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Josephson Voltage Metrology for Watt Balance Experiments at NIST

Abstract

The Planck constant, *h*, is one of the seven fundamental constants proposed to redefine the SI. It has been measured by the watt balance experiments since the 1980s. In its early days, the watt balance experiment played a vital role in determining the Josephson constant $K_{J\text{-}90}$ which was adopted internationally on January 1, 1990. The development of Josephson technology, especially the implementation of the Programmable Josephson Voltage Standard (PJVS) in voltage metrology has improved the uncertainty of voltage measurement in the watt balance experiment by more than two orders of magnitude. The Josephson voltage measurement in the watt balance experiment plays an important role in the proposed SI redefinition based on a set of fundamental constants. This paper will describe a brief history from the original NIST-1 watt balance in 1980s up to the most recent development of the NIST-4 watt balance. We will also discuss the role of voltage metrology in the watt balance experiments and the impact of the SI redefinition to the voltage metrology in the future.

Keywords: Josephson voltage standard, Planck constant, programmable Josephson voltage standard, International System of Units (SI), watt balance, uncertainty.

1. Introduction

In the mid-1980s the Josephson voltage standard became available and practical to maintain and disseminate the volt in many national metrology institutes (NMIs). However, the non-uniformity of national representations of the volt led to different values of the Josephson constant $K_J = 2e/h$ where *e* is the elementary charge and *h* is the Planck constant. In order to achieve consistency of voltage measurements around the world [1], the Consultative Committee on Electricity (CCE) of the International Bureau of Weights and Measures (BIPM) proposed a new value of the Josephson constant $K_{J\text{-}90}$ = 483 597.9 GHz/V starting from January 1, 1990. The determination of the $K_{J\text{-}90}$ value was based on ten experiments using different methods including the watt balance experiment carried out at the National Physical Laboratory (NPL), the National Institute of Standards and Technology (NIST) and other NMIs, as well as by means of the volt balance, Avogadro constant, and γ_p experiments, etc. The best uncertainty was achieved with watt balance experiments [1], so the weighted mean of the final determination for $K_{J\text{-}90}$ was attributed mostly to the watt balance experiments. The adoption of $K_{J\text{-}90}$ on–January 1, 1990 has resulted in many NMIs making adjustments to the value of their representation of the volt. The U.S. adjustment was a decrease in the volt representation of 9.264 parts in 10^6 [2].

The watt balance has played an important role in establishing uniformity of voltage metrology based on determination of the Josephson constant $K_{J\text{-}90}$. With the progress in Josephson technology, especially the invention of the programmable Josephson voltage standard (PJVS) [3], the uncertainty of the voltage measurement in watt balance experiment has improved significantly over the last decade. NIST watt balance experiments have gone through four generations from 1980s to the present. We will describe how the voltage measurement in the watt balance at NIST has contributed to the improved watt balance uncertainty and eventually will be a critical part of the SI redefinition in 2018. Currently the SI volt is represented with Josephson standards via $K_{J\text{-}90}$ but retains an uncertainty relative to the definition of the SI volt that is based on equivalence of mechanical and electrical power. Once the SI is redefined based on a set of natural constants, including the Planck constant, the volt will no longer be a derived unit as in the present SI. Rather, the volt will be directly linked to the Planck constant exactly, without the uncertainty due to its realization based on the Josephson effect.

2. Evolution of Josephson Voltage Metrology at NIST

In 1962 Brian Josephson predicted an exact correlation between the voltage generated by two superconductors separated by a thin insulator (now called a Josephson junction) and a frequency applied across the junction. This Josephson effect is represented by $V = nhf/2e$, where *V* is the voltage across the junction, *h* is the Planck constant, *f* is the frequency in the microwave range, *e* is the elementary charge and *n* is an integer [4]. In honor of the discovery by Josephson, the constant $2e/h$ is named the Josephson constant K_J. The Josephson effect was first used to measure the Josephson constant based on the SI volt references maintained in the NMIs. Because the SI volt maintained among the NMIs was different in 1970s, the Josephson constant value derived and adopted by different NMIs was slightly different.

Fig. 1 shows the timeline of Josephson technology development at NIST. In 1973, NIST (formerly the National Bureau of Standards or NBS) used Josephson junctions to generate up to 10 mV and measured the Josephson constant as 483 593.420 GHz/V_{NBS}, where V_{NBS} was the unit of voltage based on a large group of standard cells [5]. This was the beginning of Josephson technology for voltage metrology. Fig. 1 shows the milestones in the development of Josephson technology since 1973.

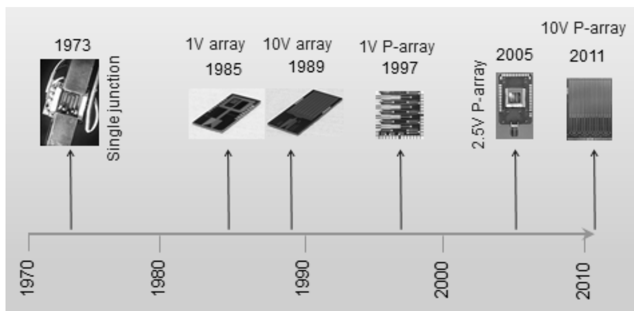

Fig. 1. Milestones of Josephson junction array development at NIST. The "array" refers to zero current bias arrays and the "P-array" refers to programmable arrays using current biased voltage steps

The practical application of the Josephson voltage standard for dissemination of the volt started in 1985, when a 1 V Josephson junction array was developed based on zero current biased voltage steps [6]. A few years later a 10 V Josephson junction array using the same principle of zero current steps was developed. The 10 V Josephson voltage standard (JVS) can be used for calibrating solid-state voltage standards and linearity measurements of digital multimeters. Although the voltage steps generated by the 1 V or 10 V Josephson voltage standard are quantized, these steps tend to "jump" to nearby steps due to electromagnetic interference (EMI) in the measurement circuit or environment. This characteristic made voltage measurements difficult in noisy environments, such as the watt balance experiments. In 1997 a new type of Josephson junction array using current biased voltage steps was developed at NIST [4]. To distinguish between the JVS's using the different bias methods, we call the zero current bias JVS the conventional JVS (CJVS) and the current biased JVS the programmable JVS

(PJVS) for its programmability. It took more than 10 years to develop programmable Josephson junction arrays from 1 V up to 10 V [7]. At present the 10 V PJVS is used in many NMIs.

JVSs have many applications in voltage metrology. The CJVS has been used to streamline the volt dissemination chain by directly comparing it with the device under test (DUT) such as solid-state voltage standard, so that the cumbersome process of many transfers from standard cell groups to the DUT can be eliminated. The uncertainty of the calibration is therefore improved by reducing the number of voltage transfers. The JVS is also used to make comparisons with other JVSs, either by using a set of transfer standards (Zeners) or by direct comparison between two JVSs. Since 1990 the International Bureau of Weights and Measures (BIPM) has carried out a series of direct JVS comparisons under the designations BIPM.EM-K10.a (1 V) and BIPM.EM-K10.b (10 V) under the framework of the mutual recognition arrangement (CIPM MRA) [8]. In North America NIST has been supporting JVS intercomparisons every 2 to 3 years since 1990 sponsored by the National Conference of Standard Laboratories International (NCSLI) [9]. In addition, there are also many regional JVS intercomparisons around the world that occur periodically. All of these activities have allowed a worldwide uniform representation of the volt with an uncertainty of few parts in 10^{10} at 10 V based on the Josephson effect, and an internationally agreed fixed numerical value for the Josephson constant $K_{J\text{-}90}$.

3. Four Generations of NIST Watt Balance

The Watt balance is an experiment to measure the Planck constant by balancing mechanical and electrical power. It has significant importance for the redefinition of the International System of Units (SI) in the near future. The principle of the watt balance was first proposed by B.P. Kibble of the National Physical laboratory (NPL) in the United Kingdom in 1975 [10]. There are many descriptions of the watt balance principle, history, and on-going experiments around the world available in the literature [11-12]. In this paper we discuss the importance of Josephson voltage metrology in the watt balance experiment and its contribution to better measurements of the Planck constant and the redefinition of the SI planned for 2018.

Beginning in the mid-1980s NIST started the first of four generations of watt balance experiments. Table 1 lists the most significant changes in each generation and the main features related to voltage measurement.

Tab. 1. Four generations of NIST watt balance

Generation	Type of magnet	Environment	Voltage reference	Purpose	Operating years
NIST-1	Electromagnet	In air	US Legal volt	Measure *h* based on US Legal volt	From 1985 to late 1980s
NIST-2	Superconducting magnet (0.1 T)	In air	Zener and CJVS	Measure *h* based on $K_{J\text{-}90}$	From late 1980s to late 1990s
NIST-3	Superconducting magnet (0.1 T)	In vacuum	PJVS-W1	Measure *h* based on $K_{J\text{-}90}$ for new SI	From late 1990s to 2013
NIST-4	Permanent SmCo magnet (0.5 T)	In vacuum	PJVS-W2	Realize mass for redefinition of new SI	From 2010 and on-going

4. Voltage Metrology in Watt Balance Experiments

In all generations of the watt balance experiment, there are two measurement modes: velocity mode and force mode. In the velocity mode, a coil is moved in a magnetic field as shown in Fig. 2, generating a voltage that is measured against a reference voltage. In the force mode, a current passing through the same coil (stationary) in the same magnetic field shown in Fig. 3, generates a force that balances the gravitational force of a known mass. The current is measured by the voltage drop across a known resistor (traceable to Quantum resistance standards via the von Klitzing constant) against the reference voltage.

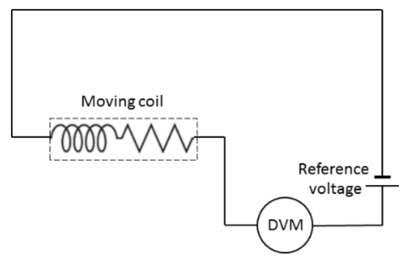

Fig. 2. Voltage measurement in velocity mode

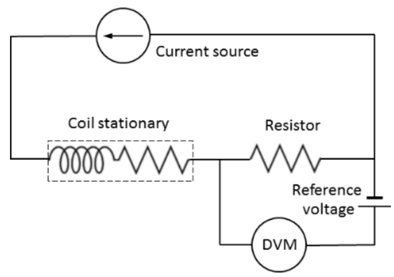

Fig. 3. Voltage measurement in force mode

Over the course of four generations of watt balances the reference voltage was changed from the US legal volt based on a group of standard cells, to solid-state voltage standards calibrated by the NIST CJVS, and most recently to the PJVS. For each step change, the reference voltage uncertainty was improved. Aside from the voltage measurements, other improvements to the watt balance experiments including better velocity measurements, better alignment, reducing buoyancy by changing the balance's operating environment from air to vacuum, and measurement of the local gravitational acceleration, all contributed to the reduction in the uncertainty of the Planck constant as listed in Table 2. This makes it clear that voltage uncertainty is important but not a dominant part of the total uncertainty.

Tab. 2. Uncertainty of voltage measurement and the Planck constant *h*

Generation	Voltage reference	Uncertainty of *h* owing to voltage measurement (nW/W)	Uncertainty of *h* owing to all other components (nW/W)	Total Combined Uncertainty of *h* (nW/W)
NIST-1	US Legal Volt	150	1321	1330
NIST-2	Zener and CJVS	30	82	87
NIST-3	PJVS-W1	1	45	45
NIST-4	PJVS-W2	1		in progress

Great improvements in the uniformity of voltage metrology were achieved after the implementation of $K_{J\text{-}90}$ around the world. It also brought direct benefit to the voltage measurements in the watt balance experiments, because the voltage reference was traceable to a CJVS. However, it was difficult to use the CJVS directly for voltage measurement in the watt balance. The coil used in the NIST watt balance has a physical radius of 31 cm, which behaved like an antenna picking up the EMI from the environment. The voltage step of a CJVS cannot be maintained at a fixed value due to EMI from the coil and other noise sources. For the NIST-2 watt balance the voltage was measured against a solid-state voltage standard (Zener) that was in turn calibrated by the CJVS. The uncertainty of the voltage measurement in this process was improved substantially from 150 nV/V for the NIST-1 to 30 nV/V for NIST-2. Further improvements to the voltage measurement uncertainty were limited by the intrinsic noise of the Zener standard.

The successful deployment of the PJVS into the NIST calibration service also brought great benefit for watt balance experiments. The superior noise immunity of the PJVS voltage step made it possible to measure voltage directly against the PJVS in both force mode and velocity mode. The PJVS was first used in the NIST-3 watt balance. A direct comparison between the PJVS for watt balance (PJVS-W1) and the PJVS for the Volt Lab (PJVS-V) was carried out in 2012 to verify the consistency of their performance at several voltages. An automatic comparison protocol was developed to acquire data using a digital nanovoltmeter as the null detector, as shown in Fig. 4. The $1/f$ noise floor of the null detector is used as the Type A uncertainty when the standard deviation of the mean of all data points becomes lower than the $1/f$ noise floor [13]. The results of the direct comparison at several voltages are listed in Table 3.

The latest watt balance, NIST-4, was constructed in preparation for the SI redefinition and the realization of mass through an exact value of the Planck constant. A new PJVS, PJVS-W2, is used for the voltage measurements in NIST-4. The difference between PJVS-W1 and PJVS-W2 is the more readily duplicated bias electronics used for PJVS-W2. The bias electronics used for PJVS-W1 of NIST-3 is custom made and powered by a group of batteries. The PJVS-W2 of NIST-4 uses commercial instrumentation, a National Instruments NI PXI-1042Q chassis with 6 PXI-6230 multifunction cards[1] along with custom-designed voltage-to-current converters to provide the bias currents to each cell on the array. In order to meet the requirement for leakage resistance of the system to ground for achieving voltage measurement uncertainty better than 1 part in 10^9, an air gap isolation transformer is used to power the PJVS-W2 PXI chassis and current bias electronics. This increased the leakage resistance of the PJVS-W2 from 48 GΩ to 120 GΩ relative to PJVS-W1 to meet the requirement for the NIST-4 watt balance experiment [14].

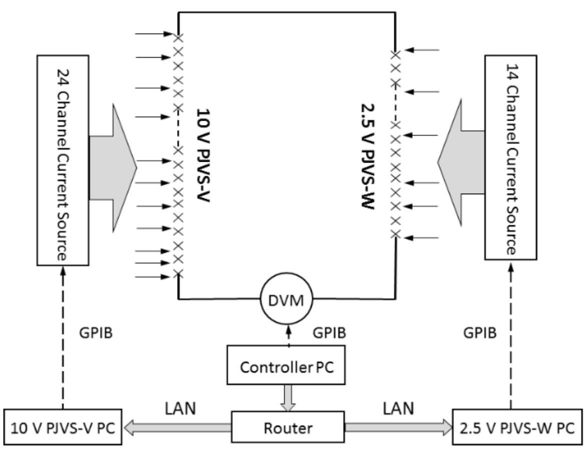

Fig. 4. Setup of an automated comparison between PJVS-W1 and the PJVS-V

The progress in voltage metrology over the last 20 years, especially the development and implementation of the PJVS for the voltage measurement in the watt balance has played a critical role in improving the uncertainty of the Planck constant measurement.

[1] Certain commercial equipment, instruments, or materials are identified in this report to facilitate understanding. Such identification does not imply recommendation or endorsement by NIST, nor does it imply that the materials or equipment that are identified are necessarily the best available for the purpose.

Tab. 3. Comparison results between PJVS-W for watt balance and PJVS-V for the Volt Lab

Voltage (V)	PJVS-V – PJVS-W1 (nV)	No. of data points	Standard Deviation of the mean (nV)	DVM $1/f$ noise floor (nV)	Type B Uncertainty (nV)	Combined Uncertainty u_c (nV)
0.748812185	0.05	52	0.28	0.37	0.11	0.386
1.017920053	0.00	251	0.17	0.37	0.14	0.396
1.250179126	-0.29	135	0.25	0.37	0.18	0.411
0.000000000	0.18	347	0.18	0.37	0.01	0.370

5. Conclusion

Early watt balances used for the measurement of the Planck constant laid down the foundation for the uniformity of voltage measurement based on a defined value of the Josephson constant $K_{J\text{-}90}$. In the following years the development of Josephson technology has helped the watt balance experiments improve the uncertainty in voltage measurements by more than two orders of magnitude. The most recent results for Planck constant measurement by watt balance experiments and Avogadro constant measurement by the International Avogadro Coordination (IAC) [15] have led the long-discussed proposal of SI redefinition to an almost certain reality in 2018. The new SI, based on a set of natural constants including the Planck constant, will have significant impact on voltage metrology. The convergence of recent results predicts a value for K_J of around 1 part in 10^7 below the $K_{J\text{-}90}$ value. For the uncertainty of a JVS at few parts in 10^{10}, the change would be a significant adjustment for voltage metrology. The change of the value for the volt would be seen along the dissemination chain, especially for those who well maintain their reference based on solid-state voltage standards. However, the benefit of the change is that the unit of the volt based on the new value of Josephson constant will be directly linked to the SI with zero uncertainty.

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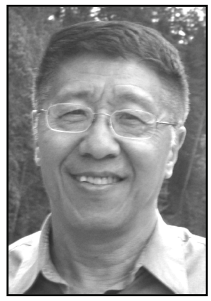

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