Bolometric Microwave Power Calibration Techniques at the National Bureau of Standards*

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Summary—**A bolometric method of calibrating low-level microwave power measuring devices is currently employed at the National Bureau of Standards in Boulder, Colo. The technique is one of direct comparison between the standard and the unknown, and utilizes NBS working standard bolometer units and self-balancing dc bridges. In general, the unknown is calibrated to an accuracy of one per cent. The following quantities are defined and the associated errors are discussed: 1) Calibration factor of a bolometer unit in combination with a directional coupler, 2) Calibration factor of a bolometer unit, and 3) Effective efficiency of a bolometer unit.**

INTRODUCTION

IMPROVEMENTS in the measurement of bolometer unit[1] efficiency by calorimetric techniques and the development of suitable bolometer units[2] have permitted the establishment of a microwave power calibration service at the National Bureau of Standards. The calibration of a bolometer unit or of a bolometer unit combined with a directional coupler is performed by comparison of the unknown unit with a standard bolometer unit. This method yields a rapid measurement of microwave power with an over-all accuracy of approximately one per cent.

In the bolometric method of power measurement, the heating effect of the RF power is compared with a measured amount of dc or AF power in a temperature-sensitive resistive element.[3] This method is widely used in the measurement of low-level microwave power. The method can be applied throughout the coherent frequency spectrum. The two essential components for carrying out the power measurement are the bolometer unit and the self-balancing resistance bridge. The latter is used in determining the substituted dc power in the bolometer unit.[4] Both of these components have been described[2,5] and are used at NBS for the calibration of bolometer units by themselves or in combination with directional couplers.

A bolometer unit contains a temperature-sensitive resistive element such as a barretter or a thermistor. These elements usually have a nominal resistance of either 100 or 200 ohms. The barretter is a short length of thin conductor having a positive temperature coefficient of resistance. The thermistor is a small bead of semiconducting material having a negative temperature coefficient. The element is placed in a terminating section of transmission line designed so that it absorbs nearly all of the RF power entering the transmission-line section. Both types of bolometer elements can be accurately calibrated as power measuring devices. Bolometer units to be used as interlaboratory standards of microwave power measurement should be of the fixed tuned, broad-band type. This obviates any possibility of disturbing tuning devices while the unit is being transported, or during subsequent use, and will thereby enhance the transfer of measurement accuracy.

Bolometer units designed to cover the frequency range from 8.2 to 12.4 Gc presently are used as NBS working standards[6] for calibration services. An expansion of services will be made to cover other frequency ranges employing both waveguide and coaxial transmission lines when standards and techniques are developed. A new comparison technique has been developed[7] which will be used in the near future. This technique is an extension of the reflectometer concept in which a four-arm junction is used for the intercomparison or calibration of power measuring devices with little or no regard for their impedance characteristics. Also, the method is substantially independent of the impedance discontinuity which may be present at the input flange or connector. The latter result is of particular value in coaxial systems.

Three different types of measurement used in the calibration of power measuring devices will be discussed. One type relates the reading of a bridge containing the bolometer unit attached to the side arm of a directional coupler (*i.e.*, the substituted dc power in the bolometer unit) to the power emerging from the main arm; the second type relates the reading of a bridge containing the bolometer unit to the power incident upon the unit; and the third type provides the effective efficiency of a bolometer unit.

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[1] In this paper the term "bolometer unit" includes both the bolometer element or elements and the bolometer mount in which they are supported.

[2] G. F. Engen, "A refined *X*-band microwave microcalorimeter," *J. Res. NBS*, vol. 63C, pp. 77–82; July-September, 1959.

[3] E. L. Ginzton, "Microwave Measurements," McGraw-Hill Book Co., New York, N. Y., chs. 2 and 3; 1957.

[4] The substituted dc power in the bolometer unit includes the substituted dc power in both the bolometer element and mount. It should be noted that the substituted dc power in a well-designed bolometer mount is negligible.

[5] G. F. Engen, "A self-balancing dc bridge for accurate bolometric measurements," *J. Res. NBS*, vol. 59, pp. 101–105; August, 1957.

[6] A. G. McNish, "Classification and nomenclature for standards of measurement," IRE TRANS. ON INSTRUMENTATION, vol. I-7, pp. 371–378; December, 1958.

[7] G. F. Engen, "A transfer instrument for the intercomparison of microwave power meters," IRE TRANS. ON INSTRUMENTATION, vol. I-9, pp. 202–208; September, 1960.

Method of Measurement

Several methods of calibrating power meters have been described in the literature.[8,9] The method to be discussed here has been developed to perform measurements upon bolometer units and bolometer units in combination with directional couplers and lends itself well to rapid and relatively simple calibrations of these devices.

Fig. 1 is a functional diagram of the microwave-power calibration system. A CW-microwave source with associated frequency monitoring circuitry is located in the left portion of the diagram. This is followed by a level-set attenuator, a ferrite-type variable attenuator, and a waveguide switch. The directional coupler and bolometer units following the switch are placed in an isothermal air enclosure. The self-balancing bridges with associated potentiometer and null indicator are used to measure the substituted dc power in the bolometer units. The microwave-power stabilizer and the ferrite-type variable attenuator operate in conjunction with the self-balancing bridge to provide a stable power level. The microwave power stabilizer can also be operated in conjunction with the self-balancing bridge in the main arm of the coupler. The basic circuit is shown in the simplified diagram of Fig. 2. It consists of a stabilized, well-isolated power source and the two bolometer units interconnected with a high directivity (40 db or more) directional coupler.

The comparison of an unknown bolometer unit with a standard bolometer unit may be accomplished by connecting the standard unit and the unknown unit in succession to the output port of the directional coupler shown in Fig. 2, and noting for each unit the substituted dc power withdrawn to maintain balance in a bridge containing the bolometer unit operating at its nominal resistance. The power level at the output port of the coupler can be determined when the standard is connected to the main arm, while at the same time the power in the bolometer unit on the side arm is measured. By using this information, it will be shown that, for a given measured power in the side arm unit, the microwave power absorbed by the unknown unit on the main arm, or the power incident upon it, can be related to the substituted dc power in the unknown unit.

It can be shown that the microwave power dissipated within the unit under calibration is

$$P_u = P_s \frac{P_{cu}}{P_{cs}} \left| \frac{1 - \Gamma_g \Gamma_s}{1 - \Gamma_g \Gamma_u} \right|^2 \frac{1 - |\Gamma_u|^2}{1 - |\Gamma_s|^2}. \quad (1)$$

The bolometer unit on the side arm of the directional coupler in Fig. 2 provides the sensing element in the feedback loop of the power stabilizing circuit and serves as a monitor for the power flowing in the main arm of the

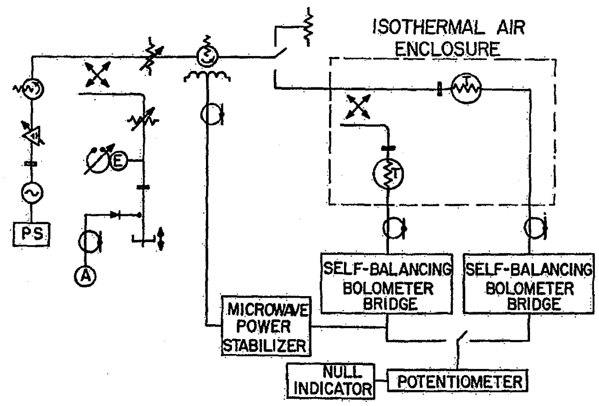

Fig. 1—Functional diagram of microwave-power calibration system.

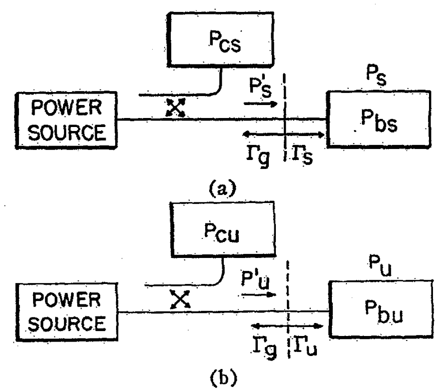

Fig. 2—Basic circuit. (a) With the NBS standard bolometer unit connected to the main arm. (b) With the bolometer unit under calibration connected to the main arm.

coupler. This technique of power stabilization using an ideal directional coupler provides not only a stable generator but also the equivalent of a matched generator.[10] Under the condition $\Gamma_g = 0$, (1) simplifies to

$$P_u = P_s \frac{P_{cu}}{P_{cs}} \frac{1 - |\Gamma_u|^2}{1 - |\Gamma_s|^2}. \quad (2)$$

Since an ideal coupler is not used in the practical application of this power measuring system, a small value of Γ_g usually remains and is used in evaluating the mismatch error in measurements made by this method. A further simplification of (1) results if P_{cu} is adjusted to equal P_{cs}. During the time required to perform a single measurement upon one bolometer unit (either the standard unit or the unit under calibration), the output of the generator is so nearly constant that any minute change in power level produces a negligible error in the measurement. However, during the time required to replace the working standard with the unit under calibration, the power level often changes significantly, and

[8] R. W. Beatty and A. C. Macpherson, "Mismatch errors in microwave power measurements," Proc. IRE, vol. 41, pp. 1112–1119; September, 1953.

[9] G. F. Engen, "Recent developments in the field of microwave power measurements at the National Bureau of Standards," IRE Trans. on Instrumentation, vol. I-7, pp. 304–306; December, 1958.

[10] G. F. Engen, "Amplitude stabilization of a microwave signal source," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 202–206; April, 1958.

although P_{cu} and P_{cs} are constant for a given measurement, they are not usually identical. In practice, it is more convenient to measure P_{cs} and P_{cu} independently than to adjust P_{cu} to equal P_{cs}.

Since

$$P_s = P_s'(1 - |\Gamma_s|^2) \tag{3}$$

and

$$P_u = P_u'(1 - |\Gamma_u|^2), \tag{4}$$

the relationship in (1) can be reduced to

$$\frac{P_{cu}}{P_u'|1 - \Gamma_g\Gamma_u|^2} = \frac{P_{cs}}{P_s'|1 - \Gamma_g\Gamma_s|^2}. \tag{5}$$

Eq. (5) is useful in subsequent discussions relating to incident power (P_s' and P_u').

Calibration of Power Measuring Devices

The method of measurement described above is employed in three ways. These are discussed in detail in this section.

Calibration Factor of a Bolometer Unit in Combination with a Directional Coupler

The combination of a directional coupler and a bolometer unit attached to the side arm of the coupler is a device commonly used to measure the power flowing in a microwave transmission line. This form of power measuring device can be calibrated as a single integral unit using the arrangement shown in Fig. 2(a).

The calibration factor K_c of a bolometer unit in combination with a directional coupler is defined as the ratio of the substituted dc power in the bolometer unit on the side arm of the directional coupler to the microwave power incident upon a nonreflecting load connected to the main arm of the directional coupler.

The calibration factor can be determined from measurable quantities. The bolometer unit on the side arm of the directional coupler is used to measure P_{cs}, and a standard bolometer unit is used to determine P_s'. The standard is adjusted so that Γ_s approaches zero. As in the case of Γ_g, a small value of Γ_s usually remains and is used in evaluating the mismatch error. If $\Gamma_s=0$, the right-hand member of (5) is equal to K_c and may be written

$$K_c = \frac{P_{cs}}{P_s'}. \tag{6}$$

Also, if $\Gamma_s=0$, P_s' will be equal to P_s, and since the effective efficiency of the standard η_{es} is known[11] and is defined and written as

$$\eta_{es} = \frac{P_{bs}}{P_s}, \tag{7}$$

(6) may be written

$$K_c = \frac{P_{cs}\eta_{es}}{P_{bs}}. \tag{8}$$

By means of this equation the calibration factor is expressed in terms of measurable quantities and can be determined to a known limit of accuracy.

In subsequent applications of the calibrated device, the expression

$$P_u' = \frac{P_{cu}}{K_c|1 - \Gamma_g\Gamma_u|^2} \tag{9}$$

gives the incident power, where the u subscripts apply to any load connected to the coupler, not just to a bolometer unit. In order to evaluate the factor $|1-\Gamma_g\Gamma_u|^2$, a knowledge of both the phase and the magnitude of Γ_g and Γ_u is required. If only the magnitudes are known, this factor contributes to the total error in P_u'. This type of error is discussed in more detail in the following section.

Eq. (9) points out the value of a matched generator because with $\Gamma_g=0$, the factor $|1-\Gamma_g\Gamma_u|^2$ reduces to unity. When calibrating a bolometer unit in combination with a directional coupler, the equivalent $|\Gamma_g|$ can have a maximum value of approximately 0.035 even when an ideal power stabilizer is used with a coupler having 40 db directivity. This results from the fact that the coupler is not ideal. The equivalent $|\Gamma_g|$ for a typical commercially available coupler was found to be less than 0.025 over the entire frequency range of 8.2 to 12.4 Gc. It is possible to reduce this value to less than 0.01 at a specific frequency by adjusting a tuning transformer at the output of the main arm of the coupler.[10] If this were done, the transformer would be adjusted before the calibration is made and would be considered an integral part of the directional coupler.

Calibration Factor of a Bolometer Unit

The calibration factor K_b of a bolometer unit is defined as the ratio of the substituted dc power in the bolometer unit to the microwave power incident upon the bolometer unit.

In terms of symbols given previously this becomes

$$K_b = \frac{P_{bu}}{P_u'}. \tag{10}$$

Once again, the arrangement of components is that shown in Fig. 2, where P_{cs} and P_{bs} are measured when the standard is connected to the main arm, and P_{cu} and P_{bu} are measured when the bolometer unit under calibration is connected to the main arm. It follows from (5) and (7) and from the assumption $\Gamma_g=\Gamma_s=0$ that

$$K_b = \frac{P_{bu}P_{cs}\eta_{es}}{P_{cu}P_{bs}}. \tag{11}$$

Eq. (11) is an expression for K_b in terms of measurable quantities and can be determined to a known limit of accuracy.

[11] The effective efficiency of the standard is measured by the microcalorimetric technique[2] not described here.

Effective Efficiency of a Bolometer Unit

The effective efficiency η_{eu} of a bolometer unit is defined as the ratio of the substituted dc power in the bolometer unit to the microwave power dissipated within the bolometer unit. Written symbolically,

$$\eta_{eu} = \frac{P_{bu}}{P_u}. \tag{12}$$

Substituting (4) into (12) yields,

$$\eta_{eu} = \frac{P_{bu}}{P_u'(1 - |\Gamma_u|^2)}. \tag{13}$$

It follows from (10) and (13) that

$$\eta_{eu} = \frac{K_b}{1 - |\Gamma_u|^2}. \tag{14}$$

It is evident from (14) that the techniques used to determine K_b also can be used to determine η_{eu} with the additional requirement that $|\Gamma_u|$ must be known. $|\Gamma_u|$ is obtained from an independent measurement not described in this paper.[12]

Error Analysis

The sources of error encountered when employing the bolometric technique of microwave-power measurement described in this paper include instability in power amplitude and frequency, temperature instability, the standard bolometer unit and the self-balancing bridge, flange misalignment, and mismatch.

The power stabilizer in the measurement system holds the microwave power applied to the bolometer units stable to within ± 0.0002 db during a measurement. This results in a negligible error.

It has been found that a frequency change of the order of ± 0.01 per cent produces a very small error, but the exact magnitude of the error is difficult to ascertain in the presence of other errors in the system. During a measurement, frequency variations are substantially less than ± 0.01 per cent and hence produce negligible error.

The ambient temperature in the laboratory is normally 23°C±1°C. The devices to be calibrated are placed in an isothermal air enclosure. The temperature within this enclosure is held to ± 0.005°C during the measurement. The problem of temperature control (as well as that of power and frequency instability) is simplified because the time required for a measurement usually is less than 15 sec. At power levels of 10 mw (at which most measurements are made) the error due to this temperature instability is negligible.

Thus the errors resulting from instability in power, frequency, and temperature can be disregarded individually, and their combined value is estimated to be no greater than ± 0.01 per cent.

The effective efficiency[13] of the standard bolometer unit, as determined using the microcalorimetric technique, is known to an accuracy better than ± 0.2 per cent.[2]

The substituted dc power in each of the bolometer units is measured with the dc self-balancing bridge to an accuracy of ± 0.1 per cent.[5]

When care is exercised in connecting the waveguide components together, the estimated limit of error from flange misalignment is no greater than ± 0.1 per cent.

In some cases the mismatch error is the largest single component of the total error. This error is discussed separately for each of the three quantities which have been defined.

The calibration factor of a bolometer unit in combination with a directional coupler is given by (8) and can be written in the more general form

$$K_c = \frac{P_{cs}\eta_{es}}{P_{bs}} \frac{1 - |\Gamma_s|^2}{|1 - \Gamma_g\Gamma_s|^2}, \tag{15}$$

where the factor on the right is used to express the mismatch error. An exact determination of the mismatch error requires a knowledge of both the magnitude and the phase of the reflection coefficients. However, only their magnitudes are known. Hence, the worst phase combination is assumed, giving the maximum value of the mismatch error, and the limits of K_c can be determined from the relationship

$$K_c = \frac{P_{cs}\eta_{es}}{P_{bs}} \frac{1 - |\Gamma_s|^2}{(1 \pm |\Gamma_g\Gamma_s|)^2}. \tag{16}$$

Since $|\Gamma_s| \leqq 0.01$ and $|\Gamma_g| \leqq 0.035$, the mismatch error lies between $+0.06$ and -0.08 per cent if the factor on the right erroneously is taken to be unity. When all previously mentioned errors are combined, the error in K_c lies between $+0.57$ and -0.59 per cent.

The question may arise why $|\Gamma_g| \leqq 0.035$ was used, since it is possible to make $|\Gamma_g| \leqq 0.01$ with the addition of a tuning transformer between the directional coupler and the standard bolometer unit. The addition of the tuning transformer is not worthwhile because the mismatch error could not be reduced beyond about $+0.01$ per cent or -0.03 per cent in this particular case. Also, as mentioned earlier, the tuning transformer necessarily would remain attached to the directional coupler and be considered as an integral part of the assembly after calibration.

[12] G. F. Engen and R. W. Beatty, "Microwave reflectometer techniques," IRE Trans. on Microwave Theory and Techniques, vol. MTT-7, pp. 352–355; July, 1959.

[13] The efficiency of a bolometer unit is defined as the ratio of the RF power dissipated in the bolometer element to the RF power dissipated within the bolometer unit. The effective efficiency of a bolometer unit combines the efficiency of the unit and the "dc-RF substitution error." This error is caused by the difference between the RF current distribution and the dc bias current distribution in the bolometer element. It should be noted that in the measurements described here, this dc-RF difference is not involved and therefore does not constitute an error.

The calibration factor of a bolometer unit is given by (11) and can be written in the more general form

$$K_b = \frac{P_{bu}P_{cs}\eta_{es}}{P_{cu}P_{bs}} \frac{|1 - \Gamma_g\Gamma_u|^2(1 - |\Gamma_s|^2)}{|1 - \Gamma_g\Gamma_s|^2}. \quad (17)$$

Again, the factor on the right is used to express the mismatch error. Both the phase and the magnitude of all three reflection coefficients are required for an exact determination of the mismatch error. Since only the magnitudes are known, the worst phase combination is assumed, and the limits of K_b can be determined from the relationship

$$K_b = \frac{P_{bu}P_{cs}\eta_{es}}{P_{cu}P_{bs}} \frac{(1 \pm |\Gamma_g\Gamma_u|)^2(1 - |\Gamma_s|^2)}{(1 \mp |\Gamma_g\Gamma_s|)^2}. \quad (18)$$

In this case it is desirable to use a tuning transformer to adjust $|\Gamma_g| \leqq 0.01$. As in the previous case $|\Gamma_s| \leqq 0.01$. However, $|\Gamma_u|$ depends entirely on the unit to be calibrated and, in general, the unit is not tunable. If a typical value of 0.05 is selected, the mismatch error lies between +0.11 and −0.13 per cent, if the factor on the right erroneously is taken to be unity. Therefore, the error in K_b lies between +0.82 and −0.84 per cent. If the tuning transformer is omitted, $|\Gamma_g| \leqq 0.035$. In this case, the mismatch error lies between +0.41 and −0.43 per cent, and the error in K_b lies between +1.12 and −1.14 per cent.

Eq. (14) which expresses the effective efficiency of a bolometer unit, can be written in a more general form

$$\eta_{eu} = \frac{P_{bu}P_{cs}\eta_{es}}{P_{cu}P_{bs}(1 - |\Gamma_u|^2)} \frac{|1 - \Gamma_g\Gamma_u|^2(1 - |\Gamma_s|^2)}{|1 - \Gamma_g\Gamma_s|^2}. \quad (19)$$

Since only the magnitudes of the reflection coefficients are known, the worst phase combination is again assumed, and the limits of η_{eu} can be determined from

$$\eta_{eu} = \frac{P_{bu}P_{cs}\eta_{es}}{P_{cu}P_{bs}(1 - |\Gamma_u|^2)} \cdot \frac{(1 \pm |\Gamma_g\Gamma_u|)^2(1 - |\Gamma_s|^2)}{(1 \mp 1\Gamma_g\Gamma_s|)^2}, \quad (20)$$

where the factor on the right expresses the mismatch error. Here, $|\Gamma_g| \leqq 0.01$ and $|\Gamma_s| \leqq 0.01$. Again, a typical value of $|\Gamma_u| = 0.05$ is selected. If it is assumed that no error exists in the measurement of $|\Gamma_u|$, the maximum error in η_{eu} is equal to the maximum error in K_b. In practice, $|\Gamma_u|$ can be measured to an accuracy of ±1 per cent. The resultant error in η_{eu} from this uncertainty in $|\Gamma_u|$ is negligible.

The factor $(1-|\Gamma_s|^2)$ is included in the mismatch error expressions for K_e, K_b, and η_{eu} in (15), (17), and (19), respectively. The maximum value of $|\Gamma_s|$ is known in each case and the factor could be considered as a part of the measurable quantities. Actually, it could have been omitted in each of the above equations in view of its minute contribution to the total error. Consequently, the position in a given equation is quite arbitrary. It is placed with the mismatch error expression because, even though its maximum value is always known, its specific value is seldom known.

Two other possible sources of error which have not been mentioned are relative humidity and pressure. Although no comprehensive tests have been made to evaluate the errors caused by these effects, no error has yet been detected which could be attributed directly to either or both of them. The relative humidity in the laboratory is normally 50 per cent ±2 per cent. However, no effort is made to control the pressure at which measurements are performed. Therefore, measurements are subjected to daily variations in atmospheric pressure.

List of Symbols

These symbols apply to quantities discussed in the sections that follow:

P_s = Microwave power dissipated within the standard bolometer unit.

P_u = Microwave power dissipated within the bolometer unit under calibration.

P_s' = Microwave power incident upon the standard bolometer unit. (Sometimes called the microwave power emerging from the main arm of the directional coupler.)

P_u' = Microwave power incident upon the bolometer unit under calibration. (Sometimes called the microwave power emerging from the main arm of the directional coupler.)

P_{cs} = Substituted dc power in the bolometer unit on the side arm of the directional coupler when the standard bolometer unit is connected to the main arm.

P_{cu} = Substituted dc power in the bolometer unit on the side arm of the directional coupler when the bolometer unit under calibration is connected to the main arm.

P_{bs} = Substituted dc power in the standard bolometer unit.

P_{bu} = Substituted dc power in the bolometer unit under calibration.

Γ_s = Voltage reflection coefficient of the standard bolometer unit, measured at the plane of connection to the generator.

Γ_u = Voltage reflection coefficient of the bolometer unit under calibration, measured at the plane of connection to the generator.

Γ_g = Voltage reflection coefficient of the generator, measured at the plane of connection to the load (bolometer unit).

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