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BIPM direct on-site Josephson voltage standard comparisons: 20 years of results

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Abstract

The discovery of the Josephson effect has for the first time given national metrology institutes (NMIs) the possibility of maintaining voltage references which are stable in time. In addition, the introduction in 1990 of a conventional value for the Josephson constant, $K_{\text{J-90}}$, has greatly improved world-wide consistency among representations of the volt. For 20 years, the Bureau International des Poids et Mesures (BIPM) has conducted an ongoing, direct, on-site key comparison of Josephson voltage standards among NMIs under the denominations BIPM.EM-K10.a (1 V) and BIPM.EM-K10.b (10 V) in the framework of the mutual recognition arrangement (CIPM MRA). The results of 41 comparisons illustrate the consistency among primary voltage standards and have demonstrated that a relative total uncertainty of a few parts in 10^{10} is achievable if a few precautions are taken with regard to the measurement set-up. Of particular importance are the grounding, efficient filters and high insulation resistance of the measurement leads, and clean microwave distribution along the propagation line to the Josephson array. This paper reviews the comparison scheme and technical issues that need to be taken into account to achieve a relative uncertainty at the level of a few parts in 10^{10} or even a few parts in 10^{11} in the best cases.

Keywords: Josephson voltage standard, SI, comparison, primary standard

(Some figures may appear in colour only in the online journal)

1. Introduction

Fifty years after Brian Josephson predicted a tunnel effect between coherent Cooper-pair wavefunctions in two weakly coupled superconductors (i.e. a Josephson junction or jj) [1], this macroscopic quantum phenomenon has become the basis of an expected future redefinition of the derived SI unit for electromotive force (EMF) and electric potential difference: the volt. The reverse ac Josephson effect was experimentally demonstrated one year after Josephson's prediction [2]. This effect occurs when the junction is irradiated with microwave radiation which frequency-modulates the Cooper-pair current through the junction. The current has a dc component for evenly spaced constant voltage steps (Shapiro steps) given by the equation $V = n \times f / K_J$, where $K_J = 2e/h$ is the Josephson constant, e is the elementary charge and h the Planck constant. From this equation, it can be seen that the achievable voltage accuracy depends only on the accuracy of the frequency of the external RF bias signal. This explains the electrical metrology community's interest in the Josephson effect for representing the unit volt. The Josephson effect provided the first means of maintaining a voltage reference that is stable in time.

In 1988, the International Committee for Weights and Measures (CIPM) decided (recommendation 1) that the representation of the SI volt in terms of the Josephson equation should be based on an internationally agreed fixed numerical value for the Josephson constant, $K_{\text{J-90}} = 483\ 597.9$ GHz V^{-1} [3], from 1 January 1990. This conventional value allows a world-wide uniform 'representation' of the volt, which is, however, not a true realization of the SI volt. The Consultative Committee for Electricity and Magnetism (CCEM) recommended at its meeting in April 2007 a redefinition of the electrical SI base unit, the ampere, based on a fixed numerical value of the elementary charge (recommendation E-1). As a consequence, the Josephson effect would become a direct realization of the SI unit volt. The CCEM document stated that since 1990 the representation of the volt using the Josephson effect and

Figure 1. The new BIPM transportable JVS on the left-hand side and the BIPM primary standard operated since the first on-site direct comparison (right-hand side). Both JVS are connected directly together for comparison in the BIPM laboratories. The arrow shows the detector used to measure the voltage difference between the two JVSs.

the conventional value of the Josephson constant, K_{J-90}, has provided references worldwide that are practical, accessible, reproducible, low noise and highly linear.

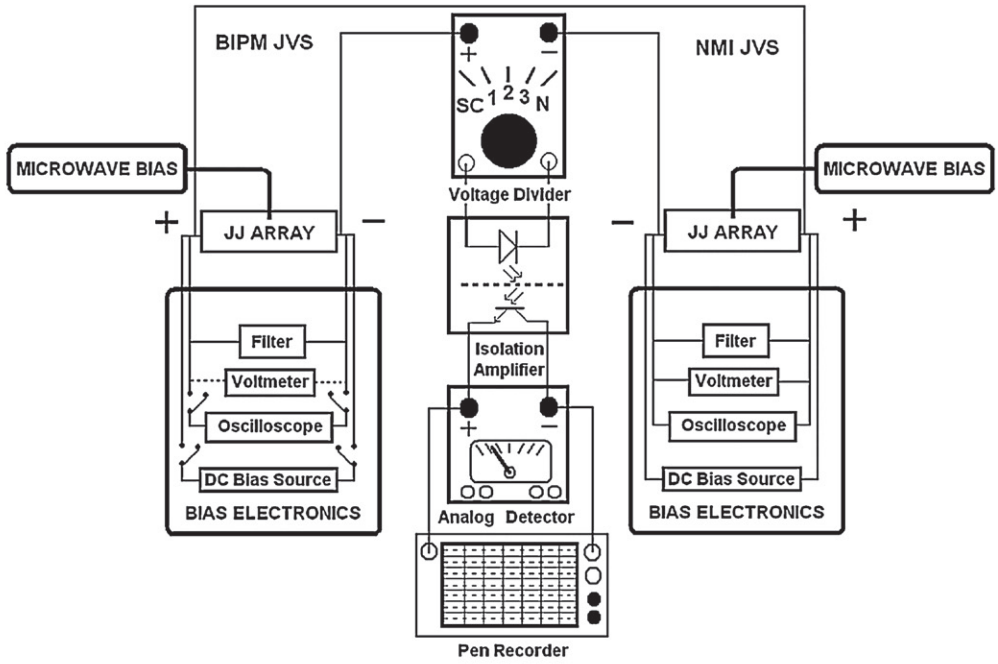
One of the roles of the BIPM is to assist with the establishment of uniformity among primary reference standards of the national metrology laboratories. The only way to examine the accuracy limits and the consistency of arrays of Josephson junctions that are used as voltage standards in different laboratories is by direct comparison. In general these systems are not easy to transport. The BIPM has therefore conducted a programme of direct on-site Josephson voltage standard (JVS) comparisons since 1991. The transportable BIPM JVS has been shipped to 26 different national metrology institutes (NMIs) where a total of 41 comparisons have been carried out because some NMIs have participated at both the 1 and 10 V levels.

We review the major technical problems encountered in these direct on-site JVS comparisons that needed to be solved in order to achieve a typical uncertainty of a few parts in 10^{10} and their impact on the overall uncertainty budget.

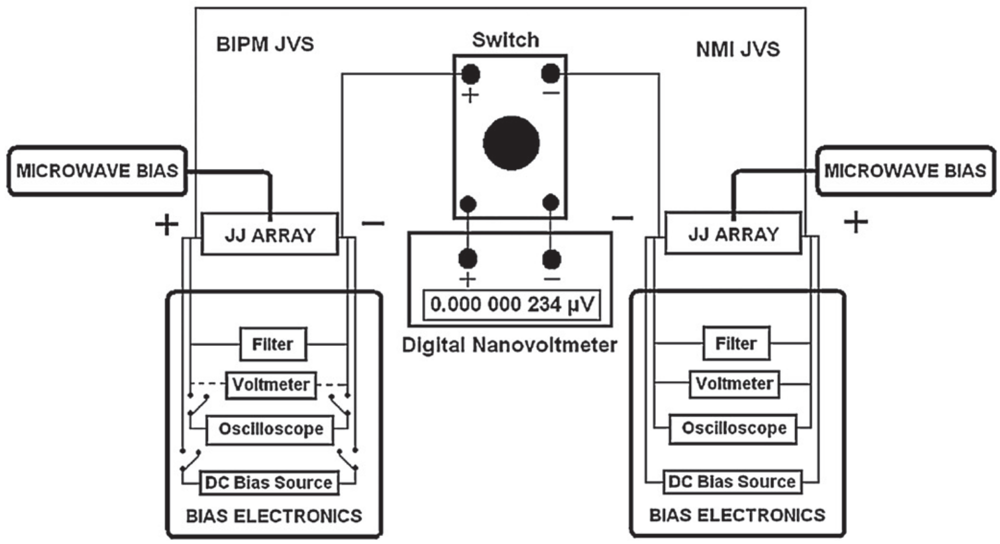
2. BIPM on-site direct Josephson comparisons

The mutual recognition arrangement for national measurement standards and for calibration and measurement certificates issued by NMIs (CIPM MRA) has the objective of establishing the degree of equivalence of national measurement standards and to provide for the mutual recognition of calibration certificates [4]. Technically, it is based on key comparisons in which NMIs demonstrate their ability to measure certain critical quantities. The CCEM has identified comparisons of JVSs at the level of 1 and 10 V as key comparisons. These standards are considered as primary voltage standards. To take advantage of the high accuracy of JVSs, on-site direct comparisons have been carried out by the BIPM since 1991. The results are listed in the BIPM key comparison database (KCDB: http://kcdb.bipm.org) under the identifiers BIPM.EM-K10.a (1 V) and BIPM.EM-K10.b (10 V). The purpose of these comparisons is to directly compare two complete and distinct JVS systems using a detector at room temperature without involving any secondary transfer voltage standard. To achieve this, arrays of Josephson junctions are biased at nearly the same voltage by slightly adjusting the frequencies of their respective external RF bias signals. In most cases, the participant does not have to change its normal working frequency, as the BIPM JVS offers a broad band of operational frequencies (72.5–76.5 GHz) and hence can adjust its external RF bias signal frequency. The JVSs are connected in series opposition, with the positive potential sides directly connected and the null detector inserted between the two low potential sides (figures 1 and 2(*a*), (*b*)). The BIPM JVS is equipped with conveniently situated binding post terminals and low thermal EMF switches for this purpose.

The impedance recorded by the null detector is mainly due to the resistance of the leads between the arrays and the output connections, and can be as low as a few ohms. This measurement method requires at least one of the arrays to operate floating from the ground. The BIPM transportable JVS is designed to be operated using a current source powered by batteries. Moreover, the current source is switched off and its output resistor is shorted for the data acquisition sequence.



(*a*)



(*b*)

Figure 2. (*a*) Arrangement of the measurement set-up for option A of the BIPM Josephson direct on-site comparison. (*b*) Arrangement of the measurement set-up for option B of the BIPM Josephson direct on-site comparison.

The two JVSs to be compared are connected in series opposition. As a result, each part of the equipment (RF and dc biasing sources, oscilloscope, etc) can strongly interfere with the other system and hence affect the stability of the quantum steps.

Two variations of this comparison exist, which differ in the measurement set-up used. This comprises the nanovoltmeter, the connection system (scanner or switch), the computer and its associated software.

2.1. Option A of the protocol

In the option A protocol, the BIPM uses its equipment to measure the voltage provided by the participant's JVS (figure 2(*a*)). The BIPM equipment consists of an analog nanovoltmeter which has its output connected to a pen recorder and a digital voltmeter (DVM) via an optically coupled isolation amplifier. The DVM is connected to a computer which is used to monitor measurements, acquire data and calculate the results. Low thermal EMF switches are used for critical switching, such as polarity reversal of the detector input. The connection of both arrays in series opposition is also controlled by a low thermal EMF switch. The equipment includes a voltage divider to prevent detector overload if one of the systems is no longer on the selected voltage step. Option A of the protocol allows achievement of the lowest Type A uncertainty (statistical dispersion of the voltage difference measured), but requires both arrays to remain exactly on the selected voltage step during the period of the data acquisition (typically 1 min) and to quickly (less than 30 s) recover the symmetrical step in the opposite polarity.

2.2. *Option B of the protocol*

In the option B protocol, the BIPM only supplies the participant with a reference voltage to be measured (figure 2(*b*)). The participating laboratory uses its own JVS standard and measuring device, usually a digital nanovoltmeter. The main advantage of this technique is that only the BIPM JVS needs to remain on its initial selected quantum voltage step during the data acquisition process. Any jump from the second JVS can be corrected for the corresponding theoretical calculated voltage.

3. Potential error sources in direct JVS comparisons

It is important to note that most JVSs are composed of the same or very similar instruments. In the following, we list this equipment and describe the potential unwanted effects related to the different components that can lead to systematic voltage errors and/or contribute to a significant increase in the noise.

3.1. *Array of junctions*

Since the first single-point contact junctions, capable of producing 10 mV when irradiated with 100 GHz, were used as a voltage reference [5], JVSs have advanced substantially in terms of voltage output capability, mostly as a consequence of the progress of microelectronic fabrication technologies.

During the 1980s, improvements in lithography and thin film processing, together with the development of niobium all-refractory junctions, made the realization of high-quality Josephson junctions possible with excellent uniformity of their intrinsic parameters (critical current, junction width and microwave path on the array). These developments allowed sputtering of the thin films and the oxidation process to be carried out to create the insulating barrier without breaking the vacuum during the fabrication process. This development, particularly when combined with the use of niobium to realize the superconducting electrodes, has produced very reliable junctions in terms of mechanical and chemical stability. These arrays are insensitive to moisture and thermal cycling under normal operating and storage conditions.

Arrays of under-damped, hysteretic Josephson junctions, consisting exclusively of SIS (superconductor/insulator/superconductor) junctions, are now the basis for the representation of the volt in NMIs. The main improvements in the development of these standards have been the following.

- the use of highly capacitive SIS junctions suggested by Levinsen *et al* [6];
- the realization of 'all refractory' junctions based on niobium to replace junctions based on lead, which have shown mechanical instabilities after a few temperature cycles [7];
- the improvement of the insulator layer using thermal methods to grow an aluminium oxide barrier, proposed by Gurvitch *et al* [8];
- the realization of the first 1 V JVS based on an array of 1474 junctions following a NIST–PTB joint project [9];
- the 10 V voltage level achieved by JVSs in the late 1980s [10, 11].

Reliable 10 V arrays of SIS junctions ($Nb/Al_2O_3/Nb$) have been fabricated and consequently have resulted in NMIs equipping their voltage laboratories with JVSs based on this technology for the representation of the volt. In this way, the development and widespread distribution of arrays of Josephson junctions have brought about one of the most remarkable improvements in electrical metrology over the last 30 years.

All the results presented in this paper were obtained by comparing SIS arrays with the one exception of a transfer JVS based on a programmable SINIS (superconductor/insulator/normal/insulator/superconductor) array [12].

Issues related directly to the chip come from defects at the level of the junction and/or of the corresponding electrical contacts. A failed junction which does not act as a perfect short circuit will present a resistance which renders the array useless. A bad electrical contact between the chip and the macroscopic contacts will produce the same effect. Resistance in series with the array results in a current-dependent voltage, which can be observed by sweeping the bias current while observing the output voltage or the shape of the steps on the scope.

In particular cases a junction can show a lower than expected value for its critical current. The direct consequence will be shorter voltage steps and instability of the output voltage in the dynamic mode [13]. This is often the case when arrays are temperature cycled. Dust and magnetic particles will be deposited on the surface. Depending on their position on the surface, the array can be damaged or its useful life reduced. In some cases, using an appropriate cleaning process for the array can be an effective solution [14].

3.2. *Ground loops*

After assembly of the measurement set-up, the grounding connections must be carefully analysed. On the BIPM JVS, precautions are taken to surround all components at high potential (typically 10 V) with a shield connected to the 'low' potential of the circuit. Furthermore, as the BIPM JVS must be floating from the potential reference of the measurement set-up, the bias circuit is floating and all connections to the scope must be either opened during measurements or made via isolation amplifiers.

The most suitable ground configuration must be identified among different possibilities (figure 3). If in the case of configuration A too much noise would be brought into the measurement loop to guarantee its stability, configuration B could be used, or vice versa [15, 16]. The reason for this lies in the different possible current leakage paths in the measurement set-up.

If the array is connected to an 'isolation ground' in the bias supply, this point must not be inadvertently connected to ground where it can add a significant systematic error [17, 18].

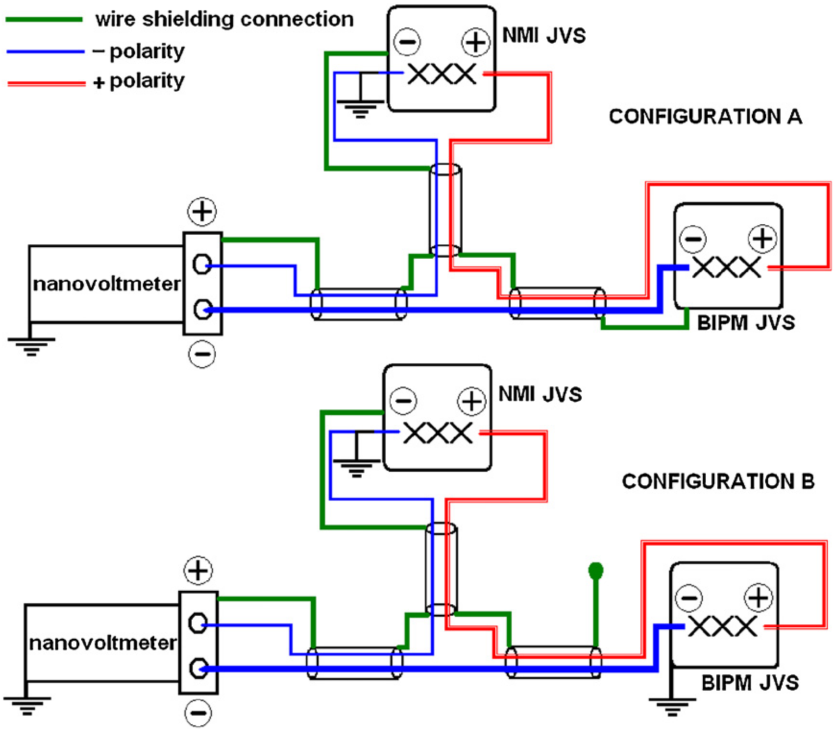


Figure 3. The grounding arrangement of the external chassis of the measurement equipment set-up. In configuration A the BIPM JVS is grounded through the shield of the measurement leads from the NMI's JVS. Configuration B shows each JVS probe grounded to the earth potential and the shielding of the measurement leads is disconnected between the two JVS. In addition, the BIPM He Dewar can be grounded, or not, depending on the consequence for the stability of the two JVS.

To reduce the coupling effects between both standards, it has been demonstrated that biasing two arrays with only one dc bias source (the array to be compared naturally goes to within a few steps of the voltage provided by the reference array) provides a useful method of determining errors originating from ground loops [19].

Despite these precautions, the effects of current leakage with long time constants could be possible on one system while it is connected to the other system if the capacitors are connected to ground, particularly in floating measurement configurations.

3.3. Filters and leakage resistance

The main qualities of the leads and filters connecting the array to the output terminals are: the stability and low value of thermal EMFs; a low value of the series resistance (a few ohms); and high insulation resistance between the measurement leads and ground (at least a few 10^{10} ohms). If there is a significant difference in the filters' equivalent impedances for each of the two JVSs, strong interference will make it impossible to carry out the measurement [20]. Furthermore, if the ratio of the insulation resistance to the series resistance is not larger than 10^{10}, a significant voltage drop will be noticeable at the voltage output of the JVS. This systematic error is typically of the order of magnitude of the comparison result. Different methods are available to cross-check the value of the insulation resistance [21]. The use of a high-resistance ohmmeter for direct measurement remains the easiest method.

PI structure *LC* filters with a low cut-off frequency (a few kHz) should be installed on each lead connected to the array in order to avoid electrical noise inducing instability on the quantum voltage steps. In the case of noise, voltage output of the JVS often varies because of frequent jumps between adjacent steps. In the worst case, no Shapiro steps are generated because of the level of noise. For the biasing leads, filters with fit-through capacitors might be sufficient. Particular precautions should be taken for the realization of filters on the measurement leads because of the high leakage resistance capacitors (PTFE dielectric) and mutual inductances (figure 4) that are required in order to maintain a low value of series resistance on the measurement leads without decreasing inductance values [22].

As the filter is symmetric, the characteristics of the components of the filter must not significantly differ from one another. If the dynamic impedances of the capacitor and the filter inductors differ too much, parasitic leakage voltages will occur which will lead to systematic errors. Therefore, it is necessary to carefully select similar components before assembly to mount a symmetrical filter [23].

3.4. Thermal EMFs

Residual thermal EMFs between the two systems can differ from zero because thermal EMFs along the two JVS can vary by a few hundreds of nanovolts (typically 100–800 nV). Linear evolution of the amplitude is cancelled out by polarity reversals of JVS voltages during the measurement sequence. Excellent repeatability of time intervals in the measurement

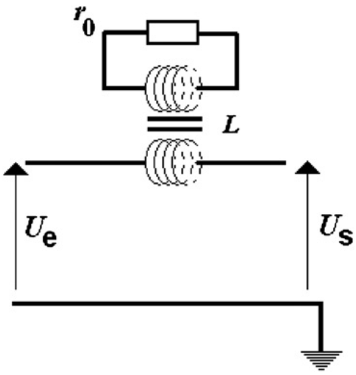


Figure 4. Details of the mutual inductances of the filter on the measurement leads of the BIPM JVS. The primary winding is connected in line with the measurement lead and the secondary winding is coupled to a resistance *r*. The mutual inductance ensures low-pass filtering of the (*LC*) cell without introducing a detrimental line resistance.

process is the best way to limit the amplitude of the residual part of the thermal EMFs and the corresponding dispersion of the measurements. The amplitude of the remaining thermal voltages, developing nonlinear in time, can be evaluated by the 'short-circuit method' described by Hamilton and Tang [24] where the two JVSs are replaced by two short circuits. This technique has been regularly used to identify issues during direct comparisons [25]. However, the result obtained with this method comprises a number of correlated components related to: the detector (bias current, offset change in the input impedance, nonlinearity and noise); rectification of the radio-frequency current; sloped steps; and possible electromagnetic interferences.

The measurement leads of the BIPM JVS are thermally anchored on copper blocks by beryllium oxide washers which guarantee both high electrical insulation and high thermal conductivity. The EMF level is therefore limited to 150 nV.

3.5. Waveguide and RF external bias signal

These two elements and the waveguide associated with the fin-line antenna transition deliver the RF power to the junctions in the array and can be considered as a propagation line. The transmitted power is determined by the quality of the propagation line in terms of transmission and reflection. The transmission coefficient between the waveguide and the fin-line antenna is a crucial parameter. The highest voltage to which a JVS can be biased is related to the type of junction, the number of junctions and the amount of RF power available for each junction. The highest step number is a function of the power at the junction but is limited to the band gap voltage. Present technology has focused on achieving large stable voltages by increasing the number of junctions while operating all junctions at relatively small step numbers. The number of junctions integrated onto a single chip also depends on the type of junctions [26]. For a given frequency, the coupling of the RF power to the junctions depends on the details of the standing waves and microwave attenuation along the stripline. For an array of SIS Josephson junctions the width of the Shapiro constant voltage steps (in terms of current) is correlated with the power distributed: as the amount of power increases, steps start appearing on some of the junctions, then progressively on all of them; the size of the steps then increases to a maximum value (typically between 15 and 25 μA) and finally decreases until the steps become unstable and/or sloped. This occurs when the microwave current is higher than the critical current in parts of the microwave network.

The level of power transmitted from the source to the array is sufficient when this last situation is observed. A lower limit of power at the level of the junctions is something which has been encountered often during direct JVS comparisons.

A number of electrical noise issues in the measurement loop are related to the step when the frequency of the RF source is changed from the free running mode to the phased-locked stabilized mode. Our experience has shown that the dispersion among a series of measurements is closely related to both the quality of the counter used and the quality of the phase locking oscillator [25, 26]. Two general rules apply: (i) the newest commercially available frequency counters are more efficient in locking a frequency far from the free running frequency and (ii) a well-designed, efficient and reliable phase-lock system is used, as for instance, the device developed by AIST in the early 1990s [27]. Following these rules will contribute to generation of wider Shapiro steps and therefore contribute to making the JVS more immune to external electrical noise. To check for problems related to frequency instabilities an experiment can be carried out that consists of implementing a single microwave source for the two systems (if they can be operated at the same frequency). This eliminates any uncertainty from variations in the frequency although this experiment is difficult to set up [28].

There were no occasions when the comparison results depended on the frequency used. Both frequency counters (in all cases either EIP model 578 or 578B) were referred to a common standard frequency for all comparisons so that, unlike the normal calibration situation, the accuracy of the reference frequency did not contribute to the uncertainty. In some cases the internal 10 MHz frequency reference of the counter was used to eliminate the clock ground potential which is transferred to the counter through the BNC connector [29]. The use of a dedicated isolation transformer is also a suitable method to achieve insulation.

3.6. Cryogenic operating temperature and magnetic shield

The superconducting electrodes of the junctions are made of niobium and thus have to be operated below 9.1 K. Liquid helium is used as a cryogen in most apparatus, although some very good results have been obtained with cryocooler-based systems where the temperature set point can be higher than the equilibrium temperature of liquid helium [18, 30]. For those JVSs, the array and its leads are permanently thermally anchored and therefore do not offer any flexibility for changing parameters such as in the 'floating mode' of the array from the ground potential or the change of the probe immersion to modify the RF signal propagation and/or thermal EMFs. New cryostats based on cryocooler systems operate by liquefying an amount of helium gas in a measurement chamber and may offer a solution to these limitations in the future.

A magnetic shield is placed around the array to prevent it from trapping magnetic flux (incomplete Meissner effect) when the transition of the niobium electrodes to the superconducting state occurs. Trapped flux results in diminished amplitudes of the critical current and consequently limits the width of the Shapiro steps. The cylindrical shield is made of an alloy of chrome/nickel which has a very large magnetic permeability at low temperature. One shielding stage is usually sufficient; however, the BIPM uses two successive shields made of different metals to reinforce the protection. The internal shield is made of niobium and the external shield is a chrome/nickel alloy.

Low humidity levels in the air increase the level of electrostatic charge which may in turn drive small currents in the JVS and generate magnetic fields which can be trapped [21]. Even if there is no evident efficient rule to avoid trapping flux, grounding the helium Dewar and probe and cooling it slowly can, in most cases, reduce the risk.

3.7. Detector (nanovoltmeter)

The internal noise of the detector used in the measurement loop, together with the residual thermal EMF, are the limiting factors in the Type A comparison uncertainty. The behaviour of digital nanovoltmeters in the measurement loop is dependent on the electromagnetic environment and can vary considerably between laboratories. On one occasion, an offset of several microvolts was observed with a corresponding important internal noise. The level of noise had a direct impact on the shape and stability of the voltage steps. Roberts and Early [31] suggested that high-quality digital multimeters show some abnormal behaviour in the presence of ac signals at their input that are related to the use of a discrete front-end amplifier. Filipski and Boecker [32] observed problems which they attributed to a common-mode effect related to a noise compensation system. Whenever possible, it is recommended that different DVMs are tested to evaluate their effect on the measurement loop [13].

If the measurement situation does not correspond to a null voltage measurement (i.e. both JVS are not on the same quantum voltage step), then the gain and linearity of the nanovoltmeter has to be taken into account by applying a correction to the readings. It is useful to measure the gain several times during a comparison, in particular because the evolution of the internal temperature of the device will strongly affect its value [20].

In the option A comparison scheme, the deviation of the null detector is calibrated in terms of the voltage to frequency relationship of the arrays. The corresponding relative Type B uncertainty due to the linearity and calibration of the null detector is below 5×10^{11}. The largest uncertainty associated with the detector is probably due to the effect of ac and dc common-mode signals on the position of the zero. This effect increases with the impedance of the measurement circuit and such effects have been observed in particular by a difference between the two polarity positions of the detector.

Different levels of noise were also observed on the detector depending on the polarity of the measurement circuit and the detector, even when all components were floating. No clear explanation for this observation is apparent.

4. Results and future perspectives

Over a period of more than 20 years, the BIPM has piloted a total of 41 on-site direct Josephson comparisons at the level of 1 V (since 1991) and 10 V (since 1994).

Twenty-six different laboratories have participated in these comparisons and the relative voltage difference of 93% of the comparisons does not exceed 3×10^{-10} within comparable relative expanded uncertainties. The other 7% of the results were above 1×10^{-9} but a systematic error was assumed to be the origin. The best results obtained in these comparisons correspond to a relative difference of a few parts in 10^{11} within a comparable relative combined uncertainty [23, 26].

A total of 22 BIPM comparisons have been carried out at the level of 10 V, 18 of which have been undertaken since 2004 when the simplified comparison protocol (option B described previously) was proposed (figure 2(*b*)). In option B of the protocol the BIPM provides only a reference voltage that the participant measures using their own Josephson standard and measuring system. Since 2007, following a decision by the CCEM, two results have appeared in the KCDB for most participants. The difference between the initial and the final results reflects the technical improvements achieved during the time period allotted to the exercise.

4.1. Uncertainty budget

4.1.1. Type A uncertainty. In most comparisons, the statistical uncertainty has been calculated as the standard deviation of the mean of a few tens of measurement points. However, if large numbers of results have been obtained under the same experimental conditions and at equal time intervals and are strongly correlated, another statistical analysis such as the Allan deviation [33] must be applied to obtain a reliable estimate of the statistical dispersion of the results [34].

The statistical uncertainty comprises several components of different origin which are difficult to separate: detector (bias current, offset change in the input impedance, non-corrected internal EMFs and noise), rectification of the external RF signal and associated frequency stability of the source, effects related to sloped steps and electromagnetic interferences. The dispersion of a few results obtained at the 0 V level must be of the same order of magnitude as those obtained at other voltage levels to guarantee that the Type A uncertainty is independent of the voltage of the JVS. A difference between the two values indicates sources of error and, in particular, the possibility of a significant leakage effect in the measurement loop [25].

4.1.2. Type B uncertainty. Table 1 lists typical Type B uncertainty components for the BIPM JVS. The calculation of uncertainty for the comparison of two JVSs comprises the Type B components related to the second JVS (except the detector) and the Type A uncertainty.

Table 1. Type B relative standard uncertainty components of the BIPM JVS and its associated measurement loop.

BIPM	Relative uncertainty
Frequency offset[a]	8.0×10^{-12}
Leakage resistance[b]	5.0×10^{-11}
Detector[c]	3.0×10^{-11}

[a] Both systems are referred to the same 10 MHz frequency reference. This component only takes into account a possible frequency offset of the frequency counter, σ_{RF} from the frequency f of the external RF bias signal. $u_{\mathrm{RF}} = a/2 \times (\sigma_{\mathrm{RF}}/f) \times U_r$ where a is the width of the selected statistical distribution and U_r is the nominal voltage.
[b] The relative uncertainty contribution of the leakage resistance R_L can be calculated from the formula $u_f = a/2 \times U_r\,(r/R_L)$ where a is the width of the selected statistical distribution, U_r is the nominal voltage and r is the series resistance of the measurement leads.
[c] A large proportion of the detector uncertainty is already contained in the Type A uncertainty of the measurements. This component only expresses the uncertainty on the internal residual thermal EMFs and possible nonlinear internal offset.

4.2. Perspectives

Over-damped, non-hysteretic or programmable arrays have been produced since the late 1990s [35, 36]. The current–voltage characteristics of these devices remain repeatable under microwave irradiation as each junction is biased on its first-order voltage step. Therefore, the array output voltage is programmable, stable and can be set quickly by external biasing. In recent years, the output voltage achievable from SNS arrays, where the barrier is made of normal metal, has reached the important level of 10 V [37–39]. The developments performed to overcome this technical challenge have been conducted in parallel with progress on using programmable arrays to synthesize ac signals. In this field, two different techniques exist: generation of stepwise approximated waveforms [40] and pulse-driven, continuous, waveform synthesis [41]. Excellent agreement of both has been demonstrated [42]. The first method is limited by the undefined voltage during the transition between two quantum states while the second needs a complex set-up to generate the short pulses transmitted to the array, which limits the output voltage. Furthermore, sampling and stepwise approximated waveform methods have been successfully operated to establish a metrological link between conventional ac power standards and voltage quantum standards and therefore offer direct applications [43, 44].

Traditional arrays of SIS junctions will be progressively replaced by 10 V programmable arrays for dc voltage metrology. This will allow NMIs to realize the volt in the new SI (if the numerical values of e and h are fixed, then the adopted value of the Josephson constant, $K_{\mathrm{J}\text{-}90}$, will disappear). This will allow automation of the calibration processes for secondary standards and DVM linearity. Programmable arrays would simplify direct Josephson comparisons because polarity reversals could be carried out faster, equally spaced in time, and would therefore contribute to a reduction in residual thermal EMFs which contribute to the Type A uncertainty [45]. However, BIPM Josephson comparisons have shown that errors introduced in the measurement loop, even if they are small, can reach the 10^{-10} level and be comparable to the most significant uncertainty components. While it is possible to totally disconnect the dc bias source of an SIS array without disturbing its operation, a programmable array needs to remain permanently connected to the current source. Therefore, the uncertainty budget might be more difficult to investigate for a comparison of two programmable arrays.

5. Conclusions

Since the introduction in 1990 of the representation of the volt using a conventional value for the Josephson constant, $K_{\mathrm{J}\text{-}90}$ (CIPM, 1988, recommendation 1) at the request of the 18th meeting of the CGPM in 1987 (Resolution 6), the consistency among voltage measurements has been improved greatly by the Josephson effect.

The BIPM, which has the mission to provide the basis for uniform SI realizations worldwide, has participated in demonstrating this consistency by organizing an on-site direct comparison of JVSs (primary representations of the volt of the NMIs). The results of 41 comparisons have shown that a relative total uncertainty of a few parts in 10^{10} is achievable when some precautions are taken: proper grounding of the measurement set-up, use of efficient low-pass filters, high insulation resistance and a clean RF power distribution along the length of the propagation line to the array including the suitable phase lock of the signal. In addition, excellent conditions of electromagnetic compatibility, high-quality temperature controlled laboratories and a reliable detector will contribute to ameliorate the stability of the quantized voltage of SIS junction arrays and to limit the impact of residual thermal EMFs. Within such exceptional conditions, a total relative uncertainty of a few parts in 10^{11} has been achieved. When uncertainties larger than 10^9 were evaluated, an uncorrected systematic error was suspected, which could be detected in several cases.

The redefinition of several of the SI base units in terms of fixed numerical values of fundamental constants, including the Planck constant h and the elementary charge e, will make the quantized Josephson voltages true SI realizations of the volt, but will also introduce a small, but acceptable, single discontinuity in the results of electrical measurements at the time when the redefinition is implemented [46]. However, bringing electrical measurements back in the SI will be a significant improvement.

The introduction of the Josephson effect into voltage metrology can be considered revolutionary. It is foreseeable that these revolutionary changes will continue to occur with the development of ac JVSs and related metrological applications worldwide.

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