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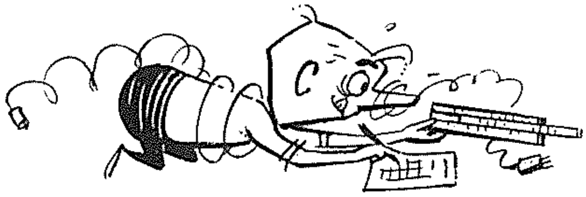
TRACEABILITY OF RESISTANCE MEASUREMENTS

BY
JACK C RILEY
DIRECTOR OF TECHNICAL SERVICES

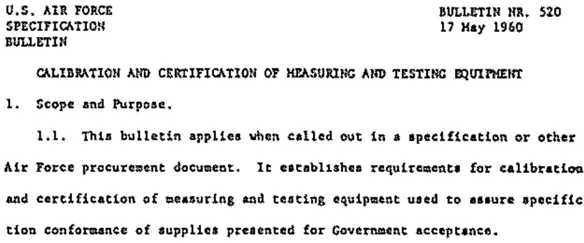


TRACEABILITY OF RESISTANCE MEASUREMENTS

A discussion of precision resistance comparison from certified standard to calibrated unit. The use of resistance transfer techniques is stressed. Four ter-resistance characteristics are discussed.

WHAT IS TRACEABILITY?

Air Force Bulletin NR. 520 which concerns calibration and certification of measuring and testing equipment (see Figure 1) calls for the use of "traceable" measurement standards, (see Figure 2). As a result of the call-out of Air Force Bulletin NR. 520, more and more purchase orders are appearing with a request for traceability certification, (see Figure 3).



U.S. AIR FORCE
SPECIFICATION
BULLETIN

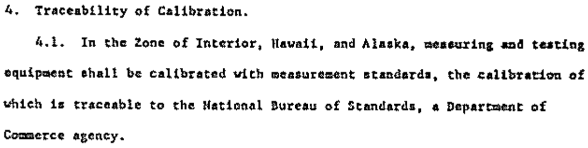
BULLETIN NR. 520
17 May 1960

CALIBRATION AND CERTIFICATION OF MEASURING AND TESTING EQUIPMENT

1. Scope and Purpose.

1.1. This bulletin applies when called out in a specification or other Air Force procurement document. It establishes requirements for calibration and certification of measuring and testing equipment used to assure specification conformance of supplies presented for Government acceptance.

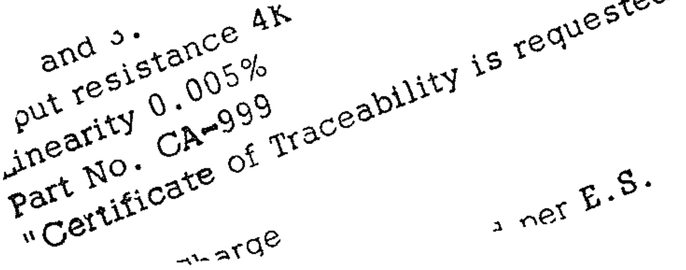
FIGURE 1. SCOPE AND PURPOSE OF U.S. AIR FORCE SPECIFICATION BULLETIN NR. 520



4. Traceability of Calibration.

4.1. In the Zone of Interior, Hawaii, and Alaska, measuring and testing equipment shall be calibrated with measurement standards, the calibration of which is traceable to the National Bureau of Standards, a Department of Commerce agency.

FIGURE 2. BEGINNING OF TRACEABILITY STATEMENT FROM USAF BULLETIN NR. 520



and ɔ.
put resistance 4K
inearity 0.005%
Part No. CA-999
"Certificate of Traceability is requested"
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arge

FIGURE 3. TYPICAL PURCHASE ORDER REQUEST

There is a good reason for this traceability requirement. Computer circuits, precision navigation equipment and other devices (see Figure 4) have increased the accuracy requirements for precision components. As a result, many industrial laboratories are now faced with making resistance calibration measurements and interlaboratory comparisons which only a few years ago were never attempted outside of national standards laboratories.

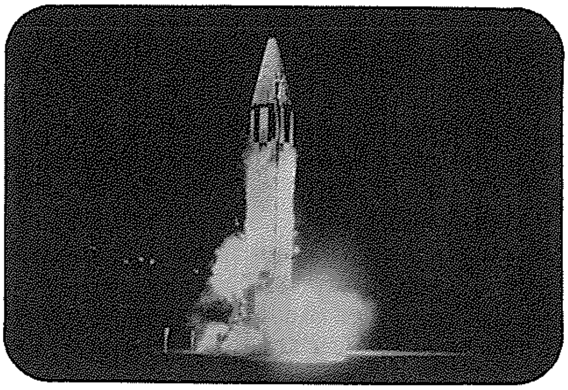

FIGURE 4. ONE REASON FOR PRECISION MEASUREMENTS

We are going to describe equipment and a technique for making resistance measurements of predictable accuracy relative to our national reference standards.

WHAT IS AN OHM?

Before we can get very far with a discussion of precision measurements, we need to reach an agreement as to what we mean by "one ohm". There are several meanings and at the one ppm level the resulting values can be different. We formerly used the "International Ohm", but we now use the

"Legal Absolute Ohm" which is the standard maintained by the National Bureau of Standards.

International Ohm

In 1894, the United States Congress defined the ohm as "the resistance offered to an unvarying electric current by a column of mercury at the temperature of melting ice, 14.4521 grams in mass of a constant cross-sectional area, and of the length of 106.3 cm". This was the "International Ohm" and many of the older standard resistors were made using this unit. These resistors are about 0.05% high in terms of the present standard.

Absolute Ohm

Since July 21, 1950, the ohm in the United States has been defined as "---one thousand million units of resistance of the centimeter-gram-second system of electromagnetic units---". This is the "absolute" ohm proposed by the International Committee on Weights and Measures.

Legal Absolute Ohm (NBS Standard)

Congress also determined that the legal value of the ohm "---shall be---represented by, or derived from, national reference standards maintained by the Department of Commerce---". This means that the resistance standard maintained by the National Bureau of Standards is exactly correct, legally, although it may vary by a few ppm from the true value of the "absolute ohm". The standards of several countries are compared frequently and the NBS standard is in agreement with the resulting value determined by the International Bureau of Weights and Measures. When we have a resistor certified, the measured value on the certificate is in "legal absolute ohms" and the accuracy value refers only to measurement accuracy and expected stability for one year. No figure is given for the accuracy of the NBS standard in "absolute ohms". In most discussions, the NBS values are called "absolute ohms" because the standard at NBS is in agreement with the internationally accepted value of the absolute ohm.

A TRACEABLE MEASUREMENT

We propose that the following procedure and equipment will make measurements of predictable traceability, and it is therefore our opinion that the resulting calibrations should satisfy the traceability requirement.

We start out with a highly stable standard resistor which is measured at the National Bureau of Standards and returned to us with a certificate stating its measured value and expected stability. This reference standard establishes our unit of resistance, the ohm. To measure other resistors of the same value as our reference standard, we need an accurate comparison device. To measure resistors of different values from the standard we need a precision transfer technique.

THE CERTIFIED STANDARD RESISTOR

The standard resistor we are going to use for our measurements is a Thomas pattern one ohm resistor. These resistors, as shown in Figure 5, are commercially available and many of them are certified by the National Bureau of Standards to an accuracy of ±2 ppm per year. One such certificate is shown in Figure 6.

FIGURE 5. STANDARD RESISTOR

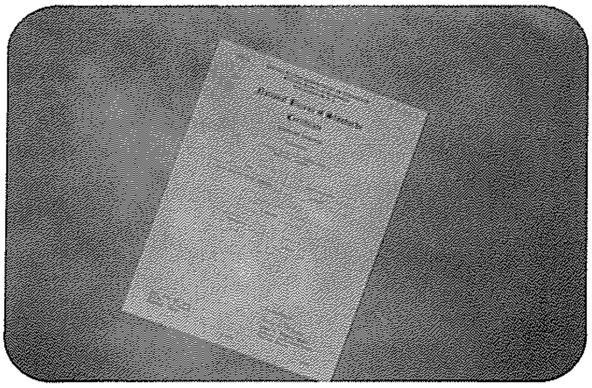

FIGURE 6. NBS CERTIFICATE

THE TRANSFER TECHNIQUE

The transfer system that we are going to discuss includes the ESI Model 242 Resistance Measuring System, used as a substitution type comparison bridge, a set of 3 ESI Model SR-1010 Transfer or Build-up Resistors and the associated shorting bars and compensation networks for calibrating resistors from one ohm to one megohm. This equipment is shown in Figure 7.

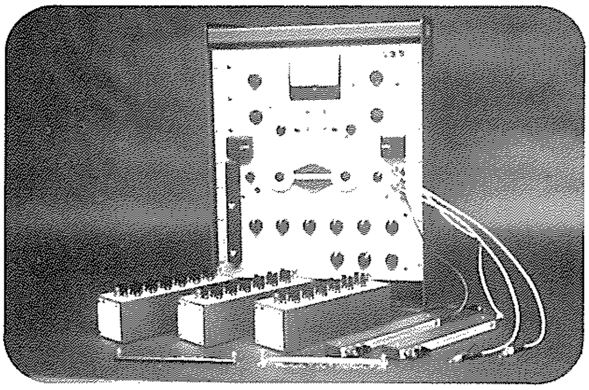

FIGURE 7. TRANSFER TECHNIQUE

HOW ARE RESISTORS CERTIFIED?

As a matter of interest let's go back to Washington DC and find out what happened when we submitted our standard resistor for certification, (see Figure 8).

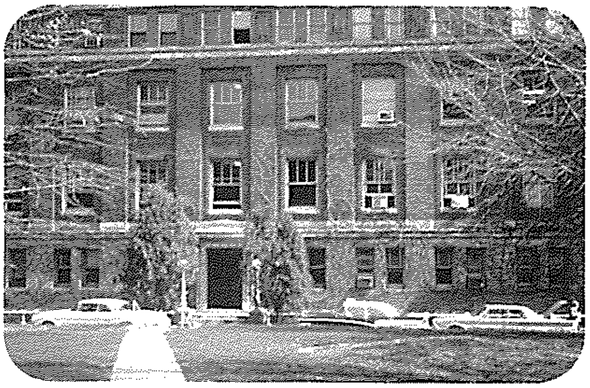

FIGURE 8. NATIONAL BUREAU OF STANDARDS, ELECTRICITY DIVISION, WASHINGTON DC

ABSOLUTE MEASUREMENT OF RESISTANCE

The National Bureau of Standards is responsible for maintaining a prototype standard of resistance from which the legal unit of resistance for the United States is determined. It is possible to derive the unit of resistance from fundamental units of length, mass and time. One method of deriving the standard ohm involves the careful physical measurement of the standard inductor shown in Figures 9 and 10 and a set of careful electrical measurements to compare the inductor with the standard of resistance. The utmost precision and care are required for such work. For example, the lamp post in Figures 10 and 11 contains the closest

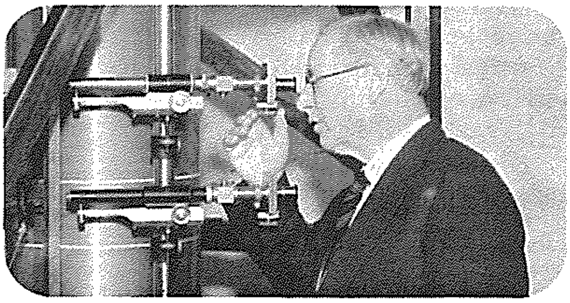

FIGURE 9. DR. FRANK WENNER MAKING PHYSICAL MEASUREMENTS OF THE STANDARD INDUCTOR (Photo Courtesy of NBS)

piece of iron to the inductor when this experiment was performed.

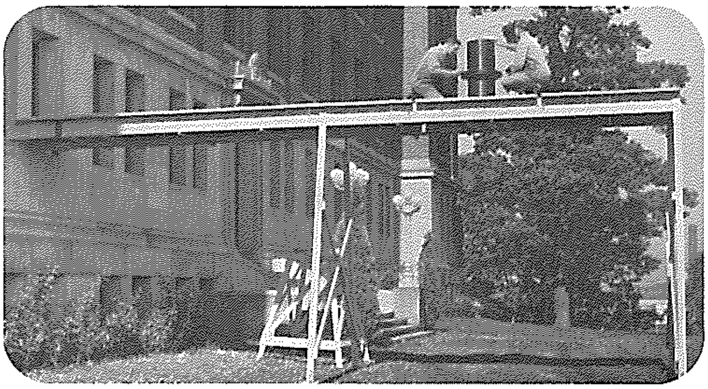

FIGURE 10. ELECTRICAL MEASUREMENTS OF THE STANDARD INDUCTOR (Photo Courtesy of NBS)

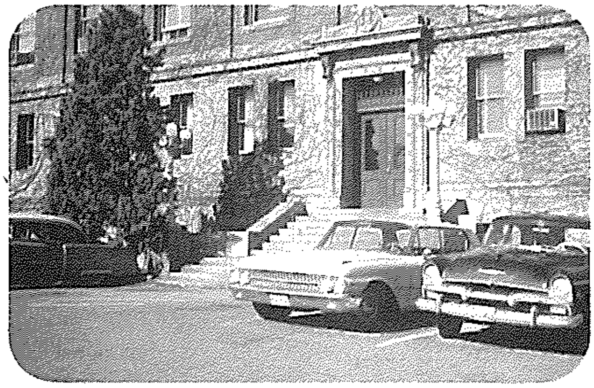

FIGURE 11. PRESENT VIEW OF THE AREA SHOWN IN FIGURE 10

Very recently a computable capacitance standard has been devised which permits an alternate means for the derivation of the unit of resistance. This unit is shown in Figure 12.

> ***Absolute Measurement of Resistance.*** An evaluation, based on the prototype standards of length and time, of the unit of resistance maintained at the Bureau was completed. The evaluation was based on a nominally 1-picofarad symmetrical cross capacitor having a value computable to high accuracy from its mechanical dimensions. The computable capacitor was used to establish the value of a 0.01-microfarad capacitor which then, through the medium of a frequency-dependent bridge, established the value of a 10,000-ohm resistor. A comparision of that resistor with the group of 1-ohm standard resistors currently used to maintain the NBS unit of resistance established the value of the unit with an estimated accuracy of the order of 2 ppm.
>
> It is expected that an even higher accuracy will be attained in the repetition of these measurements. This method will greatly improve the Bureau's ability to check maintenance of the unit of electrical resistance through the use of a group of standard resistors. When combined with repetitions of determinations of the gyromagnetic ratio of the proton, the method can be used as a check of the stability of all types of electrical standards to a much greater accuracy than previously possible.*

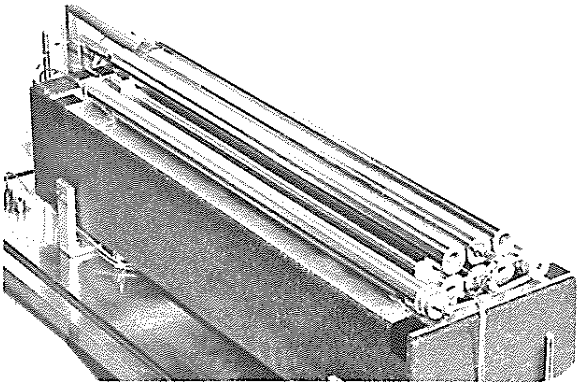

FIGURE 12. COMPUTABLE CAPACITANCE STANDARD (Photo Courtesy of NBS)

The fundamental unit of resistance for the United States is believed to be much more stable than one part per million per year. This standard is maintained by measurements on a group of precision one ohm resistors which have exhibited exceptional stability. These units are periodically checked by repeating the derivation experiment and they are also intercompared with the resistance standards of other nations. These resistors are in the back of the Wenner Bridge shown in Figure 13.

RESISTANCE COMPARISONS

Resistance comparisons of the highest accuracy are made using the Wenner resistance bridge shown in Figure 13. It can be used for comparing like values by substitution or interchange, or for making resistance ratio comparisons.

Ratio comparisons are made by using the seven-resistor build-up unit shown in Figure 14. This unit can be calibrated to provide precision ten to one and two to one ratios. Three 150 ohm resistors can be connected in parallel to give a value of 50 ohms. This resistance can be compared on a

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*Electricity. <u>Research Highlights of the National Bureau of Standards Annual Report</u>, 1962, p. 3.

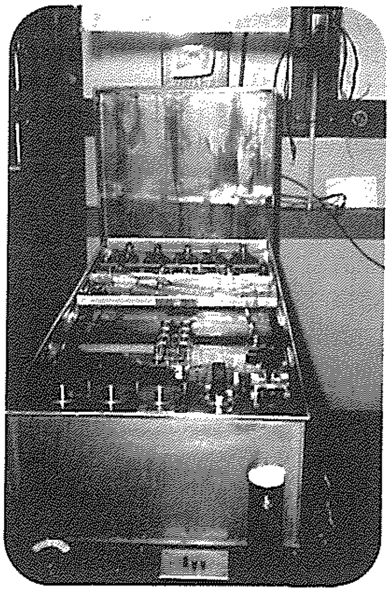
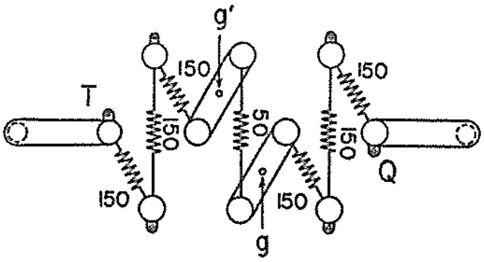


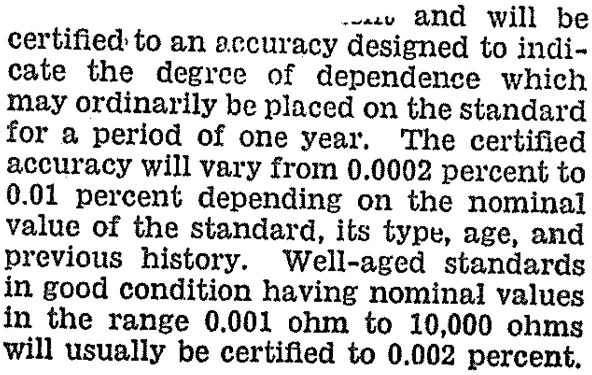
FIGURE 13. WENNER BRIDGE



Circuit diagram of the auxiliary apparatus used for determining the reading of the dial switches of the NBS precision bridge, for which the ratio of the resistance of the A arm to the resistance of the B arm is 10 to 1.

FIGURE 14. BUILD-UP CIRCUIT

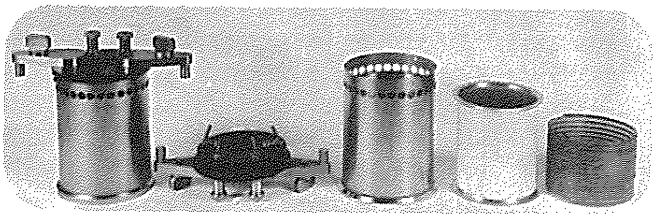
one to one basis with the 50 ohm resistor and with the other set of three 150 ohm resistors also connected in parallel. Then the first three resistors can be reconnected in series and added to the 50 ohm resistor to make a total of 500 ohms. The series and parallel accuracies of the 150 ohm resistors are almost identical so that the true value of the ten to one ratio between the 500 ohm and 50 ohm resistance can be calculated to a predictable accuracy. A two to one ratio can be obtained by using two of the 50 ohm sections to make a 100 ohm resistor. The accuracy of the two to one ratio between this 100 ohm resistor and the remaining 50 ohms is also predictable. By a series of ratio measurements with this equipment it is possible to calibrate resistors of all reasonable values relative to the fundamental standard of resistance as maintained by the National Bureau of Standards. Certificates are issued relative to the value of the maintained standard of resistance (even though it may be a few ppm different from the "one thousand million units of resistance of the centimeter-gram-second system of electro magnetic units" which is the "absolute" ohm). The certificate which we receive includes the measured value of resistance and an indication of the expected stability of the resistor for at least a one year period (see Figure 15).



and will be certified to an accuracy designed to indicate the degree of dependence which may ordinarily be placed on the standard for a period of one year. The certified accuracy will vary from 0.0002 percent to 0.01 percent depending on the nominal value of the standard, its type, age, and previous history. Well-aged standards in good condition having nominal values in the range 0.001 ohm to 10,000 ohms will usually be certified to 0.002 percent.

FIGURE 15. NBS CERTIFICATE VALUES (Reprinted from "Federal Register", Vol. 26, No. 36, February 24, 1961.)

WHY THE THOMAS PATTERN ONE OHM



complete standard, top terminal assembly, outer wall, inner wall, annealed resistance coil.

(Photo Courtesy of NBS)

The Thomas pattern one ohm resistor is recommended as a reference standard because it is likely to have the best certified accuracy.

By alternate certification of several Thomas pattern one ohm units in a planned calibration program we can maintain a standard of resistance which we can trust to better than one part per million accuracy.

This is especially true if repeated calibrations show no significant changes.

HOW TO CALIBRATE RESISTORS

We need a measurement technique to transfer accuracies of this order from one ohm to other resistance values in our own laboratory.

Relative to the Thomas pattern one ohm standard, it is often possible to measure other resistors to a much greater accuracy than they are capable of being certified. Resistors with excellent short-term stability are often less stable over a long period of time or when subjected to environmental excursions or mechanical shock. A certificate must reflect this possible instability, but a recent calibration in an unchanging environment is much more trustworthy.

The ESI Model 242 Resistance Measuring System and Model SR-1010 Resistance Transfer Standards can be used for transfer measurement. The 242 Resistance Measuring System is used as a substitution type comparison bridge. The combination of both resistance measuring dials and a deviation dial in the Model 242 System makes it particularly well suited to this type of measurement. The SR-1010 units (Figures 16 and 17) make possible 100 to 1 resistance level transfers in a single step.

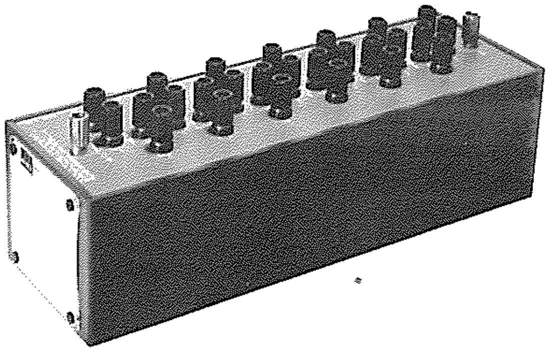


FIGURE 16. RESISTANCE TRANSFER STANDARD

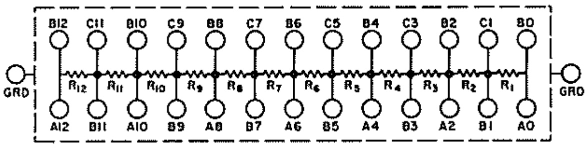


FIGURE 17. MODEL SR-1010 CIRCUIT DIAGRAM

The resistance transfer technique consists of connecting ten like resistors, first in parallel, Figure 18,

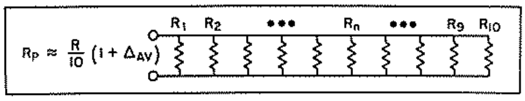


FIGURE 18. 10 RESISTORS IN PARALLEL

second in series to get a hundred to one resistance transfer, Figure 19,

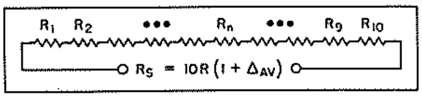


FIGURE 19. 10 RESISTORS IN SERIES

and third in a series-parallel combination of nine resistors which can be compared with either the series or parallel connection to give a ten to one difference, Figure 20.

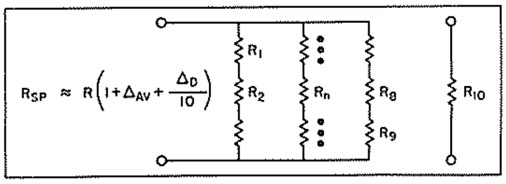


FIGURE 20. 10 RESISTORS WITH 9 IN SERIES-PARALLEL

We need to show how and why we can make transfer measurements which do not depend on the absolute accuracy of the transfer standard but only on its short term stability.

First we need some mathematical definitions so that we can derive our expected accuracy. We need a mathematical definition of resistance deviation in proportional parts which we will refer to as Δ. In Figure 21 we define

$$R_n = R(1+\Delta_n)$$

where R_n – Resistance of nth resistor

R – Nominal resistance of each resistor

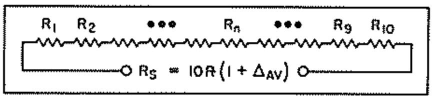
Δ_n – Deviation of R_n from R in proportional parts

FIGURE 21. WHAT Δ_n MEANS

the true resistance, R_n, of a resistor in terms of its nominal resistance R and its deviation Δ_n in proportional parts. If the resistor is close to its nominal value, Δ_n is a very small number.

SERIES RESISTANCE

We are going to use the first 10 resistors of the SR-1010 box. First, let us look at our ten resistors connected in series. The series resistance is the sum of the ten resistances. Each resistor value R_n can be stated in terms of its nominal resistance R and deviation Δ_n. The summation can be rearranged to give a resistance of 10 R with a deviation which is the average deviation of the ten resistors, as shown in Figure 22.



$$R_S = \sum_{n=1}^{10} R_n = \sum_{n=1}^{10} R(1+\Delta_n) = 10R\left(1+\frac{1}{10}\sum_{n=1}^{10}\Delta_n\right)$$

$$\Delta_{AV} = \frac{1}{10}\sum_{n=1}^{10}\Delta_n$$

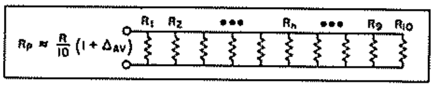
where Δ_{AV} – Average of the deviations Δ_n

$$R_S = 10R(1+\Delta_{AV})$$

FIGURE 22. SERIES CONNECTION--DEVIATION IS Δ_{AV}

PARALLEL RESISTANCE

The same ten resistors can be connected in parallel. The resulting resistance R_p deviates from R/10 by almost the average deviation of the ten resistors, as shown in Figure 23. If the ten resistors are enough alike, the "almost" is insignificant. The error which arises from assuming that the series and parallel connections have the same deviation from their nominal values is in the order of the square of the average deviation $(\Delta_{AV})^2$ of the ten resistors from their nominal value. If Δ_n is less than 100 ppm then $(\Delta_{AV})^2$ will be less than 0.01 ppm. The Δ_n of resistors of the ESI Model SR-1010 is typically less than 20 ppm so for 1 ppm measurements, the assumption that $(\Delta_{AV})^2$ terms can be dropped is quite valid.



$$R_p = \frac{1}{\sum_{n=1}^{10}\frac{1}{R_n}}$$

where R_p – Resistance of 10 resistors in parallel

$$\frac{1}{R_n} = \frac{1}{R(1+\Delta_n)} = \frac{1}{R}(1-\Delta_n+\Delta_n^2+\cdots)$$

$$R_p = \frac{1}{\sum_{n=1}^{10}\frac{1}{R}(1-\Delta_n+\Delta_n^2+\cdots)} = \frac{R}{10}\left[\frac{1}{1+\frac{1}{10}\sum_{n=1}^{10}(-\Delta_n+\Delta_n^2+\cdots)}\right]$$

$$R_p = \frac{R}{10}\left[1+\frac{1}{10}\sum_{n=1}^{10}\Delta_n-\frac{1}{10}\sum_{n=1}^{10}\Delta_n^2+\left(\frac{1}{10}\sum_{n=1}^{10}\Delta_n\right)^2+\cdots\right]$$

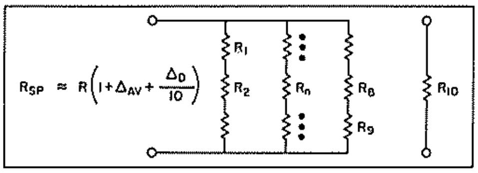
$$R_p \approx \frac{R}{10}(1+\Delta_{AV})$$

FIGURE 23. PARALLEL CONNECTION--DEVIATION IS ALSO Δ_{AV}

Because the same ten resistors with the same Δ_{AV} are used for the series and parallel connections, we can measure Δ_{AV} by comparison to a standard of either R/10 or 10R and reconnect the SR-1010 to provide a standard of the same accuracy at the other value, 10R or R/10, one hundred times removed.

SERIES-PARALLEL RESISTANCE

By one additional measurement we can calibrate nine of our ten resistors for use as a standard of similar accuracy for ten to one transfers.



$$R_{SP} = R\left[1+\Delta_{AV}+\frac{\Delta_D}{10}+\begin{Bmatrix}+0\\-(\Delta_{MAX})^2\end{Bmatrix}+\cdots\right]$$

where
R_{SP} – Resistance of 9 of 10 resistors R_i connected in Series-Parallel
Δ_D – Deviation of R_{SP} from the tenth resistor $R_{10}\left[R_{SP} \equiv R_{10}(1+\Delta_D)\right]$
Δ_{MAX} – Magnitude of largest deviation Δ_n

$$R_{SP} \approx R\left(1+\Delta_{AV}+\frac{\Delta_D}{10}\right)$$

FIGURE 24. SERIES-PARALLEL CONNECTION - - DEVIATION IS

$$\Delta_{SP} = \Delta_{AV} + \frac{\Delta_D}{10}$$

In Figure 24 we have connected the first nine resistors R_n in three parallel strings of three resistors in series. The resulting resistance R_{SP} is nominally the same as each resistor R. The deviation Δ_{SP} of this series-parallel combination is almost exactly the average deviation of the nine resistors, because each resistor's contribution to the deviation is approximately the same in either series or parallel. If we knew Δ_{SP} and the deviation Δ_{10} of the tenth resistor we could easily combine them to find the average deviation of all ten resistors which we already know as Δ_{AV}. We could also find Δ_D, which is defined as the deviation of the series-parallel nine resistors R_{SP} from the tenth resistor R_{10}. Actually if we know any two of these four variables, Δ_{AV}, Δ_{SP}, Δ_D and Δ_{10} we can find the other two.

It is easy to measure Δ_D by comparing R_{SP} with R_{10}. We can measure Δ_{AV} or Δ_{SP} relative to a standard of any one of the three decade values R/10, R, or 10R. From the two measured values we can calculate the other one, Δ_{SP} or Δ_{AV}. Thus we can calibrate the SR-1010 box at any one of the three resistance levels and use it as a calibrated standard at the other two.

We can also use R_{SP} for standardizing the bridge to calibrate each individual resistor in the SR-1010 box. Then resistance values are available in integer steps from one R to twelve R with known accuracy.

LEAD AND CONTACT RESISTANCE

We are starting a chain of measurements with a one ohm standard resistor. One part per million of one ohm is one microhm. One microhm is less than the resistance of a 0.010 inch length of number twelve copper wire. Also, each lead of the Thomas pattern one ohm standard has a resistance of about one milliohm. Lead and contact resistances are a very serious problem. Fortunately the effects of lead and contact resistance can be minimized by using four-terminal resistance connections and a Kelvin ratio bridge, such as the ESI Model 240.

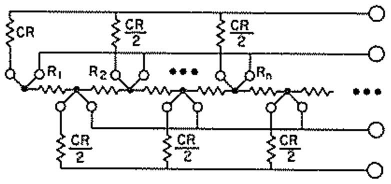
FOUR-TERMINAL SERIES MEASUREMENTS

The ESI Model SR-1010 Transfer Resistance Standard consists of twelve nominally equal resistors permanently connected in series with two terminals brought out from each resistor junction. This allows a four-terminal measurement of any individual resistor and of any series combination of adjacent resistors (See Figure 17).

FOUR-TERMINAL PARALLEL MEASUREMENTS

Fortunately four-terminal parallel connections can also be made. A special compensation network, using additional matched resistors in series with one of the leads on each end of the resistors, allows us to make accurate parallel measurements of low valued resistors.

The circuit for four-terminal parallel measurements is shown in Figure 25. The connection circuit contributes a measurement uncertainty Δ_M. The first order approximation for Δ_M in



$\Delta_M = 2M\Delta$

where M – Ratio of low connection resistance to resistance being paralleled
Δ – Unbalance of high connection resistances in proportional parts

FIGURE 25. FOUR-TERMINAL PARALLEL CONNECTION

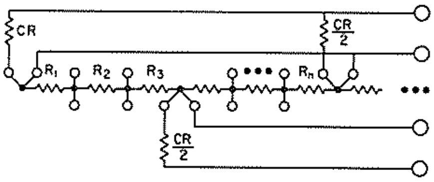
proportional parts is 2MΔ. M is the ratio of the highest shorting bar resistance to the resistance R_n of the resistors being paralleled. Δ is the relative unbalance of the compensating resistors CR. If we are paralleling 10 ohm resistors with 10 milliohm buss bars and are using compensating resistors which are matched to 0.1%, we will have a four-terminal resistor which is within 1 ppm of the parallel resistance of the resistors being paralleled,

$$R_p = (1 \text{ ohm})\,(1 + \Delta_{AV}) \pm 1 \text{ ppm}.$$

In the SR-1010 we have both lower shorting bar resistance and better matched compensating resistors, so we get much better than 1 ppm calibration accuracy at one ohm and even greater accuracy for higher resistances.

FOUR-TERMINAL SERIES-PARALLEL MEASUREMENTS

The series-parallel connection of nine low-valued resistors can be done with another compensating network and a different connection of the shorting bars (see Figure 26). We are in effect paralleling three resistors, so the same connection technique is used and the same accuracy is obtained as with the parallel connection.



$\Delta_M = 2M\Delta$

where M – Ratio of low connection resistance to resistance being paralleled
Δ – Unbalance of high connection resistances in proportional parts

FIGURE 26. FOUR-TERMINAL SERIES-PARALLEL CONNECTION

FOUR-TERMINAL JUNCTIONS

The resistors in the SR-1010 box must be connected by true four-terminal "point" junctions, with two leads going to the resistors and two to the terminals. Some physical shapes which give four-terminal junctions are shown in Figure 27. The test for a four-terminal point junction is also shown. The meter voltages divided by the generator currents represent the possible resistance measurement error. For the junctions in the SR-1010 box, shown in Figure 28. These resistances are typically less than 0.1 microhm causing much less than one ppm deviation for even a one ohm per step box.

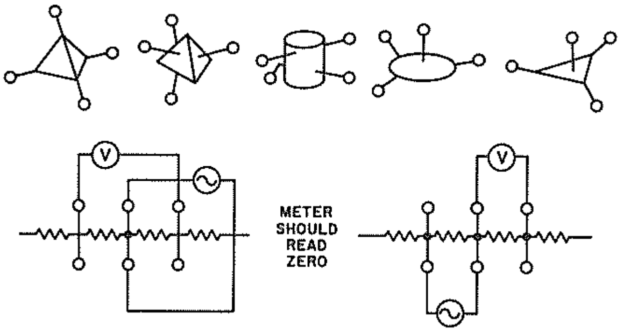


FIGURE 27. FOUR-TERMINAL JUNCTIONS

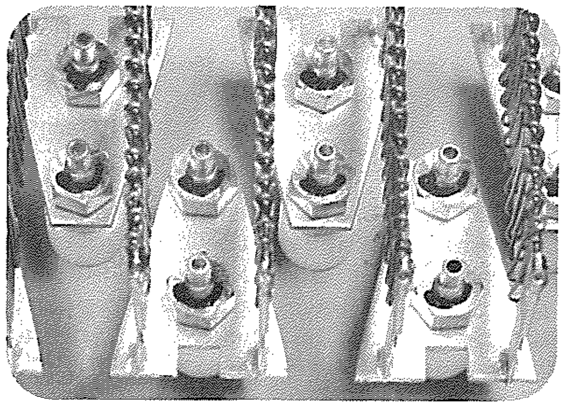


FIGURE 28. SR-1010 BOX JUNCTIONS

LET'S MAKE SOME TRACEABLE MEASUREMENTS

Our one ohm reference standard was sent to the National Bureau of Standards for certification, and we want to use it to calibrate our working standards of other values. We connect the reference standard to the bridge (Figure 29) and set the bridge deviation dial to the certified deviation of the standard (Figure 30).

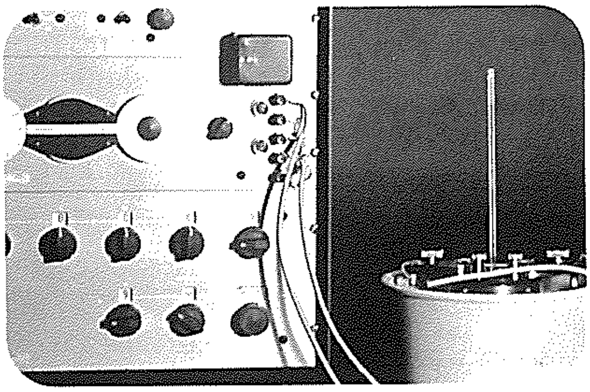
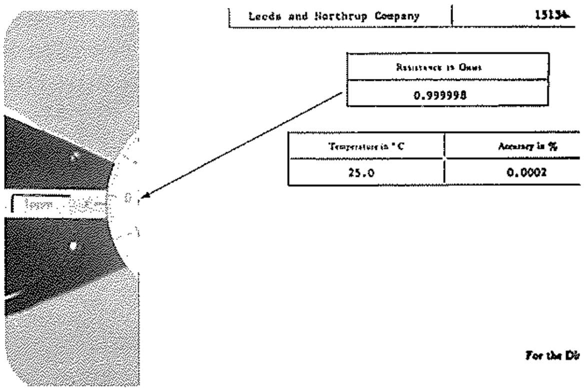


FIGURE 29. CONNECTING THE REFERENCE STANDARD



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Resistance in Ohms
0.999998

Temperature in °C	Accuracy in %
25.0	0.0002

For the Di

FIGURE 30. CERTIFIED DEVIATION

Caution: The standard resistor has a fairly high temperature coefficient and a long thermal time constant so it must be kept at the same known temperature for a long time before measurement. The resistance-temperature plots for three Thomas type one ohm resistors are shown in Figure 31.

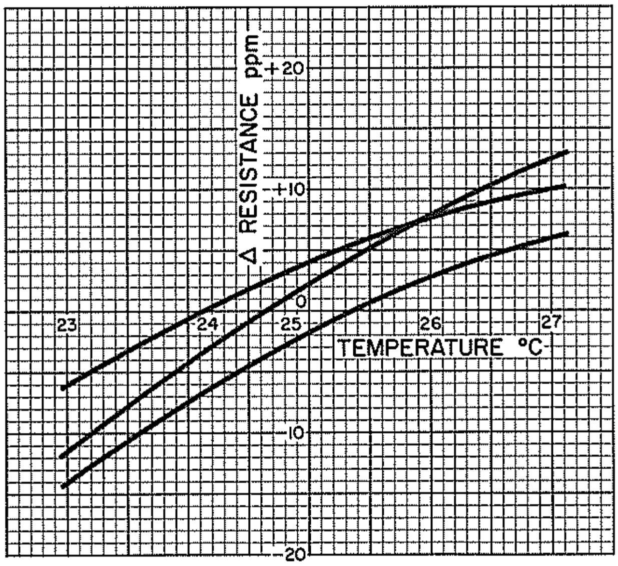

FIGURE 31. RESISTANCE TEMPERATURE CURVES

The bridge and transfer resistors do not reqire precision temperature control or monitoring for two reasons. First, they depend on short-term stability, not absolute accuracy. Second, the 100 ohm and higher bridge and transfer resistors are made of Evanohm wire so they can withstand small temperature variations with much less degradation than their Manganin counterparts. Typical temperature response curves for Evanohm and Manganin are shown in Figure 32.

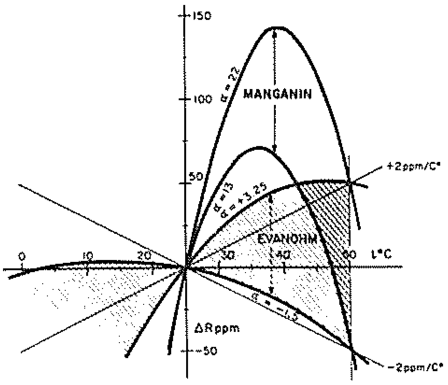

FIGURE 32. TEMPERATURE RESPONSE CURVES

Having set the bridge deviation dial to the certified deviation of the reference standard from its nominal value, we balance the bridge by means of the resistance dials. We ignore their readings; this adjustment calibrates the bridge for direct readings on the deviation dial of deviation from one ohm in parts per million.

We can now replace the one ohm reference standard by ten parallel-connected 10 ohm resistors in an SR-1010 box, rebalance the bridge by the deviation dial (Figure 33) and read directly Δ_{AV}, the average deviation of the ten resistors from the nominal value of the reference standard.

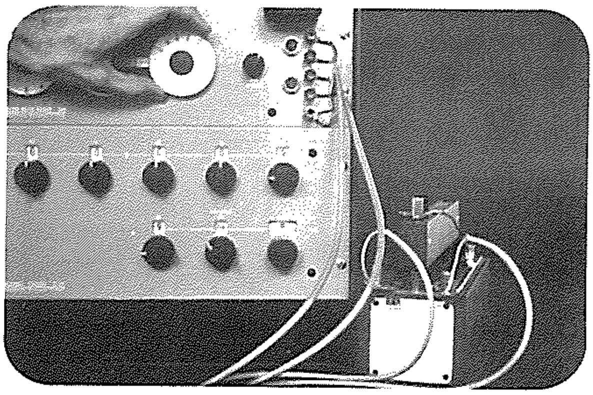

FIGURE 33. MEASURING Δ_{AV}

To calibrate the bridge at 100 ohms, we will reconnect the box to use the same ten resistors in series (Figure 34). We leave the measured value of Δ_{AV} set on the deviation dial and balance the bridge at 100 ohms by means of the resistance dials (again ignoring their readings). The bridge is calibrated for direct readings of the deviation of 100 ohm resistors from 100 times the nominal value of the reference standard as shown in Figure 35.

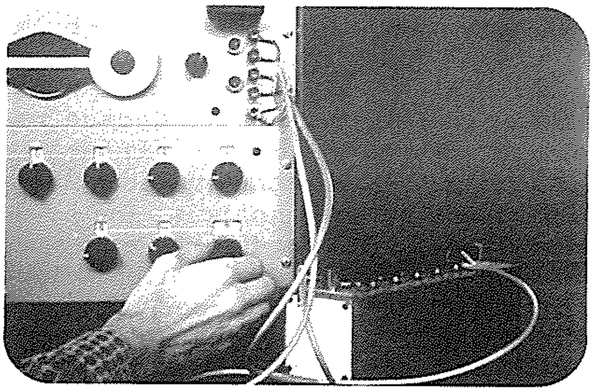

FIGURE 34. CALIBRATION OF THE BRIDGE TO READ 100 OHMS

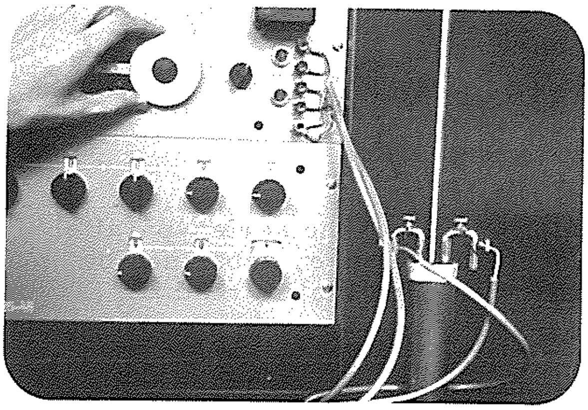

FIGURE 35. MEASURING A 100 OHM RESISTOR

With this bridge calibration, the Δ_{AV} of ten 1 kilohm resistors connected in parallel can be measured. The 1 kilohm resistors can be connected in series to calibrate the bridge deviation readings at 10 kilohms. The same procedure can be repeated with ten 100 kilohm resistors to calibrate the bridge for reading 1 megohm. Note that the transfer of calibration from one ohm to one megohm has been made in only three steps, minimizing the problem of error accumulation in a long series of measurements.

To calibrate the bridge for intermediate values, we must intercompare the resistors in an SR-1010 box. In the ten ohm per step box, for example, we will start by measuring the difference of the series-parallel connected group of nine resistors from the tenth resistor. In Figure 36, we connect the tenth resistor R_{10} to the bridge, set the deviation dial to zero and balance the bridge using the resistance dials.

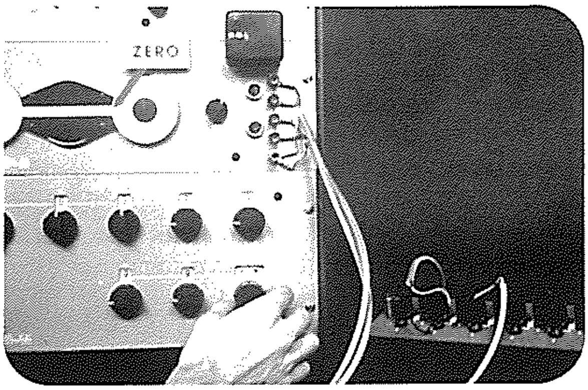

FIGURE 36. CALIBRATION OF THE BRIDGE TO READ Δ_D

We now connect the series-parallel group to the bridge, rebalance by means of the deviation dial to read Δ_D (Figure 37) and calculate $\Delta_{SP} = \Delta_{AV} + (\Delta_D/10)$. ($\Delta_D$ can be measured to the same accuracy as Δ_{AV} so $\Delta_D/10$ is ten times as accurate as Δ_{AV} therefore Δ_{SP} will have essentially the same accuracy as Δ_{AV}). Leaving the series-parallel circuit connected to the bridge, we set the deviation dial to Δ_{SP} and rebalance the bridge by the resistance dials (Figure 38). The bridge is now standardized to measure the deviation of any other ten ohm resistors as shown in Figure 39.

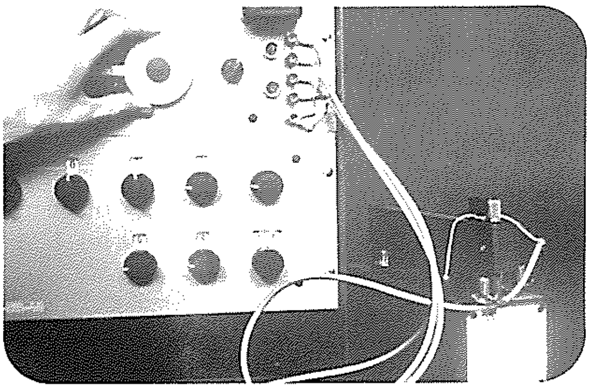

FIGURE 37. READING Δ_D

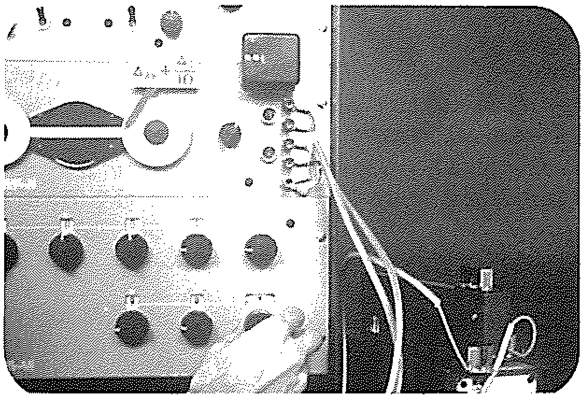

FIGURE 38. CALIBRATION OF THE BRIDGE TO READ 10 OHMS

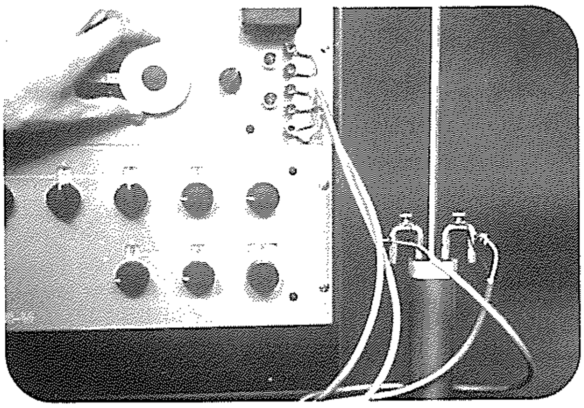

FIGURE 39. MEASURING 10 OHMS

This adjustment can also be used to measure the deviation of each of the individual resistors in the SR-1010 for use at any multiple of 10 ohms up to 120 ohms. This type of calibration of the various SR-1010 boxes can be used to calibrate each step of the decade resistance dials of the bridge. In measuring unusual resistance values, it is often sufficient to standardize the bridge at the first sginificant figure, using the deviation as a bridge calibration adjustment to make the bridge read correctly at that step on that decade. Nearby resistance values can then be read directly with good accuracy, since errors in the less significant figures will contribute much less measurement error.

SYSTEM ACCURACY

With the equipment described, a careful operator in an air conditioned laboratory can consistently compare two like resistance values in the range from an ohm to above a megohm to an accuracy of 2 ppm, except at the one ohm ohm level, where detector sensitivity may limit the accuracy to about 4 ppm. Using these figures and assuming a Thomas pattern reference standard certified to 2 ppm as the starting point, the system accuracy table shown in Figure 40 can be constructed. Note that the accuracy obtained is substantially better than present certification at all levels above one ohm. At the one megohm level, for example, the transfer standard is known to 10 ppm and any other stable one megohm resistor can be measured to 12 ppm. Where the ultimate accuracy of the system is desired, the calibration procedure should be made a routine part of the operating procedure. By using extra care and multiple readings in making a measurement the accuracy can be improved even further. At these levels of accuracy, statistical analysis of repeated measurements should be made to determine the accuracy corresponding to any specified probability or confidence factor.

			RESISTANCE VALUE	CALIBRATION ACCURACY OF STANDARD	ACCURACY OF CALIBRATED BRIDGE
LEGAL STANDARD AT NBS			1 Ω	0 ppm	———
LABORATORY REFERENCE STANDARD			1 Ω	2 ppm	6 ppm
esi MODEL SR-1010 TRANSFER STANDARDS CALIBRATED AT TIME OF USE	10 Ω/STEP	PARALLEL	1 Ω	6 ppm	———
		SERIES-PARALLEL	10 Ω	6 ppm	8 ppm
		SERIES	100 Ω	6 ppm	8 ppm
	1 k/STEP	PARALLEL	100 Ω	8 ppm	———
		SERIES-PARALLEL	1 k	8 ppm	10 ppm
		SERIES	10 k	8 ppm	10 ppm
	100 k/STEP	PARALLEL	10 k	10 ppm	———
		SERIES-PARALLEL	100 k	10 ppm	12 ppm
		SERIES	1 MEG	10 ppm	12 ppm

FIGURE 40. TRANSFER ACCURACY

Since the calibration procedure is so rapid (three substitution type comparisons to determine Δ_{AV} for all three boxes) it is easy to accumulate enough calibration history in a short time to indicate how frequently the procedure should be repeated for any particular set of ambient conditions and desired accuracies. In many air conditioned laboratories, measurements will be found to repeat consistently over a period of many weeks or even months to a closer tolerance than that listed in Figure 40. Where these limits of error are sufficient, the boxes can then be used as working standards with accuracies in air approaching those of NBS pattern resistors in an oil bath.

MORE ABOUT RESISTANCE MEASUREMENT

(1) Precision Resistance Measurement-Part I. ESI Design Ideas, Vol. 1, No. 2, July 1960.

(2) Precision Resistance Measurement-Part II. ESI Design Ideas, Vol. 1, No. 3, November 1960.

(3) A 1-100Ω Build-up Resistor for the Calibration of Standard Resistors, B. V. Hammon. Journal of Scientific Instruments, Vol. 31, No. 12, Dec. 1954.

(4) Establishment and Maintanence of the Electrical Units, F. B. Silsbee. NBS Circular 475, June 30, 1949. Reprinted in Precision Measurement and Calibration, Vol. 1, Feb. 1961

(5) Precision Resistors and their Measurement, James L. Thomas. NBS Circular 470, Oct. 8, 1948. Reprinted in Precision Measurement and Calibration, Vol. 1, Feb. 1961.

(6) Methods, Apparatus, and Procedures for the Comparison of Precision Standard Resistors, Frank Wenner. *Journal of Research of the National Bureau of Standards*, Vol. 25, Aug. 1940. Reprinted in *Precision Measurement and Calibration*, Vol. 1, Feb. 1961

(7) Calibration Procedures for Direct-Current Resistance Apparatus. *NBS Monograph #39*, March, 1962.