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Josephson voltage standard at National Physical Laboratory, New Delhi

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Abstract. A C Josephson effect is now used by several countries as the reference standard for the unit of d.c. voltage. This paper describes the work done at the National Physical Laboratory (NPL), New Delhi in the realization of the unit of volt based on the a.c Josephson effect. A voltage standard at 1 mV level using a Nb-Nb point contact junction has been established and the as-maintained volt based on a bank of standard cells has been intercompared against it using a 1 : 1000 voltage divider. The experimental set-up used in this comparison and the results of recent measurements are described. The overall uncertainty in assigning the value of emf to a standard cell is about 1 ppm. The as-maintained volt has been found to agree with the Josephson voltage within overall uncertainty.

Keywords. Josephson effect; voltage standard; superconductivity; superconducting devices.

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1. Introduction

The a.c. Josephson effect (Josephson 1962, 1964, 1965) is now used by several national laboratories (Field *et al* 1973; Harvey *et al* 1972; Melchert 1978; Hartland 1977; Witt *et al* 1983; Andreone *et al* 1983; Endo *et al* 1983; Wood and Dunn 1981) as the reference standard for the unit of d.c. voltage. The Josephson effect relates the voltage to the frequency, the most accurately known SI unit, through fundamental constants e, the charge of the electron and h, the Planck's constant. This voltage frequency relation is space- and time-invariant and forms the basis for the reference standard for the unit of volt. The earlier reference standard based on a bank of saturated Weston cadmium cells had unpredictable long-term drifts of the order of a few ppm and required periodic transportation to BIPM, France for intercomparison with their standard cells. Moreover, it was very difficult to know what portion of the difference between the values of the BIPM volt and that of the other laboratory was due to the drift in the emf of the BIPM cells. All these problems have been overcome with the development of the Josephson voltage standard. However, a bank of standard cells or a Zener-based electronic voltage standard is still maintained as the physical standard to represent the volt and is used for day-to-day calibration work. These physical standards are periodically calibrated against the Josephson voltage standard.

2. Josephson effect and the principle of voltage standard

In 1962, Brian D Josephson predicted an effect in superconductors which now bears his name (Josephson 1962, 1964, 1965). He predicted that a direct supercurrent could flow between two weakly coupled superconductors (known as a Josephson junction) even if the potential difference between the two is zero. The zero voltage supercurrent flows upto a characteristic value known as the critical current. This phenomenon is called the d.c. Josephson effect. Above the critical current a finite potential difference appears across the junction and an alternating supercurrent starts flowing between the two superconductors. The frequency ν of the alternating supercurrent is related to the potential difference V across the junction by the relation

$$2eV = h\nu, \tag{1}$$

where e is the charge of the electron and h is the Planck's constant. This phenomenon is called the a.c. Josephson effect. Josephson further predicted that in the presence of microwave radiations of frequency, ν_m, a direct supercurrent could flow between two weakly coupled superconductors when there was a finite potential difference V between the two superconductors, provided the following condition is satisfied

$$2eV = nh\nu_m, \tag{2}$$

where n is an integer. Thus in the presence of microwave radiations, the d.c. I-V characteristic of a Josephson junction looks like a staircase as shown in figure 1. The current steps appear at a constant voltage interval given by equation (2). The Josephson effect, thus relates the voltage to the frequency, the most accurately known SI unit, through fundamental constants. This voltage frequency relationship is exact and is space- and time-invariant. It is also independent of all physical parameters such as junction material, type of junction, frequency of microwave radiations, operating temperature, magnetic field etc. It has been experimentally shown that the relationship is accurate to within 2 parts in 10^{16}, the upper limit is set by the sensitivity of the

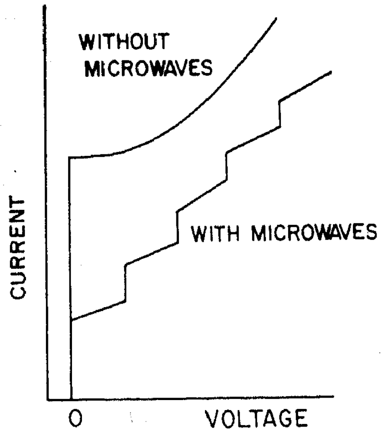

Figure 1. I-V characteristic of a Josephson junction.

instruments (Tsai *et al* 1983). These microwave-induced steps in the d.c. current-voltage characteristic of a Josephson junction forms the basis of a voltage standard. As the magnitude of a step voltage is very small ($\sim 20\ \mu$V for 10 GHz radiations), a large number of steps are generated to get a cumulative step voltage of the order of 1 mV or more. To achieve this the junction is suitably biased on the nth step. The cumulative step voltage is used to calibrate the standard cell at 1 volt level using an accurate resistive divider of suitable ratio as shown in figure 2 and described below:

A stable current is passed through two fixed resistors R_2 and R_1 which are connected in series. The ratio R_2/R_1 is accurately known. The current I through the resistive divider is adjusted until the emf of the standard cell, V_{sc}, is balanced across R_2. The frequency of the microwaves ν_m along with the step number n is then adjusted to get a null in the galvanometer G_1 also. When both the galvanometers are in the null position, the ratio of the standard cell emf to the cumulative Josephson step voltage, V_J, is equal to the ratio R_2/R_1

$$\frac{V_{sc}}{V_J} = \frac{R_2}{R_1}.$$

But $V_J = n(\hbar/2e)\nu_m$. Therefore $V_{sc} = n(h/2e)(R_2/R_1)\nu_m$. The internationally agreed value of $2e/h$ as recommended by CCE is 483594·0 GHz/V (CCE 1975). Thus by knowing the value of the divider ratio, microwave frequency and the step number and using the internationally agreed value of $2e/h$, the value of standard cell emf can be determined. Thus by adopting a fixed value for $2e/h$, voltage can be maintained and reproduced to a few parts in 10^9 using the Josephson effect (Kose 1976; Gupta 1980; Endo *et al* 1983). Unfortunately the absolute value of $2e/h$ is not known to a desired level of accuracy. The above mentioned value has an uncertainty of 2·6 ppm (Cohen and Taylor 1973). Any further reduction in the uncertainty in the value of $2e/h$ would raise the accuracy of the absolute volt to a level at which the volt can be reproduced by the a.c. Josephson effect.

3. Various types of Josephson junctions and their suitability for voltage standard

Figure 3 shows four broad types of Josephson junctions. These are (i) a thin film tunnel junction consisting of two superconducting films separated by a thin oxide layer, or a

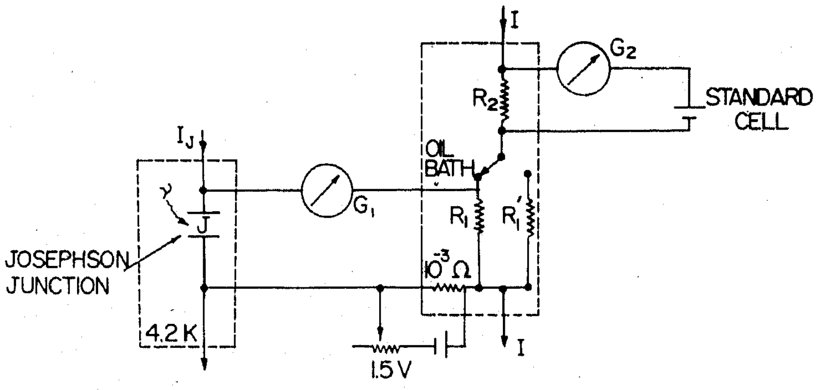

Figure 2. Block diagram of the Josephson voltage standard set-up.

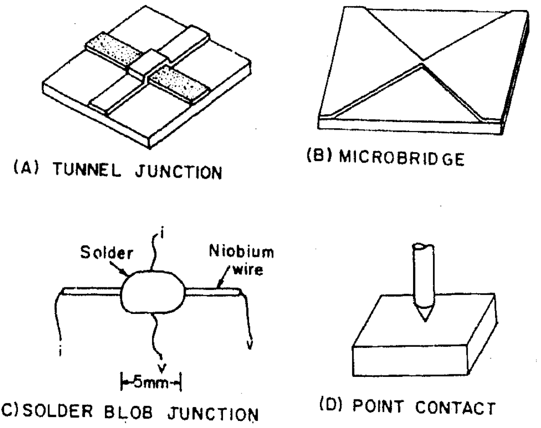

Figure 3. Various types of Josephson junctions.

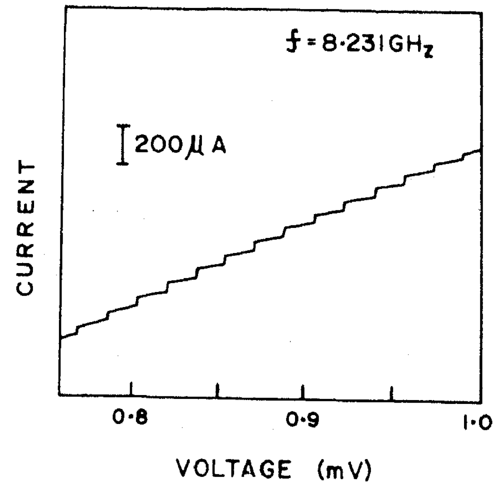

Figure 4. Microwave-induced steps at 1 mV level in I-V characteristic of a solder blob junction.

thicker layer of a normal metal, semiconductor or a photoconductor, (ii) a superconducting film with a constriction ($\sim 1\ \mu$m) called a microbridge, (iii) solder blob junction consisting of a blob of Pb-Sn solder frozen around an oxidized niobium wire and (iv) a point contact between a needle and a base, both made of superconducting material.

The usefulness of the Josephson step for voltage standard application is characterized by (i) its voltage position which should be 1 mV and preferably as large as possible, approaching 1 volt, the approximate value of the standard cell emf, (ii) its current amplitude should be 50 μA or more, and (iii) the step should be vertical having $\mathrm{d}I/\mathrm{d}V$ approaching infinity. In the case of a microbridge it is generally difficult to get steps above a fraction of a millivolt and it is, therefore, not suitable for voltage standard application. However, steps upto 1 mV or above could be obtained using thin film tunnel junctions, point contacts and solder blob junctions and all the three types of junctions are being investigated at NPL, New Delhi (Tomar *et al* 1978; Natarajan 1980; Gupta *et al* 1983, 1984, 1986). Microwave-induced steps obtained in a solder blob junction during our early experiments are shown in figure 4 (Gupta *et al* 1984). Using a single point contact (Harvey *et al* 1972) or a solder blob junction (Petley and Morris 1970) it is difficult to obtain a large amplitude ($\sim 50\ \mu$A) step above 1 mV and it is also difficult to connect several such junctions in series to achieve a larger cumulative step voltage. However, by using a tunnel junction usable steps upto 3 mV or more can be obtained (Finnegan *et al* 1971; Witt and Reymann 1983; Andreone *et al* 1983). Moreover, it is possible to fabricate an array of thin film tunnel junctions on the same substrate to get a larger cumulative step voltage (Finnegan *et al* 1971; Endo *et al* 1983) reaching upto 1 V (Niemeyer *et al* 1984a, b, 1985; Hamilton *et al* 1985).

The present Josephson voltage standard at NPL uses a simple Nb-Nb point contact and is operated at 1 mV level. The point contact junction has been selected because it is easy to make and does not require sophisticated experimental facilities for its fabrication. Moreover, the characteristics of the junction can be suitably altered in situ by changing the contact pressure using manual controls outside the liquid helium cryostat. However, work is in progress to develop an array of thin film tunnel junctions to get a larger cumulative step voltage (Gupta *et al* 1986).

4. Experimental details

4.1 *Josephson junction and liquid helium cryostat*

Figure 5 shows the schematic diagram of the cryostat and the point contact junction. The junction is placed inside a brass cavity and is irradiated with highly stabilized phase-locked microwave signal at about 10 GHz using a copper clad coaxial cable. The point contact is made of 3 mm dia Nb base and a 0·5 mm dia wire whose one end is used to make a fine point. The electric leads to the Nb are spot-welded. A total of six copper wires are connected to the point contact, four leads for the usual four terminal I-V measurement and the other two for accurate measurement of the step voltage. As the potential leads come out from liquid helium temperature (4·2 K) to room temperature

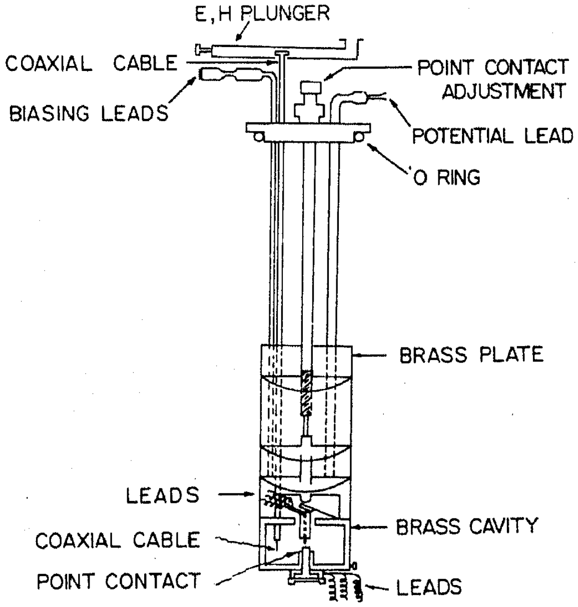

Figure 5. Schematic diagram of the liquid helium cryostat.

(295 K), they experience a large temperature gradient which gives rise to thermal-emf. Extreme care is taken to minimize the thermal emf and its variation in the potential leads. The thermal emf is minimized by twisting the potential leads which are made of single pieces of low thermal emf enamelled copper wire from the same spool. The variation in the thermal-emf is minimized by maintaining a fixed temperature distribution along their length. In order to achieve this the potential leads are taken out of the cryostat through a copper tube whose lower end is sealed and is always dipped in the liquid helium bath. Moreover, those parts of the potential leads which are at room temperature are covered with thermal insulating material and are directly connected to a copper block which is connected to the divider circuit. The copper block is kept inside a thermally insulated box.

The constant voltage steps in the I-V characteristic of the point contact are usually observed upto 1·5 mV by suitably adjusting (i) the microwave power using a variable attenuator and (ii) the contact pressure using a differential screw arrangement. A current amplitude of about 70 μA is achieved for steps at 1 mV level.

4.2 *Shielding and noise filtering*

Josephson junctions are very sensitive to a broad band of electromagnetic radiations. External noise produces a finite slope in the step (Kose and Sullivan 1970) which may introduce uncertainty in voltage determination. To achieve steps with near infinite slope the following precautions have been taken.

(i) Measurements are carried out inside a shielded room. The liquid helium cryostat and the d.c. voltage divider are kept inside the shielded room, while the microwave system is kept outside.

(ii) All the electrical measuring instruments inside the shielded room are operated with batteries.

(iii) The brass cavity containing the point contact is further shielded by using a superconducting lead shield.

(iv) A noise reduction filter is provided in the electrical power line before it enters the shielded room. This filter is effective for noise in the frequency range from 10^{-2} MHz to 10^3 MHz.

4.3 *Microwave equipment*

The schematic diagram of the X-band microwave system is shown in figure 6. Water-cooled X-band klystron (150 mW) is used as the microwave source. For frequency stabilization, the tenth harmonic of a reference signal of suitable frequency from a synthesized signal generator is mixed with the klystron signal. The resultant IF signal is compared with the reference frequency of a temperature-controlled quartz oscillator to produce a phase correction voltage. This correction voltage is fed back to the reflector voltage of the klystron. In this way short term frequency stability (over a period of 15 minutes) of ± 2 Hz is achieved. The time base of the frequency counter is calibrated against the cesium atomic frequency standard at NPL.

4.4 *Voltage comparison system*

In the present case, a resistive divider of 1:1000 ratio has been used. Ten standard

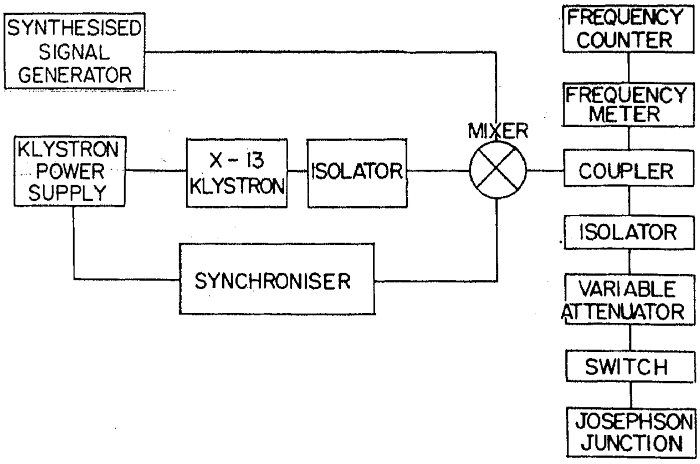

Figure 6. Block diagram of stabilized microwave source.

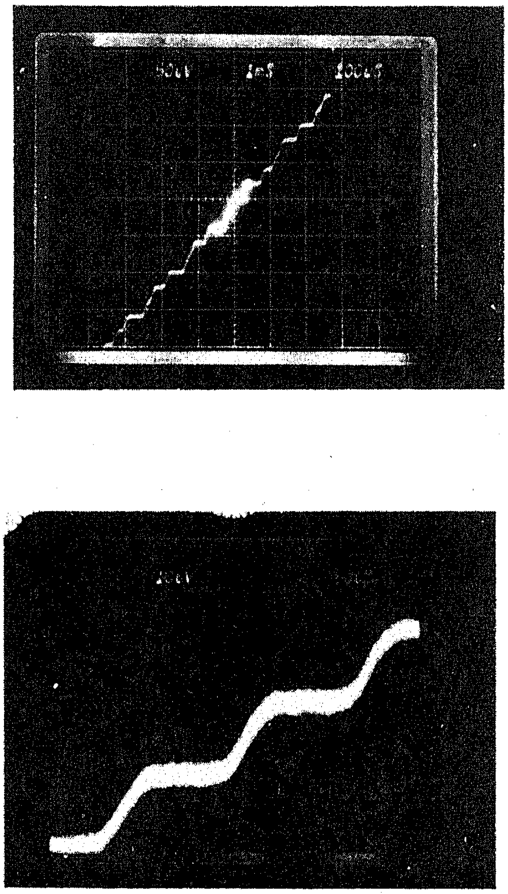

Figure 7. Oscilloscopic display of microwave induced steps at 1·02 mV level. X-axis represents current and Y-axis represents voltage.

resistances of one ohm each are connected in parallel to generate 0·1 ohm and ten standard resistances of 10 ohms each are connected in series to generate 100 ohms. The two sets of resistances connected in series, are kept inside a temperature-regulated oil bath (temperature stability ± 0·001°C). The resistance ratio R_2/R_1 is accurately measured just before and after the experiment using a d.c. comparator resistance bridge.

The current in the divider is supplied by a battery-powered constant current source which exhibits a short term stability of better than 0·1 ppm, and it is also manually adjusted between different operations. The null detector G_2 in the standard cell circuit has a sensitivity of 0·1 μV/div while the null detector, G_1, in the Josephson voltage circuit is a photocell galvanometer amplifier having a sensitivity of 0·2 nV/div.

The thermal-emf in the Josephson voltage circuit is cancelled by a small emf generated across a resistor of one milliohm as shown in figure 2. It is done by switching the divider current, I, from R_1 to R'_1 ($\sim R_1$) so that the load on the current source remains unchanged. The microwave signal to the junction is switched off and the junction is biased at the zero voltage step. The emf across the one milliohm resistor is adjusted to bring the reading of the galvanometer G_1 to zero, thus cancelling most of the thermal emf. However, there is a small drift in the thermal emf in the Josephson circuit. This drift is linear in time during the short duration ($\sim$ 3 to 4 minutes) of measurement and is compensated by correcting the junction unbalance by linear interpolation. The value of this correction is of the order of 2 nanovolts.

4.5 *Biasing circuit for oscilloscopic display of junction's I-V characteristic*

An electronic circuit has been developed to display I-V characteristic of the junction on the screen of an ordinary oscilloscope. Display of junction's characteristic helps in quickly optimizing the contact pressure and the microwave power to obtain large amplitude steps at 1 mV level. The circuit also has the capability of displaying any small portion of the characteristic on the screen which helps in locating the desired step and in seeing its quality.

The circuit essentially consists of three parts (i) an oscillator which generates the saw tooth signal, (ii) an arrangement by which the signal can be fed to the X and Y axes of the oscilloscope via the Josephson junction and (iii) a d.c. amplifier which can amplify the voltage which is fed to the Y axis of the oscilloscope to either 1000 times or 5000 times with the help of a selector switch, thus making the sensitivity of the oscilloscope either 50 μV/cm or 10 μV/cm. Provision is also made in the circuit to apply only d.c. to the oscilloscope and reach upto the desired d.c. voltage level and then sweep at that voltage. Thus the details of a small portion of the characteristic at 1 mV level can be seen as shown in figure 7.

4.6 *As-maintained volt at NPL*

The as-maintained volt at NPL is based on a bank of standard cadmium cells maintained in a constant temperature air enclosure (temperature stability ± 0·005°C). Through a recent intercomparison with Australia using a transportable standard cells and Zener-based electronic voltage standard as travelling standards, it has been found that the as-maintained volt of Australia and India agrees to 0·5 μV.

5. Results of a recent intercomparison of the as-maintained volt with the Josephson voltage standard

At the NPL, the d.c. electrical standards laboratory where a bank of standard cells are maintained as a physical standard to represent the volt is about 100 m away from the low temperature laboratory where the Josephson voltage standard is set up. Hence a direct intercomparison is not feasible. Instead, a transfer standard consisting of a bank of four standard cells in a constant temperature air enclosure of temperature stability of ±0·005°C is used to intercompare the two. The cells of the transfer standard are assigned values by intercomparison against the as-maintained volt as well as against the Josephson voltage standard. The intercomparison is carried out using the standard potentiometric technique having a resolution of 0·1 μV, while against the Josephson voltage it is done using the voltage divider described above. A cumulative Josephson step voltage of the order of 1 mV is generated by biasing the junction on the 50th step. The results are given in table 1. Estimated uncertainties are given in table 2.

Table 1. Intercomparison of the as-maintained volt with the Josephson voltage standard.

Value assigned to the standard cells against as-maintained volt (volt)	Value assigned to the standard cells against Josephson volt (volt)	Difference between two values (μV)
1·0181908	1·0181904	0·4
1·0181908	1·0181905	0·3
1·0181905	1·0181903	0·2
1·0181712	1·0181702	1·0
	Mean difference	0·5

Table 2. Estimated uncertainties in the assignment of value to the transfer standard cells.

(a)	Assignment of the value against the Josephson voltage	
(i)	Uncertainty in the balance of step voltage against the resistor R_1 which takes into account many contributions including thermal emf	0·8 ppm
(ii)	Uncertainty in the divider ratio	0·4 ppm
(iii)	Uncertainty in the microwave frequency	0·001 ppm
(iv)	Uncertainty in the galvanometer (G_1) reading	0·1 ppm
	Total R S S uncertainty	0·90 ppm
(b)	Assignment of value against the as-maintained volt	
(i)	Uncertainty due to temperature variations of the cells (56 μV/K)	0·28 ppm
(ii)	Random uncertainty in calibration	0·15 ppm
	Total R S S uncertainty	0·32 ppm

6. Conclusions and discussion

The d.c. voltage standard based on the a.c. Josephson effect using a Nb-Nb point contact junction at 1 mV level is in operation at NPL and is periodically used to check the emf of the standard cells of the as-maintained volt. The Josephson voltage at the 50th step is used to assign value to the cells of a transfer standard consisting of four Weston standard cells in a temperature regulated air enclosure (temperature stability $\pm 0{\cdot}005°C$). The same cell is also assigned a value by intercomparison against the as-maintained volt. The two values are found to agree within an overall uncertainty of about 1 ppm.

The main source of uncertainty in the present Josephson set-up is in the null detection at 1 mV level. Even a small drift of 1 nV in thermal emf in the potential leads of the Josephson circuit introduces an uncertainty of 1 ppm. The drift in the thermal emf in the potential leads is due to (i) change in the room temperature, and (ii) change in temperature distribution along the potential leads inside the liquid helium dewar. It is, therefore, desirable to generate a larger cumulative Josephson step voltage to lower the uncertainty in null detection. If the step voltage is raised to 10 mV level, a drift of 1 nV would lower the uncertainty in null detection by an order of magnitude, from 1 ppm to 0·1 ppm. Furthermore, in this situation one would need a resistive divider ratio of 100:1 rather than 1000:1. One may, therefore, use commercially available series-parallel type of Hamon resistors to make a divider of 100:1 ratio. The ratio of commercially available Hamon resistors is known with an uncertainty of 0·01 ppm, in contrast to 0·4 ppm of uncertainty prevailing in the existing resistive divider. Thus by increasing the cumulative Josephson step voltage to 10 mV, the two major sources of uncertainties, viz, null detection and calibration of the divider ratio, would be considerably reduced. Work is in progress to develop an array of tunnel junctions to achieve it (Gupta *et al* 1986).

Shifting of the transfer standard from the Josephson voltage standard laboratory to the d.c. electrical standard laboratory, which is required in the present method of intercomparison is also a source of uncertainty. Although sufficient time (about 1 week) was given to the transfer standard cells to recover after each shifting it is estimated that an uncertainty of the order of 1 ppm is introduced. It is, therefore, desirable to keep the as-maintained volt near the Josephson voltage standard so that the shifting of transfer standard is not required. One may even have a direct intercomparison between the cells of the as-maintained volt and the Josephson voltage.

An alternative approach followed by some laboratories (Harvey 1976; Kose 1976; Hartland 1977) to enhance the accuracy is to use a cryogenic resistive divider along with a SQUID as a null detector and to use superconducting current comparator (Harvey 1972) to determine the resistance ratio. Thus the entire low voltage circuit containing the Josephson junction, the resistive divider and the SQUID null detector can be in a common liquid helium bath and the uncertainties due to thermal emf's are completely eliminated.

It has recently been shown that it is possible to obtain steps in the 1 volt region from large series arrays of Josephson tunnel junctions (Niemeyer *et al* 1984a, b, 1985; Hamilton *et al* 1985). The arrays are part of an integrated microwave circuit and are driven in the zero crossing step mode (Levinsen *et al* 1977). Thus a direct intercomparison, without using a voltage divider, is feasible and the uncertainty in the intercomparison of the order of a few parts in 10^{10} can be achieved.

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