrm{BIPM}} = 1.1 \times 10^{-10}$

We found out that the best measurement setup configuration was where both arrays were floating, the BIPM probe and dewar were grounded through the shield of the measurement leads coming out of the DMDM scanner. If the BIPM probe and dewar were grounded through a direct link to the reference potential (and the wire shield discontinued to avoid any ground loop), the stability of the voltage on the DMDM array was lost.

Two consecutive series of 8 points were performed within these conditions where the best result and associated Type A uncertainty for the option B comparison protocol was achieved:

$(U_{\mathrm{DMDM}} - U_{\mathrm{BIPM}}) / U_{\mathrm{BIPM}} = -0.1 \times 10^{-10}$ with a relative Type A uncertainty $u_{\mathrm{A}} / U_{\mathrm{BIPM}} = 0.74 \times 10^{-10}$

This result confirms that the main component of the electrical noise recorded on the previous days was originated from a coupling effect on the strong BIPM filter installed on the measurement leads. Since a major technical improvement was achieved by changing the filter, we decided to switch to the option A comparison protocol again.

The first selected nanovoltmeter was a digital HP34420A. The noise recorded on the readings was that high that no measurement could be performed, whatever grounding configuration we tried.

However, we managed to get stable Shapiro voltage steps on both arrays. That was not the case on our previous attempt with the option A.

The noise on the readings was considerably reduced once the HP34420A was changed to a Keithley 2182A. However the 16 measurements performed in a row gave a result with a significant systematic error:

$(U_{DMDM} - U_{BIPM}) / U_{BIPM} = -63 \times 10^{-10}$ with a relative Type A uncertainty $u_A / U_{BIPM} = 9 \times 10^{-10}$

All the measurement points obtained within the option A are presented on Figure A3

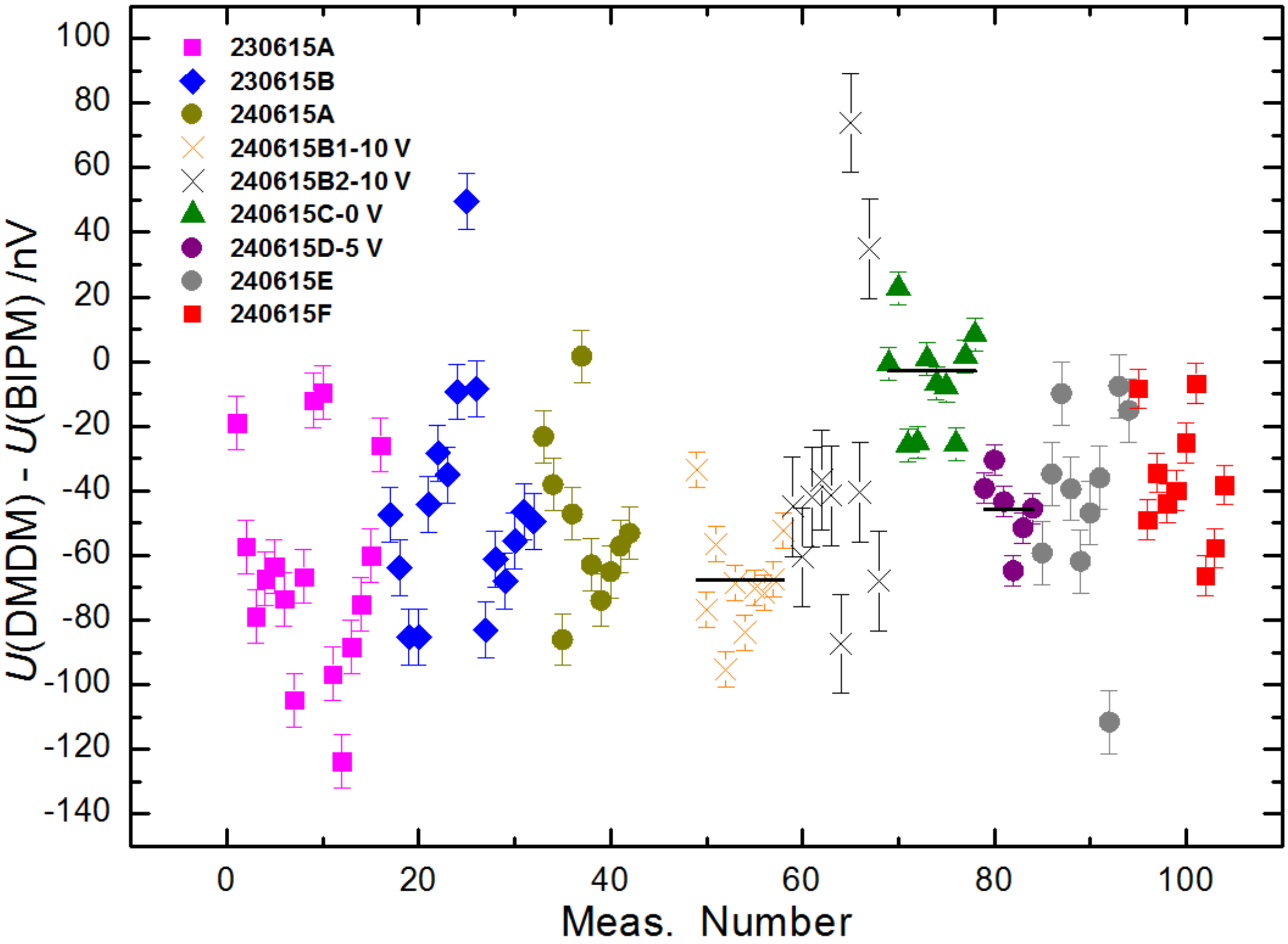


**Fig. A3**: Individual points obtained with the option A of the comparison protocol within different configurations of the measurement setup. See the text for details.

**24 June 2015:**

A first series of 16 points was performed with exactly the same configuration as on the 23rd of June: 10 mV range of the 2182A, NPLC=1 and no filter engaged on the nanovoltmeter. All the chassis of the equipment were connected together but not to the reference potential. The voltage difference and associated dispersion were of the same order as before:

$(U_{\mathrm{DMDM}} - U_{\mathrm{BIPM}}) / U_{\mathrm{BIPM}} = -45 \times 10^{-10}$ with a relative Type A uncertainty $u_{\mathrm{A}} / U_{\mathrm{BIPM}} = 9 \times 10^{-10}$

The 10 MHz reference signal of the 2 Gunn diodes was changed from the GPS receiver to the BIPM EIP counter internal quartz. For several minutes the noise reached a significant level and both arrays lost their stability. Then suddenly, the voltage stability was recovered and a series of 8 points could be performed:

$(U_{\mathrm{DMDM}} - U_{\mathrm{BIPM}}) / U_{\mathrm{BIPM}} = -32 \times 10^{-10}$ with a relative Type A uncertainty $u_{\mathrm{A}} / U_{\mathrm{BIPM}} = 17 \times 10^{-10}$.

As we suspected a correlation between the difference in the number of steps and the measured voltage difference between the two arrays, two series of 5 measurements were performed while taking great care in setting both arrays to the same step in order to record a null voltage on the detector, for which the gain error had therefore no impact. The systematic error was still present and the amplitude of the dispersion was still of the same order (Cf. Figure A3).

The first series was performed with all chassis and BIPM dewar and probe connected to the ground. For the second series the link to ground was removed. The dispersion of the measurements increased at the end of the second series.

$(U_{\mathrm{DMDM}} - U_{\mathrm{BIPM}}) / U_{\mathrm{BIPM}} = -49 \times 10^{-10}$ with a relative Type A uncertainty $u_{\mathrm{A}} / U_{\mathrm{BIPM}} = 17 \times 10^{-10}$.

We then tried to evaluate the dependence of the systematic error as a function of the voltage across the array for three different voltages: 0 V, 5 V and 10 V. The results are presented below as well as on Figure A3 (mean value represented as a black line).

At 0 V: $(U_{\mathrm{DMDM}} - U_{\mathrm{BIPM}}) / U_{\mathrm{BIPM}} = -2.92 \times 10^{-10}$ with a relative Type A uncertainty $u_{\mathrm{A}} / U_{\mathrm{BIPM}} = 4 \times 10^{-10}$.

At 5 V: $(U_{\mathrm{DMDM}} - U_{\mathrm{BIPM}}) / U_{\mathrm{BIPM}} = -45 \times 10^{-10}$ with a relative Type A uncertainty $u_{\mathrm{A}} / U_{\mathrm{BIPM}} = 5 \times 10^{-10}$.

At 10 V: $(U_{DMDM} - U_{BIPM}) / U_{BIPM} = -68 \times 10^{-10}$ with a relative Type A uncertainty $u_A / U_{BIPM} = 6 \times 10^{-10}$.

These results were promising as they could be interpreted as a consequence of a leakage resistance in the circuit. However, this conclusion couldn't be confirmed by the two consecutive series of 8points at the 10 V level which were not repeatable with respect to the first series at the same voltage level.
(Cf. Figure 5 in the core of the report).
However, in the process of trying to identify the origin of the systematic error, we decided to replace the Keithley 2182A digital nanovoltmeter with a EM-N11 analog nanovoltmeter. This device offers the possibility to monitor a AC signal at its input. A rectified AC signal at the input of the nanovoltmeter could explain the DC offset monitored with a digital nanovoltmeter.
No such AC signal was identified but we could clearly see a voltage difference in the two possible positions of the detector (measuring $U_{DMDM}$-$U_{BIPM}$ or the opposite). The mean value of the readings in the two different detector polarities gave the same offset read on the K2182A.

Since we were coming to the end of the time allotted to the comparison, the experiments were stopped here.
To explain the systematic error, we have the feeling that we faced an intermittent coupling effect between the 10 MHz RF reference signal and a component in the measurement setup but none of results obtained in the experiments could definitively confirm this assumption.