Direct DC Voltages Comparison between two Programmable Josephson Voltage Standards at SCL

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***Abstract* — Standards and Calibration Laboratory (SCL) setup in 2018 a liquid helium based programmable Josephson voltage standard (PJVS) developed by the National Institute of Standards and Technology (NIST). The system was validated by direct comparison with a NIST transportable PJVS system at 1.018 V, 4 V, 6 V, 8 V and 10 V. The difference between the systems was within 0.5 nV, with an expanded uncertainty of less than 2.2 nV (*k* = 2). In this paper, the setup and the results of the direct comparison method are presented.**

***Index Terms* — Programmable Josephson voltage standard, quantum voltage measurement, measurement uncertainty, Josephson voltage comparison.**

I. INTRODUCTION

In 1993, the Standards and Calibration Laboratory established the 1 V conventional Josephson array voltage standard (CJVS) as the primary standard of DC voltage for Hong Kong. Then the system was upgraded to 10 V in 1995. This conventional system was designed based on the National Institute of Standards and Technology (NIST) design. The system operates through a computer control interface “NISTVOLT” developed by NIST. The microwave signal was generated by a Gunn-diode oscillator at a frequency around 75 GHz. The SCL maintains 10 V Josephson array chips developed by both NIST and Physikalisch-Technische Bundesanstalt (PTB). The array chip was cooled by liquid helium stored in a 100 liter dewar.

The recent evolution of quantum voltage standard technology, namely the programmable Josephson voltage standard (PJVS), enables the generation of both dc voltage and stepwise approximated ac voltages for frequency up to around 1 kHz [1 – 2]. The PJVS system developed by NIST can produce intrinsically stable DC voltages up to 10 V at a microwave driving frequency of about 18-20 GHz.

In 2018, the SCL setup a new PJVS to upgrade the 25-year-old CJVS system. The performance of this SCL PJVS system was validated by direct comparison with a NIST transportable PJVS system, as shown in Fig. 1, and by indirect comparison with the in-service SCL CJVS system through the use of a set of Zener voltage standards.

Fig. 1. Direct comparison between NIST transportable PJVS (left) and SCL PJVS (right)

II. PJVS COMPARISON SETUP

A. SCL PJVS system

The SCL PJVS system is a liquid-helium-based system developed by NIST. The PJVS array has 23 subarrays ranging in size from 6 junctions up to 16 800 junctions. The total number of junctions with all subarrays in series is 248 312, such that the entire circuit is capable of generating 10 V with a driving frequency of approximately 20 GHz. The PJVS array bias electronics is a 24-channel current source that employ 16-bit DACs to supplies bias currents to the 23 subarrays. A microwave signal generator and a microwave power amplifier were installed to supply driving frequencies in the range of (18 – 20) GHz with sufficient power to drive all the subarrays. A digital nano-voltmeter was used as a null detector on its 1 mV range. The measurement range of the null detector was fixed to minimize noise and to avoid the change in gain when different ranges are used. The system operation is controlled by a NIST program.

B. NIST Transportable PJVS System

The NIST transportable PJVS system is similar in fundamental design and operation to the SCL PJVS system; however, the system has been implemented with a compact RF source and installed in rack cases for easy palletization and shipment. The system additionally has a frequency-to-voltage converter that enables easy operation from power supplied at any common line voltage and frequency without reconfiguration.

C. Measurement configuration at SCL

The measurement was conducted on site at the direct current laboratory of the SCL at Wan Chai, Hong Kong, China from March 12 to March 16, 2018. During the measurement, the frequency sources of both PJVS systems were locked to the same 10 MHz signal supplied by the RF laboratory of the SCL, which is traceable to the laboratory's cesium-beam frequency standards and is compared routinely with the BIPM through GPS common view comparison.

Various grounding conditions were tested prior to the start of comparisons. Both systems were connected to the same power outlet and grounded at a single point. Both systems were then verified to be stable during the course of measurement through the use of hourly quantum locking range [3] checks.

III. MEASUREMENT RESULTS

A. Direct comparison results

Automated measurement was performed by the NIST program in the following order: 10 V, 1.018 V, 4 V, 6 V, 8 V and 0 V. At least 200 polarity pairs of measurement data were collected at each test voltage. The measured difference between the two PJVS systems and their expanded uncertainty at different test voltages are tabulated at Table I. Overall, the difference between the two systems was within 0.5 nV, with an expanded uncertainty of within 2.2 nV ($k = 2$).

TABLE I. MEASURED VOLTAGE DIFFERENCES

Test Voltage	Mean difference between PJVS systems	Expanded Uncertainty ($k = 2$)
10 V	0.2 nV	2.2 nV
8 V	0.2 nV	2.0 nV
6 V	0.4 nV	1.9 nV
4 V	0.3 nV	1.8 nV
1.018 V	-0.5 nV	1.8 nV

The uncertainty budget was intended to be conservative for this comparison and was composed of eight parameters with the three largest contributors being the digital null meter noise (0.8 nV), frequency sources (0.7 nV) and the null meter non-linearity (0.6 nV). In some direct JVS comparisons, through the use of a common 10 MHz signal and similar RF synthesizers, the frequency uncertainty is removed from the budget. However, for this comparison the sources were of different design and it was chosen to include the values.

B. Leakage resistance to ground measurement

For improved precision in direct PJVS comparison, NIST custom-made polytetrafluoroethylene (PTFE) isolated cables were used between the DACs and the amplifier board, and between the cryoprobe and the amplifier board [4]. The leakage current between two precision leads to ground were measured at 10 V using the same setup for the NIST–BIPM 10 V PJVS comparison [4 - 5]. The resulting leakage current to ground of the SCL PJVS system at 10 V is tabulated in Table II. The overall leakage resistance to ground can be calculated by the sum of the measured leakage current (144 pA), as it can be assumed that the system is virtually biased at the same voltage of 10 V. The corresponding leakage resistance to ground of the SCL PJVS system was 69 GΩ, which is much better than the required leakage resistance specification of 25 GΩ.

TABLE II. MEASURED LEAKAGE CURRENT TO GROUND AT 10 V

Configuration	Leakage current to ground
(+) side to ground	105 pA
(-) side to ground	39 pA
Overall	144 pA

IV. CONCLUSION

The on-site comparison of two PJVS systems was conducted at SCL for five voltages. The overall result was a difference of 0.2 nV with an expanded uncertainty of 2.2 nV ($k = 2$) at 10 V. This comparison with a transportable PJVS system demonstrated nano-volt level uncertainties. Uncertainties were decreased through the use of low-leakage custom PTFE insulated cables.

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