A Precise Null-Balancing Technique (PNB) for the 10 V Josephson Junction Array Voltage Standard System

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***Abstract*— A precise null-balancing technique, which we call the PNB technique, has been developed for the 10 V Josephson-junction-array voltage standard system (10 V JJAVS) in order to improve the accuracy in null detection. Precision is achieved by 1) precisely capturing the desired Josephson step within ±3 step by using a newly developed mercury reed-relay switch, 2) adjusting the millimeter-wave frequency to attain strict null-balancing, and 3) using a stable chopper-type of digital voltmeter (DVM) as a null detector. This PNB technique was successfully applied to a 10 V JJAVS attaining a total uncertainty of 6×10^{-9} and reducing the calibration time to 20 min to 30 min.**

I. INTRODUCTION

PRACTICAL applications of the 10 V Josephson Junction Array Voltage Standard System (JJAVS) require 1) a millimeter-wave source, 2) a Josephson-junction-array (JJA), and 3) a precise null-balancing detection between the Josephson voltage as a reference and the voltage to be calibrated. Although a millimeter-wave source [1] and JJA [2]–[4] have already been developed successfully, precise null-balancing has remained a problem due to the difficulty in capturing the desired Josephson step. For example, the Josephson step number n must be either 51 446 or 51 447 to calibrate 10 V directly by the AC Josephson effect with an irradiating millimeter-wave frequency at 94 GHz. Unfortunately, such a high step number may not be stable due to noise in the instruments and from outside sources, such as noise coming via air-path and power lines. The reason for the difficulty is that the current amplitude of the Josephson steps obeys the Bessel function, and thus the current amplitude decreases to 10 μA to 20 μA at step numbers above 50 000 as shown in Fig. 3(c) in [4]. Inaccurate capture of the step number by conventional technique may cause a few millivolts difference between the voltage to be calibrated and the Josephson step as a reference voltage. This difference prevents precise null-balancing. If a DVM is used as a null detector, then the voltage reading includes errors from the DVM, such as those due to offset, nonlinearity, stability, and resolution. The offset-error of a direct-type, eight-digit DVM (Model R6581, Advantest) between -6 mV to $+6$ mV in the 100 mV range is shown in Fig. 1, and dc scatter is shown in Fig. 6(a). As shown in Fig. 1, the measured offset-error contains scattering and undulation. Although the offset-error can be cancelled roughly by the polarity reversing technique, it is not easy to cancel perfectly when the offset-error contains such scattering and undulation. To improve the precision in the null-balancing, we developed a technique that precisely captures the desired Josephson step and minimizes the errors in the voltage-difference reading by adjusting the millimeter-wave frequency and by using a stable chopper-type of DVM as a null detector. This paper supplements the null detection method of the newly developed 10 V JJAVS at the ETL [7].

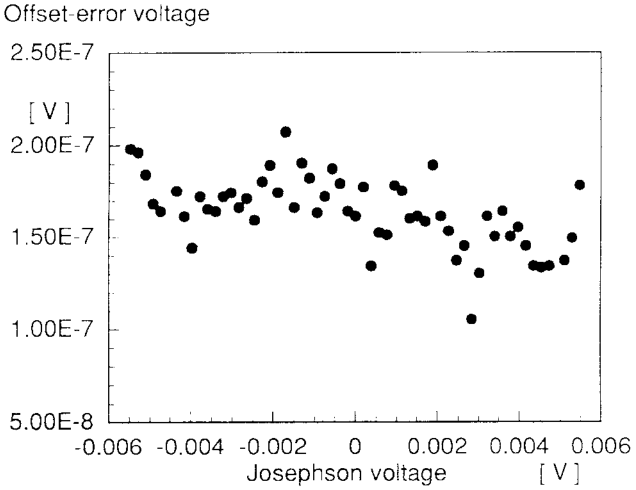

Fig. 1. Offset error voltage of the direct-type DVM R6581 between -6 mV to $+6$ mV in 100 mV range.

II. THE PNB TECHNIQUE

A. Accurate Capture of the Desired Josephson Step

The primary function of the PNB technique is to capture the desired Josephson step. A stabilized bias circuit is used to select the desired step number. If an ordinary reed-relay switch is used to remove the bias circuit, step transitions may occasionally occur due to chattering or higher harmonics of the driving pulse in this switch. Therefore, we used a special mercury reed-relay switch in which chattering is eliminated by a single-action separation due to mercury viscosity, and it also has a guard mechanism that reduces the noise to the signal line. Table I shows the specifications and Fig. 2 shows a schematic of this switch. This switch is the key in capturing the desired Josephson step within ±1 step in a noise-shielded room, at least ±3 steps in manufacturing environments. Fig. 3 shows this capture at 10 V by the mercury reed-relay switch from a large number of Josephson steps around 10 V.

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TABLE I
TYPICAL SPECIFICATION OF THE NEWLY DEVELOPED MERCURY REED-RELAY SWITCH

Driving voltage	--- 12 V DC
Driving current	--- 40 mA
Max. Contact voltage	--- 500 V DC
Max. Contact current	--- 2 A
Switching (rise) time	--- 2.5 m sec.
Recovery time	---1.5 m sec.
Max. driving frequency	---150 Hz
Initial contact resistance	---100 m Ω
Isolation resistance	
Contact to contact	---1x10E12 Ω
Contact to other lead	---1x10E12 Ω
Driving wire resistance	---300 Ω

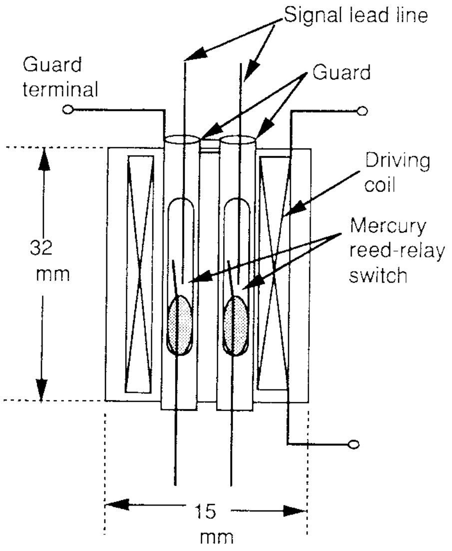


Fig. 2. Mercury reed-relay switch with guard shielding and high isolation-resistance.

Once the desired Josephson step is captured, a noise filter is required to prevent step transitions of this step caused by electromagnetic noise coming from instrumentation such as the DVM, and also coming via air-path and power-line. For this purpose, we use a signal-line noise filter and a power-line noise filter. A signal-line filter consists of a normal-mode filter for high ($f_c = 5$ kHz) and low ($f_c = 1$ kHz) frequencies, and a common-mode filter in series as shown in Fig. 4. In noisy environments, such as manufacturing facilities, noise introduced by power lines must be reduced. We therefore also inserted a power-line noise filter, PIX-1000C (Tamura Co., Ltd.), to specifically reduce common-mode noise that is higher than 80 dB ranging from 10 Hz to 10 kHz.

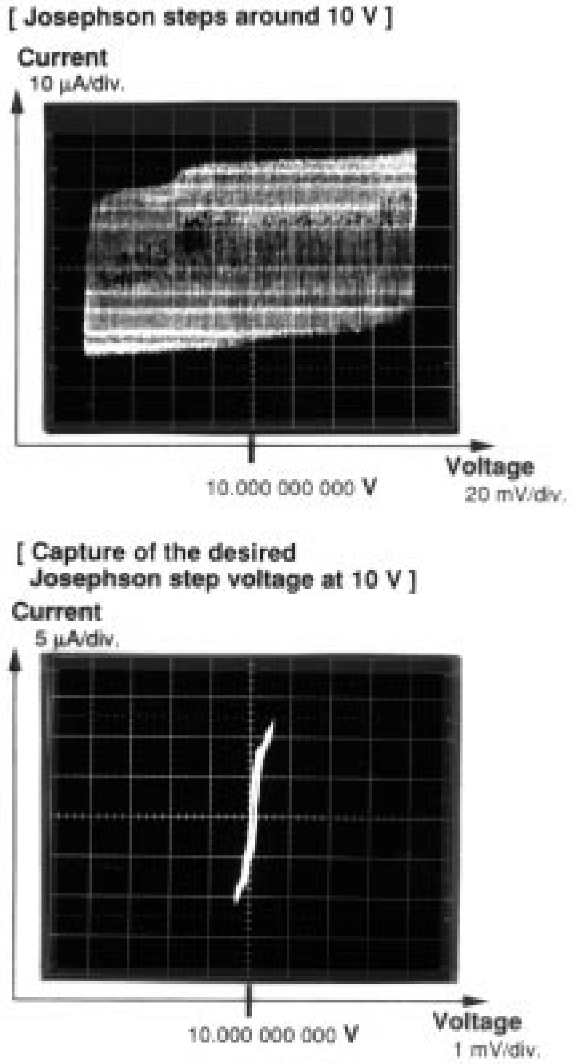


Fig. 3. Capture of the desired Josephson step voltage at 10 V.

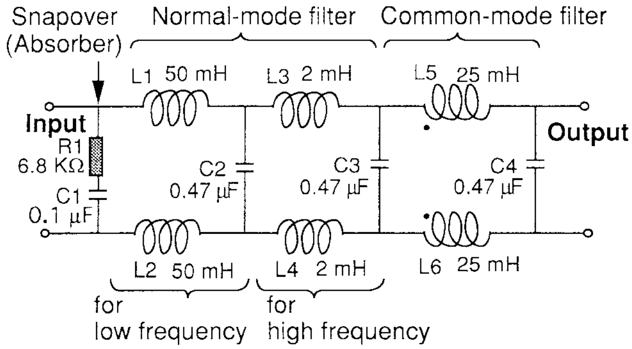


Fig. 4. Noise filter composed of a normal-mode (high and low frequencies) and a common-mode filter for the signal line of a 10 V JJAVS.

B. Precise Null-Balancing by Adjusting the Frequency of the Millimeter-Wave Source

When the nearest Josephson step for the voltage to be calibrated is captured within ±1 step, the maximum voltage difference is 194 μV for an irradiating frequency of 94 GHz. Frequency stability of the phase-locked millimeter-wave source is better than 1×10^{-10} [1]. For precise null-balancing, this voltage difference should be minimized. This is achieved by adjusting the millimeter-wave frequency. In the PNB technique, this adjustment is achieved by reading the voltage difference ΔV of a DVM as a null detector, then calculating the adjustment frequency Δf corresponding to the voltage difference by using the basic Josephson voltage-

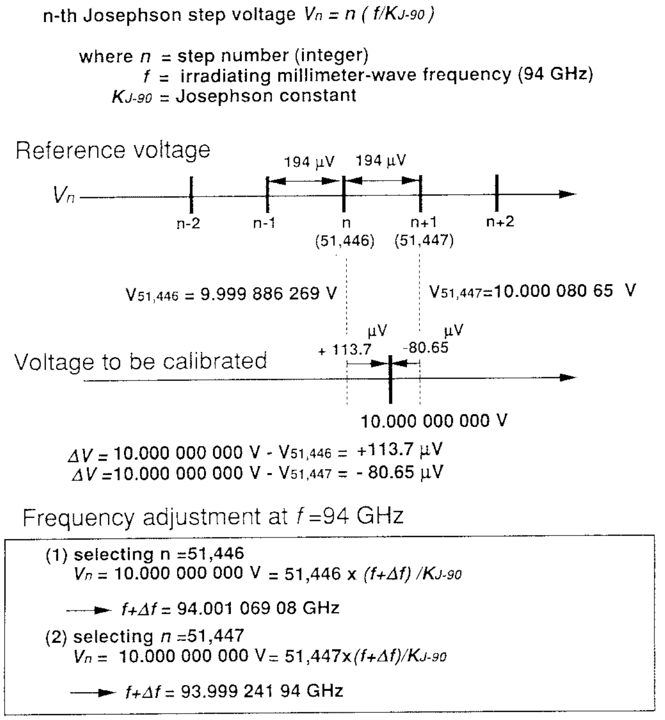


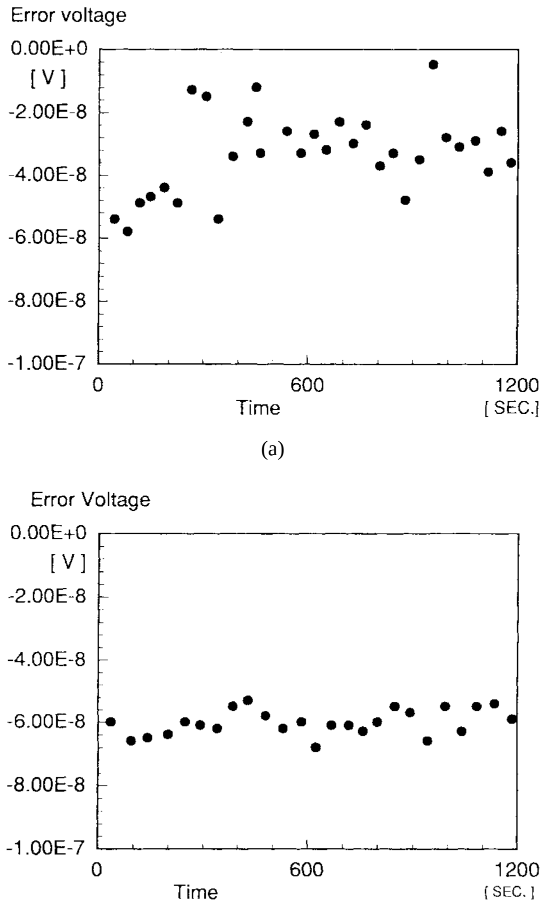
Fig. 5. Null-balancing by adjusting the millimeter-wave frequency. Once the desired Josephson step voltage is caught, the difference voltage between reference and voltage to be calibrated is balanced better than 0.5 μV by using frequency adjustment.

frequency relationship $\Delta f = \Delta V K_{\mathrm{J-90}}$, where $K_{\mathrm{J-90}}$ is the Josephson constant. To minimize the voltage difference, this calculated frequency is fed back to the millimeter-wave source-lock counter EIP-578B by using the same method as described in Section II-B in [5] via a frequency synthesizer, HP 3325A, as shown in the example in Fig. 4. The null-balance voltage is thus reduced to within ± 0.5 μV, because the fluctuation of the 10 V output voltage of the precise Zener voltage standard, Fluke 732A, to be calibrated is almost 0.5 μV as shown in Fig. 2 in [7].

C. Selecting an Appropriate DVM for a Null Detector

When the voltage difference between the selected Josephson step voltage and the voltage to be calibrated is balanced to within 0.5 μV, the nonlinearity error of a DVM as the null detector becomes relatively small. Therefore, dc stability is a significant part of the overall error in the null detection. Although linear drift in the offset voltage can be removed by a polarity-reversing procedure, random scatter in the dc stability remains as an error.

To select the most appropriate DVM as the null detector, we checked the dc stability for two types of DVM's, a direct amplifier-type, 8-digit DVM (Model R6581, Advantest) which has a 10×10^{-9} V resolution in the 100 mV range and a chopper-type, 6 1/2 digit DVM (Model R6561, Advantest) which has a 10×10^{-9} V resolution in the 1 mV range. Fig. 6(a) and (b) show a comparison of the zero-stability and the nonlinearity error, respectively, for the two DVM's. To check the internal drift, the zero-stability data were taken by reading the value of the DVM with a shorted input terminal. As shown in Fig. 6(a) and (b), the chopper-type DVM is clearly more stable than the direct amplifier-type DVM, because the chopper mechanism reduces drift in the analog circuit of the DVM by synchronous detection. Observed stability of the chopper-type DVM is 2×10^{-8} $\mathrm{V_{p\text{-}p}}$. The same comparison between a direct-type DVM (Model 3458A, HP) and the R6561 again showed the chopper-type DVM to be superior [6]. When the chopper-type DVM is used as a null detector, scattering and drifting error in the DVM becomes negligible.



(a)

(b)

Fig. 6. (a) Zero-stability of the direct-type DVM R6581 and (b) zero-stability of the chopper-type DVM R6561.

III. APPLICATION OF THE PNB TECHNIQUE TO 10 V JJAVS

During the course of developing 10 V JJAVS at the ETL, we reported that we were troubled with frequent step transitions of the JJA, and tentative uncertainty of the calibration for the 10 V output of the Zener standard was about 3×10^{-8} as described in [8] in 1995. After developing PNB, we applied our PNB technique to the 10 V JJAVS. Details of the results and estimated uncertainty are described briefly in [7] where the total rss uncertainty is improved up to 6×10^{-9} and one calibration run (three measurement sequences of $+, -, -$, and $+$ polarities) takes typically 20 min to 30 min. For reference, the agreement for calibration results on the same 10 V output of a Zener voltage standard between the new 10 V JJAVS and 10 V measurement system composed of a 1 V JJA and a 10:1 divider is better than 2×10^{-8} [7]. The 10 V measurement system has been carried out daily calibrations at the ETL, and it takes 28 h for one calibration.

IV. CONCLUSION

A technique was developed for use with a 10 V Josephson junction array voltage standard system (JJAVS) in which precise null-balancing is achieved by accurately capturing the Josephson step, adjusting the frequency of the millimeter-wave source, and using a stable chopper-type of DVM as a null detector. This technique achieved a total uncertainty of 6×10^{-9}, and reduced the calibration time to 20 min to 30 min.

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