

# THE *General Radio* EXPERIMENTER

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ELECTRICAL MEASUREMENTS AND THEIR INDUSTRIAL APPLICATIONS

## A NEW R-F BRIDGE FOR USE AT FREQUENCIES UP TO 60 MC

● THE NEED FOR A SIMPLE, ACCURATE INSTRUMENT to measure relatively low impedances in terms of their effective series resistance and reactance components has been pressing ever since quantitative information regarding antenna characteristics was first desired. The TYPE 516 Radio-Frequency Bridge,<sup>1,2</sup> first offered for sale in 1932, proved very satisfactory for such measurements at frequencies up to a few megacycles, and therefore found particular use in measurements of radiating systems in the standard broadcast band. However, as the upper frequency limit at which accurate measurements of impedance are required has increased, the limitations of this early bridge design have become increasingly apparent.

The TYPE 916-A Radio-Frequency Bridge,<sup>3</sup> described in this article, replaces the TYPE 516-C Radio-Frequency Bridge, supplying a wider range of direct impedance measurement in a more

FIGURE 1. Adjusting antenna coupling networks at Radio Station WHDH with the TYPE 916-A Radio-Frequency Bridge.



<sup>1</sup>Charles T. Burke, "Bridge Methods for Measurements at Radio Frequencies," *General Radio Experimenter*, Vol. 6, p. 1; July, 1932.

<sup>2</sup>C. E. Worthen, "Improvements in Radio-Frequency Bridge Methods for Measuring Antennas and Other Impedances," *General Radio Experimenter*, Vol. 8, p. 1; December, 1933.

<sup>3</sup>D. B. Sinclair, "A Radio-Frequency Bridge for Impedance Measurements from 400 Kilocycles to 60 Megacycles," *Proc. I.R.E.*, Vol. 28, p. 497; November, 1940.



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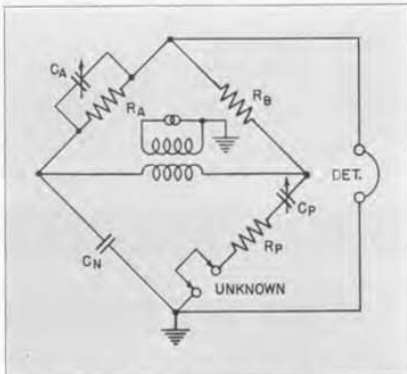


FIGURE 2. Elementary circuit diagram of the TYPE 916-A Radio-Frequency Bridge. The important feature distinguishing this bridge from the Schering bridge is the series substitution method of connecting the unknown impedance. The unknown reactance is determined from the change in setting of the condenser  $C_P$  and the unknown resistance from the change in setting of the condenser  $C_A$ .

convenient form over a wider frequency range. While useful as a general purpose instrument in the laboratory, the new bridge is particularly intended for measurements on radiating systems, and has been designed for maximum convenience in this application.

In addition to the greatly increased frequency range, the new bridge has two features that distinguish it from the older bridge, namely a considerably

greater direct-reading resistance range, and a simplified dial for reading reactance. The resistance range, from zero to 1000 ohms, is covered on a single 8" dial with a scale that is roughly linear from zero to 1 ohm and logarithmic from 1 ohm to 1000 ohms. The reactance range, from zero to 5000 ohms, is covered on a single 4" dial with a scale that is roughly linear from zero to 50 ohms and logarithmic from 50 ohms to 5000 ohms. The reactance-dial reading varies directly with frequency, the engraved scale being direct reading at a frequency of 1 Mc.

CIRCUIT AND THEORY

To achieve these greatly increased frequency and resistance ranges, the new circuit shown in Figure 2 has been developed.

Similar in appearance to the Schering bridge circuit, the new circuit differs in the method of connecting the unknown impedance and the method of measuring the reactive component. The balance conditions are:

$$R_P = R_B \frac{C_A}{C_N} \tag{1}$$

$$\frac{1}{j\omega C_P} = \frac{R_B}{R_A} \frac{1}{j\omega C_N} \tag{2}$$

When an impedance,  $Z_x = R_x + jX_x$ , is to be measured, the bridge is first balanced by means of the condensers  $C_A$

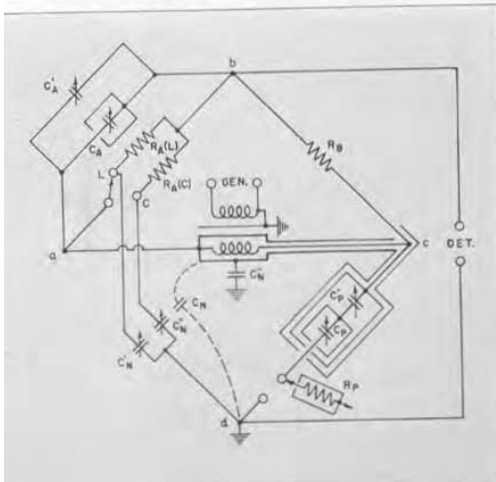


FIGURE 3. Complete circuit diagram of the TYPE 916-A Radio-Frequency Bridge. The L-C switch changes the value of the ratio arm  $R_A$ , thereby establishing the initial setting of the reactance dial at minimum or maximum for measuring inductive or capacitive reactance. The trimmer capacitances  $C_N'$ ,  $C_N''$  are used to make the capacitance from point "a" to ground the same for the two positions of the L-C switch. The trimmer capacitance  $C_N'''$  is a part of the plug-in transformer assembly and is used to equalize the ground capacitances of the two transformers.

and  $C_P$  with a short circuit across the UNKNOWN terminals. The short circuit is then removed, the impedance connected, and the bridge rebalanced. This series-substitution method leads to the simple relationships:

$$R_z = R_B \frac{C_{A2} - C_{A1}}{C_N} \quad (3)$$

$$X_z = \frac{1}{\omega} \left( \frac{1}{C_{P2}} - \frac{1}{C_{P1}} \right) \quad (4)$$

in which subscripts 1 refer to initial balance values and subscripts 2 to final balance values.

Equations (3) and (4) show that the resistance and reactance balances are independent and that each depends directly upon a change in setting of a variable air condenser. The absence of the cross terms that make the power-factor and capacitance balances interdependent in the Schering bridge results from the fact that the zero capacitance of the condenser  $C_A$  is balanced by the resistor  $R_P$  rather than by a trimmer capacitance  $C_B$  across the ratio arm  $R_B$ . The fact that the resistance component is measured in terms of the fixed re-

sistance,  $R_B$ , and variable capacitance,  $C_A$ , is vital in establishing the wide frequency range, since these elements can be made with very small residual parameters. They combine, in this circuit, to form the equivalent of a continuously variable resistor having residual reactance much less than any variable resistor currently known.

### DESCRIPTION

The complete circuit diagram of the bridge in Figure 3 shows the modifications in the basic circuit of Figure 1 necessary to meet the needs of a commercial instrument. The condensers  $C_A'$  and  $C_P'$  are trimmers for setting zero on the resistance and reactance dials when making the initial balance. The two ratio arms,  $R_A(L)$  and  $R_A(C)$ , and the associated switch are provided so that the reactance dial can be set initially at zero for measuring inductive reactances, or at 5000 ohms for measuring capacitive reactances.

A panel view of the instrument is

FIGURE 4. Panel view of the bridge. The standard connecting leads supplied with the instrument plug into the jack adjacent to the reactance dial.



shown in Figure 4. Immediately below the RESISTANCE dial, at the right, is the INITIAL BALANCE knob controlling the condenser  $C_A'$ . Immediately below the REACTANCE dial, at the left, is the INITIAL BALANCE knob controlling the condenser  $C_P'$ . Immediately above the REACTANCE dial is the  $L-C$  switch for measuring inductive and capacitive reactances. The jack to which the unknown impedance connects is mounted in the center of the circular window above and to the right of the REACTANCE dial. A connecting lead, with a probe that plugs into this jack and that houses resistor  $R_P$ , is used to connect to the unknown impedance. Two of these leads, of different lengths, are supplied with the instrument.

#### DESIGN FEATURES

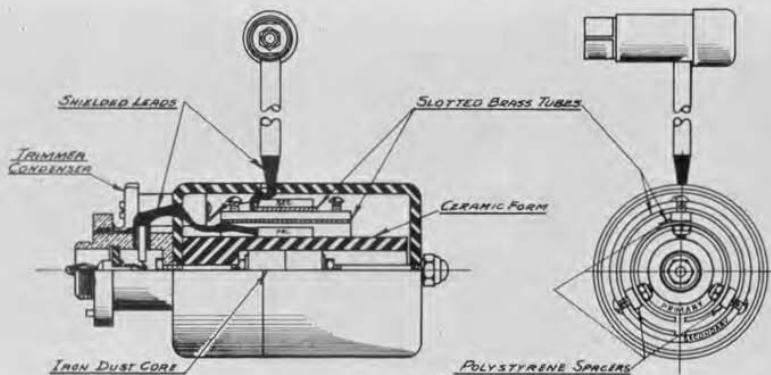
While the circuit of Figure 2 is, in general, inherently more suitable for high frequency operation than previously used circuits, the actual characteristics obtained are directly affected by the mechanical and electrical design. Some of the more interesting features are described below.

In Figure 3 triple shielding is shown surrounding the reactance-measuring

assembly comprising capacitances  $C_P$  and  $C_P'$ . The inner shield localizes the variable stray capacitance of the REACTANCE condenser,  $C_P$ , within the shield so that it cannot appear across the INITIAL BALANCE condenser,  $C_P'$ , and cause interlocking of the settings of the two condensers. The middle shield eliminates any capacitance of the inner shield to ground and substitutes an intershield capacitance across the INITIAL BALANCE condenser. The outer shield eliminates the capacitance of the middle shield to ground and substitutes an intershield capacitance across the secondary of the transformer. The assembly as a whole therefore prevents any capacitance but that of the measurement jack itself from appearing across the measurement terminals, and eliminates any capacitance to ground between the measurement jack and the right-hand corner of the bridge. The capacitance of the outer shield to ground appears across the condenser,  $C_N$ , in the lower left-hand bridge arm. Actually the outer box dimensions and the spacing to the panel and cabinet shielding are so chosen that this residual capacitance forms the capacitance,  $C_N$ , itself.

Two 1:1 plug-in shielded transformers are supplied to cover the frequency ranges from 400 kc to 3 Mc and 3 Mc to

FIGURE 5. Sectional view of the shielded plug-in transformer. To make the shielding as complete as possible each winding is individually shielded with copper foil, in addition to the slotted brass tubes.



60 Mc. As shown in Figure 3, double shielding is required to complete the shielding system of the reactance-condenser assembly. The fundamental shielding requirements are that the grounded primary be located within a shield at ground potential and that the ungrounded secondary be located within a shield connected to the left-hand corner of the bridge. The shielding must prevent capacitive coupling between the windings, must be located so that the capacitance between the two shields is small compared with the capacitance to ground of the outer shield of the reactance-condenser assembly, and must not seriously impair the magnetic coupling between the windings. The design that has been found to furnish a satisfactory compromise is shown in Figure 5.

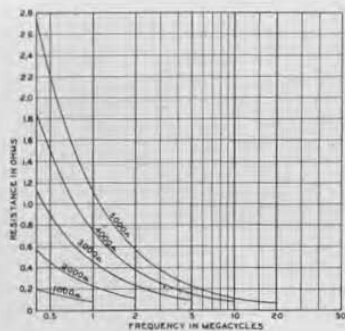
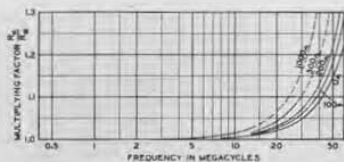
The most serious source of trouble in the design of these transformers was found to be the electromotive forces induced in the two split brass tubes used as shields between the primary and secondary. The potential difference taken along a radius between these tubes is practically zero at any point so long as the slots in the two tubes are lined up. If, however, the slots are not immediately opposite, over a sector between the two slots the radial potential difference is approximately equal to the electromotive force induced in a single turn in the magnetic field. Capacitive coupling between the two shields over this sector causes a residual component of voltage

to be introduced from the left-hand corner of the bridge to ground. This component can cause very large errors in both resistance and reactance measurements at the higher frequencies. Locating the leads to the windings directly opposite the slots connecting the brass tubes to the coil at the same point, and lining up the slots carefully, makes the error from this source negligible. Rotation of the outer brass tube with respect to the inner, in fact, is used as an adjustment to eliminate it.

Residual unwanted impedances in the various circuit elements and in the wiring cause deviations from the idealized behavior so far tacitly assumed. Since the corrections that must be made for them generally depend upon frequency, they determine basically the frequency limits between which the instrument is satisfactory. One of the two corrections to be made is necessitated by the loss in the dielectric structure of the REACTANCE condenser,  $C_p$ . This loss causes an effective series resistance that varies inversely as the frequency and inversely as the square of the capacitance. It establishes the lower frequency limit for accurate measurements in the vicinity of 400 kc. A plot of the effective series resistance as a function of dial setting and frequency is shown in Figure 6. The other correction to be made arises from the effective series induc-

FIGURE 6 (right). Effective series resistance of reactance condenser as a function of dial setting and frequency.

FIGURE 7 (below). Correction to be applied to resistance dial reading as a function of frequency.



tance of the RESISTANCE condenser,  $C_A$ . This residual inductance,  $L$ , causes the effective capacitance,  $\hat{C}_A$ , to differ from the static capacitance,  $C_A$ , according to the relation

$$\hat{C}_A = \frac{C_A}{1 - \omega^2 LC_A}$$

A plot of the correction to be made to the RESISTANCE dial reading as a function of frequency is shown in Figure 7. As the frequency is raised, the inductance is seen to reduce progressively the resistance range that can be measured and to establish an upper limit for accurate measurement in the vicinity of 60 Mc.

#### 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.

To insure standard measurement conditions, two connecting leads are supplied, one about 5" long and the other about 27" long, over-all. Approximate capacitance and inductance figures are given in the instruction book and simplified procedures for making the corrections are outlined.

#### APPLICATIONS

The wide frequency range covered by the new bridge permits convenient and accurate direct measurements of low impedances at frequencies extending up through the f-m band to the top of television channel 1. Two typical examples of measurements on an antenna and transmission line at frequencies between 2.5 and 60 Mc are shown in Figures 8 and 9. In addition to measurements of impedances that fall within the direct-reading ranges of the bridge, measurements can, of course, be made of higher impedances by indirect methods. The following examples show procedures to be followed in making typical measurements.

(a) *Measurement of 100  $\mu$ f Condenser at 500 Kilocycles.*

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 an initial balance. 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 2450 ohms. Before corrections, the observed resistance,  $R_e$ , and reactance  $X_e$ , are:

$$R_e = 2.3 \text{ ohms}$$

$$X_e = \frac{2450 - 4000}{0.5} = -3100 \text{ ohms}$$

To correct for dielectric loss in the REACTANCE condenser look up in Figure 6 the effective resistances for dial settings of 4000 ohms and 2450 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 the lead reactance chart, the corresponding reactance  $X_e$ . It is -114,000 ohms. Applying Equations (5a) and (6a), which are given in the instruction book,

$$R_z = 3.2 \left[ 1 + 2 \left( \frac{-3100}{-114,000} \right) - \left( \frac{3.2}{-114,000} \right)^2 \right]$$

$$= 3.4 \Omega$$

$$X_z = -3100 + \frac{(-3100)^2 - (3.2)^2}{-114,000}$$

$$= -3184 \Omega \text{ (capacitive)}$$

From these measurements, the capacitance,  $C_z$ , and dissipation factor,\*  $D_z = \frac{R_z}{X_z}$ , are:

$$C_z = \frac{10^{12}}{2\pi \times 0.5 \times 10^9 \times 3184} = 100 \mu\text{f}$$

$$D_z = \frac{3.4}{3184} = 0.0011 = 0.11\%$$

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.

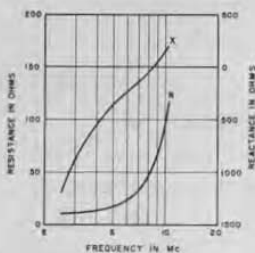
In a typical case, the antenna terminal is located within a metal rack in a small house at the foot of the antenna tower. The bridge can be set up on packing boxes to come up to the front of the rack but cannot be brought close enough to the antenna terminal to use the short connecting lead (916-P3).

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.

\*This quantity is practically equal to the power factor ( $R_z/Z_z$ ) for small values, and is often so miscalled.

FIGURE 9 (right). Input reactance and resistance of a transmission line. The solid lines show calculated values; the circles, values measured with the bridge.

FIGURE 8 (below). Reactance and resistance of an antenna system as measured by the bridge.



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. 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,  $R_z$ , and reactance,  $X_z$ , are:

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

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

The corrections for dielectric loss in the REACTANCE condenser and inductance in the RESISTANCE condenser are seen, from Figures 6 and 7, to be negligible. To correct for the connecting-lead capacitance to ground, look up, in the lead reactance chart, the corresponding reactance,  $X_a$ . It is  $-16,000$  ohms. Applying Equations (5a) and (6a), which are given in the instruction book,

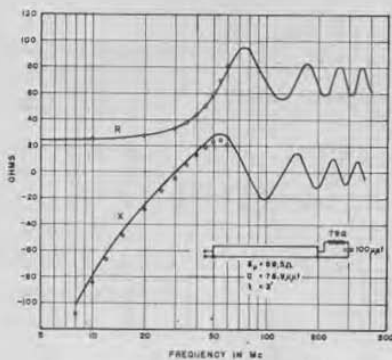
$$R_z = 193 \left[ 1 + 2 \left( \frac{-137}{-16,000} \right) - \left( \frac{192}{-16,000} \right)^2 \right]$$

$$= 196 \Omega$$

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

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

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. 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,  $R_o$ , and reactance,  $X_o$ , are:

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

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

To correct for inductance in the RESISTANCE condenser look up, in Figure 7, the correction for a dial reading of 65 ohms at 50 Mc. It is 1.17. The corrected value of  $R_o$  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 the lead reactance chart, the corresponding reactance,  $X_c$ . It is -1150 ohms. Applying Equations (5a) and (6a), which are given in the instruction book,

$$R_z = 75.4 \left[ 1 + 2 \left( \frac{19}{-1150} \right) - \left( \frac{75.4}{-1150} \right)^2 \right]$$

$$= 72.6 \Omega$$

$$X_z = +19 + \frac{(+19)^2 - (75.4)^2}{-1150}$$

$$= +23.7 \Omega \text{ (inductive)}$$

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 12%.

— D. B. SINCLAIR

## SPECIFICATIONS

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

**Reactance Range:** 5000  $\Omega$  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  $\Omega$ .

**Accuracy:** For reactance,  $\pm 2\% \pm 1 \Omega$ .

For resistance,  $\pm 1\% \pm 0.1\Omega$ , 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.

**Accessories Supplied:** Two input transformers, one covering the range from 400 kc to 3 Mc, the other from 3 Mc to 60 Mc; two leads of different lengths (for connecting the unknown impedance); two coaxial cables for connecting generator and detector.

**Accessories Required:** A radio-frequency generator and detector are required. The TYPE 605-B Standard-Signal Generator is a satisfactory generator. A well-shielded radio receiver covering the desired frequency range is recommended as the detector. The coaxial cable supplied for connection to the receiver is fitted with spade terminals at one end for connection to the receiver input terminals. For best results, however, it is recommended that the receiver be fitted with a TYPE 774-G Panel Plug and the cable with a TYPE 774-M Cable Jack.

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

**Dimensions:** 17  $\times$  13  $\frac{1}{2}$   $\times$  11  $\frac{1}{8}$  inches, overall.

**Net Weight:** 35 pounds.

Type		Code Word	Price
916-A	Radio-Frequency Bridge.....	CIVIC	\$350.00

Patent applied for.

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