Reprinted from IRE TRANSACTIONS
ON INSTRUMENTATION
Volume I-9, Number 2, September, 1960

PRINTED IN THE U.S.A.

Absolute Measurement of Temperatures of Microwave Noise Sources*

A. J. ESTIN†, MEMBER, IRE, C. L. TREMBATH†, MEMBER, IRE, J. S. WELLS†, AND W. C. DAYWITT†

COPY

Introduction

THE USE of a discharge tube as a standard source of microwave noise power has been suggested by Mumford[1] and others[2–5] with justifiable recognition of its merits; it is stable, convenient, easily adapted to microwave systems, and has a large excess temperature. There is one drawback, however, which precludes its use as a primary standard at present. In order to qualify as a primary standard of a quantity, a device must have its parameters related to the significant fundamental units of length, mass, time, etc., through an accepted system of theoretical equations.[6] Although the noise temperature is very nearly determined by the electron temperature of the plasma in the discharge tube, and the electron temperature has been calculated approximately,[7–9] this calculation hardly satisfies the requirement of being "through an accepted system of theoretical equations."

Accordingly, the black body radiator through Planck's Radiation Law still remains the primary standard against which others must be calibrated for high accuracy. In this paper, a procedure will be described for calibration of the discharge tube against a black body standard by means of an improved radiometry technique, and the black body itself will be discussed.

The Radiometer

Fig. 1(a) is an illustration of the null-balance type radiometer.[10–12] This type seems to offer the best starting point for a highly precise radiometer in that gain and linearity of the receiver amplifier and detector law do not appear in the balance equation or to a first order in the error equation. Several advantages result from modifying the radiometer to the configuration in Fig. 1(b). The signal paths for both the standard and the source under test are more nearly identical. The insertion loss of the attenuator is eliminated as a source of uncertainty, since an attenuation difference measurement is now made. Asymmetries in the junction of the arms, time variations in the mismatch of the modulators, and receiver mismatch now do not enter into the error analysis.[13] The system does depend, however, on the waveguide switch being repeatable to the desired degree of accuracy.

Ferrite modulators have been used in a scheme such as this.[14] These are rather convenient to use; however,

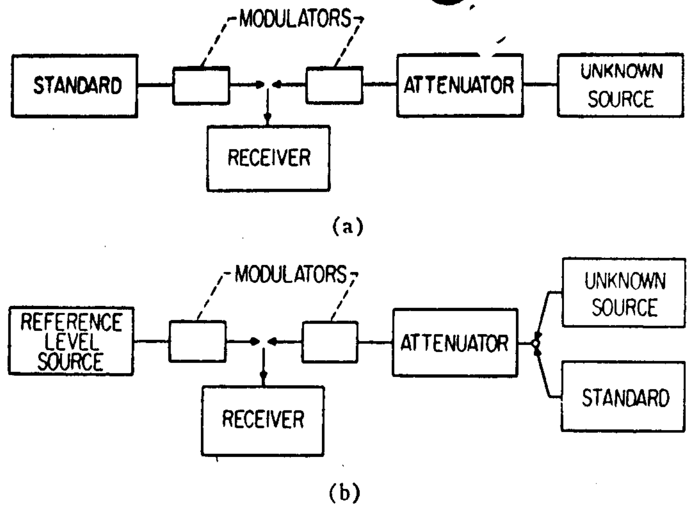

Fig. 1—(a) Block diagram of symmetric null-type radiometer. (b) Block diagram of nonsymmetric null-type radiometer.

* Received by the PGI, July 22, 1960. Presented at the 1960 Conference on Standards and Electronic Measurements as paper 4-3.

† National Bureau of Standards, Boulder, Colo.

[1] W. W. Mumford, "A broad-band microwave noise source," *Bell Sys. Tech. J.*, vol. 28, pp. 608–618; October, 1949.

[2] K. S. Knol, "Determination of the electron temperature in gas discharges by noise measurements," *Philips Res. Repts.*, vol. 6, pp. 288–302; August, 1951.

[3] H. Johnson and K. R. DeRemer, "Gaseous discharge super-high-frequency noise sources," PROC. IRE, vol. 39, pp. 908–914; August, 1951.

[4] N. Houlding and L. C. Miller, "Discharge Tube Noise Sources," Telecommunications Res. Estab. Mem. No. 593; 1953.

[5] K. W. Olson, "Reproducible gas discharge noise sources as possible microwave noise standards," IRE TRANS. ON INSTRUMENTATION, vol. I-7, pp. 315–318; December, 1958.

[6] N. E. Dorsey, "The velocity of light," *Trans. Am. Phil. Soc.*, vol. 34, pt. 1, pp. 1–110; October, 1944.

[7] M. J. Druyvestyn, "Theory of positive column," *Z. Physik.*, vol. 81, pp. 571–580; April, 1933.

[8] A. Von Engel and M. Steenbeck, "Elektrische Gasentladungen," Springer Verlag, Berlin, Germany, vol. 2; 1939.

[9] P. Parzen and L. Goldstein, "Current fluctuations in dc gas discharge plasma," *Phys. Rev.*, vol. 79, pp. 190–191; July, 1950.

[10] J. J. Freeman, "Noise comparator for microwaves," *Radio and Television News*, Radio Electronic Engrg. Sect., vol. 49, p. 11; 1953.

[11] H. Sutcliffe, "Noise measurements in the 3-cm waveband using a hot source," *Proc. IEE*, vol. 103B, pp. 673–677; September, 1956.

[12] V. A. Hughes, "Absolute calibration of a standard temperature noise source for use with S-band radiometers," *Proc. IEE*, vol. 103B, pp. 669–672; September, 1956.

[13] G. D. Ward, private communication.

[14] Based upon a suggestion by M. M. Anderson, NBS, Boulder, Colo. Although insufficiently precise for our purpose, this offers an excellent method for a less demanding radiometer.

also published in Temperature – Its Measurement and Control in Science + Industry, Vol. 3, Part 2 (Reinhold Publishing Corp, New York) 1962

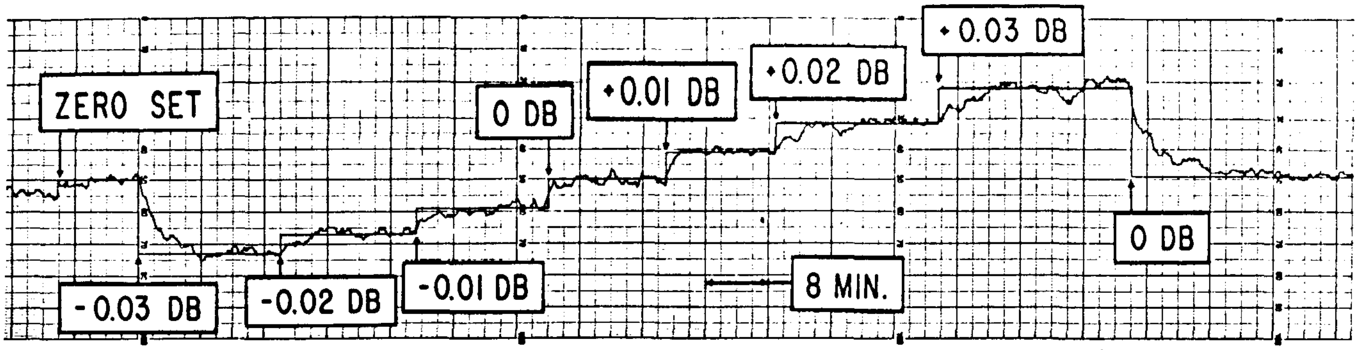

Fig. 4—Sample chart recording, which illustrates sensitivity and stability.

that an error of even as much as 1°C in T_A contributes at most 0.004 db to the final result.

The calibration of the attenuator can be performed as accurately as the attenuator resettability. By the operational technique in use, the attenuator readability and resettability throughout the range used is within 0.002 db. The most serious part of the attenuation error is that due to mismatch of an attenuator operating between imperfectly matched source and load. While the attenuator used was creditable by ordinary standards (having a VSWR of about 1.1), such a mismatch places stringent requirements on both of the isolators in order to keep the mismatch error to within 0.01 db. A refined reflectometer technique[17] was used to tune these isolators with five-stub tuners to the required match over the frequency band of interest. The waveguide switch and flange mismatch errors were also evaluated by the reflectometer technique. A third five-stub tuner located between the waveguide switch and the first isolator permits a source mismatch of up to $\Gamma_s = 0.01$, still keeping $\Delta\epsilon$ well under 0.01 db. The minimum $\Delta\epsilon$ error is actually limited by waveguide switch repeatability and is estimated at 0.002 db, based upon measurements.

The following procedure is used in making a comparison. With the waveguide switch putting the unknown source into the system, the precision attenuator indicator is set on one of the calibrated lines in the vicinity of 11 db. The balance attenuator is then adjusted for null output. After the waveguide switch is changed to the "standard" source, the precision attenuator is readjusted to null. The second balance occurs with the attenuator set in a range which is calibrated every 1/100 db; hence, the difference measurement is determined to better than 1/100 db.

Fig. 4 shows a measure of the sensitivity of the radiometer to small unbalances. It is operating at a power level about 4 db above that of the standard source with a time constant of about one minute on the output recorder. The limit of resolution is well within the requirement of 0.01 db. It should be noted that the most serious excursions of the output are associated with line voltage surges and not with the stochastic fluctuations which are discussed in Dicke's paper [1]. This is a consequence of the exceedingly high gain used in this system—of the order of 180 db. While the system theoretically operates at a null, in practice it must, of course, have a small unbalance signal present.

The Primary Standard

While there have been attempts to devise other forms of primary noise standards (such as the mercury drop impulse generator),[18] the approximate black body emitter remains the most accurate and dependable primary standard of noise. In microwave usage, it consists of a well-matched termination inserted into suitable high-temperature waveguide, all of which is heated by a furnace. This waveguide is in turn connected through waveguide of low thermal conductivity to a water-jacketed cooling section of waveguide. Such an assembly is shown in Fig. 5.

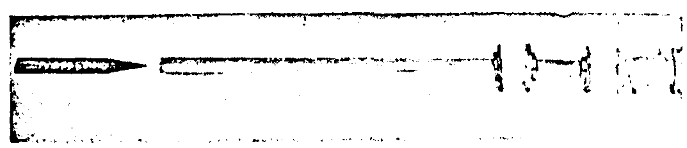

Fig. 5—Illustration of hot load (exploded).

1) The hot load is composed of vitrified-bond silicon carbide of approximately 150 grit. While the grit size does not seem to be critical, the vitrified bond is necessary to withstand the high temperature.

Various shapes of loads, such as center taper points, E-plane wedges and H-plane wedges provide reasonably good matches. The requirements held foremost here were: first, a good match; second, a large area in contact with the waveguide for efficient heat transfer; and third, that the leading edge or point be at the waveguide boundary rather than in the center of the wave-

[17] R. W. Beatty, G. F. Engen, and W. J. Anson, "Measurement of reflections and losses of waveguide joints and connectors using microwave reflectometer techniques," this issue, p. 219. A swept frequency adaptation of the reflectometer technique was used for preliminary tuning, and then point-by-point measurements were used to confirm the results.

[18] R. H. George, Purdue University, Lafayette, Ind., Progress Rept. No. 30; 1951.

they are susceptible to external magnetic fields and do not possess the best stability. In the present system, two rotary vane attenuators, as illustrated in Fig. 2, have been modified to serve as modulators by removing the stops and by replacing the bearings with others more suitable for continuous rotation. A sixty-cycle synchronous motor drives these by means of toothed pulleys and timing belts which serve to maintain a 90° difference between the orientation of the two vanes. The result is a modulation system with low insertion loss, high percentage of modulation, good stability, and a good impedance match throughout the range of attenuation.

A detailed block diagram of the modified radiometer is shown in Fig. 3. A balancing attenuator and a reference source, a discharge tube, appear to the left of the magic tee in the diagram. The average noise-power output of the reference source is assumed to remain constant throughout the time of the measurement. This has been shown experimentally to be a good assumption. The balancing attenuator is used to facilitate setting the precision attenuator to a convenient level.

The precision attenuator assembly is located to the right of the magic tee and is decoupled from the rest of the system by approximately 40 db of isolation on both sides. Broad-banded tuners on either side of the attenuator serve to minimize the mismatch error.[15]

The balanced mixer is followed by a low noise preamplifier and amplifier, both of which have a center frequency of 30 mc and a nominal bandwidth of 8 mc. The detected output from the IF amplifier is fed to an ultra-stable, high-gain, 30-cps synchronous amplifier.[16] Finally, the output of the synchronous amplifier is put through an adjustable damping circuit and observed on a strip-chart recorder.

The balance equation of the radiometer can be derived by equating the noise power at the output of the right arm of the radiometer with the standard switched in to that seen when the unknown is switched in. The excess temperature of the unknown is related to the excess temperature of the standard by the balance equation

$$10 \log_{10} \frac{T_X - T_A}{T_S - T_A} = (\alpha_2 - \alpha_1) + \Delta\epsilon, \qquad (1)$$

where

T_S is the temperature of standard source as seen at its terminal surface,

T_X is the temperature of the unknown source at its terminal flange,

T_A is the ambient temperature and temperature of the waveguide system,

$\alpha_2 - \alpha_1$ is the attenuation difference, corresponding to the two settings of the precision attenuator,

$\Delta\epsilon$ is the difference in decibels between the insertion loss of the path from the terminal flange of the noise tube mount to the first five-stub tuner and the terminal surface of the standard to that tuner.

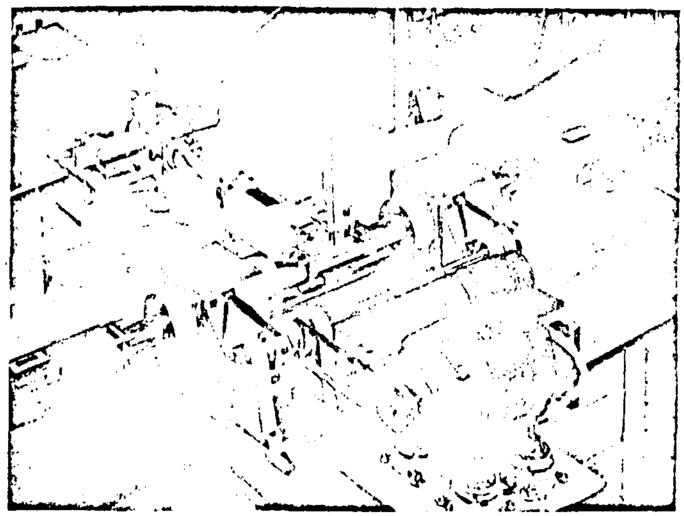

Fig. 2—Illustration of modulators.

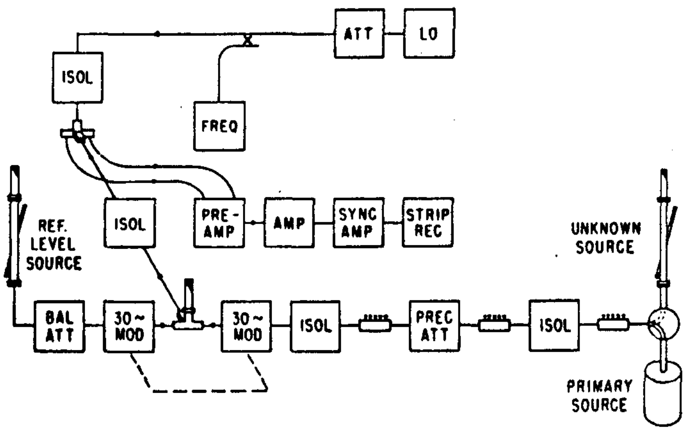

Fig. 3—Detailed block diagram of modified radiometer.

By insuring adequate decoupling following the precision attenuator, the only random errors entering, to a first order, into the radiometer set-up are those implicit in the variables and parameters of (1). These are 1) an uncertainty of T_A, 2) an uncertainty in T_S, which will be discussed in the next section, 3) an error in $\alpha_2 - \alpha_1$, which can be caused by mismatch, by calibration, and by limitation of resettability, 4) the fact that the two paths from the standard and from the unknown to the first five-stub tuner and load isolator differ slightly introduces a small error, $\Delta\epsilon$ db, because of the different insertion loss of the two paths.

Let us consider in detail these sources of error. The error in the ambient temperature can be held to within a small fraction of a degree, by keeping the entire system in a temperature controlled room and monitoring the temperature at the attenuators. By taking the differential with respect to T_A of the left side of (1), we can see

[15] R. W. Beatty, "Mismatch errors in the measurement of ultra-high-frequency and microwave variable attenuators," *J. Res. NBS*, vol. 52, pp. 7–9; January, 1954.

[16] N. Larsen, report in preparation.

guide. Since the tip of the load is subject to some heat erosion and indelicate handling, it should be located where its sharpness least affects the match. In consideration of these requirements, the load finally selected was a diagonal wedge about four inches long. The voltage reflection coefficient ranged from 0.01 to 0.002 for various loads.

2) The selection of a high-temperature waveguide material is limited to relatively few choices: Inconel, stainless steel, nickel, platinum, rhodium, palladium, silver, and gold, and plating or firing on various bases including ceramics, are all possible. Plating processes, however, are fairly uncertain, not only as to adhesion at high temperatures, but also for conductivity extrapolation to high temperatures. The most desirable choices are silver and gold, because of their high electrical conductivities. In order to operate the load at as high a temperature as possible, gold was finally chosen. The waveguide was formed of 0.025-inch sheet. Inasmuch as it is used in a dead-soft condition, the position of the waveguide is vertical to minimize sagging . The surface conductivity was measured[17] at room temperature after annealing, and an extrapolation was made to high temperatures for the necessary attenuation figures.[19] The use of a material with high electrical conductivity relaxes the accuracy requirements on this extrapolation.

3) The transition section was made of 0.010-inch nickel sheet, because the more desirable silver or gold plating on inconel or stainless steel tended to blister or peel at these temperatures. The electrical characteristics of this three-inch section were obtained in the same method as those of the gold section.

The furnace, as shown in Fig. 6, was constructed of uncemented firebrick with a minimum thickness of $7\frac{1}{2}$ inches for proper insulation. The chamber is cylindrical, six inches in diameter by eighteen inches long. The vertical surface of the chamber is formed by an aluminum oxide core on which are wound three zonal Nichrome heating elements. To facilitate uniform heating, a pile-grade graphite cylinder surrounds the waveguide and fills this chamber. The temperature is monitored by calibrated platinum/platinum-10 per cent rhodium thermocouples. Four of these are located in the graphite and three more are inserted into slots from the lower end of the hot load. Finally, to determine the temperature distribution along the waveguide, additional thermocouple measurements were made at various points of the waveguide. In order to reduce convection losses, a mica window was placed between the nickel waveguide section and the water-jacketed section.

The effective noise temperature at the terminal surface (which we define as the interface between the nickel section and the water-jacketed section) of the primary standard is calculated as follows: The curve of temperature vs distance (as measured along the waveguide from the tip of the hot load) is approximated by a series of segments of constant temperature. It can be shown[20] that the noise temperature at the output of the nth segment is

$$T_{(n+1)_e} = 10^{-A_n/10}\left[\overline{T}_{n_g}(e^{A_n/4.34} - 1) + T_{n_e}\right] \tag{2}$$

where

T_{n_e} is the noise temperature at the input end of the nth segment,

A_n is the total attenuation of the waveguide comprising that section, expressed in db, and

$\overline{T}_{n_g}$ is the average wall temperature of that segment.

If A_n is small, the expression for $T_{(n+1)_e}$ can be expanded in powers of A_n to first order with negligible error

$$T_{(n+1)_e} = T_{n_e} - 0.23A_n(T_{n_e} - \overline{T}_{n_g}). \tag{3}$$

In this manner, the total reduction in temperature of the noise power can be calculated for the length of waveguide connecting the hot load to the terminal surface. In order to evaluate the error in this calculation, the total differential of (3) is taken as follows:

$$\delta T_{(n+1)_e} \approx \delta T_{n_e} - 0.23A_n(\delta T_{n_e} - \delta\overline{T}_{n_g}). \tag{4}$$

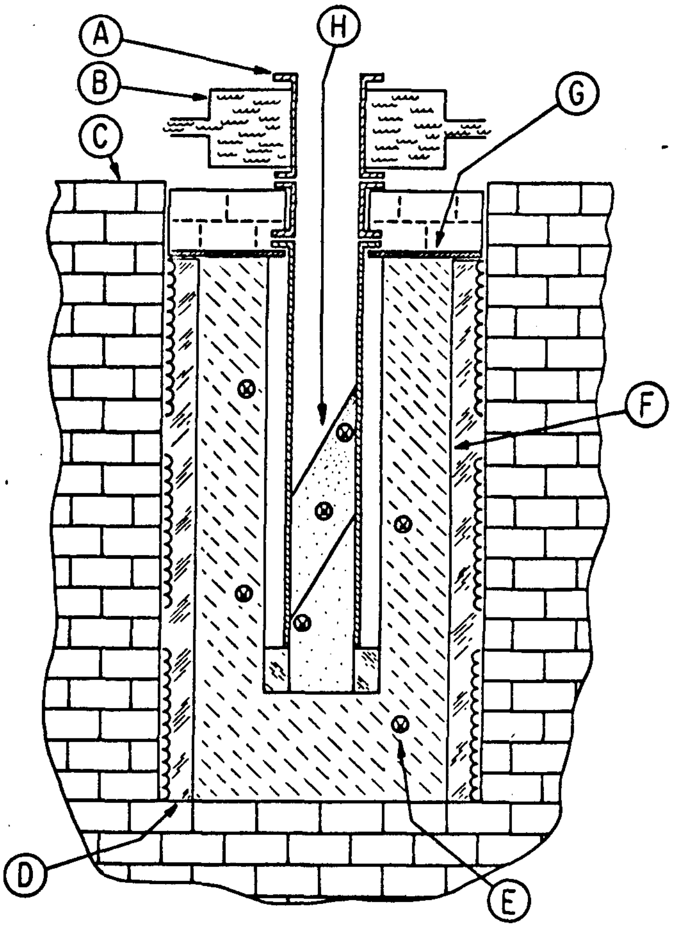

Fig. 6—Details of furnace. A. Copper waveguide section with water jacket. B. Water jacket. C. Firebrick insulation. D. Aluminum oxide core with nichrome windings. E. Thermocouples. F. Pile graphite liner. G. Inconel heat reflector. H. Hot load.

[19] D. M. Kerns and R. W. Hedberg, "Propagation constant in rectangular waveguide of finite conductivity," *J. Appl. Phys.*, vol. 25, pp. 1550–1551; December, 1954.

[20] J. E. Sees, "Fundamentals in Noise Source Calibration at Microwave Frequencies," Naval Res. Lab., Washington, D. C., NRL Rept. No. 5051; 1958.

The gold waveguide is approximately 10 inches in length from the end of the hot load to its flange; its wall temperature drop is about 230°C. The resultant drop in noise temperature along its length is about 2°C. This can be calculated accurately enough to contribute an error of less than 1°K. The nickel waveguide, on the other hand, maintains the balance of the wall temperature drop across its three-inch length. This adversely affects the error introduced, as seen from (4). In addition, the wall temperature range passes through the Curie point of nickel where the behavior of the permeability is not known to a high degree of accuracy. This leads to an error in the calculated noise temperature drop that can be as much as 3°K for the last two inches of the nickel waveguide.

Results

One of the commonly used noise sources in the laboratory in the WR-90 waveguide size is the Bendix Type TD-11 discharge tube. Nine tubes of this general type, but quality controlled by the manufacturer to closer tolerances, were measured at 9800 Mc by the technique described. Preliminary measurements of these tubes at 200.0 ma discharge current indicate an excess noise ratio, $(T_X/290)-1$ (in the mount), of about 15.60 ~~15.00~~ db above 290°K. The total variation among all tubes was 0.03 db. The mount used was a selected commercial 10° E-plane type having a reflection coefficient of approximately 0.01. The back side of the mount was terminated with a load having a reflection coefficient of 0.005. The hot insertion loss of the tube (about 30 db attenuation) was such as to make effects of the temperature and mismatch of the back load less than 0.01 db. The results reported here are not corrected for mount attenuation. Fig. 7 is an illustration of the complete system.

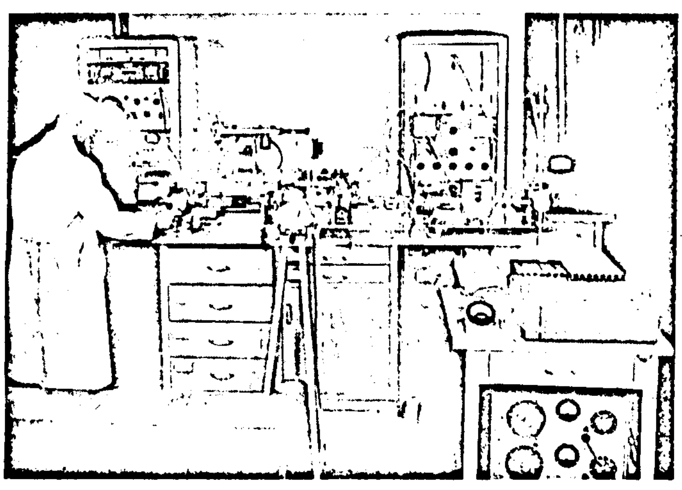

Fig. 7—Illustration of complete system.

Discussion and Conclusions

A system has been described which is capable of exceedingly accurate noise measurements. The sources of error fall into the usual categories of random and systematic errors: The random errors detailed previously can cause a limiting uncertainty of about 0.01 to 0.02 db. These are principally centered in the mismatch errors associated with the precision attenuator and with the waveguide switch and associated flanges. With the present state of the art, the most refined techniques were needed to reduce the attenuation mismatch error to allowable tolerances. Construction of a precision attenuator of better match characteristics and/or load isolators of better match would afford a simple partial solution. We recognize, though, that those used represent close to the limit of present commercially available components. Consequently, the best solution may lie in the direction of reducing the over-all frequency band which must be matched with stub tuners. This can be done either by reducing the intermediate frequency and accepting a narrower bandwidth and consequent loss of signal power, or by using a broad-band distributed amplifier in place of the IF amplifier.[21]

The more serious limitations of the system lie in the systematic errors that are insufficiently known. Though no results can be reported as yet, investigation is being carried out on the following factors:

1) Change in calibration of the precision attenuator either suddenly because of movement or gradually with aging.

2) Change in calibration of the platinum thermocouples due to crystal growth and migration as a result of repeated heating.[22]

3) The attenuation of the section of nickel waveguide is proportional to the square root of its microwave relative permeability. Above the Curie point (about 380°C), the material can to a good approximation be assumed paramagnetic; below the Curie point, however, a detailed knowledge is necessary to calculate accurately its attenuation.

4) The effect of harmonics of microwave frequencies. Although the crystal conversion loss is increased at harmonic frequencies, it is still probably sensitive enough to detect such components. If the precision attenuator calibration at these harmonic frequencies differs from that at the fundamental, a source of error is introduced. This is particularly true if higher modes, TE_{30}, TE_{60}, etc., are introduced by the sources.

Acknowledgment

The authors acknowledge with pleasure the assistance given by W. Foote and R. Figaro. Their ingenuity and competence provided the solution to many difficulties encountered in this work.

Bibliography

[1] R. H. Dicke, "The measurement of thermal radiation at microwave frequencies," *Rev. Sci. Instr.*, vol. 17, pp. 268–275; July, 1946.

[2] A. I. Reynard, "Precision Instruments for Calibrating Radiometers at 4.3-MM Wavelength," Naval. Res. Lab., Washington, D. C., NRL Rept. No. 4927; 1957.

[3] J. E. Gibson, "Comparison-Type Receivers for White Noise Radiation at 0.86-CM Wavelength," Naval Res. Lab., Washington, D. C., NRL Rept. 4864; 1956.

[21] G. P. Apushkinski, "Increasing radiometer sensitivity by expanding its band," *Radio Engrg. and Electronics* (*USSR*), vol. 3, pp. 192–194; April, 1959.

[22] "Methods of Testing Thermocouples and Thermocouple Materials," Natl. Bur. Standards, Washington, D. C., NBS Circular 590; February 6, 1958.