Comparison of the Josephson Voltage Standards of the PTB 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 *Physikalisch-Technische Bundesanstalt* (PTB), Braunschweig, Germany, was carried out in October 2014 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 PTB using its Josephson standard with its own measuring device. Option A required PTB to provide a reference voltage with its Josephson voltage standard for measurement by the BIPM using a *analogue* nanovoltmeter and associated measurement loop.

The final results were in good agreement within the combined relative standard uncertainty of 3.9 parts in 10^{11} 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 PTB, Germany, in October 2014.

The BIPM JVS was shipped to PTB, Germany, where an on-site direct comparison was carried out from 6 October to 10 October 2014. The comparison followed the technical protocols for the options A and B of the BIPM.EM-K10 comparisons. The comparison involved the BIPM measuring the voltage of the PTB JVS using its measurement loop where an analogue voltmeter was used as a detector for option A and PTB measured 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. It was biased on the same Shapiro constant voltage step for each polarity and had to stay on this step during the time required for the data acquisition. For convenience, the BIPM array irradiation RF signal was always adjusted to the same frequency with which the PTB-SIS-CJVS (Cf. §2.2 for the characteristics of this quantum voltage standard) is operated. In the case of the PTB-SNS-PJVS (Cf. §2.2), the BIPM RF frequency was adjusted order to lower the theoretical voltage difference between the two quantum standards to its minimum.

This article describes the technical details and the results 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: 2548-E6), 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 less than 3 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^{11} Ω for the BIPM JVS.

2.2 The PTB JVS

Two Josephson primary voltage standards (JVS) were operated at different time during the comparison:
A conventional JVS based on a chip containing 13 924 SIS Joesphson junctions (SN Me-168/4) which will be called PTB-SIS-CJVS in the following paragraphs [2].

A programmable JVS based on a chip containing 69 631 SNS Josephson junctions (SN 10V-SNS-2013-02/8) which will be called PTB-SNS-PJVS in the following [3].

Description of the SIS junctions based unit:

The PTB-SIS-CJVS is similar to the one used in a previous key comparison [4]. It is based on a 10 V Josephson series array fabricated in the clean room facility at the PTB. To operate the equipment at 75 GHz a Gunn diode is used. This frequency is stabilized by an EIP 578 frequency counter-stabilizer and a phase lock loop driver developed at the PTB. The array is biased with a current/voltage source built at the PTB. The filters and the output voltage leads have a series resistance of 3 Ω and a leakage resistance greater than 200 GΩ. For Zener calibrations, a Keithley 2182A nanovoltmeter and a low thermal EMF switch box specially constructed at the PTB are used. A computer with software developed at the PTB sets the EIP counter to the desired frequency, reads the data on the nanovoltmeter, and calculates the results.

Description of the SNS junctions based unit:

The PTB-SNS-PJVS is based on a programmable 10 V Josephson series array fabricated with an SNS barrier (NbSi junctions). The equipment is operated using a compact 70 GHz Jülicher Squid microwave synthesizer. The array is biased with a single channel current source on batteries. The filters and the output voltage leads have a series resistance of 1 Ω and a leakage resistance greater than 500 GΩ. For comparisons, a new Magnicon nanovoltmeter and a low thermal EMF switch box specially constructed at the PTB are used. A computer with software developed at the PTB sets the synthesizer to the desired frequency, reads the data on the nanovoltmeter, and calculates the results.

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 PTB-SIS-CJVS frequency was locked: f = 75.091 680 GHz. The BIPM JVS operates over a large RF frequency band, providing a stable quantized voltage. 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 transparent for the software. Furthermore, as it is possible to adjust the voltage difference between the two arrays to zero within one to three steps, this contributes to limit the impact of a change in the gain value of the nanovoltmeter during the measurement process.

3.1 Measurement set-up

The measurement loop operated for the option B comparison is based on the PTB connection switch, nanovoltmeter and software:

The low thermal EMFs switch provides the capability to physically open the measurement setup when required, in particular before any polarity reversal of the quantum standards voltages.

The nanovoltmeter is a Keithley 2182A set on its 10 mV range. The software asks the nanovoltmeter for 100 consecutive readings at a NPLC=1 in one polarity of the voltage standards. The measurement sequence follows the polarity sequence: positive 1, negative 1, negative 2 and positive 2 from which 2 measurement points are calculated from the two pairs (positive 1, negative 1) and (negative 2, positive 2).

The low potential side of the array of the PTB-SIS-CJVS is always connected to the reference potential and can't float from it unless the bias cable between the bias source and the probe is physically removed.

After testing different grounding configurations, we identified the following one as the best: the reference potential to which the low potential side of the array is referred is brought from the PTB dewar to the BIPM dewar through the shields of the connecting leads. All the chassis of the connection boxes and electronic equipment are also referred to this potential.

3.2 Results of the option B

3.2.1 Preliminary measurements (PTB-SIS-CJVS)

We carried out 10 consecutive preliminary measurement points. The result, calculated as the mean value is: ($U_{\mathrm{PTB}} - U_{\mathrm{BIPM}}$) = -1.89 nV with a standard deviation of the mean of 1.66 nV (Fig. 1). The simple standard deviation of the nanovoltmeter readings (NPLC=1) was of the order of 100 nV which is larger by a factor of 5 to what can be expected. We identified several sources of noise that affected the width of the voltage steps of the PTB-SIS-CJVS:

1- The Voltage Controlled Oscillator of the BIPM frequency locking loop appeared to be a strong source of noise for the PTB-SIS-CJVS, it was successfully changed to another device;

2- The galvanic isolation of the PTB-SIS-CJVS waveguide (between the RF source and the waveguide itself) was improved;

3- We tried different 10 MHz frequency reference configurations:

   a- the signal provided by the PTB Time department was isolated using an isolation transformer;

   b- the PTB EIP 578B internal 10 MHz quartz was used as the time base reference for both JVS.

4- The position of the Neutral and Phase plugs from the mains was checked for the BIPM and PTB equipment;

5- The voltmeter (HP3458A) which continuously monitors the voltage across the PTB array was removed;

6- We also measured the voltage difference between the 2 standards when both JVS were set to zero volt.

We couldn't identify a clear impact on the noise level from any of those changes. The metallic outer part of the Keithley 2182A appeared to be connected to the shield of the sensing leads making a small ground loop at the level of the nanovoltmeter. The PTB connection box was changed to a BIPM one to solve this issue which brought the simple standard deviation of a series of 100 nanovoltmeter readings to 30 nV.

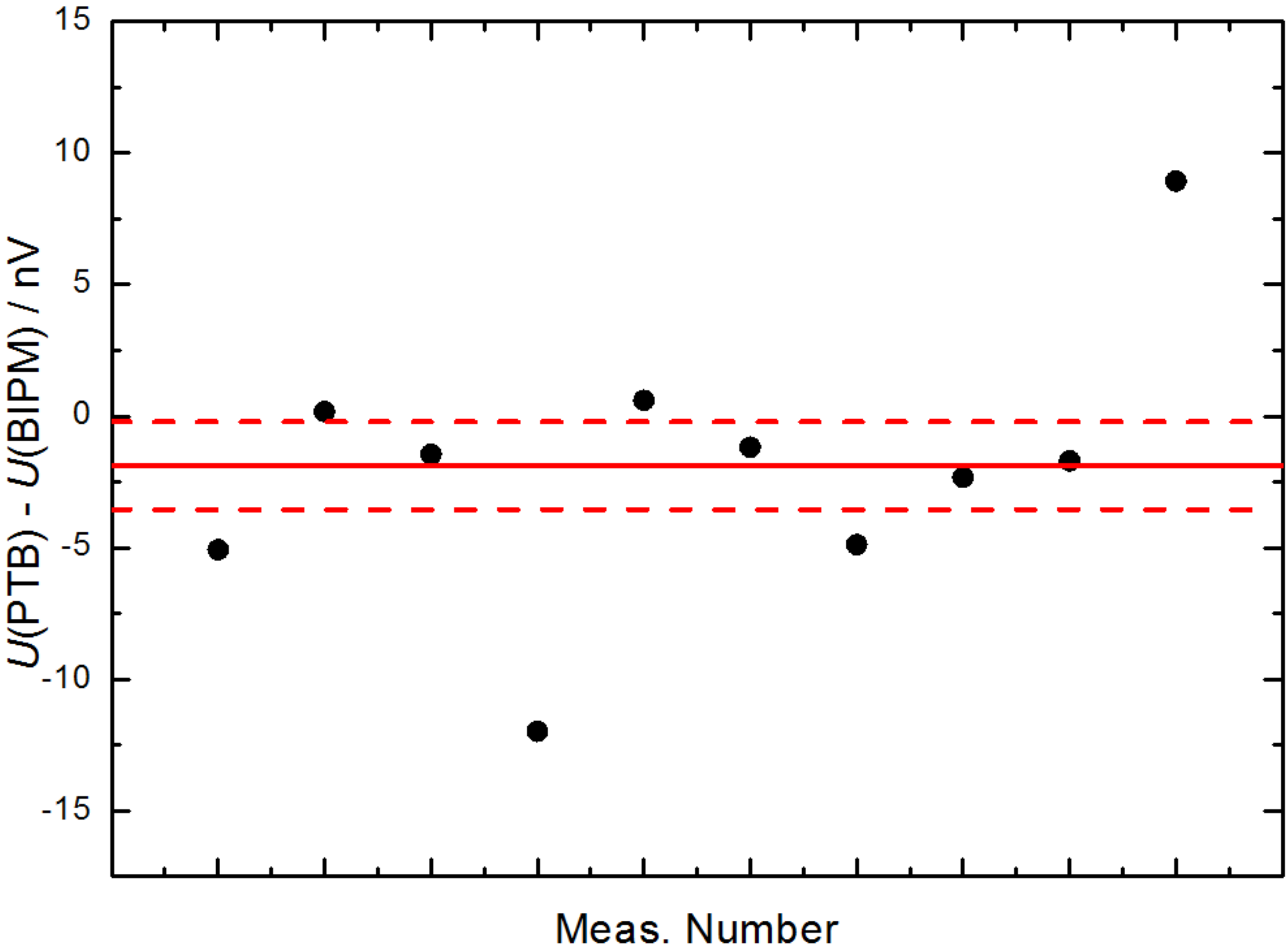

Fig. 1: Preliminary individual results obtained with the Option B comparison protocol at the 10 V level. The straight line below 0 nV represents the mean value of the 10 individual measurements (-1.89 nV). The experimental standard deviation of the mean of the 10 individual points is represented by the dashed lines for a coverage factor of (k=1).

3.2.2 Final result with the option B (PTB-SNS-PJVS)

As mentioned in the previous paragraph, after applying several modifications, we couldn't achieve a better result with the PTB-SIS-CJVS and decided to cool down a PTB-SNS-PJVS.

The selected PTB-SNS-PJVS array comprises 69 631 junctions that were biased at f=69.95 GHz. It was decided to bias the BIPM JVS at f=75.090 780 GHz, on its 64 864th Shapiro step, in order to lower the theoretical voltage difference between the two quantum standards to 198.67 nV.

3.2.2.1 Measurements with a digital nanovoltmeter

Two series of 10 points were carried out successfully using the Keithley 2182A as the nanovoltmeter. From the results presented in Figure 2, we note that even if the Type A uncertainty is expanded to the *k*=2 coverage factor, the individual results do not belong to the same statistical population. We assume that the reason is mainly due to the thermal electromotive forces that were still present in the measurement loop at the time the measurements were performed.

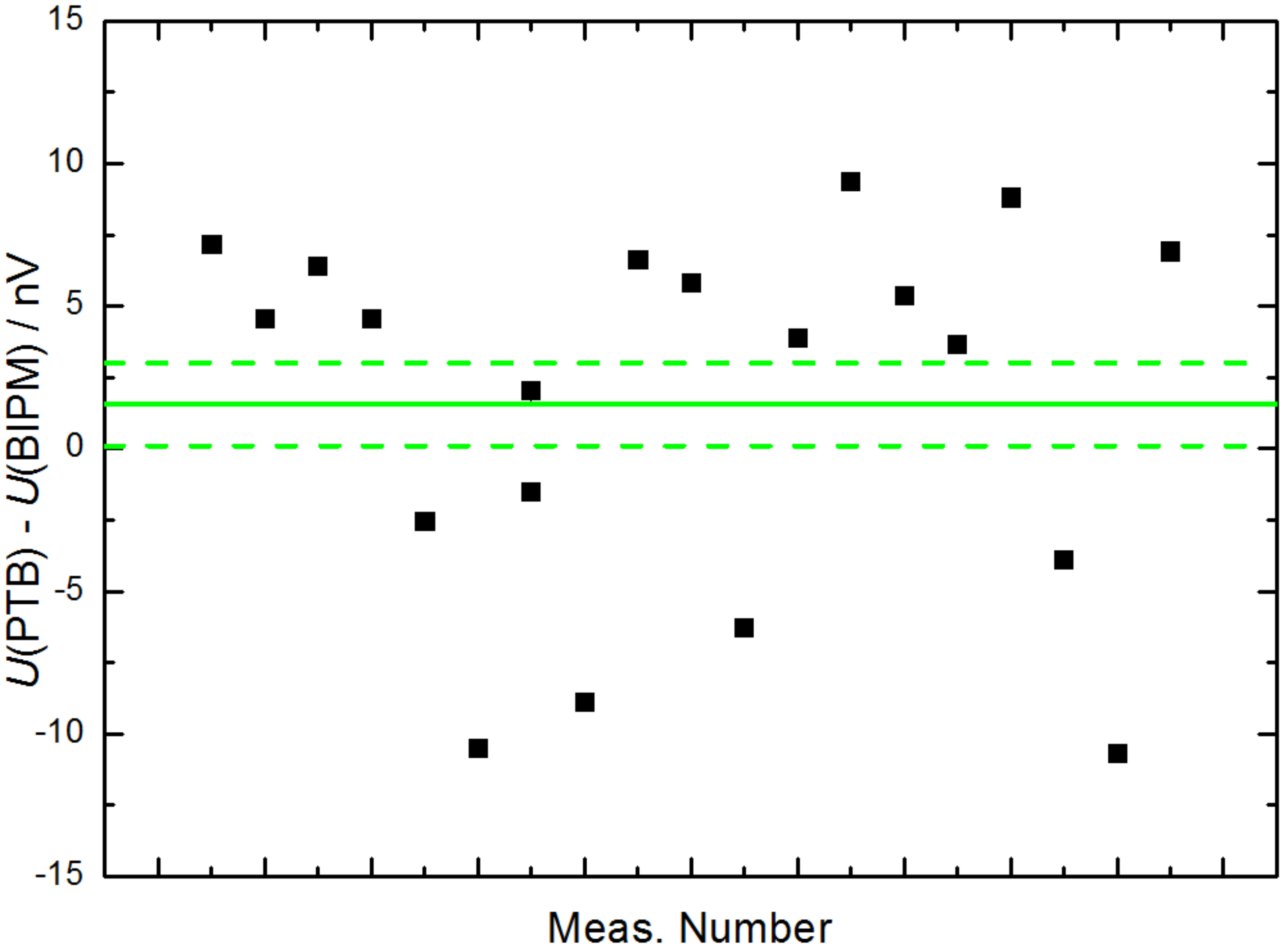

Fig. 2: Individual measurement points (black squares) obtained to calculate the result of the option B at the level of 10 V while using the PTB-SNS-PJVS and a digital nanovoltmeter. The solid line represents the mean value and the experimental standard deviation of the mean of the 20 individual measurement points (*k*=1) is represented by the dashed lines.

Several measurement configurations were tried and are presented in detail in the Appendix A of the report.

3.2.2.2 Measurements with an analogue nanovoltmeter

The best result of the option B comparison protocol was obtained from 20 individual measurements which are presented on Figure 3.

They were performed within the following configuration:

1- The PJVS was biased from its battery operated-bias source (one channel for one single segment of 69631 Josephson junctions) and was therefore floating from the reference potential;
2- The low potential side of the BIPM array is referred to the reference potential as the dewars, instruments' chassis and shields connecting the two standards;
3- The prototype of a new analogue voltmeter [5] powered from batteries was installed to measure the voltage difference between the two quantum standards based on the PTB software (Cf. Appendix A).

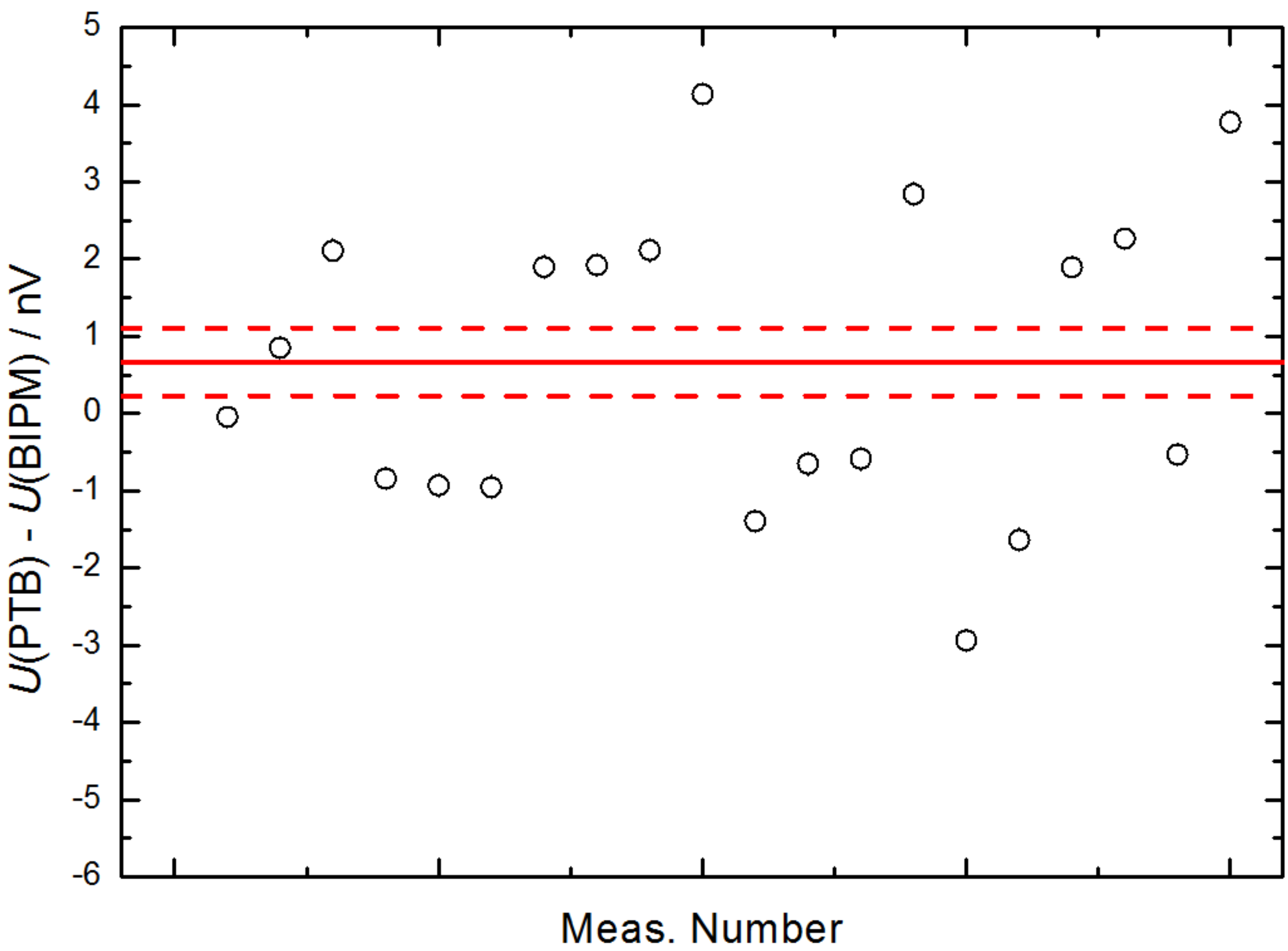

Fig. 3: Individual measurement points (black circles) obtained to calculate the final result of the option B at the level of 10 V while using the PTB-SNS-PJVS and an analogue nanovoltmeter. The solid line represents the mean value and the experimental standard deviation of the mean of the 20 individual measurement points (k=1) is represented by the dashed lines.

3.2.2.3 Direct comparison of the two PTB primary Josephson Voltage Standards

As a scientific exercise, we decided to replace the BIPM primary voltage standard with the PTB-SIS-CJVS in order to compare it directly to the PTB-SNS-PJVS and to see if we would have to face the same issues encountered with the SIS-junctions based units.

The PTB-SIS-CJVS voltage stability wasn't affected by this process and the following result was obtained with 10 consecutive measurements:

$(U_{\text{PTB-SIS-CJVS}} - U_{\text{PTB-SNS-PJVS}}) / U_{\text{PTB-SIS-CJVS}} = -0.07 \times 10^{-10}$ with a relative experimental standard deviation of the mean (Type A uncertainty) of $u_A / U_{\text{PTB-SIS-CJVS}} = 0.52 \times 10^{-10}$.

3.2.3 Conclusion

The preliminary result obtained with the PTB-SIS-CJVS couldn't be improved although many different parameters were varied (Cf. Appendix A) and despite the PTB-SIS-CJVS exhibited an excellent agreement with a PTB-SNS-PJVS. This last standard was successfully operated to obtain the best result within the option B of the protocol:

$(U_{\text{PTB}} - U_{\text{BIPM}}) / U_{\text{BIPM}} = +0.67 \times 10^{-10}$ with a relative experimental standard deviation of the mean (Type A uncertainty) of $u_A / U_{\text{BIPM}} = 0.44 \times 10^{-10}$.

4. Comparison procedures - Option A at the 10 V level

4.1 First series of measurements using a digital nanovoltmeter

In order to use an analog detector, both SIS-junctions based 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 (Keithley 2182A on its 10 mV range) as if any of the two arrays jumps away from the selected step during the readings acquisition, the detector won't go on overload.

Measurements following the option A protocol were carried out on the very first day of the exercise as both primary standards exhibited acceptable voltage stability. However we noted that the BIPM array had to be adjusted on its step and its bias source removed from the circuit once achieved in order for the PTB array to find stability conditions sufficient to proceed to its step adjustment.

Even if the conditions were satisfactory and the simple standard deviation of the nanovoltmeter readings in a polarity set (20 readings) was of the order of 20 nV, we surprisingly ended with a voltage difference larger than 15 nV with a similar Type A uncertainty.

In this situation, the Keithley nanovoltmeter was changed to a HP34420A. The input impedance circuitry of the two devices is very different and by doing this we expected to identify a corresponding interference effect in the measurement loop. However, we couldn't see any impact on the measurements.

Even though the results were not satisfactory, the stability of the voltages was excellent and let us envisage to use an analogue nanovoltmeter.

4.2 Following series of measurements using an analogue nanovoltmeter

In order to investigate on the source of noise perturbing the measurement setup, the following changes were applied, in chronological order:

1- The BIPM analogue detector (EM-N11) was installed. The objective was to look for an AC coupling signal in the measurement that would be rectified by a digital nanovoltmeter, appearing as an offset while this noise would appear as a movement of the needle on the analogue meter. Unfortunately, the installation of the N11 in the measurement was not satisfactory as it resulted in the PTB-SIS-CJVS losing its stability;

2- A PTB-SNS-PJVS was installed to replace the PTB-SIS-CJVS in the same measurement loop. The negative PTB-SNS-PJVS polarity was referred to the reference potential of the measurement setup. We couldn't carry out any measurement as the PTB-SNS-PJVS was trapping flux on every polarity change.

The PTB-SNS-PJVS configuration was modified in order to make the complete measurement loop floating from the reference potential (the EM-N11 is powered from batteries). A first series was performed for different biasing currents on the PTB-SNS-PJVS in order to evaluate the width of its voltage step; the quantization of the voltage of the PJVS was confirmed but an offset of 3.8 nV was measured in the voltage difference between the two standards (Cf. October the 10^{th} in the Appendix A). A second series of 10 consecutive points (Cf. Figure 4) was performed once the original filter of the BIPM JVS was installed again on the precision leads (Cf. "7 October" and

Fig.A2 in Appendix A). The result calculated as the simple mean value is: $(U_{\mathrm{PTB}} - U_{\mathrm{BIPM}}) / U_{\mathrm{BIPM}}$ = 3.4×10^{-11} with a relative Type A uncertainty (experimental standard deviation of the mean) $u_{\mathrm{A}} / U_{\mathrm{BIPM}} = 2.8 \times 10^{-11}$.

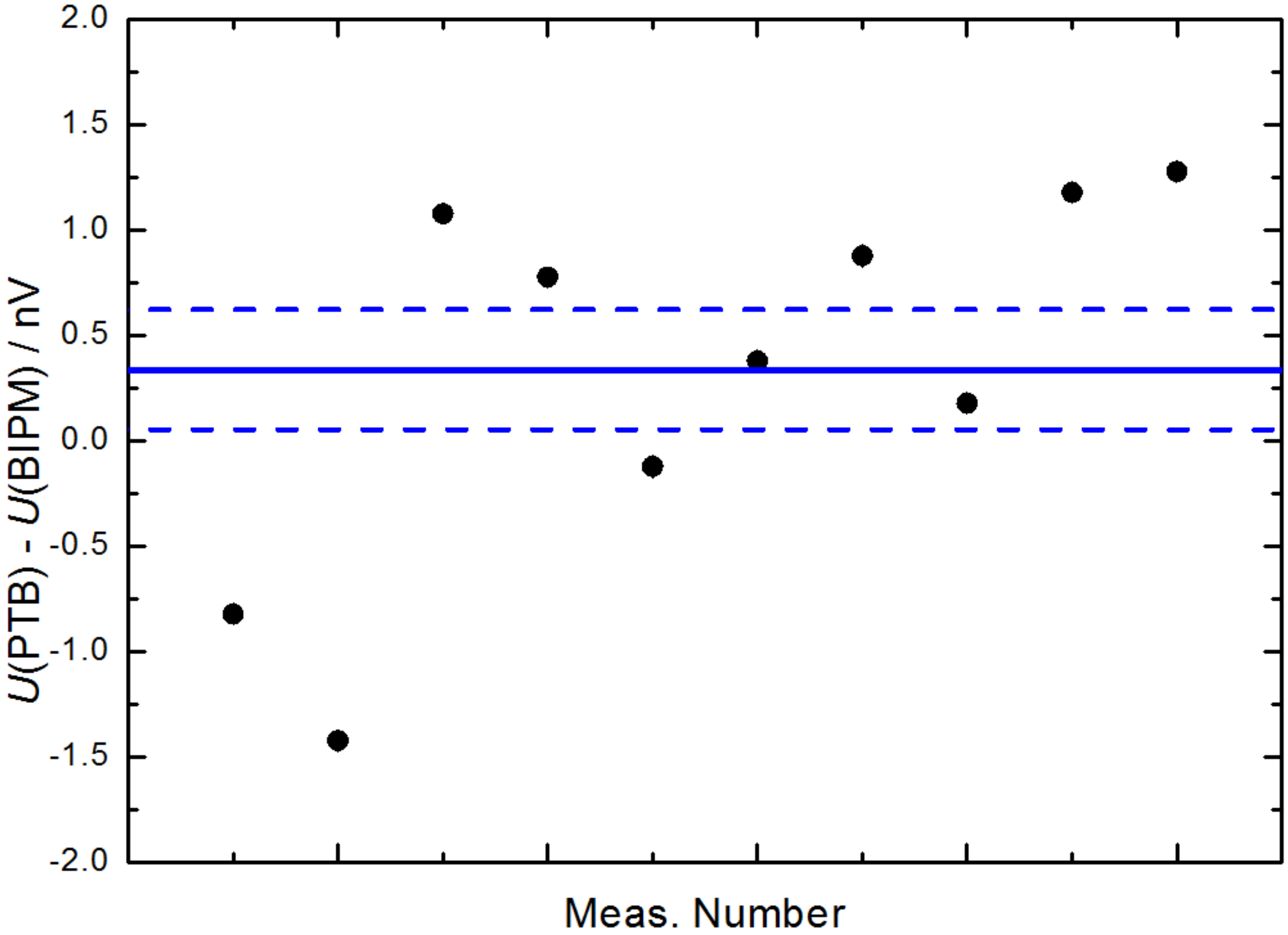

Fig. 4: Individual measurement points (black disks) obtained to calculate the result of the option A comparison scheme at the level of 10 V using an analogue nanovoltmeter. The solid line represents the mean value and the experimental standard deviation of the mean of the 10 individual measurement points (k=1) is represented by the dashed lines.

5. Uncertainties and results

5.1. Type B uncertainty components (options A and B of the protocol)

The sources of Type B uncertainty (Table 1) are: the frequency accuracy of the BIPM and the PTB Gunn diode or microwave synthesizer, 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.

For the option A comparison protocol, the total combined Type B uncertainties comprise all the BIPM Type B components to which the PTB Type B uncertainty on the frequency offset and leakage resistance are added in a quadratic sum: $u_{\mathrm{B\ (option\ A)}} / U_{\mathrm{BIPM}} = 2.7 \times 10^{-11}$

For the option B comparison protocol, the total combined Type B uncertainties comprise all the PTB Type B components to which the BIPM Type B uncertainty on the frequency offset and leakage resistance are added in a quadratic sum: $u_{\mathrm{B\ (oprtion\ B)}} / U_{\mathrm{BIPM}} = 2.7 \times 10^{-11}$

	Type	Relative uncertainty	
		BIPM	**PTB**
Frequency offset [(A)]	B	8.0×10^{-13}	4.0×10^{-12}
Leakage resistance [(B)]	B	4.2×10^{-12}	8.1×10^{-12}
Detector [(C)]	B	2.5×10^{-11}	2.5×10^{-11}

Table 1: Estimated Type B relative standard uncertainty components (Options A and B).

[(A)] As both systems referred to the same 10 MHz frequency reference, only a Type B uncertainty from the frequency measured by the EIP is included. The 10 MHz signal used as the frequency reference for the comparison was produced by the internal reference of the BIPM frequency counter EIP 578B.

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 [6]. The relative uncertainty for the offset of the frequency can be calculated from the formula: $u_f = (1/\sqrt{3}) \times (0.1/75) \times 10^{-9} = 8 \times 10^{-13}$.

For the compact microwave synthesizer a comparison with another synthesizer has been performed and the relative frequency offset between them is measured to be less than 4×10^{-12} [8].

(B) If a rectangular statistical distribution is assumed then the relative uncertainty contribution of the leakage resistance R_L can be calculated as: $u_f = (1/\sqrt{3}) \times (r / R_L)$. For PTB, the related variables are r = 2.8 Ω and $R_L = 2 \times 10^{11}$ Ω. The isolation resistance value includes all the cables from the JVS to the DVM. For BIPM, those parameters are measured to r = 3.65 Ω and $R_L = 5 \times 10^{11}$ Ω.

(C) For the option A comparison protocol, the uncertainty on the accuracy of the BIPM EM-N11 nanovoltmeter is calculated from the difference between the nominal calibration factor and the measured one. The difference is applied to the maximum voltage difference measured by the N11 on the 3 µV range which leads to: u_D = 0.25 nV.

For the option B comparison protocol, PTB operated a Magnicon analogue detector as the null detector. A maximum gain error of 10^{-3} has been evaluated for the 10 µV range. Assuming a rectangular statistical distribution for the forward and reversed measurements with EMF differences of 430 nV results in $u_D = 430\ \text{nV} \times 10^{-3} \times (1/\sqrt{3}) = 0.25$ nV.

5.2 Result at 10 V (option B)

The preliminary result which is obtained from the first series of measurements after the BIPM standard was installed is expressed as the relative difference between the values attributed to the 10 V BIPM JVS by the PTB JVS measurement set-up (U_{PTB}) and by the BIPM (U_{BIPM}):

$(U_{PTB} - U_{BIPM}) / U_{BIPM} = -1.9 \times 10^{-10}$ and $u_c / U_{BIPM} = 1.7 \times 10^{-10}$

The final result obtained following technical expertise within the option B of the protocol, is

$$(U_{PTB} - U_{BIPM}) / U_{BIPM} = 6.7 \times 10^{-11} \quad \text{and } u_c / U_{BIPM} = 5.2 \times 10^{-11}$$

where u_c is the total combined standard uncertainty and the relative Type A is $u_A / U_{BIPM} = 4.4 \times 10^{-11}$.

5.3 Result at 10 V (option A)

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

$$(U_{PTB} - U_{BIPM}) / U_{BIPM} = 3.4 \times 10^{-11} \qquad \text{and } u_c / U_{BIPM} = 3.9 \times 10^{-11}$$

where u_c is the total combined standard uncertainty and the relative Type A is $u_A / U_{BIPM} = 2.8 \times 10^{-11}$.

6. Conclusion

The comparison was carried out in the PTB Electricity Laboratories in Braunschweig where the environmental conditions allowed meeting good conditions for the stability of the quantum voltages. Two different PTB Josephson Voltage Standards were compared to the BIPM quantum voltage standard: a 10 V programmable array of SNS Josephson junctions (PTB-SNS-PJVS) and a 10 V conventional array of SIS Josephson junctions (PTB-SIS-CJVS). If the voltage differences with the PTB-SNS-PJVS rapidly converged to the sub-nanovolt, we faced a repeatable systematic error with the BIPM PTB-SIS-CJVS comparison. The amplitude of the systematic error changed with the different changes in the experimental conditions of the measurement setup. However, the systematic error was not present in the PTB-SIS-CJVS to PTB-SNS-PJVS direct comparison. In investigating this error, we switched several times between two different assumptions to explain it: a leakage resistance and an AC noise rectification in the measurement setup. Despite several experiments we neither could find a way to correct for this error nor a satisfactory explanation for its origin.

The final result fully supports PTB CMCs in the field of DC voltage metrology.

Acknowledgement

L. Palafox and R. Behr would like to thank D. Drung, O. Kieler, B. Schumacher and C. Rohrig for discussions and support in measuring the gain and linearity of the Magnicon nanovoltmeter.

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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 PTB, 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.

06 October 2014:

The electromagnetic compatibility conditions were found excellent so that the BIPM JVS was assembled and tested without encountering any difficulties. The BIPM JVS equipment was powered from the same mains plug as the PTB JVS equipment. Despite the fact that the laboratory is equipped with a dedicated earth connection line, we never used it to avoid ground loops with the mains power earth reference. The frequency of the BIPM RF signal was always adjusted to that selected by the PTB software around *f*= 75.1 GHz and the voltage of each SIS-array remained stable while the measurement loop remained closed with the two arrays connected in series opposition and once the BIPM biasing source was disconnected from the bias source. The thermal EMFs in the circuit were measured to be of the order of 500 nV to 700 nV.

The option B of the protocol was started using the PTB measurement setup to measurement the output of the BIPM JVS. We rapidly noticed that the VCO of the phase lock loop of the BIPM RF source was radiating noise that was affecting the PTB-SIS-CJVS voltage stability. The device was changed to the spare one which corrected this issue.

The first voltage difference acquisition process exhibited a significant level of noise of the order of 100 nV. We tried to reduce this level before carrying out a first complete measurement.

Note: The same level of noise was measured once the two quantum standards on their critical current (corresponding to 0 V).

Firstly, the galvanic isolation of the PTB-SIS-CJVS waveguide (between the RF source and the waveguide itself) was improved.

We also realized that the shield of the nanovoltmeter was linked to the chassis of the connection box, introducing a ground loop as the chassis of the box was already connected to the reference potential from the PTB dewar. We changed the connection box to a BIPM one.

We checked that the power line polarity of the Neutral and Phase was the same for the BIPM and PTB equipment.

We checked again the grounding configuration and connection and found that it was not ideal: once fixed, the noise level was lowered to 30 nV and a first series of 10 consecutive points was carried out and produced the preliminary result:

$(U_{PTB} - U_{BIPM}) / U_{BIPM} = -1.88 \times 10^{-10}$ with a relative experimental standard deviation of the mean (Type A uncertainty) of $u_A / U_{BIPM} = 1.66 \times 10^{-10}$.

Note: the best grounding configuration was found when the reference potential (PTB instruments earth potential) was brought to the BIPM equipment and the dewar through the shielding of the connecting leads. Any other configuration we tried, brought a significant more noise in the measurement loop.

We decided to move to the option A of the comparison. The BIPM Keithley 2182A nanovoltmeter and corresponding software were operated, but the dispersion of the measurement appeared to be of the same order (10 nV to 20 nV) together with a significant offset (10 nV) of the mean value. We changed the Keithley 2182A for an HP34420A. The input impedance circuitry of the two devices is very different [8] and by doing this we expect to identify a corresponding interference effect in the measurement loop. We couldn’t see any impact on the measurements. All the measurements are presented on Figure A1:

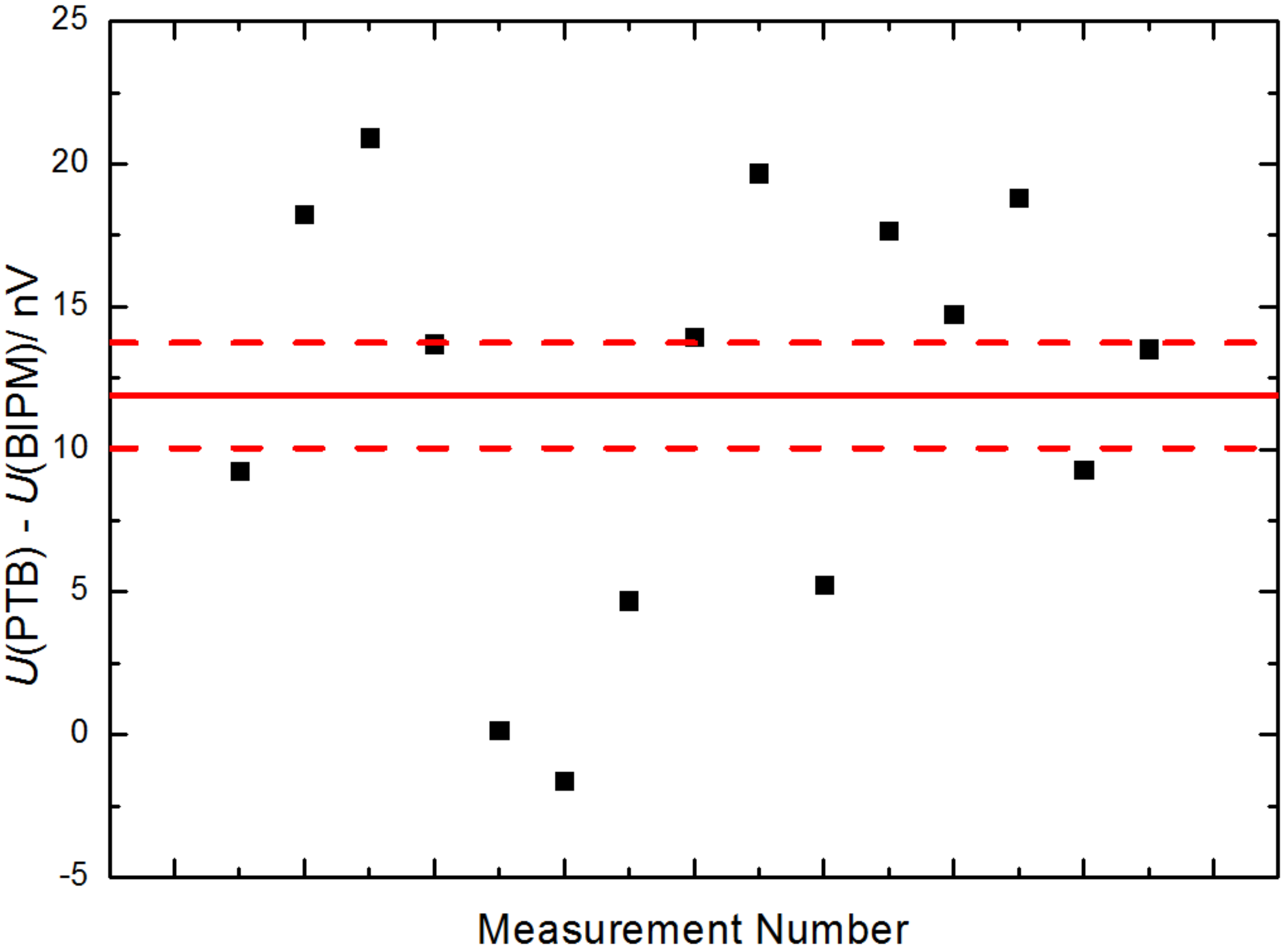

Fig. A1: Voltage difference between the two SIS-junctions-based JVS within the option A of the protocol using BIPM digital nanovoltmeters. The straight line represents the mean value of the series at m=+11.9 nV and the Type A at *k*=1 is represented by the dashed lines.

07 October 2014:

We decided to remove the PTB biasing source from the equation and therefore to bias the PTB array from the BIPM array [9]. The objective was to identify a systematic error originating from a leakage voltage on the PTB bias source. By doing this, the HP3458A which monitors the voltage across the PTB array was also removed from the measurement loop.

We used the BIPM Keithley 2182A to measure the voltage difference between the two quantum standards. The two JVS were biased at f = 75.090 GHz. As they were always a few steps away from each other, we had to calibrate the gain of the nanovoltmeter. We ended with the same noise amplitude recorded on the previous day.

We changed the PTB frequency locker (EIP) to a more recent device (Phase Matrix). The EIP578B could be a significant source of noise in some cases. We also changed the Keithley 2182A for an HP34420A without any significant impact on the results.

As we wanted to identify the source of noise, we installed the BIPM analogue detector (EM-N11) to look for a possible AC coupling signal in the measurement loop that would be rectified by a digital nanovoltmeter and appear as an offset while this noise would be recorded as a movement of the needle on the analogue meter. Unfortunately, PTB-SIS-CJVS lost its stability as a consequence of the installation of the N11.

A 10 V PTB-SNS-PJVS biased from a single battery operated source was cooled down to replace the PTB-SIS-CJVS in the measurement loop. The frequency of the BIPM array was changed to f=75.090 020 GHz in order to reduce the theoretical voltage difference to 140 nV (this particular 10 V PTB-SNS-PJVS comprises 69 630 Josephson junctions biased at f=69.96 GHz). We couldn't complete any measurement as PTB-SNS-PJVS was trapping magnetic flux at each polarity reversal. As the complete measurement setup was floating from any reference potential, we grounded the low side of the BIPM array: this doesn't bring any improvement in the PTB-SNS-PJVS sensitivy to trap flux.

We switched back to the option B comparison protocol with the PTB-SIS-CJVS as we noticed that its filter on the measurement leads is cutting high frequencies only compared to the BIPM one (the cutting frequency is 5 kHz). We decided to change the BIPM filter to a weaker one [7]. Two series of 10 measurements were performed and the detector was reversed in-between the two series. The results are respectively:

$(U_{PTB} - U_{BIPM}) / U_{BIPM} = -7.8 \times 10^{-10}$ with a relative experimental standard deviation of the mean (Type A uncertainty) of $u_A / U_{BIPM} = 1.4 \times 10^{-10}$.

$(U_{PTB} - U_{BIPM}) / U_{BIPM} = -9.3 \times 10^{-10}$ with a relative experimental standard deviation of the mean (Type A uncertainty) of $u_A / U_{BIPM} = 1.1 \times 10^{-10}$.

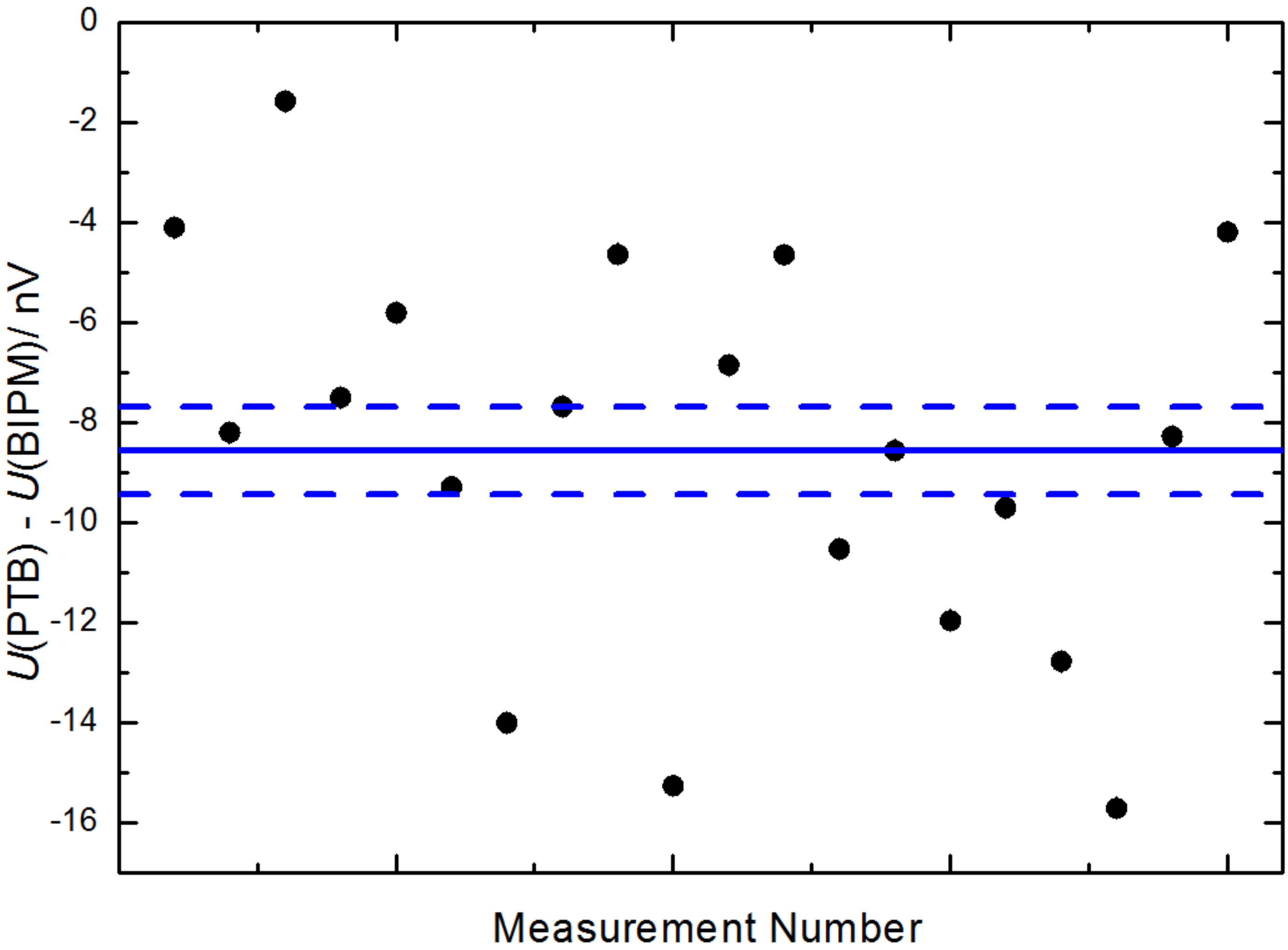

Fig. A2: Voltage difference between the two SIS-junctions-based JVS within the option B of the protocol using a PTB digital nanovoltmeter. The straight line represents the mean value of the series at m=+8.6 nV and the Type A at *k*=1 is represented by the dashed. The BIPM filter on the measurement leads has been modified for those measurements.

08 October 2014:

Even if the former experiment, where the nanovoltmeter polarity was reversed, showed that the observed offset is rather coming from a noise in the measurement loop than a leakage error, we decided to compare the two SIS-junctions-based units at the level of 5 V.

The measurement setup was still configured in the option B protocol where PTB uses its software and a Keithley 2182A nanovoltmeter to measure the BIPM JVS.

A first series of 10 measurements at 5 V was performed just before a second series of 10 measurements at 10 V. The results are respectively:

$(U_{PTB} - U_{BIPM}) / U_{BIPM} = -2.5 \times 10^{-10}$ with a relative experimental standard deviation of the mean (Type A uncertainty) of $u_A / U_{BIPM} = 1.1 \times 10^{-10}$.

$(U_{PTB} - U_{BIPM}) / U_{BIPM} = -7.1 \times 10^{-10}$ with a relative experimental standard deviation of the mean (Type A uncertainty) of $u_A / U_{BIPM} = 1.2 \times 10^{-10}$.

This experiment allows us to conclude that the amplitude of the observed systematic error is almost proportional to the nominal voltage of the quantum standards but is not due to a leakage error.

It was decided to cool down a second 10 V PTB-SNS-PJVS for which the on-chip ground is not connected to the probe. This primary standard is biased from a single battery operated source and replaced the PTB-SIS-CJVS in the measurement loop. The frequency of the BIPM array was changed to *f*=75.090 780 GHz in order to reduce the theoretical voltage difference to 199 nV (this particular 10 V PTB-SNS-PJVS comprises 69 631 Josephson junctions biased at *f*=69.95 GHz).

The PTB measurement loop was operated to measure the BIPM JVS (option B of the protocol). Several series of measurement were carried out within different conditions listed below. All of them exhibited a Type A uncertainty of 2 nV, which is 2 times larger than what can be expected from this measurement setup.

1- 2 series were carried out using a Keithley 2182A and showed that the thermal electromotive forces were still relaxing since the PTB-SNS-PJVS was cooled down.
2- The digital nanovoltmeter was changed for a new analog detector prototype [5] PTB-SNS-PJVS but no improvement on the results could be observed.
3- The comparison was run on the 0 V step of both quantum standards but the same Type A uncertainty was recorded. The same Type A was obtained when the JVS were replaced by a nice electrical short.
4- As the complete measurement setup was floating from any reference potential (the chassis, dewars and shields of connecting wires) were although connected all together, we decided to carry out a series with the low side of the BIPM array to ground.

We finally found the reason of this important level of noise in a broken wire introducting a micro cut in the measurement loop. Once this cable was replaced, a series of 10 points with the Keithley 2182A gave the following result:

$(U_{PTB} - U_{BIPM}) / U_{BIPM} = +0.51 \times 10^{-10}$ with a relative experimental standard deviation of the mean (Type A uncertainty) of $u_A / U_{BIPM} = 0.95 \times 10^{-10}$.

The digital nanovoltmeter was changed to the Magnicon prototype with which a series of 20 measurements gave the final result of the option B comparison (the first measurement was clearly identified as an outlier and discarded from the calculation):

$(U_{PTB} - U_{BIPM}) / U_{BIPM} = +0.67 \times 10^{-10}$ with a relative experimental standard deviation of the mean (Type A uncertainty) of $u_A / U_{BIPM} = 0.44 \times 10^{-10}$.

The BIPM JVS was replaced with the PTB-SIS-CJVS for a PTB internal comparison in order to investigate on the performance of the PTB-SIS-CJVS in the same measurement loop with the PTB-SNS-PJVS. A series of 10 measurements was performed and gave the following excellent result:

$(U_{PTB\text{-}SIS} - U_{PTB\text{-}SNS}) / U_{PTB\text{-}SIS} = +0.07 \times 10^{-10}$ with a relative experimental standard deviation of the mean (Type A uncertainty) of $u_A / U_{PTB\text{-}SIS} = 0.52 \times 10^{-10}$.

09 October 2014:

As the option B was successfully achieved, we wanted to get back to the option A of the protocol using the PTB-SNS-PJVS and the BIPM EM-N11 analogue detector.

Two series of respectively 6 and 5 points were carried out (the time for a single measurement point with the option B is 30 s and 2 min 30 s for the option A comparison protocol). The combination of all the results gives: $(U_{PTB} - U_{BIPM}) / U_{BIPM} = -2.38 \times 10^{-10}$ with a relative experimental standard deviation of the mean (Type A uncertainty) of $u_A / U_{BIPM} = 0.68 \times 10^{-10}$.

Despite the fact that this result wasn't fully satisfactory, we replaced the PTB-SNS-PJVS by the PTB-SIS-CJVS but we couldn't perform any measurement point as the EM-N11 was affecting the stability of the voltage steps of the PTB-SIS-CJVS. We therefore went back to option B comparison with PTB-SIS-CJVS using the Magnicon analogue detector: we recorded a significant discrepancy (100 nV) between the polarities of the detector which lead to a systematic error of the order of the one observed on the 7th of October (8 nV).

A series carried out with the Keithley 2182A nanovoltmeter confirmed this offset.

Looking closer to the filter on the measurement leads of the PTB-SIS-CJVS, we noticed that the 2 capacitors on the PI-filter have a leakage resistance to ground of R_L=2 ×10^{11} ohms and we decided to remove them in order to investigate a possible leakage error. The stability of the quantum voltage standard didn't seem to be affected. However, the Type A uncertainty was still of the order of 5 nV to 10 nV.

We also tried the following changes. None of them improved the situation:

1- Run the PTB software from a laptop powered from batteries in order to avoid any possible ground loop from the desktop computer it is usually run on.
2- Place an LC filter in front of the nanovoltmeter.

We decided to check again every connecting wire in the measurement loop and found that one of the soldered connections of the BIPM filter installed on the measurement leads was cold. The problem was fixed.

10 October 2014:

Several series of measurements were performed using alternatively the PTB and BIPM software, digital nanovoltmeters and analogue ones (Magnicon prototype and EM-N11) within different grounding conditions. Different 10 MHz reference signals were tried. We also implemented the two PTB voltage quantum standards (The PTB-SNS-PJVS was checked for its quantized voltage for different biasing current) and the BIPM equipment was powered through an isolation transformer. All the results converged to exhibit an offset in the voltage difference of the order of 2 nV on the BIPM JVS side.

We suspected the BIPM "light" filter and therefore set the BIPM JVS back to its normal conditions.

The PTB-SNS-PJVS was then compared to the BIPM JVS within the option A of the protocol using the EM-N11 nanovoltmeter. A series of 10 points was performed and gave the best result of the comparison: $(U_{PTB} - U_{BIPM}) / U_{BIPM} = 0.34 \times 10^{-10}$ with a relative experimental standard deviation of the mean (Type A uncertainty) of $u_A / U_{BIPM} = 0.28 \times 10^{-10}$.