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ELECTRICAL MEASUREMENTS AND THEIR INDUSTRIAL APPLICATIONS

Also
IN THIS ISSUE

ANTENNA MEASUREMENTS WITH THE RADIO-FREQUENCY BRIDGE

● ALTHOUGH THE TYPE 516-C RADIO-FREQUENCY BRIDGE has been discontinued and will later be replaced by the TYPE 916-A, a considerable number of these bridges are in use in broadcasting stations, where they are quite satisfactory for measurements on antennas, lines, coupling networks, and other radio-frequency impedances, at standard broadcast frequencies. The instruction booklet supplied with this bridge covers quite completely the laboratory use of the bridge in measuring radio-frequency impedance, but it does not present the material in the most convenient manner for those who are interested solely in measuring antenna systems. It is the purpose of this article to supplement the operating instructions by outlining what has been found to be the most convenient procedure and by pointing out the precautions that must be observed if satisfactory results are to be obtained.

FIGURE 1. Measuring the impedance of an antenna tower as seen from the "dog house" at the base.

SETTING UP THE BRIDGE

Adequate shielding and grounding are important. Shielded conductors must be used for connecting the bridge to the generator and to the detector. The UNKNOWN binding post marked G must be grounded through as short a lead as possible, preferably not more than one or two feet. Grounding through the knurled panel screws is not satisfactory because the screws may not be in good electrical contact with the panel. To test for proper grounding, touch the panels of the bridge, detector, and generator after the bridge has been balanced. If the grounding is adequate, no effect upon the balance will be observed. If touching the bridge panel throws the bridge out of balance, the grounding is inadequate. This condition can sometimes be remedied by using individual ground leads for the bridge, the generator, and the receiver. A better remedy is to use coaxial terminals for the connection to the receiver input. General Radio Type 774-G Panel Plug and Type 774-M Cable Jack are satisfactory.

It is important that a well-shielded generator be used to prevent pickup not only from the generator to the detector, but also from the generator to the antenna under measurement. A standard-signal generator, such as the Type 605-B, is an excellent power source for these measurements.

Even at broadcast frequencies, it is essential to use a shielded receiver. The so-called communications type is recommended. The AVC, if any, should be disconnected, since its action tends to make the balance point difficult to locate.

BALANCING THE BRIDGE

For antenna measurements, the bridge is used as an equal-arm capacitance bridge, and so the balance point depends upon the adjustment of both the CAPACITANCE and RESISTANCE controls.

If one control is not set correctly, a *minimum* in the signal may be observed when the other is turned through its correct setting. Successive adjustments of both controls must be made until the signal in the detector is reduced to zero.

The balance point is frequently very sharp and may easily be missed if adjustments are made too rapidly. For a rough preliminary balance it may be desirable to use a modulated signal, with the receiver sensitivity turned well down. As balance is approached, the sensitivity can be increased. For a final balance, maximum accuracy, sensitivity, and signal-to-noise ratio are usually obtained by using an unmodulated signal, with a heterodyning oscillator to produce an audible beat tone.

METHODS OF MEASUREMENT

Although the Type 516-C is sufficiently flexible to permit measurements to be made by a wide variety of methods, it has been found by experience that one or more of the following three methods are most suitable for antenna measurements:

(1) Series Capacitor — The resistance range with this method is the same as with the direct method, but the capacitance range is greatly increased and, in addition, inductive reactance can be measured.

(2) Parallel Capacitor — The resistance range can be extended with this method but the actual range depends on the magnitude of the antenna reactance.

(3) Series and Parallel Capacitors — This is a combination of methods (1) and (2), and permits the measurement of reactance and resistance over wide ranges.

THE SERIES CAPACITOR METHOD

Of the above three methods, the series capacitor method is the one almost universally used for antennas whose resistive component does not exceed 311 ohms.[1] Since a large number of the antennas operating at standard broadcast frequencies fall into this category, this method is discussed first, with particular reference to operating procedure, and to reduction of errors caused by lead reactance.

Connections for this type of measurement are shown in Figure 2. A condenser, C_S, of such magnitude that the total series reactance presented to the UNKNOWN terminals is within the range of the balancing condenser, C_N, is connected in series with the unknown impedance. An initial balance is established with Z_a shorted; the short is then removed and the bridge rebalanced. Connections for the two balances are indicated in Figure 3.

The series resistance and reactance of the antenna are given by

$$R_a = R_2 - R_1 \qquad (1)$$[2]

$$X_a = \frac{1}{\omega}\,\frac{C_2 - C_1}{C_1 C_2} \qquad (2)$$

where the subscript 1 refers to the initial balance and the subscript 2 to the final balance. A positive value of X_a indicates an inductive reactance; a negative value, capacitive reactance.

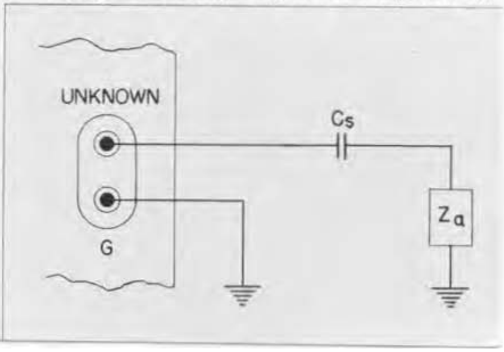
REACTANCE BALANCE

The best value of the capacitance, C_S, depends upon the reactive component of the antenna impedance. Since the value of the unknown reactance, X_a, is determined by the *difference* in capacitance settings between the two balances, fairly large errors can occur if this difference is small, and for maximum accuracy it is desirable to select a value of C_S to make $C_2 - C_1$ as large as possible. This is achieved by choosing the largest value of C_S for which the bridge will balance initially, if the antenna reactance is capacitive; and the largest value for which the bridge will balance with the antenna connected, if the antenna reactance is inductive. A good procedure to follow is to make a trial balance with a 1000 $\mu\mu$f series capacitor. If the unknown reactance is inductive, the setting of the CAPACITANCE dial will increase. Successive values of C_S then should be tried until the largest value is determined for which the CAPACITANCE control will balance with the unknown in circuit. If the unknown reactance corresponds to a capacitance greater than about 50 $\mu\mu$f, it will be possible to balance the CAPACITANCE control of the bridge, at a setting lower than the initial setting.

RESISTANCE BALANCE

In the discussion above it has been assumed that a balance can be obtained by adjustment of the RESISTANCE controls of the bridge. If the recommended fixed resistors are used, this

FIGURE 2. Diagram of connections for measuring an unknown impedance, Z_a, by using the series capacitor C_S.



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[1] The RESISTANCE control of the bridge has a direct-reading range from 0 to 111 ohms, but provision is made for inserting external fixed resistors in series. The range can be increased to 311 ohms by inserting 200 ohms in series. If a resistance larger than 200 ohms is placed in series, the shunting effect of the ground capacitance of the condenser, C_N, introduces an appreciable error, particularly at frequencies above one megacycle

The TYPE 500-D (100 Ω) and the TYPE 500-E (200 Ω) are recommended for use as series resistors.

[2] R_1 can be made zero by establishing the initial balance with the POWER FACTOR and POWER FACTOR ADJUST controls.

will be true when the unknown resistance does not exceed 311 ohms. A balance should be attempted with the SERIES RESISTOR terminals short-circuited by means of the strap that is provided. If the RESISTANCE controls cannot be balanced, the 100-ohm, or, if necessary, the 200-ohm, resistor should be plugged in. Failure to obtain a balance at 311 ohms or below indicates that the parallel-capacitance method or a series-parallel connection must be used.

LEAD CORRECTIONS

The leads from the bridge to the unknown should be as short as possible, certainly less than three feet, and should be kept a reasonable distance away from grounded metal objects, in order to minimize capacitance to ground. The series capacitor should be connected at the antenna end of the lead, as close as possible to the point at which the antenna impedance is to be measured. By this method of connection, the inductance and resistance of the lead remain in series with C_S for the initial as well as the final balance, and drop out of the calculation for the antenna impedance.

The lead *capacitance* introduces small errors into the calculated values of resistance and reactance. The lead capacitance can be easily measured, however, and allowance made for it.

The lead capacitance, C_l, is determined by a substitution method, wherein initial balance is established with a fixed capacitor connected directly across the UNKNOWN terminals of the bridge. The lead is then connected to the ungrounded terminal of the bridge. The series capacitor is disconnected from the antenna but is still connected to the far end of the lead. A new balance is made, and the difference of the two capacitance readings is C_l which includes the capacitances to ground of the series capacitor, as well as that of the lead itself. The correction for lead capacitance is made by using the following expressions:

$$R_a = R_2\left(1 + \frac{C_l}{C_2}\right)^2 \qquad (3)$$

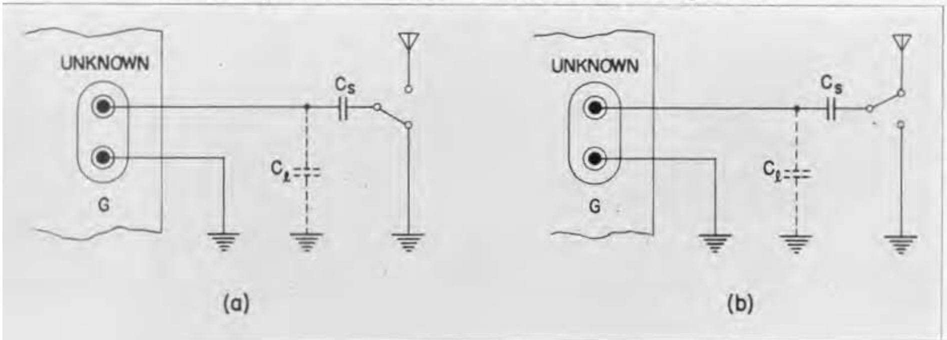
$$X_a = \frac{C_2 - C_1}{\omega C_1 C_2}\left(1 + \frac{C_l}{C_1}\right)\left(1 + \frac{C_l}{C_2}\right) \qquad (4)$$

NUMERICAL EXAMPLE

The following data illustrate the procedure and data for a typical antenna measurement at a frequency of 1500 kilocycles.

To determine the most suitable value of C_S, a balance with $C_S = 1000$ μμf was attempted. One side of the capacitor was connected to the ungrounded UNKNOWN terminal through a two-foot length of insulated wire, and the other side connected to the antenna input through a few inches of lead. With a modulated signal from the generator, and the volume control of the receiver set to a low level, it was impossible to obtain a minimum with either bridge control. A slight decrease in intensity was observed when both controls were turned to maximum, however, indicating that the antenna reactance was inductive, and that R_x was greater than 111 ohms. Consequently, the 1000 μμf series capacitor was replaced by a 500 μμf unit, and a 100 Ω

FIGURE 3. Diagram of connections for the two measurements necessary to determine antenna impedance by the series capacitor method. Additional measurements, described in the text, are necessary to determine the connection for C_l, the lead capacitance.



resistor was inserted at the series resistance terminals. A definite minimum was now observed with the CAPACITANCE control of the bridge set at about 650 $\mu\mu$f and the RESISTANCE control set at a maximum. Accordingly, the 100 Ω external resistor was replaced by a 200 Ω unit. A true null was now obtained at $R \cong 200 + 39$ Ω, $C \cong 648$ $\mu\mu$f. The CAPACITANCE dial setting suggested that a somewhat larger series capacitor might be used, and the 100 $\mu\mu$f unit was plugged in parallel with the 500 $\mu\mu$f already in circuit. This was tried and the CAPACITANCE control balanced at a setting over 900 $\mu\mu$f. With the proper value of series capacitor and SERIES RESISTOR determined, the data for calculation were obtained as follows:

(1) With the series capacitor grounded at the antenna end, the SERIES RESISTOR terminals shorted, and the RESISTANCE control set to zero, a balance was obtained by means of the POWER FACTOR ADJUST and CAPACITANCE controls. The balance occurred with the large CAPACITANCE dial set at 620, and the auxiliary dial set at −9.4. Thus

$$C_1 = 620 - 9.4 = 610.6 \ \mu\mu\text{f}$$

(2) With the series capacitor connected to the antenna, and the 200 Ω resistor connected to the SERIES RESISTOR terminals, the bridge was balanced (leaving the POWER FACTOR controls untouched) and the following data obtained:

$$R_2 = 200.0 + 38.8 = 238.8 \text{ ohms}$$
$$C_2 = 930 + 3.3 = 933.3 \ \mu\mu\text{f}$$

(3) A computation using the above data, and neglecting the lead capacitance, yields:

$$R_a = R_2 = 238.8 \text{ ohms}$$
$$X_a = \frac{1}{\omega}\frac{C_2 - C_1}{C_1 C_2}$$
$$= \frac{(933.3 - 610.6) \times 10^{-12}}{6.28 \times 1.5 \times 10^6 \times 933.3 \times 610.6 \times 10^{-24}}$$
$$= +60.0 \text{ ohms (inductive)}$$
$$Z_a = 238.8 + j60$$

(4) The value of C_l, the lead capacitance, was determined by connecting the 1000 $\mu\mu$f capacitor across the UNKNOWN terminals, disconnecting the lead at the bridge, replacing the link across the SERIES RESISTOR terminals, and balancing the bridge. The CAPACITANCE controls balanced at 990 plus 8.8 $\mu\mu$f, but were rebalanced at 1000 minus 1.2 $\mu\mu$f, thus permitting the change in capacitance to be observed entirely on the AUXILIARY dial. With the lead connected to the high UNKNOWN terminal and the series capacitor disconnected at the antenna side, the balance was obtained with the auxiliary CAPACITANCE control set at plus 5.6 $\mu\mu$f. The value of C_l was thus $5.6 - (-1.2) = 6.8$ $\mu\mu$f.

(5) The corrected values of R_x and X_x are determined by substituting the above values in Equations (3) and (4).

$$R_a = R_2\left(1 + \frac{6.8}{933.3}\right)^2$$
$$= (238.8)\,(1.0146)$$
$$= 242.3 \text{ ohms}$$
$$X_a = (60.0)\left(1 + \frac{6.8}{933.3}\right)\left(1 + \frac{6.8}{610.6}\right)$$
$$= (60.0)\,(1.0184)$$
$$= 61.1 \text{ ohms}$$
$$Z_a = 242.3 + j61.1$$

In this particular case, neglect of the lead capacitance causes an error of less than 2% in the calculation of either component.

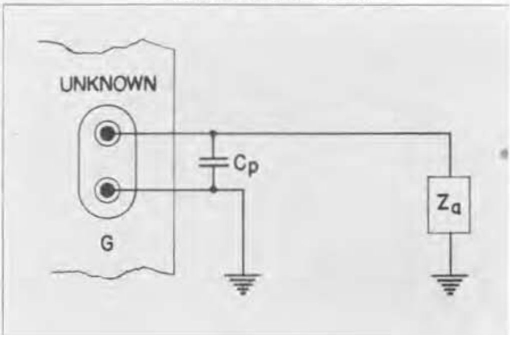
The above procedure may seem rather lengthy, but it should be borne in mind that, once a measurement has been made, additional measurements to study the effect of minor antenna adjustments, or of changes in frequency, can be made quite rapidly.

THE PARALLEL CAPACITOR METHOD

When the series resistance of the antenna exceeds 311 ohms, the parallel capacitor method should be tried. The technique of this type of measurement is quite similar to that for the series substitution method, already described. The computations, however, are somewhat more involved because of the transformation from parallel to series components that is required.

The parallel capacitor method consists essentially of connecting, in parallel with the unknown impedance, a capacitance of such magnitude that the impedance of the combination lies within the range of the bridge. Connections are shown schematically in Figure 4. The initial balance is made with the parallel capaci-

FIGURE 4. Connections for the parallel-capacitor method of measurement.



tor connected to the bridge, with the lead connected to the bridge but disconnected at the antenna end, and with the RESISTANCE decades set to zero. The lead is then connected to the antenna, and the bridge is rebalanced. The following equations give the *series* resistance and reactance of the antenna:

$$R_a = \frac{R_2}{(\omega C_1)^2} \frac{1}{R_2^2 + \left(\frac{1}{\omega}\frac{C_2 - C_1}{C_1 C_2}\right)^2} \qquad (5)$$

$$X_a = \frac{1}{\omega C_1} \frac{R_2^2 - \frac{1}{\omega C_2}\left(\frac{1}{\omega}\frac{C_2 - C_1}{C_1 C_2}\right)}{R_2^2 + \left(\frac{1}{\omega}\frac{C_2 - C_1}{C_1 C_2}\right)^2} \qquad (6)$$

where C_1 is the reading of the CAPACITANCE dial for the initial balance, and C_2 and R_2 are the CAPACITANCE and RESISTANCE setting for the second balance. The fact that the same terms appear in both expressions simplifies the calculations.

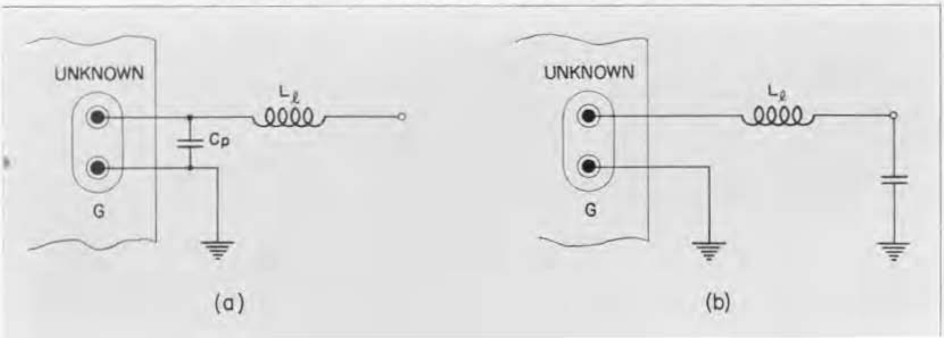
CHOICE OF PARALLEL CAPACITOR

The best value of parallel capacitance depends on the magnitude of the antenna impedance and can thus be determined only by trial. In general, the best value to use is the smallest capacitance with which a final CAPACITANCE balance can be obtained. Occasionally, however, it may be desirable to use a larger value, to permit the RESISTANCE controls to be balanced without the use of external SERIES RESISTORS. Probably the most rapid way to determine the proper value of C_P is to make a first trial balance using the 500 $\mu\mu$f parallel capacitor, and leaving the SERIES RESISTOR terminals short-circuited. If the change in capacitance is small, a smaller value of capacitance should be tried; if the resistance component of balance cannot be obtained with the internal resistance decades, an external series resistor should be added, or a larger value of parallel capacitance tried. If it is impossible to obtain a balance using the largest available capacitor (1000 $\mu\mu$f) and the largest permissible external resistor (200 ohms), the use of one of the other methods is indicated.

LEAD CORRECTIONS

Unlike the series capacitor method, the parallel capacitor method yields the most satisfactory results when the auxiliary capacitor is connected directly to the UNKNOWN terminals of the bridge. The lead to the antenna terminals should be left connected at the bridge, and the initial balance made with this lead disconnected at the antenna terminal. The lead capacitance thus remains always in parallel with the auxiliary capacitance, is measured as part of it, and introduces no error into the

FIGURE 5. Diagram of connections for the two measurements to determine the lead inductance L_l. Procedure and calculations are outlined in the text.



measurement of the antenna impedance. The lead *inductance*, however, is included in the calculated value of antenna reactance. The true value of X_a is determined simply by subtracting the lead reactance from the value given by Equation (6).

The lead inductance (L_l) can be measured as shown in the two diagrams of Figure 5. Balance the bridge with the 1000 $\mu\mu$f capacitor connected to the UNKNOWN terminals, and with the lead to the antenna in place, but disconnected at the antenna terminals. Remove the 1000 $\mu\mu$f capacitor, connect it to ground at the far end of the lead in such a manner that the position of the lead remains unchanged, and rebalance the bridge. If the first and second CAPACITANCE readings are denoted by C' and C'', respectively, the inductive reactance of the lead is given by

$$X_l = \omega L_l = \frac{1}{\omega}\frac{C'' - C'}{C'C''} \qquad (7)$$

NUMERICAL EXAMPLE

The following procedure and data are representative of measurements of an antenna having a resistance greater than 311 ohms, at a frequency of 2000 kilocycles.

By following the general procedure outlined in detail in the numerical example for the series capacitor method, 300 $\mu\mu$f was determined to be a suitable value of parallel capacitance.

(1) The initial balance was established with 300 $\mu\mu$f plugged into the unknown terminals, and with the lead to the antenna in place but disconnected at the antenna end. The POWER FACTOR and RESISTANCE controls were set at zero, and the balance obtained by adjustment of the CAPACITANCE dials and the POWER FACTOR ADJUST knob. The balance occurred with the large CAPACITANCE dial set at 300 $\mu\mu$f, and the auxiliary dial set at +8.8 $\mu\mu$f.

(2) With the lead connected to the antenna the new positions of the main and auxiliary dials were 510 and −3.2 $\mu\mu$f respectively, while the setting of the RESISTANCE decades was found to be 98.5 ohms.

(3) The data and calculations were as follows:

$$C_1 = 300 + 8.8 = 308.8\ \mu\mu\text{f}$$

$$\omega = 2\pi f = 6.28 \times 2 \times 10^6$$

$$= 12.56 \times 10$$

$$\frac{1}{\omega C_1} = \frac{1}{12.56 \times 10^6 \times 308.8 \times 10^{-12}}$$

$$= 258 \text{ ohms}$$

$$\left(\frac{1}{\omega C_1}\right)^2 = 66{,}600$$

$$C_2 = 510 - 3.2 = 506.8\ \mu\mu\text{f}$$

$$\frac{1}{\omega}\frac{C_2 - C_1}{C_1 C_2} = 258 \times \frac{506.8 - 308.8}{506.8}$$

$$= 100.8 \text{ ohms}$$

$$\left(\frac{1}{\omega}\frac{C_2 - C_1}{C_1 C_2}\right)^2 = 10{,}160$$

$$\frac{1}{\omega C_2} = \frac{1}{12.56 \times 10^6 \times 506.8 \times 10^{-12}}$$

$$= 157 \text{ ohms}$$

$$\left(\frac{1}{\omega C_2}\right)^2 = 24{,}700$$

$$R_2 = 98.5 \text{ ohms}$$

$$R_2{}^2 = 9{,}700$$

Substituting in Equations (5) and (6)

$$R_a = \frac{98.5 \times 66{,}600}{9{,}700 + 10{,}160} = 331 \text{ ohms}$$

$$X_a = 258 \times \frac{9{,}700 - 157 \times 100.8}{9{,}700 + 10{,}160}$$

$$= -80.0 \text{ ohms (capacitive)}$$

$$Z_a = 331 - j80.0 \text{ ohms}$$

(4) The inductive reactance of the lead was determined by the method outlined under LEAD CORRECTIONS above. The CAPACITANCE readings C' and C'' were 510 + 1.2 $\mu\mu$f and 540 − 4.2 $\mu\mu$f. From Equation (7)

$$X_L = \frac{1}{\omega}\frac{C'' - C'}{C''C'}$$

$$= \frac{535.8 - 511.2}{12.56 \times 10^6 \times 535.8 \times 511.2 \times 10^{-12}}$$

$$= +7.15 \text{ ohms}$$

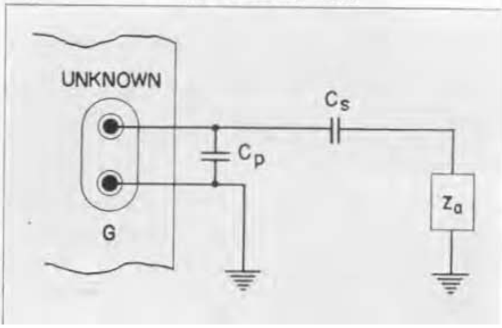
The corrected value of antenna reactance is thus

$$X_a = -80.0 - 7.15 = -87.2 \text{ ohms}$$

$$Z_a = 331 - j87.2 \text{ ohms}$$

In this case, neglect of the lead reactance would have resulted in an error of nearly 10% in the calculated antenna reactance.

FIGURE 6. For the occasional measurement where neither the series capacitor nor parallel capacitor method is satisfactory, a combination of the two can be used as shown here.



SERIES AND PARALLEL CAPACITOR METHOD

The methods described above generally suffice to measure antenna impedance over the ranges normally met in practice, but occasionally extreme values of reactance, or certain combinations of resistance and reactance, are encountered that do not permit a balance with either a series or a parallel capacitor alone. In such cases the use of both series and parallel capacitors, as shown in Figure 6, usually permits a measurement to be made.

USE OF CHARTS

When approximate results are desired, it is convenient to use a chart to determine the quantity $\frac{1}{\omega}\frac{C_2 - C_1}{C_1 C_2}$. Copies of this chart can be obtained from the General Radio Company. Another convenient chart is a log-log plot of reactance vs. capacitance for some nominal frequency such as 1 megacycle. Conversion to other frequencies can be made by dividing the 1-Mc reactance by the frequency in megacycles.

SERVICE AND MAINTENANCE NOTES

CORRECTIONS

● **ADDITIONAL ERRORS AS LISTED BELOW** have been discovered in the first printing of Service and Maintenance Notes. Please check your copies and make corrections as necessary.

Type 544-B Megohm Bridge

Page 3: Paragraph 7.1, read 6K6G for 6K5G; paragraph 7.2, read 6J5G for 6V5G.

Page 4: Paragraph 9.1, read 10.0 and 11.0 for 3.0 and 4.0; paragraph 11.1, read 10.3 for 1.0.

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