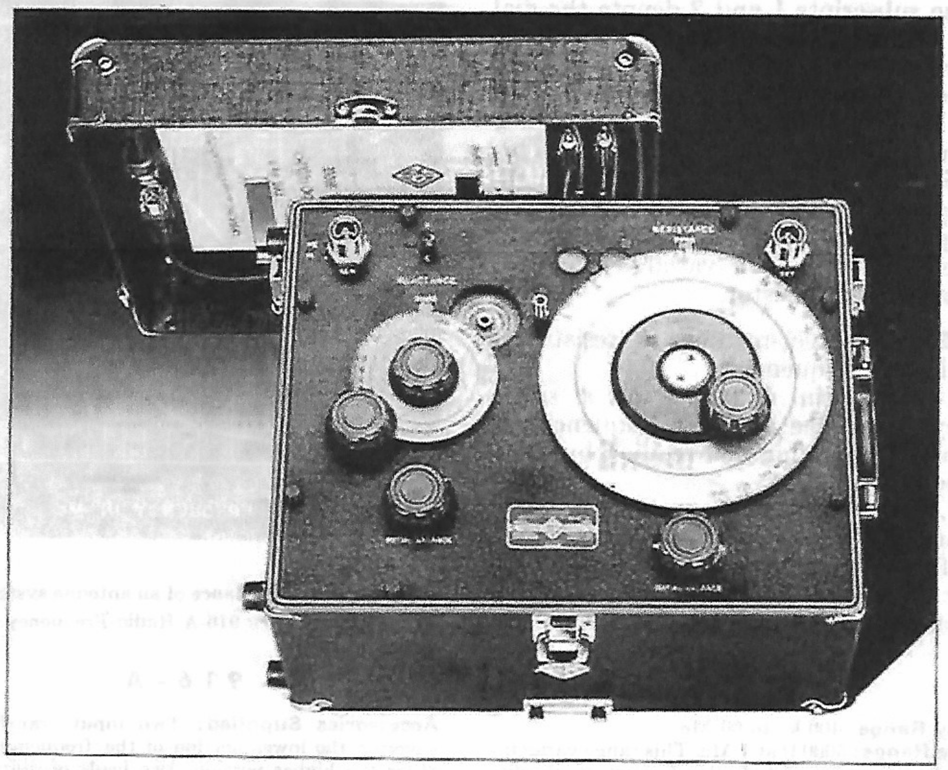
# OPERATING INSTRUCTIONS

FOR

# TYPE 916-A
# RADIO-FREQUENCY BRIDGE

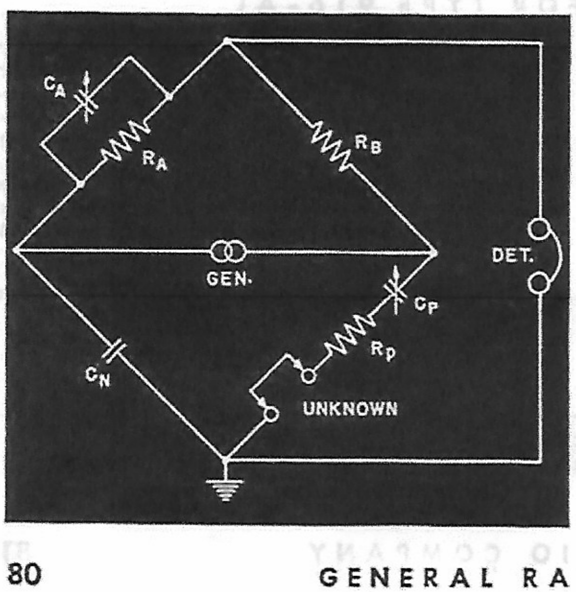
GENERAL RADIO COMPANY
CAMBRIDGE 39, MASSACHUSETTS



# TYPE 916 RADIO-FREQUENCY BRIDGE

**USES:** The Type 916 Radio Frequency Bridge is designed for impedance measurements at radio frequencies. It can be used to measure directly the reactance and resistance of antennas, transmission lines, and circuit elements. The use of an external parallel capacitor makes it possible to measure parallel tuned circuits, high resistances, and other high impedances.

The bridge is intended for measuring low impedances and complements the Type 821-A Twin-T, which is best suited for measuring high impedances. Two models are available: Type 916-A, for frequencies between 400 kc and 60 Mc; and Type 916-AL for frequencies between 50 kc and 5 Mc. For measurements in the standard broadcast band, the Type 916-AL is recommended, because of its higher sensitivity in that frequency range.




**DESCRIPTION:** The bridge circuit used is shown schematically in the diagram below. Measurements are made by a series-substitution method. The components of the unknown impedance are determined from the change in settings of capacitors $C_A$ and $C_P$. The unknown reactance at 1 Mc is read directly in ohms from the dial of $C_P$, and the unknown resistance in ohms from the dial of $C_A$.

In making measurements the bridge is first balanced by means of capacitors $C_P$ and $C_A$ with a short-circuit across the unknown terminals. The short is then removed, the unknown impedance connected, and the bridge rebalanced. The resistance is then given by

$$R_x = R_B \frac{(C_{A_2} - C_{A_1})}{C_N}$$

and the reactance by

$$X_x = \frac{1}{\omega}\left(\frac{1}{C_{P_2}} - \frac{1}{C_{P_1}}\right)$$

where the subscripts 1 and 2 denote the dial readings for the initial and final balances, respectively.

The resistive component is measured in terms of a *fixed* resistor ($R_B$), a fixed capacitor ($C_N$), and a variable capacitor ($C_A$). This feature is an important factor in the high-frequency performance of the bridge because residual parameters can be made much smaller in a fixed resistor and a variable capacitor than in a variable resistor.

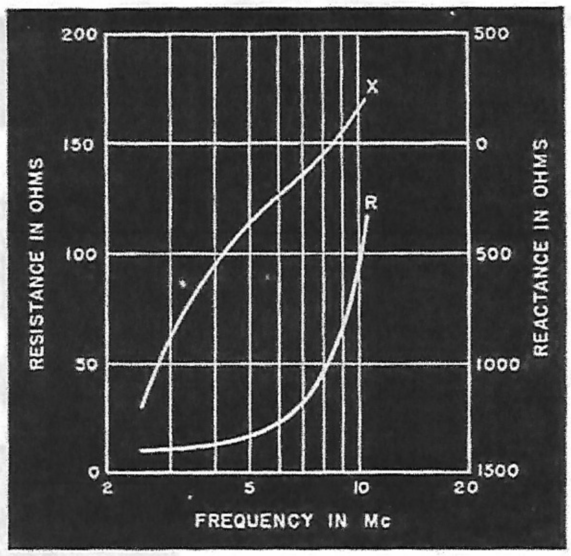
**FEATURES:** ➤ Direct-reading in resistance, independent of frequency.

➤ Direct-reading in reactance at a single frequency; reactance at other frequencies is determined by dividing dial reading by operating frequency.

➤ Rapid, convenient, and accurate for antenna impedance measurements.

➤ Wide frequency range.

➤ Easily portable — carrying case is rugged, and cover provides storage space for cables.




Reactance and resistance of an antenna system measured with the TYPE 916-A Radio-Frequency Bridge.

## SPECIFICATIONS FOR TYPE 916-A

**Frequency Range:** 400 kc to 60 Mc.

**Reactance Range:** 5000 Ω at 1 Mc. This range varies inversely as the frequency, and at other frequencies the dial reading must be divided by the frequency in megacycles.

**Resistance Range:** 0 to 1000 Ω.

**Accuracy:** For reactance, at frequencies up to 50 Mc, $\pm(2\% + 1\ \Omega + 0.0008 \times R \times f)$, where $R$ is the measured resistance in ohms and $f$ is the frequency in Mc.

For resistance, at frequencies up to 50 Mc, $\pm(1\% + 0.1\ \Omega)$, subject to correction for residual parameters. At high frequencies the correction depends upon the frequency and upon the magnitude of the unknown resistance component. At low frequencies the correction depends upon the frequency and upon the magnitude of the unknown reactance component. Plots of both these corrections are given in the instruction book that is supplied with the bridge.

Satisfactory operation can be obtained at frequencies up to 60 Mc with somewhat poorer accuracy above 50 Mc than at lower frequencies.

**Accessories Supplied:** Two input transformers, one covering the lower portion of the frequency range, the other the higher portion; two leads of different lengths (for connecting the unknown impedance); two cables for connecting generator and detector; one TYPE 874-P Panel Connector.

**Other Accessories Required:** Radio-frequency generator and detector. The TYPE 1330-A Bridge Oscillator (page 150) is recommended as the generator, and a well-shielded radio receiver covering the desired frequency range makes a satisfactory detector. It is recommended that the receiver be fitted with the TYPE 874-P Panel Connector supplied to avoid leakage at the input connection.

**Mounting:** Airplane-luggage type case with carrying handle. Both input transformers are stored inside the case. Coaxial cables, leads, and instruction book are stored in the cover of the instrument when not in use.

**Dimensions:** 17 x 13½ x 11⅛ inches, over-all.

**Net Weight:** 34½ pounds.

## SPECIFICATIONS FOR TYPE 916-AL

**Frequency Range:** 50 kc to 5 Mc. Satisfactory operation for many measurements can be obtained at frequencies as low as 15 kc.

**Reactance Range:** 11,000 Ω at 100 kc. This range varies inversely as the frequency, and at other frequencies the dial readings must be divided by the frequency in hundreds of kilocycles. To facilitate the measurement of small reactances, the instrument is provided with an incremental reactance dial which has a range of 100 ohms at 100 kc.

**Resistance Range:** 0 to 1000 Ω.

**Accuracy:** For reactance at frequencies up to 3 Mc, $\pm(2\% + 0.2 \times \frac{100}{f_{kc}}\ \Omega + 3.5 f_{kc}^2 R \times 10^{-10}\ \Omega)$ where $R$ is the measured resistance in ohms and $f_{kc}$ is the frequency in kilocycles. The errors in reactance increase relatively rapidly at frequencies above 3 Mc; and at 5 Mc the accuracy is $\pm(2\% + 0.01\ \Omega + 2.3\ R^{1.5} \times 10^{-3}\ \Omega)$. For resistance, at frequencies up to 5 Mc, $\pm(1\% + 0.1\ \Omega)$, subject to correction for residual parameters at low frequencies. The correction depends upon the frequency and upon the magnitude of the unknown reactance component. A plot of this correction is given in the instruction book supplied with the bridge.

Other specifications are identical with those for TYPE 916-A, above.

| *Type* | | *Code Word* | *Price* |
|---|---|---|---|
| 916-A | Radio-Frequency Bridge (400 kc to 60 Mc) . . | CIVIC | $475.00 |
| 916-AL | Radio-Frequency Bridge (50 kc to 5 Mc) . . . . | CLUCK | 495.00 |

PATENT NOTICE. See Notes 3, 4, and 13, page vi.

# OPERATING INSTRUCTIONS

FOR

# TYPE 916-A RADIO-FREQUENCY BRIDGE

## 1.0 DESCRIPTION

### 1.1 GENERAL DESCRIPTION

The Type 916-A Radio-Frequency Bridge is a null instrument for use in measuring impedance at frequencies from 400 kc to 60 Mc. Measurements can be made with decreased accuracy at frequencies somewhat below and above these nominal frequency limits.

The bridge is used with a series-substitution method for measuring an unknown impedance, $Z_x$, in terms of its series resistance component, $R_x$, and series reactance component, $X_x$. The resistance is read from a variable-condenser dial directly calibrated in resistance (in ohms). The reactance is read from a variable-condenser dial directly calibrated in reactance (in ohms) at a frequency of 1 Mc. The resistance dial reading is independent of frequency. The reactance dial reading increases linearly with frequency. For frequencies other than 1 Mc the reactance dial reading must therefore be divided by the operating frequency in megacycles. The resistance dial reads from 0 to 1000 Ω; the reactance dial reads from 0 to 5000 Ω at 1 Mc.

### 1.2 BASIC CIRCUIT AND BALANCE CONDITIONS

The basic circuit used is shown in Figure 1.

A measurement is made by first balancing the bridge with the UNKNOWN terminals short-circuited, then rebalancing with the short-circuit removed and the unknown impedance connected to the UNKNOWN terminals.

When the UNKNOWN terminals are short-circuited, the bridge-balance conditions are:

$$R_P = R_B \frac{C_{A_1}}{C_N} \qquad (1)$$

$$\frac{1}{j\omega C_{P_1}} = \frac{R_B}{R_A} \frac{1}{j\omega C_N} \qquad (2)$$

When the short-circuit is replaced by the unknown impedance, $Z_x = R_x + jX_x$, the new balance equations are:

$$R_P + R_x = R_B \frac{C_{A_2}}{C_N} \qquad (1a)$$

$$jX_x + \frac{1}{j\omega C_{P_2}} = \frac{R_B}{R_A} \frac{1}{j\omega C_N} \qquad (2a)$$

The unknown resistance, $R_x$, and reactance, $X_x$, are therefore related to the bridge parameters by the expressions:

$$R_x = \frac{R_B}{C_N} (C_{A_2} - C_{A_1}) \qquad (1b)$$

$$X_x = \frac{1}{\omega} \left(\frac{1}{C_{P_2}} - \frac{1}{C_{P_1}}\right) \qquad (2b)$$

The resistance, $R_x$, is seen to depend upon a change in capacitance $C_A$; the reactance, $X_x$, upon a change in capacitance $C_P$. The constant relating the resistance, $R_x$, to the change in capacitance, $C_A$, is determined by the fixed resistance, $R_B$, and fixed capacitance, $C_N$. The reactance, $X_x$, is equal to the change in reactance of the condenser, $C_P$, and is opposite in sign.

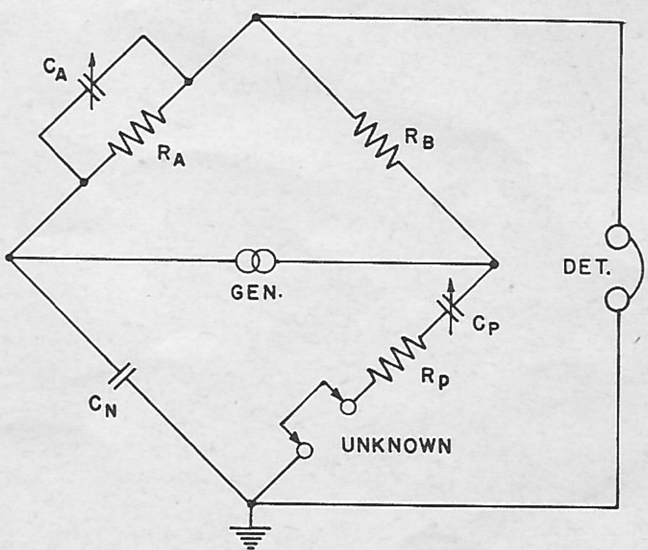



FIGURE 1. Basic circuit of Type 916-A Radio-Frequency Bridge

## 1.3 COMPLETE CIRCUIT

Through the series-substitution method of measurement, simple relationships between the unknown resistance and reactance and increments of capacitance are obtained. In order to extend this simplicity of analysis to simplicity of operation, auxiliary controls not shown in the basic diagram of Figure 1 have been added. Their functions are most easily described when the resistance and reactance balances are considered separately.

The dial of the condenser, $C_A$, that is used for resistance measurement can be calibrated in resistive ohms, with any capacitance setting chosen as zero. For maximum resistance range, this setting is chosen at minimum capacitance. A small trimmer capacitance, $C_A'$, is then connected in parallel with the resistance condenser, $C_A$, so that the initial resistance balance, with the UNKNOWN terminals short-circuited, can be made at zero dial setting, irrespective of slight changes in the bridge parameters with time or frequency.

The dial of the condenser, $C_P$, that is used for reactance measurement can be calibrated in reactive ohms at any one frequency, again with any capacitance setting chosen as zero. For maximum reactance range and best scale distribution this setting is chosen at maximum capacitance. A trimmer capacitance, $C_P'$, is then connected in series with the reactance condenser, $C_P$, so that the initial reactance balance, with the UNKNOWN terminals short-circuited, can be made at zero dial setting, irrespective of changes in the bridge parameters with time or frequency. An additional auxiliary control must, however, be added to take care of the sign of the unknown reactance. With the zero position established at maximum capacitance, the dial scale reads inductive reactance directly; for measurements of capacitive reactance, the initial balance must be made at an upscale reading so that the negative change in dial reading will remain on scale. In order to obtain maximum capacitive-reactance range a two-position switch that changes the value of the ratio-arm resistor, $R_A$, is added.[1] With the switch set in one position an initial balance can be obtained at the zero setting of the reactance dial, for measuring inductive reactance; with it set in the other position an initial balance can be obtained at the maximum setting of the reactance dial, for measuring capacitive reactance.

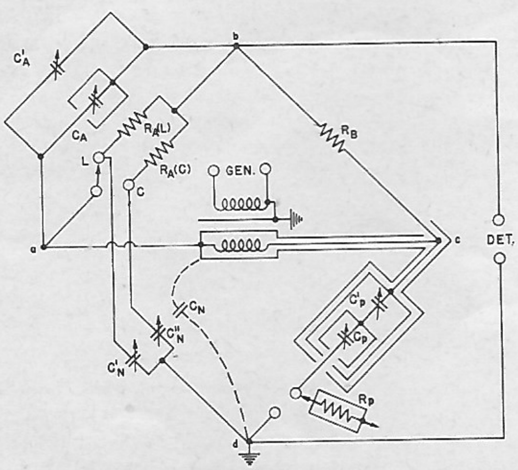



Figure 2 complete circuit diagram.

Figure 2 is a complete circuit diagram, showing the ratio-arm switch and the two trimmer condensers, $C_A'$ and $C_P'$.

In the actual instrument the fixed capacitance, $C_N$, is composed largely of the capacitance to ground of the shielding system,[2] as shown by the dotted lines in the diagram. The small adjusting condensers, $C_N'$ and $C_N''$, are used to equalize the capacitance from point "a" to ground in the two ratio-arm-switch positions.

## 1.4 PANEL LAYOUT AND CONTROLS

A panel view of the bridge is shown in the Frontispiece. The controls, plainly marked on the panel, are:

(1) The variable condenser, $C_P$, used to measure reactance (REACTANCE). The 3" dial of this condenser is calibrated from 0 to 5000 ohms at a frequency of 1 megacycle. It is provided with a small vernier knob to facilitate precise setting.

(2) The trimmer condenser, $C_P'$, used to make the initial reactance balance when the REACTANCE condenser is set at 0 or at 5000 ohms. The knob controlling this condenser is located immediately below the REACTANCE dial. It is geared down to the condenser shaft so that approximately two full terms of the knob are necessary to cover the full range.

(3) The two-position toggle switch used to establish the initial-balance setting of the REACTANCE dial in the region about 0 or 5000 ohms. This switch is lo-

1. In Equations (1) to (4) it is shown that the value of the ratio-arm resistance, $R_A$, enters only into the initial reactance balance and has no other effect upon the measurement of the unknown impedance.

2. For a description of the shielding of the bridge, see D. B. Sinclair, "A Radio-Frequency Bridge for Impedance Measurements from 400 Kilocycles to 60 Megacycles", Proc. I.R.E., Vol. 28, No. 11, pp. 497-503; Nov., 1940.

cated immediately above the REACTANCE dial. The two positions are marked L and C to indicate that the first is to be used when measuring inductive reactance and the second when measuring capacitive reactance.

(4) The variable condenser, $C_A$, used to measure resistance (RESISTANCE). The 8" dial of this condenser is calibrated from 0 to 1000 ohms. It is provided with a slow-motion drive mechanism to facilitate precise setting.

(5) The trimmer condenser, $C_A'$, used to make the initial balance when the RESISTANCE condenser is set at 0 ohms. The knob controlling this condenser is located immediately below the RESISTANCE dial.

The two adjusting condensers, $C_N'$ and $C_N''$, are accessible through holes in the panel covered by the snap buttons to the left of the indicator of the RESISTANCE dial. They are set at the factory and should not be varied unless recalibration becomes necessary. (See paragraph 3.1).

The two coaxial terminals for making the input and output connections to the bridge are marked GEN and DET on the panel.

A binding post for making the ground connection to the unknown impedance is located on the panel to the left of the RESISTANCE dial. The other connection to the unknown impedance is made to the jack in the center of the circular window, at the left of the ground binding post, through one of the two special connecting leads supplied with the instrument. (See paragraph 1.51).

## 1.5 ACCESSORIES SUPPLIED

1.51 Connecting Leads: Two leads for connecting the unknown impedance to the bridge are supplied, one about five inches long, overall, and the other about twenty-seven inches. Each of these leads terminates at one end in a cylindrical metal probe, which houses a small fixed resistor and carries a plug to fit the jack provided on the bridge panel. The resistor is connected in series with the lead and is designated by $R_P$ in Figures 1 and 2.[3] Each lead terminates in a clip at the other end for convenience in connecting One of the two leads supplied must always be used to connect to the unknown impedance since the bridge cannot be initially balanced without the resistor, $R_P$.

1.52 Shielded Transformers: Two transformers are supplied, one for use in the frequency range from 400 kc to 3 Mc and the other from 3 Mc to 60 Mc. The high-frequency transformer is shipped in place; the low-frequency transformer is held in a mounting affixed to the removable section of the instrument case.

1.53 Cables: Two single-conductor coaxial cables are supplied for connection to the generator and detector. One of these is provided with General Radio Type 774-M Cable Jacks at each end and is intended for use with a General Radio Type 605-B Standard-Signal Generator. The other is provided with a Type 774-M Cable Jack at one end and spade terminals at the other and is intended for use with any receiver having machine-screw terminals for antenna and ground. If possible, however, it is recommended that a General Radio Type 774-G Panel Plug be installed in the receiver and that the second cable also be terminated at each end with a Type 774-M Cable Jack.[4]

3. See reference of footnote 2 for reasons for mounting resistor $R_P$ in external probe unit.

4. It has been found that low-reactance connections between the outer conductors of the coaxial cables and the generator, bridge and detector panels are very important. Wherever possible, it is strongly recommended that coaxial terminals be used to complete the continuity of shielding. At the higher frequencies the reactance of a binding post or of an inch of wire may cause noticeable error.

# 2.0 OPERATION

## 2.1 GENERATOR

Any well-shielded radio-frequency oscillator having an output voltage of the order of 1 to 10 volts and adequate frequency stability will serve as generator.

## 2.2 DETECTOR

Any well-shielded receiver having a sensitivity of the order of 1 to 10 $\mu$v will serve as detector. It is recommended that the receiver used be provided with an adequate r-f sensitivity control and a local oscillator to give a heterodyne note at the intermediate frequency, and a switch to cut out the avc. Most so-called "communications receivers" fill all these requirements.

2.3 GROUNDING

The instrument should, in general, be grounded at a single point, through as low reactance a connection as possible. To facilitate making this connection a ground clamp is provided on the instrument case.

The ground lead should preferably be made with a short length of copper strip, say 1 inch wide. In laboratory set-ups a satisfactory "ground" can be obtained by covering the top of the bench with copper foil, even though the bench is physically far removed from ground. If the foil area is large enough, it will usually be found that a connection from it to ground, say through a steam radiator system, will make no appreciable difference in results.[5] In field set-ups the best "ground" is usually found to be some large metal structure, such as a relay rack.

If the grounding is not adequate it will usually be found that the panel of the instrument is at a different potential from the hand of the operator and that the balance can be changed by touching the panel, and erroneous results will be obtained.

2.4 STRAY PICKUP

If the panel of the instrument is at ground potential but those of the detector and generator are not it is usually an indication of excessive reactance in the connections from the outer conductors of the coaxial leads to those panels. The use of Type 774 Coaxial Connectors, as recommended in paragraph 1.53, will generally eliminate these potential differences. A further test for the existence of this condition can be made by removing the detector cable from the panel jack of the bridge. The detector pickup should be negligibly small if the generator is adequately shielded. If the outer shell of the Type 774-M Cable Jack can then be touched to the ground post of the bridge without significantly increasing the receiver output, no excessive reactance exists.

If the detector, when disconnected from the bridge, shows considerable pickup, it is usually an indication of poor shielding in the generator or of energy transfer from the generator to detector through the power line.

It is sometimes found, in field setups where grounding conditions cannot be carefully controlled, that individual ground connections from the panels of the generator, bridge, and detector to a common ground point will give less pickup and more consistent results than a single common ground to the bridge alone. The use of coaxial connectors at both generator and detector is particularly recommended for these field setups to avoid, as much as possible, the necessity for such multiple ground connections.

2.5 TRANSFORMER INSTALLATION

The transformers used in the Type 916-A Radio-Frequency Bridge are very carefully adjusted to introduce negligible measurement error over the rated frequency ranges. This adjustment involves not only proper internal construction[6] but proper placement of the transformer within the instrument case. To assure this proper placement the transformer mounting is keyed to the panel by means of a pin in an adjustable collar. The position of this adjustable collar is set at the factory and should not be altered.

The high-frequency transformer (3-60 Mc) is shipped in place. To remove it, first remove the rectangular section of the instrument case that is held in place by four Dzus fasteners. The low-frequency transformer (400 kc - 3 Mc) is mounted on the inside of this removable section. Next unscrew the shell of the coaxial terminal mounted on the panel (GENERATOR). The coaxial terminal that is plugged into the internal shield assembly can then be pulled out and the transformer removed through the rectangular opening. The transformers should be handled with reasonable care to avoid undue mechanical stress. No forcing is necessary in the process of removal or installation.

In installation, the transformer is slid into position as the coaxial terminal is plugged into the internal shielding assembly, and the shell of the coaxial terminal is screwed on from the front of the panel to secure the assembly. Care should be taken to see that the locating pin on the transformer is seated in the panel receptacle before the shell of the coaxial terminal is tightened.

The transformer that is not in use should be mounted on the removable section

5. The foil area should be at least great enough so that the generator, bridge and detector can all be placed upon it.

6. For a discussion of the shielding required see reference of footnote 2.

of the instrument case and the section secured in place by the Dzus fasteners whenever the instrument is operated. If the spare transformer is not mounted within the instrument the value of the capacitance $C_N$ will differ from the value for which the resistance calibration was made and inaccuracy of resistance readings will result.

In order that the transformer in circuit may be identified easily, a pin is made to engage either of two holes in the panel. When Type 916-P1 Transformer is connected, the pin can be seen in hole engraved P1, and when the pin appears in P2 hole, the Type 916-P2 Transformer is in circuit.

## 2.6 INITIAL BALANCE

To place the instrument in operation, install the proper transformer for the frequency at which measurements are to be made, connect the generator and detector with the cables provided in the cover, and ground the instrument as described in paragraph 2.3. Plug one of the two connecting leads into the panel jack and clip the free end to the ground binding post. Set the toggle switch to the L position and the REACTANCE and RESISTANCE dials to zero. Balance to a null by varying the two INITIAL BALANCE knobs. This is the initial balance normally used for measuring impedances with inductive reactance components. To check the initial balance for measuring impedances with capacitive reactance components, set the toggle switch to the C position and the REACTANCE dial to 5000 ohms, and again rebalance with the two INITIAL BALANCE knobs.

It will be noted that, at the lower frequencies, with the switch set to the L position, the initial balance can be obtained at reactance dial settings from 0 to about 1000 ohms, and, with the switch set to the C position, from about 4000 ohms to 5000 ohms. As the frequency is raised, these reactance limits tend to move up the dial because of the inductive reactance of the connecting lead. Depending upon the length of this connecting lead, a frequency will be found above which the initial balance can no longer be obtained at zero on the reactance dial with the toggle switch set to the L position. A higher frequency will be found at which the initial balance can no longer be obtained at 5000 ohms on the reactance dial with the toggle switch set to the C position. This shift in the initial balance causes no corresponding error in measurement since, in the series-substitution process, the constant inductive reactance of the connecting lead cancels out. It does, however, reduce the reactance range of the bridge since the full coverage of the reactance dial cannot be obtained. It can be corrected, when necessary, by inserting a small fixed condenser in series with the connecting lead to neutralize the inductive reactance.

Typical curves of the shift in initial balance are shown in Figure 3. With the short lead, as shown, the shift is relatively small over the entire frequency range of the instrument and it is not ordinarily necessary to use a series condenser at any frequency. With the long lead, the shift is appreciable and, at frequencies above 15 or 20 megacycles a series condenser may be necessary.

In finding the balance it is particularly desirable to use a receiver that has a good r-f sensitivity control and a switch to disconnect the avc. If the receiver gain is set too high there is a tendency for the receiver output to increase as balance is approached, and if the resistance balance is not set approximately correctly it becomes quite difficult to find the reactance balance, or vice versa. When the r-f sensitivity control is set to minimum sensitivity, and the avc is disconnected, no difficulty should be found in making the initial balance. As balance is approached, the receiver sensitivity can be increased to improve the precision of setting. For the first rough balance the generator signal can be modulated and the receiver beat oscillator turned off. The precise balance, however, should be made with the generator signal unmodulated. The avc should be left disconnected at all times. If an adequate r-f sensitivity control on the receiver is not available it is sometimes possible to accomplish the same general results by reducing the generator output, rather than the receiver sensitivity. For the precise balance the generator output should preferably be set at maximum so that the ratio of useful output to leakage is as great as possible.

## 2.7 MEASUREMENT OF UNKNOWN IMPEDANCE

2.71 Impedance Components Within Direct-Reading Ranges of Bridge: Connect the ground terminal of the unknown impedance to the ground binding post on the bridge panel with as short a lead as possible,[7] and arrange the setup so that the

7. For an inherently grounded impedance, for instance an antenna, this ground connection can be dispensed with since the bridge is already grounded through a low-reactance connection.

ungrounded terminal of the unknown impedance can be reached with one of the two connecting leads supplied, preferably the short one. Clip the connecting lead to the ground terminal of the unknown impedance[8] and establish an initial balance as described in Section 2.6. Remove the connecting-lead clip from the grounded terminal of the unknown impedance, clip to the ungrounded terminal, and rebalance with the RESISTANCE and REACTANCE controls. The location of the connecting lead should be altered as little as possible when the clip is shifted from the grounded to the ungrounded terminal.

The unknown resistance is read directly from the RESISTANCE dial; the unknown reactance is equal to the change in reading of the REACTANCE dial, divided by the frequency in megacycles. If the unknown reactance is inductive, the initial setting should be made at zero, the change in reading of the REACTANCE dial then being equal to the final dial reading. If the unknown reactance is capacitive, the initial settting should be made at 5000Ω, the change in reading of the reactance dial then being equal to 5000 ohms minus the final dial reading.

When the capacitive reactance is small, the precision of measurement may be low because of the cramping of the reactance scale at the high-reactance end. To improve the precision of reactance measurement, set the toggle switch to the L position, the RESISTANCE dial to $R_x$ and the REACTANCE dial to zero, with the connecting lead clipped to the ungrounded terminal of the unknown impedance. Balance with ~~the~~ BOTH OF THE INITIAL BALANCE ~~reactance~~ CONTROLS control. Clip the connecting lead to the grounded terminal and rebalance with the RESISTANCE and REACTANCE dials. The REACTANCE dial will then read up-scale for capacitive reactance and the precision of reading will be the same as for inductive reactance. This method of reading capacitive reactance has, however, the disadvantage of requiring four balances, one pair to determine the resistance component and the other to determine the reactance component. It is also not universal, because reactance balances with the UNKNOWN terminals short-circuited can only be set over a scale range of about 0 to 1000 ohms. Since the "final" balance must be made under this condition, only reactances that fall within the 1000-ohm scale range can be so measured.

8. For an inherently grounded impedance, the connecting lead can be clipped to the ground binding post on the bridge panel.

If it is not known whether the reactance component of the impedance to be measured is inductive or capacitive the following procedure is helpful. For the initial balance, set the toggle switch to the C position and the REACTANCE dial to the lowest setting that can be obtained, normally about 4000 ohms (see Section 2.6 and Figure 3). This reactance setting permits a change in scale reading of 1000 ohms inductive or 4000 ohms capacitive. If the receiver sensitivity control is turned down, this available reactance range is sufficient to indicate the direction in which the dial must be turned for a reactive balance and a new initial balance can be established accordingly.

<u>2.72 Impedance Components Outside Direct-Reading Ranges of Bridge:</u> If the resistance or reactance component of the unknown impedance falls outside the direct-reading range of the bridge, indirect measurements can be made through the use of an auxiliary parallel condenser.

When a pure reactance, $jX_a$, is connected in parallel with the unknown impedance, $Z_x = R_x + jX_x$, the effective input impedance, $Z_e = R_e + jX_e$, becomes:

$$R_e = \frac{R_x X_a^2}{R_x^2 + (X_x + X_a)^2} \qquad (3)$$

$$X_e = \frac{X_a \left[ R_x^2 + X_x (X_x + X_a) \right]}{R_x^2 + (X_x + X_a)^2} \qquad (4)$$

As $X_a$ is made smaller, these equations approach zero, in the limit, according to the relations

$$R_e = X_a^2 \frac{R_x}{R_x^2 + X_x^2} \qquad (3a)$$

$$X_e = X_a \qquad (4a)$$

"Shunting down" a high impedance with a parallel condenser will, accordingly, bring either or both the resistance and reactance component within the measurement range of the bridge.

To measure a high impedance by this method, connect one lead of the auxiliary condenser[9] to the ground terminal of the unknown impedance and locate the other lead near the ungrounded terminal of the

9. "Postage stamp" condensers, such as the Cornell-Dubilier Type 5-W will ordinarily be found adequate for use as auxiliary condensers.

unknown impedance. Establish an initial balance as described in Section 2.6 and measure the capacitive reactance, $X_a$, of the auxiliary condenser as described in Section 2.71. Connect the ungrounded lead of the auxiliary condenser to the ungrounded terminal of the unknown impedance, using as nearly as possible the same auxiliary-condenser lead length as was used in making the reactance measurement, and measure the effective impedance, $Z_e = R_e + jX_e$, of the parallel combination. The unknown impedance can then be found from the relations

$$R_x = \frac{R_e (X_a)^2}{(R_e)^2 + (X_e - X_a)^2} \qquad (5)$$

$$X_x = -\frac{X_a \left[(R_e)^2 + X_e(X_e - X_a)\right]}{(R_e)^2 + (X_e - X_a)^2} \qquad (6)$$

It should be noted that, since the auxiliary reactance, $X_a$, is capacitive, the number to be inserted for $X_a$ in Equations (5) and (6) will be negative. The sign of the number for the effective reactance, $X_e$, will be positive or negative accordingly as the measured value is inductive or capacitive.

The value of the auxiliary capacitance to use is easily found by experiment. It should be kept reasonably small so that the impedances to be measured are not reduced so far that precision of dial readings is lost, but it will not ordinarily be found critical. A value between 35 μμf and 200 μμf will usually be found adequate. The resistance, $R_a$, of the auxiliary condenser is generally negligible but can be corrected for, when necessary, by subtracting from the effective resistance, $R_e$, of the parallel combination, a resistance,

$$R = R_a \frac{X_e^2 - R_e^2}{X_a^2} \qquad (7)$$

The corrected value of $R_e$ can then be substituted in Equations (5) and (6).

2.73 Lead Corrections: In common with other types of impedance-measuring equipment, the bridge can only measure impedance at its own terminals. The residual impedances of the leads used to connect the unknown impedance to these terminals, however, often causes this impedance to differ from the impedance appearing at the terminals of the device under test. Under some circumstances the difference can be ignored and the measured impedance taken as the impedance of the device under test, including the leads. In most cases, however, the device will not be used with the same leads used to connect it to the measuring instrument and it is necessary to compensate for the effect of these leads to obtain the desired impedance. An exact correction for the effect of the leads requires analysis as a transmission line and is laborious and cumbersome. For specific measurements, however, approximate corrections will yield satisfactory accuracy.

In the procedure outlined in Sections 2.6 and 2.71 for measuring impedance components within the direct-reading ranges of the bridge it is noted that the length and location of connecting leads to the unknown impedance should be altered as little as possible when the clip is shifted for initial and final balances. This precaution assures that the inductive reactance of the leads is very nearly equal under the two conditions and that it therefore cancels out in the series-substitution process. The capacitance to ground of a connecting lead, however, will cause errors in measurement that increase as the frequency is raised.

Since the capacitance of a connecting lead to ground has the same effect as a capacitance deliberately placed in parallel with the unknown impedance, the corrections for its effect can be obtained directly from Equations (5) and (6), where $Z_e = R_e + jX_e$ is the observed impedance, and $X_a$ the reactance of the lead capacitance. The reactance, $X_a$, however, is usually very high compared to both $R_x$ and $X_x$ and the equations can be written in the simple, approximate form

$$R_x = R_e \left[1 + 2\frac{X_e}{X_a} + 3\left(\frac{X_e}{X_a}\right)^2 - \left(\frac{R_e}{X_a}\right)^2\right] \qquad (5a)$$

$$X_x = X_e + \frac{X_e^2 - R_e^2}{X_a} + \frac{X_e}{X_a}\left(\frac{X_e^2 - 3R_e^2}{X_a}\right) \qquad (6a)$$

Equations 5a and 6a contain both first and second order correction terms; however in many cases the second order terms are negligibly small and can be neglected.

It should be noted that, since $X_a$ is capacitive, the number to be inserted for $X_a$ in Equations (5a) and (6a) is negative. If the connecting leads are kept at a reasonable distance from metal objects, say an inch or more at the closest point, their capacitances to ground are, approximately:

Short connecting lead (916-P3) - 3.2 μμf
Long connecting lead (916-P4) - 8.5μμf[10]

For convenience in making corrections, the reactances corresponding to these capacitances are plotted in Figure 4.

When measurements are made of impedance components beyond the direct-reading ranges of the bridge, no lead corrections are necessary. Precaution in keeping the length and position of the connecting lead as nearly the same as possible insures constant inductance, which cancels out in the series-substitution process; the reactance of the connecting-lead capacitance to ground is included in the measured reactance, $X_a$, of the parallel condenser.

It should be emphasized that the above treatment of lead corrections is approximate. If, for instance, the inductive reactance of the connecting lead is comparable to the unknown impedance, the voltage to ground will vary along the lead and the effective capacitance to ground will not be the same as it is when the inductive reactance of the lead is small compared to the unknown impedance. When the unknown impedance is zero, in fact, the effective capacitance to ground of a connecting lead will be only one third the static value. In compensation, it should be noted that the lower the unknown impedance, the less the effect of lead capacitance. Obviously, the shorter the connecting lead, the smaller will be the lead corrections and the more nearly exact Equations (5a) and (6a). The short connecting lead (916-P3) should therefore be used wherever possible, especially at the higher frequencies, say above 5 megacycles. To aid in estimating the inductive reactance of the leads relative to the unknown impedance, approximate inductance values are given below:

Short lead (916-P3) - 0.05 μh
Long lead (916-P4) - 0.6 μh

<u>2.74 Corrections for Residual Parameters:</u> Frequency limits for accurate operation of radio-frequency impedance-measuring equipment are nearly always determined by residual parameters, in the wiring and in the impedance elements, that they are not accounted for in the basic theory of operation. While these have been made extremely small in the bridge, they are still large enough to affect performance at the lowest and at the highest frequencies and to set the respective limits of operation at about 400 kc and 60 Mc.

The low-frequency limitation arises from dielectric loss in the REACTANCE condenser, $C_P$. This loss causes an effective series resistance that varies with the dial setting and the frequency as shown in Figure 5. Since the resistance changes with the setting of the REACTANCE condenser, incorrect measurements of the resistive components of impedances with substantial reactive components will occur unless corrections are made. The change of resistance is such that resistance associated with capacitive reactance will appear too low, resistance with inductive reactance too high. From the curves it is evident that reactance measurements should be made at the low-reading end of the REACTANCE dial whenever possible in order to minimize corrections for dielectric loss.

The high-frequency limitation arises from inductance in the RESISTANCE condenser, $C_a$. This inductance causes the effective capacitance to increase as the frequency is raised and, consequently, the dial reading for a given resistance value to decrease. A set of correction curves is given in Figure 6.

<u>2.75 Illustrative Examples:</u> As a guide to the practical application of the material of Sections 2.6 and 2.71 to 2.74, three illustrative examples follow.

(a) <u>Measurement of 100 μμf Condenser at 500 Kilocycles.</u>

The unknown impedance, in this example, is a small mica condenser of good power factor.

Plug short connecting lead (916-P3) into panel jack and fasten one lead of unknown condenser to panel binding post. Adjust location of unknown condenser so that clip of connecting lead can be transferred from ungrounded condenser lead to grounded condenser lead with minimum change in connecting-lead position. Reactance of condenser will be about 3200 ohms (1600-ohm change in dial reading) so balance cannot be made with switch in L position.

With switch in C position establish initial balance as described in Section 2.6. Set the REACTANCE dial at the lowest convenient reading, say 4000 ohms.

Transfer clip of connecting lead to ungrounded lead of unknown condenser and rebalance with RESISTANCE and REACTANCE dials. Suppose the respective readings are 2.3 ohms and 2460 ohms. Before corrections, the observed resistance, $R_e$, and reactance $X_e$, are:

10. This capacitance was measured with lead held about 6" away from the panel, on the average. It will depend more upon the position of the lead than will the capacitance of the short lead.

$R_e = 2.3$ ohms

$$X_e = \frac{2460 - 4000}{0.5} = -3080 \text{ ohms}$$

To correct for dielectric loss in the REACTANCE condenser look up in Figure 5 the effective resistances for dial settings of 4000 ohms and 2460 ohms at 0.5 Mc. The corrected value of $R_e$ then becomes

$$R_e = 2.3 + 1.5 - 0.6 = 3.2 \text{ ohms}$$

To correct for the connecting-lead capacitance to ground, look up, in Figure 4, the corresponding reactance $X_a$. It is -114,000 ohms. Applying Equations (5a) and (6a) and omitting the second-order correction terms, as they are negligible in this case:

$$R_x = 3.2 \left[ 1 + 2 \left( \frac{-3080}{-100,000} \right) \right] = 3.4\ \Omega$$

$$X_x = -3080 + \frac{(-3080)^2 - (3.2)^2}{-100,000}$$

$$= -3175\ \Omega \text{ (capacitive)}$$

From these measurements, the capacitance, $C_x$, and dissipation factor,[11] $D_x = \frac{R_x}{X_x}$, are:

$$C_x = \frac{10^{12}}{2\pi \times 0.5 \times 10^6 \times 3175} = 100\ \mu\mu f$$

$$D_x = \frac{3.4}{3175} = 0.0011 = 0.11\%$$

This example is cited as an extreme case, in which failure to correct for the dielectric loss of the REACTANCE condenser leads to an error in resistance measurement of nearly 30%. For impedances in which the resistance component is larger compared with the reactance component the correction is of less importance.

(b) Measurement of Broadcast Antenna at 1170 Kilocycles

In a typical case, the antenna terminal is located within a metal rack in a small house at the foot of the antenna tower. The bridge can be set up on packing boxes to come up to the front of the rack but cannot be brought close enough to the antenna terminal to use the short connecting lead (916-P3).

Plug long connecting lead (916-P4) into panel jack. Ground bridge to rack with short lead, preferably of copper strip 1" or so wide. If this connection cannot be made conveniently to the clamp provided on the instrument case the panel can be loosened and a piece of copper foil slid onto the crack between the panel and the instrument case. Do not ground to panel screws as they may not be making contact to the panel because of paint. Arrange connecting lead so that it can be clipped to antenna terminal or to nearest ground point on rack with as little change in physical location as possible. The lead should be kept as far away from metal objects as possible throughout its length by any convenient means such as suspending it with string.

Suppose the antenna to be about 0.6 wavelengths long, with an impedance having a capacitive reactance component. With the toggle switch set to the C position, and the connecting lead grounded to the rack, establish an initial balance as described in Section 2.6. Set the REACTANCE dial to 5000 ohms pending further knowledge of the magnitude of the reactance.

Transfer clip of connecting lead to antenna terminal and rebalance with RESISTANCE and REACTANCE dials. Suppose the respective readings are 193 ohms and 4850 ohms. The resistance reading is adequate; the reactance reading is not as precise as might be desired because of crowding of the REACTANCE scale. To obtain a more precise reactance measurement, throw the toggle switch to the L position, set the REACTANCE dial to zero and rebalance the bridge with the two INITIAL BALANCE controls. Transfer clip of connecting lead to ground on rack and rebalance with RESISTANCE and REACTANCE dials. The RESISTANCE dial should rebalance at zero; suppose the REACTANCE dial reading is 160 ohms. Before corrections, the observed resistance, $R_e$, and reactance, $X_e$, are:

$$R_e = 193 \text{ ohms}$$

$$X_e = \frac{-160}{1.17} = -137 \text{ ohms}$$

The corrections for dielectric loss in the REACTANCE condenser and inductance in the RESISTANCE condenser are seen,

11. This quantity is practically equal to the power factor ($R_x/Z_x$) for small values, and is often so miscalled.

from Figures 5 and 6, to be negligible. To correct for the connecting-lead capacitance to ground, look up, in Figure 4, the corresponding reactance, $X_a$. It is -16,000 ohms. Applying Equations (5a) and (6a) and omitting the second-order correction terms, which are negligible:

$$R_x = 193 \left[ 1 + 2\left(\frac{-137}{-16,000}\right) \right] = 196\ \Omega$$

$$X_x = -137 + \frac{(-137)^2 - (193)^2}{-16,000}$$

$$= -136\,\Omega \text{ (capacitive)}$$

**In this example, corrections are very small. The Type 916-A Radio-Frequency Bridge is particularly suited for such measurements.**

(c) Measurement of Terminated 72-Ohm Coaxial Line at 50 Mc

At very high frequencies, lead corrections become very important. It is, therefore, necessary to use the short connecting lead (916-P3). It is also desirable, if possible, to bring up the outer conductor of the coaxial line over the panel and make contact to it directly at the ground binding post on the panel.

Plug short connecting lead (916-P3) into panel jack. Clip to outer conductor of line or to ground binding post on panel, set toggle switch to the L position and establish an initial balance as described in Section 2.6. Set REACTANCE dial to as low a value as possible, say 500 ohms.

Transfer clip of connecting lead to center conductor of coaxial line and rebalance with RESISTANCE and REACTANCE dials. Suppose the respective readings are 64.5 ohms and 1450 ohms. Before corrections, the observed resistance, $R_e$, and reactance, $X_e$, are:

$$R_e = 64.5 \text{ ohms}$$

$$X_e = \frac{1450 - 500}{50} = +19 \text{ ohms}$$

To correct for inductance in the RESISTANCE condenser look up, in Figure 6, the correction for a dial reading of 65 ohms at 50 Mc. It is 1.17. The corrected value of $R_e$ then becomes

$$R_e = 64.5 \times 1.17 = 75.4 \text{ ohms}$$

To correct for the connecting-lead capacitance to ground, look up, in Figure 4, the corresponding reactance, $X_a$. It is -1150 ohms. Applying Equations (5a) and (6a) and in this case including the second-order terms, because they are significant:

$$R_x = 75.4\left[1 + 2\left(\frac{19}{-1000}\right) + 3\left(\frac{19}{-1000}\right)^2 - \left(\frac{75.4}{-1000}\right)^2\right]$$

$$= 75.4\ [1 + .038 + .001 - .006] = 72.1\ \Omega$$

$$X_x = 19 + \frac{(19)^2 - (75.4)^2}{-1000} + \frac{19}{-1000}\left[\frac{(19)^2 - 3(75.4)^2}{-1000}\right]$$

$$= 19 + 5.32 - .32 = 24.0\ \Omega \quad \text{(inductive)}$$

This example is cited as an extreme case, in which failure to correct for the inductance of the RESISTANCE condenser leads to an error in resistance measurement of the order of 11%.

2.76 Balanced Lines and Antennas: The measurement of three-terminal devices, such as balanced lines and antennas, can be made with the bridge, although the computations involved are quite laborious.

The method depends upon the analysis of the unknown impedance in terms of the equivalent circuit of Figure 7 and requires three separate measurements, as follows:

(1) Short-circuit impedance $Z_1$ by grounding line A at point of measurement, and measure impedance, Z', from line B to ground.

$$Z' = \frac{Z_2 Z_3}{Z_2 + Z_3} \qquad (8)$$

(2) Short-circuit impedance $Z_2$ by connecting line A to line B at point of measurement, and measure impedance, Z", from the junction to ground.

$$Z'' = \frac{Z_3 Z_1}{Z_3 + Z_1} \qquad (9)$$

(3) Short-circuit impedance, $Z_3$, by grounding line B at point of measurement, and measure impedance, Z"', from line A to ground.

$$Z''' = \frac{Z_1 Z_2}{Z_1 + Z_2} \qquad (10)$$

Combining Equations (8), (9) and (10) gives:

$$Z_1 = \frac{2Z'Z''Z'''}{Z'Z'' - Z''Z''' + Z'''Z'}$$

$$= \frac{2}{-\frac{1}{Z'} + \frac{1}{Z''} + \frac{1}{Z'''}} \qquad (11)$$

$$Z_2 = \frac{2Z'Z''Z'''}{Z'Z'' + Z''Z''' - Z'''Z'}$$

$$= \frac{2}{\frac{1}{Z'} - \frac{1}{Z''} + \frac{1}{Z'''}} \quad (12)$$

$$Z_3 = \frac{2Z'Z''Z'''}{-Z'Z'' + Z''Z''' + Z'''Z'}$$

$$\frac{2}{\frac{1}{Z'} + \frac{1}{Z''} - \frac{1}{Z'''}} \quad (13)$$

This method gives each component of impedance, detecting any unbalance. At perfect balance, $Z_1 = Z_3$, $Z' = Z'''$.

$$Z_1 = Z_3 = 2Z'' \quad (11a)$$

$$Z_2 = \frac{2Z'Z''}{2Z'' - Z'} = \frac{1}{\frac{1}{Z'} - \frac{1}{2Z''}} \quad (12a)$$

When the balanced line is fed from a balanced source, the effective input impedance is given by

$$Z_{AB} = \frac{2Z_1Z_2}{2Z_1 + Z_2} = \frac{4Z'Z''}{4Z'' - Z'} \quad (14)$$

$Z_{AB}$ is the input impedance seen from the source. It should be measured once with the far end of the line open and once with it closed if it is desired to compute the characteristic impedance and propagation constant by the usual method. No grounds should be made to the line at any point other than the input when making measurements.

In Equations (11) to (14) the component impedances must, of course, be written in their complex forms.

## 3.0 CHECKS AND ADJUSTMENTS

### 3.1 RESISTANCE CALIBRATION

If the calibration of the RESISTANCE dial changes slightly, with time or rough usage, it can be restored by adjusting the trimmer condensers $C_N'$ and $C_N''$ (See Figure 2), which are mounted behind snap buttons on the panel. $C_N'$, mounted behind the left-hand snap button, adjusts the RESISTANCE dial span with the toggle switch set to the L position; $C_N''$, mounted behind the right-hand snap button, adjusts the RESISTANCE dial span with the toggle switch set to the C position.

To check the calibration, measure at 1 Mc, the resistance of a good radio-frequency resistor, such as a General Radio Type 663-G Resistor or a small "metallized" resistor, preferably of the ceramic type. The measured resistance should check the d-c value within 1%. If it does not, adjust $C_N'$ and $C_N''$. Turning these condensers clockwise decreases the dial reading for a given resistance and vice versa.

Similar trimmer condensers are mounted on the two transformers. If measurements of the same resistor at 3 megacycles made with the two transformers are not the same, the trimmer condenser on the high-frequency transformer (3-60 Mc) can be adjusted to bring them into agreement. Unless the transformers are subjected to abuse these condensers should not require readjustment.

### 3.2 CORRECTION FOR DIELECTRIC LOSS IN REACTANCE CONDENSER

The dielectric loss described in Section 2.74 is subject to some variation among different instruments because of variations in the ceramic insulation, and the curves of Figure 5 may not be sufficiently accurate for the most refined work. An independent check of the resistance of this condenser can be made by measuring the resistance of a 200-μμf condenser at a frequency of 1 Mc as follows:

First measure the resistance of the condenser with an initial REACTANCE dial setting of 5000 ohms (switch in C position). Say the readings are:

$$R_e' = 0.05 \text{ ohms}$$

$$X_1' = 5000 \text{ ohms}$$

$$X_2' = 4180 \text{ ohms}$$

$$X_x = X_2' - X_1' = -820 \text{ ohms}$$

Next measure the resistance of the condenser with a final REACTANCE dial setting of zero ohms (switch in L position). Say the readings are:

$$R_e'' = 0.31 \text{ ohms}$$

$$X_1'' = 820 \text{ ohms}$$

$$X_2'' = 0 \text{ ohms}$$

$$X_x = 0 - 820 = -820 \text{ ohms}$$

The effective resistance, $R_e$, read on the RESISTANCE dial, is equal to:

$$R_e = R_x + G\left[(X_2)^2 - (X_1)^2\right] = R_x + GX_x\,(X_1 + X_2 + 2X_o) \quad (15)$$

where G is the effective conductance of the REACTANCE condenser caused by dielectric loss and $X_o$ is the reactance of the REACTANCE condenser at zero dial setting ($X_o$ = 432 Ω at 1 Mc).

If $R_e$ is plotted as a function of $X_1 + X_2 + 2X_o$, a straight line results, having a slope equal to $GX_x$ and an intercept at $X_1 + X_2 + 2X_o = 0$ equal to $R_x$.

The two end points above are sufficient to determine this straight line without plotting. The slope is:

$$GX_x = \frac{R_e'' - R_e'}{(X_1'' + X_2'' + 2X_o) - (X_1' + X_2' + 2X_o)}$$

$$= \frac{0.31 - 0.05}{820 - 9180} = -0.31 \times 10^{-4}$$

The intercept is:

$$R_x = 0.31 - (-0.31 \times 10^{-4})(820 + 864) = 0.36\,\Omega$$

From the slope and the measured value of $X_x$

$$G = \frac{-0.31 \times 10^{-4}}{-820} = 0.038 \times 10^{-6}$$

The resistance of the REACTANCE condenser at any setting, X, is:

$$R = G(X + X_o)^2$$

At X = 5000, this becomes

$$R = 0.038 \times 10^{-6}\,(5000 + 432)^2 = 1.12\,\Omega$$

The resistance at other settings can be computed in the same way. Since the power factor of the ceramic used is essentially constant at frequencies above 400 kc, the resistance at any setting varies inversely as the frequency and curves can be drawn accordingly from the 1-megacycle figures.

## 3.3 CORRECTION FOR INDUCTANCE IN RESISTANCE CONDENSER

The change in effective capacitance of the RESISTANCE condenser, noted in Section 2.74, is subject to some variation between instruments. Direct use of the average correction curves of Figure 6 may therefore lead to error in the measurement of resistance with any given instrument. This error is a constant fraction of the correction percentage and amounts to about ±0.3. That is, if the average correction factor is, say, 1.15 (correction percentage = 15%) as read from Figure 6, the correction for any individual instrument may be from 1.10 to 1.20. For small deviations of the effective capacitance from the static value such departures from the average correction are, in general, negligible. At the highest frequencies, however, they may be large enough to warrant an individual check on the correction curves.

To check the curves of Figure 6, it is recommended that a 100 Ω General Radio Type 663-G Resistor or a 100 Ω resistor such as the IRC Type F-1/2 be measured at a frequency of 50 Mc with the toggle switch set to the L position. Suppose the measured resistance and reactance are:

$$R_e = 83.5 \text{ ohms}$$

$$X_e = -\frac{330}{50} = -6.6 \text{ ohms}$$

Apply the lead correction for the short connecting lead (916-P3). At 50 Mc, as read from Figure 4, the reactance of the lead capacitance is

$$X_a = -1000 \text{ ohms}$$

Equation (5a) then gives the corrected resistance, $R_x'$

$$R_x' = 83.5\left[1 + 2\left(\frac{-6.6}{-1000}\right) + 3\left(\frac{-6.6}{-1000}\right)^2 - \left(\frac{-83.5}{-1000}\right)^2\right]$$

$$= 83.5 \times 1.006 = 84.0 \text{ ohms}$$

The true resistance, $R_x$, at this frequency should be well within 1% of the d-c value, which is, say, 100.7 ohms. The correction should therefore be

$$\frac{R_x}{R_x'} = \frac{100.7}{84.0} = 1.199$$

As read from Figure 6 the correction factor is about 1.175. The use of this average figure would therefore lead to an error of about -2% in the answer.

The correction factor for this particular instrument can be obtained for any resistance setting from this one measurement through the relation

$$\frac{R_x}{R_x'} = \frac{1}{1 - kf^2(R_x' + 2R_p)} \qquad (16)$$

where $R_x$ is the true resistance, $R_x'$ is the dial reading, corrected for the lead capacitance, $2R_p = 500\,\Omega$, f is the frequency in megacycles, and

$$k = \frac{1}{f^2}\,\frac{R_x - R_x'}{R_x}\,\frac{1}{R_x' + 2R_p} \qquad (16a)$$

For the example given

$$k = \frac{1}{50^2} \cdot \frac{100.7 - 84.0}{100.7}\,\frac{1}{84.0 + 500}$$

$$= 1.135 \times 10^{-7}$$

A complete new set of curves can now be drawn for the particular instrument, either by computation of points by equation (16) or by finding the frequency at which the average correction as read from Figure 6, agrees with the observed correction and multiplying all frequencies by the ratio of this frequency to the measurement frequency.

In the example cited, for instance, Figure 6 shows a correction factor of 1.199 at about 52 Mc. If all frequencies are multiplied by the ratio $\frac{52}{50} = 1.04$, the curve of Figure 6 may be used directly or, for simplicity, new curves may be drawn with a correct frequency scale.

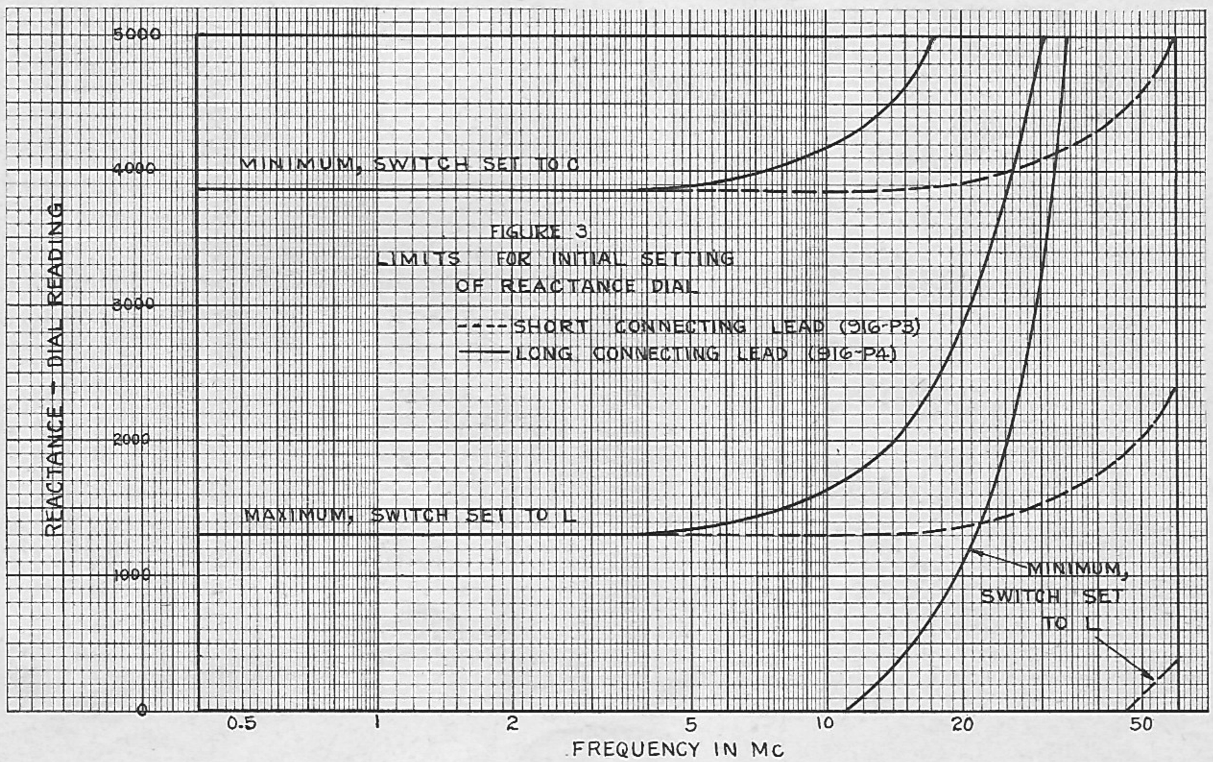



FIGURE 3
LIMITS FOR INITIAL SETTING OF REACTANCE DIAL

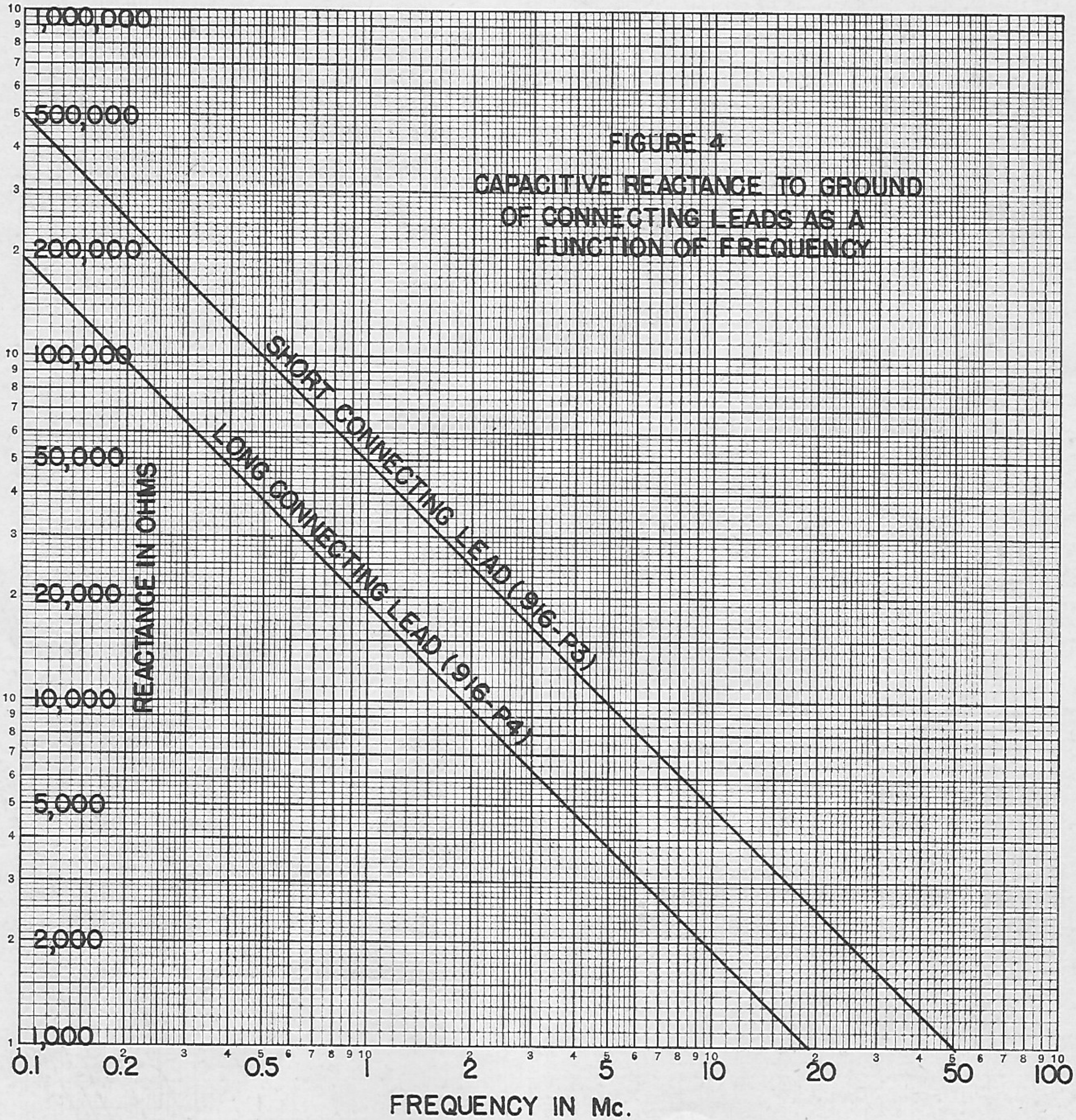


FIGURE 4
CAPACITIVE REACTANCE TO GROUND
OF CONNECTING LEADS AS A
FUNCTION OF FREQUENCY
SHORT CONNECTING LEAD (916-P3)
LONG CONNECTING LEAD (916-P4)
REACTANCE IN OHMS
1,000,000
500,000
200,000
100,000
50,000
20,000
10,000
5,000
2,000
1,000
0.1
0.2
0.5
1
2
5
10
20
50
100
FREQUENCY IN Mc.

Fig. 4

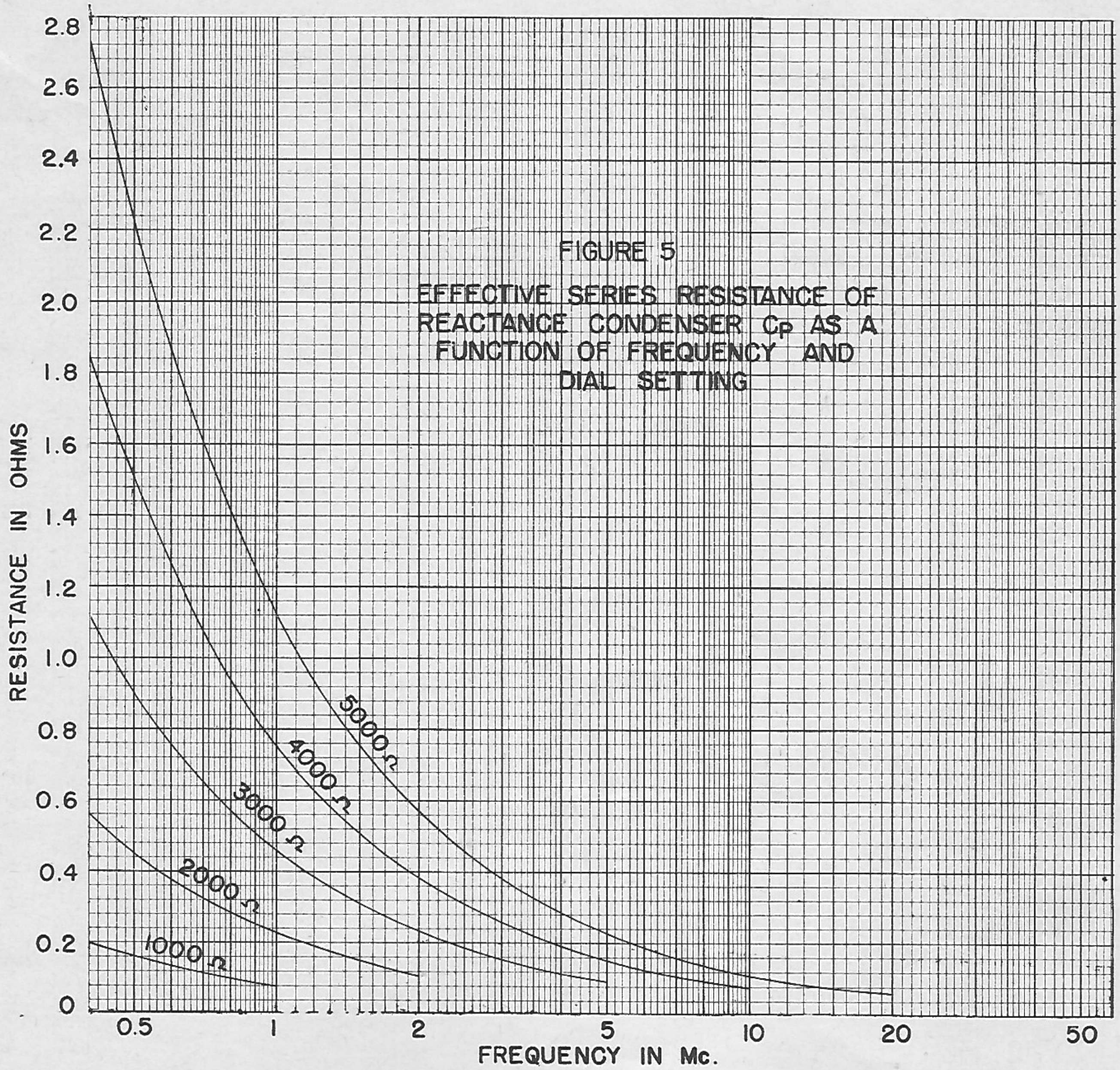


FIGURE 5
EFFECTIVE SERIES RESISTANCE OF REACTANCE CONDENSER $C_P$ AS A FUNCTION OF FREQUENCY AND DIAL SETTING
RESISTANCE IN OHMS
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
5000 Ω
4000 Ω
3000 Ω
2000 Ω
1000 Ω
0.5
1
2
5
10
20
50
FREQUENCY IN Mc.

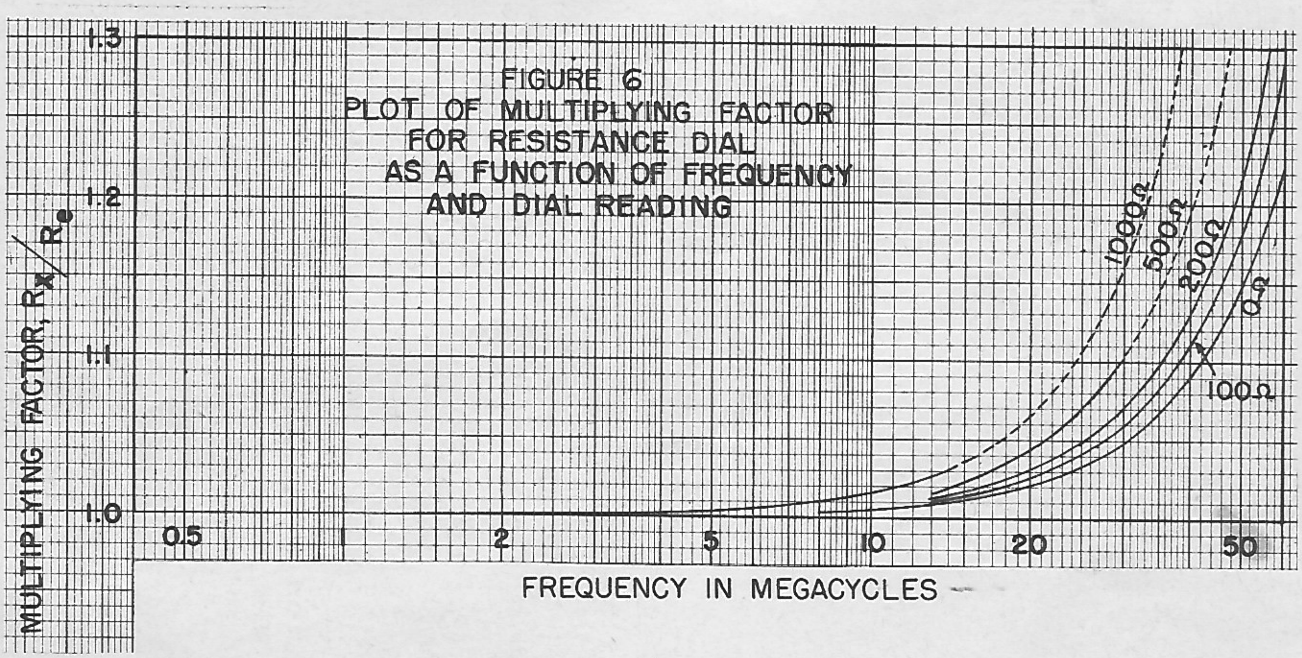


FIGURE 6
PLOT OF MULTIPLYING FACTOR FOR RESISTANCE DIAL AS A FUNCTION OF FREQUENCY AND DIAL READING
MULTIPLYING FACTOR, $R_X/R_e$
1.3
1.2
1.1
1.0
1000Ω
500Ω
200Ω
0Ω
100Ω
0.5
1
2
5
10
20
50
FREQUENCY IN MEGACYCLES

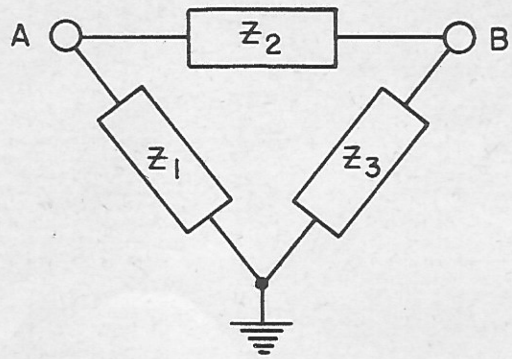



FIGURE 7.

<u>PARTS LIST</u>

<u>Condensers</u>

C-1 =
C-2 = 50 μμf
C-3 = 360 μμf
C-4 = 360 μμf
C-5 = 2-12 μμf
C-6 = 2-12 μμf
C-101 = 2-12 μμf

<u>Resistors</u>

R-1 = 300 Ω
R-2 = 91 Ω
R-3 = 330 Ω
R-101 = 250 Ω

<u>Transformers</u>

T-1 = 916-P1 Low Freq.
= 916-P2 High Freq.

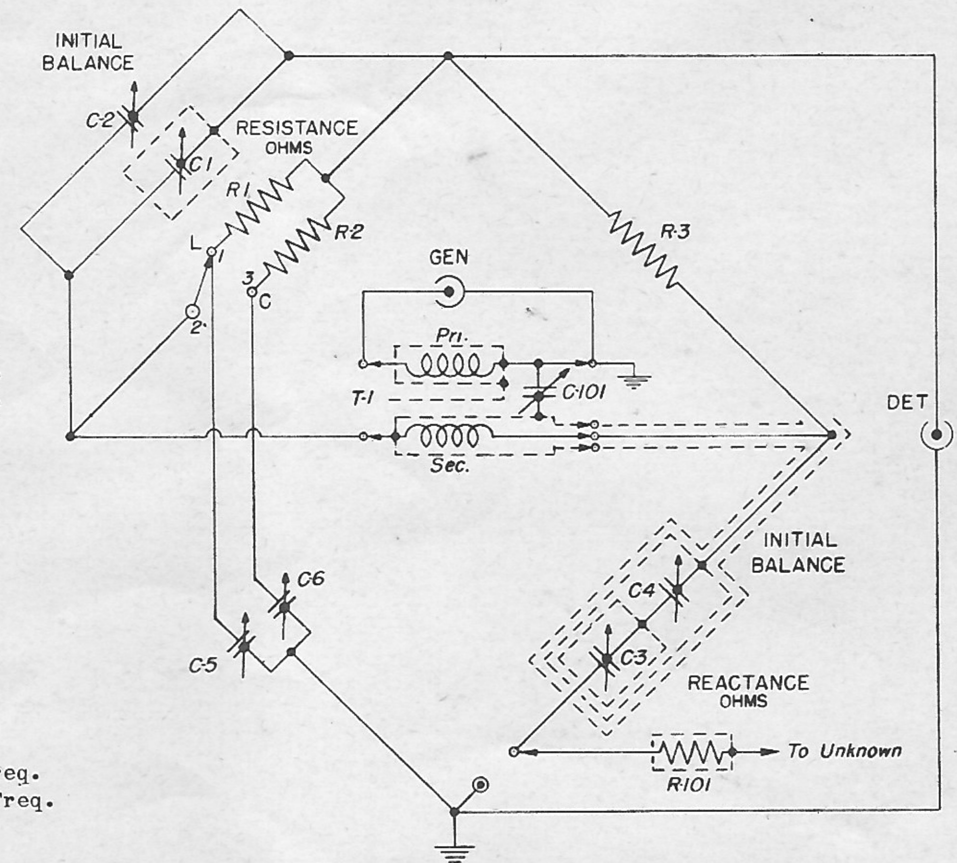



FIGURE 8. Complete wiring diagram with parts list.