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IN THIS ISSUE

Capacitance Measurements
Voltage Dividers
WESCON 1959

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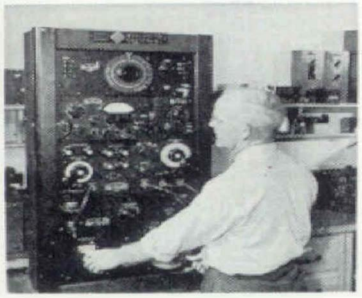


This scene in the General Radio Standards Laboratory shows the Type 1610-A Capacitance Measuring Assembly in use for the measurement of 3-terminal capacitors.

A CLOSE LOOK AT CONNECTION ERRORS IN CAPACITANCE MEASUREMENTS

The growing interest in capacitance measurements both of higher accuracy and of smaller capacitance has led to a re-examination of some of the problems involved in the *precise* and *accurate* measurement of small capacitance. It has been evident for some time that errors and uncertainties of the order of a few tenths of a picofarad were present in most measurements of two-terminal capacitors.[1] Such errors are not very significant in the calibration of standard capacitors as long as the capacitance exceeds 100 pf and the desired accuracy is no greater than 0.1%. Any attempt however, to calibrate smaller capacitors to this accuracy, or to increase the accuracy of other calibrations, demands a consideration of the accuracy limitations imposed by the connection errors in the usual two-terminal measurements.

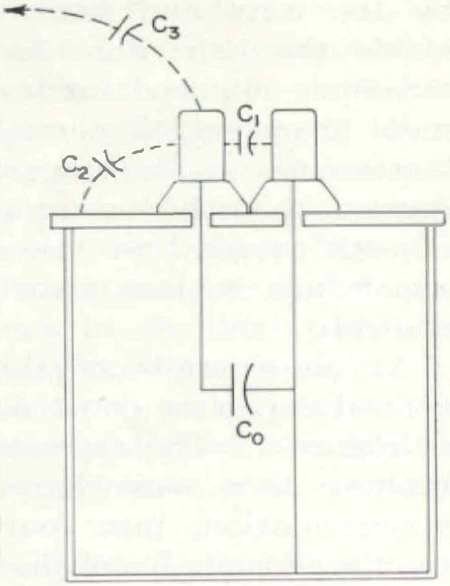
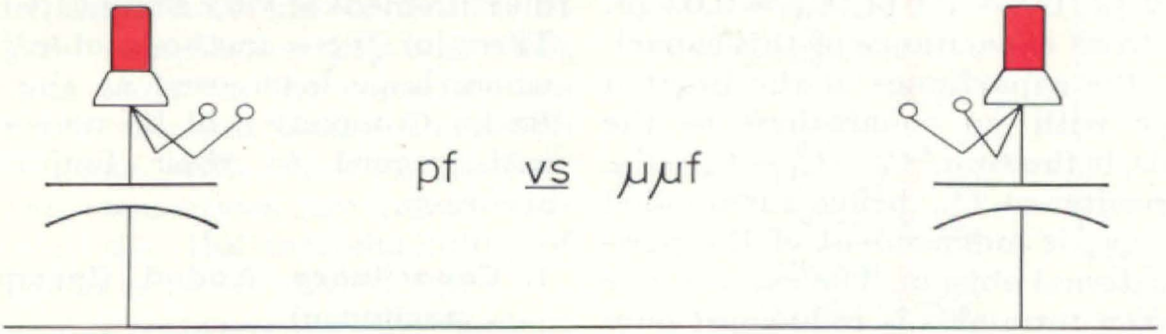


Figure 1. Schematic diagram showing the terminal capacitances of a capacitor.

The problems arise from the connections that must be made to a capacitor in order either to use or to measure its capacitance. The capacitance is, of course, determined by the geometrical configuration of the conductors (and by the dielectric material, which will here



As our capacitance measurements and standards move toward the millionth part of the millionth part of the millionth part of the farad (10^{-18} f), we have found increasing advantage in following the lead of the National Bureau of Standards and others in calling 10^{-12} farad a *picofarad* instead of a micromicrofarad. A privilege most prized by proponents of the picofarad is the right to write the abbreviated abbreviations 1 pf instead of 1 μμf for 10^{-12} farad and 1 μpf instead of 1 μμμf for 10^{-18} farad.

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[1] The common capacitor is here characterized specifically as two-terminal because a three-terminal capacitor will be introduced and defined later.

be assumed to have simple and constant characteristics). Only when one conductor completely surrounds the other is the capacitance simply defined by the form and nature of materials inside the capacitor. As soon as the terminals required for use or measurement are provided, these terminals add increments to the capacitance, which depend upon the nature and position of objects external to the capacitor and which are seldom easy to define or control.

As an example of this, consider a typical capacitor constructed as shown in Figure 1.[2] The capacitance has been broken, as a somewhat arbitrary first approximation, into four components: C_0, the capacitance of the multiple-plate capacitor and leads within the case; C_1, the capacitance between the external binding posts; C_2, the capacitance between the high terminal and the case, which is connected to the other terminal; C_3, the capacitance between the high terminal and all objects external to the capacitor and its terminals. Typical of the magnitudes of these components are the values $C_0 = 100$ pf, $C_1 = 0.2$ pf, $C_2 = 1.3$ pf, $C_3 = 0.03$ pf.

The "free" capacitance of this capacitor, i.e., the capacitance of the isolated capacitor with no connections to the terminals, is the sum,[3] $C_0 + C_1 + C_2 + C_3$. The capacitance C_0, being surrounded by the case, is independent of the position of external objects. The capacitance C_1 between terminals is influenced only by intrusions very close to or between the terminals. But C_3, and to a lesser extent C_2, can readily be affected by more distant environment of the capacitors, and variations of 0.01 pf or more can result from a slight change of position.

More radical changes in these external capacitances are produced by any connections made to the terminals. A wire connected to the high terminal, for example, obviously introduces new components of capacitance between the wire and the capacitor parts. It also, not so obviously, reduces the "free" capacitance by as much as 0.1 pf by changing the distribution of field around the terminals. There is a similar reaction of the capacitor on the connections, which makes the capacitance of the leads when connected to the capacitor differ from that of the leads alone. Indeed, the complexity of this mutual interaction is such that it is impractical to define the dividing line between capacitor and leads with a precision much better than ±1 pf.

A consideration of these difficulties suggests several possible methods of measurement in which the errors and uncertainties can be reduced or eliminated in order to obtain accuracy in the measurement of very small capacitances. Three of these methods of calibration which have been used at the General Radio Company will be reviewed here with regard to their limitations in accuracy.

1. Capacitance Added (Insertion Capacitance).

Since the capacitance of the two-terminal capacitor depends upon the environment of the capacitor and upon the method of connection, an accurate calibration can be made only by defining with sufficient precision the geometry of both the environment and the connections. One practical method of achieving

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[2] This is the structure used until recently in the General Radio Type 1401 Standard Air Capacitors.

[3] When the capacitor is isolated, C_3 is the capacitance to infinity. The similar capacitance from the low terminal to infinity is in series with C_3 in the "free" capacitance, but it can be neglected here because this capacitance to infinity is much larger than C_3 when the low terminal is connected to the capacitor case and is infinite when the low terminal is grounded, as it usually is in two-terminal measurements.

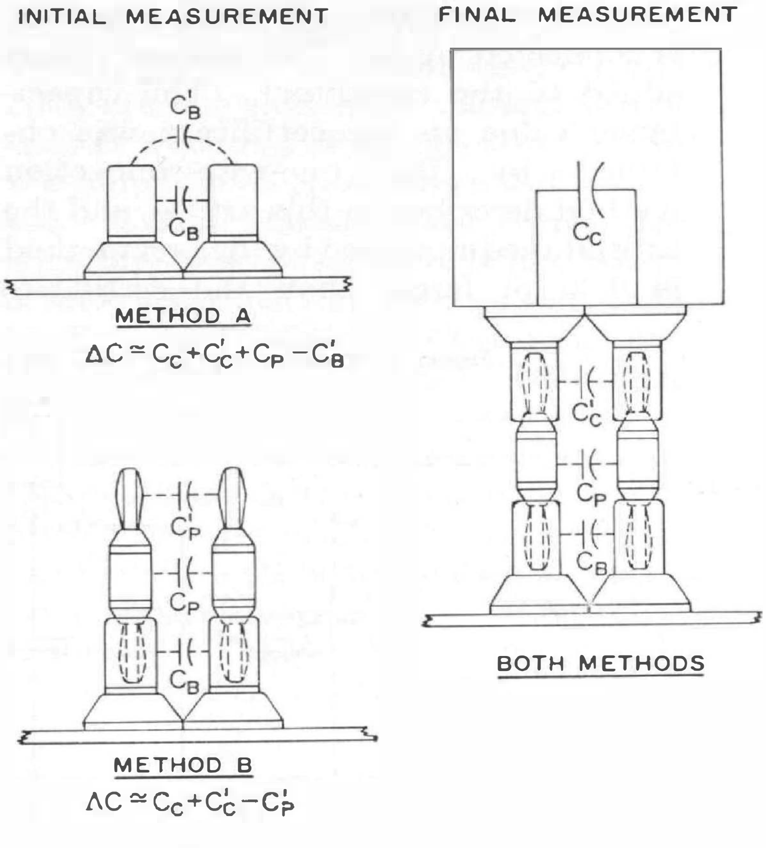
high accuracy is to calibrate in terms of the capacitance change at a pair of terminals when some change is made in the capacitor or its position. Two measurements are required to determine the capacitance change, and, hence, terminal conditions for both measurements must be either invariant or precisely specified. When the capacitor has variable capacitance, the shielded internal capacitance can be varied in an environment determined solely by the capacitor construction; while the external capacitances at the terminals, although dependent upon external connections and environment, can easily be held so constant during the capacitance change that they make no appreciable contribution to the difference. Such variable capacitors can be calibrated[4] in terms of the capacitance added or removed by rotation of the capacitor plates with essentially no limitation of accuracy by connection errors.

When the capacitor has a fixed capacitance, a calibration of high accuracy of the capacitance added requires that the capacitor be connected with specified leads to a specified set of terminals. For example, the General Radio Type 1409 Standard Capacitors are calibrated in terms of the capacitance they add when the banana plugs on the capacitor are plugged into General Radio Type 938 Binding Posts with ¾-inch spacing. When the connections are made with reasonable care, the reproducibility of measurement is better than 0.1 pf.

For greater accuracy the environment of the terminals must also be defined, for any change in terminal position or panel size (which results, for example, from the use of different bridges or of terminals on an external capacitor instead of the bridge terminals) can produce a change in the measured capacitance. The value assigned to the capacitor is the difference between two bridge measurements: the first with the bridge terminals open, and the second with the capacitor connected to the terminals. In the second measurement the capacitor case and bridge panel are usually effective in shielding the bridge terminals, so that this measurement is not very sensitive to changes outside the radius of a few inches. The capacitance of the open bridge terminals in the first measurement (and of any open terminals on the capacitor, such as those on top of the 1409 Capacitors) is affected to a greater extent by panel size and terminal position.

The General Radio Type 1401 Standard Air Capacitor is another example of a fixed capacitor calibrated in terms of the added or "insertion" capacitance. These capacitors are now being made, as shown in Figure 3, with banana-plug

Figure 2. Two methods for the measurement of capacitance added. The capacitances shown represent only major components in the complete expression of the self and mutual capacitances of the terminals.



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[4] The General Radio Type 722-MD and Type 722-ME Precision Capacitors are calibrated in terms of capacitance removed.

terminals on the case, similar to those on the Type 1409 Capacitors. In previous production the Type 1401 Capacitors have had the jack-top Type 938 Binding Posts on their cases, and two double-ended banana plugs have been provided with each capacitor to connect it to another pair of similar binding posts. With these connectors two different methods of added-capacitance calibration can be made. In the first method, shown in Figure 2-A, the initial measurement is made with the bridge terminals open and the final measurement with the capacitor connected by means of the double-ended plugs. In the second method, shown in Figure 2-B, the initial measurement is made with the plugs in the bridge terminals and the final with the capacitor added to the plugs.

This choice of methods has in the past resulted in some confusion. The National Bureau of Standards has used the second method (plugs added to the bridge) in its calibrations of these capacitors, but the General Radio Company has given on its calibration certificates a correction of the certificate value to obtain the capacitance when the capacitor is connected by the first method (plugs added to the capacitor). The capacitance value on the certificate was obtained by the fine-wire-connection method described in this article, and the capacitance measured by the first method is 0.35 pf larger than the certificate value. When the second method is used, the measured capacitance is 0.7 pf lower than that of the first method because the capacitance added to the bridge terminals by the plugs in the initial measurement $(C_p + C_p' - C_B')$ in Figure 2) is 0.7 pf. In neither method is the added capacitance the same as the "free" capacitance.[5] In the first method the added capacitance is greater than the "free" capacitance because of the capacitance, C_p, added by the plugs. In the second method the added capacitance is less than the "free" capacitance because the connection of the capacitor removes from the final measurement the capacitance, C_p', between the ends of the plugs that was included in the initial measurement.

To avoid both this choice between connection methods and also the limitations of the fine-wire-connection method,

Figure 3. Type 1401 Fixed Air Capacitor as now supplied.

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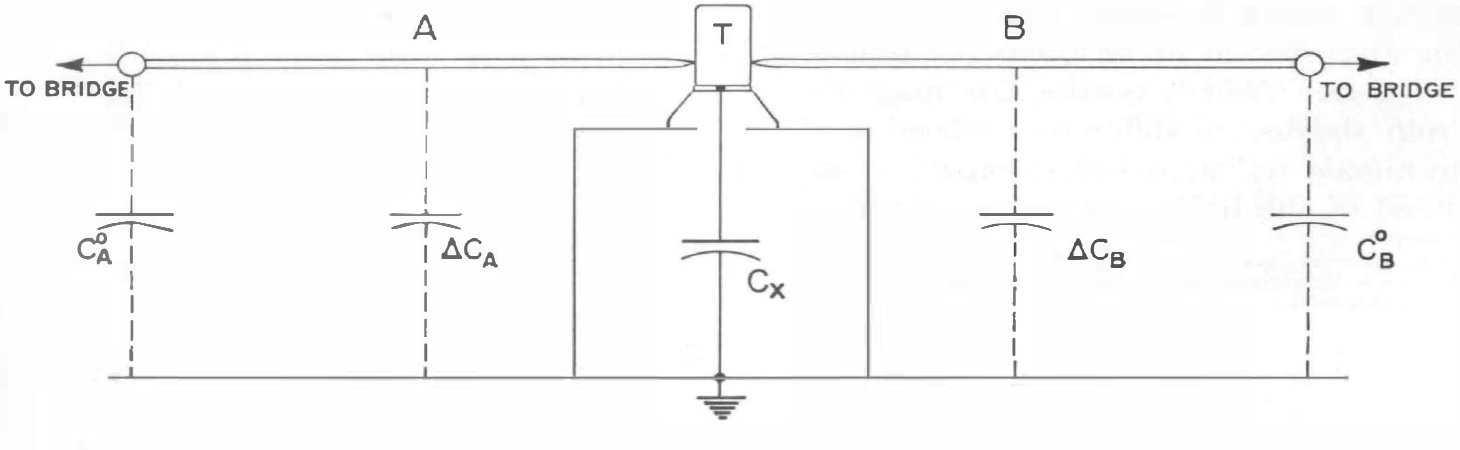
[5] The value on the certificate, obtained by the fine-wire-connection method, also differs by about 0.2 pf from the "free" capacitance for reasons explained in this article.

Figure 4. Measurement of "free" capacitance by the Rosa and Dorsey method.



the 1401 Capacitors are now provided with only banana-plug terminals, and they are calibrated by both the National Bureau of Standards and General Radio Company, as the 1409 Capacitors are, in terms of the capacitance added when the capacitor is plugged directly into General Radio type binding posts.

2. "Free" Capacitance.

In the attempt to define a capacitance with high accuracy, an alternative to the method of specifying with sufficient precision the geometry of the connections is a method which eliminates all connections and defines the "free" capacitance of the capacitor with all disturbing connections and surroundings removed. In this method the difficulties of measuring the capacitance of a capacitor, isolated from its surroundings and without connections, are substituted for the difficulties of controlling the geometry of the connections and the environment.

It is possible to determine this "free" capacitance by evaluation of the disturbing effects of the connections and application of a correction for these effects to the measured capacitance. A method for doing this has been described by Rosa and Dorsey.[6] The effects of the connections can be eliminated from the measurement by the use of two sets of connecting leads which are not necessarily identical but which have no mutual interaction. As a simplified illustration of this method, consider the arrangement shown in Figure 4. The capacitor to be measured has a "free" capacitance C_x, which includes external components corresponding to C_1, C_2, C_3 in Figure 1. For simplicity only the high terminal, T, is shown in Figure 4, but the ground connection to the case and to one side of the capacitor shown in the figure can be made to a second, similar terminal on the capacitor. A first measurement is made with connecting wire A connected to the terminal and to the bridge and with wire B removed. The measured capacitance is $C_1 = C_A^\circ + C_B^\circ + \triangle C_A + C_X - \triangle C_X^A$. A similar measurement with wire B connected and A removed gives $C_2 = C_A^\circ + C_B^\circ + \triangle C_B + C_X - \triangle C_X^B$, where

$C_A^\circ + C_B^\circ$ is the measured capacitance of leads, bridge, etc., when both wires A and B are removed,

$\triangle C_A$ and $\triangle C_B$ are the increments added by wires A and B,

$\triangle C_X^A$ and $\triangle C_X^B$ are the changes in C_X resulting from the presence of A and of B.

With both wires A and B connected to the terminal the capacitance measured is $C_{12} = C_A^\circ + C_B^\circ + \triangle C_A + \triangle C_B + C_X - \triangle C_X^A - \triangle C_X^B$. These relations can be combined to show that $C_X = C_1 + C_2 - C_{12} - (C_A^\circ + C_B^\circ)$. The "free" capacitance C_X can thus be determined from four measured capacitances, C_1, C_2, C_{12}, and $C_A^\circ + C_B^\circ$.

In this derivation the wires A and B are assumed to have no mutual interaction, e.g., the capacitances $\triangle C_A$ and $\triangle C_X^A$ are not altered by the addition of wire B when C_{12} is being measured. In the simple connection shown in Figure 4 there is some mutual effect (which can with care be kept below 0.01 pf), but in a spherical capacitor such as that used by Rosa and Dorsey the two leads can be thoroughly shielded from each other by their locations on opposite sides of the sphere. The assumption that the calculated C_X is the "free" capacitance further requires that the initial measurement of $C_A^\circ + C_B^\circ$ be made with all measuring apparatus so far removed from the terminal T that it has no significant effect on the capacitance. In practice it

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[6] E. B. Rosa and N. E. Dorsey, "A New Determination of the Ratio of the Electromagnetic to the Electrostatic Unit of Electricity," Bull. Bureau of Stand., Vol. 3, Nos. 3 and 4, 1907.

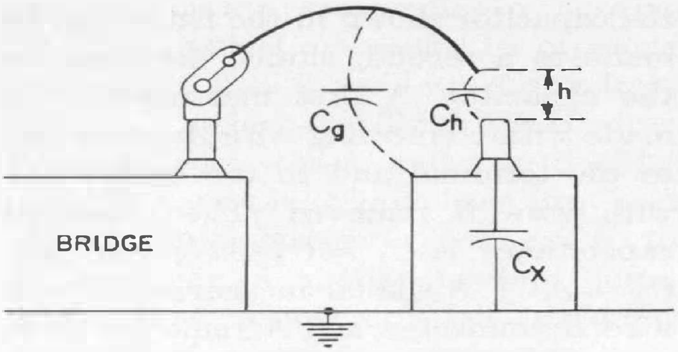

Figure 5. Diagram of connection method using a fine wire.

is difficult to approximate this condition to better than 0.01 pf unless, as in the Rosa and Dorsey capacitor of concentric spheres, one of the conductors surrounds and shields the other.

Another method which removes most, but not all, of the effects of the connections is the fine-wire-connection method described by R. F. Field.[7] In this method, as shown in Figure 5, the connection between the bridge and the high terminal of the unknown capacitor is made by a wire of small diameter pivoted near the bridge terminal so that its separation from the capacitor terminal can be varied. An initial measurement is made with the wire separated from the terminal by a distance h. With the assumption that the capacitance C_h between the wire and terminal is small compared to the unknown C_x, so that $C_hC_x/(C_h + C_x) \simeq C_h$, the measured capacitance is $C_1 = C_g^h + C_h$, where C_g^h is the capacitance between wire and ground when the separation is h. When the wire is moved in to touch the terminal, the capacitance C_h becomes infinite and the capacitance between wire and ground increases to C_g°. The measured capacitance now becomes $C_2 = C_g^\circ + C_x$. The unknown capacitance can thus be related to the measured values C_1 and C_2 by $\triangle C = C_2 - C_1 = C_x + (C_g^\circ - C_g^h - C_h)$. At some particular distance h, the capacitance C_h is equal to the change in C_g as the wire is moved, i.e., $C_h = C_g^\circ - C_g^h$, and the term in parentheses vanishes, leaving simply $C_x = C_2 - C_1$.

When the wire is curved and pivoted at the bridge end to approach the capacitor terminal from above in the manner described by Field, the change of $\triangle C$ with h is fairly linear, as shown in Figure 6 from Field's article. A plot of $\triangle C$ against h can then be extrapolated to $h = 0$, where $\triangle C = C_x$, and the value of h which corresponds to this $\triangle C$ was found by Field to be ¼ inch. The difference between the two capacitances measured with the wire touching the terminal and then ¼ inch above it should, therefore, be the value C_x of the unknown capacitor.

This method is simple and useful for calibrations where uncertainties less than 0.1 or 0.2 pf are not significant. It has in the past been used in the calibration of our TYPE 722-D Precision Capacitors, where the direct-reading accuracy limit is ±0.1% or ±0.2 pf,[8] and in the calibration of TYPE 1401 Standard Air Capacitors, with a limit of ± (0.1% + 0.1 pf). There are, however, several reasons why this method has connection errors which can be of the order of 0.1 pf. In the first place, even in the absence of other errors, the capacitance measured, C_x, is not the "free" capacitance (C_x^F), but the capacitance (C_x^w) in the presence of the connecting wire.[9] Even though the added capacitance to ground of the wire has been eliminated from the measurement, the wire still reduces the capacitance of the terminal

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[7] R. F. Field, "Connection Errors in Capacitance Measurements," *General Radio Experimenter*, Vol. 12, No. 8, January, 1938, pp. 1-4; reprinted: Vol. 21, No. 11, April, 1947, pp. 1-4.

[8] Note that the catalog accuracy limit of ± 0.05 pf for the TYPE 722-ME Precision Capacitor refers to capacitance removed, that is, to a calibration with the capacitance varied but the connections unchanged.

[9] This was pointed out to us by Dr. F. R. Kotter of the National Bureau of Standards.

from its "free" value by disturbing the field around the terminal and, hence, the charge distribution on it. The fine-wire connector used by Field makes the measured capacitance of the TYPE 938 Binding Posts on TYPES 1401 and 722 Capacitors about 0.1 pf less than the "free" capacitance, i.e., $C_x^F = C_x^w + 0.1$ pf.

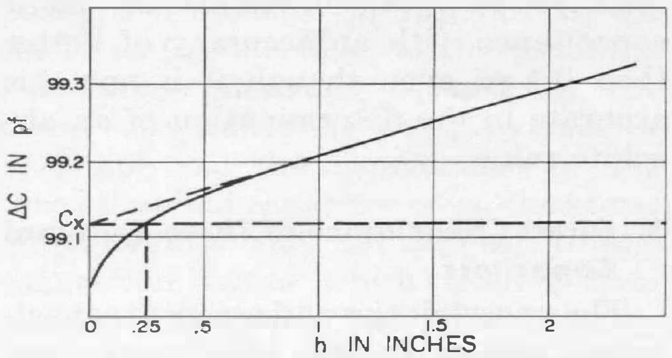

Figure 6. Determination of unknown capacitance C_x from ΔC measured with fine-wire connector. At $h = \frac{1}{4}$ inch $C_x = \Delta C$. (From Field paper[7])

A recent analysis of the component capacitances in the fine-wire method with a three-terminal capacitance bridge has revealed that even the capacitance C_x^w in the presence of the wire is hard to determine without errors of the order of 0.1 pf. The measurements were made on a capacitor which was externally identical to a TYPE 722-D Precision Capacitor but which had internal, guarded connections to the terminals to permit measurement of the "free" capacitance and the effects of the connector upon it.[10] To simulate the stray capacitances to external grounds in two-terminal measurements, the three-terminal measurements were made with a wire cage (30″ x 30″ x 30″) surrounding the capacitor and its connections and connected to the "ground" terminal of the capacitor.

The measured capacitances, C_x, C_g^h, $C_g^h + C_h$, and $\triangle C = C_x + C_g^o - (C_g^h + C_h)$, are plotted in Figure 7 as a function of the separation h between wire and terminal. For convenience, the capacitance level has been adjusted to make $C_x^F = 100$ pf. The upper curve shows the variation in C_x as the wire moves away from the terminal, with an increase of about 0.1 pf as the influence of the wire vanishes with increasing h. The next curve shows the results of the fine-wire method, with $\triangle C$ plotted as a function of h. The lower curves, with the level of the capacitance axis shifted, show the variations of the wire capacitances, C_g^h and $C_g^h + C_h$, with h.

The fine-wire method, when corrected for the effects of the wire on C_x, pre-

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[10] These measurements were checked within ± 0.01 pf by a measurement of "free" capacitance by the Rosa and Dorsey method.

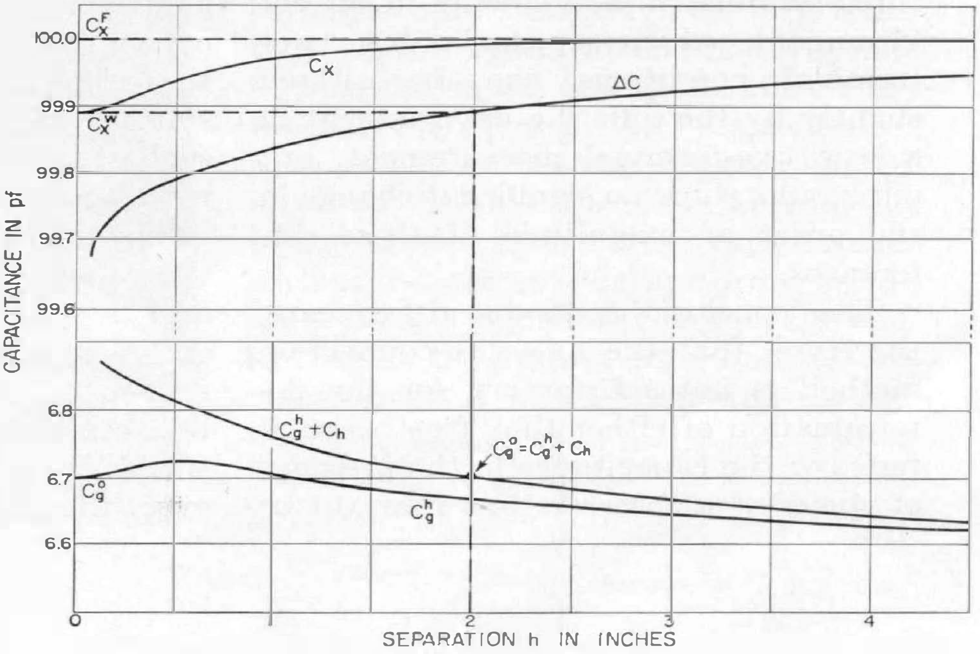


Figure 7. Variation of measured capacitances with fine-wire connector as a function of the separation h.

dicts that, at the distance which makes $C_g^h + C_h = C_g^\circ$, the capacitance difference $\triangle C$ will be equal to C_x^w. In Figure 7 this condition is shown to be satisfied at a distance $h = 2$ inches. Any attempt, however, to determine C_x^w here by extrapolation of the $\triangle C$ curve to $h = 0$ encounters difficulty because the curve is not very linear. Examination of the C_g^h, $C_g^h + C_h$, and C_x curves shows that C_h does, as expected, cause deviation from linearity at small h, that C_g^h is itself not linear for h less than about 2.5 inches, and that C_x is not constant with h, as assumed in the derivation of the method. In the region beyond 2.5 inches C_x is almost constant and C_g relatively linear, as desired, and it seems possible that a linear region beyond the range of the graph might extrapolate to C_x^w at $h = 0$.

The important point, however, is the obvious difficulty in determining C_x^w by this method without variations of 0.1 pf. Attention should also be directed to the difference between the $\triangle C$ value at the ¼-inch separation and the values of C_x^w and C_x^F. With the ¼-inch spacing, the fine-wire method would give under these conditions a capacitance 0.14 pf less than the capacitance C_x^w in the presence of the wire and 0.25 pf less than the "free" capacitance C_x^F. These results of three-terminal measurements in an environment which approximates two-terminal conditions can be altered slightly by the differing environment in a true two-terminal measurement, but our results show no significant change in the order of magnitude of these differences.

The conclusions to be drawn are, therefore, that the fine-wire-connection method is not satisfactory for the determination of either the "free" capacitance or the capacitance in the presence of the wire with errors less than 0.1 or 0.2 pf unless considerable care is taken in both making and correcting the measurements. As in the other methods of making connection to two-terminal capacitors, the results are reproducible with a precision of 0.01 or 0.02 pf if adequate care is taken to keep the geometry of the connections invariant. The fine-wire method can, therefore, be used to calibrate in terms of *added* capacitance with an accuracy of better than 0.1 pf even though it is not this accurate in the determination of an absolute value.

3. Direct Capacitance of Three-Terminal Capacitors.

The uncertainties and errors in capacitance measurements considered here have been the result of the variations in terminal capacitances produced by changes in the connections and in the environment. These problems associated with the capacitor terminals can be eliminated if the terminal capacitances can be separated from the capacitance to be defined and measured. One way of doing this is to introduce a third conductor as a shield or guard which completely surrounds all of at least one of the pair of conductors forming the capacitor to be measured except the area which produces the desired direct capacitance. The pair of conductors of the original capacitors and the added shield form a *three-terminal capacitor*, such as the one shown in Figure 8, along with its equivalent circuit.

The addition of the shield changes the capacitance that existed between 1 and 2 before the introduction of the shield by altering the field, and it also results in new capacitances, C_{13} and C_{23}, between the original conductors and the shield. If the shielding is complete, however, the capacitance C_{12} is now inde-

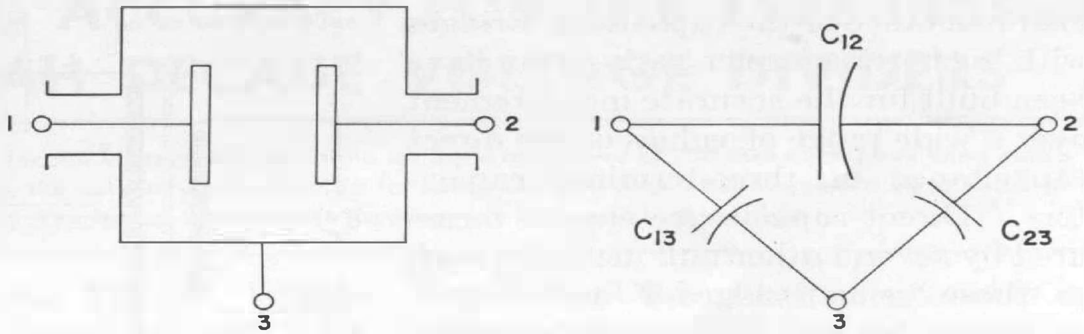
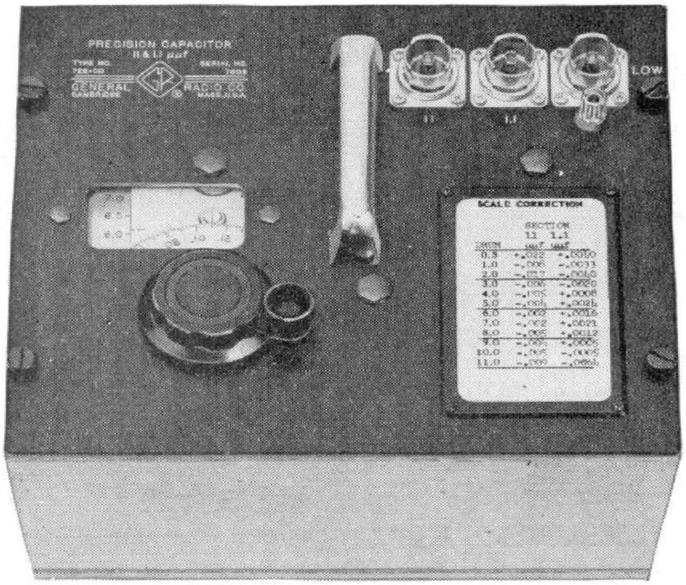


Figure 8. Diagram and schematic of 3-terminal capacitor.

pendent of the surroundings outside the shield and connections to the terminals 1 and 2 can affect only C_{13} and C_{23}. The direct capacitance C_{12} — usually referred to simply as the capacitance of the three-terminal capacitor — is, therefore, quite definite and not subject to the connection errors which trouble two-terminal capacitors.

Note, however, that if in this three-terminal capacitor one of the capacitor terminals, say 2, is connected to the shield, 3, the capacitor reverts to the usual *two-terminal capacitor*, with terminals 1 and 2. The capacitance C_{23} has thus been shorted; the capacitance C_{13} is now parallel with C_{12}, and the capacitor has the capacitance $C = C_{13} + C_{12}$. The capacitor is, thus, equivalent to that shown in Figure 1. Although C_{12} is still shielded from external influences, C_{13} is a function of connections and environment, and the total capacitance measured is subject to the variations described previously for such two-terminal capacitors.

Figure 9. View of the Type 722-CD Three-Terminal Precision Capacitor. Outer conductors of Type 874 Coaxial Connectors provide the shield. Inner conductors are the capacitor terminals.



The well-defined direct capacitance of the three-terminal capacitor is of practical use in a capacitance standard only if it can be measured with high accuracy and with reasonable ease. A bridge with transformer ratio arms is well-suited for just such measurements.[11] In the transformer bridge shown in Figure 10, the unknown and standard capacitors are driven by emf's of opposite phase and known ratio from a tapped transformer secondary winding, and the difference in the capacitor currents is measured by a detector. When the bridge is balanced for zero current through the detector, the currents through the direct capacitances C_{12} and C_s must be equal, and the balance relation is $C_{12}/C_s = n$. Any capacitance, such as C_{23}, across the detector has no effect at balance because there is no potential across it. Any capacitance, such as C_{13}, across the transformer winding will have negligible effect on the emf as long as the output impedance of the transformer is small compared to the

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[11] The three-terminal capacitor and its measurement are well described by A. M. Thompson, "The Precise Measurement of Small Capacitances," I. R. E. Transactions on Instrumentation, Vols. 1-7, Nos. 3 and 4, Dec., 1958, pp. 245-253.

load reactance of the capacitors. Bridges with such transformer ratio arms have been built for the accurate measurement over a wide range of values of the direct capacitance of three-terminal capacitors.[12] Direct capacitance can be measured by several other null methods, such as those using bridged-T and twin-T networks. Most bridge networks can be adapted to the three-terminal measurement by the use of auxiliary bridge arms to balance the unwanted components,[13] but the double balance required is never convenient and it is difficult to obtain accuracy when the direct capacitance is very small compared to the other capacitances. In some bridges three-terminal measurements can also be made over a limited range by connecting the unwanted capacitances across low-impedance arms of the bridge and across the generator or detector where the shunting effect is negligible.[14]

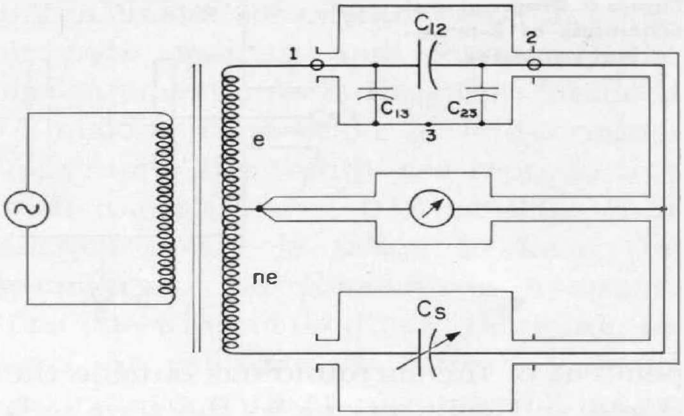

Figure 10. Schematic of transformer-ratio-arm bridge with 3-terminal capacitor connected for measurement.

In all these three-terminal measurement methods the connection errors in capacitance can be eliminated by having a complete external shield around at least one of the capacitor terminals. In Figure 10 the case of the capacitor and a shield lead from terminal 2 to the shielded detector complete the shielding around that terminal of the capacitor. A shielded lead to the other terminal is not usually required to eliminate connection capacitances but may be needed to prevent pickup from other sources. With such three-terminal measurements the measured direct capacitance should depend solely upon the construction of the capacitor and the accuracy of measurement should be limited only by the bridge or the reference standards used.

— John F. Hersh

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[12] The Type 1613-A Capacitance Bridge is a transformer bridge covering the range from 5 to 11,000 pf.

[13] The Type 716-P4 Guard Circuit provides the components required to make three-terminal measurement with the Type 716-C Capacitance Bridge.

[14] Three-terminal measurements can be made with the Type 1650-A Impedance Bridge in this way.

Next month new 3-terminal capacitors, both fixed and variable, will be described. In a forthcoming issue Dr. Hersh will continue the discussion of accuracy considerations and calibration methods for capacitance.

VACATION CLOSING

During the weeks of July 27 and August 3, our Manufacturing Departments will be closed for vacation.

There will be business as usual in the Sales Engineering and Commercial Departments. Inquiries, including requests for technical and commercial information, will receive our usual prompt attention.

Our Service Department requests that, because of absences in the manufacturing and repair groups, shipments of equipment to be repaired be scheduled to reach us after the vacation period.

INCREASED ACCURACY FOR THE TYPE 1454-A AND -AH DECADE VOLTAGE DIVIDERS

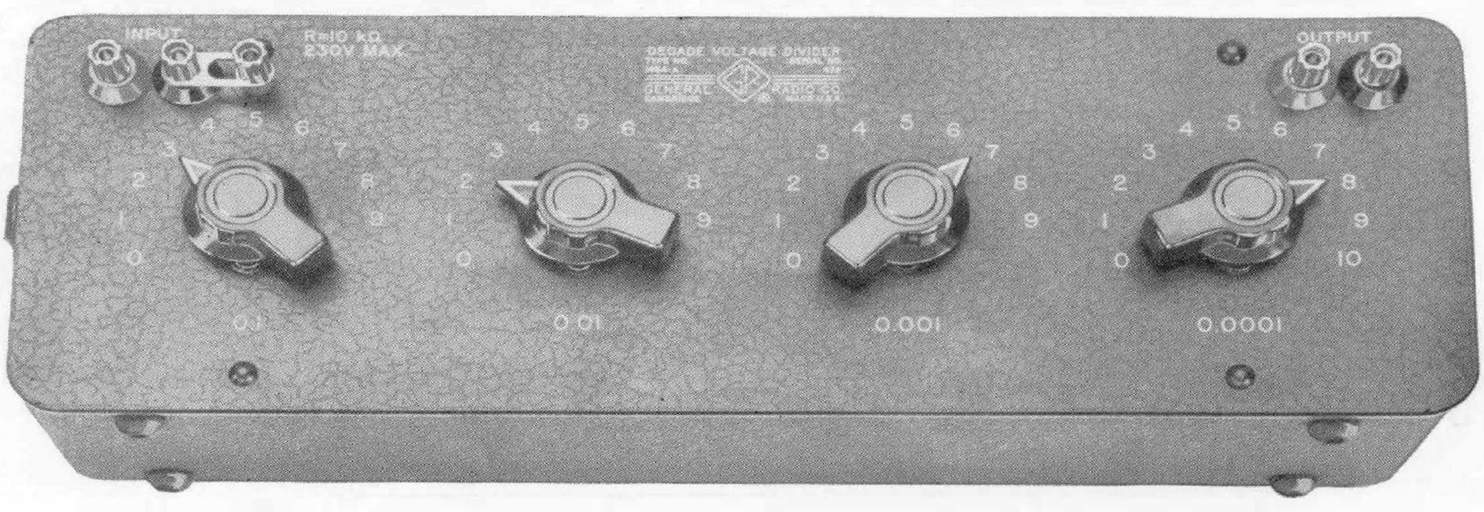
A new model of the Decade Voltage Divider, with an input resistance of 100,000 ohms, has been made available. In addition, the accuracy specification for these dividers has been improved by a factor of 2.5. The factors affecting the accuracy are discussed in this article.

THE TYPE 1454-A Decade Voltage Divider was introduced in 1955[1] with accuracy specifications of 0.1% in voltage ratio ±0.000001. The intent was to take advantage of the inherently good characteristics of the TYPE 510 Decade Resistors and to keep the voltage divider in the same price class by avoiding expensive adjustment to closer limits. Since the tolerance on the resistance decades is ±0.05%, it is evident that the worst combinations can produce an error in the voltage ratio of twice this value, or ±0.1%. The specification limits on the voltage divider were set accordingly.

It was recognized that the catalog limit of error was very seldom approached in actual service and most instruments would readily meet tighter tolerance specifications. A recent study has shown that only a few of the component resistors are critical and that proper selection of these during assembly would enable us to guarantee a considerably higher accuracy, 0.04%, for ratios above about 0.1 without appreciably increasing the price of the instrument.

The additive constant term of one part in a million in the expression for the error, however, was still the limiting factor at low settings. This could amount to 1% at a ratio of 0.0001. This error is caused by the contact resistance of the switches and is introduced in the manner shown in Figure 1. In the Kelvin-Varley circuit used in this divider, the resistors of the second decade parallel two adjacent resistors of the first decade, and so on. It will be seen that, in the present arrangement of four decades, the voltage drop of three switches in series appears in the output circuit. This causes a residual output voltage at the zero setting and an increased error at the lower outputs.

The cure for this second accuracy limitation was suggested by the fact that the switch contact resistance was found to be remarkably constant. The resistance may increase by a factor of two or three when the instrument is not in use but returns quickly close to its initial value after a few operations. The



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[1] Ivan G. Easton, "An Accurate Voltage Divider for DC and Audio Frequencies," *General Radio Experimenter*, Vol. 30, pp. 1-5, August, 1955.

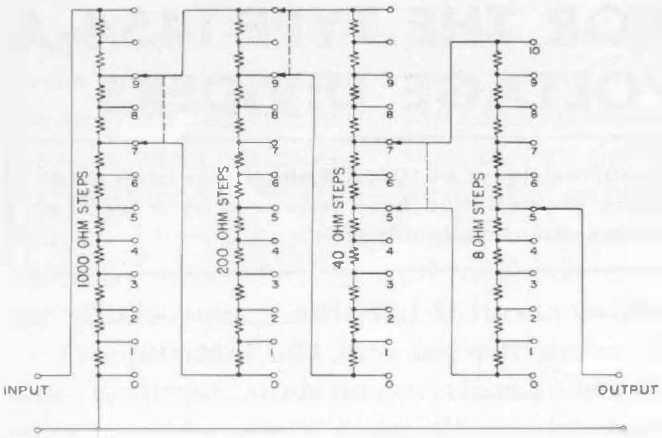

Figure 1. Schematic diagram of Type 1454 Decade Voltage Divider.

accuracy of the divider at low settings can be greatly improved if a bucking voltage equal to the average switch drop is introduced into the output loop.

The contact-drop balancing arrangement is shown in Figure 2. A small resistor, *R*, is placed in series with the first decade at its low end and the low output terminal is connected to the high side of the resistor. The low output terminal thus differs in potential from the low input terminal by the voltage across the resistor, which is made equal to the switch contact drop. The voltage at the output terminals can be balanced to a negligible value by this arrangement. The balancing resistor is very small, about 5 milliohms, so that its presence is never noticed in ordinary use of the divider. When highest accuracy is needed at low ratios, the user must remember to keep the input and output circuits separate. The user must also remember to turn each switch back and forth several times whenever the instrument is first used. The tendency is to forget the first or second decade when these are left at the zero setting, but these contribute the most to the contact drop, since they carry more current, and must be restored to normal resistance if the compensation scheme is to be effective.

Although the selection and matching of the component resistors should insure meeting the new tolerances, a check to one part in 10^6 is made of each ratio of each decade in the final inspection of the instrument.

When maximum accuracy is required, temperature effects must be allowed for and the input voltage must be reduced considerably below that corresponding to the dissipation limit of the resistors. Since all resistors are of similar construction and have more or less equal temperature coefficients, the effects of ambient temperature variations are very small. The effects from self-heating are not balanced out, however. Referring to Figure 1, it will be seen that in the first decade between points 7 and 9, which are bridged by the second decade, only half of the input current is carried. The resistors between these points will have only one-quarter of the temperature rise of the others of the decade, causing an error in the output voltage. The temperature rise of the second and following decades is much smaller and can be neglected. The temperature effect is largest at the zero position of the first decade. It has been found that, to keep the self-heating error at this first position within the specification limits, the input to the Type 1454-A Decade Voltage Divider should be limited to 120 volts. The normal dissipation limit is

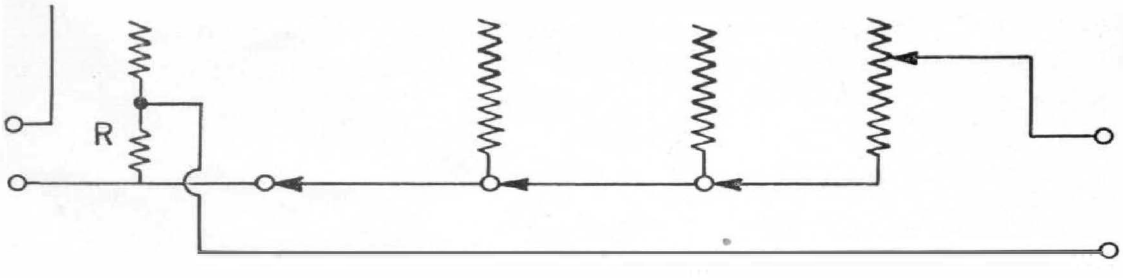

Figure 2. Arrangement for balancing the switch contact voltage drop.

230 volts. Neither limit applies to the high-resistance model, Type 1454-AH, which has one-tenth the dissipation at a given voltage.

— W. N. Tuttle

SPECIFICATIONS

Voltage Ratio: .0001 to 1.0000 in steps of .0001.

Accuracy: ±0.04% of indicated ratio, for input voltages below 120. The voltage drop in switch contacts and wiring is balanced out so that full accuracy is maintained down to the lowest setting, 0.0001.

Linearity: ±0.02% of full-scale setting.

Frequency Characteristics: If the external capacitance placed across the output terminals of Type 1454-A is less than 50 μμf, the frequency error is less than 0.1% to 20 kc for any setting. For the Type 1454-AH, the frequency limit is 2 kc for the same capacitance.

Input Resistance: Type 1454-A, 10,000 ohms; Type 1454-AH, 100,000 ohms.

Output Resistance: Varies with output setting, depending primarily on the setting of the highest decade in use.

Maximum Input Voltage: 230 volts rms (or dc) for 40° C. rise of the resistors of the input decade. Input voltage should be limited to 120 for maximum accuracy. At maximum rated voltage the total error can approach ±0.1%.

Resistance Units: Type 510 Decade-Resistance Units.

Temperature Coefficient: Of the individual resistors, less than ±0.002% per degree. Since the voltage ratios are determined by resistors of similar construction, ambient temperature effects are very small.

Terminals: Jack top binding posts with standard ¾-inch spacing at input and output. A separate ground post is provided, so that the divider circuit can be used grounded or ungrounded, with the shield grounded.

Mounting: Aluminum panel and cabinet.

Dimensions: (Length) 15¾ x (width) 5¼ x (height) 5 inches, over-all.

Net Weight: 7¼ pounds.

Type		*Code Word*	*Price*
1454-A	Decade Voltage Divider (10,000 ohms)..........	ABACK	$145.00
1454-AH	Decade Voltage Divider (100,000 ohms)........	ABASH	145.00

WESCON 1959

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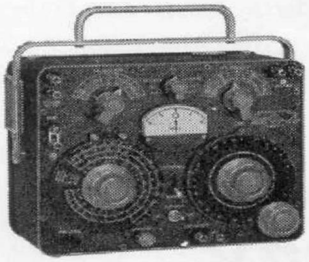
When you attend the Western Electronic Show and Convention, drop in at Booths 2015 and 2016 to see these new General Radio instruments:

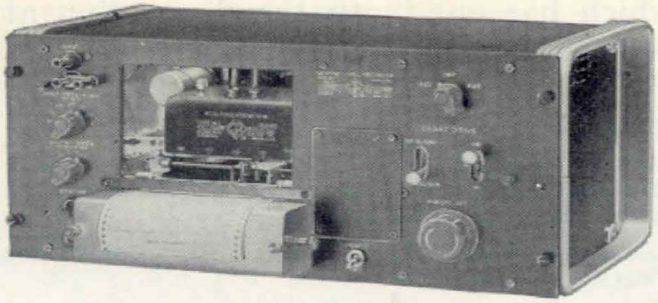
Type 1650-A	Impedance Bridge
Type 1521-A	Graphic Level Recorder
Type 1305-A	Low-Frequency Oscillator
Type 1632-A	Inductance Bridge
Type 1554-A	Sound and Vibration Analyzer

Each of these instruments has features of electrical and mechanical design that will interest you, performance specifications that will please you, and the same high quality of manufacture that you expect in General Radio products.



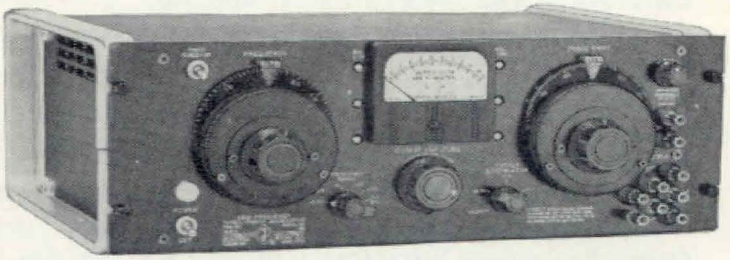
Type 1650-A Impedance Bridge

A wide-range, accurate, general-purpose bridge, measuring R, L and C. Completely new design with exclusive, patented *Orthonull* feature and self-contained, transistorized generator and detector. See *Experimenter* for March, 1959, for further details.



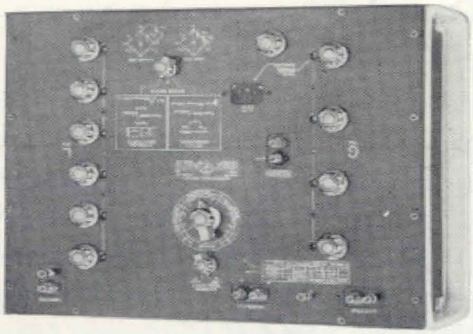
Type 1521-A Graphic Level Recorder

Fully described in last month's (June) *Experimenter*. High-sensitivity, single-channel recorder, which plots rms level of an ac signal as a function of either time or frequency. Simple to operate. Completely transistorized.



Type 1305-A Low-Frequency Oscillator

Sine-wave generator covering frequency range from 0.01 to 1000 cycles per second. Single phase, three-phase, and four-phase output, with single-phase output continuously variable in phase from 0 to 360°. Excellent stability, low distortion. To be described in a forthcoming issue of the *Experimenter*.

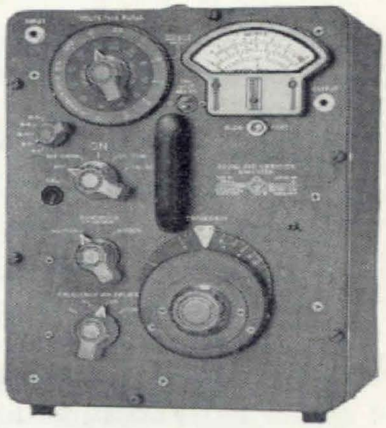


Type 1632-A Inductance Bridge

Wide-range inductance bridge for the precise measurement and standardization of two-terminal grounded inductors at audio frequencies. Range is 0.001 μh to 1111 h. Normal accuracy is 0.1%. Convenient to operate, has in-line read-out. Six-figure resolution gives high precision. To be described in a forthcoming issue of the *Experimenter*.

Type 1554-A Sound and Vibration Analyzer

Measures amplitude and frequency of the individual components of waveforms between 2.5 and 25,000 cycles per second. Has both 8% and one-third octave pass bands. Portable, battery powered, uses 6 tubes and 11 transistors. Can be used with sound-level meter, vibration meter, or microphone input for acoustic work, or directly as a general-purpose electric-wave analyzer. To be described in a forthcoming issue of the *Experimenter*.



Other Instruments

Many other General Radio products will be on display, including Unit Instruments, Variac® autotransformers, and standards of capacitance and inductance.

General Radio Company

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