Comparison of the Josephson Voltage Standards of the MIKES 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 National Metrology Institute of Finland (VTT MIKES), Espoo, Finland, was carried out in October 2019 at the level of 10 V. For this exercise, the option A of the BIPM.EM-K10.b comparison protocol was partially applied. Option A required the MIKES to provide a reference voltage with its Josephson voltage standard for measurement by the BIPM using an analogue nanovoltmeter and associated measurement cables. Since no sufficiently stable voltage could be achieved in this configuration, a digital detector was used instead. 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 2.5 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 VTT MIKES, Finland.

The BIPM JVS was shipped to MIKES, where an on-site direct comparison was carried out from 9 to 16 October 2019. The comparison followed in principle the option A of the technical protocol but some deviations needed to be made. The comparison involved the BIPM measuring the voltage of the MIKES JVS with its measurement loop using a digital voltmeter as a detector (cf. Fig 1).

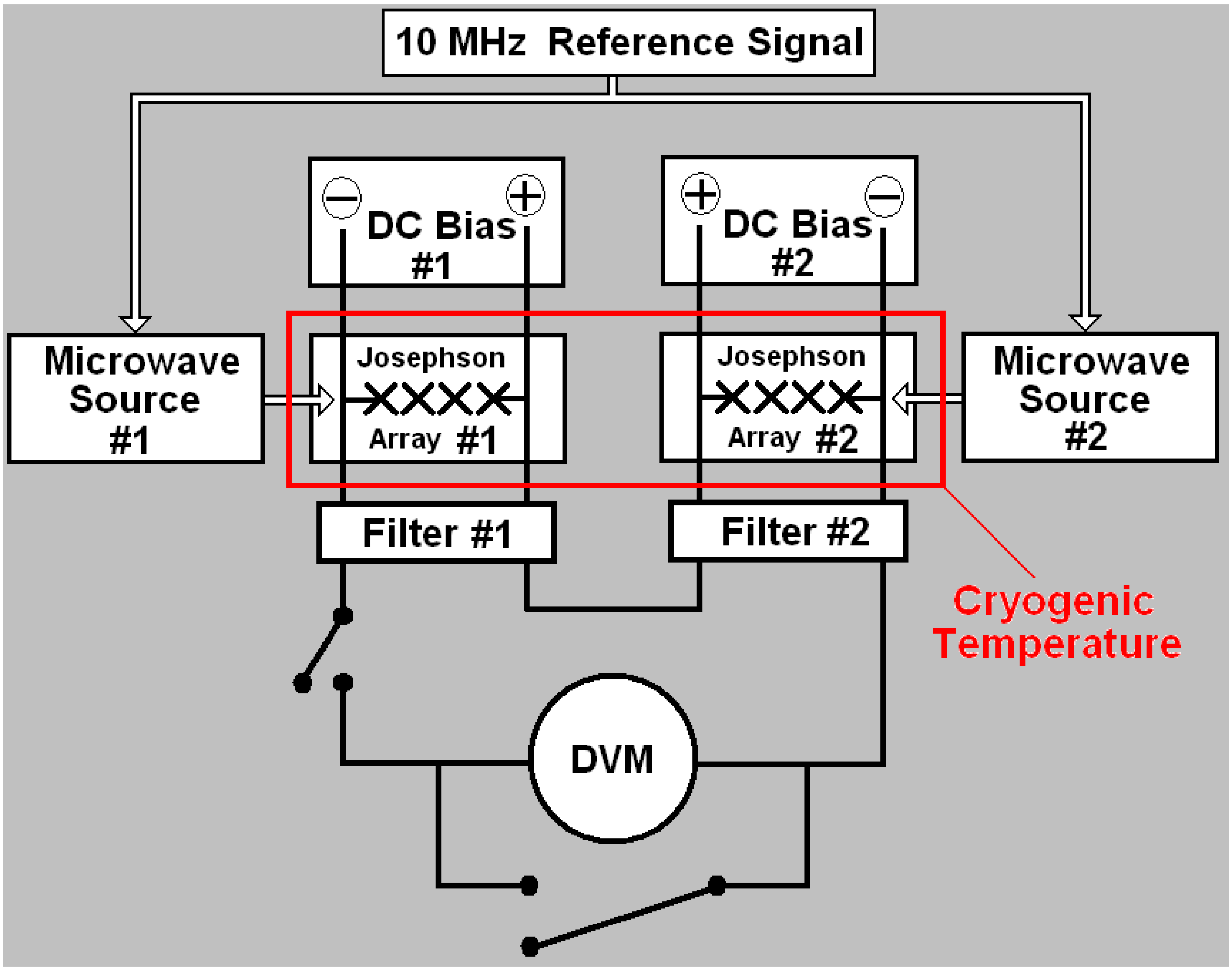

Fig 1: Schematic of the comparison measurement setup also called “measurement loop”.

This report 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's to zero and in most cases, the BIPM array can operate at the frequency of the participating laboratory.

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.

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 500 nV to 700 nV. Their influence was eliminated by polarity reversal of the arrays. The leakage resistance between the measurement leads was greater than 5×10^{10} Ω for the BIPM JVS.

2.2 The MIKES JVS

The MIKES JVS is normally used to calibrate Zener based working standards and for DVM linearity measurements. A 10 V SIS Josephson array (PTB, Ox1-Test3/5) is assembled in an IPHT cryoprobe. Bias current for the array is supplied from a modified battery-operated JBS-501 source. There is a switch in the bias source which should allow disconnection of the array from the bias electronics. However, in practice operation of the switch causes voltage jumps and therefore MIKES operates the array with bias source connected. The bias source connects the LO end of the array close to the potential of the shield of the voltage measurement cable. This means that if the shield is not left floating, the array potential will be fixed as well. The RF source of MIKES is a Farran GN-12 oscillator with 69 - 71 GHz frequency span. However, the measurements were partly performed using a 75 GHz oscillator supplied by BIPM in order to adjust the frequency to match exactly the BIPM source frequency. The frequency is locked by an EIP578B counter.

3. Comparison procedure - Option A

The option A comparison protocol has been designed to achieve the lowest Type A uncertainty of the voltage difference between the two JVS, using an analogue nanovoltmeter which offers a lower internal noise than a digital nanovoltmeter. However, the Option A protocol is always started with a digital nanovoltmeter to investigate the stability of the JVS voltage, in particular after the polarity reversal process. If sufficient stability is obtained in the course of the measurement process and if the Type A uncertainty of the series of points reaches the noise floor of the digital detector, it is worthwhile to switch to the analogue detector, which may improve the Type A uncertainty. In the present case, the noise level achieved was too high and the option A was operated with a digital nanovoltmeter only.

After the BIPM JVS was set up, the array of Josephson junctions was checked for trapped flux and the lowest critical current was measured at 60 µA while all the other junctions were at the level of 105 µA. A careful temperature cycle (warming up to the He gas temperature and cooling down to liquid He temperature) slightly improved the critical current amplitude of the weakest junction to 70 µA. The BIPM array was then successfully biased at the frequency of f = 74.795 GHz.

The BIPM JVS offers a large RF frequency band over which the quantum voltage is stable (from 73.6 GHz to 76.6 GHz) and in most cases this permits the BIPM to bias its array to the same frequency as the participant. This flexibility simplifies the measurement process since if one of the two arrays jumps during the data acquisition, the effect is independent on which one of the two arrays' voltage changes and the software can deal easily with the change. 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 of the nanovoltmeter during the measurement process.

MIKES normally operates its array of Josephson junctions in the frequency range between 69 GHz and 71 GHz. In the present comparison, since there is no overlap between the frequency operating intervals, the BIPM array had to be adjusted in such a way that the theoretical voltage difference is minimized. Furthermore, both arrays had to remain on their designated quantum voltage step during the measurement acquisition process.

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

3.1 Grounding of measurement set-up

3.1.1 Initial configuration

At MIKES, the power line of the laboratory is defined by 115 V (0° phase angle) between the phase and the earth potential and 115 V (180° phase angle) between the neutral and the earth potential (“115 V/115 V”, rather than the usual “230 V/0 V”) using a dedicated voltage transformer. This installation is made on purpose to reduce the electromagnetic fields induced by e.g. power cords of the instruments, and especially capacitive coupling to high impedance devices.

As described in Section 2.2, the MIKES array was always connected to the bias source, forcing low potential of the measurement loop to be within 1 mV of the shields of the connection cables. The laboratory’s instrumental earth is dedicated to metrological applications and is coupled, together with the safety earth, to the ground of the power line filters at the entrance to the shielded room. In order to equalize the potentials of the chassis of the instrumentation together with the shields of the connection cables in the measurement loop, the following configurations were investigated:

- The MIKES He dewar is connected to the closest point of the instrumental earth, and this reference potential is brought to the BIPM He dewar through the shields of the connection cables including the chassis of the connection boxes and switches (Cf. Fig 2).

- The BIPM He dewar is connected to the closest point of the instrumental earth, and this reference potential is brought to the MIKES He dewar through the shields of the connection cables.

- The BIPM He dewar and the MIKES He dewar are each connected to the closest point of the “instrumental Earth” but the equipotential line is interrupted at the level of the connection box between the two systems to avoid any ground loop.

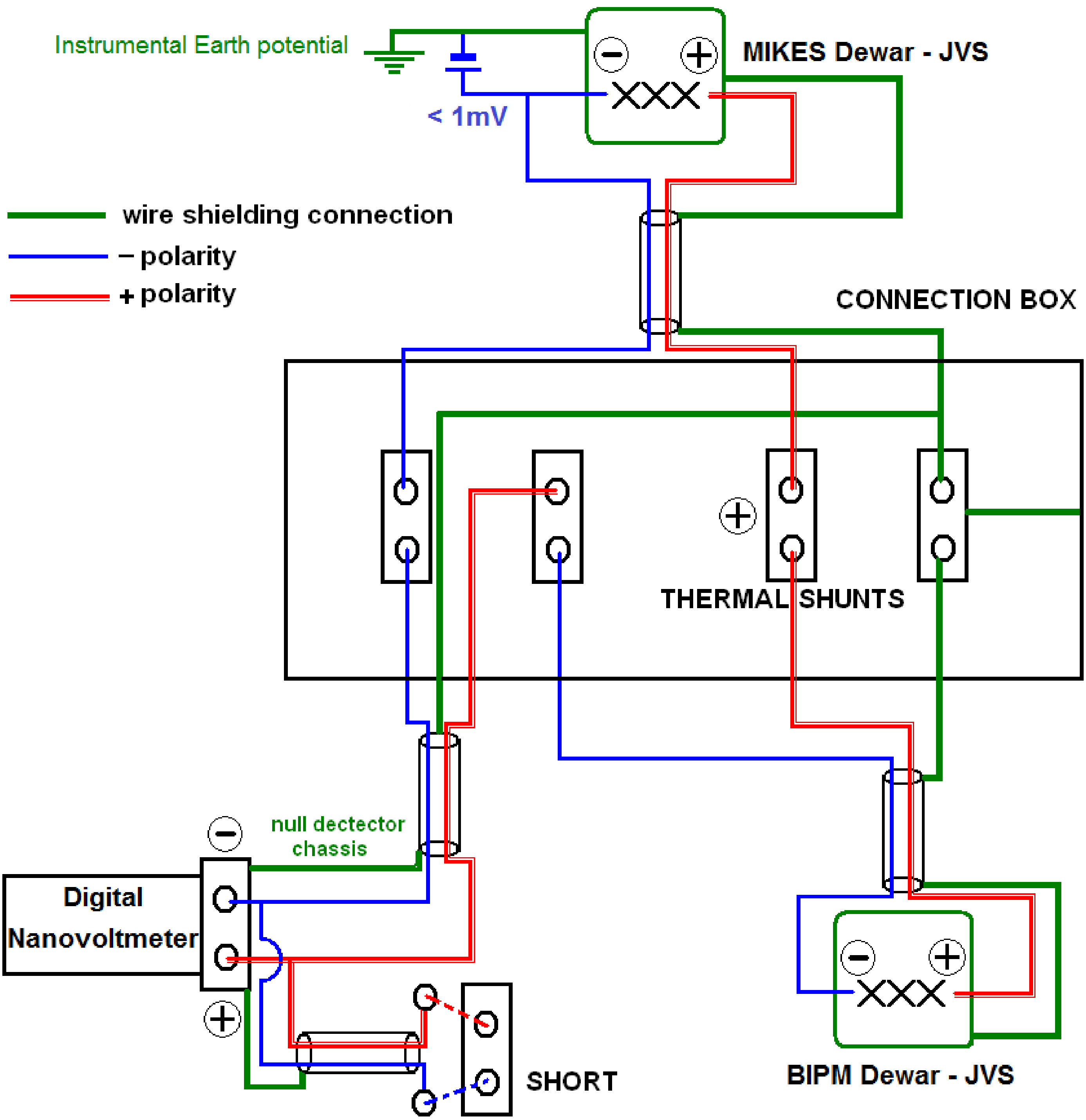

Fig. 2: Schematics of the selected grounding configuration of the direct comparison measurement setup.

In most comparison schemes, one these three possibilities brings sufficient stability of the Shapiro steps of both arrays while the two others bring some instability to one or the other array voltage. In the present case, none of the configurations was satisfactory for using the analogue nanovoltmeter.

3.1.2 Alternative configuration

Since unidentified transient/impulse type noise seemed to impair stability of the voltage steps an additional isolation transformer was added to further filter the mains. This configuration changed the power distribution to a “230 V/0 V” scheme (cf. Fig. 3).

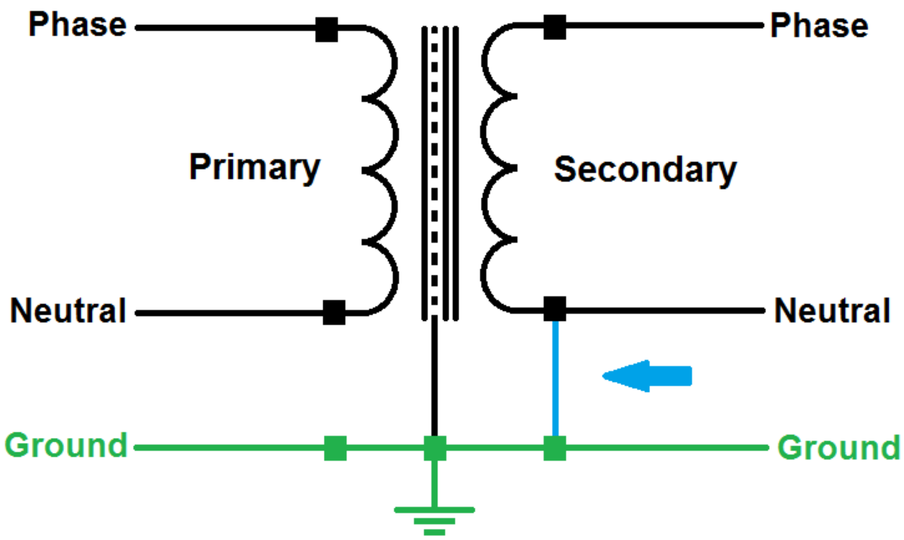

Fig. 3: Schematics of the isolation transformer used to power both JVS equipment and related instrumentation.

When the secondary’s neutral is grounded, inbound common-mode noise is converted to normal-mode noise with roughly a 60 dB attenuation (1000:1) [2].

Within this configuration, the first of the three grounding scenarios presented in the previous paragraph was found to be the best in terms of the stability of the voltage achieved on each JVS. However, sufficient improvement was still not achieved to enable the use of an analogue nanovoltmeter.

3.2 Preliminary Measurements

3.2.1 Investigations in preparation of the measurements

During the first three days of the exercise, we had to find the experimental conditions which would provide both JVS’s with sufficient voltage stability to be compared using a digital nanovoltmeter (Keithley 2182A). When the MIKES bias source is connected (with a particular switch in position “on”) to the array, the electronics connects the array LO end close to the potential of the voltage measurement cable shield. Within this configuration, the complete measurement setup is referred to this potential.

Note: The chassis of the MIKES bias source is internally isolated from the printed circuit board ground plane potential (equal to the cable shied potential), but in practice grounded to the instrumental earth with a separate wire.

The following modifications were successively applied:

- To improve the stability of the measurement, we tried to bias the BIPM array from an independent battery-operated source.

- To evaluate the effect of the nanovoltmeter, we replaced the Keithley 2182A with an Agilent 34420A. It appeared that the gain error of the detector (HP34420A) was measured to be 16 ppm on its 10 mV range (this nanovoltmeter type was later replaced during the experiment). Since both arrays were operated at different frequencies, (f = 69.910 GHz for MIKES and f = 74.795 140 GHz for BIPM), the operators struggled a lot to adjust the voltage steps (n = 69174 for MIKES and n = 64656 for BIPM) to obtain the lowest theoretical voltage difference ($U_{\mathrm{MIKES}} - U_{\mathrm{BIPM}}$) = -273.40 nV, but the measurements could not be completed owing to step instability.

- The BIPM array was biased at f = 73.585 GHz which is the lowest frequency for which the stability of the voltage is suitable for the comparison. The MIKES array was biased to 71.185 GHz which is the highest frequency for which the MIKES array voltage exhibits sufficient stability. By doing so, we tried to reduce the theoretical voltage difference between the two systems. Unfortunately, we couldn’t manage to achieve measurements because of instabilities in the negative polarities of the MIKES array voltage.

- An additional voltmeter was added in parallel to the biasing leads of the BIPM array in order to monitor precisely the voltage across it. The corresponding effect was to reduce the size of the BIPM voltage steps and therefore to increase its sensitivity to external noise.

- The filter installed on the measurement leads of the BIPM array comprises inductances of large value (20 mH to 30 mH) and they are known to possibly bring instability to the voltage of the participant’s array. It was decided to replace them with smaller value inductances (1 mH) [3].

Remark: a low pass passive filter is mandatory on the precision leads of a conventional array of Josephson junctions to prevent it from trapping magnetic flux.

- The BIPM dewar was in electrical contact with the floor of the laboratory which is by construction “semi-conducting”. The insulation was measured as $R = 400$ kΩ. A proper insulation was installed between the dewar and the floor.

- An investigation on the stability of the voltage and the size of the step was carried out on the MIKES array as a function of the biasing frequency. The array was found to offer much better margins and corresponding voltage stability at frequencies around $f = 74.6$ GHz than in the range 69 GHz to 71 GHz. At $f = 74.6$ GHz, the size of the Shapiro steps doubled, reaching 20 µA. Furthermore, the BIPM array could also be biased at the same frequency.

3.2.2 Preliminary Measurements

The result of these latest investigations allowed the direct comparison between the two JVS’s to be started in good conditions, even if we couldn’t connect the BIPM dewar to the reference potential of the measurement setup as this connection was bringing instabilities on the MIKES quantum voltage steps. The BIPM array could be biased at exactly the same frequency as that of the MIKES ($f = 74.622$ GHz), simplifying the voltage adjustment process. Two independent series of 10 points were performed (cf. Fig. 4). For the second series, special care was taken to short the nanovoltmeter between each polarity reversal and to open the connection between the two low potential sides of the arrays at the same time. This technique prevents the nanovoltmeter going into overload and thus leaving the two arrays “facing” each other. A third series of 10 points was performed after changing the grounding of the measurement setup where the BIPM dewar could finally be referred to the reference potential. The preliminary measurement result is considered to be the mean value of the 30 points: $(U_{\mathrm{MIKES}} - U_{\mathrm{BIPM}}) = 7.8$ nV with a standard deviation of the mean of 4.4 nV which represents the Type A uncertainty.

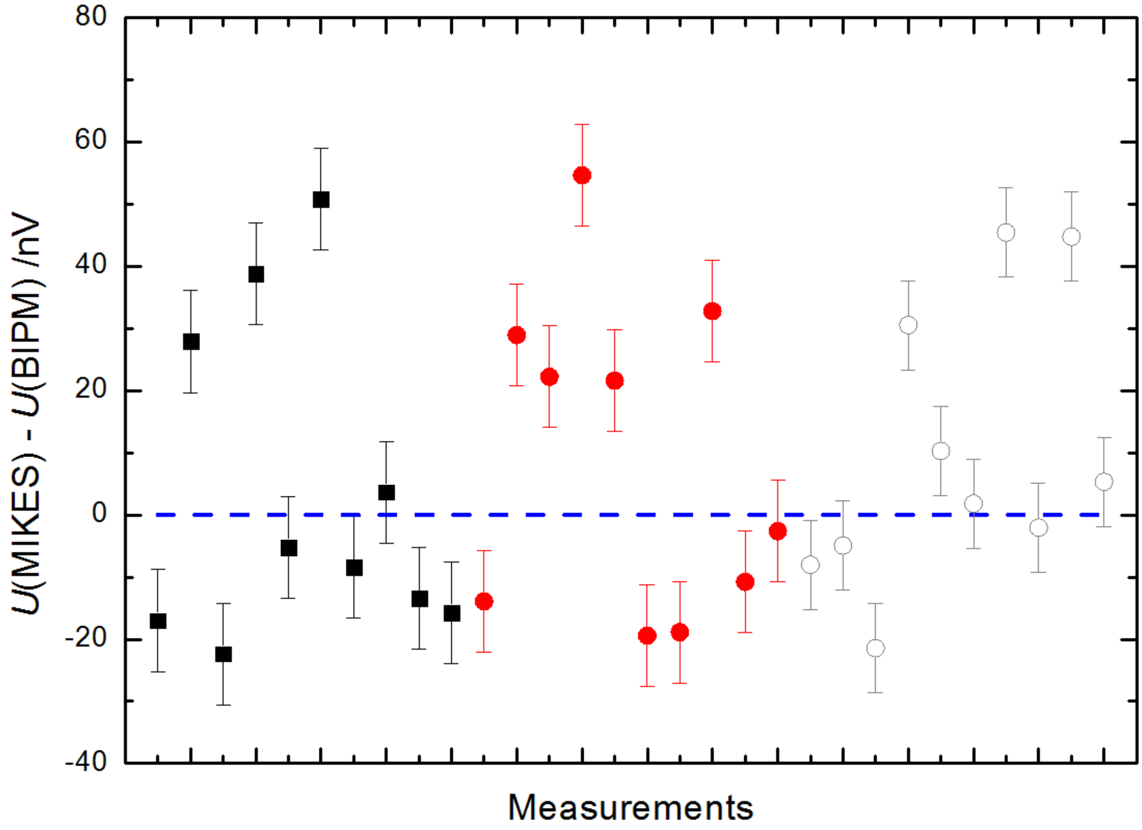

Fig. 4: Individual results obtained during the preliminary measurements of the Option A comparison protocol at the 10 V level using a digital nanovoltmeter. The uncertainty bars represent the Type A standard uncertainty. The two first series were performed in the same grounding configuration of the measurement setup (the BIPM dewar was not referred to the reference potential). In the third series, the BIPM dewar could be connected to the reference potential.

3.3 Final Measurements

3.3.1 Investigations performed to reduce the Type A uncertainty

The following modifications have been implemented on the measurement setup to try to reduce the dispersion obtained during the preliminary measurements.

- To evaluate the impact of the MIKES biasing source and since it was not possible to disconnect it without disturbing the selected Shapiro step, we tried to bias the MIKES array with the BIPM battery operated source [4]. Unfortunately, it was not possible to obtain sufficient stability to carry out a measurement.
- The trial to replace the Keithley 2182A with an Agilent 34420A was unsuccessful as it resulted in a significant level of noise in the measurement loop resulting in a DC offset of several millivolts on the meter.

- Going back to the Keithley 2182A, we activated the internal analogue filter of the nanovoltmeter to evaluate its impact on the dispersion of the results. For these measurements, a MIKES switch was connected in parallel to the nanovoltmeter allowing the voltage across the MIKES array to be monitored (with an Agilent 3458A) while shorting the nanovoltmeter. The switch allows keeping the voltage close to zero at the input of the nanovoltmeter while being able to adjust the voltage of the MIKES array to the selected step.
- The first four series of measurements were performed using the usual power line of the laboratory (cf. §3.1.1). It was decided to change the power line distribution of the laboratory to a *230 V/0 V* scheme using an isolation transformer (cf. Fig 3). In the last three measurements (#5-#7), all the instruments using mains supply, were therefore powered in a more traditional way which may affect the operation of transformers, filters etc. producing the internal supply voltages for the circuits.

The series of measurements which led to the computation of the final results is presented on Figure 4 for a total of 50 individual points. Each point was obtained as follows: The array polarity sequence +, -, -, + gives one measurement point (voltage difference between the two JVS's). In each polarity, after waiting for 10 s for stabilization (discharge due to the polarizability of the dielectrics in the capacitors in the circuit), 20 readings were acquired at NPLC=1.

- Series#1: 10 measurements points (*115 V/115 V scheme*) for which the reference potential in the setup is taken from the instrumental earth of the laboratory, set to the MIKES dewar and brought to the BIPM dewar through the cable shielding (cf. Fig 2). The analogue filter engaged on the Keithley 2182A (represented by filled squares on Figure 5);

- Series#2: 5 measurements points (*115 V/115 V scheme*) with reference potential on the MIKES side and no filter activated on the Keithley 2182A (represented by blank circles on Figure 5);

- Series#3: identical to series#1: 5 measurements points (*115 V/115 V scheme*) with the reference potential on the MIKES side and the analogue filter engaged on the Keithley 2182A (represented by filled triangles on Figure 5);

- Series#4: identical to series#2: 10 measurements points (*115 V/115 V scheme*) with the reference potential on the MIKES side and no filter activated on the Keithley 2182A (represented by blank squares on Figure 5);

- Series#5: 10 measurements points (*230 V/0 V scheme*) with the reference potential on the MIKES side and no filter activated on the Keithley 2182A (represented by filled diamonds on Figure 5);

- Series#6: 5 measurements points (*230 V/0 V scheme*) with the reference potential taken from the instrumental earth on the BIPM side and connected to the MIKES equipment through the cable shielding, and no filter activated on the Keithley 2182A (represented by filled disks on Figure 5);

- Series#7: 5 measurements points (*230 V/0 V scheme*) with the reference potential on the BIPM side and the analogue filter engaged on the Keithley 2182A (represented by blank diamonds on Figure 5).

The final result is calculated as the simple mean of the 50 individual measurement points and the Type A uncertainty calculated as the standard deviation of the mean:

$(U_{\mathrm{MIKES}} - U_{\mathrm{BIPM}})$ = 2.19 nV with a standard deviation of the mean of 2.05 nV.

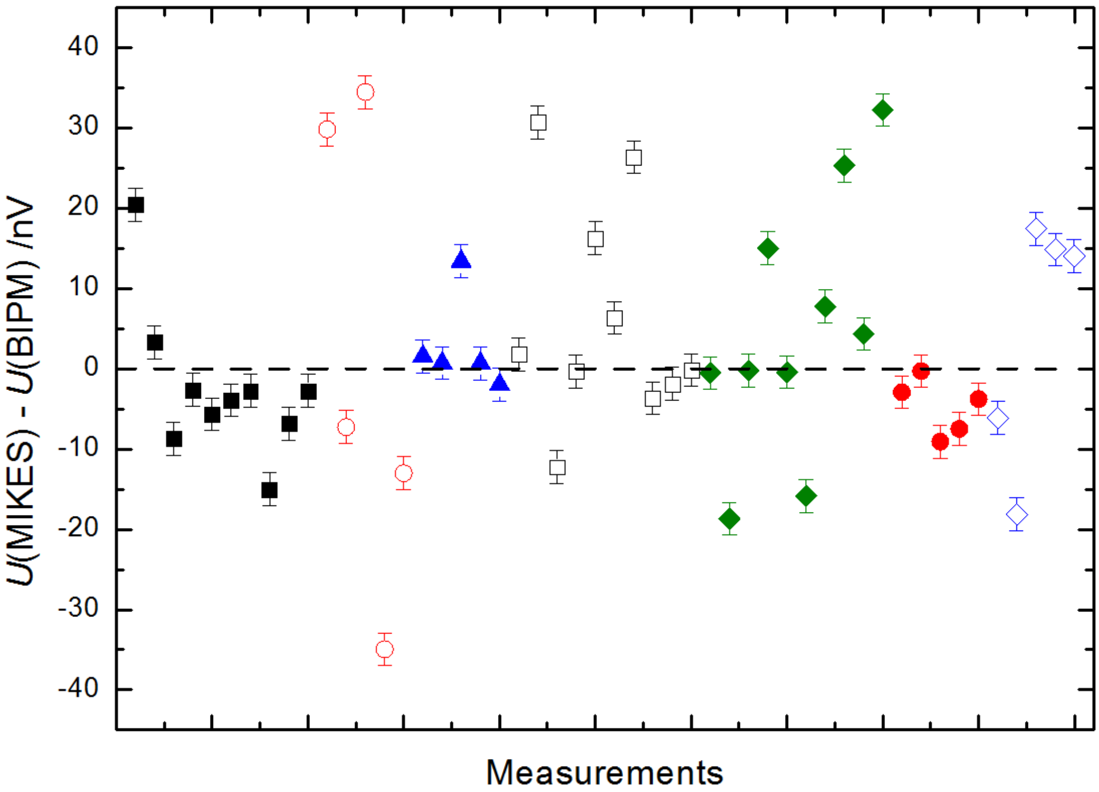

Fig. 5: Individual results obtained for the final result of the Option A comparison protocol at the 10 V level using a digital nanovoltmeter within different measurement conditions (see the text for details). The uncertainty bars represent the Type A standard uncertainty.

3.3.3 Conclusion

To overcome the technical difficulties encountered at the beginning of the exercise which did not allow the direct comparison to be carried out, the scheme of the power distribution to the instrumentation was changed: since there was more noise than expected when using the MIKES 115 V/115 V power supply configuration, a conventional 230 V/0 V configuration was also used. However, no significant difference in the measurement data was observed. Finally, by using a biasing frequency of 74.6 GHz on the MIKES array instead of 70 GHz, suitable stability of the two arrays was achieved. At this point, we could investigate the effect of moving the potential reference point from the MIKES side to the BIPM side and investigate on a possible effect arising from the type of nanovoltmeter measuring the voltage difference between the two arrays.

The result obtained from the option A comparison protocol (using a digital nanovoltmeter) is: $(U_{\mathrm{MIKES}} - U_{\mathrm{BIPM}}) / U_{\mathrm{BIPM}} = +2.19 \times 10^{-10}$ with a relative experimental standard deviation of the mean (Type A uncertainty) of $u_{\mathrm{A}} / U_{\mathrm{BIPM}} = 2.05 \times 10^{-10}$.

4. Uncertainties and results

4.1. Type B uncertainty components (option A protocol)

The sources of Type B uncertainty (Table 1) are: the frequency accuracy of the BIPM and the MIKES 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	**MIKES**
Frequency offset (A)	B	8.0×10^{-13}	4.0×10^{-11}
Leakage resistance (B)	B	4.2×10^{-11}	1.7×10^{-11}
Detector (C)	B	1.24×10^{-10}	
Total (RSS)	B	1.31×10^{-10}	4.35×10^{-11}

Table 1: Estimated Type B relative standard uncertainty components.

(A) As both systems were 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 is distributed from the time and frequency laboratory and is locked to the main atomic clocks of MIKES.

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 [5]. 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 MIKES, the related variables were measured to be $r = 3\ \Omega$ and $R_L = 10 \times 10^{10}\ \Omega$. The isolation resistance value includes all the cables from the JVS to the DVM. For BIPM, those parameters are measured to be $r = 3.65\ \Omega$ and $R_L = 5 \times 10^{10}\ \Omega$.

(C) 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 from the standard deviation of the mean of 10 measurements of the gain performed at different times after the comparison using the BIPM PJVS based on NIST technology [6]. 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 of the detector can be calculated as $u_d = 1.24 \times 10^{-10}$.

5. Conclusion

The comparison was carried out in the MIKES electricity laboratories. A proper grounding of the measurement setup is essential for the stability of the quantum voltages. After biasing the MIKES array at 74.6 GHz instead of 70 GHz, several grounding conditions and two different mains supply arrangements (115 V/115 V and 230 V/0 V scheme) were used. We chose to start the comparison as the option A of the protocol and finding satisfactory grounding conditions left no time slot for the option B. Even protocol A could not be strictly followed, since no measurement could be performed with the analogue nanovoltmeter. The disturbing noise source could not be identified and we had to operate only using a digital nanovoltmeter.

The result obtained, is expressed as the relative difference between the values attributed to the 10 V MIKES JVS by the BIPM JVS measurement set-up (U_{MIKES}) and by the BIPM (U_{BIPM}):

$$(U_{\mathrm{MIKES}} - U_{\mathrm{BIPM}}) / U_{\mathrm{BIPM}} = +2.19 \times 10^{-10} \text{ and } u_c / U_{\mathrm{BIPM}} = 2.47 \times 10^{-10}$$

where u_c is the total combined standard uncertainty, and the relative Type A uncertainty is $u_A / U_{\mathrm{BIPM}} = 2.05 \times 10^{-10}$.

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

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] https://www.head-fi.org/threads/topaz-low-capacitance-isolation-transformers-for-affordably-clean-power.857448/.

[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.

[4] 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.

[5] Djordjevic S. et al, Direct comparison between a programmable and a conventional Josephson voltage standard at the level of 10 V, 2008 Metrologia 45, 429.

[6] Yi-hua Tang *et al.*, Application of a 10 V Programmable Josephson Voltage Standard in Direct Comparison With Conventional Josephson Voltage Standards, *IEEE Trans. Instrum. Meas*., 2015, 64, Issue: 12, 3458-3466.

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