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NRL Report 4230

R-F IMPEDANCE BRIDGES FOR MILITARY USE

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Radio Techniques Branch
Radio Division II

November 13, 1953

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ABSTRACT

R-F impedance-measuring instruments are needed in the military services for the study, installation, and maintenance of antennas, transmission lines, and high-frequency components. Commercial equipments available in this field do not meet military design and construction requirements. These instrument designs are based on a variety of techniques, viz, bridge, resonant and twin-T circuits, slotted-line principles, etc., and each possesses its own advantages and limitations and is more or less adaptable to military requirements.

As an instrument useful to the military services, the General Radio Company type 916-A r-f impedance bridge was specifically studied to determine the feasibility of producing a satisfactory military version thereof. Using a special T-network, a technique was devised that provided for the comparison of measurements on a standard impedance made by the bridge under test and by a reference bridge, so that only the test bridge was subjected to adverse ambient conditions. The performance of the 916-A was better than had been anticipated; however, several deficiencies were detected, e.g. (a) the method of specifying the bridge accuracy, (b) the method of identifying transformers and indicating which one is in the circuit, (c) the lack of a tool necessary to change transformers, and (d) an incomplete instruction book. The correction of these deficiencies and the inclusion of certain desirable modifications such as (a) only one transformer to cover the entire frequency range, or internal switching if more than one transformer is required, (b) an improved drive ratio and stops for the initial balance controls, (c) an increased drive ratio and a longer scale for the reactance control, (d) the removal of the resistor from the plug of the unknown connecting lead and its insertion in the bridge proper, (e) the reduction of size and weight to a practical minimum, and (f) the use of a metal case along with appropriate circuit ruggedization, should result in an instrument satisfactory for military use.

PROBLEM STATUS

This is a final report on the problem. Unless otherwise notified by the bureau, the Laboratory will consider the problem closed thirty days from the mailing date of this report.

AUTHORIZATION

NRL Problem R10-70
BuShips Problem S1547 and NE 101-116

Manuscript submitted September 4, 1953

R-F IMPEDANCE BRIDGES FOR MILITARY USE

INTRODUCTION

A definite need for commercially available r-f impedance-measuring devices has been established for the study, installation, and maintenance of Navy electronic equipment which involves the use of antennas, transmission lines, and high-frequency components. Although the inherent inadequacies of many such commercial equipments under military conditions are recognized, these instruments are now in use because corresponding military equipment is not available. A broad survey of all pertinent factors and specific investigations of the effects of temperature, altitude, humidity, and shock and vibration on one (commercially available) r-f bridge was requested by the Bureau of Ships.[1] The vast scope of this problem necessitates a rather complete discussion of all background material related to the use of r-f bridges in the laboratory as well as in the field. Since the ultimate intent of any impedance-measuring instrument and/or technique is the achievement of accurate measurements in the shortest possible time, a general criticism of bridge methods cannot be avoided. Bridges do not occupy a unique position in the r-f impedance-measurement field and are acceptable for military use only insofar as they compare favorably with such measurement networks as twin-T or resonant circuits.

In this problem actual field measurements cannot be made and used as a basis for evaluating the effectiveness of the instruments to be studied. This situation exists as a result of time and fiscal limitations and because actual field tests would subject all auxiliary equipment and their interconnections to the same conditioning. Consequently, the difficulty of actually evaluating only the bridge unit would be increased. On the other hand, in the laboratory it is possible to study the bridge under simulated field conditions and at the same time to isolate the auxiliary equipment. In this regard, it is apparent that any basic laboratory techniques which are required will be adaptable to the study of many types of impedance-measuring instruments other than r-f bridges.

The specific problem objectives covered in this report are:

(a) The discussion of the readily determined features and limitations of several r-f impedance-measuring instruments (assuming their contemplated use under military conditions),

(b) The derivation of techniques for the study of r-f bridges in the laboratory so that any deleterious effects which arise from the bridge alone will be isolated,

(c) A study on the general characteristics and normal operation of the General Radio type 916-A r-f impedance bridge, and

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[1] BuShips ltr S67-(15)(837) Serial 837D-240, 4 May 1950

(d) A study on the effects of temperature, humidity, altitude, and shock and vibration upon the General Radio type 916-A r-f impedance bridge.

A rather complete dissertation on factors affecting precise r-f impedance measurements under military conditions has been given by Connor[2] for frequencies up to VHF.

BRIEF EVALUATION OF PACKAGED INSTRUMENTS

Navy Model OH-1 Bridge

In this study, the model OH-1 (General Radio type 516-A)[3] is of particular interest because it represents an attempt to package an r-f impedance-measuring instrument for use in the Naval services. Figure 1 shows this equipment together with a heterodyne receiver and a signal generator set up for laboratory measurements and connected in a manner designed to assure shielded connections and an adequate ground plane. The bridge unit is housed in a metal cabinet (lid not shown in Figure 1) which has a covered opening in the front panel to facilitate the changing of internal bridge transformers. Two transformers are provided to cover the frequency ranges of 25 to 500 kc and 500 to 5000 kc. In addition, three pairs of ratio-arm resistors are provided to give maximum bridge sensitivity over the entire frequency range. These elements are also connected into the bridge through the opening in the front panel.

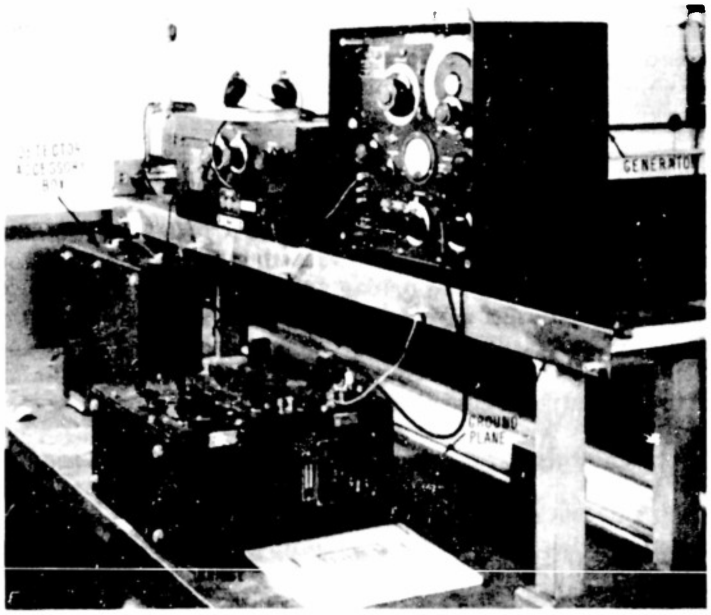

Figure 1 - Navy model OH-1 impedance-measuring equipment

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[2] Connor, J. A., "Factors Affecting Precise R-F Impedance Measurements Under Military Conditions," NRL Memorandum Report 223, October 1953

[3] Worthen, C. E., "Improvements in Radio-Frequency Bridge Methods for Measuring Antennas and Other Impedances," Gen. Radio Exp., 8 (No. 7), December 1933

The OH-1 bridge, a basic circuit of which is seen in Figure 2, can be used as an equal-arm capacitance bridge and thus provides direct measurements of an unknown impedance (Z_X) in terms of equivalent-series resistance (R_N) and equivalent-series capacitance (C_N). This circuit can also be made to measure the unknown in terms of equivalent-series capacitance and power factor* or dissipation factor. Such measurements are accomplished by setting R_N to zero, and adjusting C_A to obtain resistive balance, and C_N to obtain reactive balance. Capacitor C_N indicates directly the series capacitance of the unknown for either the equal-arm or Schering bridge techniques. Resistor R_N is calibrated to read equivalent-series resistance directly at all frequencies throughout the measurement range. Capacitor C_A, however, is calibrated to read power factor directly at 1 Mc with the 100-ohm ratio arms in place, at 100 kc with the 1000-ohm ratio arms, and at 10 kc with the 10,000-ohm ratio arms. For other frequencies, the power factor must be multiplied by the frequency in megacycles. This complication makes the bridge more flexible but also somewhat more difficult to use. The instrument is essentially a direct-reading bridge but can be used with many substitution techniques, both series and parallel.

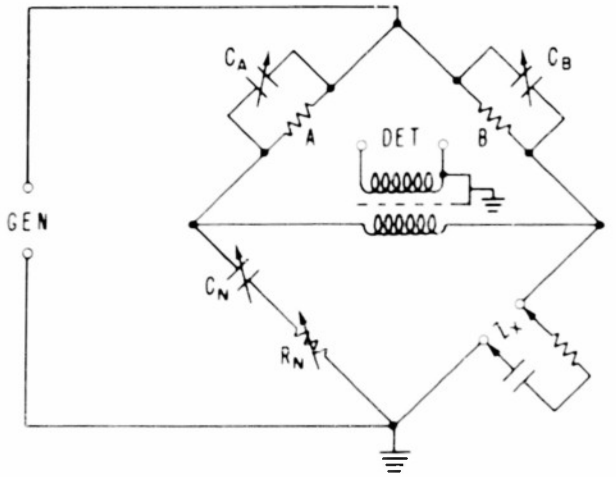

Figure 2 - Basic circuit of OH-1 bridge

It is believed that the flexibility and sound design used in the OH-1 bridge makes it an instrument with considerable utility even to the present date. The convenient method provided for changing internal bridge elements is particularly advantageous. The steel case implies ruggedness far beyond the degree of abuse to which the internal bridge elements should be subjected and thus gives a false confidence as to the over-all ruggedness of the equipment. For measurements up to 1.5 Mc, the OH-1 bridge (General Radio type 516-A) has many current uses; however, as the upper limit of 5 Mc is approached, the limitations of residual parameters, the direct-measurement techniques, and the bridge-transformer design introduce errors greater than are normally acceptable.

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* Power factor (cosine of the phase angle) is nearly equal to dissipation factor (cotangent of the phase angle) over the useful range of this bridge.

General Radio Type 916-A R-F Bridge

The general physical characteristics of the 916-A bridge and an arrangement for using it in the laboratory with the necessary generator, detector, and test-specimen connection is shown in Figure 3. A good ground plane is essential to the proper utilization of this instrument particularly at frequencies approaching the upper limit of 60 Mc. Since one of its principal applications is in the measurement of antenna characteristics it is obvious that this instrument is designed for field use. In this regard, it makes a good example for careful study in this survey.

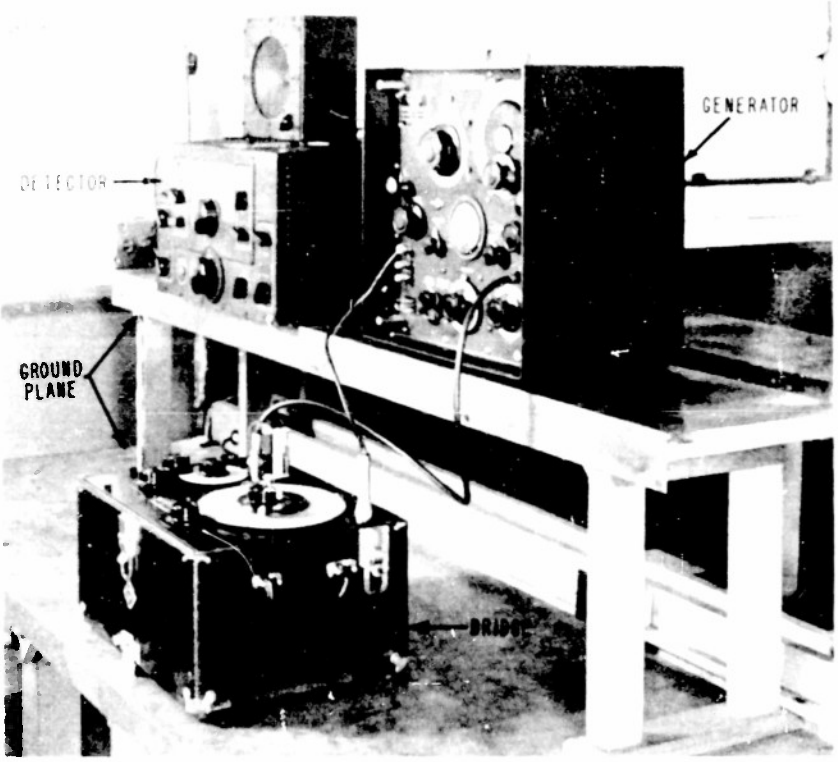

Figure 3 - General Radio type 916-A r-f bridge

General Radio Type 916-AL R-F Bridge

The General Radio type 916-AL r-f bridge, a new instrument designed to make measurements below the lower limit of the 916-A bridge (0.4 Mc), is capable of accurate measurements down to 50 kc. Measurements with this instrument can be made at frequencies up to 5 Mc using procedures nearly identical to those required by the 916-A bridge. The main difference between these instruments lies in their frequency ranges and the fact that an expanded reactance range (extra dial) is used in the 916-AL bridge. Figure 4 shows the front panel of a 916-AL bridge which has been subjected to severe field-service conditions for many months. The general dial calibrations ranging from 0 to 1000-ohms resistance and 0 to 11,000-ohms reactance are augmented by means of a ΔX dial which provides a change of 100 ohms of reactance. This instrument is included in the present survey because

Radio twin-T circuit[4] (Figure 6) are given by

$$G_L - R\omega^2 C_1 C_2 \left(1 + \frac{C_G}{C_3}\right) = 0$$

and

$$C_B + C_1 C_2 \left(\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}\right) - \frac{1}{\omega^2 L} = 0.$$

If a substitution technique is employed when an unknown is connected across C_B, the admittance constituents of this unknown can be determined in terms of C_G, C_1, C_2, and R. Thus

$$G_X = \frac{R\omega^2 C_1 C_2}{C_3} \Delta C_G$$

and

$$B_X = \omega \Delta C_B.$$

Thus, the C_G and C_B dials can be directly calibrated in terms of G_X and B_X, respectively.

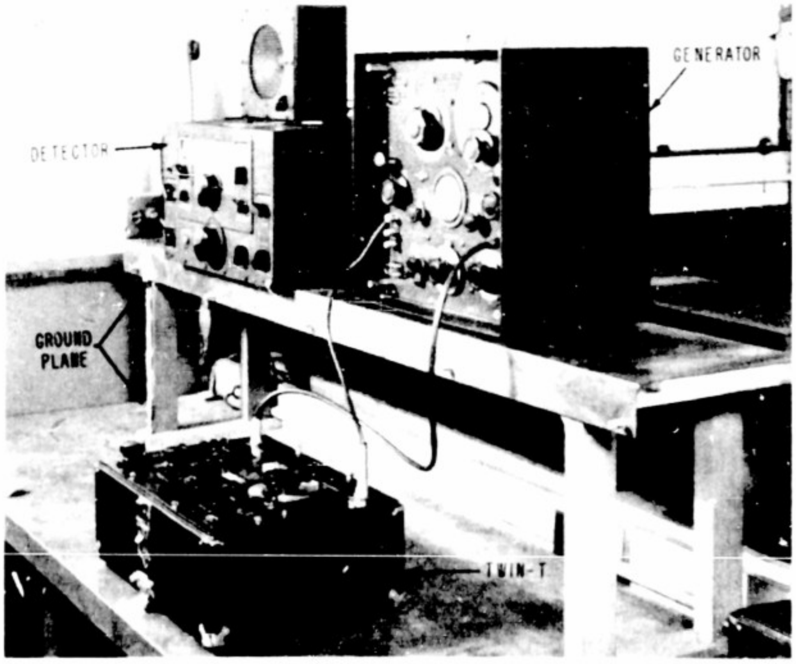

Figure 5 - General Radio type 821-A twin-T impedance-measuring circuit

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[4] Sinclair, D. B., "A New Null Instrument for Measuring High-Frequency Impedance," Gen. Radio Exp., 15 (No. 7), January 1941

The principal features of the type 821-A twin-T circuit are (a) the absence of internal shielded transformers, (b) measurement of an unknown in terms of admittance components (parallel-substitution), and (c) ability to measure low values of equivalent shunt conductance. The direct-reading conductance range at 1 Mc is from 0 (open circuit) to 100 micromhos. The measurement precision of this instrument is an additional matter for further study when the use of the unit in the field is contemplated eventually.

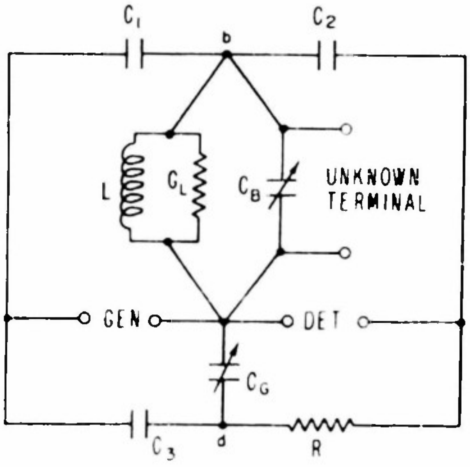
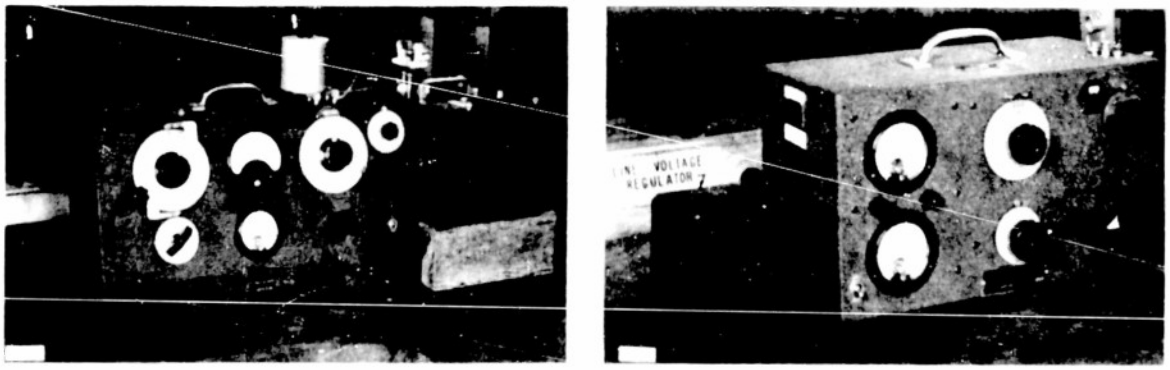


Figure 6 - Basic twin-T circuit

Boonton Types 160-A and 170-A Q-Meters

The Boonton Q-meters (Figure 7a and 7b) are extremely flexible self-contained instruments capable of making a wide variety of r-f impedance measurements. Although these instruments were not designed for rugged field use, their versatility makes them a significant factor in this survey. The electrical circuitry of the measuring network for each instrument is essentially that of Figure 8. The basis for impedance measurements made with these instruments can be established by studying the network analysis associated with a series-resonant combination of inductor and capacitor driven by a constant voltage source. The Q-meter principles have no inherent limitations, i.e., when parallel-substitution ranges expire, series-substitution methods are applicable. However, the frequency range of the included generator, the sensitivity of the vacuum tube voltmeter, and the internal residual parameters do impose definite measurement limitations. Since this survey is intended to explore the feasibility of field measurements, it is appropriate to recognize the extreme versatility of the Q-meter technique and to suggest future development of such devices for this purpose.



(a) Type 160-A

(b) Type 170-A

Figure 7 - Boonton Q-meters

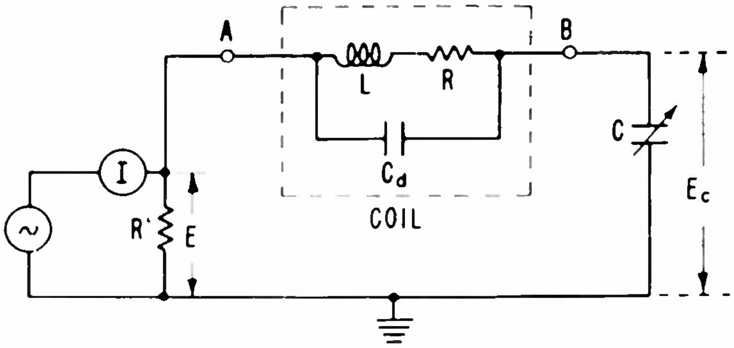


Figure 8 - Fundamental circuit of Q-meter

General Radio Type 1601-A VHF Bridge

This survey cannot be considered complete without a brief mention of some representative vhf impedance-measuring instruments. Figure 9 shows the General Radio type 1601-A vhf bridge and a possible combination of auxiliary equipment which includes the Hewlett-Packard model 608-A signal generator and the Hewlett-Packard model 417-A vhf detector. The 1601-A, an instrument designed to measure r-f impedances between 10 and 165 Mc, uses a series-substitution bridge circuit similar to the one employed in the 916-A r-f bridge.[5] The resistance range (0 to 200 ohms) is independent of frequency whereas the reactance range (0 to ±230 ohms at 100 Mc) is direct-reading only at 100 Mc. For measurements at frequencies other than 100 Mc, the reactance reading is divided by the frequency in hundreds of megacycles. The instrument has one fixed internal bridge transformer. Special care must be exercised in shorting the unknown terminals for establishing initial-balance conditions. This instrument, which does not have a completely enclosed case, was designed primarily for use on the laboratory bench, and special care must be exercised when it is carried into the field.

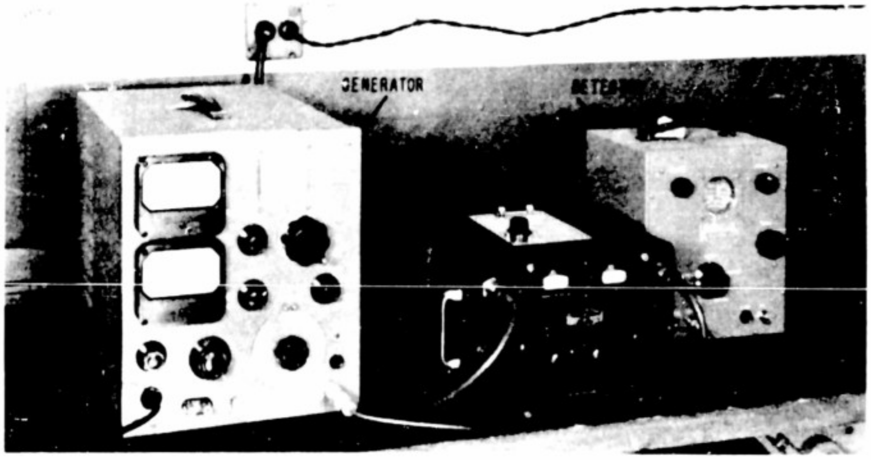


Figure 9 - General Radio type 1601-A VHF bridge

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[5] Soderman, R. A., "A New Bridge for the Measurement of Impedances Between 10 and 165 Mc," Gen. Radio Exp., 24 (No. 9), February 1950

Hewlett-Packard Model 803-A VHF Bridge

The instruments mentioned so far have all used either conventional bridge circuits or resonant circuits. At very high frequencies, a departure from these classical methods has been introduced in the form of a "slotted-line" bridge. The Hewlett-Packard model 803-A vhf bridge, which is shown in Figure 10 with its auxiliary generator and detector, does not use the same method of operation as employed in conventional slotted-line procedures.[6] The measured characteristics of the unknown impedance are not presented in terms of resistance and reactance (or conductance and susceptance) as in a true bridge but, instead, are introduced in terms of absolute impedance and a phase angle. Thus, the technique is related somewhat to the voltmeter-ammeter-wattmeter method for measuring impedances at audio frequencies. The way in which this instrument is packaged makes it easily adapted to field operations. From a brief study of this bridge and its auxiliary equipment, it is apparent that the latter could easily be the weakest element when the equipment is used under rigorous field conditions. This instrument is a currently available device for the measurement of r-f impedances over a frequency range of 50 to 500 Mc (phase angles from -90° to + 90°); it can be extended to 5 and 700 Mc with restricted range of phase angle. The useful impedance range covers from 2 to 2000 ohms. The ranges available make this instrument useful in solving many laboratory and field measurement problems.

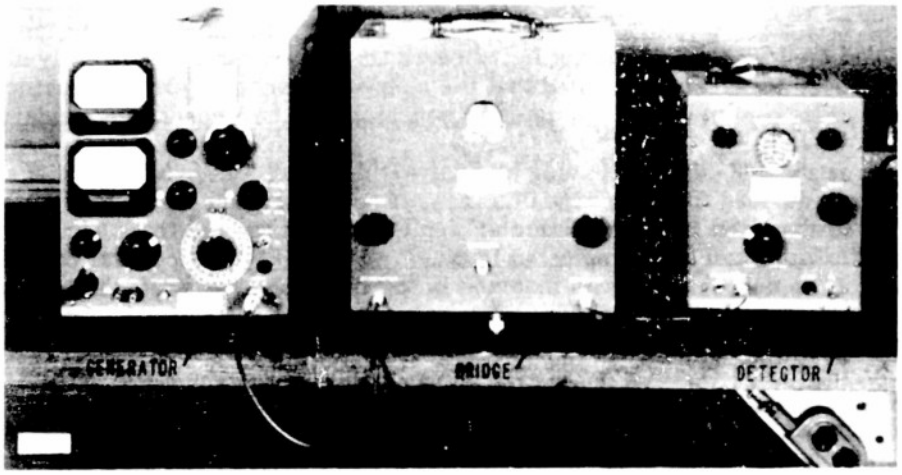

Figure 10 - Hewlett-Packard Type 803-A VHF Bridge

A TECHNIQUE TO EVALUATE ENVIRONMENTAL EFFECTS ON AN R-F BRIDGE

General Considerations

The laboratory determination of temperature and humidity effects on equipment usually involves the use of a test chamber in which the equipment is exposed to controlled conditions. In establishing the operating characteristics of the equipment, one primary factor requires special consideration, i.e., the means of electrically connecting the equipment under test to reference standards or measuring instruments which are being used to monitor the test

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[6] Staff, Radio Research Laboratory, Harvard University, "Very High-Frequency Techniques," Vol. 1, pp. 26-52, New York: McGraw-Hill, 1947

unit. There are two general approaches to this problem. First, the monitoring units can be placed directly in the chamber with the unit under test. Generally, this approach is not practical because either the monitoring equipment is too large to fit into the remaining chamber space or, more important still, the measurements made by the monitoring equipment would contain unknown errors resulting from the effects of the test-chamber conditions. A second method of determining the operating characteristics is to leave the monitoring units outside the test chamber and transfer the quantity to be monitored. In using this second procedure, quantities such as frequency, voltage, etc., can be readily transferred with little or no effect on their magnitude. On the other hand, certain quantities cannot be transferred without appreciable effect on their magnitude unless special means are provided to accomplish the transfer. One item in this latter category is r-f impedance, the specific case at hand.

A Particular Solution

The specific problem was to determine the effects of temperature and humidity on the General Radio type 916-A r-f impedance bridge without including any effects on the impedance being measured or the associated auxiliary connections. An attempt to obtain standard impedances that would be independent of the adverse test-chamber conditions was considered impractical. Thus, the only approach left was to find a special means of connecting the impedance standard (on the outside of the chamber) through the wall to the bridge (on the inside). To be sure that any change in indicated impedance could be directly attributed to the bridge under test, it was decided that the connection scheme should provide for direct monitoring of its own stability and also the constancy of the impedance standard.

A symmetrical T-network having an equivalent circuit essentially as diagrammed in Figure 11 was devised to implement this measurement. Figure 12, a view of the actual network as constructed for this particular application, shows the front and bottom sides and a transfer standard (Z_X) connected in place. The right-hand coaxial portion of the T is the part of the network that was inserted in the test-chamber wall; the left-hand portion was made identical merely to maintain network symmetry. Figure 13 is a close-up view of the back and top with the cover plate removed to show the switch (S_C) and its symmetrical layout. In Figure 11, Z_1, Z_2, Z_1', and Z_2' all represent the impedance-to-ground of the feed-through insulators in the coaxial portion of the network. Here L and L' represent the series inductance of the center coaxial conductor, which has a diameter of 3/16 inch. This conductor, along with the 1/8-inch-wall outer conductor, represents a good thermal transfer medium through the test-chamber wall. Thus, at low test temperatures, water condensation on the surface of the insulator (represented by impedance Z_2') could easily develop and directly upset the impedance balance of the network. To prevent this condition, a blower was used to create an air stream over the surface of the insulator.

As a result of careful design and construction, Z_2 equals Z_2' and L equals L'; however, Z_1 does not equal Z_1' because of the slightly different ground-strap configuration which consequently contributes different amounts of shunt capacitance to Z_1 and Z_1'. This small inequality can be eliminated easily in the normal procedure of measurement which is as follows:

(a) With S_A and S_B grounded (Figure 11), use the impedance-measuring instrument (a Q-meter in this particular problem) to determine impedance equality of the two arms of the T when switch S_C is in positions 2 and 4, respectively. (In this specific application, the adjustment of Z_1 equal to Z_1', i.e., equalizing the impedances of the two arms of the T, is accomplished by adjusting a small strip of copper attached to the ground strap of bridge A. The position of the strip relative to the high potential conductor provides a small variation in the shunt capacitance of Z_1).

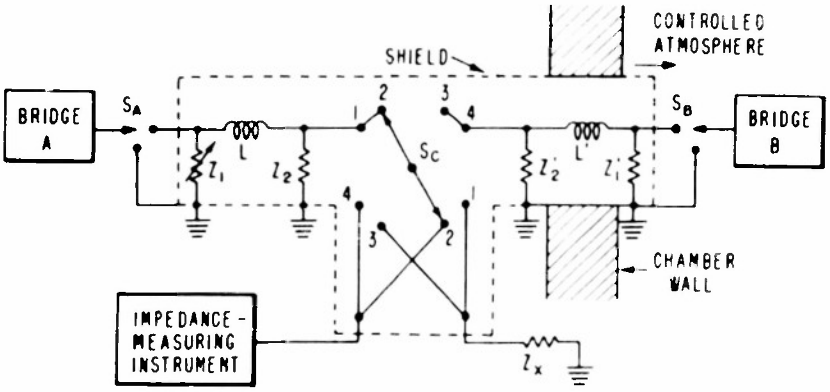

Figure 11 - Equivalent circuit of symmetrical T-network

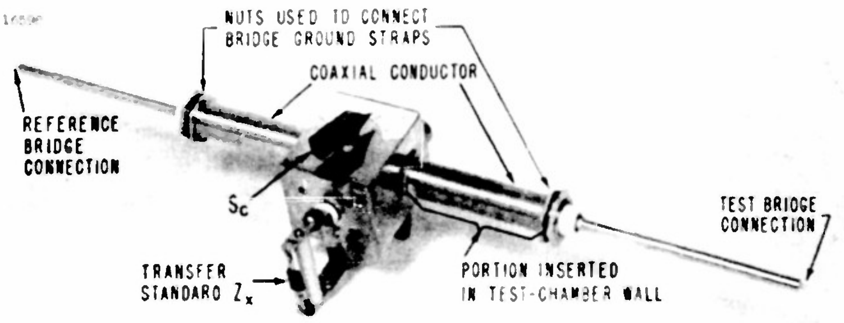

Figure 12 - Front and bottom view of symmetrical T-network

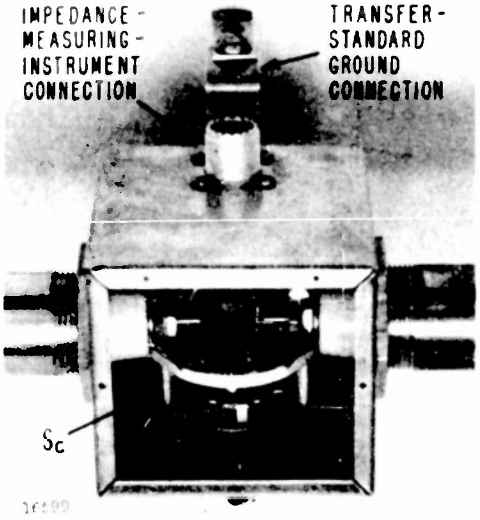

Figure 13 - Back and top view of symmetrical T-network with cover removed

(b) Change S_A and S_B in order to connect the bridges to the T-network. Then measure the transfer impedance Z_C with each bridge when S_C is in positions 1 and 3, respectively.

Thus, the circuit provides for ready checking of its arm stability as well as the stability of the transfer standard at any time during the test program.

Figure 14, an outside view of the test chamber, shows the blower and the network installed and connected to the reference bridge A. Figure 15, a close-up view inside the test chamber, shows the connection of the test bridge to the T-network.

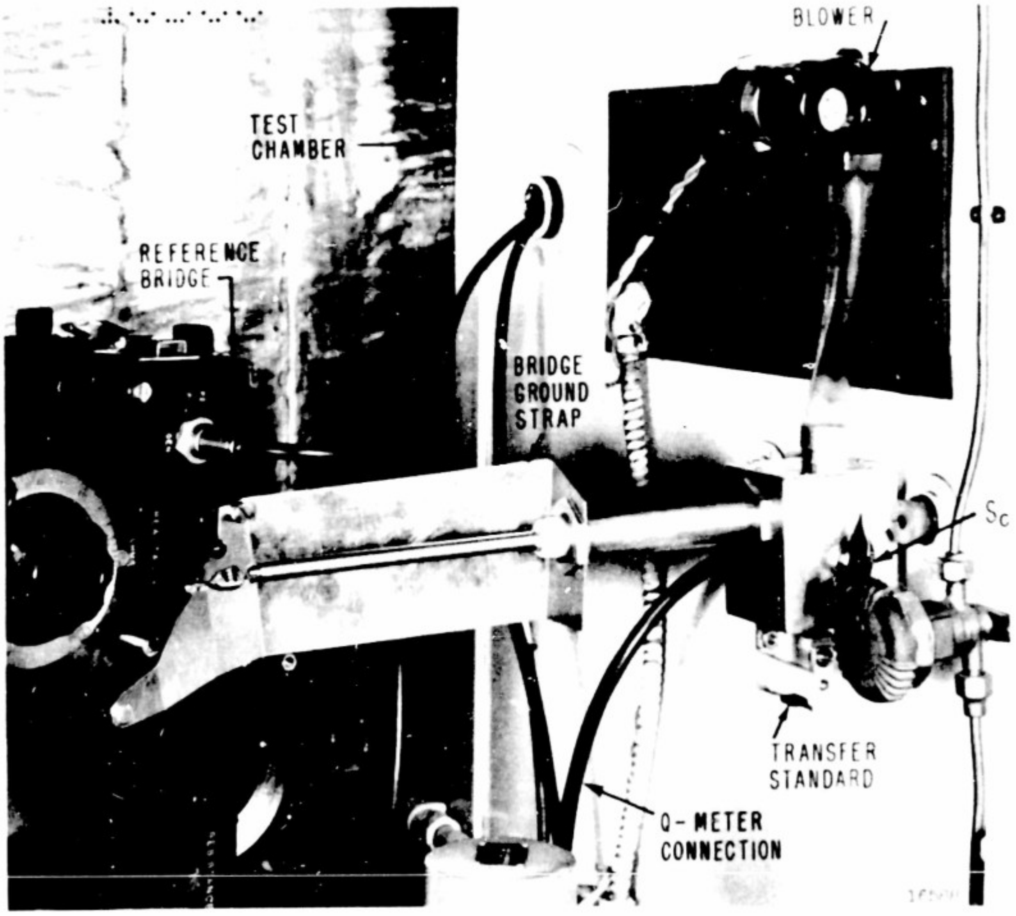

Figure 14 - Outside view of test chamber showing symmetrical T-network installed in chamber wall and connected to reference bridge

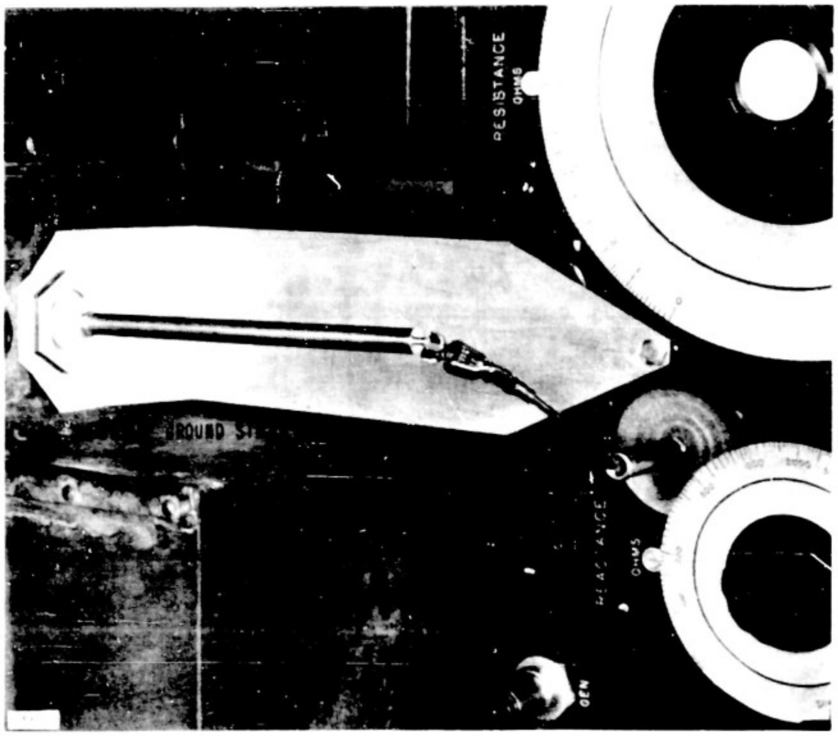

Figure 15 - Inside view of test chamber showing connection of test bridge to symmetrical T-network

GENERAL RADIO TYPE 916-A R-F BRIDGE

Description

The 916-A r-f bridge[7,8] is a null instrument for measuring impedances in the nominal frequency range of 400 kc to 60 Mc. By series substitution, the bridge measures an unknown impedance, Z_X, in terms of its series-resistance component, R_X, and its series-reactance component, X_X. The resistive component is read from a variable-capacitor dial directly calibrated in ohms resistance (0-1000); this calibration is independent of frequency. The reactive component is also read from a variable-capacitor dial which is calibrated directly in ohms reactance (0-5000); this calibration, however, is direct-reading only at 1 Mc. The ratio of actual impedance to indicated impedance (dial reading) decreases linearly with frequency, and therefore, reactance dial readings are divided by the operating frequency in megacycles.

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[7] General Radio Company, Catalog M, pp. 80-81, October 1951

[8] General Radio Company, Form 567-J, "Operating and Maintenance Instructions for Type 916-A Radio-Frequency Bridge"

Basic Theory

Using the 916-A, the fundamental circuit of which is shown in Figure 16, an unknown is measured by first balancing the bridge with the UNKNOWN terminals short-circuited; then the short circuit is replaced by the unknown impedance and the bridge is rebalanced. When the UNKNOWN terminals are short-circuited, the bridge-balance equations are

$$R_P = R_B \frac{C_{A_1}}{C_N} \tag{1}$$

and

$$\frac{1}{j\omega C_{P_1}} = \frac{R_B}{R_A} \frac{1}{j\omega C_N}. \tag{2}$$

When the short circuit is replaced by the unknown impedance $Z_X = R_X + jX_X$, the balance equations become

$$R_P + R_X = R_B \frac{C_{A_2}}{C_N} \tag{1a}$$

and

$$jX_X + \frac{1}{j\omega C_{P_2}} = \frac{R_B}{R_A} \frac{1}{j\omega C_N}. \tag{2a}$$

Thus, the unknown resistance, R_X, and unknown reactance, X_X, can be expressed in terms of the bridge parameters as follows:

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

and

$$X_X = \frac{1}{\omega} \left(\frac{1}{C_{P_2}} - \frac{1}{C_{P_1}} \right). \tag{2b}$$

From these expressions it can be seen that R_X is proportional to the change in the capacitance C_A, and the proportionality factor is determined by the fixed resistance R_B and the fixed capacitance C_N. Similarly, X_X is a function of the frequency and the change in the reactance of C_P.

Specified Range and Accuracy

Specified range and accuracy of the type 916-A bridge[6,7] is as follows:

"FREQUENCY RANGE: 400 kc to 60 Mc.

REACTANCE RANGE: 0-5000 ohms 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-ohms.

ACCURACY: For reactance, at frequencies up to 50 Mc, ±(2% + 1Ω + 0.0008Rf), where R is the measured resistance in ohms and f is the frequency in Mc.

For resistance, at frequencies up to 50 Mc, ±(1% + 0.1Ω), subject to correction for residual parameters. At high frequencies the correction depends upon the frequency and 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 of 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."

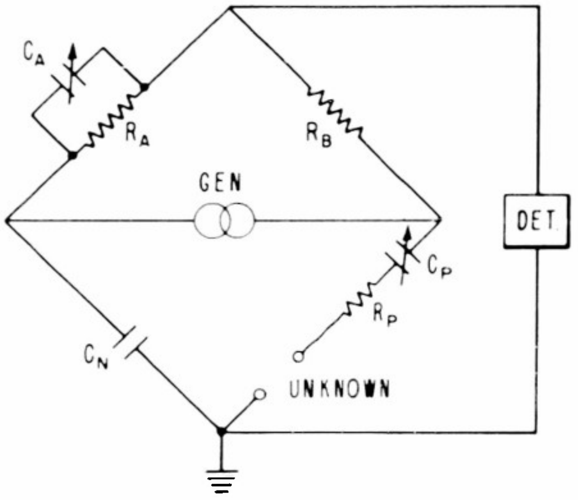

Figure 16 - Fundamental circuit of General Radio Type 916-A r-f bridge

A general tabulation of characteristics for all General Radio bridges[7] indicates that the approximate accuracies for the 916-A are two percent for reactance and one percent for resistance.

The reactance specification (±2% + 1Ω + 0.0008Rf) is not explicitly stated because the third term does not carry any indicated unit. The inference, however, is that the unit is ohms and that "f" is used as a numerical value without units. This third term can thus be added directly to the second term (1Ω). A clearer understanding of this specification can be obtained by presenting it in graphical form. In Figure 17, measurement error in percent has been plotted against unknown reactance for various values of frequency and unknown resistance. It is immediately apparent that the measurement error is variable and has a two-percent minimum.

Bridge Design and Operating Procedures

Specific operating details and certain features of the bridge can be analyzed without making measurements or without subjecting the bridge to any conditioning processes. The instrument in its luggage-style carrying case is shown in Figure 18 with the cover in place. Figure 19, a view of the inside of the cover, shows the stowage of the instruction book and accessory cables supplied with the bridge. The front panel and all the bridge controls are shown in Figure 20.

The front panel of any test or measurement instrument should be marked and labeled in such a manner that the operation is as self-explanatory as possible. The markings certainly should not leave the operator in doubt or lead to any misunderstanding of the intended operation. It is felt that the 916-A bridge is deficient in this respect.

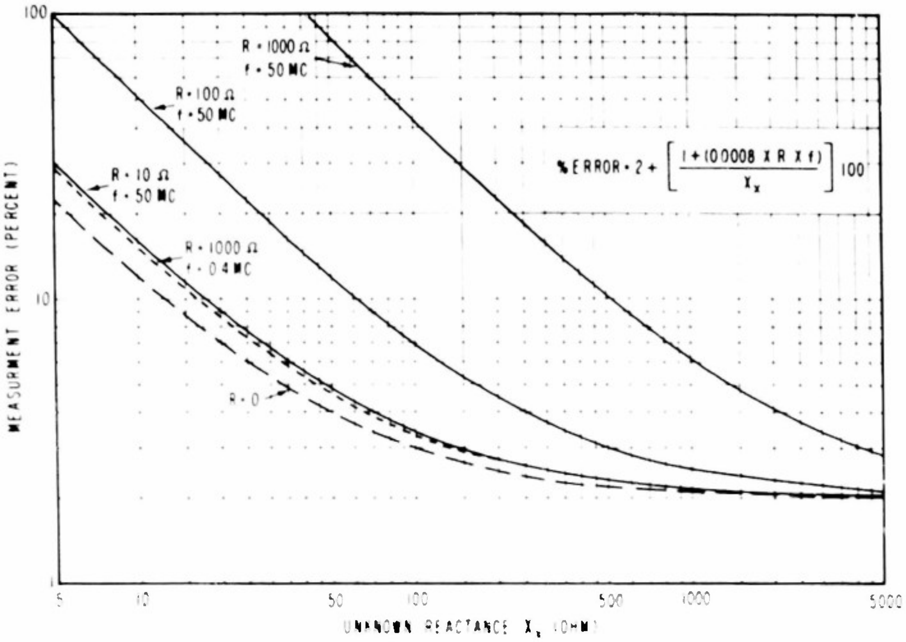

Figure 17 - Specified accuracy for General Radio Type 916-A r-f bridge

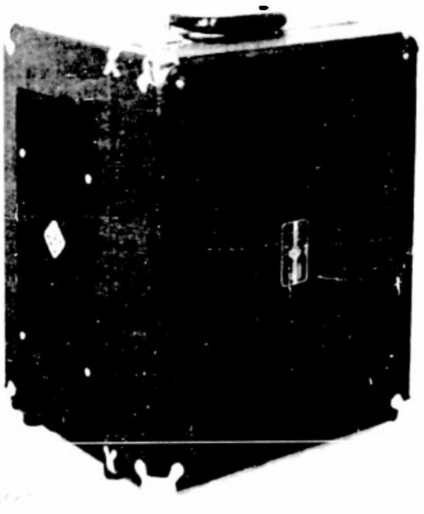

Figure 18 - Luggage-style carrying case of the General Radio Type 916-A r-f impedance bridge with the cover in place

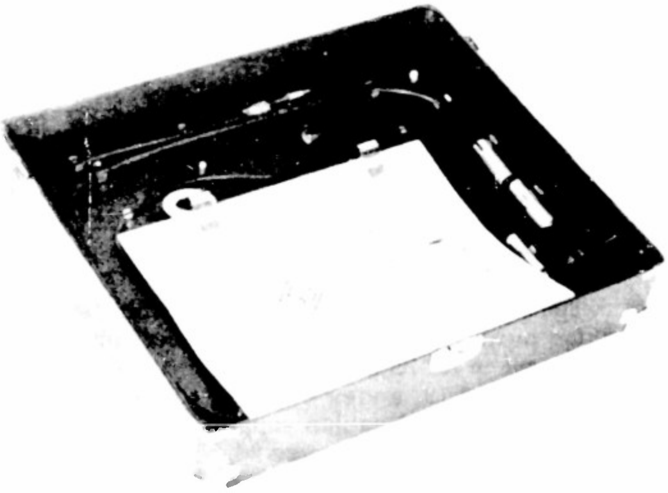

Figure 19 - Inside view of cover showing instruction book and accessory cables

Figure 20 - Front panel of General Radio Type 916-A r-f impedance bridge

Auxiliary Equipment - In addition to the bridge itself, a generator and a detector are necessary to complete the measurement setup. The generator should be a well-shielded oscillator capable of producing an output voltage on the order of 1 to 10 volts. The detector should be a well-shielded receiver having a sensitivity on the order of 1 to 10 microvolts. To facilitate the adjustment of the bridge to a null, the receiver should have an r-f sensitivity control and should also be equipped to cut out the automatic gain control. A typical laboratory setup is shown in Figure 3.

Preliminary Adjustments - The subjects of grounding and stray pickup appear to be adequately presented in the operating and maintenance instructions.[8] Deviations from the prescribed procedures should not be made unless the operator is well-versed in r-f circuits and bridge theory.

The bridge uses transformer input. To cover the specified frequency range, two transformers are employed: one for 400 kc to 3 Mc and the other for 3 to 60 Mc. These transformers employ an interwinding shield and are specially designed for this bridge application. They are individually adjusted so as to introduce negligible measurement error over their designed frequency range. Only one transformer is mounted to the front panel and connected into the circuit at any one time. The other transformer is carried on the inside of the access panel which must be opened to change transformers (Figure 21). Even though the unused transformer is not directly connected, it must be properly mounted to the access panel because it is indirectly a part of the circuit since it contributes to the bridge capacitance C_N.

Several aspects of the method used to incorporate the transformers are among the bridge deficiencies. First of all, it would be far better to have both transformers permanently installed so that only a switch would have to be operated in order to change from one transformer to the other. This method would eliminate the necessity for opening the bridge case, and as a result, a possible source of damage to the bridge elements would be removed. The case could be more effectively sealed against dirt and other foreign particles – an important consideration when this type of instrument is intended for field use. Also, the transformers themselves would not be subjected to repeated handling, and thus the possibility of damage, maladjustment, or improper connection into the circuit would be practically nil. A second deficiency of the present design lies in the method of indicating which transformer is in the circuit. The transformers are designated P1 and P2, and each has an attached pin that shows through a similarly designated hole in the panel, thus indicating which transformer is in the circuit (Figure 20). There is no panel marking, however, to indicate the frequency range associated with P1 and P2. In addition, this information is not even available in the operating instructions and can be determined only by examining the transformers themselves or the parts list. Thus, since the operator must determine that the transformer covering the intended measurement frequency is connected into the circuit, he should be able to do so directly from the bridge panel markings. A third point that should be mentioned concerns the changing of transformers in the present model. To change a transformer, the panel nut of the "generator" connector must be unscrewed; the remainder of the connector is constructed as an integral portion of the transformer. Since the proper installation of a transformer requires the use of a wrench to loosen and tighten the panel nut, a tool for this purpose should be included with the accessories of the bridge.

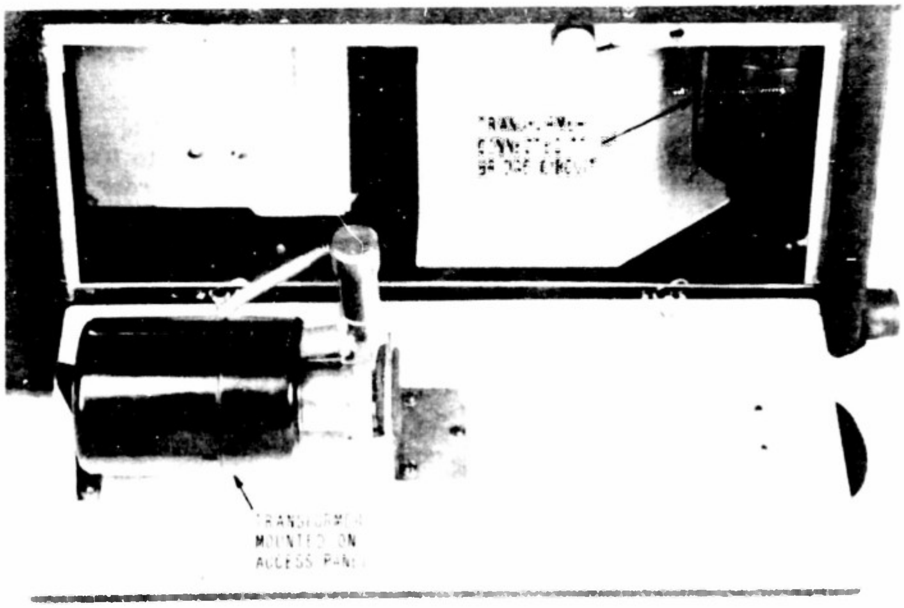

Figure 21 - Input transformers of the General Radio Type 916-A bridge

Measurement Techniques - After setting the L-C switch and the calibrated dials to their appropriate positions,* the basic measurement procedure then consists of connecting the "high" lead of the bridge to ground and making an initial balance. Then the high lead is connected to the high terminal of the grounded unknown, and the bridge is rebalanced by using the calibrated dials. The difference between the initial and final setting, corrected when necessary, gives the resistance and reactance of the unknown. The instruction book[8] together with the instrument panel markings adequately cover most detailed measurement procedures; some, however, that are insufficiently outlined are discussed in the following paragraphs along with other aspects of bridge operation.

The initial balance controls are a possible source of difficulty in operating the bridge. Neither the panel markings nor the instruction book properly indicate the situation that actually exists. From Figure 20 it will be observed that both initial balance controls have pointer knobs. From this arrangement, the operator gets the impression that the total variation of the parameter being adjusted will occur for an angle of rotation not exceeding 360°. Both of these controls are adjustable air capacitors. The resistance initial balance has a direct drive, and as a result, the total effective change occurs in 180°. The reactance initial balance, however, has a drive ratio (4-1/2 to 1) which results in spreading the total change over 810° of knob rotation. Thus, if the position of the reactance-initial-balance control is not close to the balance condition, it is possible for the operator to arrive at the erroneous conclusion that an initial balance cannot be obtained. Also, these controls do not have stops at their extremes of variation. This fact leads to ambiguity and possible measurement errors because the operator is left in doubt as to whether he is tuning to a true null or to an artificial null which exists at the minimum or maximum capacitance settings.

The initial balance, particularly at lower frequencies, can actually be made over a range of settings of the reactance dial.** The instruction book[8] indicates the nominal limits as follows:

L Position -------- 0-1000 ohms

C Position ----- 4000-5000 ohms.

The inductive reactance of the connecting lead is the main factor in determining the actual limits. Thus, as the frequency is increased, the limits move further up the reactance scale. There is a frequency above which an initial balance cannot be obtained at 0 in the L position, and, at a slightly higher frequency, for 5000 in C position. The frequency at which this condition occurs depends upon the length of the connecting lead. This change does not introduce any corresponding error in measurement because the inductive reactance cancels out in the series-substitution techniques. Such an effect reduces the reactance range of the bridge; it can be compensated, however, by placing a small capacitor in series with the connecting lead to neutralize the inductance.

Typical curves taken from the Instruction book[8] are shown in Figure 22a for the shift in initial balance vs. frequency associated with both the short and long connecting leads supplied with the bridge. Similar curves applicable to the short lead only are presented in Figures 22b, c, and d for the test bridge E and the comparison bridges F and G, respectively.

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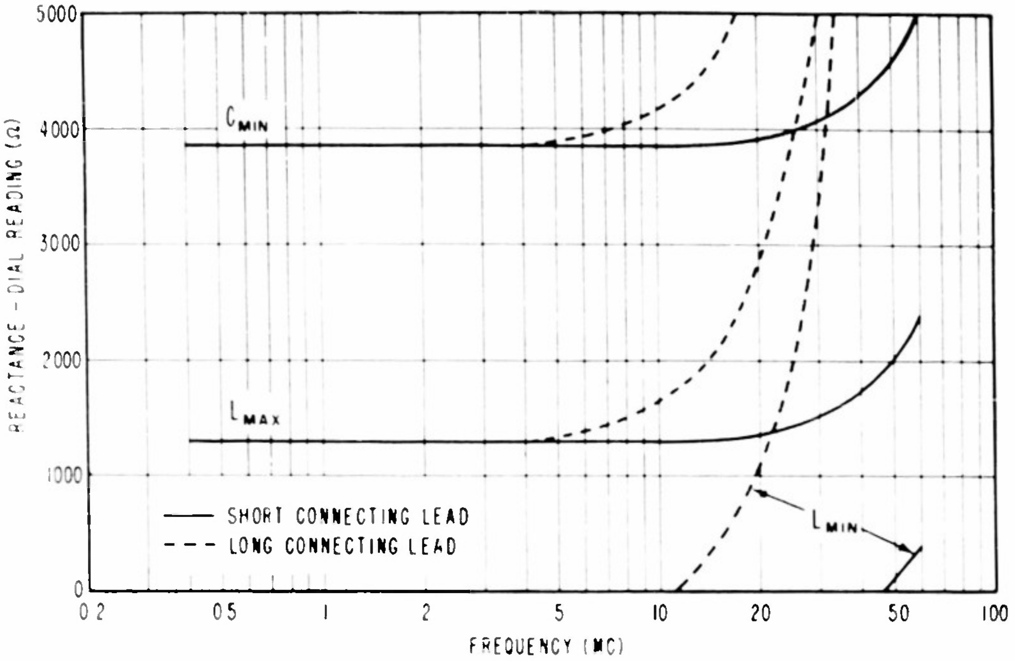
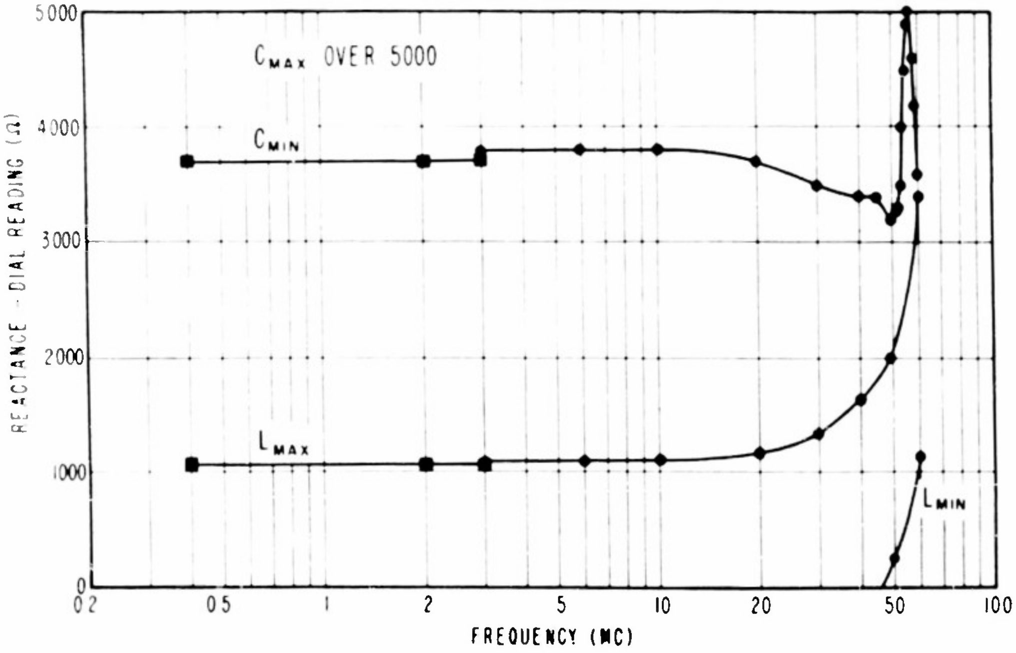
*The selection of appropriate settings is adequately discussed in the instruction book.

**As pointed out in the instruction book, this ability to establish an initial balance for various reactance dial settings is useful in making certain measurements.

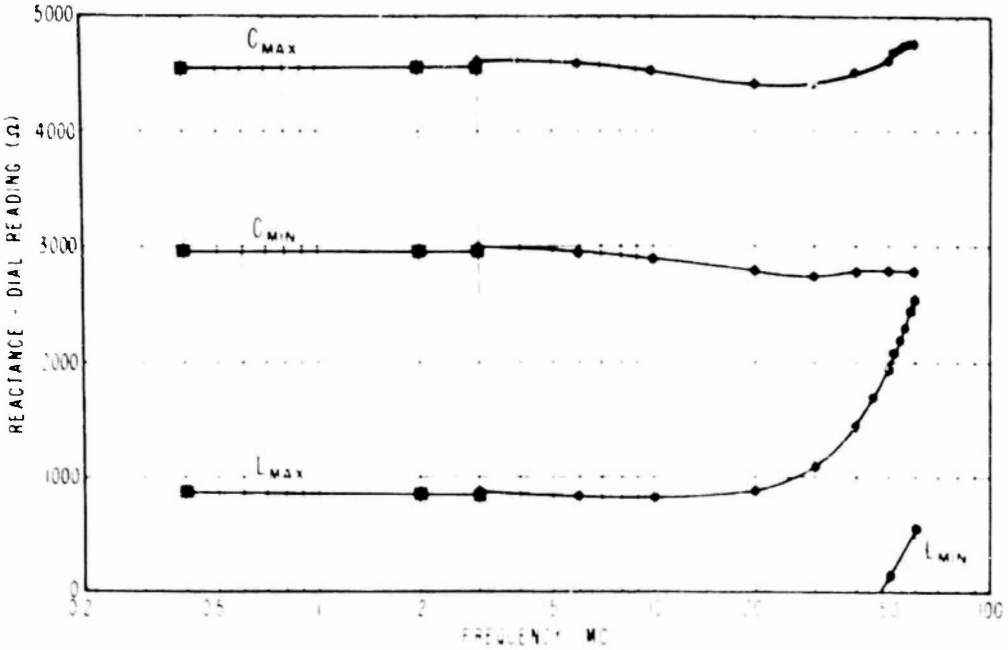


(a) NOMINAL LIMITS FROM INSTRUCTION BOOK

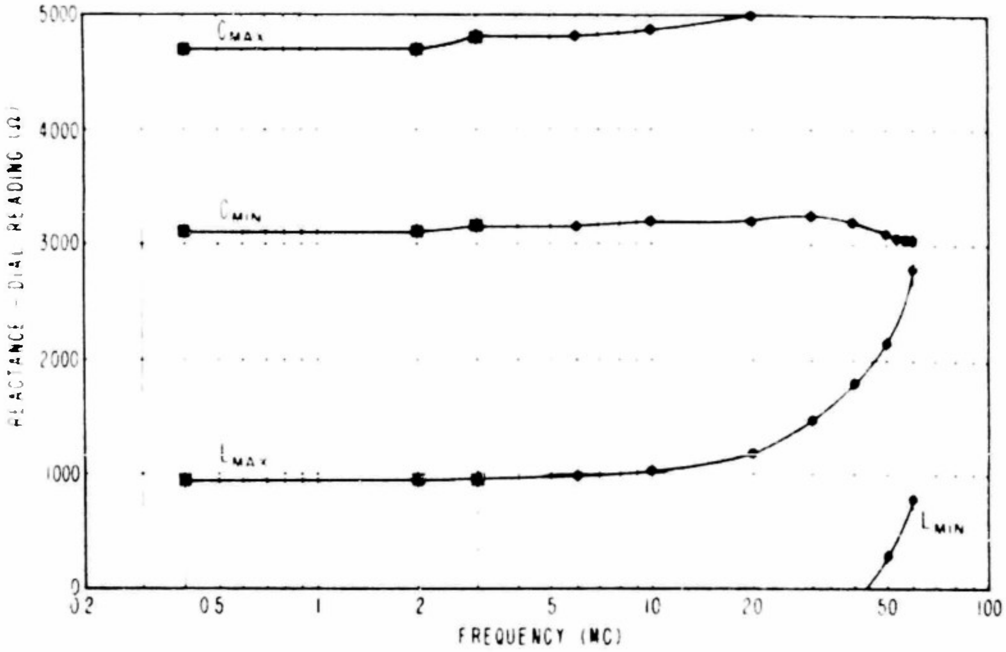


(b) ACTUAL LIMITS FOR BRIDGE E

Figure 22 (a and b) - Limits for initial setting of reactance dial



(c) ACTUAL LIMITS FOR BRIDGE F



(d) ACTUAL LIMITS FOR BRIDGE G

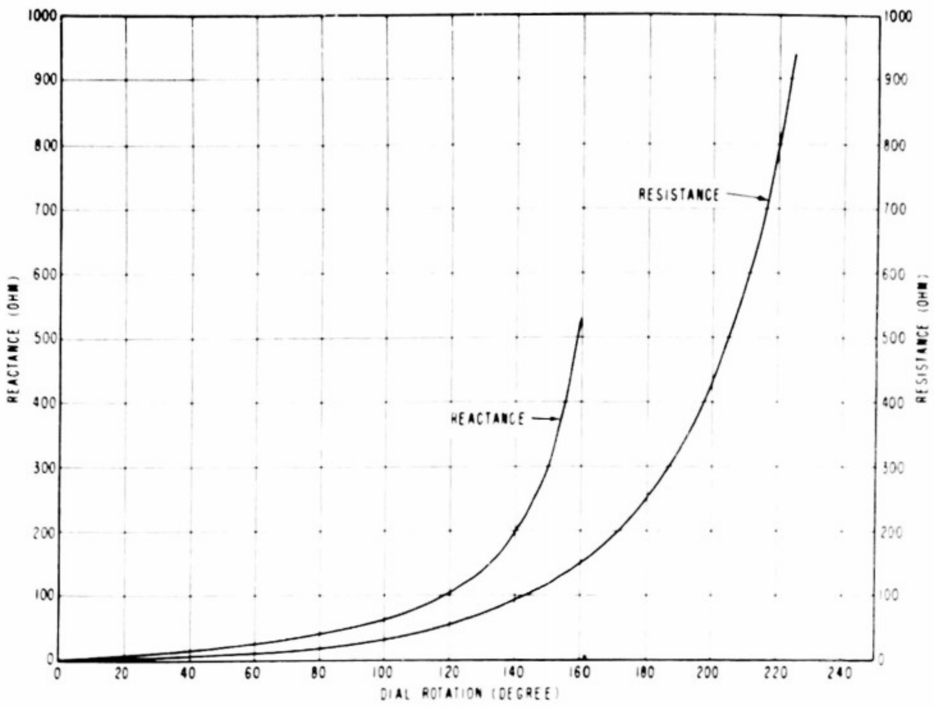
Figure 22 (c and d) - Limits for initial setting of reactance dial

A comparison of these figures shows that for the L position the curves of the three individual bridges correspond closely to the typical curve. The curves for the C position, however, show lack of similarity in several ways. For bridge E the curve of C_{min} corresponds at low frequencies, but instead of rising with increasing frequency it drops off and then increases sharply to a peak value and again drops off. The same curves for bridges F and G are nearly alike, but show relatively little change throughout the frequency range. The C_{max} setting, as specified, was found to be greater than 5000 for bridge E. For the comparison bridges, however, C_{max} (indicated by the appropriate curve) was less than 5000 over most of the frequency range. The result, a reduction in the maximum available range of C measurement, is believed attributable to changes in one or more bridge parameters caused by handling or long-time ageing.

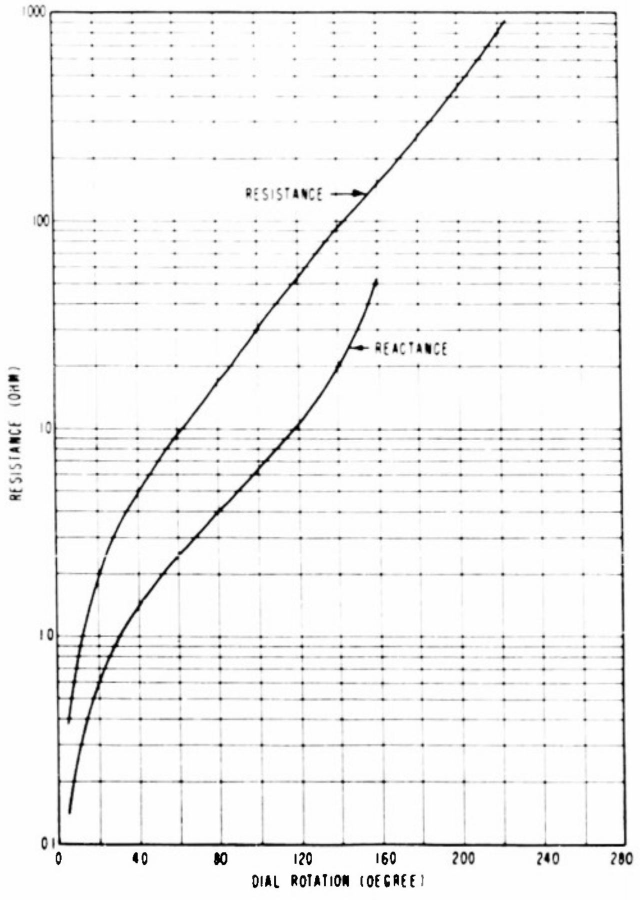
Interpretation of Observations - It is important to note that both the resistance and reactance scales, except for the low ends which approach linearity, are approximately logarithmic. These characteristics are depicted in graphic form in Figure 23a and 23b. The semilog plots clearly show the approximate logarithmic calibration of most of each dial. This characteristic is particularly significant because measurements are made on a substitution basis and involve the difference of two readings. As a result, the proper appraisal of the precision of any dial reading and the correct use of significant figures is most important in arriving at a justifiable value for the unknown impedance.

The first of these two readings represents the initial balance and in reality is not an abstract reading because the operator attempts to set the dials to definite values. Thus, it is significant to know how precisely this setting can be made. A special test was established to determine this and other similar factors. Special scales, calibrated in degrees and attached to the regular bridge dials, were used to determine the angular precision of the dial setting. The smallest scale division was 0.1 degree, and it was possible to estimate quarter units of this division or 0.025 degree. Six people made five attempts each to set the reactance dial to exactly 5000 ohms, and there was no significant difference in the results for each individual. The thirty settings are summarized in graphical form in Figure 24a. Therefore, except for one case out of thirty, it was possible to set the impedance dials within ±0.025 degree. From Figure 23a it is apparent that the slope of the reactance-dial calibration at 5000 ohms is about 260 ohms per degree and 0.025 degree is equivalent to approximately 6.5 ohms. Considering the single trial for which the error was 0.05 degree, it is possible to set the reactance dial to 5000 ohms with a precision of ±13 ohms. Similarly, the dial can be set to 0 with a precision of ±0.15 ohm. The most important factor contributing to variations in setting the dial to any calibrated value is the coarseness of the calibration and index lines.

The second dial reading obtained in the process of measuring an unknown impedance is from the final balance, and this reading is truly abstract because the position of the dial depends on the impedance being measured. A series of tests, undertaken by the same operators as before, were conducted to obtain an indication of how fine an interpolation could be made on the reactance dial. The largest single dial space, 1000 - 1100 ohms, was used in order to obtain the most favorable result. The test series was conducted to determine how closely the dial could be set to a value of 1050, 1025, and 1010 ohms. This test amounted to subdividing the dial division into 1/2, 1/4, and 1/10 units, respectively. Each operator performed each of the three tests six times, and an interval of at least two hours was maintained between tests in order to reduce any influence of one test upon another. The results are presented in Figure 24b, c, and d. In the 1050-ohm test, practically all settings were made to values actually higher than 1050 ohms instead of centering them around the correct value. This result occurred because all operators overemphasized a logarithmic subdivision, whereas the true subdivision of this log-scale interval is nearly linear. The maximum deviation from the true value is 0.35 degree of arc or about 9 ohms, and consequently there should be no difficulty in estimating half divisions.



(a) LINEAR PLOT



(b) SEMILOG PLOT

Figure 23 - Resistance and reactance dial indications vs. dial rotation

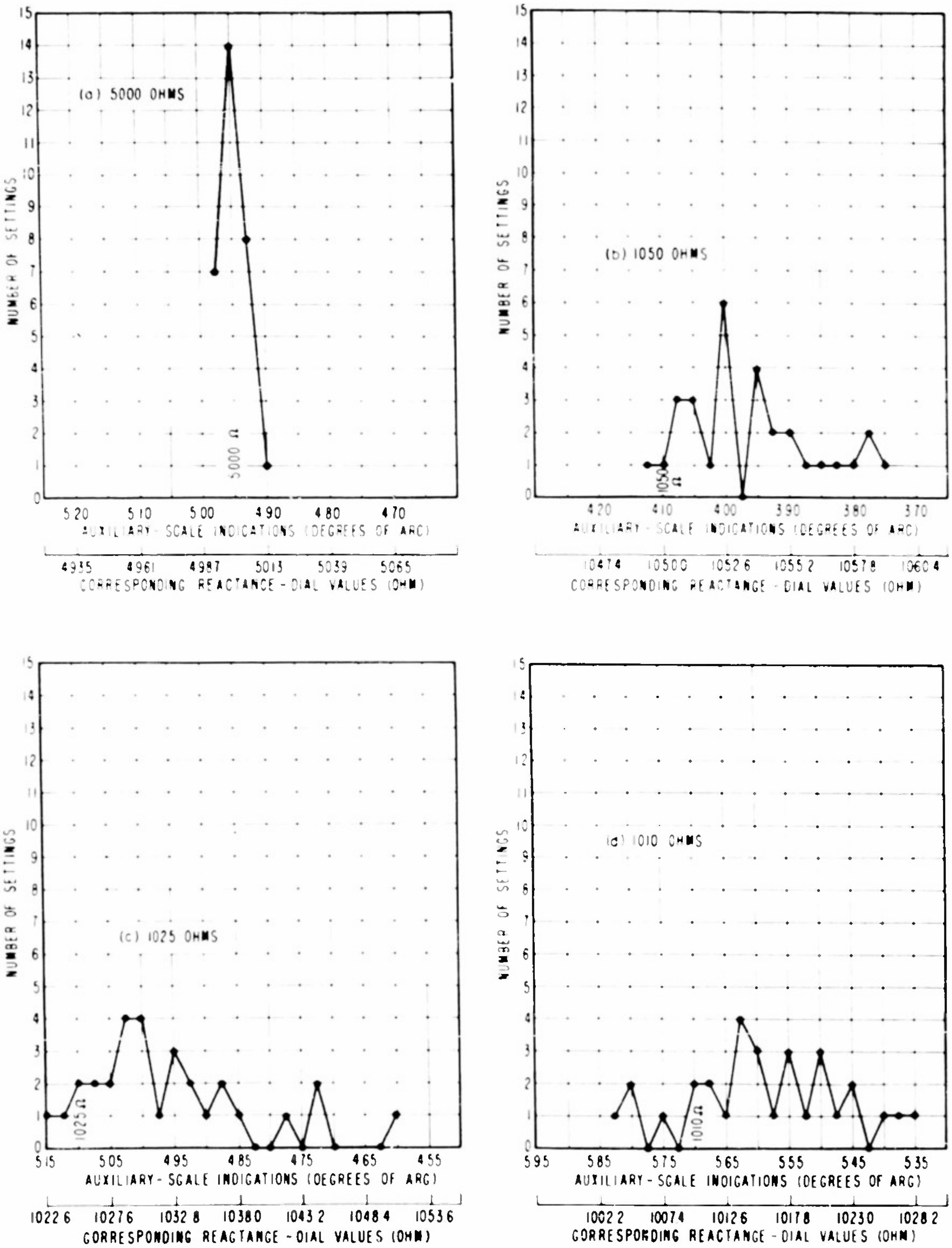


Figure 24 - Determination of ability to set reactance dial to various values

For the 1025-ohm test, the same overemphasis of the logarithmic division existed. The maximum deviation from the true value was 0.5 degree or about 13 ohms, but this wide deviation occurred for only one setting and all others remained within 10 ohms. As a result, there should be no ambiguity in dividing the unit into quarters. In the 1010-ohm test, uncertainty in dividing by tenths as well as logarithmic overemphasis contributed to the variation in dial setting. The maximum deviation from the true value was 0.35 degree or about 9 ohms. Thus, since 1/10 subdivisions are 10 ohms for this dial division, 9 ohms uncertainty in dial setting would result in an overlapping ambiguity of 8 ohms between successive 1/10 subdivisions. It is therefore impractical to divide the dial divisions finer than 1/4, and thus, the precision of dial reading is ±1/8 division. This interpretation is considered valid for all parts of the reactance dial except from 0 to 20 ohms and 4000 to 5000 ohms. For these two portions, the dial divisions are small and it is not feasible to subdivide them more than once (that is, into 1/2 division units); thus the corresponding precision would be ±1/4 division.

The percent error in reactance based only on the precision with which the reactance dial can be read has been plotted in Figure 25a as a function of reactance. The curves for inductive and capacitive reactance are the same up to 1000 ohms because their respective values are both measured on the same portion of the dial. In contrast for higher reactance values, the X_L and X_C curves are different because X_L is measured on a different portion of the dial from that used for X_C of the same magnitude. Also plotted in this figure is the specified accuracy which is found to be somewhat optimistic for capacitive reactance in the range 1000 to 1500 ohms. It should be noted that this comparison is not direct because the specified accuracy must account for all sources of error including limitations imposed by dial precision.

A similar plot and comparison for resistance (Figure 25b) shows that the percent error resulting from the precision of dial reading only is never greater than the specified accuracy.

<u>Portability</u> – Since the 916-A bridge is suitable for measuring the impedance of antennas and other circuits that are essentially fixed installations, it is important to consider the portability of the equipment. The bridge unit, which is equivalent in weight and size to a well-loaded suitcase (about 35 pounds and 17 x 13-1/2 x 11 inches) is relatively portable. The bridge, however, is only one of three units necessary to make measurements; a signal generator and a receiver must be included in the complete setup. If the particular set of measurements to be made cover a series of different frequencies, it is possible that two signal generators and two receivers may be required to cover the range of interest. The total weight of equipment, therefore, may easily reach 150 pounds.

Normal Operating Performance

While making impedance measurements under normal laboratory conditions, the actual operating characteristics of the particular test bridge were examined and compared with those of two other 916-A bridges.

<u>Resolution and Precision</u> – Since the null indication was generally narrower than a small fraction of a dial division, the resolution of the bridge was found to be satisfactory for all ranges. For certain values of unknown impedance, the resolution of the resistance and reactance dials are different. For example, there are instances where the resolution of the resistance dial is rather broad unless the reactance control has been adjusted to its ultimate null condition. As a consequence of the present ratio on the reactance vernier drive, this adjustment sometimes becomes a rather delicate and tedious operation. For this reason, therefore, it would be advantageous to alter the drive ratio and thus produce a slower motion on the controlled capacitor.

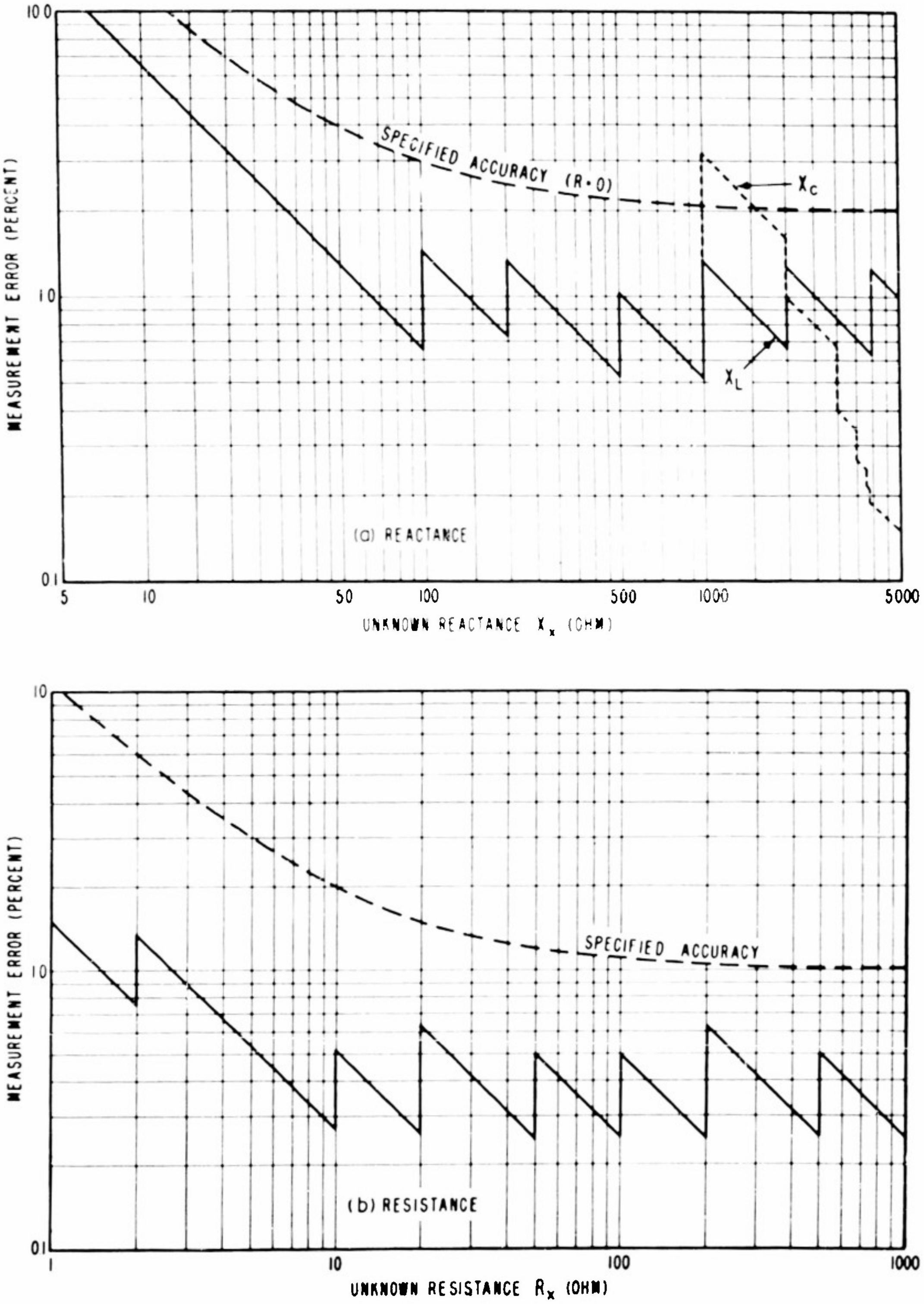


Figure 25 - Reactance and resistance error based only on the precision of dial reading

A set of fixed resistors was used to obtain an indication of the measurement precision of the resistance dial. Because of the need for good r-f characteristics, General Radio type 663 resistors were used for values from 1 to 100 ohms and General Radio type 500 resistors were used for values from 200 to 1000 ohms. These units are shown as group A in Figure 26. Each resistor was measured on all three type 916-A bridges, and the results are tabulated in Table 1.

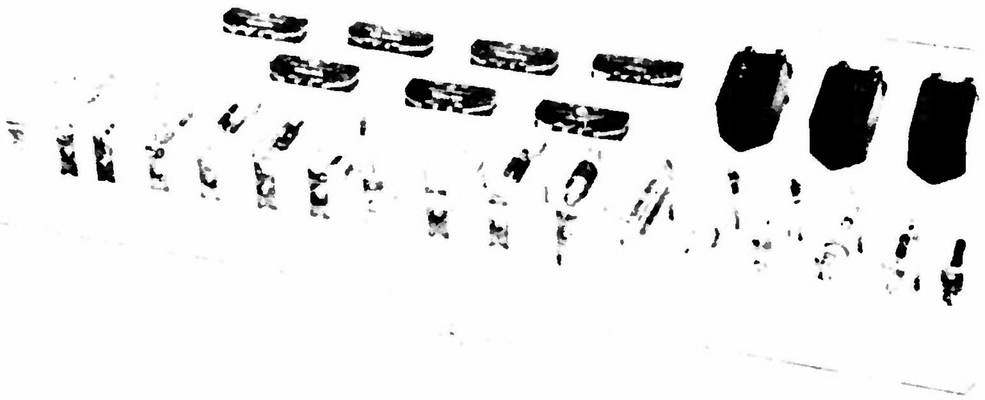


Figure 26 - Standard resistors and impedance transfer standards used for bridge measurements

Here the test bridge is designated as E, and F and G are the two comparison bridges. The tabulated dc values of the test resistors were obtained by using a precision Wheatstone bridge to compare them against standardized resistors. Table 1 is a "three-dimensional" type of presentation used to facilitate the comparison of the measured values as a function of any of the three variables – resistance, frequency, or bridge unit. The variation in resistance measurement as a function of frequency for any one bridge and resistor is obtained by reading a horizontal row. The variation in indicated values among the three bridge units for any one frequency and resistance combination is obtained from the appropriate diagonal section. The examination of any single vertical column of figures permits the rapid analysis of all resistance measurements for any one bridge at any one frequency.

The values in Table 1 have all been corrected according to the average correction data given in the instruction book for the 916-A bridge.[8] An asterisk (*) signifies that the corrected value differs from the measured dc value by more than the specified bridge accuracy (±1% + 0.1 ohm). In establishing this difference for the 30 Mc measurements, the tabulated dc values were adjusted to the effective series-resistance values for 30 Mc in accordance with the specifications given for type 663 resistors.[9] For bridge E, 20 of the 36 readings differed by more than the specified accuracy, whereas for bridges F and G, the number is only 5 and 2, respectively. However, the majority of the measurements that exceed the limit are borderline cases and can justifiably be considered doubtful because the true r-f resistance is not known with certainty. The 1000-ohm measurements were off scale at 3 Mc not because of bridge error but because there is an appreciable correction factor which results in the uncorrected balance being off scale.

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[9] General Radio Company, Catalog M, pp. 38-39, October 1951

TABLE 1

Direct Evaluation of Precision of Resistance Measurement

DC Resistance (ohm)	Bridge	Bridge Indication (ohms)			
		Transformer P1		Transformer P2	
		400 kc	3 Mc	3 Mc	30 Mc
1.046	E	1.05	1.09	1.04	1.31*
	F	1.0	1.03	1.04	1.27*
	G	1.03	1.00	1.04	1.07
1.993	E	2.05	2.05	2.05	2.28*
	F	2.0	2.00	1.95	2.30*
	G	2.0	2.00	2.00	2.27*
4.999	E	5.1	5.05	5.05	5.34*
	F	5.0	5.00	4.90	5.26*
	G	5.0	5.00	5.00	5.17
10.03	E	10.2	10.3*	10.2	10.7*
	F	9.9	10.2	10.1	10.6*
	G	9.9	10.0	10.0	10.3
20.17	E	20.5	20.5	20.5	20.9*
	F	20.1	20.0	20.0	20.6
	G	20.2	20.0	20.0	20.6
50.02	E	51.0*	51.0*	50.5	52.4*
	F	50.0	50.0	50.0	50.0
	G	50.0	50.0	49.5	50.1
100.7	E	103*	103*	102*	104*
	F	101	101	100	99.4*
	G	100	100	99.5	98.1*
200.0	E	205*	206*	204*	‡
	F	201	202	201	‡
	G	199	200	199	‡
500.1	E	515*	520*	515*	‡
	F	500	505	505	‡
	G	500	500	500	‡
1000	E	1050*	†	†	‡
	F	1010	†	†	‡
	G	1000	†	†	‡

[*] The difference between these values and the measured dc value is greater than the specified accuracy of the bridge (±1% + 0.1 ohm).

[†] These readings were off scale, not because of bridge error, but because there is an appreciable correction factor which results in the uncorrected balance being off scale.

[‡] The reactance of these resistors at 30 Mc is too high to be balanced on the bridge.

Intercomparison of Three 916-A Bridges – A set of impedance transfer standards was prepared to cover an assortment of impedance values within the range of the 916-A bridge and for the three frequencies at which the bridge was specifically studied–400 kc, 3 Mc, and 30 Mc. These transfer standards were primarily intended for use in ascertaining what changes occurred in bridge indications under various environmental conditions. However, it was decided that a determination of the amount of difference existing in the measured impedance values obtained from the test bridge and the two comparison bridges would be significant. In a comparison of these measurements (Table 2), the test bridge E consistently indicates higher values for both R and X (except low values of X) than the comparison bridges. The difference in indication between the two comparison bridges is generally less than the difference in indication between the test bridge and either of the comparison bridges. A numerical index of this difference between indicated values can be established by dividing the maximum difference between any two of the three bridge indications by the average of the three and then multiplying by 100 to convert to a percentage. This "maximum deviation" ranged from 1.3 to 12.4 percent for R measurements; 7 out of 20 exceeded 4 percent, and the average was 4.6 percent. The maximum deviation ranged from 0 to 153 percent for X measurements; 7 out of 20 exceeded 10 percent, and the average was 24.7 percent. These computed maximum deviation values are shown in Table 3.

An attempt to interpret bridge quality directly from these data can be misleading because the specified accuracy of bridge measurement is not a constant. A more applicable figure of merit for each bridge measurement can be obtained by dividing the maximum deviation value by the specified bridge accuracy for the particular resistance or reactance value* (Table 3). Thus, a figure of merit of 1 means that the maximum deviation among bridge readings is equal to the specified accuracy. A figure of merit less than 1 means the maximum deviation is within the specified accuracy, whereas a figure of merit greater than 1 means the maximum deviation exceeds the specified accuracy. For the resistance component, 15 out of 20 are greater than 1; for reactance, 17 out of 20 exceed 1. It is apparent, therefore, that at least one of the three bridges is not measuring within the specified accuracy.

Frequency-Range Overlap Error – In shifting from one range to another, the only change made in the bridge is a substitution of input transformers. The data presented in Table 2 provide a basis to determine the difference in measurement that occurs for the two different transformers at the range overlap frequency of 3 Mc. The percent difference in these two readings, i.e., the difference between the two readings divided by the average value multiplied by 100, is shown in Table 4 for several impedance values for each of the three bridges. The corresponding figures of merit are also presented. In this case, it will be noted that only one figure of merit is over 1 and the amount by which it exceeds 1, namely 0.07, is so small that it could easily be within the region of uncertainty for dial reading. Disregarding this one case, the frequency-range overlap error is less than the specified accuracy for all three bridges.

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* In computing these figures of merit, the specified accuracy value was doubled because it is a plus or minus value and is therefore equivalent to only one half of the maximum deviation value.

TABLE 2
Comparison of Measurements Made on Test Bridge and Two Comparison Bridges

Frequency (Mc)	Transformer	Impedance Standard		Impedance						L-C Switch Setting used for Measurement
				R (ohm)			X (ohm)			
				Bridge			Bridge			
		No.	L or C	E	F	G	E	F	G	
0.4	P1	16	L	885	855	850	17.5	17.0	17.0	L
		15	L	167	162	162	2700	2550	2600	L
		1	C	810	785	780	3	3	3	L
		3	C	805	780	775	520	500	495	L
		7	C	9.6	9.0	9.2	4367	4160	4180	C
3	P1	9	L	855	830	820	25	33	36	L
		10	L	18.7	18.6	18.3	4050	3900	3900	L
		1	C	800	780	775	155	147	144	L
		3	C	795	770	765	674	641	630	L
		6	C	6.4	6.2	5.8	4175	3980	3995	C
3	P2	9	L	850	825	820	21	37	38	L
		10	L	18.3	18.0	18.3	4100	3900	3900	L
		1	C	795	775	770	160	147	144	L
		3	C	790	770	765	680	640	630	L
		6	C	6.2	6.2	6.0	4180	3990	4000	C
30	P2	20	L	99.0	95.0	94.0	12.5	140	131	L
		19	L	495	468	465	102	680	350	L
		12	L	1.50	1.48	1.50	4600	4400	4400	L
		21	C	283	270	265	2250	1800	1550	C
		13	C	1.98	1.85	1.75	4303	4125	3745	C

TABLE 3
Maximum Deviation and Figure of Merit Values for Measurements Tabulated in Table 2 Comparing Three Bridges

Frequency (Mc)	Transformer	Impedance Standard No.	Maximum Deviation R (%)	Maximum Deviation X (%)	Figure of Merit R	Figure of Merit X
0.4	P1	16	4.0	2.9	2.0	0.60
		15	3.1	5.7	1.5	1.4
		1	3.8	0	1.9	0
		3	3.8	5.0	1.9	1.1
		7	6.5	4.9	1.6	1.2
3	P1	9	4.2	35	2.1	1.5
		10	2.2	3.8	0.65	0.94
		1	3.2	7.4	1.6	1.1
		3	3.9	6.8	1.9	1.4
		6	9.8	4.8	1.9	1.2
3	P2	9	3.6	53	1.8	2.3
		10	1.6	5.0	0.52	1.2
		1	3.2	11	1.6	1.4
		3	3.2	7.7	1.6	1.7
		6	3.3	4.7	0.62	1.2
30	P2	20	5.2	140	2.4	12
		19	6.3	150	3.1	14
		12	1.3	4.5	0.08	1.1
		21	6.6	38	2.4	7.8
		13	12	14	0.10	3.4

TABLE 4
Frequency-Range Overlap Error

Impedance Standard No.	Difference in Measurements at 3 Mc between Transformers P1 and P2*					
	R			X		
	Bridge			Bridge		
	E	F	G	E	F	G
9	0.59 (0.29)	0.60 (0.30)	0 (0)	17 (0.57)	11 (0.54)	5.4 (0.27)
10	2.2 (0.71)	3.3 (1.07)	0 (0)	1.2 (0.30)	0 (0)	0 (0)
1	0.63 (0.31)	0.64 (0.32)	0.65 (0.32)	3.2 (0.42)	0 (0)	0 (0)
3	0.63 (0.31)	0 (0)	0 (0)	0.89 (0.18)	0.16 (0.03)	0 (0)
6	3.2 (0.62)	0 (0)	3.4 (0.63)	0.12 (0.03)	0.25 (0.06)	0.13 (0.03)

* Figures not in parenthesis indicate the difference in readings in percent, while those figures in parenthesis represent the corresponding figure of merit values.

Effects of Ambient Conditions

To determine how satisfactorily the bridge operated under various temperature and humidity conditions, it was placed in a chamber having both temperature and humidity control. Electrical connections to the bridge were made by the technique previously described. Figure 27 shows the test bridge E in position in the chamber and the comparison bridge F outside the chamber; both are connected to the symmetrical T-network. Also shown are the Q-meter for checking the symmetrical T-network, the signal generator in the background, and one of the two receivers used as the detector. Auxiliary mechanical controls were added to the test bridge (Figure 28) to facilitate operating the bridge through a port in the chamber door during the environmental tests.

To permit evaluation of both transformers, two identical runs were made for each environmental condition investigated with the bridge in operation. The frequencies used were 400 kc and 10 Mc. Each measurement was made twice using two different shorting methods to obtain the initial balance. In the first method (A), the standard procedure of clipping the high terminal lead to the ground post was used. In the second method (B) the impedance terminals on the symmetrical T-network were shorted. This dual scheme provided an auxiliary check on the condition of the symmetrical T-network. For the exposure and storage tests, only one run was made. "Before and after" measurements were made at 0.4 and 30 Mc, and their results were used to determine the ability of the bridge to withstand these tests. The various environmental tests and the resulting bridge performance will now be discussed in the order in which the tests were conducted. The summarized performance of the bridge during these tests is presented in Table 5.

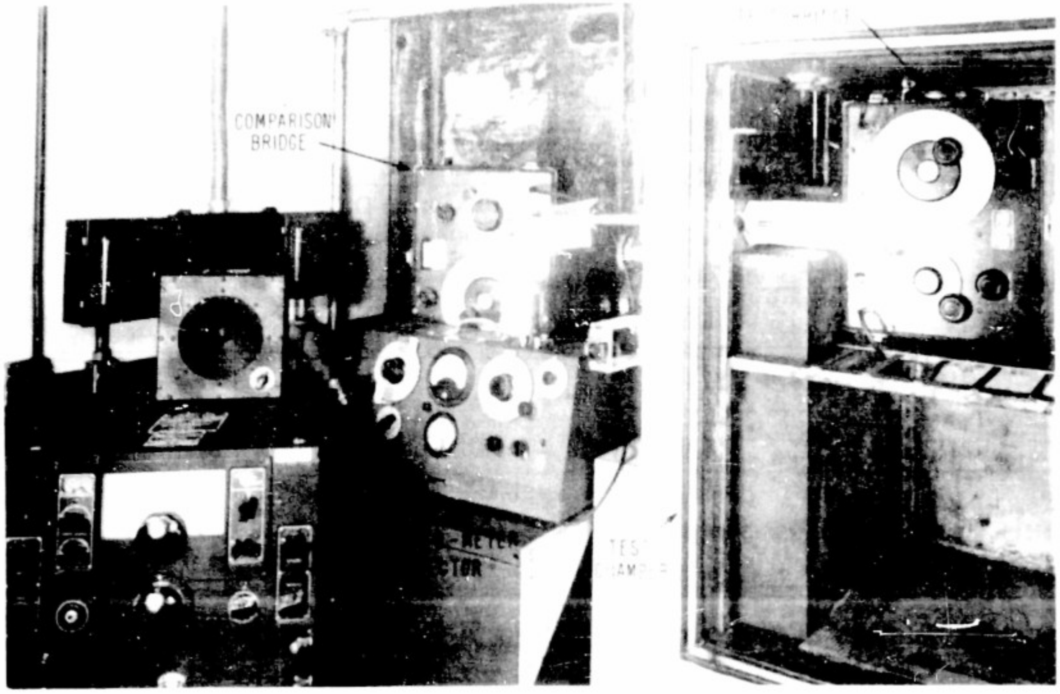

Figure 27 - Arrangement used to determine bridge characteristics under various environmental conditions

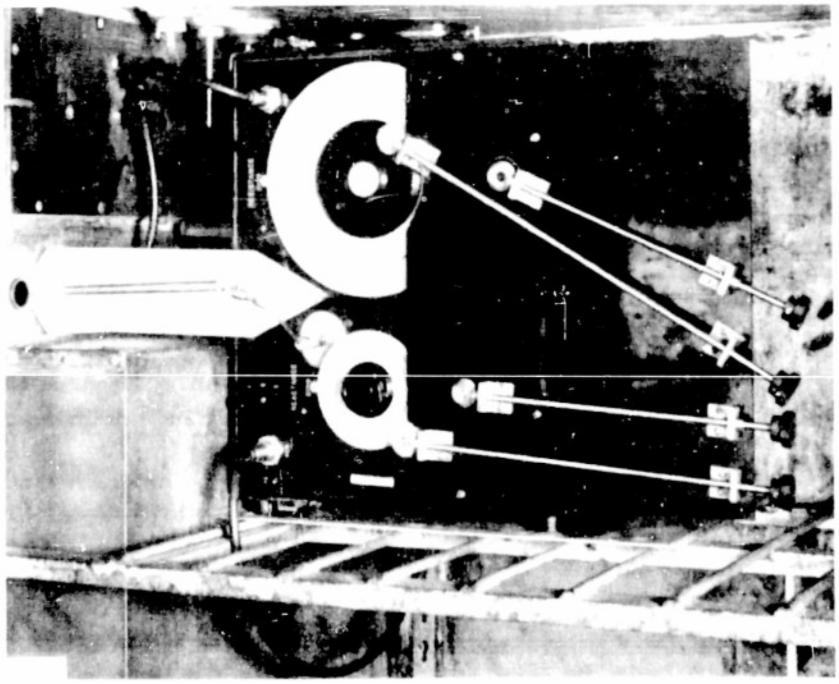

Figure 28 - Auxiliary mechanical controls added to test bridge to facilitate operation during environmental tests

TABLE 5
Summary of Environmental Tests

Test Description and Nominal Conditions	Freq. (Mc)	Maximum Difference Among Values Measured During Test[*] (%)				Residual Changes[†] (%)			
		Bridge E		Bridge F		Bridge E		Bridge F	
		R	X	R	X	R	X	R	X
Low Temperature, 25°C to -33°C	0.4	2.2	1.7	1.1	1.2	1.2	0.7	1.7	0.9
	10	14	11	7.6	4.6	9.2	3.6	7.1	2.3
High Temperature, 25°C to 60°C	0.4	2.4	4.0	2.9	0.7	9.1	4.9	0.7	1.0
	10	0.9	2.1	1.1	0.6	0.9	1.3	0.7	0.6
High Humidity 25°C, 38% R.H. to 40°C, 95% R.H.	0.4	[§]	[§]	1.2	0	2.2	2.0	1.7	0.7
	10	2.8	2.1	0.4	0.3	0.4	0.8	0.4	0
High-Altitude Exposure, 1.3 in. Hg at 25°C for 1 Hr.	0.4	-	-	-	-	0	1.0	0	1.9
	30	-	-	-	-	1.0	3.9[‡]	0.2	1.3
Low-Temperature Storage -60°C for 16 Hours	0.4	-	-	-	-	2.0	0.8	1.1	1.9
	30	-	-	-	-	1.0	0.9[‡]	0	0
High-Temperature Storage 85°C for 16 Hours	0.4	-	-	-	-	0.6	0.5	0	0.1
	30	-	-	-	-	1.0	0.4[‡]	0	0

[*] The maximum percent difference among values measured during the test was computed by dividing the maximum difference in any two measurements in the test concerned by the average value of all the measurements of that test, times 100.

[†] Residual change, in percent, is the difference between the initial and final 25°C readings or between the before and after readings (whichever applies to the particular test) divided by the average of the two values concerned, times 100.

[§] No reading could be made at 40°C because the R initial balance point was beyond the range of the control.

[‡] The values do not include standard No. 19 for which the test bridge measurements changed from inductive to capacitive reactance.

Low-Temperature Operation - The bridge was subjected to a low-temperature run of 25 to -33°C and a return to 25°C. Measurements were made at these temperatures and at various intermediate points as the temperature was decreased. The bridge was stabilized approximately one-half hour at each temperature before measurements were made. The return from -33 to 25°C was made overnight. At these low temperatures, the general physical operation of the bridge was found to be satisfactory except that the controls tended to become stiff and harder to move (but not to any serious degree). The data of Tables 5 and 6 show that the variations in the measured values of any one transfer standard at 0.4 Mc are relatively small and comparable to those of the comparison bridge. Also, there was relatively little residual changes, i.e., difference between initial and final 25°C readings. A similar temperature run was made at 10 Mc, and this time the measured values showed fairly large variations (Tables 5 and 7). The measurements on the comparison bridge, however, showed a similar shift but of lesser degree. The change in the test bridge should be modified by the amount of change in the comparison-bridge measurements. The net residual change, after adjusting for the similar change in the comparison-bridge measurements, is rather small.

High-Temperature Operation - The bridge was subjected to a high-temperature run of 25 to 60°C and a return to 25°C; measurements were made at these temperatures and various intermediate points. Physical operation of the bridge was the same as under normal temperature conditions. Variations in measurements throughout the run were only moderate; upon return to 25°C, however, there was a rather large residual shift in the higher-resistance measurement (Tables 5 and 8) which was substantially retained during the subsequent humidity test. A similar run was made at 10 Mc (Tables 5 and 9), and relatively little difference in measurements occurred throughout the run or between the initial and final 25°C readings.

High-Humidity Operation - The bridge operating at 0.4 Mc was next subjected to a high-humidity run; the conditioning sequence and resulting measurements are given in Table 10 and summarized in Table 5. Operation of the bridge was not completely satisfactory at 95-percent relative humidity because the balance point for the R "initial-balance" control shifted beyond the range of the control; therefore, measurements could not be made. With impedances connected to the bridge, however, a sharp null in the circuit indicated that otherwise the bridge was still functional. Residual change that occurred after overnight drying was rather small. No difficulty was encountered in another run made at 10 Mc (Tables 5 and 11) and differences in measurements and residual changes were both fairly small.

High-Altitude Exposure - After initial measurements were made at both 0.4 and 30 Mc (Table 12), the bridge was subjected to a simulated one-hour high-altitude test with the pressure at 1.3 inches of mercury and the temperature at 25°C. The percent difference between initial readings and the readings after the test was small (Table 5) except for standard 19. Particularly when measuring this standard, the resistance balance of the test bridge appeared to have an erratic contact. This condition was worse after the altitude test, and satisfactory measurements could not be made at first. All control dials were given 15 complete cycles of operation. The system then appeared fairly normal except that the X balance was rather broad for standard 19 at 30 Mc, and the bridge indication was now approximately 40 to 80 ohms capacitive reactance. Before the altitude test, however, the measured value was 90 ohms inductive reactance. No specific reason was found for this malfunctioning of the bridge.

TABLE 6
Low-Temperature Test – 0.4 Mc

Temp. (°C)	Standard		Bridge E		Bridge F		Method of Initial Balance	Time of Day
			R	X	R	X		
	No.	L or C	(ohm)	(ohm)	(ohm)	(ohm)		
25	17	L	422	2450	410	2350	B	1000
	17	L	427	2450	410	2350	A	1015
	4	C	179	2980	177	2875	B	1020
	4	C	182	2990	178	2900	A	1025
14	17	L	425	2450	410	2350	B	1115
	17	L	425	2450	410	2350	A	1120
	4	C	180	2990	176	2900	B	1128
	4	C	180	3000	176	2875	A	1125
5	17	L	422	2450	410	2350	B	1210
	17	L	422	2450	410	2350	A	1215
	4	C	179	2970	176	2900	B	1220
	4	C	180	3020	176	2900	A	1228
-5	17	L	423	2450	410	2350	B	1315
	17	L	423	2450	410	2350	A	1320
	4	C	180	2990	177	2910	B	1322
	4	C	180	2980	177	2910	A	1325
-15	17	L	422	2450	410	2350	B	1400
	17	L	423	2450	410	2350	A	1405
	4	C	179	2960	176	2900	B	1408
	4	C	180	2970	176	2900	A	1412
-25	17	L	420	2450	410	2350	B	1508
	17	L	420	2450	410	2350	A	1513
	4	C	178	2960	176	2900	B	1518
	4	C	178	2970	176	2900	A	1521
-33	17	L	420	2450	*	*	B	1624
	17	L	*	*	*	*	A	-
	4	C	181	2970	*	*	B	1627
	4	C	*	*	*	*	A	-
25	17	L	427	2450	408	2350	B	0900
	17	L	427	2450	410	2350	A	0903
	4	C	180	3000	175	2875	B	0907
	4	C	180	2990	175	2875	A	0909

*Measurement not made.

TABLE 7
Low-Temperature Test – 10 Mc

Temp. (°C)	Standard		Bridge E		Bridge F		Method of Initial Balance	Time of Day
	No.	L or C	R (ohm)	X (ohm)	R (ohm)	X (ohm)		
25	18	L	580	2150	540	2200	B	1000
	18	L	600	2300	550	2350	A	1003
	3	C	282	3760	280	3550	B	1008
	3	C	307	3700	293	3440	A	1012
15	18	L	550	2200	535	2100	B	1122
	18	L	570	2450	525	2450	A	1130
	3	C	282	3680	273	3550	B	1135
	3	C	305	3570	280	3300	A	1137
0	18	L	560	2200	530	2150	B	1235
	18	L	575	2400	520	2350	A	1240
	3	C	277	3690	275	3560	B	1247
	3	C	305	3570	273	3300	A	1249
-15	18	L	535	2200	530	2150	B	1337
	18	L	520	2500	525	2350	A	1342
	3	C	275	3800	273	3570	B	1346
	3	C	267	2370	272	3340	A	1351
-32	18	L	530	2150	530	2150	B	1554
	18	L	520	2450	525	2350	A	1600
	3	C	270	3770	274	3570	B	1606
	3	C	265	2310	272	3330	A	1612
25	18	L	550	2150	530	2150	B	0915
	18	L	550	2350	530	2350	A	0920
	3	C	280	3770	274	3580	B	0923
	3	C	280	3570	273	3380	A	0924

TABLE 8
High-Temperature Test – 0.4 Mc

Temp. (°C)	Standard		Bridge E		Bridge F		Method of Initial Balance	Time of Day
	No.	L or C	R (ohm)	X (ohm)	R (ohm)	X (ohm)		
25	17	L	420	2450	408	2350	B	1143
	17	L	420	2450	408	2350	A	1145
	4	C	178	2990	174	2880	B	1147
	4	C	178	2990	174	2900	A	1150
40	17	L	425	2450	405	2350	B	1309
	17	L	420	2450	405	2350	A	1311
	4	C	178	3020	174	2900	B	1314
	4	C	180	3000	174	2890	A	1315
50	17	L	425	2450	407	2350	B	1438
	17	L	425	2450	405	2350	A	1440
	4	C	178	3020	177	2900	B	1443
	4	C	179	3010	178	2900	A	1444
60	17	L	430	2500	406	2350	B	1542
	17	L	430	2500	405	2350	A	1545
	4	C	180	3110	173	2900	B	1547
	4	C	178	3090	173	2890	A	1551
25	17	L	460	2500	405	2350	B	0947
	17	L	460	2500	405	2350	A	0950
	4	C	182	3140	175	2910	B	0952
	4	C	182	3140	175	2900	A	0955

TABLE 9
High-Temperature Test – 10 Mc

Temp. (°C)	Standard		Bridge E		Bridge F		Method of Initial Balance	Time of Day
	No.	L or C	R (ohm)	X (ohm)	R (ohm)	X (ohm)		
25	18	L	555	2200	530	2150	B	1035
	18	L	555	2450	530	2350	A	1038
	3	C	284	3900	276	3570	B	1041
	3	C	284	3680	276	3380	A	1049
40	18	L	560	2200	530	2150	B	1145
	18	L	560	2400	530	2150	A	1147
	3	C	285	3920	276	3570	B	1150
	3	C	285	3680	276	3380	A	1152
50	18	L	560	2200	530	2150	B	1320
	18	L	560	2400	530	2150	A	1323
	3	C	285	3915	274	3570	B	1325
	3	C	285	3680	276	3370	A	1328
59	18	L	560	2200	530	2150	B	1424
	18	L	560	2400	530	2150	A	1428
	3	C	285	3905	273	3560	B	1430
	3	C	285	3680	274	3360	A	1432
25	18	L	560	2200	530	2150	B	1616
	18	L	560	2450	530	2150	A	1618
	3	C	285	3930	274	3550	B	1619
	3	C	285	3730	274	3360	A	1622

TABLE 10
High-Humidity Test - 0.4 Mc

Temp. (°C)	Relative Humidity (%)	Standard		Bridge E		Bridge F		Method of Initial Balance	Time of Day
		No.	L or C	R (ohm)	X (ohm)	R (ohm)	X (ohm)		
25	38	17	L	465	2550	410	2350	B	1053
		17	L	465	2550	410	2350	A	1055
		4	C	184	3150	176	2900	B	1058
		4	C	184	3170	176	2890	A	1100
25	95	17	L	470	2550	410	2350	B	1359
		17	L	470	2550	410	2350	A	1401
		4	C	*	*	*	*	B	—
		4	C	*	*	*	*	A	—
40	95	17	L	475	2550	405	2350	B	1508
		17	L	475	2550	405	2350	A	1513
		4	C	*	*	*	*	B	—
		4	C	*	*	*	*	A	—
25	36	17	L	455	2500	405	2350	B	0936
		17	L	455	2500	403	2350	A	0938
		4	C	182	3160	174	2900	B	0940
		4	C	182	3160	174	2910	A	0942

*Readings could not be made because the R initial balance point was beyond the range of the control.

TABLE 11
High-Humidity Test - 10 Mc

Temp. (°C)	Relative Humidity (%)	Standard		Bridge E		Bridge F		Method of Initial Balance	Time of Day
				R	X	R	X		
		No.	L or C	(ohm)	(ohm)	(ohm)	(ohm)		
25	36	18	L	555	2200	530	2150	B	1006
		18	L	555	2400	530	2350	A	1009
		3	C	283	3890	275	3570	B	1012
		3	C	282	3660	275	3370	A	1014
25	95	18	L	555	2200	530	2150	B	1323
		18	L	555	2400	530	2350	A	1326
		3	C	275	3860	274	3570	B	1335
		3	C	275	3670	275	3380	A	1337
40	95	18	L	560	2200	530	2150	B	1449
		18	L	560	2400	530	2350	A	1452
		3	C	282	3940	275	3560	B	1455
		3	C	283	3710	276	3380	A	1458
26	42	18	L	555	2200	530	2150	B	0944
		18	L	555	2400	530	2350	A	0947
		3	C	283	3900	274	3570	B	0950
		3	C	283	3690	275	3370	A	0955

TABLE 12
High-Altitude Low-Temperature and High-Temperature Storage Tests

Measurement Status	Frequency (Mc)	Standard		Bridge E		Bridge F	
		No.	L or C	R (ohm)	X (ohm)	R (ohm)	X (ohm)
Initial Readings before High-Altitude Test	0.4	15	L	170	2800	162	2600
		7	C	9.8	4665	9.2	4200
	30	19	L	500	90	468	780
		21	C	285	2280	268	1750
Readings after High-Altitude Test and before Low-Temperature Test	0.4	15	L	170	2800	162	2550
		7	C	9.8	4610	9.2	4185
	30	19	L	495 to 500*	-40 to -80*	467	790
		21	C	282	2370	268	1750
Readings after Low-Temperature Test and before High-Temperature Test	0.4	15	L	171	2800	162	2600
		7	C	10	4575	9.1	4180
	30	19	L	500	-65 to -125*	470	770
		21	C	284	2350	268	1750
Readings after High-Temperature Test	0.4	15	L	172	2800	162	2600
		7	C	10	4600	9.1	4175
	30	19	L	505	70 to 75*	468	750
		21	C	286	2360	268	1750

* A broad reactance balance was characteristic of these measurements.

Low-Temperature Storage - The bridge was then subjected to a 16-hour storage at -60° C followed by 24-hour storage at 25° C; the relative humidity was maintained between 35 and 40 percent for the 25°C test. Relatively little change in readings occurred, and standard 19 measured somewhat more capacitive (Tables 5 and 12). While making the measurements after this test, it was discovered that the final reactance indication on bridge E was dependent upon the amount of pressure applied to the resistance-balance knob during its adjustment.

High-Temperature Storage - Next the bridge was exposed to a high-temperature storage test at 85°C for 16 hours, and low relative humidity was maintained. Again, only small changes occurred in the measured values with one exception–the test bridge now measured standard 19 at 70 to 75 ohms inductive reactance.

Effects of Mechanical Abuse

Following the series of environmental tests, the bridge was scheduled to have vibration and shock tests. The bridge, however, became inoperative early in the vibration test, and it was not subjected to shock.

With the cover in place, the bridge was secured to the vibration table by two metal straps fitted over the top of the case. The bridge panel was horizontal and parallel with the vibration table. The bridge was then subjected to vibration tests as outlined in Military Specification MIL-T-945A.[10] The first period of vibration lasted 15 minutes, and the frequency varied from 10 to 33 cps and return approximately every 30 seconds at a total excursion of 0.06 inch. Comparison of measurements before and after this run show little change (Table 13). As a result of the vibration, two panel screws, four screws holding the reactance unit, and the high-potential terminal all came loose to some extent. All screws, however, were returned to their normal condition before the next vibration run which was the same as the first except the top frequency was changed from 33 to 55 cps. After this run, the bridge became completely inoperative. There was no apparent null on either the resistance or reactance initial-balance controls for the low-frequency range. In the high-frequency range, a slight null appearing only on the resistance initial-balance control seemed to occur at a capacitance limit. Inspection of the bridge components disclosed no definite reason for the bridge becoming inoperative.

RECOMMENDATIONS

This detailed study of the General Radio 916-A r-f bridge has shown that the modification of certain operational and design features would be desirable, particularly when the unit is intended for military field use. The following modifications are recommended.

(a) It would be desirable to use only one transformer to cover the frequency range or, if two transformers are necessary, provide panel switching so that the transformers can be permanently mounted.

(b) A wrench should be provided if transformer changing is necessary.

(c) If more than one transformer is used, the appropriate frequency coverage for each should be shown on the front panel.

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[10] Military Specification MIL-T-945A, "Test Equipment, For Use with Electronic Equipment: General Specification," pp. 33-34, March 1950

TABLE 13
Vibration Test

Measurement Status	Frequency (Mc)	Standard		Bridge E	
				R	X
		No.	L or C	(ohm)	(ohm)
Readings before vibration	0.4	15	L	172	2800
		7	C	10	4600
	30	12	L	1.8	4800
		21	C	286	2360
Readings after first 15 minute vibration run	0.4	15	L	168	2900
		7	C	10	4780
	30	12	L	1.7	4800
		21	C	280	2350

Note: After second 15 minute vibration run the bridge was inoperative.

(d) Initial balance controls should have stops or at least a notation on the front panel or each knob to show how many turns effect complete control.

(e) A higher drive ratio on the initial balance controls would be desirable to make their adjustment to balance less critical.

(f) A similar increase in ratio would be desirable for the reactance scale.

(g) Consideration should be given to the desirability of spreading the reactance scale over more degrees of arc or using a larger diameter scale.

(h) The resistor contained in the plug of the unknown connecting leads should be placed inside the bridge so that these special leads are not necessary.

(i) Insulating materials having a minimum change in properties under varying atmospheric conditions should be used throughout.

(j) The case should be all metal, preferably aluminum.

(k) Size and weight should be reduced to a practical minimum.

(l) The bridge should be completely ruggedized to withstand normal shock and vibration requirements.

(m) A more complete and detailed instruction book should be provided for maintenance and calibration checking procedures.

SUMMARY

Since the General Radio type 916-A r-f bridge is an instrument intended for normal laboratory and "protected" field usage, it was not expected to meet the usual requirements for military test instruments. Its performance, however, during the temperature and humidity tests, was better than had been anticipated. This type of instrument, because of its field of use, will not be subjected to the most rigorous military treatment. With proper modification of certain features as outlined, it is believed that a bridge of the 916-A type can be developed to fulfill military requirements.

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Naval Research Laboratory. Report 4230.
R-F IMPEDANCE BRIDGES FOR MILITARY USE, by J. A. Connor and D. I. Troxel. 45 pp. & figs., November 13, 1953.

R-F impedance-measuring instruments are needed in the military services for the study, installation, and maintenance of antennas, transmission lines, and high-frequency components. Commercial equipments available in this field do not meet military design and construction requirements. These instrument designs are based on a variety of techniques, viz. bridge, resonant and twin-T circuits, slotted-line principles, etc., and each possesses its own advantages and limitations and is more or less adaptable to military requirements.

As an instrument useful to the military services, the General Radio Company type 916-A r-f impedance bridge was specifically studied to determine the feasibility of producing a satisfactory military version thereof. Using a special T-network, a technique was devised that provided for the comparison of measurements on a standard impedance made by the bridge under test and by

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I. Impedance bridges - Design

I. Connor, J. A.

II. Troxel, D. I

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Naval Research Laboratory. Report 4230.
R-F IMPEDANCE BRIDGES FOR MILITARY USE, by J. A. Connor and D. I. Troxel. 45 pp. & figs., November 13, 1953.

R-F impedance-measuring instruments are needed in the military services for the study, installation, and maintenance of antennas, transmission lines, and high-frequency components. Commercial equipments available in this field do not meet military design and construction requirements. These instrument designs are based on a variety of techniques, viz. bridge, resonant and twin-T circuits, slotted-line principles, etc., and each possesses its own advantages and limitations and is more or less adaptable to military requirements.

As an instrument useful to the military services, the General Radio Company type 916-A r-f impedance bridge was specifically studied to determine the feasibility of producing a satisfactory military version thereof. Using a special T-network, a technique was devised that provided for the comparison of measurements on a standard impedance made by the bridge under test and by

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I. Impedance bridges - Design

I. Connor, J. A.

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a reference bridge, so that only the test bridge was subjected to adverse ambient conditions. The performance of the 916-A was better than had been anticipated; however, several deficiencies were detected, e.g. (a) the method of specifying the bridge accuracy, (b) the method of identifying transformers and indicating which one is in the circuit, (c) the lack of a tool necessary to change transformers, and (d) an incomplete instruction book. The correction of these deficiencies and the inclusion of certain desirable modifications such as (a) only one transformer to cover the entire frequency range, or internal switching if more than one transformer is required, (b) an improved drive ratio and stops for the initial balance controls, (c) an increased drive ratio and a longer scale for the reactance control, (d) the removal of the resistor from the plug of the unknown connecting lead and its insertion in the bridge proper, (e) the reduction of size and weight to a practical minimum, and (f) the use of a metal case along with appropriate circuit ruggedization, should result in an instrument satisfactory for military use.

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