Deployment of a Compact, Transportable, Fully Automated Josephson Voltage Standard

Stuart L. Kupferman and Clark A. Hamilton, *Fellow, IEEE*

***Abstract*—A compact, transportable, Josephson voltage standard, first reported at CPEM96, has now been field tested and has had ten months of use as a primary standard by National Aeronautics and Space Administration (NASA) laboratories. We discuss here its uncertainty assessment, the results of intercomparisons with conventional Josephson standards, operator training, and the experience of users. A second similar standard with an improved microwave system has been fabricated at the National Institute of Standards and Technology (NIST) and delivered to Sandia National Laboratories (SNL) for use by Department of Energy (DOE) standards laboratories.**

***Index Terms*—DC, Josephson, standard, transportable, voltage.**

I. INTRODUCTION

A COMPACT, transportable, fully automated 10 V Josephson voltage standard (JVS) for calibrating dc reference standards and digital voltmeters has been described previously [1]. Here we discuss improvements, uncertainty, accuracy intercomparisons, field testing, operator training, and the experience of users since its deployment as a traveling primary standard for nine National Aeronautics and Space Administration (NASA) standards laboratories. The portable standard is now being circulated among the NASA laboratories, spending about one month at each. A second, similar standard, with an improved microwave system, has been built for use by Department of Energy (DOE) standards laboratories.

The portable standard, which has a mass and volume of only 21 kg and 0.03 m^3 (excluding the liquid helium Dewar), is highly automated and designed to be operated by technicians without higher level technical support. The standard can be easily transported by next-day air shipment in two custom containers and set up in less than an hour. It is cooled in a standard 100 L liquid helium transport Dewar that is sufficient to operate the Josephson array for six to eight weeks. By using a commercial 100 L transport Dewar, no liquid helium transfer is required.

The portable system consists of three components:

1) a notebook control computer;
2) an electronics package in a 13 cm high rack-width box;
3) a cryoprobe designed to fit in a wide variety of commercial Dewars.

In addition, a compact printer and two solid-state voltage references, used as check standards, travel with the system.

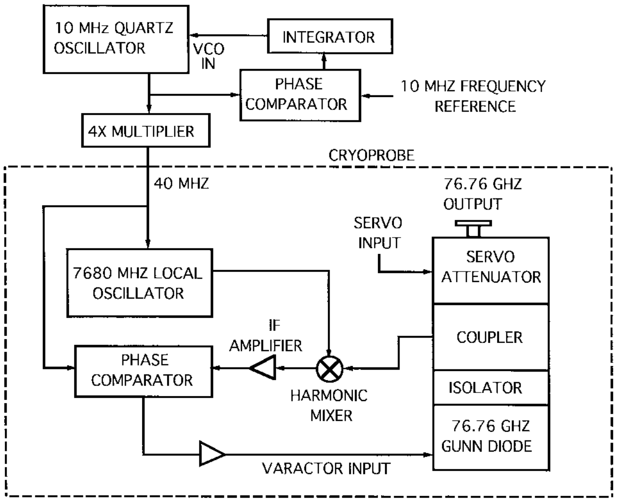

Fig. 1. A block diagram of the 76.76 GHz phase-locked oscillator.

Software for the system has the same basic calibration and data display algorithms used in the program NISTVolt [2]. The software includes control of all system parameters as well as complete self-calibration and self-diagnosis. In the system's automatic mode there is no need for user adjustment of controls. Pressure, temperature, and humidity data are automatically recorded with each measurement. Over 70 pages of help documentation are available on-line and can be easily searched for any word or phrase.

II. MODIFICATIONS

The rigid dielectric waveguide used in an earlier version of the cryoprobe [1] has been replaced by a more reliable rigid tube waveguide [3] consisting of a 12.7 mm diameter internally gold-plated stainless steel tube with launching horns at each end. Typical attenuation of this 1.25 m long waveguide is 1.2 dB at 77 GHz [4]. In addition, a superconducting level sensor has been added to the cryoprobe to simplify monitoring the liquid helium level in the Dewar. New software determines the step stability as a function of microwave power and automatically sets the power to the optimum value. An improved microwave oscillator has been developed for the DOE system. As shown in Fig. 1, it consists of a 40 MHz reference oscillator and a 76.76 GHz phase-lock loop. An external 10 MHz reference is used to phase-lock a voltage tunable 10 MHz quartz oscillator. The low bandwidth of the 10 MHz phase-lock loop results in the generation of a 10 MHz reference with the purity of the quartz oscillator even

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S. L. Kupferman is with Sandia National Laboratories, Albuquerque, NM 87185-0665 USA (e-mail: slkupfe@sandia.gov).

C. A. Hamilton is with the National Institute of Standards and Technology, Boulder, CO 80303-3328 USA.

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when locked to an external reference with considerable noise. This makes the system relatively immune to the quality of the external reference. A 4× multiplier generates the 40 MHz reference required by the 76.76 GHz phase-lock loop. Half of the 40 MHz signal is used as the reference for a 7.68 GHz dielectric resonant oscillator (DRO). The tenth harmonic of the DRO is mixed with the Gunn oscillator output at 76.76 GHz to produce an IF at 40 MHz. The 40 MHz IF is phase detected with the other half of the 40 MHz reference to produce an error signal that modulates the Gunn frequency via a varactor in the Gunn oscillator cavity. A servo-driven attenuator controls the power at the chip mount flange over the range 0.1 to 40 mW. All of the 76.76 GHz phase-locked oscillator fits in a 5 cm × 10 cm × 13 cm package that is small enough to fit within the top of the cryoprobe.

III. UNCERTAINTY

To evaluate the uncertainty of the transportable JVS, we first define a procedure that is typical of the measurements performed with the system. As an example, we define a procedure in which eight measurements of a Zener dc reference standard are made over a period of 8 h. Each measurement uses the NISTVolt $+-+-$ reversal algorithm [1], [2] and a total integration time of 2000 power line cycles. After each measurement the wires at the Zener terminals are reversed so that one cycle of the procedure results in four measurement pairs. The final result, in which the effect of thermals is minimized, is the mean of the absolute values of the eight measurements. Since we are interested here in the performance of the JVS, only uncertainty components originating in the JVS are considered.

Uncertainty in the system arises from the following components: reference frequency, leakage, null meter noise and errors, uncorrected thermal emf's, electromagnetic interference (emi), possible nonzero impedance of the Josephson voltage, and perhaps other unknown effects. Since many of these uncertainty components are quite sensitive to the laboratory environment, a rigorous uncertainty evaluation appears quite difficult. However, the evaluation is greatly simplified by recognizing that only the frequency and leakage components are dependent on the voltage being measured. All of the other components, except perhaps emi [5], are the same regardless of the voltage measured and they can be lumped together as a single component that we call the zero offset uncertainty, u_z. Zero offset uncertainty can be determined from a statistical analysis of the results of short circuit measurements [5]. To do this, we use the JVS to make measurements of a short circuit under identical conditions to the Zener measurements. In particular, the measurement process, microwave frequency and power, timing, reversals, integration time, mathematical algorithm, and laboratory environment should all be matched as closely as possible. When this is done, the zero offset uncertainty is given by

$$u_z = \left(\frac{\sum_{i=1}^{N} V_i^2}{N} \right)^{\frac{1}{2}} \tag{1}$$

with N degrees of freedom. The V_i are the results of the measurement procedure, repeated N times. In our evaluation of the eight measurement procedure we obtained $u_z = 4.1$ nV, as listed in Table I. Note that u_z is not a standard deviation since the variable V_i appears in (1) simply as $(V_i)^2$, not subtracted from its average value, i.e. as $(V_i - Vaverage)^2$.

TABLE I
UNCERTAINTY OF THE COMPACT JVS FOR 10 V MEASUREMENTS

Component	Type	Standard Uncertainty (parts in 10^9)	Degrees of Freedom
Zero offset, u_r	A	0.41	15
Leakage, u_l	B	0.20	5
Frequency, u_f	B	0.03	5
Combined, u_C		0.46	20
Expanded, U (k=2.1, 95 % conf.)		0.97	20

An independent measurement of leakage [6] gives a value $u_l = 2$ nV for 10 V measurements. For this evaluation, the system reference frequency is derived from a cesium clock and contributes an uncertainty of $u_f = 0.03$ nV for a 10 V measurement. When a cesium clock is not available, the software can correct for a known error in the reference frequency. For u_l and u_f we use a default value of five for the number of degrees of freedom. This is equivalent to an uncertainty in u_l and u_f of about 30%. Values are listed in Table I together with a calculation of the expanded uncertainty [7]. Based on the t-distribution with 20 degrees of freedom, a coverage factor of $k = 2.1$ yields a confidence interval of 95%. Thus, when the above procedure is used to measure a 10 V standard on the compact JVS, the uncertainty contribution of the JVS is 4.6 nV × 2.1 = 9.7 nV with 95% confidence. Uncertainty arising from noise in the device under test must be independently evaluated and combined with the result in Table I.

IV. INTERCOMPARISONS

In early 1997, the 3 V Josephson array chip used for the initial intercomparisons was replaced by a 10 V chip. After installation of the 10 V chip, the portable standard was compared to laboratory JVS standards both at NIST, Boulder, CO, and at Sandia National Laboratories (SNL), Albuquerque, NM, using solid-state voltage standards to make the transfers. The results of all intercomparisons can be seen in Table II. Shown are the month and year of the intercomparison, the laboratory at which it took place, the number of solid state standards used in the tests, the test voltage, the means of the measured differences in voltage between the portable and laboratory JVS systems, the uncertainty of the measurement process, the number of measurements, and the number of degrees of freedom for each intercomparison. The Type A uncertainties are dominated by the low frequency noise of the solid state standards used to make the transfers. The Type B uncertainties are due primarily to uncertainties in the

TABLE II
INTERCOMPARISONS BETWEEN THE COMPACT AND LABORATORY JVS'S

Date	Lab	# Solid State Stds. Used	Voltage (V)	$\Delta V_{P\text{-}L}$	U (k=2)	# Meas.	Degrees of Freedom
				(parts in 10^9)			
6/96	NIST	1	1.018	22	58	32	3
10/96	SNL	2	1.018	-4	14	112	13
1/97	NIST	2	10	2.5	11.3	16	3
2/97	SNL	2	10	4.7	5.2	64	7
2/97	SNL	4	10	2.3	2.8	128	15

uncorrected thermal offsets, the leakage corrections, and the frequency, and are similar for the three systems. The combined standard uncertainty seen in Table II is still dominated by the low frequency noise in the solid state standards and shows no significant indication of any real difference between the portable and the laboratory JVS systems. As can be seen in Table II, "# Meas." differs significantly from "Degrees of Freedom" because of preliminary averaging of forward and reverse values, and multiple measurements.

Both the SNL laboratory JVS and the transportable system participated in the National Conference of Standards Laboratories (NCSL) Josephson Voltage Interlaboratory Comparison early in February 1997 at SNL. This comparison was based on a set of 64 measurements by each JVS, of a set of four traveling solid state reference standards. The overall uncertainty ($k = 2$) of the NCSL comparison based on the variation in the data from all 15 participants is 16 parts in 10^9 [8]. The measured values of all 15 participants fell within this uncertainty. The NASA transportable JVS and the SNL laboratory JVS agreed within 2.3 parts in 10^9 with an expanded uncertainty ($k = 2$) of 2.8 parts in 10^9, as shown in the last row of the table. The design accuracy of the portable JVS at 10 V was 20 parts in 10^9.

V. FIELD TESTING, TRAINING AND USER EXPERIENCE

The JVS has been successfully field tested at two NASA facilities, the White Sands Test Facility in New Mexico and the Kennedy Space Center in Florida, remaining at these locations for one and three months, respectively. After one day of training, the staff at each facility were able to successfully operate the standard and produce excellent calibration results. Extensive notes taken during these tests were used to improve the operating instructions and software so as to simplify the setup and operation of the standard.

In early December 1997, 17 operators from the nine participating NASA facilities received three days of lecture and hands-on training in procedures for setting up and operating the JVS. Approximately one half of the operators were electrical engineers and one half were experienced electrical metrology technicians. A users group was formed to manage the operation of the standard, which was delivered to the Kennedy Space Center, the lead laboratory for the project, early in 1998 to begin its cycle through the NASA complex.

The standard has been shipped 14 times by overnight air express. The only problems encountered that could be directly attributed to shipping were apparently caused by shock and vibration. Shock sensors rated at 25 and at 50 times the acceleration of gravity mounted both inside and outside of the shipping containers are often tripped during shipment. On several occasions the system suffered minor damage during shipment. On one occasion the system failed to work at all because of a noisy electrical environment.

TABLE III
RESULTS OF MEASUREMENTS WITH THE COMPACT JVS AT USER LABORATORIES

Lab	Date	# 10 V Taps	$\Delta V_{Lab\text{-}JVS}$	U_{Lab} (k=2)
			------- (parts in 10^6)---------	
A	4/97	3	0.8	1.5
B	8/97	4	-0.12	0.3
B	1/98	4	- 0.15	0.3
C	2/98	3	-0.1	0.2
A	4/98	3	0.12	1.5
D	7/98	3	0.2	1.0
E	8/98	4	-0.35	0.7
F	10/98	4	-0.16	0.6

The JVS has been operated successfully at six NASA calibration laboratories as of mid-October 1998. The results of measurements are shown in Table III. Shown are the laboratory, the month when the JVS arrived, the number of solid state 10 V taps used to maintain the Volt at the given laboratory, the difference between the maintained Volt and the Volt realized by the JVS, and the uncertainty in the maintained Volt. In this table, measurements made during the field tests, the first two rows of data, have been included along with JVS volt transfer data shown in the rest of the table. As can be seen, the JVS resulted in a marked improvement in the value of the maintained Volt for laboratory A and verified the uncertainties claimed at the other laboratories.

Problems encountered by the users of the standard, both in the field tests and during use for volt transfer are listed below, roughly in the order and frequency of the resulting difficulty. For a user's perspective, see [9].

1) First-time users are almost unanimously surprised at the sensitivity of the JVS to electrical noise, both ambient, and front end noise in the standards being calibrated. Although this potential problem was emphasized both during training and in the operating instructions, the operators are generally caught off guard. Such diverse items as power cords placed too close to critical components or wires, and noisy computers result in reduced stability or inoperability of the system. These problems, if truly due to electrical noise [see 3)], were usually resolved with some coaching from experienced JVS operators.
2) There are nine pages of set-up/quick-start instructions backed up by over 70 pages of on-line help files. New users tend to have problems that would be unlikely to occur if they made full use of these instructions and help files. The problem seems due to their relative unfamiliarity with this device, since they have no trouble operating $8\frac{1}{2}$ digit DMM's that have larger and almost equally complex instruction sets.
3) The array chip used in the field tests became unstable and eventually was unable to run calibrations at 10

V near the end of the systems stay at the first field test laboratory. The chip failed at the second field test laboratory and was replaced.

VI. CONCLUSION

Josephson voltage standards have traditionally been semipermanent laboratory installations. In cases where these standards have been transported, it has been for the purpose of a direct comparison with another JVS, and a highly trained operator has traveled with the system. We have described here a new mode of operation for JVS's, that is, as a traveling standard that transfers the volt and brings a greatly improved level of uncertainty to working standards laboratories. The volt is transferred with significantly better uncertainty than in a measurement assurance program using solid state voltage standards. In addition, the level of effort required is much smaller for the parent laboratory and is not significantly increased for the laboratory receiving the transfer.

A key reason for the success of this traveling standard is the integration of the system hardware and software into a relatively compact, light weight, and easy (for a Josephson standard) to use system that does not require a resident expert. The effectiveness of this approach has been proven by the successful operation of the system at six different NASA laboratories. As more experience is gained and further refined systems are developed, traveling Josephson standards may become the norm for dissemination of the volt.

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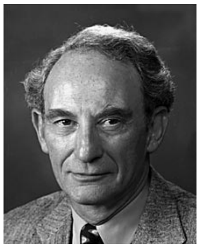
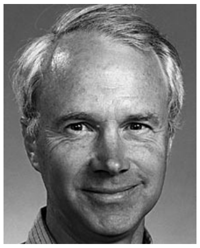


Stuart L. Kupferman was born on June 30, 1937 in Brooklyn, NY. He received the B.S. Degree in physics from the Polytechnic Institute of Brooklyn in 1959 and the M.S. and Ph.D. degrees in physics from Harvard University, Cambridge, MA, in 1964 and 1966, respectively.

From 1966 to 1968, he was in the U.S. Army, Geology and Geochemistry Branch, Johnson Space Center, Houston, TX. From 1968 to 1970, he was a Research Associate, Graduate School of Oceanography, University of Rhode Island, Kingston, where he investigated the use of fallout radioisotopes to study the large scale ocean circulation. He was on the faculty of the College of Marine Studies, University of Delaware, Newark, from 1970 to 1977, and a Visiting Investigator, Woods Hole Oceanographic Institution, from 1978 to 1980 where he continued his studies of ocean circulation and began to investigate how large-scale ocean circulation could influence the feasibility of disposing of radioactive wastes in the ocean. In 1980, he moved to Sandia National Laboratories, Albuquerque, NM, where he worked on the Subseabed Disposal Project. In 1986 he joined the staff of the Sandia Laboratories Primary Standards Laboratory. He is presently DC Project Leader in the Primary Standards Laboratory.



Clark A. Hamilton (S'64–M'71–F'95) was born in Rochester, NY, on April 22, 1944. He received the B.S. degree in electrical engineering from Union College, Schenectady, NY, in 1966, and the M.S. and Ph.D. degrees in electrical engineering from the University of Rochester in 1968 and 1971.

He joined the National Institute of Standards and Technology (formerly the National Bureau of Standards), Boulder, CO, in 1971 and became a NIST Fellow in l987. He has authored 71 publications and holds three patents.

Dr. Hamilton has shared IR100 awards for his work on infrared detectors (1976) and Josephson array voltage standards (1987), and he has received two U.S. Department of Commerce Gold Medals for his work on superconducting integrated circuits using Josephson devices (1984, 1989). He received the 1995 IEEE Electrotechnology Transfer Award.