

An Automated Guarded Bridge System for the Comparison of 10 k Ω Standard Resistors

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Abstract—An automated guarded resistance bridge has been specifically developed at the National Institute of Standards and Technology (NIST) for the calibration of high-quality 10 k Ω standard resistors. The system is designed to compare up to 30 nominally equal, four-terminal resistors with a resolution and combined relative standard uncertainty of 0.01×10^{-6} and 0.02×10^{-6} , respectively. It features a self-balancing detector circuit, and a programmable coaxial connector switch for selecting resistors. With a few minor modifications, the system is capable of comparing other nominally equal resistors in the range 100 Ω to 1 M Ω .

Index Terms—Automatic testing, bridge circuits, calibration, resistance, resistance measurement, resistors, standards.

I. INTRODUCTION

THE National Institute of Standards and Technology (NIST) establishes and maintains the US representation of the ohm in terms of the quantized Hall resistance, and disseminates it to other standards laboratories through its measurement service. This service provides measurements of standard resistors with decade nominal values that range from 100 $\mu\Omega$ to 1 T Ω [1]. Many standards laboratories maintain their reference standard of resistance at 10 k Ω , the middle of the resistance range; consequently, this resistance level constitutes a significant portion of the resistance measurements workload at NIST. To improve these measurements, NIST has developed an automated guarded system for the comparison of 10 k Ω standard resistors. The goal was to develop an automated system equal or superior to the existing manual system in repeatability and accuracy.

This automated system has improved the quality of 10 k Ω calibrations. Automation has eliminated the bias of the operator and errors that result from transcribing data. Measurements can be taken outside of working hours when electrical and mechanical environmental noise is minimized. Measurement precision improves when more measurements are taken under a controlled and repetitive balancing algorithm. Also, the precise timing of measurement sequences greatly reduces the errors caused by short-term linear drifts of thermal emf's. After a description of the system components and an analysis of the major sources of uncertainty, these improvements in system performance will be summarized.

Manuscript received May 24, 1997; revised February 20, 1999.
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Publisher Item Identifier S 0018-9456(99)04999-2.

II. SYSTEM DESCRIPTION

The system was developed to replace the NIST manual system [1] for calibrating high-quality 10 k Ω standard resistors. The main components of this automated system are: the main guarded bridge circuit, the self-balancing detector circuit, the programmable switch, the reversible battery supply, and the computer control network.

A. Main Guarded Bridge Circuit

All main bridge resistors are terminated using coaxial connectors. The shields of the coaxial connectors are driven by a guard network that maintains the shields at potentials nearly equal to the potentials of the inner conductors of the coaxial connectors. This greatly reduces leakage currents from the main bridge circuit through the insulation of the coaxial connectors. The action of the guard network is shown in the simplified bridge circuit Fig. 1, where A , B , X , and R are the main bridge resistors, and a , b , x , and r are their respective guard resistors. As indicated in Fig. 1, the guard network is connected to the main bridge circuit at the supply terminations. If the ratios of the main bridge resistances to their respective guard resistances are equal, the potential difference between points labeled 1 and 2 or 3 and 4 would be zero, and no leakage current would flow from these critical branch point terminations. The only leakage currents possible would be across the supply or the detector, which would have no effect on the bridge balance.

The measurement system is based on the Warshawsky bridge [2], which includes auxiliary or fan resistors at the branch points of the bridge to eliminate first-order errors caused by lead resistances. A schematic of this bridge without its active guard network is shown in Fig. 2. The main bridge circuit consists of ratio arms $(A + c)$ and $(B + e)$, the dummy resistor R , the test resistor X , and fan resistors a , b , r , and x . The ratio arm resistances are nominally 1010 Ω , where $A = B = 1$ k Ω , and $c = e = 10$ Ω . Resistors d and f provide known offsets in the detector circuit when connected into the bridge circuit via switches S1 and S2. The values of the fan resistors are nominally equal to the main bridge resistances and satisfy the following relationships:

$$x/a = X/(A + c) = r/b = R/(B + e) \quad (1)$$

$$x/r = X/R. \quad (2)$$

Resistors are compared using the substitution technique, where the working standards and unknown resistors are indirectly compared by substitution in the X-arm of the bridge circuit.

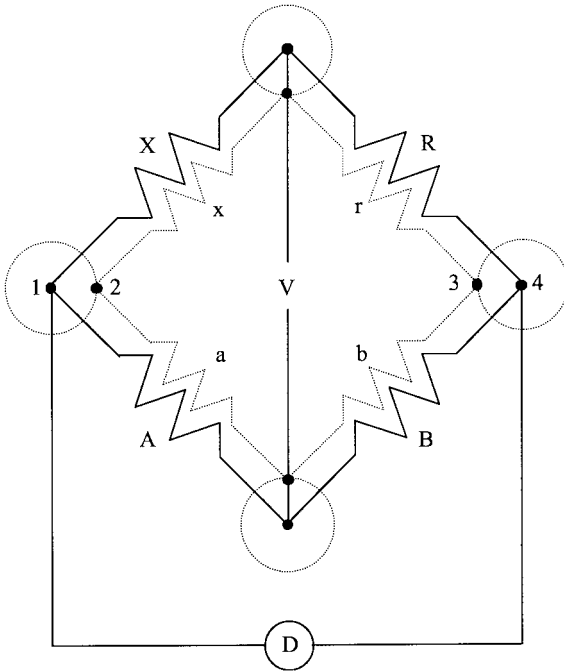


Fig. 1. Simplified bridge circuit with guard network.

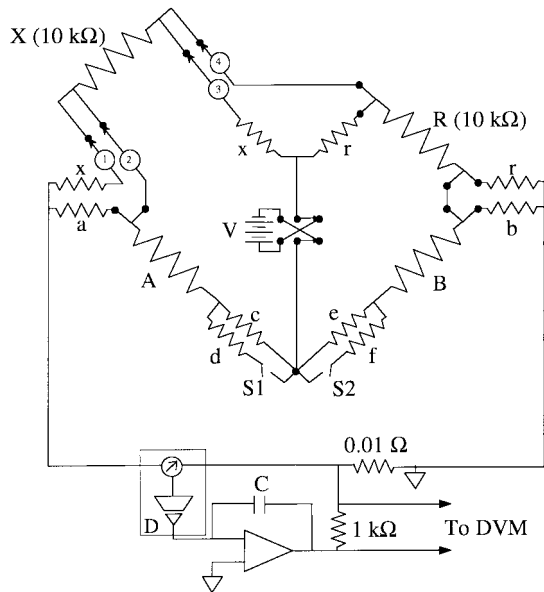


Fig. 2. Automated 10 kΩ guarded resistance bridge shown without its guard network.

The value of the dummy resistor, R , need not be known; however, it must remain stable or predictable during a measurement run. This substitution technique tends to cancel errors resulting from nonlinearity, leakage currents, lead resistances, and contact resistances.

B. Self-Balancing Detector Circuit

The bridge is self-balancing using a novel feedback network in the detector circuit, as shown in Fig. 3. The electronic detector, D , is a low-noise nanovoltmeter with an output

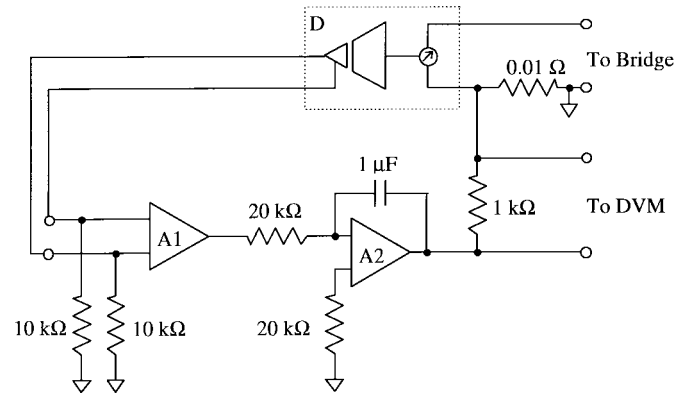


Fig. 3. Self-balancing detector circuit.

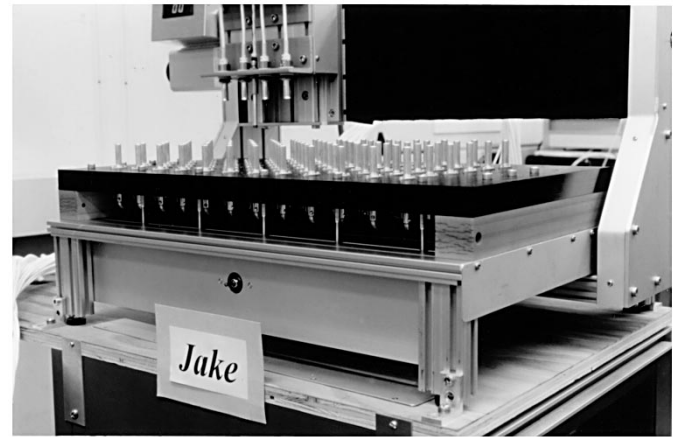


Fig. 4. Photograph of "Jake," the programmable guarded coaxial switching system.

isolated from the input. This output signal is connected to a precision differential instrumentation amplifier, A1, operating at unity gain. Finally, this signal is integrated using an operational amplifier integrator that provides a feedback current to a 0.01 Ω resistor. The voltage drop across this resistor drives the detector to a null condition. The feedback current is monitored by a digital voltmeter (DVM) connected across a 1 k Ω resistor, which is connected in series with the 0.01 Ω resistor. The sensitivity of the feedback system is determined by introducing known offsets in the ratio arms via switches S1 and S2 (see Fig. 2). These switches connect the shunt resistors d and f across resistors c and e , which change the $(A + c)/(B + e)$ ratio by $+10 \times 10^{-6}$ or -1×10^{-6} , respectively. Changes in the feedback current can be equated to changes in resistance as different resistors are switched into the X-arm of the bridge. The measurement range of the feedback circuit is $\pm 100 \times 10^{-6}$.

C. Programmable Switch

The automatic selection of resistors is achieved by a unique programmable guarded coaxial connector panel [3] as shown in Fig. 4. A computer-controlled XYZ positioning system is used to move a four-connector Z-axis panel over a panel of coaxial connectors mounted in the XY plane. The Z-axis connector panel contains four in-line socket-type coaxial con-

nectors along with a guide rod, which triggers a safety stop switch if the connectors do not align properly. The *XY* connector panel contains 72 plug-type coaxial connectors arranged in six rows of 12 each. This provides for 30 four-terminal channels, five along each row. However, there are only 18 independent four-terminal channels having separate voltage and current terminals. The coaxial connectors have either sterling silver or silver-plated inner conductors separated from the outer shields with polytetrafluoroethylene (PTFE) insulation. Variations of thermoelectric potentials of the plug-socket connections over a 10-min measurement run for a single resistor are typically less than 10 nV. The outer shields of the connectors are electrically isolated from one another to allow the shields to be driven by the active guard network.

The length of each coaxial cable, from the *Z* connector panel to the bridge circuit, and from the *XY* connector panel to the test resistors, is approximately 3 m. The PTFE-insulated coaxial cable has a stranded silver-plated copper inner conductor of nominal size AWG 12 and a braided silver-plated copper shield.

D. Reversible Battery Supply

A floating battery supply is used to energize the bridge to reduce possible problems with ground loops in the system. The voltage across a test resistor is nominally 10 V, and the current drain on the supply is approximately 2.2 mA with both the main and guard circuits of the bridge energized. For an extreme condition of measuring a resistance change of 100×10^{-6} from the bridge zero point, the supply needs to be stable to 100×10^{-6} over the 15-min measurement time for a single resistor in order to reduce this source of uncertainty to less than 0.01×10^{-6} . These current and stability requirements are easily met by using mercury or lithium batteries. Shielded reed relays are used to reverse the battery supply voltage. The shields are located between the relay coils and contacts, and are connected to the guard circuit.

E. Computer Control Network

A personal computer (PC) controls the measurement system using BASIC language with multiple subroutines to handle the data collection and processing. The flowchart shown in Fig. 5 indicates the specific PC operations. The programmable switch is interfaced to the PC via a standard RS-232 serial port. All other operations including DVM measurements, temperature, humidity, and pressure measurements, polarity switching, and offset switching are controlled by an IEEE-488 interface board. A second DVM and commercial scanner are used to monitor the temperatures of the resistors using calibrated thermistor probes.

III. MAJOR SOURCES OF UNCERTAINTY

A. Fan Resistors and Leads

As noted earlier and as shown in Fig. 2, fan resistors are added to the bridge corners to reduce errors caused by lead and contact resistance variations. Further reduction of these errors is realized by using the substitution measurement

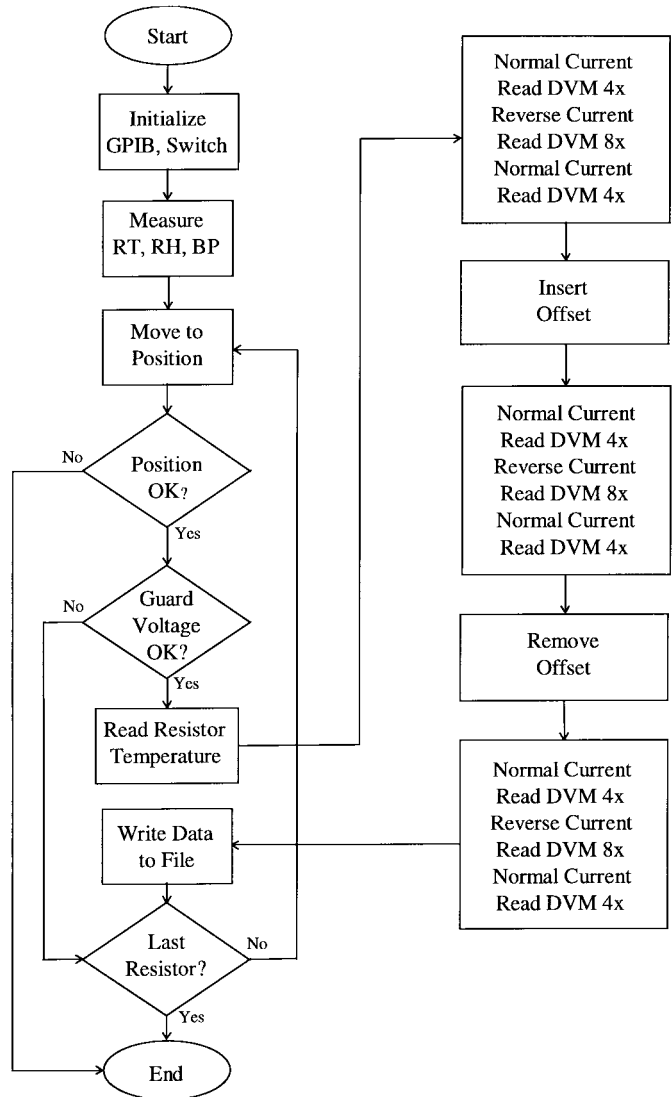


Fig. 5. Flowchart of the measurement routine for 10 k Ω measurements. RT, RH, and BP refer to room temperature, relative humidity, and barometric pressure, respectively.

technique. Only two bridge corners may have significant resistance variations during a measurement run, namely, the corners with the four leads that connect to the resistor under test and labeled 1–4 in Fig. 2. The remaining bridge corners are not altered during a measurement run, and in addition, they are located in an oil bath controlled at $(25.000 \pm 0.003)^\circ\text{C}$. It is possible to replace the compensating circuits of fan resistors with active circuits using operational amplifiers [4]; however, these active components significantly increase the circuit noise while also increasing the complexity of the measurement procedures and system maintenance.

Each lead labeled 1–4 in Fig. 2 represents the resistance of 6 m of AWG 12 coaxial cable and three plug-socket connections. Measurements of the possible 72 lead combinations with the programmable switch indicate a mean lead resistance of 0.0370Ω with the standard deviation of the mean of 0.0002Ω . Measurements of the internal lead resistances of oil-type

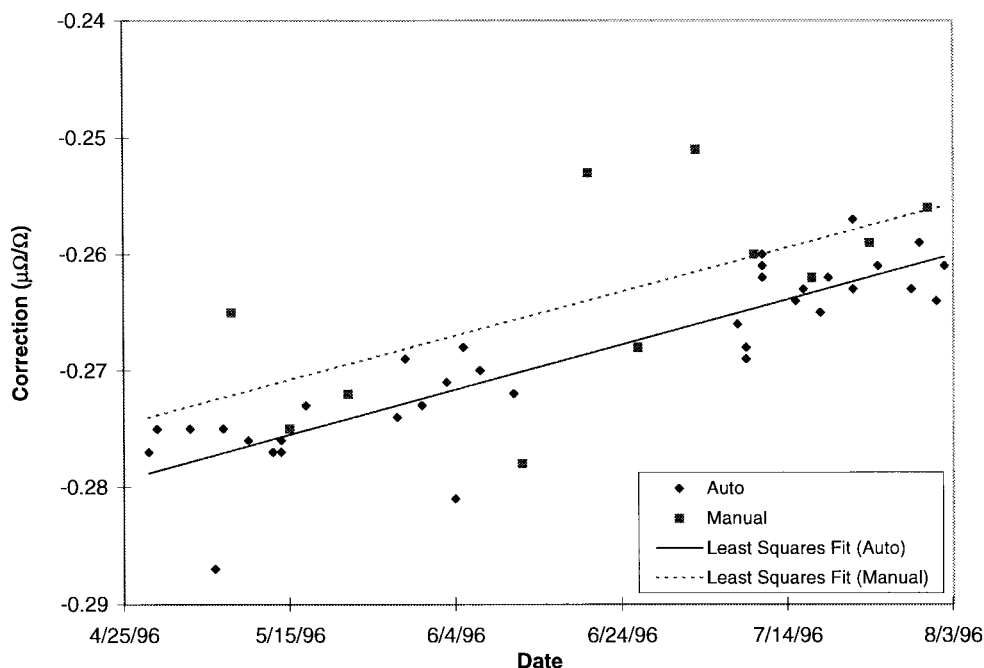


Fig. 6. Differences between automatic and manual systems for 10 k Ω check standard C1410. The residual standard deviations of the linear fits are 0.004×10^{-6} and 0.008×10^{-6} for the automatic and manual systems, respectively.

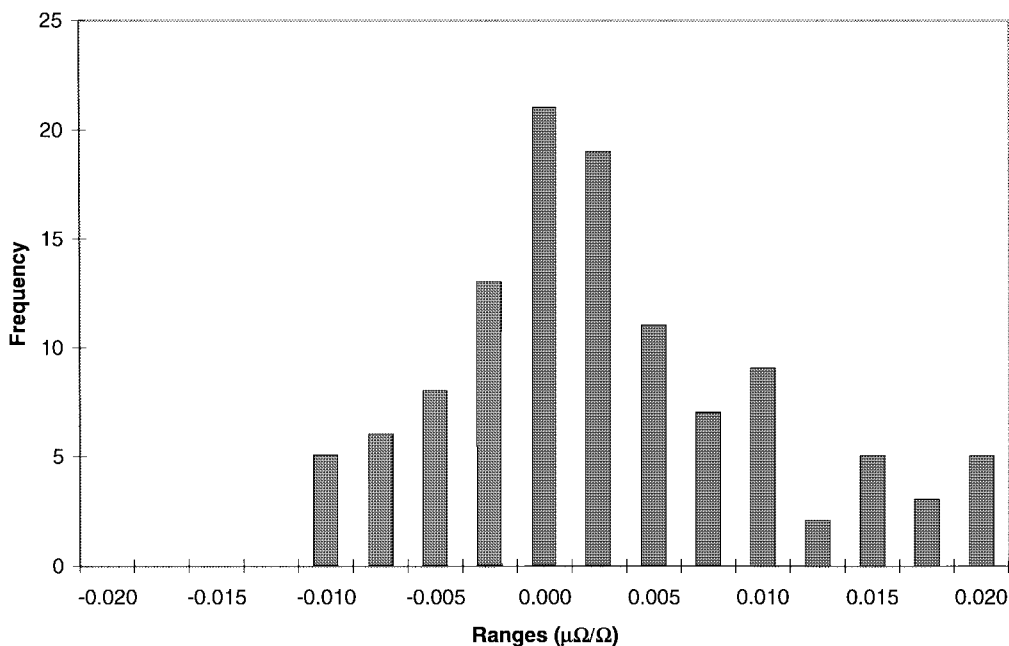


Fig. 7. Histogram of differences between automatic and manual systems of 17 resistors over a four-month period.

or air-type special 10 k Ω standard resistors calibrated at NIST indicate the resistances of current-potential lead pairs to be within 1 m Ω . The precision wirewound fan resistors are located in the oil bath, and their ratios [as indicated in (1) and (2)] are initially adjusted to within a few parts in 10^6 from nominal. Assuming a worst case scenario during a measurement run where leads 1 and 3 with fan resistors would vary up to 2 Ω and leads 2 and 4 would vary up to 0.1 Ω ,

the resulting maximum measurement uncertainty from these effects would be less than 0.0015×10^{-6} .

B. Self-Balancing Circuit

The uncertainties associated with the self-balancing circuit include detector instability, unstable or insufficient gain in the feedback network, nonlinearity of feedback resistors, and sensitivity determination. A method of checking the detector

and gain stabilities, including the system noise, is to monitor the detector output during a measurement run. Several measurement runs indicate that the detector null output is stable to within $13 \mu\text{V}$ during a measurement run. Since the detector gain is 10^3 and the voltage across a test resistor is 10 V , this amounts to a relative uncertainty of 0.0013×10^{-6} .

The $1 \text{ k}\Omega$ and 0.01Ω wirewound resistors in the feedback network have temperature coefficients of resistance less than $10^{-5}/\text{K}$ and are located in the temperature-controlled oil bath. Any nonlinearities of these resistors, presumably caused by self-heating, would introduce a second-order effect and are considered to be negligible. The sensitivity of the feedback network can be calculated from the values of the feedback resistors and the voltage across the test resistor. Alternatively, known offsets are inserted in the ratio arms during a measurement run to determine the bridge sensitivity. These offsets change the bridge ratio by $+1 \times 10^{-5}$ or -1×10^{-6} by shunting the 10Ω resistors with 9891Ω and $99 \text{ k}\Omega$, respectively. These bridge sensitivities need only be known to 0.01 and 0.1% , respectively, so as not to introduce an uncertainty greater than 0.01×10^{-6} . This corresponds to measuring the changes of resistance across the 10Ω resistors to 1 and 10% , respectively. These measurements are easily accomplished using an auxiliary bridge [5] having a relative standard uncertainty of 0.2×10^{-6} .

IV. SYSTEM PERFORMANCE

Measurement results from the automated system were compared with those from the manual system by measuring the same $10 \text{ k}\Omega$ check standard resistor C1410. Results of these measurements over a three-month period are shown in Fig. 6. The residual standard deviations of the linear least-squares analysis of the data for the automatic and manual systems are 0.004×10^{-6} and 0.008×10^{-6} , respectively. There appears to be a slight bias of 0.005×10^{-6} between the two systems that cannot be fully explained. Fig. 7 is a histogram of 117 differences between the two systems when measuring 17 different resistors over approximately a four-month time interval. The mean of these differences is 0.002×10^{-6} with the standard deviation of the mean of 0.008×10^{-6} . The analyses of the data in Figs. 6 and 7 indicate that the automated system is capable of a resolution of 0.01×10^{-6} , and a combined standard uncertainty of 0.02×10^{-6} relative to the manual measurements. It should be noted that the reported expanded uncertainty with the manual system for customer $10 \text{ k}\Omega$ resistor calibrations is 0.15×10^{-6} , using a coverage factor of two [1].

V. FUTURE PLANS

Preliminary measurements comparing resistors of nominal values 6453.2Ω and 1000Ω have been made with this automated system. The results of these measurements agreed with traditional methods [1] to approximately 0.01×10^{-6} . The only necessary changes to the system were the adjustments of the fan resistor ratios and the reduction of the battery supply voltage. No changes to the self-balancing detector circuit were necessary. Future plans are to use this automated system to

compare resistors of nominal values 100Ω , $100 \text{ k}\Omega$, and $1 \text{ M}\Omega$. The adjustment of the fan resistor ratios will be more critical at 100Ω , consequently, an automated method of making these adjustments may have to be employed. No significant problems are expected at the $100 \text{ k}\Omega$ or $1 \text{ M}\Omega$ resistance levels.

VI. CONCLUSION

This automated system for comparing $10 \text{ k}\Omega$ standard resistors has improved the repeatability by a factor of two with respect to the previous manual system. It is expected that, after a reevaluation of the uncertainties in the measurement process, an improvement of the uncertainty of these measurements will be demonstrated. Using the appropriate fan resistance ratios, this system is capable of comparing other nominally equal resistors in the range from 100Ω to $1 \text{ M}\Omega$.

ACKNOWLEDGMENT

The authors wish to thank D. Jarrett and R. Elmquist for their useful suggestions and assistance during the completion of this project.

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