

10 kV DC Resistive Divider Calibration

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Abstract

A calibration method for a 10 kV dc ratio divider was developed. The method uses a high-precision digital voltmeter, at the 10 V level, to establish a 10:1 voltage ratio for each decade of the resistive divider and combines these results to obtain an overall voltage ratio of 10 000:1. The linearity of the voltmeter was checked using a Josephson-array voltage standard. The overall ratio agreed with measurements made at 10 kV using a Park-type divider to within the uncertainty limits.

INTRODUCTION

Background

A resistive ratio standard for dc input voltages up to 10 kV was designed and built at the National Bureau of Standards (now the National Institute of Standards and Technology [NIST]) in 1975¹. The divider was constructed using three tapped resistor decades and a Kelvin-Varley circuit for the lowest two decades (Fig 1). The resistors, wound on cards, were surrounded by a guard circuit using similar-valued resistors to provide equipotential shields for each resistor card. The whole assembly was immersed in a temperature-controlled oil bath for insulation and ambient temperature control. At each node, the junction of the divider resistors and the junction of the corresponding guard resistors, respectively, were connected to the inner and outer conductors of a British Post Office-type (BPO) coaxial connector. Desired voltage ratios could be selected by appropriate connections to the nodes in the resistance network and the Kelvin-Varley divider.

The high-voltage divider was originally built for an absolute volt experiment and has not been in use for several years. Current interest in establishing a medium high-voltage dc divider calibration capability (10 kV to 1 kV) prompted a decision to put the existing 1975 resistive-divider standard back into service. In preparation for the resumption of calibrations of dividers in this voltage range submitted to NIST by customers, the standard itself needed to be recalibrated. The following describes the steps taken and the results obtained in the recalibration.

Calibration Method

In the original construction of the divider, materials had been selected that had resistors with small voltage and temperature coefficients to ensure stability. By using the same materials for all resistors, the stability of the ratio is further enhanced because external influences, such as temperature or applied voltage, will affect the resistances in proportion to their values and thus

¹

C. B. Childers, R. F. Dziuba, L. H. Lee, "A Resistive Ratio Standard for Measuring Direct Voltages to 10 kV," *IEEE Transactions on Instrumentation and Measurements*, IM-25, No. 4, December 1976.

leave the ratio substantially unchanged. It is possible, therefore, to calibrate the divider at low voltage and make only spot checks at rated voltage. The divider consists of a string of nine resistors with nominal resistance values of 2 M Ω each for the upper decade, 200 k Ω for the second decade, and 20 k Ω for the third decade, respectively (Fig. 1). The tenth 'member' of each decade string is the equivalent resistance of the resistor network of all the lower valued resistors. The lowest (fourth) divider decade is composed of a Kelvin-Varley divider using 2 k Ω individual resistors and a shunt to make its input resistance a nominal 20 k Ω (Fig. 2a and 2b). The most significant two digits of the Kelvin-Varley divider are selected using short, shielded (coaxial) jumper cables equipped with BPO connectors at each end. The remaining three digits can be selected by ten-position rotary switches. During the calibration tests described here, all switches were left in the zero position.

At the time the divider was built, a bootstrap calibration procedure using bridge circuits was used to establish the resistance ratios. The bridge measurements use sensitive dc detectors which can be susceptible to stray noise and ac pick-up. At the present time, using the bootstrap method with an available commercial bridge circuit yielded uncertainties for each resistor comparison of at least 1×10^{-6} caused by electrical noise and induced parasitic ac signals, particularly when checking the 2 M Ω resistors. Since the uncertainties would accumulate at each step of the ratio determination, the overall uncertainty would have been unacceptably high.

An alternate method using a high-resolution digital-voltmeter provides a better way to obtain results. The voltmeter automatically averages readings to reduce noise and power-line induced disturbances and is sufficiently linear to establish accurate voltage ratios of ten-to-one. Higher ratios then can be determined by partitioning the divider and combining the measured ratios from each section.

Using the digital-voltmeter method, the determination of the divider ratio is carried out at low voltage. The ten-to-one ratios of the highest four decades of the divider are measured in turn, and by multiplying the intermediate results, a corrected value for the nominal ratio of 10 000 to 1 can be computed. As a cross check, the divider can then be compared at the rated operating voltage with a Park-type high-voltage divider. The high-voltage comparison uses the same bridge configuration that is employed for routine calibrations of customer-owned dividers.

Low-Voltage Calibration

A precision temperature controlled, Zener-stabilized voltage source with a nominal output of 10 V serves as the supply across the ratio resistors. A stabilized source is desirable to obtain consistent readings and lower electrical noise. To maintain sufficient resolution in the voltmeter readings, the measured ratios are kept at 10:1 or less for each determination. To get a ratio of 1000:1, the divider has to be calibrated in stages, and the resistor decades provide a convenient choice for such stages.

With the voltage source connected across each stage of the divider, four sets of dc-voltage readings are taken to determine the actual ratio of each decade. For both negative and positive polarity of the voltage source, readings are then taken across the whole of the decade stage and across the section connected between the chosen divider tap and the common terminal, with the tap usually one tenth of the decade.

For each measurement, the digital voltmeter is programmed to average ten readings spaced over an integral number of cycles of the power-line frequency to reduce any effects of induced 60 Hz voltages. A manually operated rotary switch is used to select the polarity of the dc source and the voltmeter connection either across the whole or the tapped section of the resistor decade. The standard deviation and variation from minimum to maximum of each set of digital voltmeter readings are calculated in real time and displayed so that unusually noisy readings could be detected and remeasured. At the completion of the four sets of digital voltmeter readings, the ratio of the divider section under test is computed from the measurements. The result is expressed in terms of the deviation (in parts in 10^6) from the nominal ratio. The overall ratio is calculated by combining the corrected ratios for each stage.²

Calibration of the Digital Voltmeter

Since the ratio determination depended critically on the linearity of the digital voltmeter, a thorough calibration of the voltmeter was undertaken by comparing the voltmeter readings with a series of voltage levels available from a 10 V Josephson-junction voltage standard over a ten-to-one range. Applying this calibration to each of the four stages in the determination of the 10 000 V/1 V ratio, the lack of perfect linearity added a total additional uncertainty of only 1.5 parts-per-million (ppm). This is of the same order of magnitude as the uncertainty in the ratio determination and certainly much smaller than the uncertainty of the ratio intercomparison using the Park-resistor divider. Frequent recalibration of the voltmeter, therefore, does not appear to be necessary.

CALIBRATION PROCEDURE FOR DIVIDER DECADES

Equipment Configuration

The divider resistors are immersed in a temperature controlled, stirred oil bath. Four Peltier heating and cooling units are built into the oil bath wall. The current to the series-connected

² The calibration of the digital voltmeter against a Josephson Array were carried out by Richard Steiner of NIST. The calibration data are included in Appendix C.

Peltier units is supplied by a programmable current source controlled from an IBM³ compatible personal computer (PC). Four thermistors immersed in the oil bath provide the temperature input for the control program.

The moveable relay rack containing the computer, current source, and thermistor control circuit also houses the precision voltage source, digital voltmeter, and voltmeter switch selector. The voltmeter readings are controlled from a separate desktop, laboratory computer.

Voltmeter Circuit

To determine the ten-to-one ratio of the most significant decade of the divider, the stabilized 10 V supply is connected to the "10 kV" and the "0 V" terminals. These two terminals form the top and bottom connection of the divider. Both the stabilized power supply and the digital voltmeter are connected to the resistor network through a switch box (see Fig. 3). A set of leads connects the supply voltage to the polarity reversing switch and a second set links the switch to the divider. A third set of leads connects the switch to the digital voltmeter. The leads to the voltmeter are wound on a coaxial choke to reduce common-mode ac signals as explained below. Two more sets of leads make connections between the divider and the digital voltmeter. One pair, the "A" leads, are connected to the divider in parallel with the supply leads, the other pair, the "B" leads, are connected to the "1 kV" and "0 V" terminals. These terminals form the 'output' of the first decade of the divider under test.

The source impedance the voltmeter sees is dependent on the selector switch position. When measuring the drop across the entire decade ("A" position of the switch), the source impedance seen by the digital voltmeter is low because it is essentially that of the voltage supply. However, when the voltmeter is connected to the "output" terminals of the resistor chain of the highest decade ("B" position of the switch), the source impedance is just slightly less than 2 M Ω . The "B" readings, therefore, tend to be noisier than the "A" readings for measurements of the upper decades of the divider. On the lower decades, the difference in source impedance between the "A" and "B" configurations is proportionally less pronounced.

To reduce common-mode ac signals, the shielded, twisted pair of leads to the voltmeter input terminals are wound (~22 turns) through a toroidal high-permeability core to form a "coaxial choke." This choke provides a low-impedance circuit for the signal and return leads, because the magnetic induction is cancelled, but represents a relatively high-impedance path for external, common-mode ac currents.

³ Throughout this report, commercial instruments are identified by manufacturer and model number only to describe the experiment. This does not imply an endorsement by the National Institute of Standards and Technology, nor does it imply that the equipment mentioned is necessarily the best available for the purpose.

The switch that selects the polarity and divider tap connections is a ganged, four-position, multicontact, low-thermal switch. It connects the input of the digital voltmeter across either the whole or part of the string of resistors and also controls the polarity of the applied voltage. For the test, it is rotated sequentially to each of the four settings, A+, A-, B+, B- in any desired order. At each switch position, a series of voltage readings is recorded under computer control after the letter designation of the selected switch position has been entered through the keyboard.

Data acquisition program

The voltmeter used for these calibration measurements is a Hewlett-Packard 34558A Multimeter. The meter can be programmed to take a chosen number of readings over a period defined by a given number of power-line cycles. Because of the integrating mode of operation, effects due to power-line ripple will be largely compensated. Built-in mathematical functions calculate the standard deviation and the high and low limits of each set of data. The external computer program displays the measured values and calculates the mean. For successive sets of readings on the same data point, the program stores the mean value and standard deviation of the current set of data as well as the mean of a set of previously recorded data having the lowest standard deviation. The software driving the voltmeter operation is programmed to accept a set of readings automatically if the standard deviation is less than or equal to one part per million. If the standard deviation is greater, the voltmeter will continue taking further sets of data. The operator can override this process (with key K1 or K2 on the Hewlett-Packard Model 85 computer) by accepting the current set of data or that with the lowest standard deviation. A printed record is kept of the "override" and the mean and standard deviation of the set of data that is accepted.

Readings of the voltage drops across the whole decade resistor chain and across the selected portion of the resistors are taken with both positive and negative polarities. Combining the averages of corresponding readings of opposite polarity (e.g., switch positions "A+", "A-" and "B+", "B-") tends to reduce the effects of small voltage offsets in the voltmeter circuit. From the averages of the four sets of voltmeter readings the desired ratio of the decade resistor string is calculated and recorded as a numerical ratio and as a correction (in ppm) to the nominal ratio selected {e.g., $10+(\text{correction} \times 10^{-6})$ }.

A similar procedure is followed for the three lower decades, by connecting the "A" leads to the "1 kV" and "0 V" terminals and the "B" leads to the "100 V" and "0 V" terminals, and continuing with the pairs of

$$\begin{aligned} & \text{"100 V" — "0 V" : "10 V" — "0 V",} \\ & \text{"10 V" — "0 V" : "1 V" — "0 V"} \end{aligned}$$

terminal connections. The overall ratio (or ratio correction) is then computed by combining the results from all the decade ratio determinations. If the divider needs to be calibrated for applied

voltages below 10 kV, the highest decade ratio can be chosen to match the nominal applied voltage.

Temperature Control

The resistors of the voltage divider are immersed in a cylindrical oil bath equipped with a stirring device at the bottom center. The stirrer is driven by an external motor coupled through a belt to a pulley and shaft protruding from the bottom of the bath. The motor is located at one corner of a square support table so that the heat generated by the motor does not affect the temperature of the oil.

The oil bath has several functions: To insulate the high-voltage parts of the circuit, to prevent flash-overs and corona discharges, and to stabilize the temperature of the resistors forming the divider. Heating and cooling of the oil in the bath is accomplished with four Peltier units spaced evenly around the circumference of the metal enclosure. The Peltier units are powered from a programmable dc power supply that is computer controlled. Four thermistors are inserted into the oil through openings in the acrylic top cover of the bath.

The thermistors are connected to a control unit that can be programmed to scan the thermistor resistances and convert them into bus-compatible numerical readouts in degrees Celsius (or Fahrenheit). A computer is programmed to interrogate the thermistor control unit periodically, average the measured temperatures, and compare the average to a reference temperature. If the average measured temperature is less than the reference, then the programmable dc power supply is set to send current through the Peltier units in a direction that will supply heat to the oil in the bath. If the average measured temperature is greater than the reference, the direction of current from the power supply is reversed so that the Peltier units will cool the oil. At each transition between heating and cooling commands, the power supply is turned off for one cycle between thermistor interrogations.

Since the thermistors are immersed in the main oil bath, the heat capacity of the oil will cause considerable thermal inertia. A response to a simple on-off control would result in significant temperature overshoot because of the thermal inertia. To obtain better control, the reference temperature is modulated with a waveform which is close to triangular. This results in a band of proportional control near the desired setpoint temperature. The reference temperature modulation is implemented in the control software with an algorithm based on a theoretical model and subsequent empirical adjustment of the amplitude and period of the quasi-triangular wave.

With the temperature-control algorithm developed, the standard deviation between successive runs was found to be 0.01 °C or less. Between days, the temperature at the set point could be reproduced to within ± 0.05 °C.

The computer program provides a color-coded bar-graph representation of the average and reference temperatures and indicates whether the quantities are increasing or decreasing by a change in color and by arrows pointing in the appropriate direction. The bar graph display alternates with the numerical display of the latest thermistor readings and average temperature, as well as extremes of the temperature fluctuations. Useful voltage ratio measurements can be performed while the average temperature is within a ± 0.1 °C interval around the setpoint. By changing the color of the text on the screen (from yellow to white), extra emphasis is given that the working temperature range has been attained.⁴

Calibration Data

The following tables, Tables 1 through 5, list the data obtained in measuring the ten-to-one ratios of the divider decades on various dates. The tables are arranged by date and list the most significant resistor decade first. Tables 6 and 7 summarize the ratio corrections calculated for each decade (Table 6) and the overall 10 000:1 ratio (Table 7).

(The following tables are extremely faint and illegible in the provided image. They would typically contain calibration data such as dates, temperatures, and ratio corrections.)

⁴ An annotated listing of the BASIC program is given in Appendix B.

Table 1, RESULTS OF THE LOW-VOLTAGE CALIBRATION (December 1, 1993)

10 kV to 1 V Ratio Calibration Using the Digital-Voltmeter Method

Corrections to the Nominal 10:1 Ratio:

1 Dec 93 DVM Connections: 10 kV/1 kV/0 V

11:27 am	Run 1; correction:	+0.7 × 10 ⁻⁶	Oil Temperature:	24.484 °C
	Run 2; correction:	+3.9	Oil Temperature:	24.483
	Run 3; correction:	+1.1	Oil Temperature:	24.496
	Avg. Ratio Correction:	+1.9	Avg. Temperature:	24.49
	Std. Dev.:	1.74		0.007

1 Dec 93 DVM Connections: 1 kV/100 V/0 V

11:37 am	Run 1; correction:	-8.0 × 10 ⁻⁶	Oil Temperature:	24.494 °C
	Run 2; correction:	-7.9	Oil Temperature:	24.491
	Run 3; correction:	-8.8	Oil Temperature:	24.497
	Avg. Ratio Correction:	-8.2	Avg. Temperature:	24.49
	Std. Dev.:	0.49		0.008

1 Dec 93 DVM Connections: 100 V/10 V/0 V

11:45 am	Run 1; correction:	-1.5 × 10 ⁻⁶	Oil Temperature:	24.499 °C
	Run 2; correction:	-1.7	Oil Temperature:	24.495
	Run 3; correction:	-1.6	Oil Temperature:	24.488
	Avg. Ratio Correction:	-1.6	Avg. Temperature:	24.49
	Std. Dev.:	0.10		0.010

1 Dec 93 DVM Connections: 10 V/1 V/0 V

11:56 am	Run 1; correction:	+7.9 × 10 ⁻⁶	Oil Temperature:	24.491 °C
	Run 2; correction:	+7.6	Oil Temperature:	24.485
	Run 3; correction:	+10.2	Oil Temperature:	24.481
	Avg. Ratio Correction:	+8.6	Avg. Temperature:	24.49
	Std. Dev.:	1.42		0.011

Overall Ratio	=	10000.007	Correction:	+0.7 × 10⁻⁶
standard deviation:		6.90 × 10⁻⁶		

Overall average temperature: 24.490 ± 0.038 °C

Table 2, RESULTS OF THE LOW-VOLTAGE CALIBRATION (December 3, 1993)

10 kV to 1 V Ratio Calibration Using the Digital Voltmeter Method

Corrections to the Nominal 10:1 Ratio:

3 Dec 93 DVM Connections: 10 kV/1 kV/0 V

11:43 am	Run 1; correction:	-3.3×10^{-6}	Oil Temperature:	24.528 °C
	Run 2; correction:	-1.9	Oil Temperature:	24.521
	Run 3; correction:	-2.5	Oil Temperature:	24.517
	Avg. Ratio Correction:	-2.6	Avg. Temperature:	24.52
	Std. Dev.:	0.70		0.008

3 Dec 93 DVM Connections: 1 kV/100 V/0 V

11:37 am	Run 1; correction:	-8.3×10^{-6}	Oil Temperature:	24.520 °C
	Run 2; correction:	-8.0	Oil Temperature:	24.516
	Run 3; correction:	-8.1	Oil Temperature:	24.522
	Avg. Ratio Correction:	-8.1	Avg. Temperature:	24.52
	Std. Dev.:	0.15		0.006

3 Dec 93 DVM Connections: 100 V/10 V/0 V

11:31 am	Run 1; correction:	-2.3×10^{-6}	Oil Temperature:	24.533 °C
	Run 2; correction:	-2.1	Oil Temperature:	24.533
	Run 3; correction:	-2.2	Oil Temperature:	24.528
	Avg. Ratio Correction:	-2.2	Avg. Temperature:	24.53
	Std. Dev.:	0.10		0.005

3 Dec 93 DVM Connections: 10 V/1 V/0 V

11:0:25 am	Run 1; correction:	$+9.0 \times 10^{-6}$	Oil Temperature:	24.535 °C
	Run 2; correction:	+8.7	Oil Temperature:	24.530
	Run 3; correction:	+8.7	Oil Temperature:	24.527
	Avg. Ratio Correction:	+8.8	Avg. Temperature:	24.53
	Std. Dev.:	0.17		0.004

Overall Ratio = 9999.959 Correction: -4.1×10^{-6}
3 x standard deviation 23.0×10^{-6}

Overall average temperature: 24.526 ± 0.025 °C

10 kV to 1 V Ratio Calibration using the DVM Method

Table 3, RESULTS OF THE LOW-VOLTAGE CALIBRATION (May 1994)

10 kV to 1 kV Ratio Calibration Using the Digital Voltmeter Method

Corrections to the Nominal 10:1 Ratio:

20-23 May 94 DVM Connections: 10 kV/1 kV/0 V

Avg. Ratio Correction: $+24.2 \times 10^{-6}$ Avg. Temperature: 24.566 °C
Std. Dev.: 1.1 0.066

Table 4, RESULTS OF THE LOW-VOLTAGE CALIBRATION (June 4, 1994)**10 kV to 1 V Ratio Calibration Using the Digital Voltmeter Method**

Corrections to the Nominal 10:1 Ratio:

1 Jun 94 DVM Connections: 10 kV/1 kV/0 V

11:00 am	Run 1; correction:	+26.4 × 10 ⁻⁶	Oil Temperature:	24.564 °C
11:02 am	Run 2; correction:	+24.1	Oil Temperature:	24.552
2:16 pm	Run 3; correction:	-1.3	Oil Temperature:	24.582
2:19 pm	Run 4; correction:	+0.5	Oil Temperature:	24.574
	Avg. Ratio Correction:	+12.4	Avg. Temperature:	24.568
	Std. Dev.:	14.86		0.013

1 Jun 94 DVM Connections: 1 kV/100 V/0 V

11:05 am	Run 1; correction:	+11.8 × 10 ⁻⁶	Oil Temperature:	24.549 °C
11:07 am	Run 2; correction:	+11.3	Oil Temperature:	24.555
2:14 pm	Run 3; correction:	-6.3	Oil Temperature:	24.571
2:22 pm	Run 4; correction:	-6.7	Oil Temperature:	24.578
	Avg. Ratio Correction:	+2.53	Avg. Temperature:	24.563
	Std. Dev.:	10.42		0.014

1 Jun 94 DVM Connections: 100 V/10 V/0 V

11:09 am	Run 1; correction:	+2.5 × 10 ⁻⁶	Oil Temperature:	24.567 °C
11:12 am	Run 2; correction:	+2.5	Oil Temperature:	24.568
2:12 pm	Run 3; correction:	-0.2	Oil Temperature:	24.577
2:24 pm	Run 4; correction:	-0.1	Oil Temperature:	24.574
	Avg. Ratio Correction:	+1.18	Avg. Temperature:	24.572
	Std. Dev.:	1.53		0.005

**Table 4, RESULTS OF THE LOW-VOLTAGE CALIBRATION (June 4, 1994)
continued**

1 Jun 94 DVM Connections: 10 V/1 V/0 V

11:18 am	Run 1; correction:	+6.3 × 10 ⁻⁶	Oil Temperature:	24.584 °C
11:19 am	Run 2; correction:	+6.2	Oil Temperature:	24.586
2:08 pm	Run 3; correction:	+7.1	Oil Temperature:	24.579
2:26 pm	Run 4; correction:	+4.0	Oil Temperature:	24.574
	Avg. Ratio Correction:	+5.90	Avg. Temperature:	24.581
	Std. Dev.:	1.33		0.005

Overall Ratio = 10000.219 Correction: +21.91 × 10⁻⁶
3 x standard deviation: 54.79 × 10⁻⁶

Overall average temperature: 24.571 ± 0.008 °C

Table 5, RESULTS OF THE LOW-VOLTAGE CALIBRATION (August 8, 1994)

10 kV to 1 V Ratio Calibration Using the Digital Voltmeter Method

Corrections to the Nominal 10:1 Ratio:

8 Aug 94 DVM Connections: 10 kV/1 kV/0 V

11:30 am	Run 1; correction:	-1.44×10^{-6}	Oil Temperature:	24.557 °C
2:57 pm	Run 2; correction:	-1.47	Oil Temperature:	24.560
3:00 pm	Run 3; correction:	-0.33	Oil Temperature:	24.571
	Avg. Ratio Correction:	-1.08	Avg. Temperature:	24.563
	Std. Dev.:	0.65		0.007

8 Aug 94 DVM Connections: 1 kV/100 V/0 V

11:35 am	Run 1; correction:	-7.86×10^{-6}	Oil Temperature:	24.593 °C
11:36 am	Run 2; correction:	-8.33	Oil Temperature:	24.602
2:53 pm	Run 3; correction:	-6.62	Oil Temperature:	24.572
2:55 pm	Run 4; correction:	-6.85	Oil Temperature:	24.566
	Avg. Ratio Correction:	-7.42	Avg. Temperature:	24.583
	Std. Dev.:	0.81		0.017

8 Aug 94 DVM Connections: 100 V/10 V/0 V

11:41 am	Run 1; correction:	-1.52×10^{-6}	Oil Temperature:	24.594 °C
11:42 am	Run 2; correction:	-1.56	Oil Temperature:	24.585
2:48 pm	Run 3; correction:	-0.41	Oil Temperature:	24.561
2:50 pm	Run 4; correction:	-0.44	Oil Temperature:	24.567
	Avg. Ratio Correction:	-0.98	Avg. Temperature:	24.577
	Std. Dev.:	0.64		0.015

8 Aug 94 DVM Connections: 10 V/1 V/0 V

11:45 am	Run 1; correction:	$+2.77 \times 10^{-6}$	Oil Temperature:	24.567 °C
11:47 am	Run 2; correction:	+2.77	Oil Temperature:	24.555
2:36 pm	Run 3; correction:	+4.26	Oil Temperature:	24.566
2:37 pm	Run 4; correction:	+4.08	Oil Temperature:	24.567
	Avg. Ratio Correction:	+3.47	Avg. Temperature:	24.564 °C
	Std. Dev.:	0.81		0.006

Overall Ratio = 9999.940 Correction: -6.01×10^{-6}
3 x standard deviation: 4.39×10^{-6}
Overall average temperature: 24.571 ± 0.008 °C

Table 6, RATIO DETERMINATION SUMMARY**Comparison of Ratios by Resistor Decade**

Date	Correction to the Nominal Ratio	Oil Bath Temperature
DVM Connections: 10 kV/1 kV/0 V		
1 Dec 93	+1.9 ±1.74 × 10 ⁻⁶	24.49 ±0.007 °C
3 Dec 93	-2.6 ±0.70 × 10 ⁻⁶	24.52 ±0.008 °C
20-23 May 94	+24.2 ±1.10 × 10 ⁻⁶	24.566±0.066 °C
1 Jun 94	+12.4±14.86 × 10 ⁻⁶	24.568±0.013 °C
8 Aug 94	-1.08±0.65 × 10 ⁻⁶	24.563±0.007 °C
DVM Connections: 1 kV/100 V/0 V		
01 Dec 93	-8.2 ±0.49 × 10 ⁻⁶	24.49 ±0.008 °C
3 Dec 93	-8.1 ±0.15 × 10 ⁻⁶	24.52 ±0.006 °C
1 Jun 94	+2.53±10.42× 10 ⁻⁶	24.563±0.014 °C
8 Aug 94	-7.42±0.81 × 10 ⁻⁶	24.583±0.017 °C
DVM Connections: 100 V/10 V/0 V		
1 Dec 93	-1.6 ±0.10 × 10 ⁻⁶	24.49 ±0.010 °C
3 Dec 93	-2.2 ±0.10 × 10 ⁻⁶	24.53 ±0.005 °C
1 Jun 94	+1.18±1.53 × 10 ⁻⁶	24.572±0.005 °C
8 Aug 94	-0.98±0.64 × 10 ⁻⁶	24.577±0.015 °C
DVM Connections: 10 V/1 V/0 V		
1 Dec 93	+8.6 ±1.42 × 10 ⁻⁶	24.49 ±0.011 °C
3 Dec 93	+8.8 ±0.17 × 10 ⁻⁶	24.53 ±0.004 °C
1 Jun 94	+5.90±1.33 × 10 ⁻⁶	24.581±0.005 °C
8 Aug 94	+3.47±0.81 × 10 ⁻⁶	24.564±0.006 °C

Table 7, RATIO DETERMINATION SUMMARY**Overall Ratio \pm 3 Standard Deviations.**

Date	Actual ratio	Correction to the nominal ratio $\times 10^6$
1 Dec 93	10 000.007	+0.7 \pm 6.90
3 Dec 93	9 999.959	-4.1 \pm 2.23
1 Jun 94	10 000.208	+20.83 \pm 54.79
8 Aug 94	9 999.940	-6.01 \pm 4.39
Mean (excluding data from May and June 94)		-3.1 \pm 4.9

DISCUSSION OF RESULTS.

Low-Voltage Calibration (Table 1 to Table 7)

The computed ratio corrections have a mean value of $(-3.1 \pm 4.9) \times 10^{-6}$ to the nominal ratio of 10 000:1 if the readings taken in May and June 1994 are excluded. Both the June '94 readings and the partial ratio determinations in May of that year give a result that differs from the mean by more than four times the standard deviation. In addition, the uncertainty of the June result is almost ten times greater than any of the other uncertainties. The exact cause of this large uncertainty has not been established. The observed anomaly could be attributed to excessive electrical noise due either to outside interference through the power line, or to improper grounding of the oil bath enclosure or shielding of the sensing leads. As a precaution, the wiring was partially reworked before the next set of readings were taken. Because of the large discrepancy of the results in May and June from those obtained earlier and later, it seemed reasonable to assume that they were an artifact of the measuring system rather than a real change in the resistance ratios. They were, therefore, excluded from the overall results. The remainder of the results fall well within the estimated statistical uncertainty and differ from the nominal ratio by about 5×10^{-6} .

Over the eight-month period from December 1993 to August 1994 no statistically significant drift in the calibration could be detected. The time needed to perform a recalibration using the digital voltmeter method is approximately one work day including the time required for the oil bath to reach operating temperature.

Comparison with the Park Voltage Divider (Table 8)

The intercomparison with the Park resistors is carried out by means of a manually adjusted bridge circuit using the both the Park divider and the 10 kV divider in parallel, each adjusted for a nominal 10 000 to 1 ratio. The high-voltage side of the Park divider consists of three sections in series of 100 M Ω each, while the low-voltage section is composed of three nominal 10 k Ω resistors in series with an adjustable resistor. The low-voltage section is part of the bridge circuit used for the intercomparison. The measurements were made with 10 kV applied to the high-voltage terminals of the dividers.

To compare the two dividers, the one-volt taps of the 10 kV divider is connected as one input to the bridge and the 10 k Ω sections in series with an adjustable resistor forms the low-voltage end of the Park divider. Setting the adjustable resistor effectively changes the ratio of the Park divider until the bridge detector indicates a null. The actual ratio of the Park divider can then be inferred from the resistance setting. The sensitivity of this arrangement allows the ratio to be adjusted in steps of about 7×10^{-6} . The data from measurements made on several days varied over a range of 40×10^{-6} and with a standard deviation of 8.9×10^{-6} .

The three configurations referred to as "A," "B," and "C," in the table of results correspond to the use of three, two, or one section (100 M Ω) of the Park divider and correspondingly three, two, or one 10 k Ω resistors in the lower leg of the divider. The values obtained do not show a significant dependence on the configuration.

Averaging the data from both the 10 kV divider and the Park divider shows that the ratio values agree to within the uncertainties stated in the tables and are very close to the nominal ratio of 10 000:1. The bridge comparison is sensitive to ground impedance and care has to be taken use the shortest possible ground connections. However, the ground impedance cannot be completely eliminated and thus contributes to the measurement uncertainty.

CONCLUSIONS

A 10 kV dc divider consisting of resistor networks immersed in a temperature controlled oil bath has been recalibrated to be used as a laboratory standard for ratio calibration of other instruments. A calibration method was developed to determine the ratio of each decade of the divider using a precision digital voltmeter at low voltage. The overall ratio could then be calculated from the decade ratios. The average, taken over an eight-month period, of the determinations of the 10 000 to 1 ratio of the divider was 9 999.967 with an uncertainty of $\pm 4.9 \times 10^{-6}$ (3 standard deviations). This ratio was compared at 10 kV with a Park-type divider on several occasions and the results agreed within the combined experimental uncertainties. The digital voltmeter method provides a relatively simple and quick method to recalibrate the divider.

With this recalibration of the nearly twenty-year old divider, the National Institute of Standards and Technology is now in a position to offer a dc divider calibration service in the 1 kV to 10 kV voltage range. The estimated uncertainty of such calibrations would be of the order of $\pm 10 \times 10^{-6}$.

ACKNOWLEDGEMENTS

The author would like to thank Martin Misakian for help with setting up the experiment and for obtaining the Park resistor ratio data at 10 kV, and Richard L. Steiner for providing the Josephson calibration data.

Table 8, Park-System Data Summary

Date	Configuration	Actual Ratio	Correction to nominal ($\times 10^6$)	10 kV Divider Correction ($\times 10^6$)	
07 Dec 93	A	9999.951	-4.9	+0.7 \pm 2.30 (1 Dec 93)	
		9999.812	-18.8	-4.1 \pm 0.77 (3 Dec 94)	
	B	9999.970	-3.0	-6.0 \pm 1.46 (8 Aug 94)	
		9999.876	-12.4		
		9999.926	-7.4		
	C	9999.989	-1.1		
		9999.924	-7.6		
	08 Dec 93	A	9999.878	-12.2	
			9999.850	-15.0	
9999.911			-8.9		
9999.878			-12.2		
B		9999.970	-3.0		
		9999.921	-7.9		
C		9999.959	-4.1		
09 Dec 93		A	9999.945	-5.5	
			9999.945	-5.5	
	B	10000.071	+7.1		
		10000.021 to 9999.970	+2.1 to -3.0		
	C	10000.048	+4.8		
		10000.048	+4.8		
13 Dec 93	A	10000.216	+21.6		
		10000.016	+1.6		
		10000.150	+15.0		
	B	9999.876	-12.4		
	C	9999.954	-4.6		
		9999.883	-11.7		
		9999.910	-9.0		
	Mean \pm (3 \times std dev)			-4.0 \pm 26.7	-3.1 \pm 4.9 (both dates combined)

Table 8, Park-System Data Summary (continued)

Date	Configuration	Actual Ratio	Correction to nominal (x 10 ⁶)	10 kV Divider Correction (x 10 ⁶)
26 Jan 94	A	9999.845	-15.5	+0.7±2.30 (1 Dec 93)
		9999.911	-8.9	-4.1±0.77 (3 Dec 93)
	B	9999.869	-13.1	-6.0±1.46 (8 Aug 94)
		9999.818	-18.2	
27 Jan 94	A	9999.923	-7.7	
	B	9999.930	-7.0	
09 Feb 94	A	9999.819	-18.1	
		9999.901	-9.9	
	B	9999.877	-12.3	
		9999.908	-9.2	
Mean ±(3 × std dev)			-11.99±12.4	-3.1±4.9 (both dates combined)

APPENDIX A: Detailed Experimental Calibration Procedures

1. Introduction

The calibration of the high-voltage divider consist of a series of four-step resistance ratio determinations making use of the highly linear 10-volt range of the voltmeter function of the Hewlett-Packard Model 3458A⁵ digital multimeter to measure ratio. The linearity of the 10 V range has been proven to be highly stable and has been calibrated against a 10 V Josephson array standard. The results of this linearity check show a departure from linearity over a ten-to-one ratio which does not exceed one part per million.

2. Setting Up the Calibration Experiment

The experimental system comprises the resistor network in an oil bath, a rack with the electronic control equipment including a personal computer (PC), and an additional table-model computer that is used for the voltage-ratio measurements. Two separate IEEE-488 Interface bus circuits are used. One bus, connected to the PC (IBM Model XT), controls the oil-bath temperature by interconnecting the thermistor control unit (Instrulab System Thermometer Model 3312-14-15) and the programmable power supply (Kepco Bipolar Operational Power Supply/Amplifier, Model BOP 20-20M 488D). The other IEEE-488 bus links the digital multimeter (Hewlett-Packard Model 3458A) to the table-model computer (Hewlett-Packard Model 85) which is programmed to control the digital voltmeter readings.

3. Resistor Network

a. Physical Layout⁶

i. Upper Decades

The resistor network, which forms the actual voltage divider (Fig. 1), is composed of three decades of wire-wound resistors (2 M Ω , 200 k Ω , and 20 k Ω). Each decade has nine nominally equal resistors with the tenth (virtual) resistor consisting of the combined resistance of all lower resistors. Each node of the network is tied to the center pins of two BPO connectors in parallel. The outside conductors of the connectors are connected to the nodes of the guard circuit consisting of an auxiliary network of resistors having the same resistances as the main wire-wound resistors. Nodes of the guard circuit are also connected to (equipotential) metal shields surrounding the main divider resistors. The nodes

⁵ Commercial instruments are identified by manufacturer and model number only to describe the experiment and do not imply an endorsement by the National Institute of Standards and Technology, nor does it imply that the equipment mentioned is necessarily the best available for the purpose.

⁶ C. B. Childers, R. F. Dziuba, L. H. Lee, "A Resistive Ratio Standard for Measuring Direct Voltages to 10 kV," *IEEE Trans. Instrum. & Meas.*, Vol IM-25, No. 4, December 1976.

are marked with the nominal input voltages near their respective connectors ranging from 10 kV to 10 V.

ii. Lower Decades (Kelvin Varley)

The lower decades of the ratio divider consist of a Kelvin-Varley divider that is shunted to give it a 20 k Ω input impedance (see Fig. 2(a)). The Kelvin-Varley has two decades of wire wound resistors, with a guard circuit similar to that used for the upper decades of the main divider followed by a six-dial commercial Kelvin-Varley divider (see Fig. 1). Ratio connections for the upper two decades are made with pairs of jumper cables equipped with BPO plug connectors. The remaining six decades of the commercial Kelvin-Varley divider use rotary dial switches.

Note: For the purpose of this calibration the dials of the commercial Kelvin-Varley are not used and are set to zero. The upper two decades are connected (see section b. vi. below) to give a one-volt output for a 10 kV input applied to the main divider.

b. Connections for the Calibration

i. Supply Leads

Calibrations are carried out with a ten-volt stabilized dc source. The dc voltage is connected from the source to the divider decade under test through a multipole rotary switch. The switch has several functions one of which is the reversal of the polarity of the applied voltage.

The leads from the source to the switch and from the switch to the divider consist of a pair of twisted leads with a shield. Near the connections to the divider, the cable is split into two separate shielded leads that connect to the divider (Fig. 3). The shields of the cable from the source to the switch and from the switch to the cable junction are connected to ground to reduce interference. The shield sections for the two single conductor lead wires, from the cable junction to the divider, are tied to the outer conductors of the respective BPO connectors.

Note that while the inner conductor of the male BPO connector is tied to a node of the divider resistance network, the outer conductor is not grounded but tied to the corresponding node of the guard circuit. The outer conductor, therefore, should not be at ground potential but at nominal the same voltage as the inner conductor. This requires that the shield attached to the mating outer shell of the connector also not be at ground potential. Therefore, the shield of the cable leading to the connector has to be isolated from the grounded shields of other parts of the cable. For convenience, the break in the shields has been made at the cable junction point by trimming the shielding braid back a short distance.

To establish effective guard potentials, the supply leads must feed both the main divider as well as the guard circuit, since the resistor network making up the guard circuit is by itself electrically

isolated from the main divider. To feed both the divider and guard circuits, the inner conductor and outer shield of each of the (single-conductor ends (see Fig. 3) of the) supply leads are connected together so that the main divider and the guard circuit are at the same voltage at their corresponding endpoints. The intermediate nodes of the divider network, however, remain without a direct connection to the corresponding nodes of the guard circuit but are at approximately the same dc voltage.

ii. Sensing Leads

There are two pairs of otherwise identical sensing leads referred to as "A" and "B" leads. These are routed from the divider to the channel selector switch and from the switch to the digital voltmeter. Similar to the arrangement of the supply leads, the cables to and from the switch consist of a pair of twisted conductors that are shielded except for about a decimeter of the cable at the divider end where the cables are each split into two single-conductors. The shields of the two-conductor portions are connected to ground, while the shields of the single-conductor cables are connected only to the respective outer conductors of the (female) BPO connectors and isolated from the shields of the two-conductor cables. Unlike the supply leads, the inner (divider circuit) and outer (guard circuit) of the sensing leads are not connected together so that the voltage sensed is that across the divider network only.

iii. Divider Calibration Supply Connections

To calibrate the highest decade (10 kV to 1 kV) the supply leads (labeled current) are connected to one of the "10 kV"⁷ BPO connectors and the other supply lead is connected to the "0" input terminal of the Kelvin-Varley divider (see Fig. 2(a)). To check whether the polarity is correct, measure the voltage applied to the divider when the switch is in the "A+" position. The voltage at the "10 kV" terminal should be +10 volts (nominal). If the voltage is -10 volts, interchange the supply leads.

iv. Kelvin-Varley Connections

The Kelvin-Varley divider is electrically a separate unit from the main voltage-divider resistance network and is connected to it by two jumper cables (Fig. 2(a)). An additional jumper cable is used to configure a chain of three 10 k Ω resistors into a 25 k Ω shunt which combined with the input resistance of the Kelvin-Varley divider forms the equivalent of the tenth 20 k Ω resistor of the lowest decade of the main divider.

The 1 V tap of the divider is obtained by connecting the first set of jumper leads of the Kelvin-Varley circuit from the "X" and "Y" terminals to the connectors on either side of the "1" marking and connecting the other set of jumper cables across the "0" marking on the next (10^{-1}) range. All

⁷ The numbers and units enclosed by quotation marks correspond to labelling on the cover of the oil bath placed next to the BPO connectors.

switches in the switched section of the Kelvin-Varley divider should be set to zero. The output connectors of the Kelvin-Varley circuit are then the 1 V tap of the overall divider network.

v. Digital Voltmeter Connections

The rotary channel selector switch connects the input of the digital voltmeter either to the "A" or "B" leads, and it also selects the polarity of the supply voltage so that there are four active switch positions: "A+, A-, B-, B+." Intermediate switch positions are open circuits. The control software for the digital voltmeter (on the Hewlett-Packard Model 85 computer) assumes that the "A" leads are connected across the higher voltage. In most cases that means that the "A" leads are connected to the same divider nodes as the supply leads. The "B" leads are normally connected to the divider tap and the bottom connection of the resistor network under test.

The pair of twisted, shielded leads from the switch to the input terminals of the digital voltmeter are wound around a toroidal, high-permeability magnetic core forming a coaxial choke. The co-axial choke presents a low impedance path for signals going to the voltmeter, in one lead and returning through the other. For any ac leakage or induced currents that are asymmetrically going in one lead and returning through an alternate path, the coaxial choke represents a relatively high impedance. The choke, therefore, acts as a filter for unwanted common-mode signals. This is important since the divider is not particularly well shielded against stray ac pickup that would appear as noise in the digital voltmeter readings.

At the digital voltmeter, the white lead of the cable is connected to the "HI" (two-wire) input terminal at the front of the meter, and the black lead to the "LO" terminal. The green lead is connected to the "Guard" terminal.

vi. Divider-Voltage Connection, "A" Leads

One of the BPO female connectors attached to the "A" leads is plugged into the male connector which is in parallel with that connected to the supply (e.g., 10 kV terminal for the highest decade). The other connector is plugged into a special adaptor plug which allows two BPO plugs to be connected in parallel. The parallel connection ensures a common point in the measurements of the ratio voltages. The adaptor is plugged to the male BPO connector marked "0" and is located near the "LO" output terminal on the pie-shaped section covering the Kelvin-Varley divider (see Fig. 2(a)). To check the polarity of the lead connections, set the switch to position "A+" and read the digital voltmeter; a reading of a nominal +10 V should be obtained. If the reading is -10 V, interchange the connection of the "A" leads.

vii. Divider-Voltage Connection, "B" Leads

The "B" leads are connected across the divider decade tap and the common point to obtain the desired ratio voltage, a fraction (usually 1/10th) of the voltage applied across the entire decade section. The BPO connector for the signal return is plugged into the special adaptor mentioned in

vi. above. The other connector is plugged into one of the pair of parallel male BPO connectors at the desired voltage tap. A polarity check similar to that described above should be carried out.

viii. Selection of Connections for the "A" and "B" Leads.

The following sets of divider connections are used to calibrate the decades of the divider. The order in which the decades are calibrated is not significant.

"A" Leads		"B" Leads	
High Terminals	Low	High Terminals	Low
10 kV	0 V	1 kV	0 V
1 kV	0 V	100 V	0 V
100 V	0 V	10 V	0 V
10 V	0 V	1 V	0 V

The "1 V" connection is made at the output of the Kelvin-Varley divider, at the plug connection marked "LO". (See also section iv, above).

ix. Ratios Other Than Ten-to-One

If ratios other than 10 000 to 1 are required, for instance if the voltage applied to the divider is 5 kV, the supply and "A" leads are connected to the desired input voltage, e.g., 5 kV and 0 V, while the "B" leads remain connected to 1 kV and 0 V as before when testing the highest decade string of resistors.

c. Combining Decade Calibrations

i. In Terms of Ratios

The overall ratio of the divider for a nominal 10 000 to 1 ratio is the product of the ratios determined for all four decades. Note that the individual ratios printed out by the Hewlett-Packard Model 85 desktop computer are rounded to six decimal places and have thus limited resolution. Better resolution can be obtained by using the indicated ratio corrections ($\times 10^6$) and applying them to the nominal ratios.

4. Temperature Control

To keep the resistance of the wire-wound ratio resistors stable, the temperature of the resistors and the oil in which they are immersed has to be closely controlled. Temperature control is accomplished with the heating/cooling control subsystem. The temperature measuring subsystem consists of four thermistor sensors connected to a "thermometer" unit that converts the thermistor resistances into corresponding digital temperature values. The thermistors are immersed in the oil through openings in the translucent acrylic cover of the oil bath. Each thermistor is connected individually to the thermometer unit which is mounted on the rack with the rest of the electronic equipment.

The heating/cooling subsystem consists of a set of four Peltier units powered from a programmable power supply and designed to change the temperature of the oil. The four Peltier heating and cooling units are mounted evenly spaced on side of the cylindrically shaped oil bath. Small fan units remove the heated air from each of these units. The fans are powered directly from the 120 V, 60 Hz line using a flexible twin-lead line cord. The Peltier units are electrically connected in series and are powered from a rack-mounted, programmable, dc current supply. The current can be varied remotely via the IEEE 488-interface bus from minus to plus full scale. Also, the supply has provisions for limiting the output current to protect the Peltier units.

Initially, when the bath is at room temperature, the heating current is limited to approximately 7.5 A. After the oil temperature comes to within ± 0.1 °C of the set point (24.5 °C), the current limit is reduced to 5 A for both heating and cooling.

5. Operation of the Temperature Control Program.

The program is written in GW Basic for use with the National Instruments 488 Interface Card. Following the instructions for interface programming provided by National Instruments, the default parameters have been set up for the two subsystems, such as time-outs, etc.

After switching on the computer, and after it has completed the initialization, type "run" at the DOS prompt and follow the instructions displayed on the screen. The "run" command will start the basic program. When the program is running, the first two statements are queries to make sure the oil is stirred and that the fans are cooling the Peltier units. It will take about three to four hours to bring the oil up to operating temperature.

a. Program Screen Display

While the program is running, the screen alternately displays numerical data and a graphic (bar graph) display. The program samples the temperature data about every 15 seconds during normal operation. Four thermistors are actually connected; a maximum of six thermistors could be plugged into existing connectors. The thermometer unit is programmed to scan five of the six possible connections. (Since, normally, there are only four thermistors, one position is shown as "OPEN"). The program computes the correct average of the temperature irrespective of how many thermistors are connected and into which connectors they are plugged in.

b. Numerical Display

The display shows the following:

- i. Elapsed time in seconds since the beginning of the run.
- ii. The number of the measurement cycle; i.e., the number of times the thermometer unit has been queried.
- iii. The five scanned outputs of the thermometer unit.
- iv. The average temperature and the number of active thermistor probes.
- v. The current Reference Temperature and the set-point temperature
- vi. The range of average (measured) temperatures. [Minima and maxima displayed are valid only after the measured temperature reaches the set-point temperature minus 0.1 °C. Up to that time Min=26 and Max=0]
- vii. The range of the reference temperature (rMin, rMax). These values should be symmetrical about the set-point temperature.
- viii. The cumulative number of seconds that the reference temperature has ramped up and down.
- ix. The state of the heating/cooling function is indicated by a text message and by the color border of the display. A red background indicates that heating is turned on, blue that cooling is turned on, and green indicates that both are turned off.

c. Bar-graph display.

The bar-graph display alternates with the numerical display. The bar graphs picture the average temperature measured and the reference temperature, as well as indicating the set point.

- i. The upper bar graph provides an indication of the measured temperature. Temperature is plotted from left to right. To obtain greater resolution, the temperature zero is displaced off-screen to the left. The setpoint temperature is approximately at the center of the display. Change from the last reading is shown by a change in color; red (brown) for increases in temperature, blue for decreases in temperature. The trend, increasing or decreasing, is also indicated by arrows pointing to the right or left respectively.
- ii. The lower bar graph shows the reference temperature. As with the measured temperature, arrows indicate the increasing or decreasing trend.
- iii. The temperature is shown, rounded to three decimal places, at the left-hand extreme of the bar graph. The setpoint temperature is indicated by a vertical arrow.

d. Error Conditions

The program monitors the 488-Interface bus status, and if a malfunction occurs in the Thermometer unit or if the power supply (heater current source) does not respond, a diagnostic message is displayed on the screen. If the malfunction can be cleared, for instance, by turning off the thermometer unit and turning it back on again which reinitializes various functions, the temperature control program can be restarted (continued) by pressing the ENTER key. Instructions are shown on the screen.

6. Terminating the Program

The temperature control program can only be terminated by pressing the control+break keys which stops execution of the BASIC routines. On the "OK" prompt, after BASIC program execution has terminated, type SYSTEM [ENTER] which will cause the program to exit BASIC and return control to DOS.

Before shutting off the computer, the hard disk should be "parked" with a BYE [ENTER] command.

Appendix B

OIL-BATH TEMPERATURE CONTROL PROGRAM

Appendix B contains an annotated listing of the temperature control program. The program is written in GW BASIC and the statements 1 to 67 follow the code published by National Instruments for their IEEE-488 interface bus. The remainder of the program was written for this application by the author.

```

1000 REM *****
1001 REM *****
1002 REM *****
1003 REM *****
1004 REM *****
1005 REM *****
1006 REM *****
1007 REM *****
1008 REM *****
1009 REM *****
1010 REM *****
1011 REM *****
1012 REM *****
1013 REM *****
1014 REM *****
1015 REM *****
1016 REM *****
1017 REM *****
1018 REM *****
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1111 REM *****
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1177 REM *****
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1186 REM *****
1187 REM *****
1188 REM *****
1189 REM *****
1190 REM *****
1191 REM *****
1192 REM *****
1193 REM *****
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1195 REM *****
1196 REM *****
1197 REM *****
1198 REM *****
1199 REM *****
1200 REM *****

```

APPENDIX B

This program is designed to control the temperature of the oil bath for the high-voltage dc divider within $\pm 0.1^\circ\text{C}$. The temperature is measured with up to five probes using an INSTRULAB[™] Thermometer system and a KEPCO[™] power supply in the current mode (limited to a maximum of 5 A) that feeds thermoelectric (Peltier) modules for heating and cooling.

Lines 1 through 67 initialize the functions and constants necessary for operation of the IEEE-488 Interface Bus

```

1 CLEAR , 600001 : IBINIT1=600001 : IBINIT2=IBINIT1+3 : IBINIT3=IBINIT1+6 : IBINIT4=IBINIT1+9 : BLOAD="bib.m", IBINIT1
2 CALL IBINIT1(IBFIND, IBTRG, IBCLR, IBPCT, IBSIC, IBLOC, IBPPC, IB8NA, IBONL, IBRSC, IBRE, IBRSV, IBPAD, IBSD,
  IBST, IBDMA, IBEOS, IBMO, IBEOT, IBRDF, IBWRTF, IBTRAP, IBDEV, IBLN, IBLINES, IBCONFIG)
3 CALL IBINIT2(IBGTS, IBCAC, IBWAIT, IBPOKE, IBWRT, IBWRTA, IBCMD, IBCMDA, IBRD, IBRDA, IBSTOP, IBRPP, IBRSP,
  IBDIAG, IBXTRC, IBRD1, IBWRT1, IBRDIA, IBWRTIA, IBEVENT, IBSTAX, IBERRX, IBCNTX)
4 CALL IBINIT3(SEMDCMDS, SENDSETUP, SENDDATABYTES, SEND, SENDLIST, RECEISETUP, RCVRESPMSG, RECEIVE, SENDIFC,
  DEVCLEAR, DEVCLEARLIST, ENABLELOCAL, ENABLEREMOTE, SETRWLS, SENDLLO)
5 CALL IBINIT4(PASSCONTROL, READSTATUSBYTE, TRIGGER, TRIGGERLIST, PPOLLCONFIG, PPOLLUNCONFIG, PPOLL, RESETSYS,
  FINDRQS, ALLSPOLL, FINDLSTN, TETSYS, IBRDKEY, IBWRTKEY, WAITSRQ, TESTSRQ)
6 REM
7 REM GPIB Commands:
8 REM
9 UNLX = &H3F : UNTX = &H5F : GTLX = &H1 : SDCX = &H4 : PPCX = &H5 : GGETX = &H8 : TCTX=&H910 : LLOX = &H11 :
  DCLX = &H14 : PPUX = &H15 : SPEX = &H18 : SPDX = &H19 : PPEX = &H60 : PPDX = &H70
11 REM
12 REM GPIB status bit vector:
13 REM
14 EERR = &H8000 : TIMO = &H4000 : EEND = &H2000 : SRQI = &H1000 : RQS = &H800 : SPOLL = &H400 : EEVENT = &H200
15 CMPL = &H100 : LOK = &H80 : RREM = &H40 : CIC = &H20 : AATN = &H10 : TACS = &H8 : LACS = &H4 : DTAS = &H2 : DCAS
  = &H1
16 REM
17 REM Error messages returned in global variable iberr:
18 REM
19 EDVR = 0 : ECIC = 1 : ENOL = 2 : EADR = 3 : EARG = 4 : ESAC = 5 : EABO = 6 : ENEB = 7
20 EOIP = 10 : ECAP = 11 : EFSO = 12 : EBUS = 14 : ESTB = 15 : ESRO = 16 : ETAB = 20
21 REM
22 REM EOS mode bits:
23 REM
24 BINX = &H1000 : XEOSX = &H800 : REOSX = &H400
25 REM
26 REM Timeout values and meanings:
27 REM
28 TNONEX = 0 : T10USX = 1 : T30USX = 2 : T100USX = 3 : T300USX = 4 : T1MSX = 5 : T3MSX = 6 : T10MSX = 7
29 T30MSX = 8 : T100MSX = 9 : T300MSX = 10 : T1SX = 11 : T3SX = 12 : T10SX = 13 : T30SX = 14 : T100SX = 15
30 T300SX = 16 : T1000SX = 17
31 REM
32 REM Miscellaneous:
33 REM
34 SX = &H8 : LFZ = &HA
35 REM
36 REM IBLN Constants:
37 REM
38 ALL.SADX = -1 : NO.SADX = 0
39 REM
40 REM IBEVENT Constants
41 REM
42 EVENTDTASX = 1 : EVENTDCASX = 2
43 REM
44 REM "OPTION" Selection codes for IBCONFIG function:
45 REM

```

```

46  IBCPADX = &H1 : IBCSADX = &H2 : IBCTMOX = &H3 : IBCEOTX = &H4 : IBCPPCX = &H5 : IBCREADORX = &H6
47  IBCAUTOPOLLX = &H7 : IBCCICPROTX = &H8 : IBCIROX = &H9 : IBCSCX = &HA : IBCSREX = &HB : IBCEOSROX = &HC
48  IBCEOSWRTX = &HD : IBCEOSCHPX = &HE : IBCEOSCHARX = &HF : IBCPPZX = &H10 : IBCTININGX = &H11 : IBCOMAX = &H12
49  IBCREADADJUSTX = &H13 : IBCWRITEADJUSTX = &H14 : IBCEVENTQUEUOX = &H15 : IBCSPOLLBITX = &H16 : IBCSEMDLLOX =
    &H17
50  IBCSPOLLTIMEX = &H18 : IBCPPOLLTIMEX = &H19 : IBCNOENDBITONEOSX = &H1A
51  REM
52  REM These values are used by the Send 488.2 command:
53  REM
54  MULLENDX = &H0 : NLENDX = &H1 : DABENDX = &H2
55  REM
56  REM This value is used by the 488.2 Receive command:
57  REM
58  STOPENDX = &H100
59  REM
60  REM The following values are used by the IBLINES function:
61  REM
62  VALIDEOI = &H80 : VALIDATM = &H40 : VALIDSRQ = &H20 : VALIDREN = &H10 : VALIDIFC = &H8 : VALIDNRFD = &H4 :
    VALIDOAV = &H1
63  BUSEOI = &H8000 : BUSATN = &H4000 : BUSSRQ = &H2000 : BUSREN = &H1000 : BUSIFC = &H800 : BUSNRFD = &H400 :
    BUSNDAC = &H200 : BUSDAV = &H100
64  REM
65  REM This value is used to terminate an address list. It should be assigned
66  REM to the last entry.
67  REM

```

Lines 100 through 200 define the program names of the bus controller, the temperature measurement system, and the heater power supply.

```

100 REM Parameter Values
110 CONTROLLERS="GP180" : CALL IBFIND (CONTROLLERS, BRDX)
120 THERMOMETERS="TSYS" : CALL IBFIND (THERMOMETERS, TEMPX)
130 DEVNAMES="KEPCO" : CALL IBFIND (DEVNAMES, PWRX)
140 DIM TSTORE (500), TEMPSTORE(500), AVESTORE(500)
150 PRINT : PRINT "Are the fans turned on ? " : INPUT YS : IF MIDS(YS, 1, 1)="Y" OR MIDS(YS, 1, 1)="y" THEN 160 ELSE 150
160 PRINT : PRINT "Is the stirrer running ? " : INPUT YS : IF MIDS(YS, 1, 1)="Y" OR MIDS(YS, 1, 1)="y" THEN 170 ELSE 160
170 COLOR 14, 2, 2 'green background=heating/cooling off
180 TAVG=0 : T=0 : NOW=0 : SPAN=-.2 : SETPOINT=24.5 : OFFSET=ABS(SPAN/2)
190 SAMPLES=10 : INTERVAL=5 : PERIOD=SAMPLES * INTERVAL : INCR=0 : REFTMP=SETPOINT+OFFSET
200 MIN=26 : MAX=0 : MFLAG=1 : DFLAG=0 : RMIN=100 : RMAX=0 : COUNT=0 : ERNUM=0

```

The temperature measurement control cycle starts by determining the elapsed time from the start of the program in seconds. If this time is a multiple of the 'Interval' (defined as one of the program parameters), then a set of temperature readings is taken. An additional 1-second delay is introduced before readings are actually taken.

```

300 ***** Start of measurement/control cycle
310 ON ERROR GOTO 1810
320 PRINT 'determine sampling time
330 GOSUB 400 :
340 IF TIME MOD INTERVAL > 0 THEN 330
350 PRINT "Elapsed time ";TIME;" seconds" : TIME1=TIME
360 GOSUB 400 : IF TIME > TIME1+1 THEN 450 ELSE GOTO 360 'loop until sampling time
370 '

```

Subroutine to convert 'time' into elapsed seconds

```

400 ***** DETERMINE TIME AND CONVERT TO SECONDS
410 TIME= VAL(MIDS(TIME$, 1, 2))*3600+VAL(MIDS(TIME$, 4, 2))*60+VAL(MIDS(TIME$, 7, 2))
420 IF TIME0=0 THEN TIME0=TIME

```

```
430      TIME=TIME-TIMEO
440      RETURN
```

Temperature measurement routine: definition of bus address, bus 'name' of the temperature measurement system, and temperature 'read' command. The 'RESULTS\$' string variable is filled with the appropriate number of blanks, and the interface and the 'device' are initialized. If a bus error is detected, the bus status (10 most recent values) is stored in a register. A command to read outputs of 5 thermocouples is then sent to the temperature measurement system. Again the bus status is checked, and if an error has occurred the status is stored, and the program branches to an error routine that turns off the power supply and permits the temperature system to be reset. If no error occurs, a two-second waiting period allows the thermometer unit to settle before the reading is fetched and stored in the computer.

```
450 ' measure thermocouple outputs
460 IF DFLAG<>0 THEN 800
500 ***** measure temperature
510 ACTIVE$="Instrulab"
520 BOARDX=0 : ADDRZ = 7      : COMMANDS="MEAS:DATA ? (01, 2, 3, 4, 5)
530 'FOR I=1 TO 10
540 N=N+1
550 RESULTS$=SPACES(106)
560 CALL SENDIFC (BOARDX)
570 CALL DEVCLEAR (BOARDX, ADDRZ)
580 IF IBSTAX >1 THEN ERRORVAR(ER MOD 10)=IBSTAX : ER=ER+1
590 CALL SEND(BOARDX, ADDRZ, COMMANDS, NLENDX)
600 IF IBSTAX >1 THEN ERRORVAR(ER MOD 10)=IBSTAX : ER=ER+1
610 IF IBSTAX AND EERR THEN 1840
620 GOSUB 400 : DELAYSTART=TIME '2 s delay between command reading data to prevent hangups
630 GOSUB 400 : DELAY=TIME-DELAYSTART : IF DELAY < 2 THEN 630
640 CALL RECEIVE(BOARDX, ADDRZ, RESULTS, STOPENDX)
650 IF IBSTAX >1 THEN ERRORVAR(ER MOD 10)=IBSTAX : ER=ER+1 'record 10 previous error messages
660 PRINT N, MIDS(RESULTS, 1, 15)+"" + ""+MIDS(RESULTS, 18, 15) 'print temperature readings
670 PRINT N, MIDS(RESULTS, 35, 15)+"" + ""+MIDS(RESULTS, 52, 15)
680 PRINT N, MIDS(RESULTS, 69, 15)+"" + ""+MIDS(RESULTS, 86, 15)
690 N=0 : AVETEMP=0
```

Temperature is averaged by scanning the input strings, summing values in non-blank in fields, and dividing by the number of values found. The individual readings and the average is displayed.

```
700 FOR K=4 TO 103 STEP 17 ' determine average temperature
710 PRINT
720 IF MID$(RESULT$, K, 1)=" " THEN 760 ELSE
CHANNEL(N)=VAL(MID$(RESULT$, K, 1))
730 IF MID$(RESULT$, K+8, 4)="OPEN" THEN 760 ELSE
TEMPERATURE(CHANNEL(N)) =VAL(MID$(RESULT$, K+4, 8))
740 AVETEMP=AVETEMP+TEMPERATURE(CHANNEL(N))
750 N=N+1
760 NEXT K
770 IF N=0 THEN 1840 ELSE AVETEMP= AVETEMP/(N)
780 PRINT TIME$;" ";DATE$;" Run #";M;"Average measured temperature is:
";AVETEMP;"N= ";N
790 '
```

Because the temperature is being measured in the main vessel and because of the large thermal inertia of the oil, it is necessary to modulate the reference temperature to decrease the hysteresis in the controlled temperature fluctuations. The reference temperature is successively increased and decreased linearly.

```
800 ' determine reference temperature (modulated about the setpoint)
810 COUNT = COUNT + 1
820 IF COUNT MOD (2*SAMPLES)=0 THEN SPAN=-SPAN : TSTORE(TO MOD 500)=TIME : TEMPSTORE(TO MOD 500)=REFTEMP : AVESTORE(TO
MOD 500)=AVETEMP : TO=TO+1 : COUNT=0
830 IF SPAN >0 THEN UP=UP+TIME-LASTTIME : LASTTIME=TIME ELSE DOWN=DOWN+TIME-LASTTIME : LASTTIME=TIME
840 REFTEMP=REFTEMP + SPAN/PERIOD
850 'PRINT T, SIN(T/100)*SPAN;INCR, REFTEMP, (T*SAMPLES MOD PERIOD*SAMPLES)/SAMPLES, SPAN, OFFSET
```

Records the maximum and minimum excursions of the reference temperature and counts the number of up and down gradients. (Ideally these should average to zero.)

```
860 IF REFTEMP > RMAX THEN RMAX=REFTEMP
870 IF REFTEMP < RMIN THEN RMIN=REFTEMP
```

Records the maximum and minimum excursions of the average temperature after the temperature has reached the interval of ($\pm 0.1 \cdot$ + Setpoint temperature).

```
880 IF AVETEMP > SETPOINT-.1 AND AVETEMP < SETPOINT+.1 THEN MFLAG=0
890 IF MFLAG=0 AND AVETEMP > MAX THEN MAX=AVETEMP
900 IF MFLAG=0 AND AVETEMP < MIN THEN MIN=AVETEMP
910 PRINT "Measured temperature= ";AVETEMP;" Min.= ";MIN;" Max.= ";MAX
920 PRINT "Reference temperature= ";REFTEMP;" rMin= ";RMIN;" rMax= ";RMAX
930 PRINT "Setpoint Temperature= ";SETPOINT
940 PRINT "up= ";UP;" down= ";DOWN
950 '
```

On the basis of the relative values of the reference and average measured temperatures, the power supply current is switched to heating, off, or cooling.

```
1000 **** determine control points
1010 IF AVETEMP < REFTEMP AND HEAT=0 THEN HEAT=1 'heating
1020 IF AVETEMP > REFTEMP AND HEAT=1 THEN HEAT=0 'off between heating and cooling
1030 IF AVETEMP > REFTEMP AND HEAT=0 THEN HEAT=-1 'cooling
1040 IF AVETEMP < REFTEMP AND HEAT=-1 THEN HEAT=0 'off between cooling and heating
1050 IF DFLAG<0 THEN 320
```

The value of the 'HEAT' variable determines the code word that controls the magnitude and direction of the (power)supply current source.

```
1100 ***** Heater control routine: Determine control code word
1110 ACTIVE$="Kepco"
1120 KAMPL=5 : DEVNAME$="KEPCO" : LIMIT=5 : CONTROLLERS="GPIB0"
1130 KEPCO= INT(ABS(KAMPL*HEAT)/20*999) : IF HEAT < 0 THEN PREFIX=5 ELSE PREFIX=4
1140 IF KEPCO > 99 THEN CONTROLWORDS = MIDS(STR$(PREFIX), 2, 1)+MIDS(STR$(KEPCO), 2, 3)+MIDS(STR$(INT(LIMIT/20*99)), 2, 2)+" "
1150 IF KEPCO > 9 AND KEPCO < 100 THEN CONTROLWORDS=MIDS(STR$(PREFIX), 2, 1)+"0"+MIDS(STR$(KEPCO), 2, 2)+MIDS(STR$(INT(LIMIT/20*99)), 2, 2)+" "
1160 IF KEPCO < 10 THEN CONTROLWORDS=MIDS(STR$(PREFIX), 2, 1)+"00"+MIDS(STR$(KEPCO), 2, 1)+MIDS(STR$(INT(LIMIT/20*99)), 2, 2)+" "
```

The power supply control word is transmitted over the bus. If the supply does not respond to the bus command, the program branches to an error routine that permits the malfunction to be corrected before continuing the control function.

```

1200 ***** Heater control routine: Send control code word to supply
1210 ON ERROR GOTO 1810 : GOSUB 1220 : GOTO 1400 'set up power supply
1220 IF PMRX < 1 THEN PRINT "Power Supply not found" : END 'Check supply is active
1230 BOARDX=0 : PADDRX = 6
1240 CALL SENDIFC (BOARDX)
1250 CALL DEVCLEAR (BOARDX, PADDRX)
1260 CALL SEND(BOARDX, PADDRX, CONTROLWORDS, NLENDX)
1270 POWERSTATUS(PS MOD 10)=IBSTAX : PS=PS+1
1280 IF IBSTAX AND EERR THEN 2110
1290 BOARDX=0 : ADDR = 7
1300 RETURN

```

The state of the current supply (heating/off/cooling) is indicated by the screen background color (red/green/blue) and by text displayed when the power supply control function is executed.

```

1400 ***** Change display background color to correspond to heater setting
1410 IF HEAT=1 THEN COLOR 14, 4, 4
1420 IF HEAT=0 THEN COLOR 14, 2, 2
1430 IF HEAT=-1 THEN COLOR 14, 3, 3
1440 IF PREVIOUSHEAT <> HEAT THEN PREVIOUSHEAT=HEAT : PRINT "Change in setting"
1450 IF HEAT=1 THEN PRINT "Heater turned on ";
1460 IF HEAT=0 THEN PRINT "Heating/Cooling turned off ";
1470 IF HEAT=-1 THEN PRINT "Cooling turned on ";
1480 GOSUB 2410 ' display temperature bar graph
1490 GOTO 300 ' next measurement cycle

```

This routine can generate simulated temperature fluctuations for test purposes.

```

1500 **** simulate temperature fluctuations -- only used for program testing
1510 INCR=INCR+.5*HEAT : IF HEAT=0 THEN INCR=0
1520 AVETEMP=SIN (T/100)*SPAN +INCR
1530 RETURN
1540 '
1550 '

```

This subroutine analyzes the Interface Bus status and displays the result on the screen.

```

1600 ' ***** Decode 488 Interface Status Word
1610 PRINT "Status Word is "; ACTIVE$;IBSTAX : X=IBSTAX : IF IBSTAX=0 THEN 1770
1620 'IF IBSTAX AND EERR THEN 237
1630 IF IBSTAX AND 1 THEN PRINT "GPB-PC is in DEVICE CLEAR state"
1640 IF IBSTAX AND 2 THEN PRINT "GPB-PC is in DEVICE TRIGGER state"
1650 IF IBSTAX AND 4 THEN PRINT "GPB-PC is LISTENER"
1660 IF IBSTAX AND 8 THEN PRINT "GPB-PC is TALKER"
1670 IF IBSTAX AND 16 THEN PRINT "ATTENTION is asserted"
1680 IF IBSTAX AND 32 THEN PRINT "GPB-PC is CIC"
1690 IF IBSTAX AND 64 THEN PRINT "GPB-PC is in REMOTE state"
1700 IF IBSTAX AND 128 THEN PRINT "GPB-PC is in LOCKOUT state"
1710 IF IBSTAX AND 256 THEN PRINT "I/O is completed"
1720 IF IBSTAX AND 2048 THEN PRINT "Device requesting service"
1730 IF IBSTAX AND 4096 THEN PRINT "SERVICE REQUEST (SRQ) bit on"
1740 IF IBSTAX AND 8192 THEN PRINT "GPB-PC detected END or EOS"
1750 IF IBSTAX AND 16384 THEN PRINT "Time limit exceeded"

```

```

1760 IF IBSTAX AND EERR THEN PRINT "GB18 error" : BEEP
1770 RETURN
1780 '

```

Routines to pause the program in case of malfunction or other program errors. If the temperature measuring systems fails, the power supply is turned off. The interface bus is reset, and the program pauses waiting for an input from the keyboard. This provides an opportunity to reset (turn off/on) the INSTRULAB™ system before continuing the program. Similarly, if the power supply does not respond to commands via the bus, the program pauses and waits for an input from the keyboard. For other types of errors, the error number (see GW Basic Manual) and program line on which the error was detected are displayed. The first five errors on the list are ignored.

```

1800 *****Thermometer and Power Supply error routines
1810 ***** "On Error" Routine
1820 IF ERR= 189 THEN 2110 'Power Supply malfunction
1830 IF ERR< 188 THEN 2210 'Analyze status word or print error type
1840 PRINT TIMES, DATES : GOSUB 1600
1850 T1= TIMER
1860 T2 = TIMER : WHILE T2 < T1+2 : GOTO 1860 : WEND : GOTO 1980 '2 s delay
1900 ***** INSTRULAB malfunction; shut down power supply
1910 GOSUB 1920 : GOTO 1980 ' Reset bus
1920 RINT "Resetting System": IBSTAX=0
1930 ADDRESSLISTX (0) = ADDR
1940 ADDRESSLISTX (1) = PADDR
1950 ADDRESSLISTX (2) = NOADDR
1960 CALL RESESYS (BOARDX, ADDRESSLISTX (0))
1970 ON ERROR GOTO 1810 : RETURN
1980 CONTROLWORDS="400000" : COLOR 14, 2, 2 : GOSUB 1220 'set power supply to zero
2000 ' Thermometer system error
2010 PR : BEEP : PRINT DATES, TIMES; " *** E R R O R *** " : PRINT : PRINT
2020 PR:AT " *****
2030 PRINT " * Reset INSTRULAB THERMOMETER System *"
2040 PRINT " *****
2050 PRINT "Hit ENTER key to continue" : INPUT X : GOTO 180 'restart
2060 '
2100 ***** Power supply failure
2110 PRINT : BEEP : PRINT DATES, TIMES; " *** E R R O R *** " : PRINT : PRINT
2120 PRINT " *****
2130 PRINT " # KEPCO Power Supply not responding #
2140 PRINT " *****
2150 GOSUB 1600 : GOSUB 1920 : PRINT "Hit ENTER key to continue" : INPUT X : GOTO 180 'restart
2160 '
2200 ***** Other types of error
2210 COLOR 14, 5, 5 : PRINT "Line ";ERL; ", error number ";ERR;
2220 ERNUM=ERNUM+1 : IF ERNUM < 5 THEN RESUME NEXT : GOSUB 1920 : GOTO 180 'Reset system, start over
2230 PRINT "To reset system hit ENTER key" : INPUT X : GOTO 170
2300 ***** Display routines
2310 CLS : VIEW PRINT ' set up for bar graph display
2320 SETPOINT=25 : IAVETEMP=10
2330 REFTEMP=SETPOINT+(RND*10)-5 : RT=INT(REFTEMP+.5) : AVETEMP=RND*50 : GOSUB 2400 'display temperature bar graph
2340 RETURN

```

Subroutine to display the average oil-bath temperature and reference temperature in bar-graph format. The bar graphs have the following features:

- To achieve better resolution, the zero temperature point is offset to the left and is not shown.
- An arrow at the top of the screen marks the Set Point
- The top horizontal bar indicates the average oil temperature; changes in temperature are differentiated with color (red for increases, blue for decreases). The trend is also indicated by an arrow at the end of the bar.
- The lower bar represents the Reference Temperature with an arrow at the end of the bar indicating the direction of change.
- An arrow below the two bars indicates the average measured temperature for emphasis.
- Numerical values of temperature are displayed on the left-hand side of the graph.
- The text color changes from yellow to white when the average temperature is within $\pm 0.1^{\circ}\text{C}$ of the setpoint.

```

2400 ***** Plot temperatures
2410 DEF FNTEMP(TEMP)=INT(TEMP+.5)-25
2420 IF ABS(AVETEMP-SETPOINT)>=1 THEN 2440
2430 DEF FNTEMP(TEMP)=INT((TEMP-SETPOINT)*10+.5)
2440 A=FNTEMP(AVETEMP)+25 : IA=FNTEMP(IAVETEMP)+25 : RT=FNTEMP(REFTEMP)+25 : SP=FNTEMP(SETPOINT)+25
2450 IF A<0 THEN A=0
2460 IF IA<0 THEN IA=0
2470 IF RT<0 THEN RT=0
2480 T1= TIMER
2490 T2 = TIMER : WHILE T2 < T1+2 : GOTO 2490 : WEND ' 2 s delay
2500 CLS : VIEW PRINT 1 TO 20
2510 COLOR 14, 0 : LOCATE 1, SETPOINT+7 : PRINT"SET POINT ";CHR$(25)
2520 COLOR 0, 0 : LOCATE 4, 1 : S=1 : X=1 : Y=80 : GOSUB 2800
2530 IF (A-IA) < 0 THEN COLOR 11, 4 ELSE COLOR 14, 4
2540 LOCATE 2, 1 :PRINT"Meas Temp "; : PRINT USING "##.###";AVETEMP
2550 COLOR 0, 0 : LOCATE 2, 17 : S = 1 : X=1 : Y=64 : GOSUB 2800
2560 IF INT(AVETEMP*1000) <= INT(IAVETEMP*1000) THEN 2590
2570 COLOR 14, 0 : LOCATE 2, 17 : S=1 : X=1 : Y=IA : GOSUB 2800
2580 COLOR 12, 0 : LOCATE 2, 17+IA : S=1 : X=IA : Y=A-1 : GOSUB 2800 : PRINT CHR$(8)+CHR$(26) : GOTO 2610
2590 COLOR 14, 0 : LOCATE 2, 17 : S=1 : X=1 : Y=A : GOSUB 2800
2600 COLOR 11, 0 : LOCATE 2, 17+A : PRINT CHR$(8)+CHR$(27)
2610 COLOR 11, 0 : LOCATE 2, 18+A : S=1 : X=A+2 : Y=IA : GOSUB 2800
2620 COLOR 14, 0 : LOCATE 3, 1 : PRINT "Ref Temp "; : PRINT USING "##.###";REFTEMP
2630 COLOR 0, 0 : LOCATE 3, 17 : S=1 : X=1 : Y=67 : GOSUB 2800
2640 IF SPAN > 0 THEN ARROWS=CHR$(26) ELSE ARROWS=CHR$(27)
2650 COLOR 13, 0 : LOCATE 3, 17 : S=1 : X=1 : Y=RT : GOSUB 2800 : PRINT CHR$(8); : PRINT ARROWS
2660 COLOR 0, 0 : LOCATE 4, 1 : S = 1 : X=1 : Y=80 : GOSUB 2800
2670 IF ABS(AVETEMP-SETPOINT)>.1 THEN 2690
2680 COLOR 15, 0 : LOCATE 4, A+5 : PRINT "TEMPERATURE"+CHR$(32)+CHR$(24) : GOTO 2700
2690 COLOR 14, 0 : LOCATE 4, A+5 : PRINT "TEMPERATURE"+CHR$(32)+CHR$(24)
2700 IAVETEMP=AVETEMP

```

```
2710 'IF HEAT=1 then COLOR 14, 4, 4 ELSE IF HEAT=0 then COLOR 14, 2, 2 ELSE COLOR 14, 3, 3
2720 VIEW PRINT
2730 'COLOR 14, 2, 2 : LOCATE 6, 17 : PRINT"012345678901234567890123456789012345678901234567890123"
2740 T1= TIMER
2750 T2 = TIMER : WHILE T2 < T1+5 : GOTO 2750 : WEND '5 s delay to read bar graph
2760 CLS : VIEW PRINT 'restore screen
2770 RETURN
```

Subroutine to draw bars on the graph

```
2800          FOR I= X TO Y STEP S 'routine to draw bars for graph
2810          PRINT CHR$(219);
2820          NEXT I : RETURN
2830 END
2900 'APPLICX Version 04 AUG 93
```


Appendix C

CONTROL PROGRAM FOR THE DIGITAL VOLTMETER

Appendix C contains as listing of the program that controls the operation of the digital voltmeter through a IEEE-488 interface bus and calculates the ratio of the voltages measured. The program was written Raymond S. Turgel in Hewlett-Packard BASIC (Model 85 Version). The program is interactive and requires entry of the date, terminals of the divider to which the voltmeter is connected separated by forward slashes, e.g., 1K/100/0 (1 kV, 100 V, and 0 V), and the position of the selector switch (+A, -A, +B, and -B). The digital voltmeter is programmed to measure sets of ten readings during ten periods of the power-line frequency and calculate the highest reading, lowest reading and standard deviation of the set.

The computer screen displays all ten readings, the standard deviation, the peak-to-peak deviation (in ppm), and the lowest standard deviation recorded on previous runs of the same measurement. If the standard deviation is less than 1 106, and the ratio between the highest and lowest reading differs by not more than 2 106, the average reading is recorded automatically. Otherwise, more sets of readings are taken. On "noisy" readings, where the standard deviation always exceeds 1 106, the operator can override the decision to take more readings by pressing K1 or K2. K1 will record the average of a set of previous readings with the lowest standard deviation. K2 records the latest set of readings taken. After readings corresponding to all four positions of the selector switch have been taken (in any desired order), the ratio is computed and printed on the tape of the built-in printer. The program then asks for the parameters of the next test point.

Digital Voltmeter Control Program

```

4 ! FILE "DVM RA"
5 ! REVISED JUNE 8, 1994
10 ON ERROR GOTO 240
15 ON TIMEOUT 7 GOTO 5000 @ SET TIMEOUT 7;2000
20 DIM V(10),A1(2,2)
22 R0$="2 M RESISTORS"
28 V$=" "
30 N=10 @ F1=0 @ F2=0 @ F3=0 @ F4=0 @ X$="1" @ Y$="0" @ Z$="00000" @ T1=1 @ T2=2
5 @ C1=0
35 S2=-1 @ M2=0
36 DISP "ENTER DATE" @ INPUT D3$
37 IF D3$<>" " THEN D9$=D3$
40 ! Set up Voltmeter
45 DISP "VOLTAGE TERMINALS" @ DISP V$ @ INPUT V1$ @ IF V1$<>" " THEN V$=V1$
46 DISP "Enter TIME and TEMPERATURE" @ INPUT T1$,H$
47 F$=CHR$(171)&CHR$(193)&CHR$(173)&CHR$(193)&CHR$(171)&CHR$(194)&CHR$(173)&CHR$(
(194)
49 IF C1 THEN CLEAR
50 IF C1 THEN CLEAR
51 DISP "ENTER SWITCH POSITION (+A,-A;+B,-B)" @ DISP "Choose any underlined swit
ch position "
52 DISP "      "&F$ @ INPUT S$
55 S2=-1 @ C1=0
56 CLEAR
60 IF S$="+A" THEN F1=1 @ I1=1 @ I2=1 @ GOTO 80
61 IF S$="-A" THEN F2=1 @ I1=2 @ I2=1 @ GOTO 80
62 IF S$="+B" THEN F3=1 @ I1=1 @ I2=2 @ GOTO 80
63 IF S$="-B" THEN F4=1 @ I1=2 @ I2=2 @ GOTO 80
70 DISP "ENTRY ERROR" @ GOTO 50
80 ! Set up voltmeter
81 ON KEY# 1,"ACTUAL" GOTO 3000
82 ON KEY# 2,"LOWEST" GOTO 4000
83 ON KEY# 5,"ACCEPT" GOTO 87
84 IF C1 THEN KEY LABEL
87 F=2*(2*(I2-1)+I1) @ F[F-1,F]=S$[1,1]&CHR$(NUM(S$[2,2])+32)
88 OUTPUT 722 ;"PRESET NORM"
90 OUTPUT 722 ;"NRDGS 10 "
100 OUTPUT 722 ;"NPLC 10"
110 OUTPUT 722 ;"MATH STAT"
120 ! ENTER 722 ; V(1),V(2),V(3),V(4),V(5),V(6),V(7),V(8),V(9),V(10)
121 FOR I=1 TO 10 @ ENTER 722 ; V(I) @ NEXT I
130 OUTPUT 722 ;"RMATH SDEV"
140 ENTER 722 ; S1
150 OUTPUT 722 ;"RMATH UPPER"
160 ENTER 722 ; U
170 OUTPUT 722 ;"RMATH LOWER"
180 ENTER 722 ; L
190 M=0 @ FOR I=1 TO 10 @ DISP V(I);S$ @ M=M+V(I) @ NEXT I
195 IF ABS(S1)<S2 OR S2=-1 THEN S2=S1 @ M2=M/N
200 DISP USING 201 ; ABS(S1*1000000),S2*1000000

```

Digital Voltmeter Control Program

```
201 IMAGE "sd=",DDDDZ.D,10X,DDDDZ.D/  
202 IMAGE "p-p=",DDDDZ.D  
205 DISP USING 202 ; ABS(U/L-1)*1000000  
210 A=I2 MOD 2 @ B=(I2+1) MOD 2 @ IF ABS(S1*1000000)>T1 THEN KEY LABEL @ C1=1 @  
GOTO 80 ELSE C1=0  
220 IF ABS((U/L-1)*1000000)>T2 THEN 80  
230 GOSUB 1000 @ GOSUB 2000 @ GOTO 50  
240 DISP "ERROR";ERRL;ERRN @ PAUSE  
245 IF ERRN=2 THEN 60  
250 END
```

```
1000 M1=M/N  
1010 A1(I1,I2)=M1  
1020 RETURN
```

```
2000 ! Calculate Averages  
2001 IF F1*F2*F3*F4=0 THEN RETURN  
2002 PRINT @ PRINT "INPUT ";A1(1,1) @ PRINT " ";A1(2,1)  
2003 PRINT "OUTPUT ";A1(1,2) @ PRINT " ";A1(2,2)  
2015 PRINT @ PRINT "TERMINALS= ";V$ @ PRINT T1$;" ";H$ @ PRINT  
2017 PRINT D9$;" ";R0$  
2020 PRINT USING 2025 ; (A1(1,1)-A1(2,1))/2  
2025 IMAGE "REFERENCE VOLTAGE= ",DDZ.DDDDD  
2030 PRINT USING 2035 ; (A1(1,2)-A1(2,2))/2  
2035 IMAGE "DIVIDER VOLTAGE= ",DDZ.DDDDD  
2040 PRINT USING 2045 ; (A1(1,1)-A1(2,1))/(A1(1,2)-A1(2,2))  
2045 IMAGE "MEASURED RATIO= ",DDZ.DDDDD  
2050 IMAGE /"DEVIATION OF THE ACTUAL RATIO FROM THE NOMINAL ",SDDDDZ.DD,X,"ppm  
"  
2055 GOSUB 6000  
2060 PRINT USING 2050 ; (ABS((A1(1,1)-A1(2,1))/(A1(1,2)-A1(2,2)))*N1-1)*1000000  
2061 CLEAR @ DISP USING 2050 ; (ABS((A1(1,2)-A1(2,2))/(A1(1,1)-A1(2,1)))/N1-1)*1  
000000  
2070 PRINT @ DISP V$ @ DISP  
2080 PAUSE @ GOTO 30  
2090 RETURN
```

```
3000 PRINT "OVERRIDE"  
3010 PRINT "SETTINGS: ";V$;" ";S$  
3020 PRINT "STD DEV MAX-MIN(ppm)"  
3030 PRINT USING "2(DDDDZ.D,X)" ; ABS(S1*1000000),ABS(U/L-1)*1000000  
3040 GOTO 230  
3060 GOTO 230
```

Digital Voltmeter Control Program

```
4000 PRINT USING 4010 ; S2*1000000,V$,S$
4010 IMAGE /"MIN STD DEV=",SDDDDZ.DD,"ppm"/"SETTING ",20A,X,2A
4020 A1(I1,I2)=M2
4030 GOSUB 2000 @ GOTO 50

5000 ABORTIO 7 @ CLEAR 7 @ RESET 7
5010 DISP "TIMEOUT"
5050 GOTO 50

6000 J1=1 @ K1=0 ! Calculate nominal ratio
6001 FOR J=1 TO LEN(V$)
6002 IF V$(J,J)<>"/" THEN 6010
6003 K1=K1+1
6004 V2$=V$(J1,J-1) @ J1=J+1
6005 V2(K1)=VAL(V2$) @ IF V2$[LEN(V2$),LEN(V2$)]="K" THEN V2(K1)=V2(K1)*1000
6010 NEXT J
6020 V2$=V$(J1,LEN(V$))
6030 K1=K1+1
6040 V2(K1)=VAL(V2$) @ IF V2$[LEN(V2$),LEN(V2$)]="K" THEN V2(K1)=V2(K1)*1000
6060 N1=(V2(2)-V2(3))/(V2(1)-V2(3))
6066 RETURN

9999 END
```

To run QUME printer from HP Model 85

1. Use Serial Interface and special cable
2. Type 'CONTROL 10, 3 ;15'
3. Type 'PRINTER IS 10,80'

Any PRINT statement will then be printed on the QUME printer

4. To change back to the Model 85 printer, type 'PRINTER IS 2'

Appendix D

CALIBRATION OF THE DIGITAL VOLTMETER AGAINST A JOSEPHSON ARRAY STANDARD

The data for the calibration of the digital voltmeter was obtained from R. L. Steiner of the Electricity Division, Electronics and Electrical Engineering Laboratory. The method used is described in the literature.⁸

Standard Voltage (V)	Measured Voltage (V)	Correction (V)	Relative Error (%)
1.000000	1.000000	0.000000	0.000000
1.000001	1.000001	0.000000	0.000000
1.000002	1.000002	0.000000	0.000000
1.000003	1.000003	0.000000	0.000000
1.000004	1.000004	0.000000	0.000000
1.000005	1.000005	0.000000	0.000000
1.000006	1.000006	0.000000	0.000000
1.000007	1.000007	0.000000	0.000000
1.000008	1.000008	0.000000	0.000000
1.000009	1.000009	0.000000	0.000000
1.000010	1.000010	0.000000	0.000000
1.000011	1.000011	0.000000	0.000000
1.000012	1.000012	0.000000	0.000000
1.000013	1.000013	0.000000	0.000000
1.000014	1.000014	0.000000	0.000000
1.000015	1.000015	0.000000	0.000000
1.000016	1.000016	0.000000	0.000000
1.000017	1.000017	0.000000	0.000000
1.000018	1.000018	0.000000	0.000000
1.000019	1.000019	0.000000	0.000000
1.000020	1.000020	0.000000	0.000000
1.000021	1.000021	0.000000	0.000000
1.000022	1.000022	0.000000	0.000000
1.000023	1.000023	0.000000	0.000000
1.000024	1.000024	0.000000	0.000000
1.000025	1.000025	0.000000	0.000000
1.000026	1.000026	0.000000	0.000000
1.000027	1.000027	0.000000	0.000000
1.000028	1.000028	0.000000	0.000000
1.000029	1.000029	0.000000	0.000000
1.000030	1.000030	0.000000	0.000000
1.000031	1.000031	0.000000	0.000000
1.000032	1.000032	0.000000	0.000000
1.000033	1.000033	0.000000	0.000000
1.000034	1.000034	0.000000	0.000000
1.000035	1.000035	0.000000	0.000000
1.000036	1.000036	0.000000	0.000000
1.000037	1.000037	0.000000	0.000000
1.000038	1.000038	0.000000	0.000000
1.000039	1.000039	0.000000	0.000000
1.000040	1.000040	0.000000	0.000000
1.000041	1.000041	0.000000	0.000000
1.000042	1.000042	0.000000	0.000000
1.000043	1.000043	0.000000	0.000000
1.000044	1.000044	0.000000	0.000000
1.000045	1.000045	0.000000	0.000000
1.000046	1.000046	0.000000	0.000000
1.000047	1.000047	0.000000	0.000000
1.000048	1.000048	0.000000	0.000000
1.000049	1.000049	0.000000	0.000000
1.000050	1.000050	0.000000	0.000000

⁸ R. L. Steiner, R. J. Astalos, "Improvements for Automating Voltage Calibrations Using a 10-V Josephson Array," *IEEE Trans. Instrum. & Meas.*, Vol. IM-40, No. 2, April 1991.

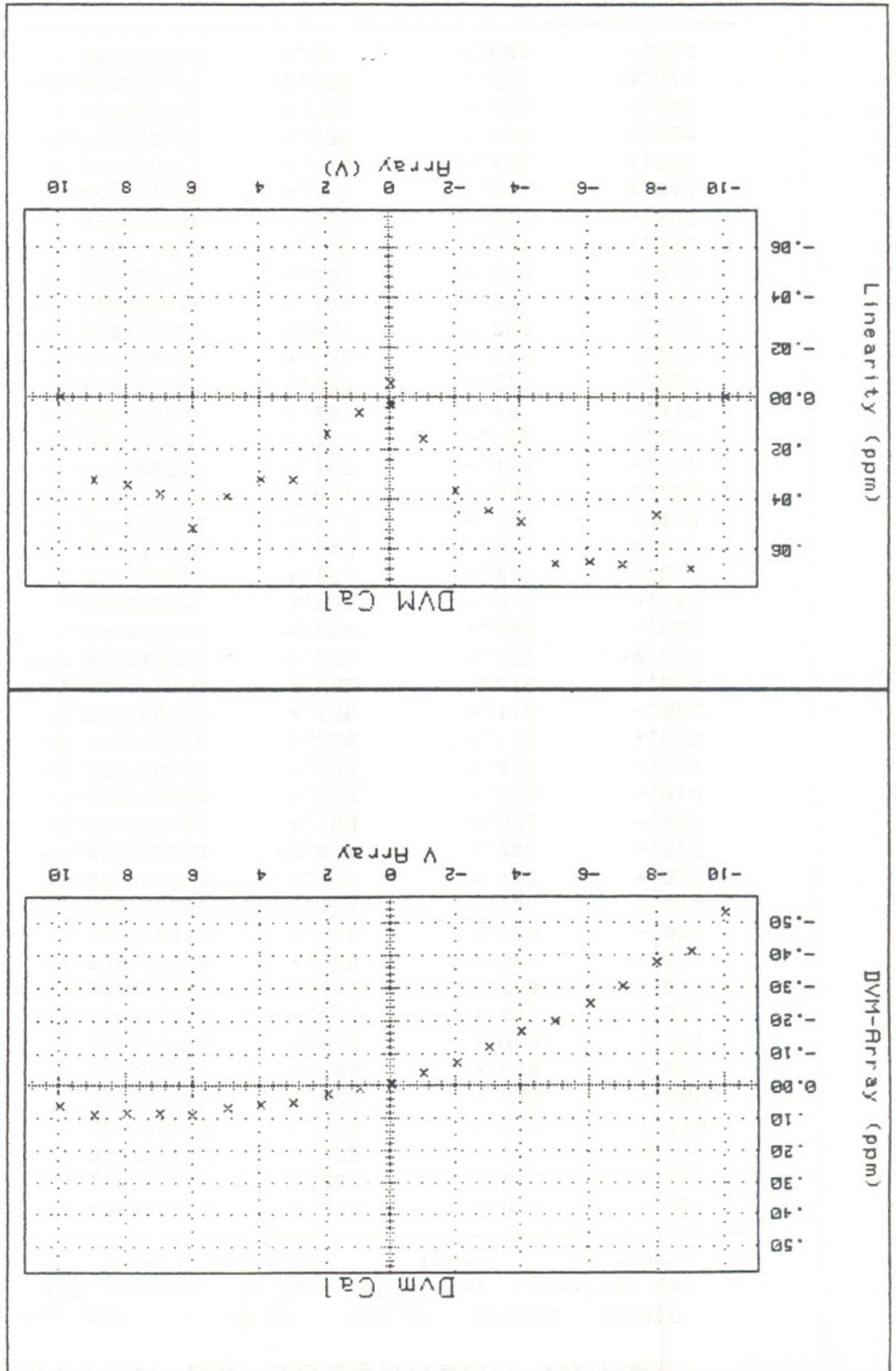
Appendix D

DVM Calibration by Josephson Array

File D92080601 6 Aug 1992 10:48:49 DVM_HP 545190 HP3458
 Pt # Voltage array DVM voltage St Dev DVM-Array Linearity Dev
 (Volts) (Volts) (microV) (ppm) (ppm)

1	+0.00000000	+0.00000286	+0.090	-.005	-.005
2	+1.00003458	+1.000035049	+0.030	+0.013	+0.006
3	+2.00006917	+2.000069782	+0.103	+0.028	+0.015
4	+3.00040721	+3.000408073	+0.084	+0.053	+0.033
5	+4.00044179	+4.000442718	+0.119	+0.059	+0.033
6	+5.00077983	+5.000780890	+0.000	+0.072	+0.040
7	+6.00066269	+6.000663940	+0.138	+0.091	+0.052
8	+6.99978691	+6.999788086	+0.000	+0.084	+0.038
9	+7.99982149	+7.999822705	+0.258	+0.087	+0.035
10	+9.00000780	+9.000009058	+0.238	+0.092	+0.033
11	+9.99989066	+9.999891651	+0.138	+0.065	+0.000
12	+0.00000000	+0.00000369	+0.120	+0.003	+0.003
13	-1.00018631	-1.000186332	+0.135	-.036	+0.017
14	-2.00052435	-2.000524693	+0.091	-.068	+0.037
15	-3.00040721	-3.000407993	+0.097	-.112	+0.045
16	-4.00059352	-4.000594787	+0.119	-.160	+0.049
17	-5.00062810	-5.000629726	+0.138	-.196	+0.066
18	-6.00005578	-6.000057932	+0.000	-.249	+0.065
19	-6.99993864	-6.999941303	+0.097	-.300	+0.066
20	-8.00012495	-8.000128337	+0.275	-.373	+0.047
21	-9.00000780	-9.000011502	+0.000	-.403	+0.068
22	-10.00019412	-10.000199020	+0.138	-.524	+0.000
23	+0.00000000	+0.00000356	+0.113	+0.002	+0.002

DVM slope(+) = +1.000000065 DVM slope(-) = +1.000000524
 Measurement offset = +.337 microVolts
 Number of points = 23 Frequency = 73.37499999 GHz
 St. Dev. of Zero Pt. = 0.0000 ppm Elapsed Time = 00:14:05

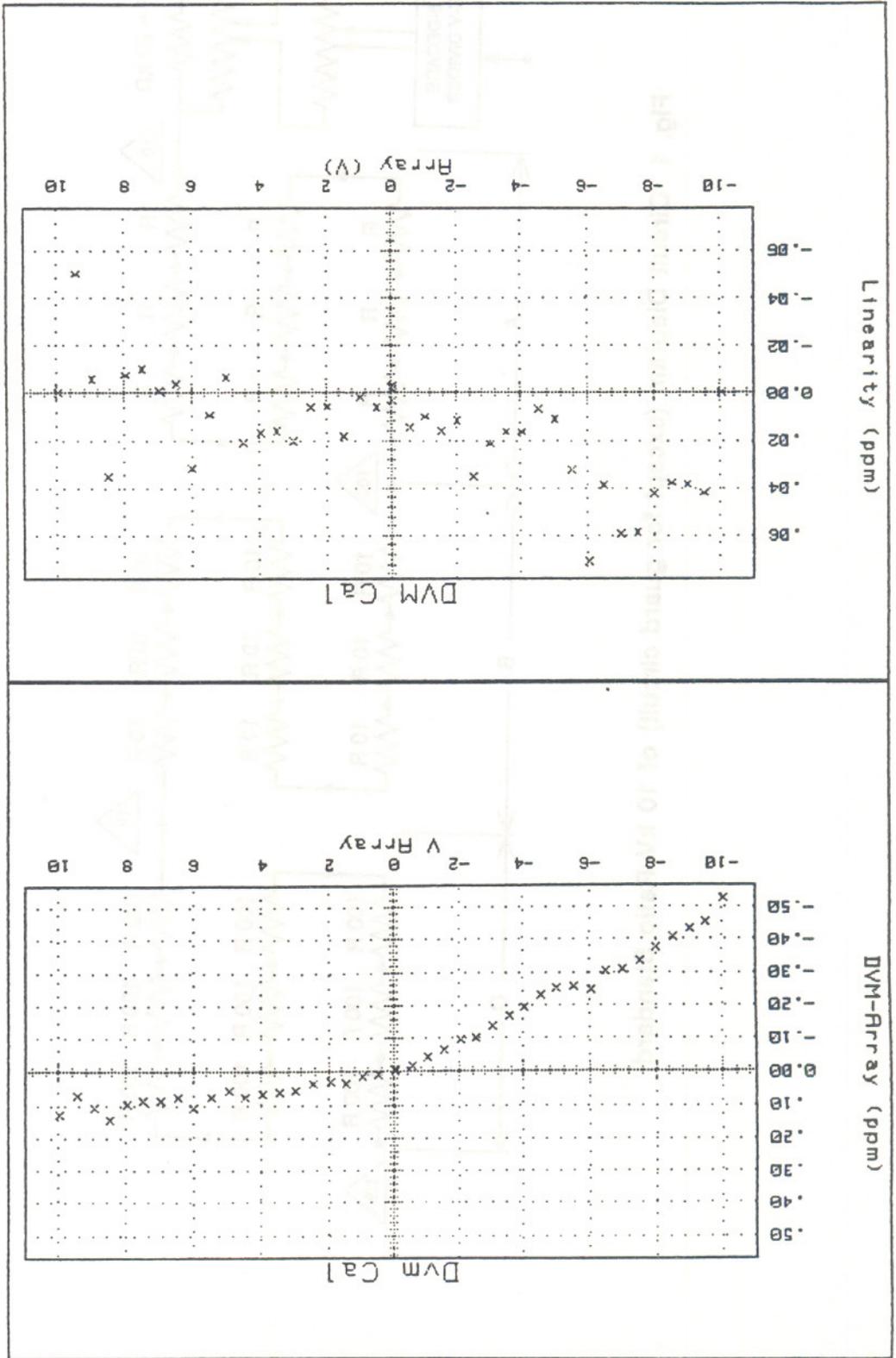


DVM Calibration by Josephson Array

File D92080602 6 Aug 1992 11:40:22 DVM_HP 545190 HP3458
 Pt # Voltage array DVM voltage St Dev DVM-Array Linearity Dev
 (Volts) (Volts) (microV) (ppm) (ppm)

Pt #	Voltage array (Volts)	DVM voltage (Volts)	St Dev (microV)	DVM-Array (ppm)	Linearity Dev (ppm)
1	+0.00000000	+0.00000163	+0.058	-.001	-.001
2	+0.50009316	+0.500093465	+0.068	+0.013	+0.007
3	+1.00003458	+1.000034913	+0.038	+0.015	+0.002
4	+1.50012774	+1.500128299	+0.106	+0.038	+0.018
5	+2.00022090	+2.000221399	+0.000	+0.033	+0.006
6	+2.50046578	+2.500466352	+0.109	+0.040	+0.007
7	+3.00055893	+3.000559716	+0.049	+0.060	+0.021
8	+3.50034864	+3.500349438	+0.069	+0.063	+0.016
9	+4.00044179	+4.000442669	+0.069	+0.070	+0.017
10	+4.50068667	+4.500687658	+0.069	+0.081	+0.021
11	+5.00062810	+5.000628878	+0.119	+0.060	-.006
12	+5.50072126	+5.500722259	+0.154	+0.082	+0.010
13	+6.00005578	+6.000057070	+0.138	+0.112	+0.032
14	+6.49984548	+6.499846480	+0.000	+0.082	-.003
15	+6.99993864	+6.999939729	+0.169	+0.092	-.001
16	+7.50003179	+7.500032860	+0.169	+0.089	-.010
17	+8.00012495	+8.000126105	+0.138	+0.098	-.007
18	+8.49991465	+8.499916301	+0.238	+0.148	+0.036
19	+9.00015953	+9.000160837	+0.195	+0.113	-.006
20	+9.50010096	+9.500101890	+0.195	+0.075	-.050
21	+10.00004239	+10.000043882	+0.238	+0.132	+0.000
22	+0.00000000	+0.00000149	+0.094	-.003	-.003
23	-.50009316	-.500093091	+0.063	-.011	+0.015
24	-1.00018631	-1.000186551	+0.034	-.042	+0.011
25	-1.50027947	-1.500279906	+0.049	-.061	+0.017
26	-2.00037262	-2.000373367	+0.119	-.092	+0.012
27	-2.50031405	-2.500314819	+0.091	-.094	+0.036
28	-3.00040721	-3.000408376	+0.109	-.134	+0.022
29	-3.50050036	-3.500501841	+0.119	-.165	+0.017
30	-4.00044179	-4.000443531	+0.097	-.191	+0.017
31	-4.50053495	-4.500537044	+0.097	-.227	+0.007
32	-5.00062810	-5.000630416	+0.138	-.249	+0.012
33	-5.50072126	-5.500723617	+0.097	-.253	+0.033
34	-6.00005578	-6.000058015	+0.169	-.241	+0.071
35	-6.50014893	-6.500151748	+0.097	-.299	+0.040
36	-7.00024209	-7.000244958	+0.138	-.304	+0.060
37	-7.49988006	-7.499883204	+0.097	-.332	+0.059
38	-8.00012495	-8.000128509	+0.138	-.374	+0.043
39	-8.49991465	-8.499918517	+0.138	-.404	+0.038
40	-8.99985608	-8.999860198	+0.308	-.430	+0.039
41	-9.49994923	-9.499953579	+0.238	-.452	+0.042
42	-10.00019412	-10.000199147	+0.000	-.521	+0.000
43	+0.00000000	+0.00000215	+0.051	+0.004	+0.004

DVM slope(+) = +1.000000132 DVM slope(-) = +1.000000521
 Measurement offset = +.176 microVolts
 Number of points = 43 Frequency = 73.37499998 GHz
 St. Dev. of Zero Pt. = 0.0000 ppm Elapsed Time = 00:27:27



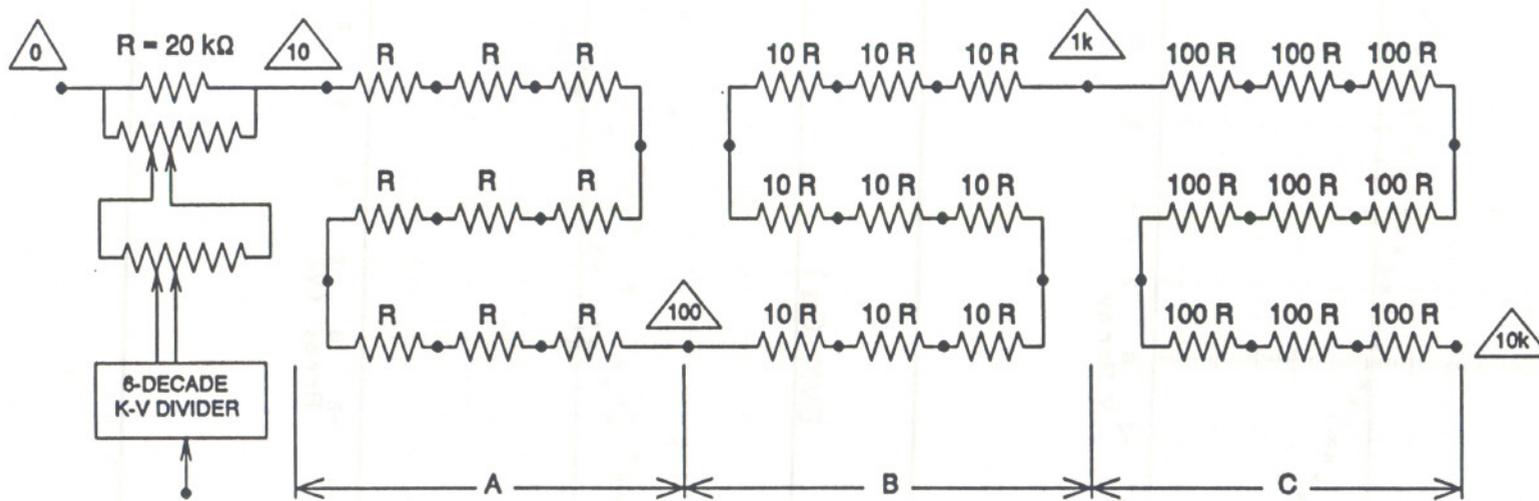


Fig. 1 Circuit Diagram (except for guard circuit) of 10 kV Ratio Standard

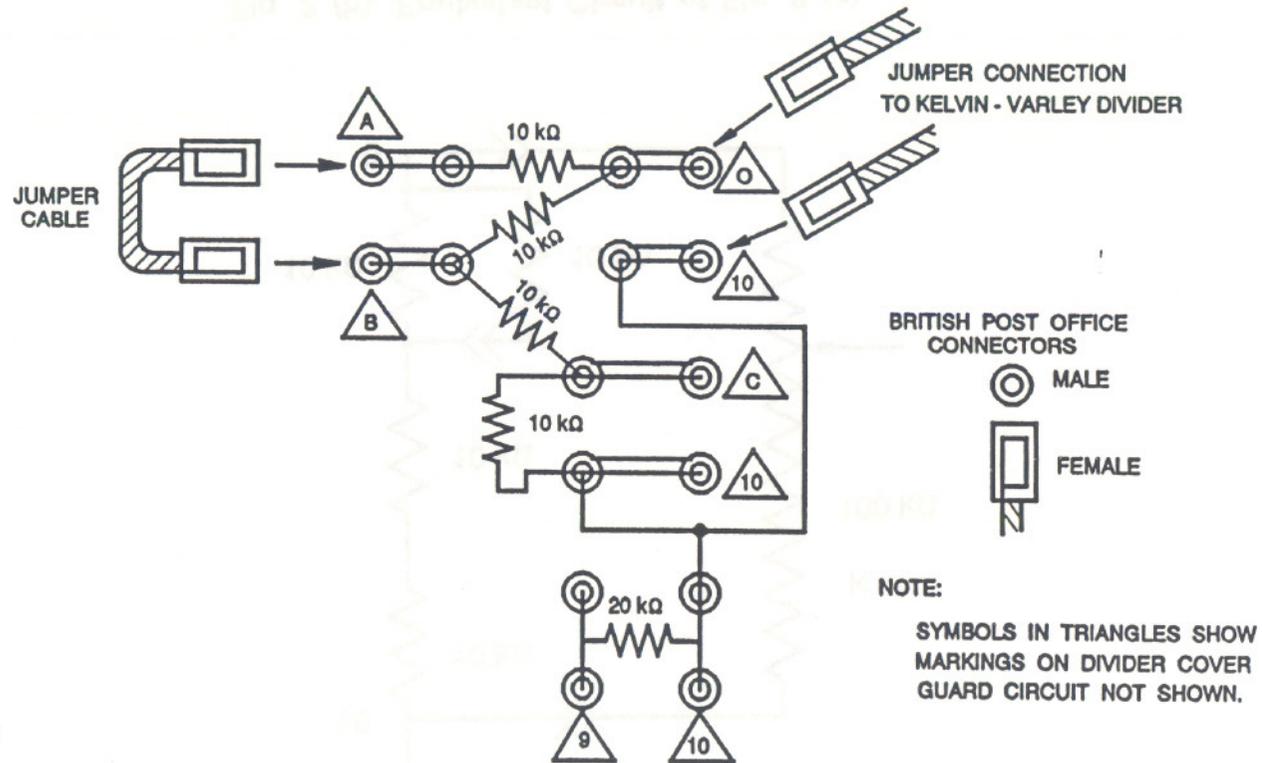


Fig. 2(a) Diagram Showing Transition to Kelvin-Varley Divider

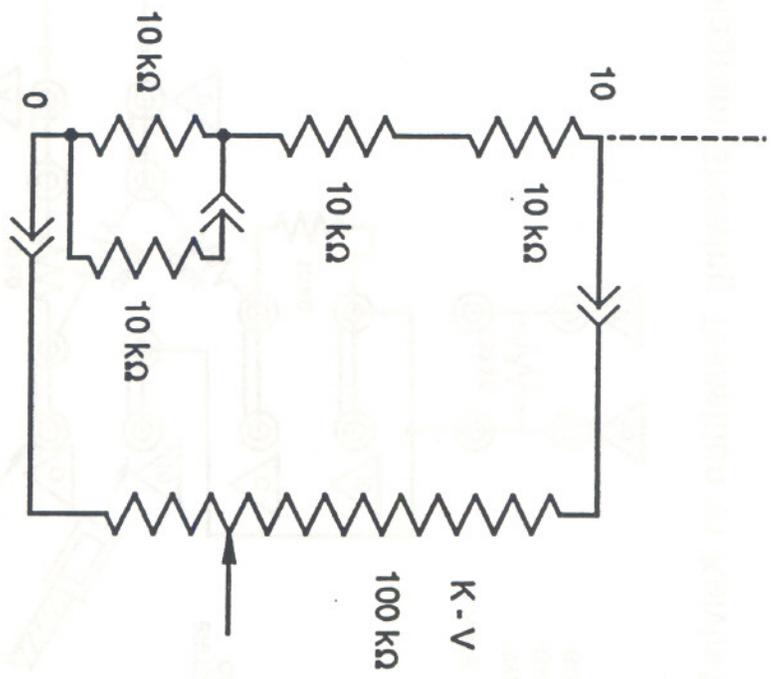


Fig. 2 (b). Equivalent Circuit of Fig. 2 (a).