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

(part of the ongoing BIPM key comparison BIPM.EM-K10b)

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Abstract. A comparison of the 10 V Josephson array voltage standard of the Bureau International des Poids et Mesures (BIPM) was made with that of the National Research Council (NRC), Ottawa, Canada, in October 2004. The results are in very good agreement and the overall uncertainty is about 3 parts in 10^{10}.

1. Introduction

In 2004, the BIPM sent to the national laboratories a questionnaire to propose, among different options, a new type of comparison, where a stable reference voltage produced across the BIPM Josephson array is measured using the laboratories Josephson array voltage standards (JAVS). This makes possible direct comparisons using the routine measurement technique used for calibration in the laboratories, requiring only the BIPM array, but not both arrays, to maintain a perfectly stable output (i.e. stay on the right step) throughout the measurements. This article describes the comparison of the BIPM 10 V standard with that of the NRC that was carried out at the NRC in October 2004.

2. Comparison equipment

2.1 The BIPM JAVS

The part of the BIPM JAVS used in this comparison comprises the cryoprobe with a Hypres 10V SIS array, the microwave equipment and the bias source for the array. The Gunn diode frequency is stabilised using an EIP 578 counter and an ETL/Advantest stabiliser.

To observe the array characteristic, while keeping the array floating from the ground, an optical isolation amplifier is placed between the array and the oscilloscope[*]; during the measurements the array is disconnected from this instrument.

To verify the step stability, a digital voltmeter[*] (DVM: HP 34401A) is used to measure the array voltage between the bias leads. The series resistance of the measurement leads is 4 Ω and the thermal electromotive forces (EMFs) are typically below 100 nV. The leakage resistance between the measurement leads is more than $10^{11}\,\Omega$.

Fig.1. Schematic of the NRC calibration chain.

2.2 The NRC JAVS

The NRC voltage calibration system (Fig. 1) is routinely used to calibrate Zener diode based standards (Zeners); it is designed to run in an automated acquisition manner once the operator has adjusted the array parameters (microwave frequency and power level). NRC's working standards and some customer standards are directly measured against the primary standard, thereby significantly reducing the traceability chain. The array is biased with a modified commercial bias source; step biasing, array monitoring and Zener selection are manually operated. The bias source and hence the array float from ground, which means that the measurement ground reference point can be chosen arbitrarily. A specially designed

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[*] The frame of the oscilloscope and the DVM were borrowed from the NRC laboratory: they are not part of the precision measurement chain.

Visual Basic™ program records the data and computes the results. A more detailed description is given in Appendix A.

- Array: 10V SIS-NIST (sn 67T-04) then 10V SIS-Hypres (sn 2786F-7)
- Detector: HP34420A, scale used 10 mV
- Bias source: Astro Endyne JBS 501
- Frequency source stabilizer: EIP 578B
- Thermal EMFs (including array connections) approximately 100 nV
- Measurement leads resistance: 1.24 Ω.
- Leakage resistance: better than 10^{11} Ω.

3. Comparison procedure

During the measurements, both the BIPM and the NRC arrays were disconnected from their bias source. The two arrays were connected in series opposition and left floating from ground. In this new procedure (option "B"), the NRC's JAVS was used to measure the voltage of the BIPM array as if it were that of a Zener. In fact, in Zener measurements, the polarity of the output voltage is reversed using a low thermal EMF switch, whereas in the Josephson comparison it is the bias of the array which is reversed and no reversing switch is used.

4. Description of the measurements

The following is a description of the procedure used by the NRC software to obtain a single measurement value of the BIPM array voltage.

Data acquisition is automated and includes, at the beginning, measurement of the microwave frequency and calculation of the step voltage and step number. The following algorithm is then used for the voltage data acquisition. The HP34420A is configured to acquire a set of voltage readings into its internal memory. All IEEE 488 bus activity is then halted while the voltage readings are being made. The burst of readings are then read into the computer and analysed. A single data point is accepted if that data point and the data points immediately before and after are within a tolerance, typically 500 nV. This helps ensure that no voltage step jump occurred during the acquisition of that individual data point. Should a step jump occur the following data are corrected to take the new step number into account. The accepted data set is then analysed in particular for mean, standard deviation and maximum

differences. Provision exists to remove data points from the statistical calculation and replace them with the next accepted data point if certain statistical limits are exceeded, but in practice this rarely happens if the step stability is adequate.

During the direct comparison of the BIPM array with the NRC system, the BIPM array and its associated bias circuitry replaced the Zener and the right-hand reversing switch of Fig 1. Both the NRC and BIPM systems were allowed to float, although the cases of the various instruments, as well as all shields, were connected to safety ground. A selector switch (provided by the BIPM) was initially used to open both array circuits during current reversal but this was later found to be unnecessary and it was left closed during current reversal.

5. Results and uncertainties

On 26 and 27 October 2004, during the measurements, a few problems were encountered and then fixed by appropriate changes. Satisfactory results were then obtained for the comparison. A detailed description of the adjustments made to improve the measurement process is given in Appendix B.

On 28 October 2004, five series of measurements were carried out: the BIPM switch to open the measurement circuit was only used in series 1 and 2. Series 4 consists of 3 data points representing different connections between the NRC and the BIPM arrays, and reversed polarity of the detector for the last point. The conditions for series 5 are identical to those of series 4. On 29 of October 2004, another series of measurements was carried out with the BIPM system shield disconnected from the NRC shield. The results of series 4 and 5 were associated such that each result is derived from 5 individual points (Fig. 2).

The results of these series are presented in Table 1.

Series	28/10 S1	28/10 S2	28/10 S3	28/10 S4-5	29/10 S6
$(U_{BIPM} - 10\ V)/\mu V$	−0.361	−0.361	−0.361	−0.361	0.115
$(U_{NRC} - 10\ V)/\mu V$	−0.352	−0.356	−0.358	−0.353	0.114
$(U_{NRC} - U_{BIPM})/\mu V$	0.009	0.005	0.003	0.007	0.000
$\sigma_{(1\ obs.)}/\mu V$	0.003	0.003	0.002	0.005	0.002
$\sigma_{(mean)}/\mu V$	0.002	0.002	0.001	0.002	0.001

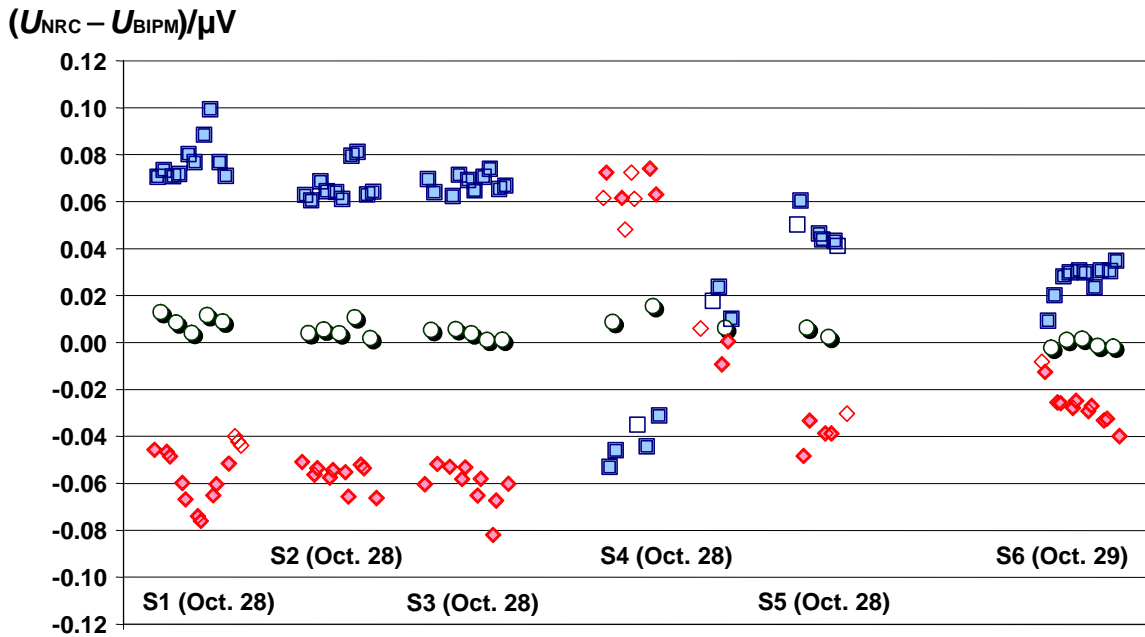Table 1. Measured difference of the voltage between the two systems.

Fig. 2. Individual measurements carried out on October 28 and 29. The squares are for positive polarity (+) measurements, the diamonds for negative polarity (–) measurements and the circles for the mean value of four (+, –, –,+ or –, +, +, –) measurements. Open squares and diamonds represent supplementary measurements not taken into account for the results.

These five results were then combined using as a weight the reciprocal of the square of the Type A uncertainty. The uncertainty of the weighted mean was computed using criteria of internal and external consistency: the latter (1.5 nV) is three times larger than the former (0.5 nV), probably because it already contains part of the Type B uncertainties. The a priori uncertainty is therefore adopted as the Type A uncertainty of the comparison. The weighted mean with series 4 and 5 considered as a single series is not significantly different from the weighted mean without those series, as their weight is only 6% of the whole.

The main sources of Type B uncertainty (Table 2) are frequency stability and measurement, leakage resistance, gain and linearity of the detector (details about some components of the uncertainty budget are given in Appendices A and B.) and electromagnetic interference (EMI). The uncertainty of the 10 MHz reference signal used for both systems is obtained directly from the NRC time standard and is negligible. As both array polarities were reversed during the measurements, the effect of the residual thermal EMFs is already included in the Type A uncertainty of the measurements.

		Uncertainty/nV	
	Type	BIPM	NRC
Frequency	B	0.2	0.4
Leakage resistance	B	0.4	0.1
Detector	B		2.8
EMI	B		1.0
Total (RSS)	B	0.4	3.0

Table 2. Estimated Type B standard uncertainty components.

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

$$(U_{NRC} - U_{BIPM})/ U_{BIPM} = 2.8 \times 10^{-10} \qquad u_c / U_{BIPM} = 3.1 \times 10^{-10}$$

where u_c is the combined standard uncertainty (k=1).

6. Complementary measurements

In order to investigate possible sources of errors due to leakage currents, some additional measurements were carried out at the end of the comparison. These are described in Appendix C.

7. Discussion and conclusion

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

The BIPM equipment was installed and preliminary measurements were performed on the day after arrival; during the next two days, adjustments were made to various parts of the measurement circuit, including in particular a change of the NRC array and the use of a different Gunn diode brought as a replacement part for the BIPM system. The comparison itself was then carried out with these improved conditions.

The results of the comparison demonstrate the ability of NRC in 10 V measurements. This comparison allowed the laboratory to carefully study different arrays, and improve the measurement conditions by selecting more appropriate parameters to reduce the noise and increase the stabilily of the primary standard.

It should be pointed out that the NRC system as it was at the beginning of the comparison was convenient for Zener measurements, as the observed deviations were of a few parts in 10^9; the limiting parameters could not have been determined without a direct Josephson comparison.

Appendix A

Detailed description of the NRC voltage calibration system (B. Wood).

The NRC Josephson Array Voltage System (JAVS) was originally developed in the late 1980s and is made of a combination of commercial and home-made components. The NRC JAVS probe is housed in a thin-walled stainless steel tube that has a sliding O-ring seal. This seal is connected to a chamber into which the array section may be withdrawn. A gate valve is used to seal the array section into dry room-temperature helium gas for longer-term storage. The microwave portion of the NRC JAVS probe consists of a metal WR12 waveguide with a thin-walled gold-plated section for thermal isolation. The room temperature section of the waveguide has a mylar DC break and vacuum seal. An outer cryoperm and inner superconducting shield surrounds the Josephson array chip. The chip wiring is thermally anchored and connected to a three-stage rf filter at the top of the probe. The potential leads have a series impedance of 1.24 Ω and terminate in BPO connectors.

The bias control for the Josephson array is an Astro Endyne JBS 501. This unit has been modified by adding (floating) battery operation, electrical isolation of the voltage and current monitors provided by FET input instrumentation amplifiers and optical isolation of all digital control lines.

The rf source is a Milletech Gunn diode driven by the Gunn diode power supply of the JBS 501. Frequency phase locking and counting is effected with an EIP 578B Source Locking Microwave Counter, which has been calibrated at a single frequency against an NRC frequency standard and at many frequencies using the PTB/IMST synthesizer (Fig. A1). Calibration deviations in the operating frequency range of this voltage comparison are within 3 Hz. The 10 MHz reference for the EIP is a chain of synthesizers that are linked to the NRC ensemble of caesium clocks.

Most clients' Zeners may be measured with or without ac power applied. Typically, both the Zener guard and chassis terminals are connected to the safety ground. Potential switching, both selection and polarity reversal, is done with Guildline low thermal switches that have been specially cleaned. The detector is a HP34420A nanovoltmeter, which has been calibrated at 23 points on the 10 mV range.
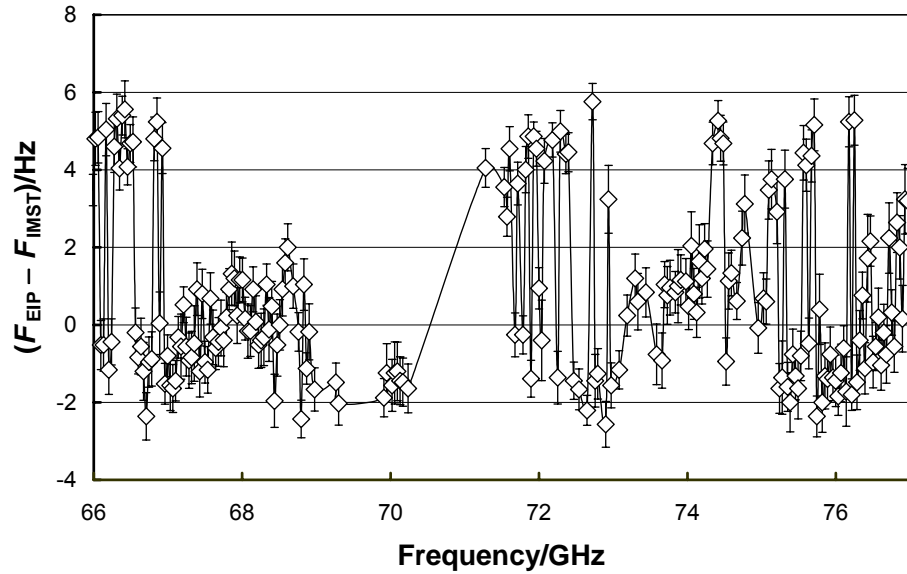
Fig. A1. Calibration of the NRC EIP 578B source locking microwave counter with respect to the PTB/IMST synthesizer.

The gain and linearity of the nanovolt detector, an HP34420A, were determined by direct comparison with the NRC JAVS system (Fig. A2) and represents a significant uncertainty component in this comparison. Although most measurements were made within two voltage steps, no rejection was made of data, so long as it was within the 10 mV range. The linearity of this particular nanovolt detector on the 10 mV range can be determined at any point to about 1 nV, however, the detector response is neither linear nor smooth at this level of resolution. For this reason the linearity of the detector was corrected with a 23-point histogram at approximately 1 mV intervals covering ±11 mV. Even with this type of linearity correction the average variation between successive intervals was 2.8 nV. Compared to this, other sources of uncertainty due to the detector (such as bias current, offset impedance and noise) are non-significant.
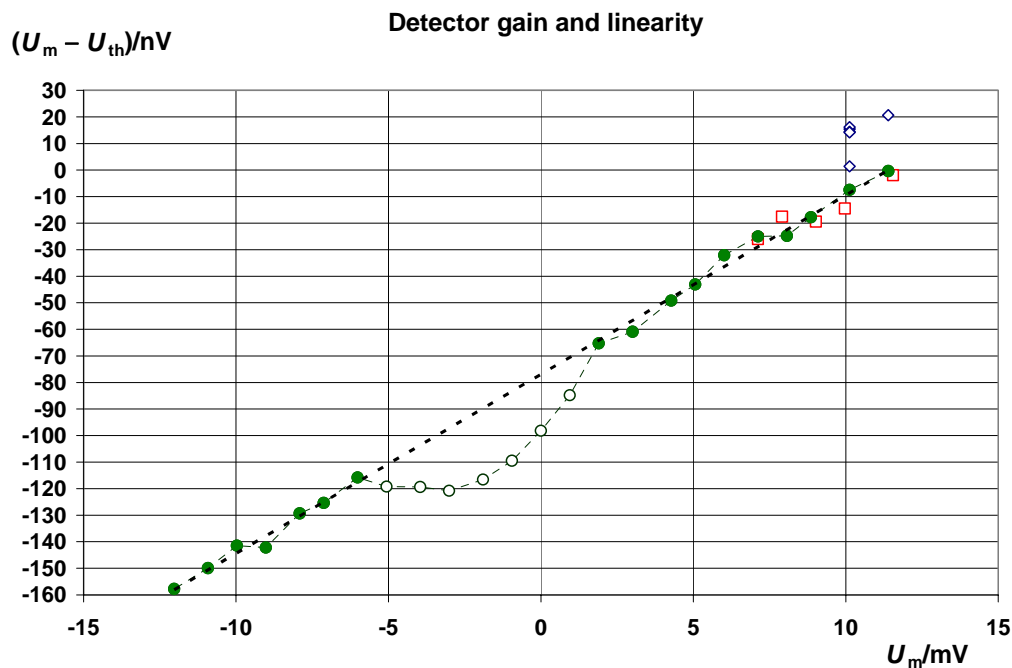
Detector gain and linearity

Fig. A2. Linearity plots of the HP34420A. Note the smooth consistent response on both positive and negative sides and the varying and non-smooth response between –6 mV and +2 mV.

The uncertainty component due to leakage is difficult to assess completely without the full set of 1 kΩ measurements (see Appendix C). It is possible that this effect cancels almost to zero if the systems are symmetric. An upper limit of this effect can be estimated from the voltage dividers formed by the potential lead resistance (1.24 Ω) and the leakage resistance (typically 10^{11} Ω).

Finally, the overall Type B uncertainty estimated by the NRC for a 10 V Zener calibration with the system as it was before the comparison (and including the RF rectification) was 3.6 parts in 10^{10}.

Appendix B

Detailed description of the problems encountered
during measurements carried out on 26 and 27 October 2004.

As it is often the case for such comparisons, some difficulties were encountered at the beginning and preliminary measurements were used to uncover the sources of the problems and to fix them. The following record may serve as a kind of checklist for further measurements.

Mains compatibility

If not all the instruments are connected to the same mains, some unexplained phenomena can occur. This was previously seen during the 1992 comparison with METAS (then called OFM). At the NRC, part of the BIPM equipment (the Gunn diode power supply and the EIP counter) were powered at 220 V using a transformer, whereas all other BIPM and NRC equipment were powered at 110 V. At the beginning, when changing the scope sensitivity, different voltage offsets were observed. This was traced to the transformer where the 220 V had no "neutral". This problem disappeared after changing the transformer wiring.

Array stability

In laboratory routine measurements, array step stability is not usually a crucial problem. Nevertheless, when trying to connect together two array systems, it appears in most cases that the sources of instability increase and make the measurements more difficult. It is then essential to find the best operating conditions for the arrays. At the NRC, the Gunn diode frequency could only be adjusted in a rather narrow bandwidth that did not include the optimum array "resonance frequency". More microwave power was then needed and power adjustment had to be modified when changing the measurement conditions. The BIPM had brought a replacement Gunn diode which was used for the BIPM system and the original BIPM Gunn diode with a large frequency bandwidth adjustment was used with the NRC array; much better NRC array stability was then obtained.

Microwave rectification by the array connection

At the BIPM and then during the comparison with BNM/LCIE in 1993, some abnormal offsets depending on the microwave power were observed in series with the array voltage. This was traced to rectification of the microwave signal by imperfect contact between the niobium superconductive pads of the array and the springs. The problem was fixed by adding to new arrays a gold layer on the niobium. As the array used at the NRC was supposed to be of the new type, such a problem was not expected. Nevertheless, at the end of 27 October 2004, intentional variations of the microwave power showed that the NRC array was exhibiting such spurious offsets amounting to about 0.1 µV for the maximum variation for which measurements could be made. It was then decided to warm up this array and replace it by another one. It was discovered then that this array was a NIST-made one, probably of the original type. The new one from Hypres was free of these offsets.

Measurement results

As explained above, it should be pointed out that these measurements were made under bad conditions, worse than for routine Zener measurements at the NRC. To increase the step stability the NRC microwave power had to be frequently readjusted, hence increasing the effect of power-dependent offsets. As for the measurements taken into account in the calculation of the comparison results, individual points consisted of four individual measurements in different polarity in one of the following sequences: (+, −, −, +) or (−, +, +, −). More than 20 points were obtained, 19 of them being made in a sufficiently short sequence to be considered as significant. The largest relative difference between the measured and the theoretical value was about one part in 10^8, and the mean relative difference and Type A uncertainty were respectively 2 parts in 10^9 and less than 1 part in 10^9. Once again, this proves that routine measurements of 10 V Zeners at the NRC were accurate to within a few parts in 10^9.

<u>**Appendix C**</u>

Complementary measurements.

Measurement configurations

Figure C1 represents the measurement connections for the direct Josephson array comparison. In this configuration, all the equipment is floating from ground. The series resistance in the circuit is only that of the leads (including the filters) connecting the arrays, typically a few ohms. At the end of the comparison, it was decided to check the accuracy limitation due to possible leakage between the measurement leads and/or between them and the ground.
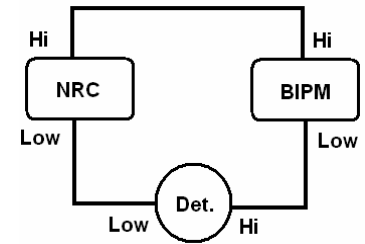
Fig. C1. Typical measurement circuit

To evaluate these effects of leakage resistances, it is convenient to add series resistors and/or to make a ground connection at different points of the circuit.

On 28 October 2004, measurements were made in the three configurations represented in Figure C2. Only in configuration "A" was a relative difference of 3×10^{-9} observed.
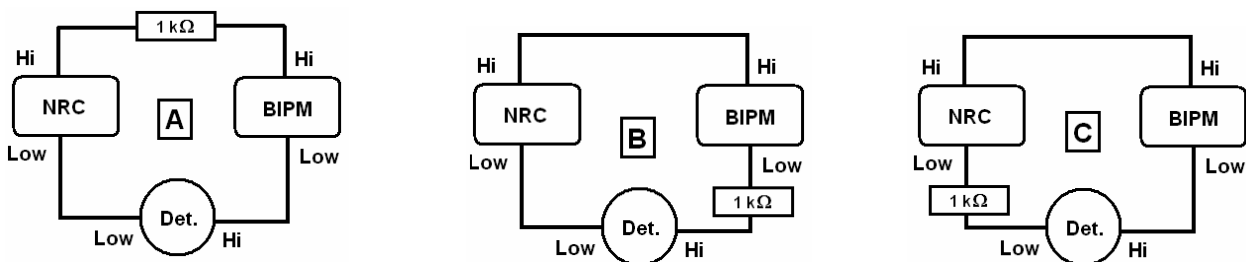

Fig. C2 : measurement circuits with added 1 kΩ series resistor

On 29 October 2004, measurements were again made in the three configurations represented in Figure C3. Five measurements were made in configurations A and B, and four were made in C). The results are given in Table C1. No difference is observed when the NRC

side is grounded, whereas a relative difference of less than 1×10^{-9} is measured when the BIPM side is grounded.

series	A	B	C	D
$(U_{\text{BIPM}} - 10\,\text{V})/\mu V$	0.115	0.115	0.115	0.115
$(U_{\text{NRC}} - 10\,\text{V})/\mu V$	0.116	0.110	0.107	0.114
$(U_{\text{NRC}} - U_{\text{BIPM}})/\mu V$	0.001	−0.005	−0.007	0.000
$\sigma_{(1\ \text{obs.})}/\mu V$	0.003	0.004	0.003	0.003
$\sigma_{(\text{mean})}/\mu V$	0.001	0.002	0.001	0.001

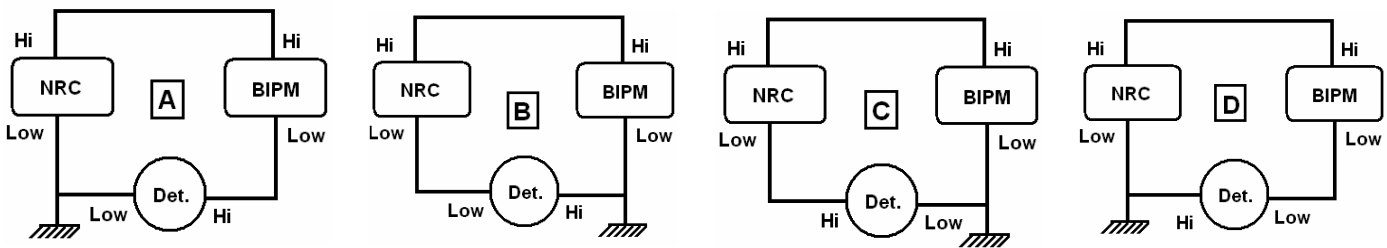Table C1. Measured difference of the voltage between the two systems.

Fig. C3. Measurement circuits with ground connections.

Finally, on the same day, a few measurements were made in the configurations represented in Figure C4. The relative difference was then 1×10^{-8} (A) or -2×10^{-8} (B).
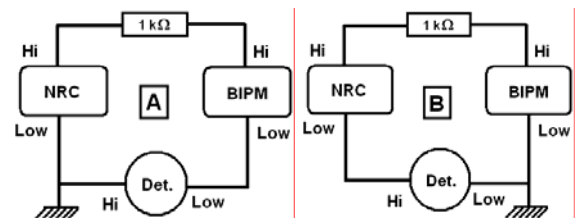

Fig. C4. Measurement circuits with added 1 kΩ series resistor and ground connections.

Conclusion

In this case, adding a 1 kΩ series resistor in the measurement circuit and connecting it to ground increases the effects of leakage resistance by more than 100. In the configuration used for the comparison these effects would not be measurable.