PART III. ELECTRONICS COMES OF AGE 1946–1965

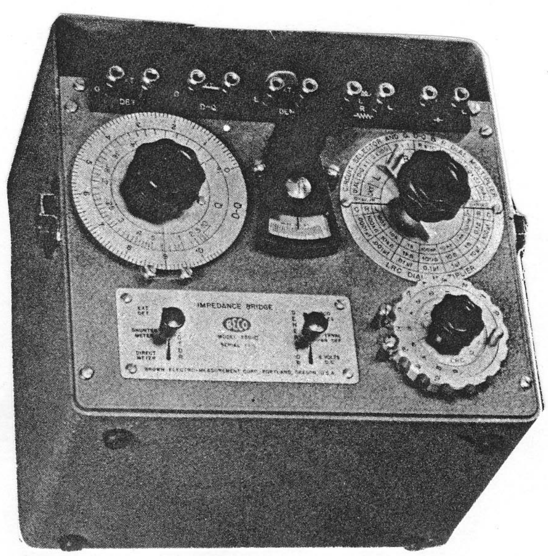
3.1 Comment

World War II changed a relatively small "radio" industry into a broad "electronics" industry that included television, "hifi", microwaves, radar, calculators, computers, automatic controls, expanded telecommunications and many other new applications for electronics. The needs of the "cold war" and "space age" accelerated the process with heavy funding in the U.S. from the Department of Defense and NASA. The requirement for calibration "traceability" to the National Bureau of Standards (NBS),(now the National Institute of Standards and Technology, NIST) for all suppliers to the US military was introduced by in 1959 and amplified in later documents[1]. This requirement gave a strong impetus to measurements of all sorts. Moreover industry demanded instruments that were easier to use and that gave direct-reading results. They needed instruments to measure wider ranges of impedance values and at higher frequencies. They demanded speed to test the millions of components being made and better accuracy to test them to tighter tolerances.

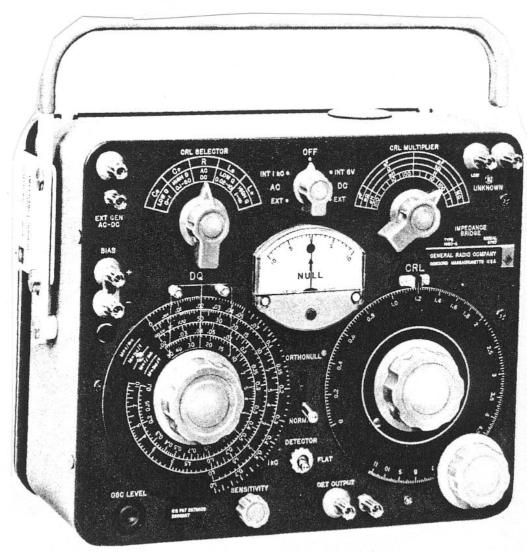
3.2 General Purpose Impedance (“RCL" or "Universal") Bridges

General Radio couldn't keep up with the demand for their general-purpose Type 650-A bridges during WWII, and moreover, the US government wanted to have a second source that was located away from the East coast in case of an enemy attack. Therefore GR farmed assembly out to Brown Engineering Co. (BECO, later Brown Instruments), in Portland, Oregon who made 400 of them[2]. They then rearranged the 650 parts to form a neater package with only two dials by ganging the three D-Q rheostats and this came to be called the “Brown Bridge” both for its color and its designer Frank Brown who was aided by Doug Strain. Strain joined Brown to form Brown Electro-Measurement Corp, BECO, and he developed a brand new RLC bridge, the popular Model 250, Figure 3-1. After two more name changes BECO became ESI, Electro-Scientific Industries, a company headed by Strain, which became a major supplier of both ac and dc bridges and standards and GR’s main competitor.

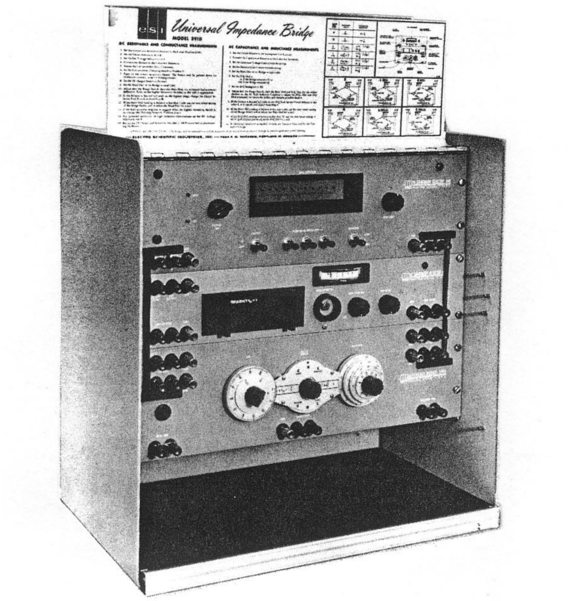
ESI’s compact 250 series used a high-resolution, coaxial arrangement of two decades and a pot, called a “Dekapot”, as the a main adjustment which allowed much better accuracy specifications (0.1% for R and ¼% for C). GR replaced their old type 650 with a "transistorized" Type 1650 (1959)[3] and, while this still had the same single-dial readout limiting the accuracy to



3-1 Impedance Bridge
BECO (ESI) Type 250 1949

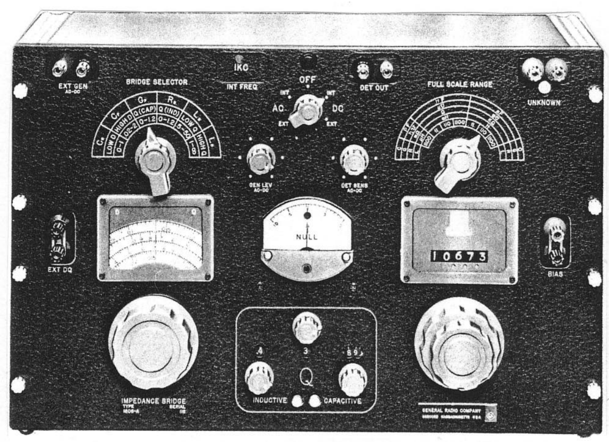


3-2 Impedance Bridge
GR Type 1650-A 1959



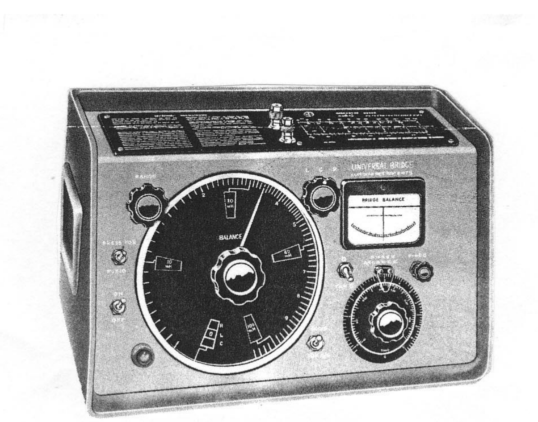
3-3 Impedance Measuring System
ESI Type 291-A 1961

1% (figure 3-2), it was nevertheless very popular. ESI achieved 0.1% C and L accuracy (.05% for R) in their Type 291-A Impedance Measuring System designed by Merle Morgan in 1960 (figure 3-3). In 1962 GR countered with their high-resolution GR 1608 that had a concentric 100-position, switched resistance (a "centade") and a pot (rheostat) that drove an odometer-type mechanical counter. Initially this instrument had a specified accuracy of 0.1% in R, L and C, but later this was improved to .05%, the best for this class of instrument[4], see figure 3-4.

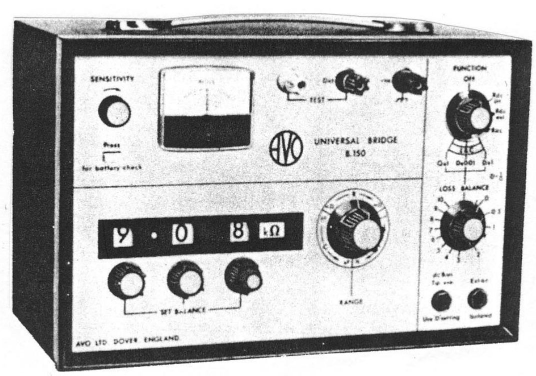


3-4 Impedance Bridge
GR Type 1608-A 1962

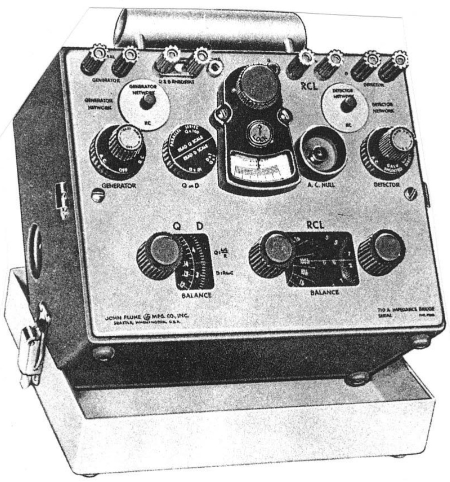
Many other companies joined in the competition for the general purpose RLC bridge market and their bridges used a variety of readout methods from large dials (RCA LB-50/52, Winslow 385-B), fixed dials and pointers (Marconi 868A, figure 3-5), knob-driven decades (AVO B-150, figure 3-6), lever-driven decades (GR 1656), coaxial decades (Fluke 710A, figure 3-7), coaxial dials and decades (Marconi 1313 & 2700) and RINCO 502-A) and linear "slide-rule" adjustments (Wayne-Kerr B500, AVO Type 1, and Simpson 2785, figure 3-8). Some other companies that made low-frequency "RLC" or "Universal" bridges were British Physical Laboratories, Cambridge Instruments, Muirhead, Nash & Thompson, Tinsley, Rhode & Schwarz, Philips, Siemens and even Heathkit who had one you could build yourself (see appendix B).



3-5 Universal Bridge
Marconi Model 868 c1958



3-6 Universal Bridge
AVO Type B 150 c1968

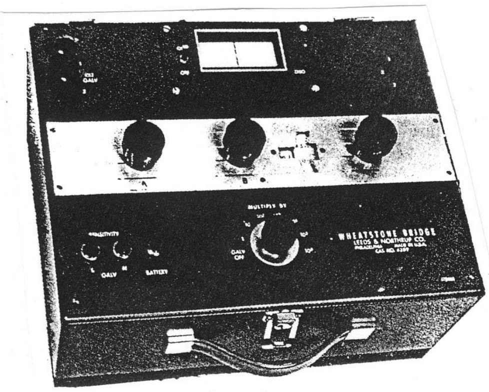


3-7 Impedance Bridge
Fluke Type 710A 1962

3-8 Impedance Bridge
Simpson Model 2785 1968

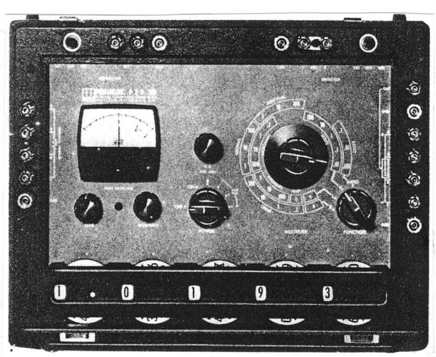
3.3 DC Bridges

Portable, self-contained (with source and detector) dc bridge systems also had a competitive market. While L&N continued to make new versions of and Wheatstone Bridges, types 4287 (figure 3-9) and 4289 which were more



3-9 Precision Portable Kelvin Bridge
L&N 4287 c1970

3-10 Portable/Laboratory
Wheatstone Bridge
Biddle Type 72-434 c1975

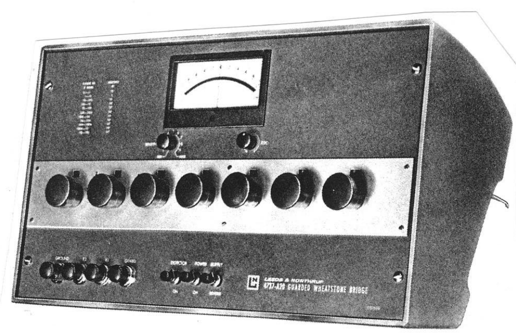


3-11 Potentiometric Voltmeter Bridge
ESI Model 300 1964

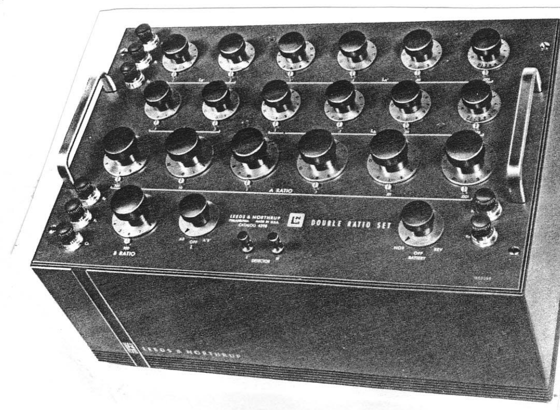
modern looking and more accurate. Other companies, such as Industrial Instruments and Shallcross, made resistance bridges in wooden boxes that looked much like the others made portable bridges (such as the Cambridge type 41157) with similar specifications. Biddle-Gray made an attractive series of portable dc bridges (figure 3-10) and ESI came out with a convenient-to-use "Potentiometric" bridge designed by N. Morrison that also had voltage-measuring capability (type 3000, figure 3-11). Later even GR got in the dc market with a 6-lever Kelvin/guarded-Wheatstone bridge (type 1666). There was also a class of small, less-accurate "single knob" bridges, perhaps the most unique being the Croydon ("Cropico") Type PW4 that saved panel space by putting the null-detecting galvanometer inside the dial.

The precision dc bridge arena was just as active. L&N, the long-time leader, made many new precision Wheatstone and Kelvin bridges, such as their Type 4232 that still had taper-pin ratio arm adjustments (figure 3-12), and later the handsome 4737 Guarded Wheatstone Bridge shown in figure 3-13, and the elegant 4398 Double Ratio Set, figure 3-14, a direct-reading ratio set (DRRS) that had a "lead" balance as well as the Kelvin "yoke" balance[5]. (The lead balance compensates for connection resistance put in the R_A arm of the Kelvin Bridge shown in figure 1-4.) ESI captured a large portion of the precision dc market with several precision dc bridge systems, particularly the model 242 Kelvin bridge also by Morgan (figure 3-15), which won important military contracts. This was a complete measurement system with a very sensitive detector that allowed part-per-million sensitivity over a wide resistance range. Much of their success was due to excellent application notes such as that by Jack Riley[6] that detailed calibration procedures for the "traceability" measurements now required of all suppliers to the military.

3-12 Guarded Wheatstone Bridge
L&N 4232A c1955

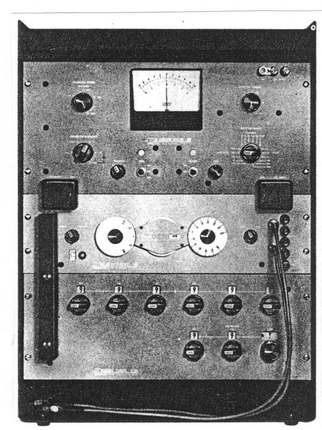


3-13 Guarded Wheatstone Bridge
L&N 4737A c1960



3-14 Double Ratio Set
L&N 4398 1965

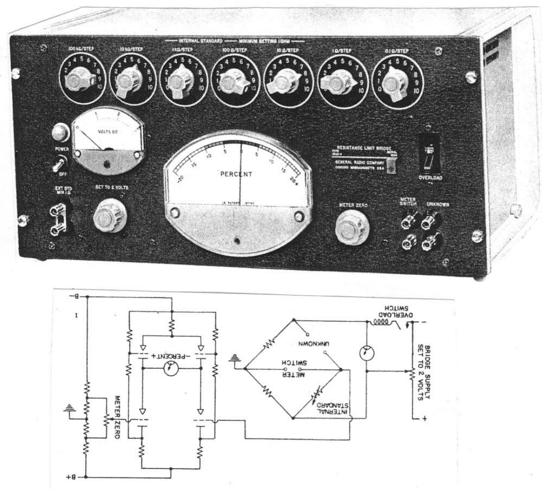
Loeb Julie, of Julie Research, designed a "Ratiometric®" dc bridge[7] that used an easily-calibrated, voltage divider as the balancing adjustment. This gave good accuracy and made traceability easier. However, the divider, which had a high resistance, was placed in series with the unknown and balanced against a pair of ratio arms and, as a result, the system had reduced sensitivity when measuring low-valued resistors and it was not direct reading in resistance. Other suppliers of more conventional precision bridges were Biddle, Otto-Wolff, Rubicon, Sullivan, Tinsley and Yokagawa Electric (YEW). One of the most important developments in dc bridges, the Guildline Current-Comparator



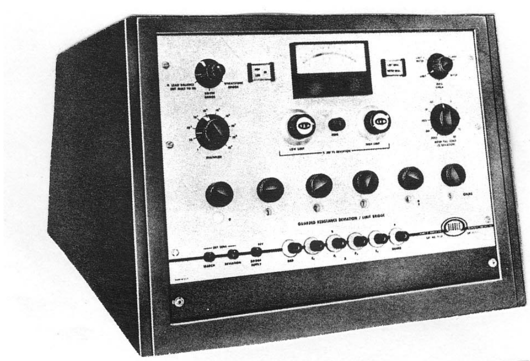
3-15 Resistance Measuring System
ESI Model 242 1960

Bridge, uses transformer ratio arms and is discussed below.

A new class of dc instruments, the Resistance Limit or Deviation Bridge, became popular for the fast sorting of resistors. Perhaps the first was the GR 1652 in 1952[8], (figure 3-16) but there were many similar instruments made with multi-decade resistance standards, but later ones had switched ratio arms to extend the measurement range thus making them excellent precision bridges when balanced. However for sorting, these bridges are not balanced as were earlier deviation bridges. Instead the standard is set to the nominal resistance value and the bridge unbalance voltage is indicated on a meter calibrated in percent deviation. Thus the test speed is limited only by dexterity of the operator in connecting the parts and the speed of the meter movement. Some, such as the Biddle 71-131 (figure 3-17) added "High-Go-Low" lights for increased testing speed. Other later units had limit-actuated relays to permit automatic sorting with external equipment. Also later units, such as the ESI type 263 (figure 3-18) and the GR type 1662, used feedback to linearize the deviation meter scale that, unaided, is quite non-linear as shown in figure 3-16.



3-16 Resistance Limit Bridge
GR 1652 1952



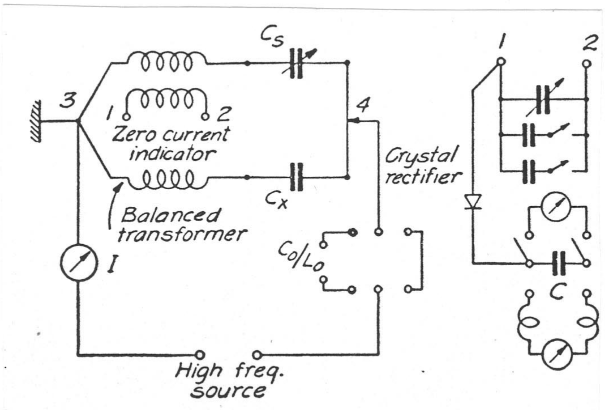
3-17 Guarded Resistance
Deviation/Limit Bridge
Biddle 71-131 1970

3-18 Deviation Bridge
ESI Model 263 1971

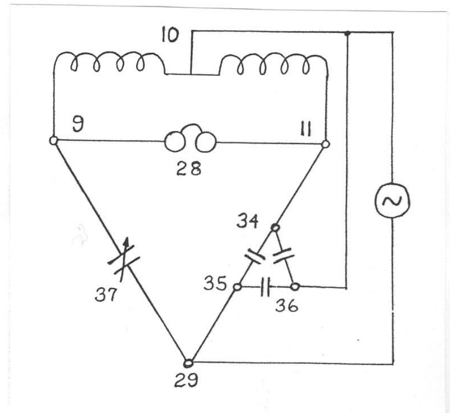
3.4 Precision AC Bridges: The Transformer-Ratio Arm Bridge

An important development in precision ac bridges was the use of a pair of inductively-coupled bridge arms, or "transformer ratio arms", which have the advantages of a precise and constant ratio and of high tolerance to shunt loading (refer to Appendix A).This technique has early roots in the use of a two-coil differential telephone invented by Chrystal[9] (1880) only four years after Bell's invention of the telephone. The revised Hague book[10] says “this instrument was used to compare an unknown impedance against a standard of the same kind” and “its principle is the foundation of modern measurements with high precision using ratio transformers”. Elais[11] (1891) and Trowbridge[12] (1905) showed that a three-winding transformer could be connected to a single-winding telephone to get the same result. Diagrams of their circuits would look much like later three-winding “transformer” bridges, but the pair of balanced coils was probably thought of more as a differential detector, analogous to Becquerel’s differential galvanometer (figure 1-2), than as the ratio arms of a bridge.

In his book of 1933 August Hund[13] describes an audio frequency "differential system" that uses a three-winding transformer with a core made of iron wire wound on a toroid.
o. He notes that the turns ratio may be other than 1:1 to similar impedances of unequal value. He also shows differential circuits for radio frequencies that use wooden core and have an output winding that is resonated for high sensitivity (figure 3-19). His circuits have been referred to as "Hund's Differential Method"[14], but one reference[15] calls one of these circuits "Hund's bridge".

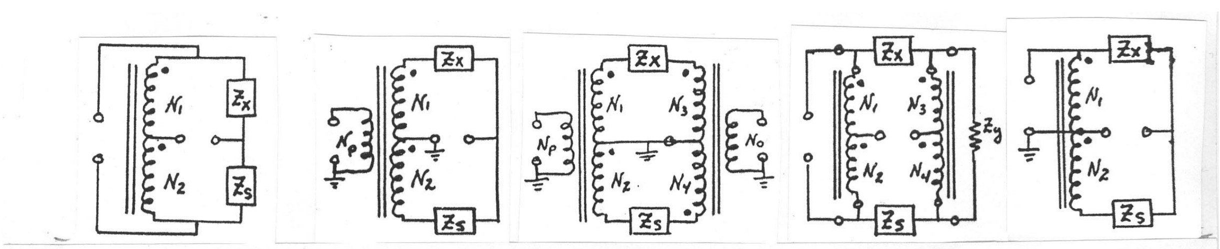


3-19 Differential System for Measuring High Frequency Capacitance
A. Hund 1924



3-20 Diagram from UK Patent 323037
A. Blumlein Filed in 1928

The modern TRA bridge also has roots in early self and mutual inductance comparison bridges particularly those of Heaviside and Campbell. The latter[15] noted the guarding capability of tightly coupled windings in 1922, but it was the versatile genius Alan Blumlein[17] who first clearly stated the advantages of using coupled ratio arms in a four-arm bridge. A figure from one of his patents[18] shows a guarded measurement of a three-terminal capacitor (see figure 3-20). In this and later patents he showed a variety of "transformer bridge" circuits including some using transformers in both input and output circuits. His circuits were discussed in papers by Walsh[19] (1930) and Starr[20] (1932) which describe the use of three-winding transformers in bridge circuits.



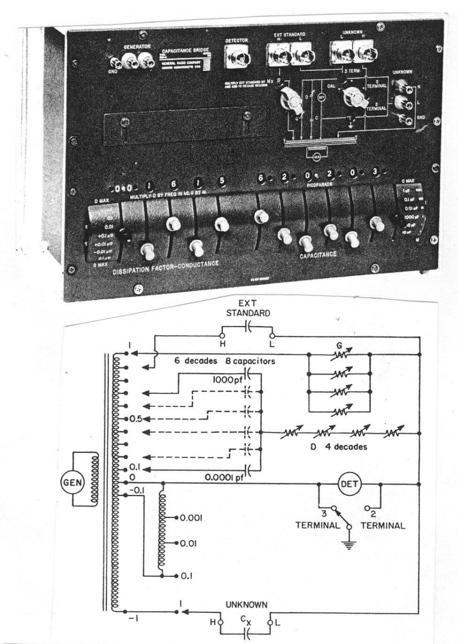
a. Coupled-Ratio-Arm Br. b. 3-Winding Br. c. Double-Ratio Br. d. Ac Kelvin Br. e. Lynch Bridge

3-21 Transformer-Ratio-Arm Bridge Circuits

Five basic transformer-bridge connections are shown in figure 3-21. The first uses the pair of inductively coupled windings as ratio arms. Ideally $N_1/N_2 = Z_x/Z_S$ but the winding impedances, resistance and leakage inductance, do affect the balance somewhat but the effect can be very small if high-permeability toroidal cores are used (μ values greater than 10^5 are possible) and if the windings are carefully made. The second circuit uses a third windings that allows a common ground for the source and detector. Here the winding impedances don't affect the ratio, but instead they are put in series with Z_x and Z_S and thus this circuit is not good for comparing very low impedances. The third circuit, referred to as a double-ratio bridge, is capable of an extremely wide impedance range because the balance equation depends on two winding ratios: $Z_x/Z_s = (N_1/N_2)(N_3/N_4)$. The next is an ac version of a Kelvin bridge that uses a second transformer to balance the "yoke" impedance, Z_y. This is sometimes referred to as the Hill Bridge because Hill made good use of it[21]. Here the ratio N_3/N_4 should be set equal to N_1/N_2. Note that 4-terminal connections are made to both Z_x and Z_s. The last circuit is unbalanced and thus has somewhat poorer ratio accuracy. The transformer is used as an inverter to get a signal of opposite phase. A.C. Lynch[22] used this circuit in a substitution capacitance bridge in which the unknown capacitance was added in parallel with a variable capacitance and a difference measurement made. Hence the ratio was not critical. It has the advantage of tolerating extreme loading to ground on either side of the DUT because these admittances are placed directly across either the source or the detector where they don't affect the balance conditions. (One should note that like all true (passive) bridges the source and detector of these bridges can be interchanged, at least in theory. However there are practical considerations, particularly pickup in the transformer from external sources that causes more trouble if the transformer is in the output. Note that if the detector is connected to the transformer in the 3-winding bridge (Figure 3-15b) the circuit diagram is the same as that of the early “differential method”.

One of the earliest applications of the method for precision measurements was a bridge by Garton[23] (1940) that could detect 2 micro-radians of loss angle. Clarke and Vanderlyn[24] (1949) developed a commercial general-purpose mutual admittance bridge using the circuits of Blumlein. Oatley and Yates[25] (1954) discussed the use of this type of bridge for the precise comparison of impedance standards which proved to be the most important application of "transformer" bridges". Siemens and Halske made an early commercial TRA bridge. An interesting application was the capacitive aircraft altimeter designed by Watton and Pemberton[26] (1949) that measured capacitances down to 1 aF (then referred to as μμμF) to detect the effect of the earth on the capacitance between two wing-mounted electrodes. In spite of this high sensitivity to capacitance changes it had a very limited range as an altimeter.

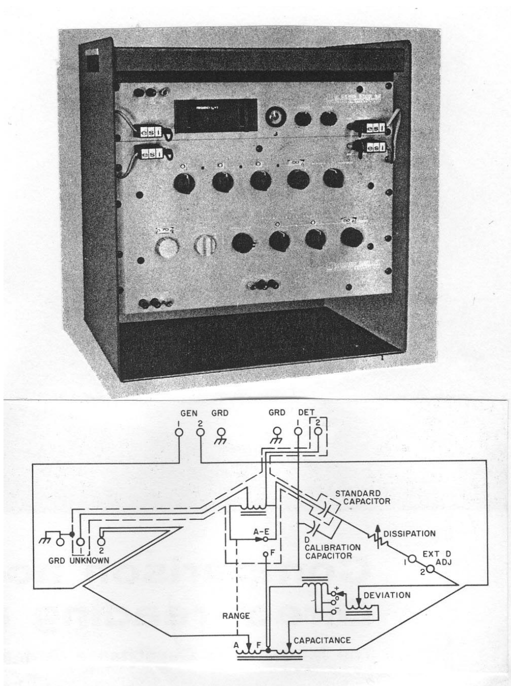
The particular advantages of transformer-ratio-arm bridges were critical in the application of "A New Theorem in Electrostatics" by Thompson and Lampard[27] (1956) that showed it was possible to have a calculable standard of capacitance whose value depended only on a single length measurement. The practically realizable value of capacitance was very low, less than 1 pF, so that accurate measurements required good guarding and precise ratios were needed to extend the calibrations to higher, more useful values. A team of scientists was assembled at NBS to work on the design of a bridge with extreme accuracy for these absolute measurements[28]. Their work was the basis for the precision NBS bridge still in use. It uses the three-winding transformer connection (see Figure 3-21b) with eight precision capacitors of decade values, 10 aF to 100 pF, switched, by lever switches, between fixed transform taps of decimal steps. Thus each capacitor represented one digit of the readout. A modified version of this design, the GR 1615 designed by John Hersh[29] (1962), uses six low-temperature-coefficient air capacitors and second transformer with decade ratios to extend the range, see figure 3-22. This bridge and an even more precise version, the GR 1616, also designed by Hersh[30], are used in most every standards lab in the world and the 1615 is still being made (by IET Labs).



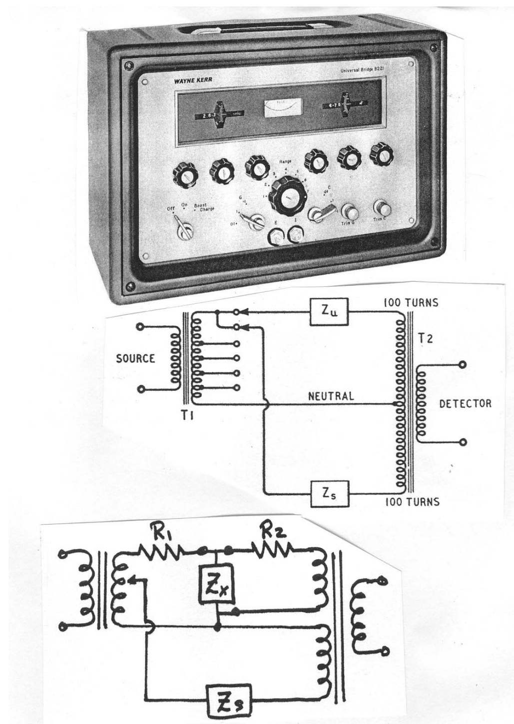
3-22 Capacitance Bridge
GR 1615-A 1962

The competing ESI models 700 and 701 used a single temperature-compensated capacitance standard and an adjustable multi-decade transformer (or IVD, inductive voltage divider) as the main adjustment as shown in figure 3-23. This made calibration easier but resulted in higher transformer output impedance that limited the frequency range[31].

The company that made the most use of transformer-ratio-arm bridges was Wayne-Kerr in England, founded in 1946 by Richard Foxwell and Raymond Calvert and named for movie stars Naughton Wayne (a British comedy star) and Deborah Kerr who were then working for a film company owned by a relative of Foxwell's. (Thus Kerr is pronounced "car".) They used transformer ratio arms in almost all of their bridges including their low-frequency B-221 Universal Bridge designed by Calvert[32]. While this bridge measured admittance over a wide range, an external adaptor (Model Q221) was used to measure extremely low impedances by connecting them in the leg of a Tee network as shown in figure 3-24. The transfer impedance of this Tee network is $R_1 + R_2 + R_1R_2/Z_x$. The first two terms can be balanced by a fixed resistor in series with the standard Z_S making $Z_X \sim R_1R_2Y_S$ but for very low values of Z_X the resistors R_1 and $_2$ are negligible and can be ignored.

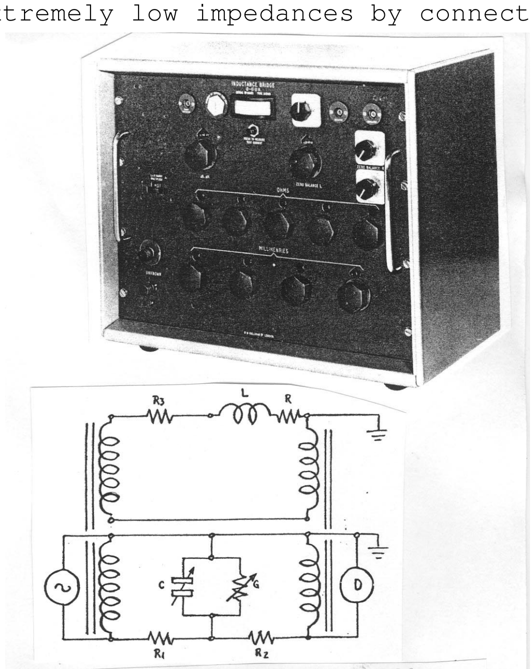


3-23 Capacitance Measuring System
ESI Model 700 1960



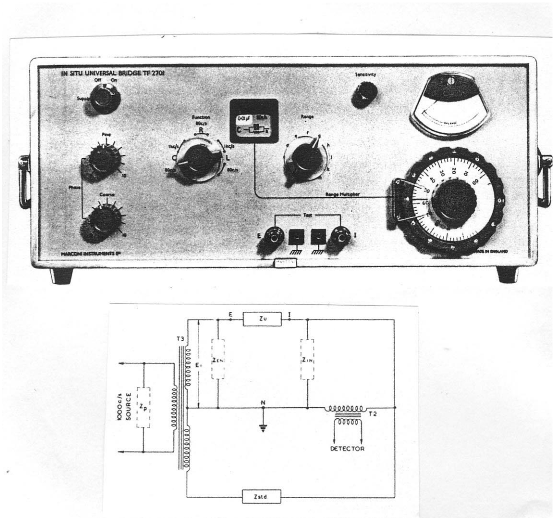
3-24 Universal Bridge
Wayne-Kerr Model B221 c1955
Lower diagram shows bridge with
Low-Impedance Adaptor

H.W. Sullivan Ltd. also used transformers with a Tee network as the standard in their model R4000 "Decade Inductance Bridge"[33]. In this case the network was an R-C network whose transfer impedance is $R_1 + R_2 + R_1R_2(G + C)$ which at balance equaled $R_3 + R_X + j\omega L_X$. Note that the "spoiler" resistor R_3



3-25 Decade Inductance Bridge
Sullivan Type R4000 c1967

was added to balance the resistance $R_1 + R_2$. This bridge used the transformer asymmetrically (as does the circuit of figure 21e) and it also used the isolating property of a transformer to permit the grounding of both the unknown inductor and the variable standards C and G (see figure 3-25).

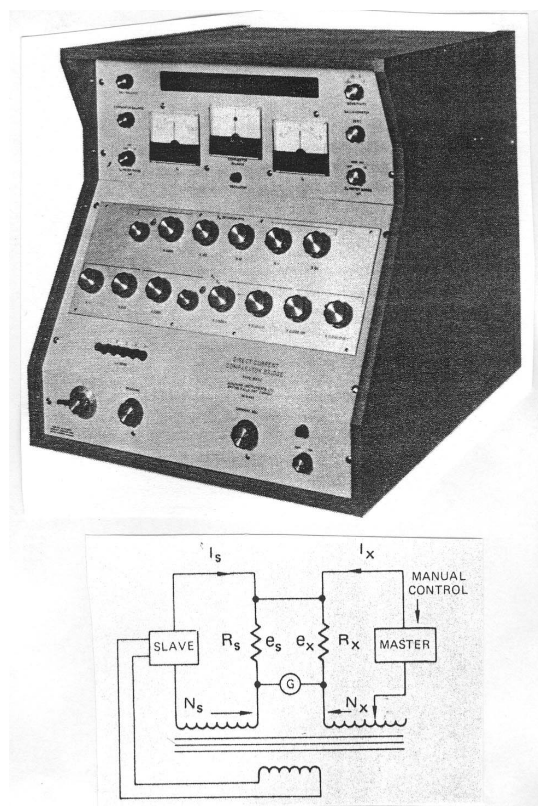


3-26 In Situ Universal Bridge
Marconi TF 2701 1964

The inherent guarding capability of a transformer-ratio-arm bridge allowed them to make "in-situ" or "in-circuit" measurements as long as all circuit paths shunting the DUT were guarded. The Marconi model TF 2701 In-Situ Bridge was made especially for this purpose (see figure 3-26).

The advantages of using inductively-coupled ratio arms for precision low-frequency ac measurements on resistance standards were discussed by D.L. Gibbings[34] of NSL (National Standards Laboratory, Australia) and by J.J. Hill[21] of the NPL (National Physical Laboratory, England) both of whom designed Kelvin-type transformer bridges with a transformer dividers as the auxiliary, yoke-balancing arms (see figure 3-15d). Gibbings' version used a two-stage transformer for the main ratio which improves the ratio accuracy. Foord, Langlands and Binnie[35] [3.35] of the University of Glasgow made a four-terminal bridge by using transformers to inject the yoke-lead voltage drops into the main transformer-ratio ratio arms thus canceling the errors they caused to a high degree.

Transformer ratio arms were adapted for dc resistance measurements in the Guildline Current Comparator Bridge, Type 9920 (figure 3-27), a design based on the work of MacMartin and Kusters[36] at the Canadian NRC (National Research Council). In this circuit a dc ampere-turn unbalance in the ratio transformer is detected by its distorting effect on a square-wave modulating signal. This unbalance controls the slave supply that keeps $I_S N_S = I_X N_X$. The bridge is manually balanced until the detector is nulled and $R_X I_X = R_S I_S = R_S I_X N_X / N_S$ or $R_X = R_S N_X / N_S$. This bridge allows precise scaling of dc resistance over a wide range of resistance with the extreme accuracy and stability of a precision ratio transformer.



3-27 Direct Current Comparator Br.
Guildline Model 9920 1966

Yet another application of transformer-ratio-arm bridges was in the measurement of high-voltage capacitors. A paper by Kusters & Petersons[37] of the NRC was a classic on this subject.

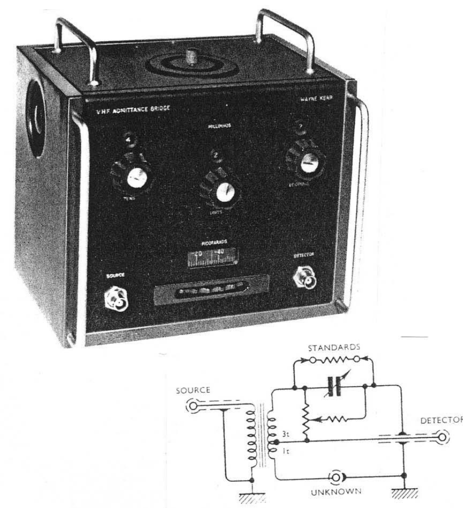
A clever application of transformers is their use in bridges that make electrodeless measurements on high-conductivity, electrolytic fluids. In one method[38] the fluid is in a tube that forms one turn on both an input and on an output toroidal transformer. In another method, patented by Relis[39], was used in the Beckman RS5-3 In-Situ Salinometer and RS7-B Induction

Salinometer. In both instruments two toroidal transformers are placed side by side and immersed in the fluid which forms a one-turn “winding”. The conductivity of the sample is balanced by adjustable components connected between opposed windings on the two transformers.

3.5 RF Bridges

Transformer ratio arms were also used in RF bridges. Kirke[40] (1945) described bridges designed at the BBC (many by Mayo) including one designed 1935 and a ultra-short-wave bridge that went up to 200 MHz. Calvert of Wayne-Kerr designed a series of HF transformer-ratio-arm bridges, the types B201, B601, B602, B-701, B801 and B901, the last (figure 3-28) operating up to 250 MHz[41]. Note that there are very few turns on the ratio transformer of this VHF bridge.

Direct capacitance bridges designed by John Mennie[42], the Boonton Electronics Models 74 (100kHz) and 75 (1 MHz), used a circuit patented by C. H. Young[43] of Bell Labs in 1945 which combined a three-winding transformer with a differential capacitor see figure 3-29. Mennie also used transformers in his Model 63 Inductance Bridge (to 500 kHz) and his Model 33 Admittance Bridge (to 100 MHz).

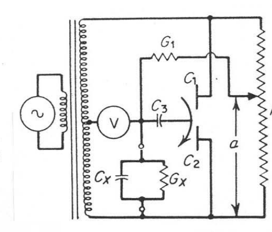


3-28 V.H.F Admittance Bridge
Wayne Kerr Model B901 1962

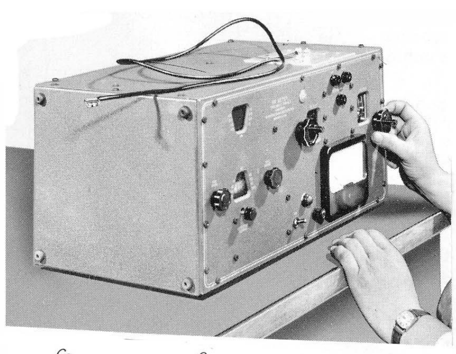
The latter was a parallel substitution circuit in which the change in admittance between the unknown and an open-circuit was measured. This was similar to his earlier (1952) Model 250 RX Meter[44], figure 3-30, which he designed for the Boonton Radio Corp, (later acquired by HP). This was not a meter but a bridge, a transformer bridge with two Tee networks (a so-called "Opposed T") but was referred to as a modified Schering

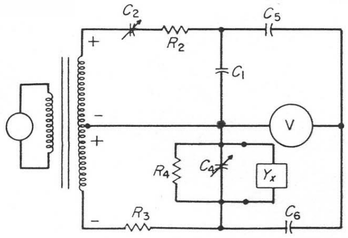
$$C_x = \frac{(C_1 - C_2)C_3}{C_1 + C_2 + C_3}$$

$$G_x = \frac{G_1(2a - 1)}{1 + G_1R(a)(1 - a)}$$



3- 29 Capacitance Bridge
Boonton Electronics Model 74 1955





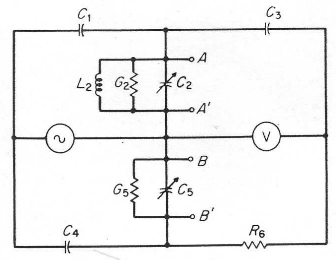
$C_X = \Delta C_4$

$R_X \sim C_2$
Parallel R

3-30 R-X Meter
Boonton Radio Model 250 1952

Bridge. It measured equivalent parallel resistance and capacitance and, at certain frequencies, parallel inductance, and it operated from 0.5 to 250 MHz.

Donald Woods[45] of the British Ministry of Aviation modified the Twin-T of Sinclair (see figure 2-38) to have two pairs of measurement terminals, making it a so-called "dual" bridge (1952) (figure 3-31). His bridge was an assembly of coaxial components with precision connectors and used variable capacitors for both capacitance and conductance balances. The unknown was measured first at one terminal pair and then the other giving added information that removed bridge errors. Les Huntley[46] (1965) at NBS (NIST) modified and improved this circuit and his instrument is still used to make high frequency calibrations of standards with coaxial connectors.



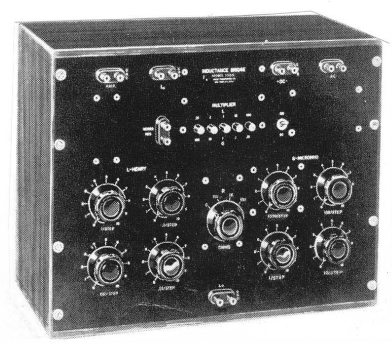
$$C_1 + C_2 + C_3 + \frac{C_1C_3}{C_4}(1 + R_6G_5) = \frac{1}{\omega^2 L}$$

$$\omega^2 R_6 C_1 C_3\left(1 + \frac{C_5}{C_4}\right) = G_2$$

3-31 Dual Admittance Bridge
D. K. Woods 1952

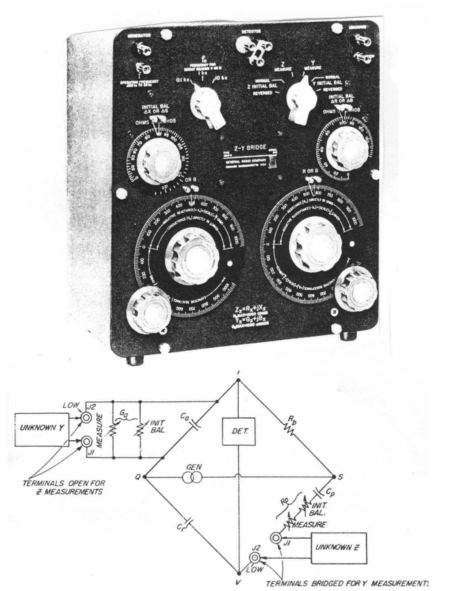
3.6 Special Purpose Bridges

Besides the special bridges designed for measuring electrolytic capacitors, high-voltage capacitors and vacuum-tube parameters (see part II), another type of special purpose bridge was the "incremental inductance bridge" designed to measure iron-cored coils and transformers while dc bias current was applied[47]. If the signal was small compared to the bias, the measured inductance was called the incremental value at that bias. Most of these bridges could also apply large ac signals to simulate line-voltage. Many of these, such as the Freed 1110-A, figure 3-32, applied the dc between opposite corners of the bridge and used the Hay or the series Owen circuits which had arms containing series capacitors which blocked the applied dc current from the adjustable arms putting it all through the DUT. Bridges such as Maxwell's bridge that used parallel R-C arms required an added blocking capacitor. Other instruments used novel circuits to measure biased inductors such as the GR 1633, which used a bridge circuit containing active elements, see section 3.9 below.



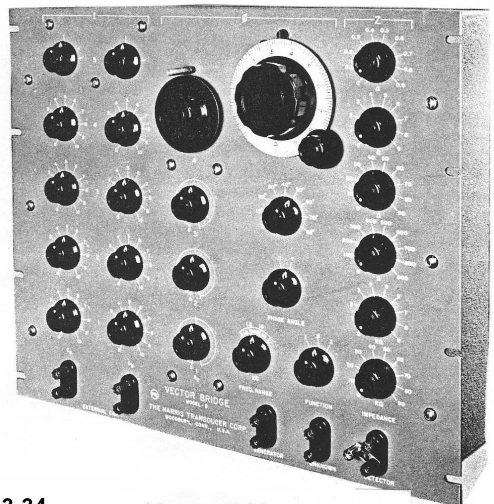
3-32 Incremental Inductance Bridge
Freed Type 1110-A c 1954

Another large class of special bridges heretofore unmentioned is so-called "temperature" bridges; bridges used to measure resistance thermometers, particularly platinum resistance thermometers (see review of these bridges in reference 3.48). Classic dc bridges for this purpose were designed by Callender (1891), Northrup (1906), Smith (1912) and Mueller (1917). Because the resistance of the temperature sensors was relatively low (usually 25 ohms) and of narrow range, many of these bridges used Waidner-Wolff adjustments that greatly reduced the effect of switch contact resistance (see part II). As shown by Hunter[49] and Hill & Miller[50], low-frequency transformer bridges could be used in this application and they had the advantages of being immune to thermoelectric emfs as well as having precise and constant ratios.

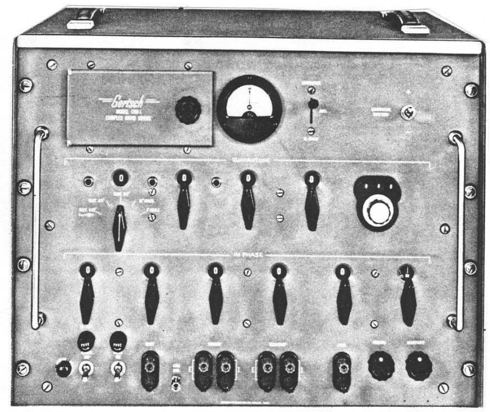


3-33 Z-Y Bridge
GR Type 1603-A 1955

While most bridges were designed to test components or standards and therefore had displays that read R, L or C, there were bridges (and meters, see below) that read other quantities such as complex impedance and admittance or their magnitudes and phase angle. A good example was Easton's GR1603[51], figure 3-33, which was an audio-frequency Schering bridge that used variable resistors ("pots") rather than the variable capacitors used in RF bridges and made both series and parallel substitution measurements to measure either R and X or G and B. This was a useful instrument for measuring electrical devices and networks that had large phase angles. The Harris Transducer Corp. Type B "Vector Bridge" that read impedance or admittance and phase angle had 26 knobs on the panel. Another unusual bridge was the Gertsch/Singer CRB series Complex Ratio Bridges that measured complex voltage ratios of networks, transformers, resolvers etc. These used precision inductive dividers for the main balance and active circuits to get the quadrature signal for the phase-angle balance[52].

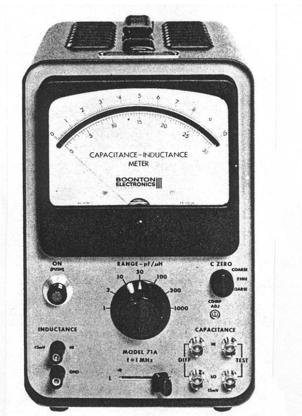


3-34 Vector Bridge
Harris Transformer Co. Model B



3-35 Complex Ratio Bridge
Gertsch/Singer Model CRB 1 1958

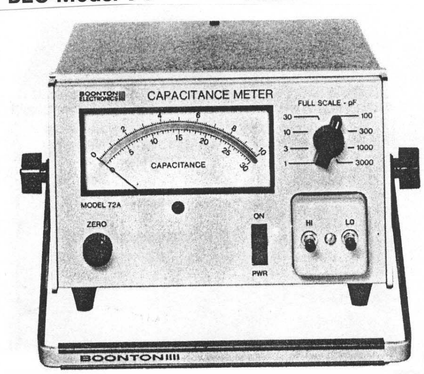
3.7 Impedance Meters



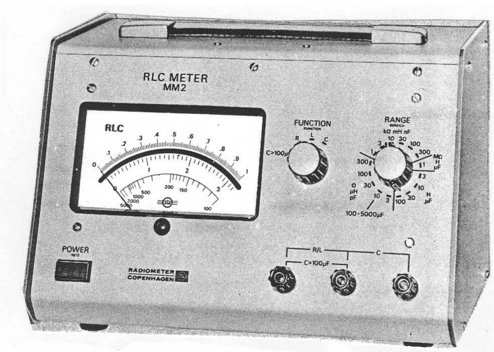
3-36 Capacitance Meter
BEC Model 71 1965

Though usually not as accurate as bridges, impedance meters were much easier to use because no manual balancing was necessary. Several companies made C and L meters that were the ac equivalent of dc ohmmeters and either measured the current through the DUT with a constant voltage applied or the voltage across it with a current applied. A good example was the BEC (Boonton Electronics Corp.) model 71A designed by R. E. Lafferty[53], figure 3-36, which measured both C and L at 1 MHz. BEC later sold an improved model 72A, figure 3-37. The sloping-panel Radiometer Type MM2, figure 3-38, read R, L and C over a wide frequency range.

Boonton Radio's popular Q meter was revised and its frequency range extended in new models. Other manufacturers such as Freed, Marconi and Yokagawa

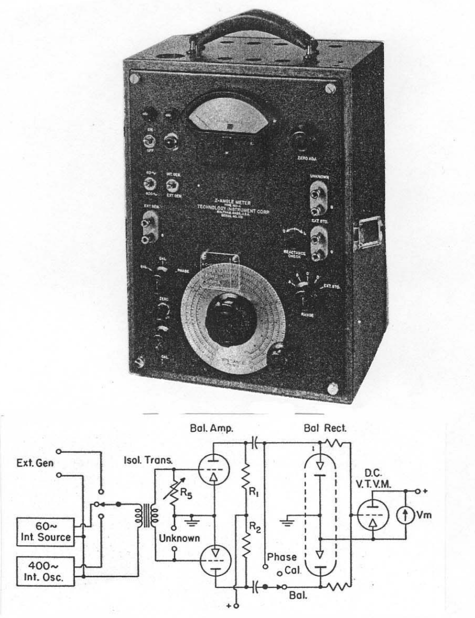


3-37 Capacitance Meter
BEC Model 72A 1971



3-38 RLC Meter
Radiometer Type MM2 c1970

Electric (YEW) also made Q meters. Note both BRC and YEW were later bought by HP who included a more modern version, the Type 4342A, in their 1993

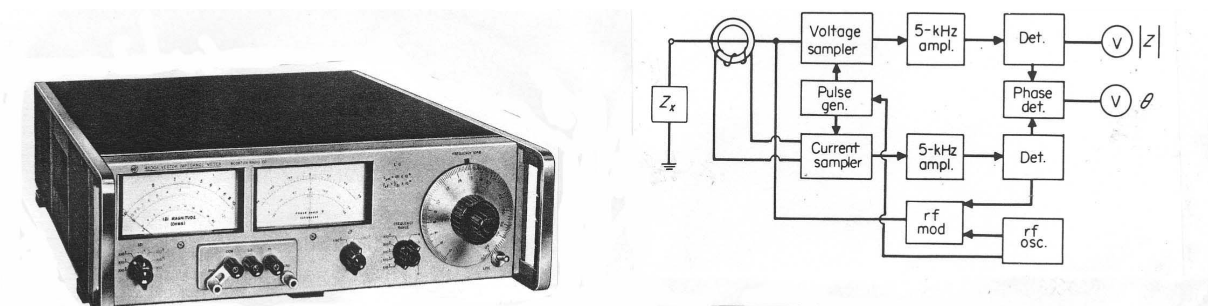


3-39 Z-Angle Meter
Technology Inst. Co. c1947

3-40 Vector Impedance Meter
Radiometer Type GB11 c1950

catalog. Series resonance was also used in capacitance meters such as the Rhode & Schwarz (Federal) Type FT-KARA which used an inductor as the standard to resonate with the unknown capacitance, the opposite of the Q meter.

A disadvantage of most impedance meters is that they measure only one quantity, not C and D or L and Q. The Z-Angle Meter of Technology Instruments Corporation), figure 3-39, was designed by Luke Packard (who left GR to co-found TIC, which was called Acton Labs for some years.) This is a hybrid instrument that uses bridge-like balance for impedance magnitude but, when balanced, reads phase angle on a meter. Another somewhat similar instrument is the Radiometer GB-11 Vector Impedance Meter[54] (figure 3-40) that uses the "Grützmacker" Bridge[55]. This also requires a magnitude balance and reads phase angle on a meter. The later Boonton Radio (later HP) model 4800 Vector Impedance Meter, figure 3-41, reads both magnitude and phase with no balancing required over a wide frequency range, to 500 kHz, using a



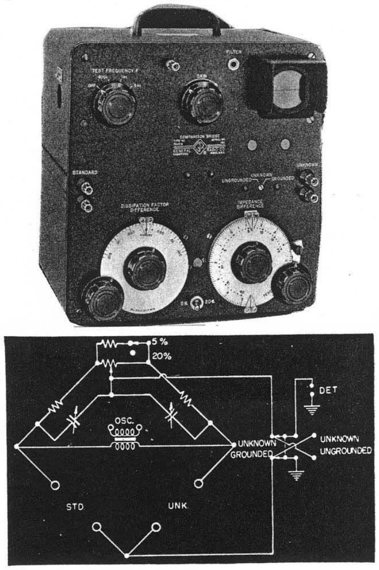
3-41 Vector Impedance Meter
BRC/HP Type 1965

48

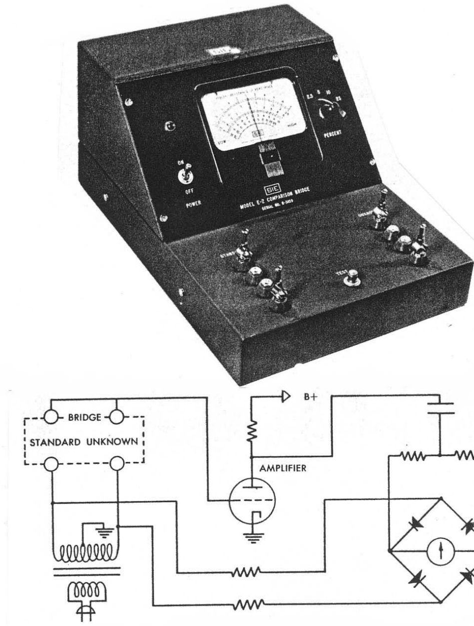
toroidal transformer to sample the current in the unknown.

3.8 Impedance Comparators

The "limit bridge" principle discussed above as used for sorting resistors at dc was also used to sort components, C, L and R, at ac. These instruments provided only the ratio arms, thus requiring an external standard as well as DUT, and hence some were called "impedance comparators". They required phase-sensitive detectors not only to get the sign of the deviation, but also to separate out the real and imaginary parts. The first was the GR 1604-A Comparison Bridge designed by Holtje[56] that used 1:1 resistive arms that could be adjusted over a 20% range and for null on the



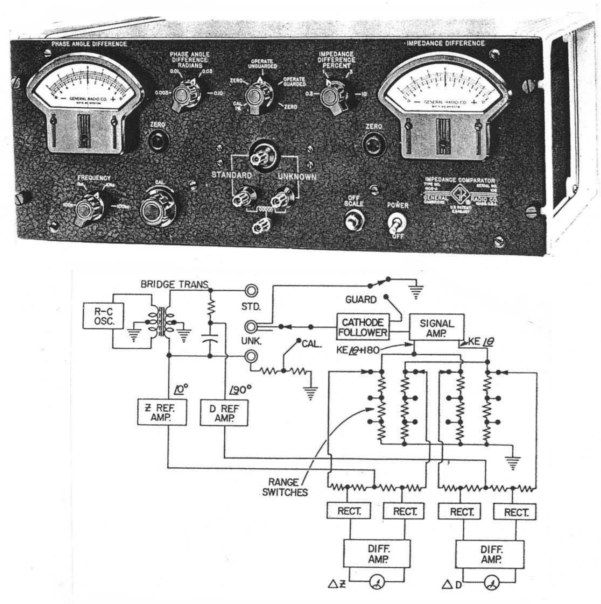
3-42 Comparison Bridge
GR Type 1604-A 1954



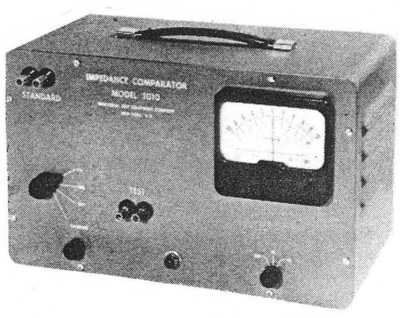
3-43 Comparison Bridge
S.I.E. Model E2 1954

CRT detector. It also had a phase or D-Q balance. The unbalance indicated by the CRT could be used for fast sorting. Later instruments used meters to indicate the percent unbalance. The Southwestern E2 Comparison Bridge, figure 3-43, designed by Erath[57] used balanced windings on the power transformer to drive the standard and unknown and thus was a transformer bridge. By contrast other instruments, such as the Industrial Instruments Type 1110 Impedance Comparator, figure 3-44, used resistive ratio arms and a 1 kHz test signal. These instruments, and several other similar ones, read only magnitude difference. The GR 1605-A Impedance Comparator[58], figure 3-45, also read phase angle difference. It had several ranges with resolution down to .01%. If the components were reasonably pure, the magnitude difference reading was closely equal to percentage differences in R, L or C and the phase difference was closely equal to D differences for capacitors or inductors or Q differences for resistors. This was one of the first instruments to use a high-permeability toroidal transformer with twisted-pair windings for its precise 1:1 ratio arms. Comparators became very popular for incoming inspection and production testing and were made by many companies including ESI, Rohde & Schwarz, Bruel & Kjaer and many others.

Ac Comparators and dc limit bridges were built into many early



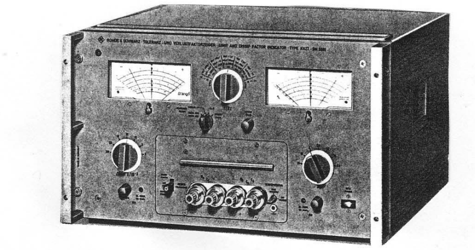
3-45 Impedance Comparator
GR Type 1605-A 1955



3-44 Impedance Comparator
Industrial Inst. Type 1110 c1955

automatic test systems that included mechanical component handlers. One of the earliest in the USA was the Industrial Instruments AB series (1958) and in Germany such systems were made by Klemt. The GR 1605 was used in one of the first in-circuit test systems. It compared the impedances between terminals on a terminal strip or printed-circuit card to those of a "known good" similar assembly[59].

3.9 Electronics in Instruments



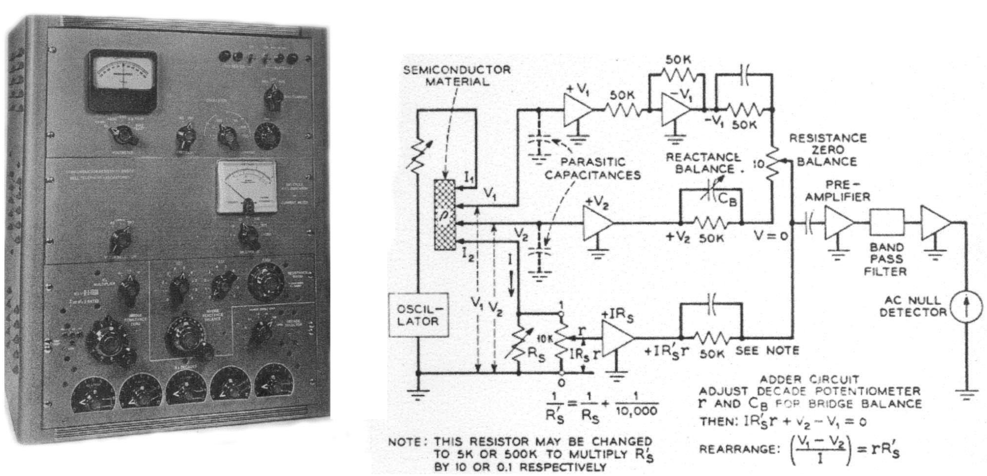
3-46 Limit & Dissipation Factor Indicator
Rhode & Schwarz KVZT c1965

As soon as vacuum tubes were available they were used in making better signal sources. Perhaps the earliest was Vreeland's mercury-cathode triode oscillator in 1908[60] and many famous vacuum-tube oscillator circuits many followed Eccles-Jorden, Colpitts, Hartley etc. An early use of tubes in ac detectors was that by Adams & Hall[61] (1919). Probably the first oscillator-detector system built in a commercial bridge system was Lamson's[62] 650-P1 module for the famous GR 650 bridge. It used R-C Twin-T Circuits both in the oscillator and the selective amplifier. The 650's successor, the 1650-A, was one of the first bridges to use transistors in its internal source and detector.

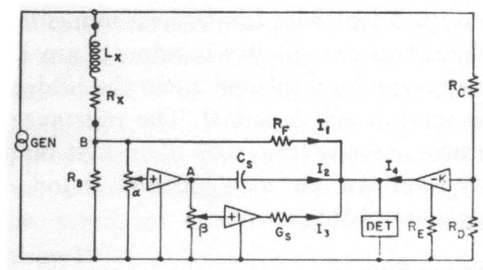
Active null detectors were also used in dc bridges where the main problem was getting low drift in the input circuits. Many detectors used "choppers" to modulate the dc and these were mechanical vibrators, transistor switches or non-linear magnetic devices. High resistance ("megohm") bridges such as the GR 1644, used sub-miniature "electrometer" vacuum tubes that have extremely low grid current.

Impedance meters used active circuits in the measuring circuit such that the accuracy of the instrument depended directly on the precision of the active elements which usually were feedback amplifiers. In the case of comparators, it was the measured impedance *difference* that depended on the accuracy of the amplifiers. Gertsch Complex Ratio Bridges used voltage followers in the secondary balance (see above).

M. A. Logan[63] of Bell Labs was probably the first (1961) to use amplifiers in the main balance of a bridge circuit. He used vacuum tubes in three-stage, unity-gain amplifiers and inverters to get good 4-terminal (four-point probe) ac measurements on semiconductor samples even though there was high resistance in each connection (figure 3-47). Probably the first commercial "active" bridge was the GR 1633, (see figure 3-48)



3-47 Four-Point-Probe Bridge
Logan, Bell Labs 1961



3-48 Incremental Inductance Bridge
GR Type 1633 1962

If

$$R_F = \frac{R_E(R_C + R_D)}{R_D}$$

then

$$L_X = \frac{\alpha C_S R'_B R_E(R_C + R_D)}{R_D}$$

$$Q_X = \frac{\omega L_X}{R_X} = \frac{\omega C_S}{\beta G_S}$$

introduced in 1962 that used high-feedback transistor amplifiers to allow a bridge circuit that could display Q directly at several frequencies well as series inductance and resistance[64]. W. P. Harris[65] of NBS (1967) made a ULF bridge operating down to .001 Hz for low-frequency measurements on dielectric materials that used Philbrick dc operational amplifiers. It used a Lissajous pattern on a long-persistence oscilloscope as a detector down to 0.1 Hz and on a Z-Y recorder below that. Needless to say, making a balance at .001 Hz took considerable time.

References Part III

3.1 MIL-Q-9858, US Dept of Defense, April 9, 1959
"Quality Control Requirements"
Air Force Bulletin NR. 520, May 17, 1960
"Calibration and Certification of Measuring and Testing Equipment"
MIL-C-45662A US Dept of Defense, 1962 (revised in 1980 & 1988)
"Calibration System Requirements"

3.2 Lee, M.M., "A Passion for Quality, The First Fifty-Five Tears of Electro Scientific Industries 1944-1999"
Electro Scientific Industries 1999

3.3 Hall, H.P., "A New Universal Impedance Bridge"
GR Experimenter, March 1959

3.4 Hall, H.P., "A Precise, General-Purpose Impedance Bridge"
GR Experimenter, March 1962

3.5 Harris, F.K., "Electrical Measurements", John Wiley & Sons, 1952, p.285, or Thomas, J.L., "Precision Resistors and Their Measurement", NBS Circular 470, p.18

3.6 Riley, J.C., "Traceability of Resistance Measurements"
ESI Engineering Bulletin #30

3.7 Julie, L. "Ratio Metrics -- A New, Simplified Method of Measurement Calibration and Certification" *IEEE Conv. Rec.* Pt.8 p.225, 1964
See "Notes on the Julie Ratiometric Method of Measurement", p. 31, Julie Research Laboratories, Inc., New York, NY (1964)

3.8 Hague, W.H. Jr., "Versatile Limit Bridge Doubles as a Laboratory Standard" *GR Experimenter* January 1952

3.9 Chrystal, G., "On the Differential Telephone"
Trans Roy. Soc Edin., 29, 609-636 (1880), see also Ho, H., "The use of differentially wound telephone receiver in electrical measurements" *Elec. World*, Vol 41, p. 884-885 (1903)

3.10 Hague, B. & Foord, T.R., "Alternating Current Bridge Methods", Pitman, 1971. p.245

3.11 Elais, A., "Ueber Widerstandsmessungen mit dem Differentialinductor" Ann. der Phys, Vol. 335, p. 828-833 (1888), Also Vol 42, p. 275-279 (1891) See also reference 3.10.

3.12 Trowbridge, A. "On the Differential Transformer
Phys Rev, Vol. 20, p. 67-76 (1905), see also reference 3.10

3.13 Hund, A., "High-Frequency Measurements", McGraw-Hill 1933, p. 217
See also Hund, A., "Measurements at Radio Frequencies"
Electrical World, Vol. 84, No 19, p998, Nov 1924

3.14 Campbell & Childs, "The Measurement of Inductance Capacitance and_ Frequency", McMillan 1935, p. 355

3.15 Brown, H.A., "Radio Frequency Electrical Measurements", McGraw-Hill 1931, p. 37.

3.16 Campbell, G.A. "Measurement of Direct Capacitance",
Bell Sys Tech J. vol. 1, p. 18-30, 1928

3.17 Scroggie, M.G., "The Genius of A. D. Blumlien"
Wireless World Sept 1960, pp 451-456

3.18 Blumlein, A.D., British Patent No. 323,037 "Alternating Bridge Circuits"

3.19 Walsh, R. "Inductive Ratio Arms in Alternating Current Bridge Circuits"
Phil Mag, 7th Series, Vol 10, p 47-70 1930

3.20 Starr, A.T., "A Note on Impedance Measurement"
Wireless Eng & Experimental Wireless, Vol 9, p. 615-617 Nov 1932

3.21 Hill, J.J. "Calibration of d.c. resistance standards and voltage-ratio boxes by an a.c. method", *Proc IEE*, Vol.112, No.1 January 1965

3.22 Lynch, A.C. "A Bridge Network for the Precise Measurement of Direct Capacitance", *Proc IEE* 104B p.363 1956

3.23 Garton, C.G. "The Drying Process in Paper as Determined by Electrical Methods" *Jour IEE*, Vol 86, p. 369-378, (1940)

3.24 Clark, H.A.M and Vanderlyn, F.B., "Double-Ratio A-C Bridges with Inductively-Coupled Ratio Arms" *Proc IEE,* Vol 92 Part III, p 189-198, 1949
3.25 Oatley, C.W. and Yates, M.A., "Bridges with Coupled Induuctive Ratio Arms as Precision Instruments for the Comparison of Laboratory Standards of Resistance and Capacitance" *Proc IEE,* vol. 101. Part III March 1954
3.26 Watton, W.L. and Pemberton, M.E.,"A Direct-Capacitance Aircraft Altimeter" *Proc IEE*, Vol. 92, Part III pp 203-213, 1949
3.27 Thompson, A.M. and Lampard, D.G., "A New Theorem in Electrostatics and Its Application to Calculable Standards of Capacitance" *Nature*, Vol 166, p. 888 1956
3.28 McGregor, M.C., Hersh, J.F., Cutkosky, R.D., Harris, F.K. and Kotter, F.R., "New Apparatus at the National Bureau of Standards for Absolute Capacitance Measurements", *IRE Trans on I&M*, Dec 1958 pp 253-261
See also: Thompson, A.M., "The Precise Measurement of Small Capacitances", IRE Trans on Inst & Meas Dec 1958, Vol. I7, Nos. 3&4 p 245
3.29 Hersh, J.F., "Accuracy, Precision and Convenience for Capacitance Measurements", *GR Experimenter*, Aug-Sept 1962
3.30 Abeniam, D. and Hersh J.F., "New Fused-Silica-Dielectric 10- and 100-pF Capacitors and a System for Their Measurement" (GR 1616 Capacitance Br.) *IEEE Trans on Inst & Meas,* Vol. IM-19, No.4, p. 302-307 N ov 1970
3.31 ESI Catalog Sheet C-28
3.32 Calvert, Raymond "The Transformer Ratio-Arm Bridges" Wayne Kerr monograph No.1
3.33 Silcocks, A.H., "Developments of Transformer Ratio Arm Bridges", IEE Lecture to the Joint Group on Basic Electrical Theory, May 1967 See also H.W. Sullivan Ltd. catalog Sheet No. 141
3.34 Gibbings, D.L.H., "Alternating current analogue of Kelvin Double Bridge", Proc IEE, Vol 109 Pt C, no 16. p. 307-316, Sept 1962
3.35 Foord, T.R., Langlands, R.C. and Binnie, A.J., "Transformer-Ratio Bridge Network with Precise Lead Compensation", *Proc. IEE*, Vol. 110 #9, Sept. 1963, p.86.
3.36 MacMartin, M.P. and Kusters, N.L., "A Direct-Current Comparator Ratio Bridge for Four-Terminal Resistance Measurements", *IEEE Trans on Inst & Meas* Vol IM-15, p.2132-219, Dec 1966
3.37 Kusters, N.L. and Petersons, O., "A Transformer-Ratio-Arm Bridge for High-Voltage Measurements" *IEEE Trans on Communications & Electronics*, Nov 1963. See also: Petersons, O., "A Self-Balancing High-Voltage Capacitance Bridge", *IEEE Trans on Inst & Meas,* Dec. 1964 pp.216-224
3.38 Calvert, R. "Industrial Applications of Transformer Bridge Circuits" *British Communications and Electronics*, April 1956, p. 180-183
3.39 Relis, M.J., "Method and Apparatus for Measuring the Conductivity of an Electrolyte", US Patent 2,542,057, Feb. 1951 (Filed May 1948). See also Beckman Instruments Catalog #33 "Conductivity Meters and Electrodeless Salinometers For Measurement of Fresh Water and Sea Water"
3.40 Kirke, H.L., "Radio-Frequency Bridges" *Jour IEE*, Vol.92, Part III, p. 2-7, 1945
3.41 “Electronic Measuring Instruments” Wayne-Kerr 1969
3.42 Lafferty, R.E., memo to R.A. Soderman, 1992
3.43 Young, C.H. "Measuring inter-electrode capacitances" *Bell Lab Rec* vol.24, p.433-438, Dec 1946
3.44 Mennie, J., "A Wide-Range VHF Impedance Meter", (BRC "R-X Meter") *BRC Notebook*, #2, Summer 1954. (Also paper at the 1952 IRE Convention)
3.45 Woods, D. "A Precision VHF Twin-T Dual Admittance Bridge and Associated Standards", Report No. A.I.D Rad Elec 17 (Jan **1950**)
3.46 Huntley, L.E. "A Self-Calibrating Instrument for Measuring Conductance at Radio Frequencies", *NBS J. Res*, Part C, Vol.69C #2, April-June, 1965 p. 115
3.47 Terman, F.E., “Measurements in Radio Engineering”, McGraw-Hill, 1935

Section 15 "Measurement of Incremental Inductance"
See also Golding, J.F., "Incremental Inductance Measurement"
Electronics and Communications, April 1966 and also reference 3.64
3.48 Daneman, H.L. and Merger, G.C., "Precise Resistance Thermometry - A Review", *Instrum. Technol.* 1967 Vo. 14 pp 51-56 & 65-69
3.49 Hunter, J.J, "Precision Temperature Measuring Equipment" *Jour British I.R.E.,* Sept 1962
3.50 Hill, J.J. & Miller, A.P., "An a.c. double bridge with inductively coupled ratio arms for precision Platinum resistance thermometry" *Proc. IEE*, No. 110 no. 2, Feb 1963, pp. 453-8.
3.51 Easton, I.G., "The 1603-A Z-Y Bridge" *GR Experimenter,* July 1955
3.52 Gertsch-Singer Digest Catalog 1958
3.53 Lafferty, R.E., Memo to R.A. Soderman, 1992
3.54 Lund, R., "Direct-Reading Meter Gives Impedance and Phase Angle" *Electronics*, Jan 3, 1964
3.55 Grützmacher, M., "Eine neue Brucke für betriebsmassige Messungen von Wechselstromwiderstanden nach Betrag und Phase", *Telegraphen- und Fernsprechtechnik,* vol 23, p27 February 1934.
3.56 Holtje, M.C., "A New Comparison Bridge for the Rapid Testing of Components", *GR Experimenter*, February 1954
3.57 Smith F.C., private correspondence
3.58 Holtje, M.C, Hall, H.P., & Easton, I.G., ""An Instrument for the Precise Comparison of Impedance and Dissipation Factor" *Proc Nat Elect Conf*, Vol 10, 1955.
See also *GR Experimenter*, April 1956
3.59 Brammer, F.C., "The Semiautomatic Circuit Component Tester", *IRE Trans on Industrial Electronics*, August 1958, pp. 4-10
See also *GR Experimenter,* Nov 1957
3.60 Vreelnd, F.K.,"On a Sine Wave Electrical Oscillator of the Organ Pipe Type", *Physical Review*, vol. 27, p.286, 1908 See also Laws page 420
3.61 Adams, L.H. and Hall, R.E., "Application of the thermionic amplifier to conductivity measurements", *Jour Amer Chem Soc*, vol 41, pp 1515-1525, 1919
3.62 Lamson, H.W., "Have You a Type 650 Impedance Bridge" *GR Experimenter*, April, 1946
3.63 Logan, M.A., "An Ac Bridge for Semiconductor Resistivity Measurements Using a Four-Point Probe", *BSTJ* vol 40, No. 3, pp885-920, May 1961
3.64 Hall, H.P. & Fulks, R.G., "The Use of Active Devices in Precision Bridges", *Electrical Engineering*, May 1962. (See H&F Chapter 9) or see Hall & Fulks, "A New System for Measuring the Inductance of Iron-Cored Coils", *GR Experimenter,* May 1962
3.65 Harris, W.P., "Operator's Procedure Manual for Harris Ultra Low Frequency Impedance Bridge", *NBS Report* 9627, 1967
or "A New Ultra-Low-Frequency Bridge for Dielectric Measurements," *1966 Annual Report, Conference on Electrical Insulation and Dielectric Phenomena*, p72