A COMPACT TRANSPORTABLE JOSEPHSON VOLTAGE STANDARD*

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Abstract

The development of a compact, portable 10 V Josephson calibration system is described. Its accuracy is the same as typical laboratory systems and its weight and volume are reduced by more than a factor of three. The new system will replace travelling voltage standards used within several NASA and DOE standards laboratories.

Introduction

A new Josephson Voltage Standard (JVS), with a weight and volume of only 21 kg and 0.03 m³, has been developed. The system is highly automated and is designed to be operated by technicians without higher level support. In contrast to typical laboratory systems that are semipermanent installations, the new system is easily shipped in two custom shipping containers and can be set up in less than an hour. The first prototype will be cooled by liquid helium with a 100 liter Dewar that will be sufficient to operate the Josephson array for six to eight weeks. The final version is designed to be cooled with a compact portable 4-K refrigeration system currently under development.

System Design

As shown in Fig.1, the system has three components: (1) a notebook computer, (2) an electronics package in a single 13-cm high rack-width box, and (3) a cryoprobe adaptable to fit in a wide variety of Dewars. In addition, two solid-state voltage standards, used as check standards, travel with the system. Figure 2 is a functional diagram of the system. A notebook computer controls the system through the parallel port. A commercially available IEEE interface splits the parallel port into both a printer port and an IEEE port. The IEEE port controls a low thermal scanner, external instruments

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such as digital voltmeters under test and an internal DVM module that was especially developed for the compact JVS. The DVM module includes two fixed range, 7-digit meters (10 V and 10 mV) and a serial output data port. The 10 V meter uses a 7-channel relay multiplexer to monitor and record the system environment (temperature, humidity, and atmospheric pressure) as well as to make diagnostic measurements on the Josephson array and its bias system. The internal temperature of the electronics package is monitored and stabilized by a variable speed fan. The 10 mV meter has a noise level of 18 nV in a 1 Hz bandwidth and is used as the null meter for measurements of dc reference standards. The serial data port provides the digital codes to control the multiplexer, system control relays, a 16-bit digital to analog converter (DAC), and the microwave attenuator servo. The five system control relays provide the following functions: (1) Bias current to the Josephson array is selected to be either a manual, variable-impedance dc offset and sweep generator, or the output of a 16-bit DAC. (2) A 10 k Ω resistor can be substituted in place of the array in order to provide self-calibration of the bias current and to disconnect the bias circuit from the array during null measurements. (3) An open circuit can be substituted for the array to provide self calibration of the bias voltage. (4) A 120 V ac outlet can be switched on and off so that dc standards under test may be automatically put on battery power during measurements. (5) The 77 GHz Gunn oscillator can be switched on and off.

Cryoprobe and Microwave Source

The cryoprobe for the new system, shown at the right side of Fig. 2, differs from previous designs [1] in two respects: First, the 77 GHz source and RFI filters in the array bias and potential leads are all enclosed within several different compartments of a single rf-tight box at the top of the cryoprobe. Since this source is fixed frequency and the attenuator is servo controlled, there are no user adjustments on the microwave system. Second, microwave power is delivered to the Josephson array through a rigid dielectric waveguide constructed from a 25 mm dia. Teflon tube with a rectangular 2 x 4 mm solid Teflon core as shown in Fig. 4. The core is centered in the tube by eight Teflon membrane spacers. The ends of the core are tapered at 15° and pushed into WR-12 horns attached to each end of the outer Teflon tube. Typical attenuation of this 1.25 m long waveguide is 2.2 dB at 75 GHz. The six bias and potential leads are enclosed in two 1-mm diameter stainless-steel tubes enclosed within the waveguide tube. This dielectric waveguide design is more economical than commercial flexible dielectric waveguides and it is easily disassembled for modification or repair. Since condensation on the core causes a substantial increase in attenuation, care must be taken to keep the waveguide sealed and slightly over pressurized with dry helium gas from the liquid helium Dewar.

The microwave source is a fixed frequency, 77 GHz, phase locked oscillator (PLO). A block diagram of the PLO is shown in Fig. 3a. Its 10 MHz reference frequency comes from either a high stability internal quartz crystal oscillator or (preferably) a 10 MHz frequency standard derived from a rubidium clock or a GPS receiver. The local oscillator at 7.690 GHz is phase locked to the 10 MHz reference frequency. The 77 GHz Gunn oscillator output is mixed with the tenth harmonic of the local oscillator to generate an IF at 100 MHz. The phase difference between the IF and the tenth harmonic of the reference frequency is the error signal that is used to bias tune the Gunn oscillator and establish the phase lock. The wide bandwidth of the phase lock loop in this system results in a phase noise of -55 dBc at a 2 KHz offset from the carrier. This is three orders of magnitude improvement over the phase noise that is achieved with the microwave counters used to stabilize the frequency in typical Josephson voltage standard systems. Figure 3b compares the spectral line width of our system and a typical microwave counter stabilized source. The 77 GHz power is controlled by a servo driven vane attenuator.

Software

Software for the system has the same calibration and data display algorithms used in the program NISTVolt version 5.0 [2] and is based on the circuit in Fig. 5. Here, $V_a = nf/K_j$ is the Josephson array voltage, V_z is the best estimate of the unknown reference voltage, V_o is a combination of thermal offset voltages and any offset voltage in the null meter, mt represents a linear drift component of the offset voltage, $P = +1$ is the polarity of the reversing switch, V_e is an initial direct measurement of V_z by the system 10-V meter, V_{null} is the null voltage measured by the system 10-mV meter and V_{noise} represents noise in the unknown, the null meter, and any other random noise contributions. The circuit equation can be written:

$$V_a - V_{null} = nf/K_j - V_{null} = PV_z - V_o - mT - V_{noise}.$$

Based on measurements of V_e and V_{null} a set of 12 values of V_i and T_i is accumulated:

$$V_i = nf/K_j - V_{null} \quad i = 1 \text{ to } 12$$

T_i = the elapsed time at which V_{null} is measured.

$P_i = +1$ = initial polarity of reversing switch.

The integer n is determined from V_{null} and the initial measurement V_e :

$$n = \text{Round}\{ (K_j/f) (V_e + V_{null}) \},$$

and the "Round" function means rounded to the nearest integer. For each of the 12 data points, 3 successive values of V_{null} are examined for consistency within $2 \mu\text{V}$ before the data are accepted. This eliminates data that may be corrupted by the transient that occurs when there is a spontaneous transition between quantum voltage steps. Since V_a and V_{null} change by equal amounts during a step transition, V_i remains constant thus making the data collection process relatively immune to step transitions. Data are collected efficiently even for a Josephson array chip that may be making as many as 5 transitions per minute. The scatter in the data that results from noise in the unknown and in the null meter can generally be modeled by a Gaussian process with one sigma on the order of 20-100 nV. There are however occasional noise spikes that do not fit this process and generate glitches in the V_i data that may lie 1-10 μV away from the well behaved data. For this reason, the set of 12 points is reduced to 10 points by eliminating the two points furthest from the mean.

After the collection of the first data set, the polarity of the unknown is reversed ($P_i = -1$) and a second set of data is accumulated for $i = 11$ to 20. Two more reversals generate data for $P_i = +1$, $i = 21$ to 30, and $P_i = -1$, $i = 31$ -40. The change from a $+-+$ reversal sequence to a $+-+$ sequence in this version of NISTVolt reduces some potential uncertainty resulting from an asymmetric influence of dielectric absorption and noise averaging.

The 40 data points are used in a 3 parameter least squares fit to obtain best estimates of V_z , V_o , and m . The matrix equation for the best estimate values is:

$$\begin{bmatrix} N & 0 & \sum P_i T_i \\ 0 & N & \sum T_i \\ \sum P_i T_i & \sum T_i & \sum T_i^2 \end{bmatrix} \begin{bmatrix} V_z \\ V_0 \\ m \end{bmatrix} = \begin{bmatrix} \sum P_i V_i \\ \sum V_i \\ \sum V_i T_i \end{bmatrix}$$

The Type A uncertainty for V_z is computed as the standard deviation of the mean for the set

$$V_i - P_i V_z - V_0 - m T_i \quad i = 1 \text{ to } 40.$$

Type B uncertainty includes components from the reference frequency, the null meter gain, leakage currents, and uncompensated offset voltages and is computed according to previously published guidelines [3].

The value of V_z computed above contains information about the unknown reference voltage for only the relatively short time required to obtain the 40 data points (typically 5 minutes). The single measurement uncertainty is therefore not very relevant to the long term behavior of the unknown and serves more as an indicator of system performance. A reliable measurement of a Zener reference requires the analysis of many measurements made over a period of a week or more.

An internal simulator has been used to test the response of the calibration algorithm to a variety of nonideal behavior including thermal offsets and drifts, null meter gain, offset, and drift errors, step transitions, Gaussian noise, 1/f noise, outlying null measurements, etc.

There are manual bias controls for diagnostic purposes but in the normal operating mode the manual bias controls are disabled and there are no user adjustable controls. The system software includes control of all system parameters as well as complete self-calibration and self-diagnosis. For example, to calibrate the microwave subsystem, a microwave power meter is substituted for the array. The system then automatically measures the 77 GHz power while driving the attenuator through its full range. A table of power vs. attenuator position is automatically recorded and used in all subsequent power adjustments. A self test function in the main menu provides a quantitative measurement of important system parameters including environmental conditions, bias system calibration, thermal offsets, and array critical current, leakage, and stability. Parameters that fall outside the acceptable range are flagged. Over 50 pages of help documentation are available on-line and can be easily searched for any word or phrase.

A prototype system has been constructed and will be shipped between NIST in Boulder, Colorado and Sandia National Laboratories in Albuquerque, New Mexico where its capabilities will be further evaluated against 10-V laboratory Josephson array standards. It will then be shipped to selected NASA and DOE laboratories for field testing. The final version of the NASA and the DOE systems will be delivered in 1997.

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Figure Captions

Figure 1. The physical layout of the Josephson voltage standard.

Figure 2. A block diagram of the portable JVS.

Figure 3. (a) A block diagram of the 77 GHz phased locked oscillator and (b) a comparison of its line width (narrow spike) with the line width of a typical counter stabilized Gunn oscillator (broad peak).

Figure 4. A cross-sectional drawing showing the construction of the rigid dielectric waveguide used to transmit 77 GHz power into the liquid helium Dewar.

Figure 5. The circuit used to compare the Josephson array and an unknown dc standard.

References

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PORTABLE JOSEPHSON VOLTAGE STANDARD