NIST TECHNICAL NOTE 1310

COMMERCE / National Institute of Standards and Technology

Performance Evaluation of Radiofrequency, Microwave, and Millimeter Wave Power Meters

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DEPARTMENT OF COMMERCE · UNITED STATES ·
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Issued December 1988

National Institute of Standards and Technology
Technical Note 1310, 158 pages (Dec. 1988)
CODEN:NTNOEF

U.S. GOVERNMENT PRINTING OFFICE
WASHINGTON: 1988

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402-9325

FOREWORD

The purpose of this performance evaluation procedure is to provide recommended test methods for verifying conformance with typical performance criteria of power meters that are commercially available for use in the radiofrequency, microwave, and millimeter wave regions. These methods are not necessarily the sole means of measuring conformance with the suggested typical specifications, but they represent current procedures which use commercially available test equipment and which reflect the professional level and impartial viewpoint of the Institute of Standards and Technology (NIST) (formerly the National Bureau of Standards (NBS)).

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PERFORMANCE EVALUATION OF RADIOFREQUENCY, MICROWAVE AND MILLIMETER WAVE POWER METERS

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Measurement techniques for evaluation of the electrical performance of commercially available power meters are described. The type of power meter of interest uses bolometric power sensors and operates in the range from 10 MHz to 26.5 GHz with an average power of 10 μW to 10 mW with appropriate attenuation for higher power ranges.

Power measurements at dc and low frequencies are relatively straightforward since voltage, current, and impedance are discrete entities from which values of power may be calculated through the use of Ohm's law. For rf, μw, and mmw frequencies, however, these become complex, interactive, distributed parameters. Impedance mismatch, leakage, and nonlinear responses must also be considered. The principle of the bolometric method of measurement of rf, mw and mmw power is presented.

Techniques are described for analysis of: ranges of frequency and power, operating temperature, stability, response time, calibration factor, extended power measurement, overload protection, and characteristics of the internal power reference source. Some automated methods are discussed. Block diagrams of test setups are presented. Some typical measurement results are included.

Sources of uncertainty in the bolometric method are analyzed.

Key words: bolometer; dc substitution; microwave power; millimeter wave power; power measurement; radiofrequency power; temperature compensation; thermistor; uncertainty.

1.0 Introduction

1.1 Importance of Power Measurements

Operating power level is frequently critical in the design and performance of almost all radiofrequency (rf), microwave (μw) and millimeter wave (mmw) equipment. It is equally significant for each component within the equipment. Power measurements on devices and systems are frequently required and are often monitored continuously.

1.2 What Power Measurements Indicate About a Device or System

The term "power" is the rate at which energy is used to do work. In rf, μw and mmw systems, power measurement is an indication of the work capability of the equipment used to transmit information at these ranges of frequencies [1]. To determine whether a device or system is performing as designed, it must be tested. At rf, μw and mmw frequencies, power flow is easier to measure and more useful than other parameters as an indication of the ability of the equipment to transmit information [2].

2.0 Background

2.1 Definitions of Relevant Terms

2.1.1 Energy: Energy is the capability of doing work. In a system or device, energy is a basic value which may be expressed as the product of instantaneous power (p) and time (t). For a specified time interval (0 to T) the total energy (E_T) in a system may be expressed as:

$$E_T = \int_0^T p\,dt \qquad (2.1)$$

2.1.2 Power:

a. Low frequency or dc:

Ohm's law applies here:

$$V = IR \qquad (2.2)$$

where V = voltage

I = current

R = resistance

Then low frequency or dc power, P, is:

$$P = VI \cos\phi \qquad (2.3)$$

where ϕ is the angle of phase between the voltage vector and the current vector.

b. High frequency:

1) Instantaneous power (p) is related to instantaneous voltage (v) and instantaneous current (i) from Ohm's law as follows:

$$p = vi. \qquad (2.4)$$

2) Average power (P) is average energy or work done in a specific time interval (0 to T):

$$P = \frac{1}{T} \int_0^T vi\,dt. \tag{2.5}$$

Average power is more closely related to work done by a device or system than is instantaneous power. Hence, energy per unit time is a definition of average power, or the time rate of doing work.

Power is often expressed in decibels (dB). This unit is defined as 10 times the common logarithm of the ratio of a measured value of power, P, to a specified reference value of power, P_{ref} [2]. Thus,

$$dB = 10 \log (P/P_{ref}). \tag{2.6}$$

P and P_{ref} must be expressed in the same units. The ratio is dimensionless because the decibel unit always indicates a relationship between two parameters. If P_{ref} is 0.001 W (1 mW), then the ratio may be expressed in dBm which indicates a value of P relative to 1 mW. The ratio may be positive or negative whenever P is greater than or less than P_{ref}, respectively.

The decibel, neper and other logarithmic units are acceptable in the International System of Units.

2.1.3 Transmission line: Any structure which guides the flow of energy from one point to another is a transmission line [3]. The cross section of this line may take many forms, such as coaxial cable for frequencies up to approximately 26.5 GHz (the upper limit considered in this report), and waveguide configurations for frequencies above a few GHz.

2.1.4 Characteristic impedance: "The ratio V/I is called the characteristic impedance Z_o of the transmission line. Z_o is the ratio of the voltage to the current traveling in a particular direction. This means that Z_o is the ratio of voltage to current traveling together in one direction or the other on the line. By this definition it can be seen that any change in voltage and current on a transmission line has a constant of proportionality which is the characteristic impedance Z_o of the line. This also indicates that regardless of the initial current and voltage conditions, if a wave of voltage and current is sent down the line, the voltage and current waves still travel at the velocity determined by the line parameters, and the ratio of the voltage to current is still Z_0 because the transmission line is a linear device" [3].

In addition, the following IEEE standard definitions [4,5] are included here.

2.1.5 Accuracy: The quality of freedom from mistake or error; that is, conformity to truth or to a rule.

2.1.6 Ambient temperature time constant: At a constant operating resistance, the time required for the change in (bolometer unit) bias power to reach 63 percent of the total change in bias power after an abrupt change in ambient temperature.

2.1.7 Bolometer mount: A waveguide or transmission-line termination that houses a bolometer element(s).

2.1.8 Bolometer unit: An assembly consisting of a bolometer element or elements and a bolometer mount in which they are supported.

2.1.9 Bolometric detector (bolometer element): The primary detector in a bolometric instrument for measuring power or current, consisting of a small resistor, the resistance of which is strongly dependent on its temperature.

2.1.10 Bolometric power meter: A complete power measuring instrument that consists of a bolometer unit and a bolometer bridge.

2.1.11 Calibration factor (of bolometer unit): The ratio of the dc substitution power to the rf power incident upon the bolometer unit.

2.1.12 Effective efficiency: For bolometer units only, the ratio of the dc substitution power to the total rf power dissipated within the bolometer unit.

2.1.13 Feedthrough power meter: A power-measuring system in which the detector structure is inserted or incorporated in a waveguide or coaxial transmission line to provide a means for measuring (monitoring) the power flow through or beyond the system.

2.1.14 Precision: (of a measurement process) The quality of coherence or repeatability of measurement data [5].

2.1.15 Random uncertainty: That uncertainty which can be predicted only on a statistical basis.

2.1.16 Reflection coefficient: At a given frequency, at a given point, and for a given mode of propagation, the ratio of some quantity associated with the reflected wave to the corresponding quantity in the incident wave. Note: The reflection coefficient may be different for different associated quantities, and the chosen quantity must be specified. The voltage reflection coefficient is most commonly used and is defined as the ratio of the complex electrical field strength (or voltage) of the reflected wave to that of the incident wave [5].

2.1.17 Resolution: The smallest discrete or discernible change in power that can be measured. NOTE: In [4] resolution includes the estimated uncertainty with which the power change can be determined on the readout scale.

2.1.18 Response time: The time required for the bolometric power meter indication to reach 90 percent of its final value after a fixed amount of rf power is applied to the bolometer unit.

2.1.19 Substitution power: The difference in bias power required to maintain the resistance of a bolometer at the same value before and after radiofrequency power is applied.

2.1.20 Systematic uncertainty: The inherent bias (offset) of a measurement process or one of its components.

2.1.21 Uncertainty: The assigned allowance for the systematic uncertainty, together with the random uncertainty attributed to the imprecision of the measurement process.

2.1.22 Zero carryover: A characteristic of multirange direct-reading bolometer bridges that is a measure of the ability of the meter to maintain a zero setting from range to range without readjustment after initially being set to zero on the most sensitive range.

2.2 General Methods of Measuring Power

2.2.1 Direct Methods

Power is usually measured in terms of voltage, impedance, and current at dc and low frequencies, where discrete values for these parameters may be measured with facility and with acceptable levels of accuracy, precision and reproducibility. The values of power are derived from the relationships of these basic parameters in Ohm's law.

2.2.2 Need for Alternate Methods at Radiofrequencies and Above

At rf, μw and mmw frequencies, however, power values obtained as described in Section 2.2.1 lose identity because the basic parameters no longer may be observed as discrete terms. They become distributed throughout the circuitry and system. Waves reflected from any impedance mismatch between source and load can introduce interference, which produces ambiguity in voltage and current measurements whose values change with positions along the line. This may occur in either coaxial or waveguide transmission lines. However, average power remains independent of position within a transmission medium and therefore is the parameter of interest.

2.2.3 Indirect Methods

For the reasons stated in Section 2.2.2, an alternate form of power measurement has been developed for rf, μw, and mmw frequencies. This is done through the conversion of rf energy to heat in a thermally sensitive element which in turn experiences changes in resistance. These changes are nonlinear in relation to the heating effect and hence to the power dissipated in the element. They are also functions of the material in the element and of the operating temperature of the device, as shown in the curves discussed in Section 4. Values of these nonlinear temperature coefficients form a family of curves for a set of operating temperature values. These are correlated to values of average power, since most power-measuring devices indicate average power, rather than peak power. With proper construction of the thermally sensitive element, the heating effect of dc and low frequency power may be considered an equivalent substitute for the heat energy generated by rf, μw and mmw power.

3.0 Theory of Measurement

3.1 Conversion of Radiofrequency Energy to Heat

Radiofrequency energy can be detected by changes in the electrical characteristics of thermally sensitive devices. Four general types of thermally sensitive devices used for high-frequency power measurements are: (1) calorimeters; (2) bolometers; (3) thermocouples and (4) diodes. Types 3 and 4 are not discussed in this Technical Note. Average microwave power up to about 10 mWis usually measured by bolometric methods [1]. Changes in bolometer resis-tance caused by heat absorbed in the sensing element from an rf, µw, or mmw system can be measured and calibrated in terms of the equivalent heating effect from a dc source of power.

The most accurate microwave power measurements are based on the principle of dc substitution, in which an input of radiant power to a thermoelectric detecting device is assumed to be equivalent to the input dc power required to generate the same response of the device. The uncertainty in the equivalence of these two parameters is determined by: (1) the effective efficiency of the detecting device, which by definition does not include effects of impedance mismatch errors of the system but only the efficiency of the sensing device [6]; (2) the power losses in the bolometer mount [7].

3.2 Calorimeter as National Reference Standard of Power

A calorimetric method for determination of the combined effect of these two sources of uncertainty was described by Macpherson and Kerns at the National Institute of Standards and Technology (NIST), in 1955 [8]. The technique has been further refined at NIST but retains the original objective of an adjustment factor for power measurements that are determined by the bolometer mount technique. "In the microcalorimeter technique the bolometer mount serves as the calorimetric body or object in which the power is dissipated and whose temperature rise is measured by means of a suitable thermopile". Calibration is effected by observing the thermopile response to dc power dissipated in the bolometer element [7].

Calorimeters for calibrating sensors in both coaxial and waveguide connectors have been developed at NIST. Table 3.2.1 lists some of the calorimeters reported in the NIST literature, with their respective reference numbers.

Table 3.2.1 Types and capabilities of calorimeters developed at the National Institute of Standards and Technology

Sensor	System	Frequency	Output	Uncert.	Year	Ref.
bolometer	waveguide	5.2-10.9 GHz	~ 10 mW	<0.2%	1959	[7]
resistor	coaxial	0-300 MHz	20 mW-12 W	±0.5%	1958	[9]
bolometer	waveguide	9.315 GHz	~ 10 mW	<1%	1955	[8]
bolometer	waveguide	50-75 GHz		±0.23%	1972	[10]
ultrasonic	coaxial	1-15 MHz	1 mW-10 W	<±7.0%	1976	[11]
bolometer	waveguide	95 GHz		±0.83%	1981	[12]

4.0 Measurement Devices

4.1 Power Sensors

The bolometer may be either a: (1) barretter, or (2) thermistor. The barretter is a short length of metal, in the form of either a fine wire or metal film, with suitable encapsulation and support. The thermistor is a small bead of metallic oxides, such as manganese, nickel, cobalt, or other similar materials [13], with either intrinsic or added impurities [14]. The family of curves of resistance vs. power of the barretter follows a positive nonlinear slope, shown in figure 4.1.1 (a), while that of the thermistor is negative and also nonlinear, shown in figure 4.1.1 (b). For small changes in temperature the barretter experiences small changes in resistance, whereas the changes in resistance of the thermistor can be considerably larger for similar small changes in temperature. It is possible for some types of thermistors to double their resistance with a temperature change of 17°C [13]. Figure 4.1.2 indicates the changes in resistivity of germanium due to temperature changes, for a temperature range from below 20 K to over 400 K; there are regions of positive as well as negative temperature coefficients within the temperature range. However, the operating region of interest for power-meter thermistors occurs in the neighborhood of 400 K where a change in temperature of very few degrees will exert a change in resistivity of several hundred ohm-centimeters. For example, an operating temperature of 60°C or 333 K [14] could produce a resistivity in the neighborhood of 0.06 Ω·cm; at an operating temperature of 27°C (300 K), the resistivity for this material could be approximately 0.08 Ω·cm.

The resolution of a thermistor's negative temperature coefficient (NTC) response can be enhanced by addition of extrinsic semiconductor doping materials. Figure 4.1.3 indicates not only a typical NTC sensitivity and resolution (steep linear slope) but also demonstrates the effect of extrinsic additives to increase p-type (hole) or n-type (electron) conductivity. The valence and polarity of the additive determine the type of conductivity while the concentration of additive determines the extent of change in resistivity of the thermistor element. A change of less than +1 mole percent can alter the resistivity of this particular semiconductor material at 300 K by a factor of several hundred [15]. For the range of operating temperatures shown in figure

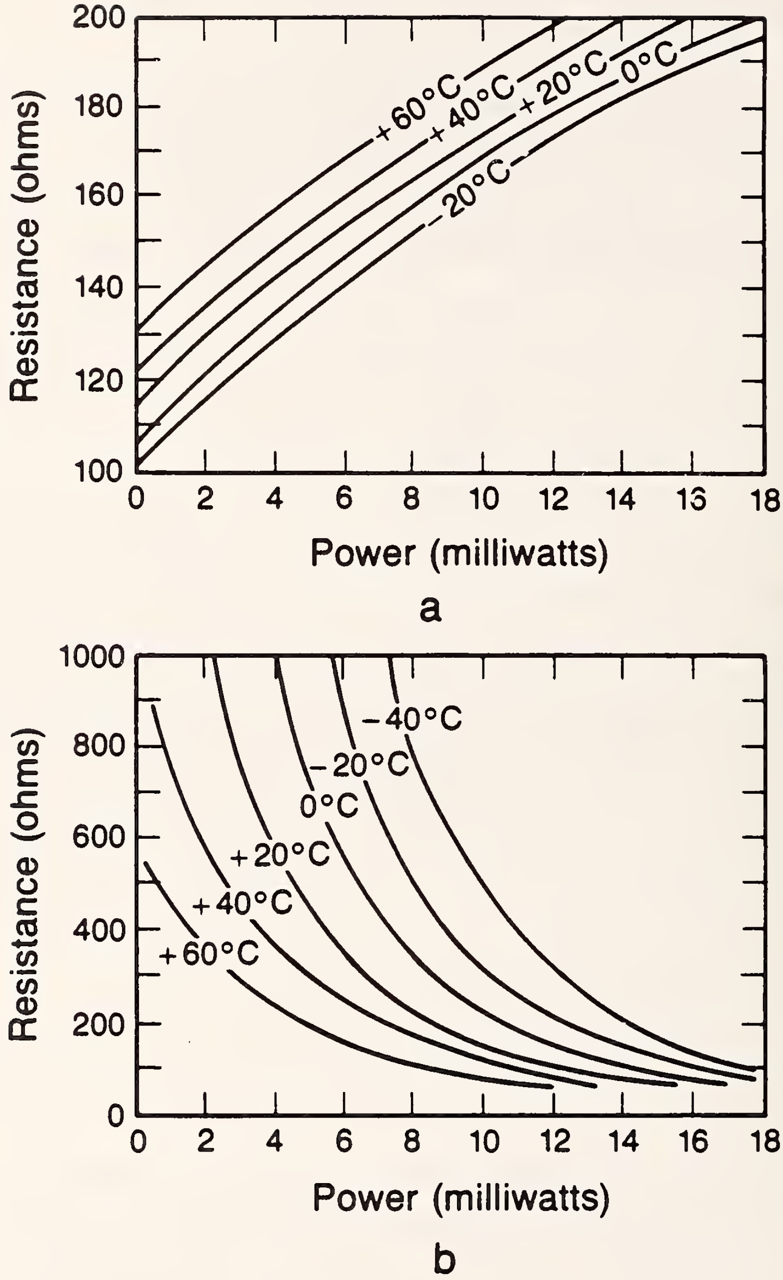

Figure 4.1.1 Resistance vs dissipated power in (a) typical wire barretter (b) typical bead thermistor, at various ambient temperatures.

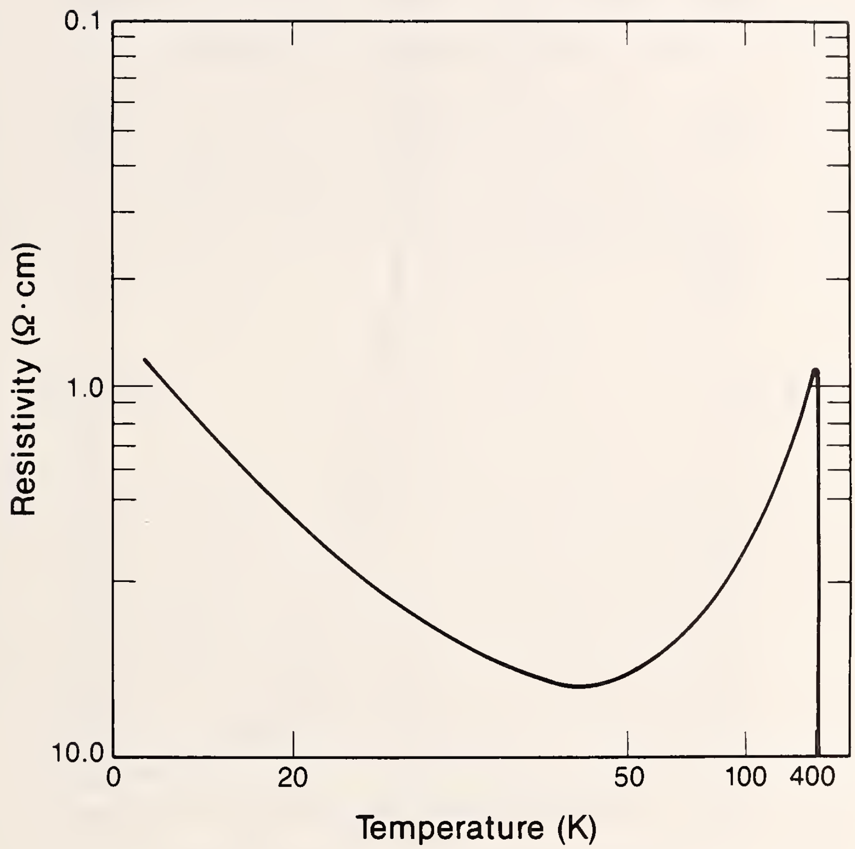

Figure 4.1.2 Experimentally determined dependence of resistivity on temperature for an arsenic-doped η-type sample of germanium.
(After Hemenway, Henry and Carlton).

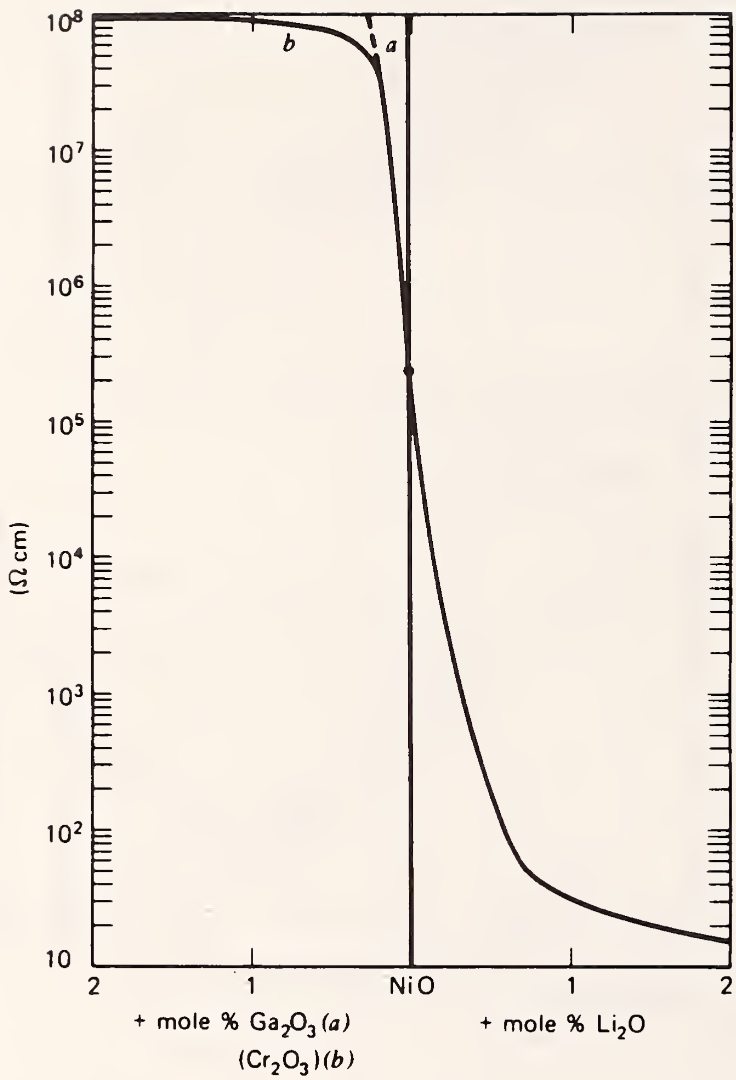

Figure 4.1.3 Resistivity at approximately 300 K of NiO doped with Ga^{3+} or Li^{+}. NiO with Ni^{2+} vacancies has an equivalent concentration of Ni^{3+} to establish electroneutrality resulting in p conduction. (a) Li^{+} doping increases Ni^{3+} concentration, thus increasing p conductivity. (b) Cr^{3+} (or Ga^{3+}) doping decreases Ni^{3+} concentration with resulting decrease in p conductivity. Each Ni^{+} eliminates one Ni^{3+} corresponding to one hole.

4.1.1 (b), the number of electrons excited from the valence band to the conduction band exceeds the number of electrons excited from the donor atoms into the conduction band [14]. This provides rapid changes in conductivity and hence a sensitive response to small changes in temperature for these operating temperatures. Figure 4.1.1 (b) shows that the temperature coefficient curves of the bolometer are fairly close together and most nearly linear for a thermistor resistance in the region of 200 Ω. This is also the region of "zero-power resistance of the thermistor," which is that region where little or no self-heating of the thermistor occurs. This thermistor temperature is measured by special techniques, and is defined as the Thermistor Standard Reference Temperature. This is shown in figure 4.1.4, at 25°C for a typical thermistor [13] and a zero-power resistance of approximately 450 Ω.

4.2 Impedance Bridges

In the bolometric method of power measurement a bolometer is placed in one arm of a Wheatstone bridge circuit. A basic circuit of this type is shown in figure 4.2.1. This method is useful to measure levels of average power up to about 10 mW. In the absence of the rf, μw, or mmw source, the bridge is balanced by adjustment of the dc power level supplied by the bias source. This reference level of dc voltage is recorded. When the bolometer, T in figure 4.2.1, is exposed to rf, μw, or mmw power, the bridge again becomes unbalanced by the change in resistance of the bolometer. The value of dc power that is required to rebalance the bridge is deemed equivalent to the rf power sensed by the bolometer and is a measurement of this power [3]. The difference between the power readings (the difference between the squared value of each voltage measurement divided by the resistance of the element) represents the high frequency power applied to, or absorbed by, the sensor.

A single-thermistor bridge, however, requires inductances to keep rf current out of the dc circuit, as shown in figure 4.2.2, whereas a two-thermistor bridge, in figure 4.2.3, or dual-element bolometer mount, has no rf voltage across the dc circuit, thus eliminating the need for inductances. Radio-frequency chokes in the single-thermistor bridge reduce errors caused by incidental rectification of rf voltages entering the dc circuit, at the same time reducing loading effects of the bridge on the rf source. However, these induc-

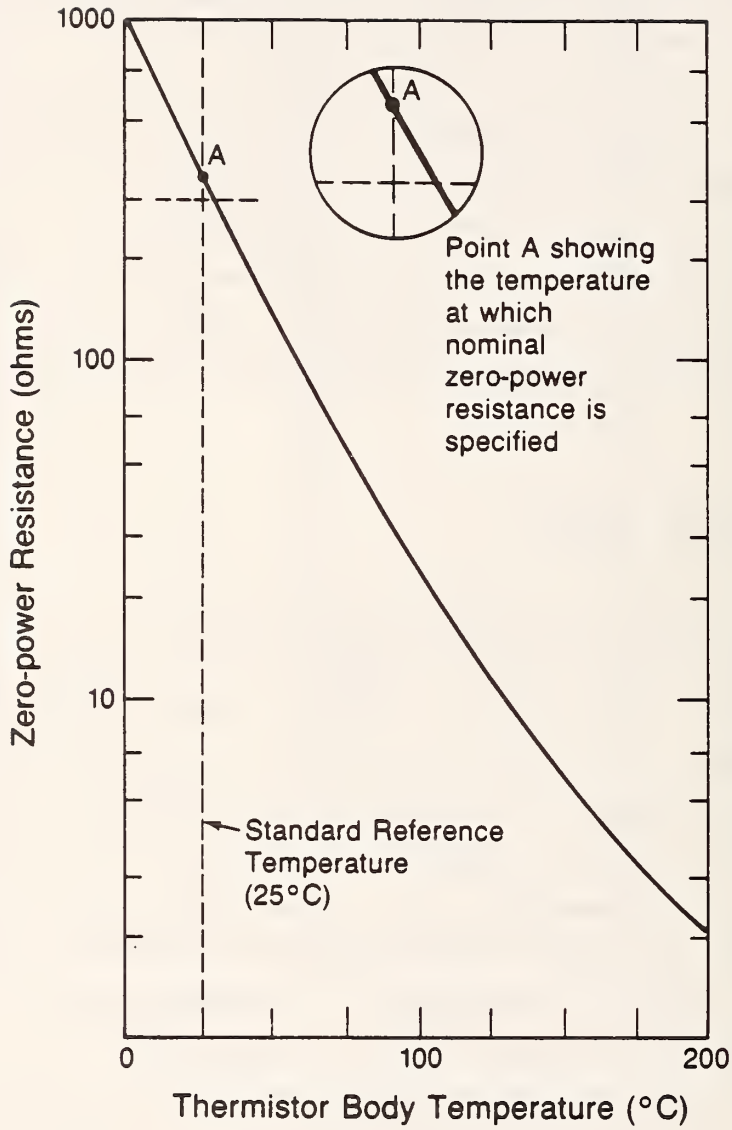

Figure 4.1.4 Zero-power resistance vs body temperature for a typical thermistor, showing standard reference temperature.

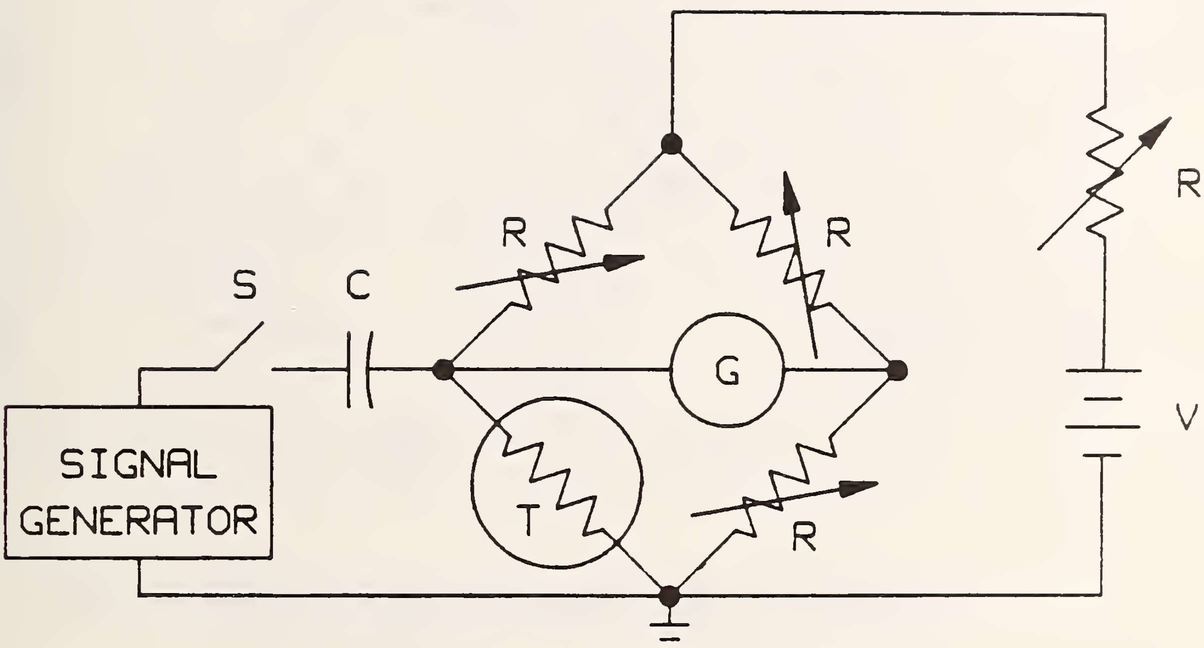

Figure 4.2.1 Basic circuit diagram of a bolometer bridge.

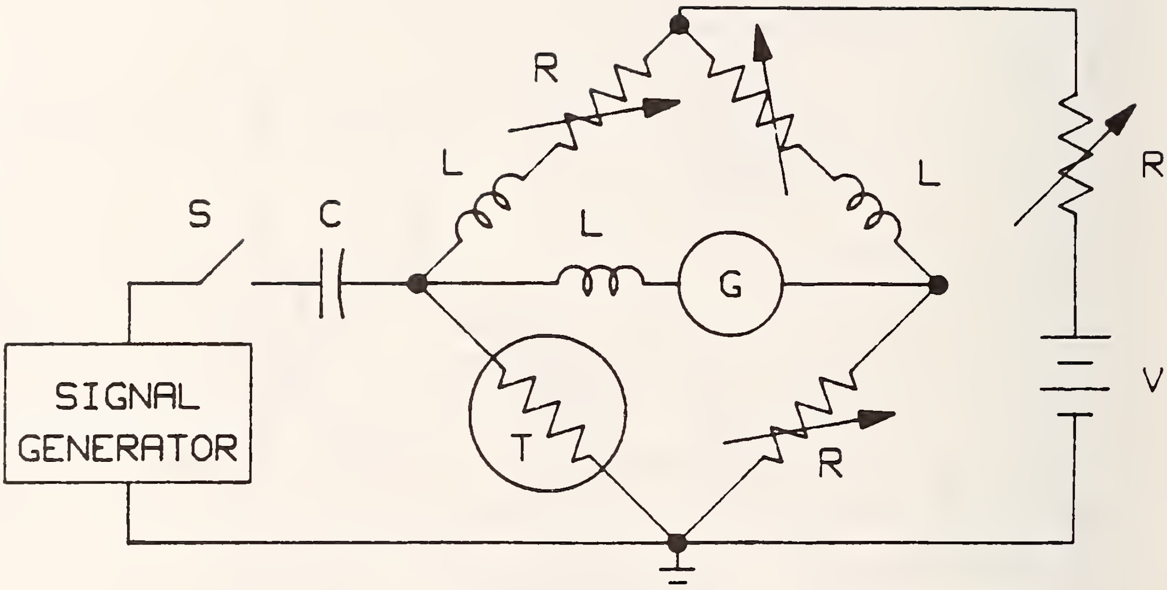

Figure 4.2.2 Single-thermistor bridge showing inductances required to keep rf current from dc circuit.

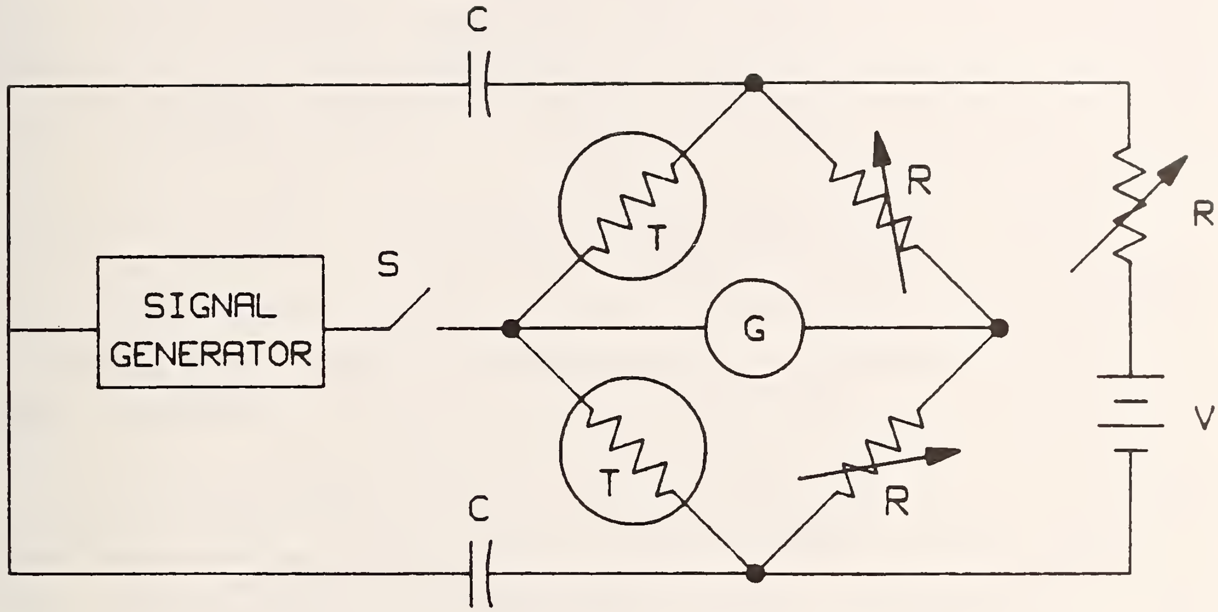

Figure 4.2.3 Diagram of two-thermistor bridge.

tances must be properly installed and shielded, must be stable, and must have sufficiently high impedance over the frequency range of operation. Because of these difficulties, the two-thermistor bridge has been the device of choice [16].

Since the bolometer temperature coefficient varies with the rf, μw or mmw wave power it absorbs, power measurements will experience drift as the bridge detector circuit approaches equilibrium. Compensation for this may be provided by including an additional matching thermistor, to balance the drift such as R_7 in figure 4.2.4. The heat accumulated in R_7 thermistor is dissipated to the environment. This temperature compensation significantly enhances the bolometer response in the microwatt region [1]. The efficiency of this compensation depends on the degree of similarity between the two thermistors R_4 and R_5.

Uncertainties can occur in measurements with dual-element bolometer mounts if the division of resistance between the two thermistors is unequal. Figure 4.2.5 (a) shows the basic circuit of a coaxial mount. R_{T_1} and R_{T_2} are the detection thermistors. If only dc power is applied to the bolometer mount, the two thermistors appear to be in series. The equivalent dc circuit of figure 4.2.5 (b) shows these two thermistors in series. With the rf source in the circuit and the proper coupling capacitors for ac coupling, the thermistors appear to the rf source to be in a parallel circuit into the power meter. The equivalent circuit for this appears in figure 4.2.5 (c). If the values of R_{T_1} and R_{T_2} are unequal, more power is dissipated in the largest resistor in the series configuration, in which the currents are equal. On the other hand, the rf voltages across the two parallel elements are equal, and as a result, more rf power is dissipated in the smaller resistance which carries the larger amount of current. This source of uncertainty increases as power increases, but for power levels of 10 mW or less, it is less than 1 percent for bolometer mounts with well-matched thermistors [1, 17].

The indicating instrument may have a zero-centered scale, so that either an increase or decrease in the temperature of one thermistor with respect to the other can be detected. The sensitivity of the bridge detection circuit thus determines the smallest detectable temperature change. Sensitivity of the detection device may, however, be enhanced with amplification. For example, a bridge circuit with a high-gain amplifier connected to the output could measure temperature differentials of 0.0005°C (0.001°F) [13]. Feedback

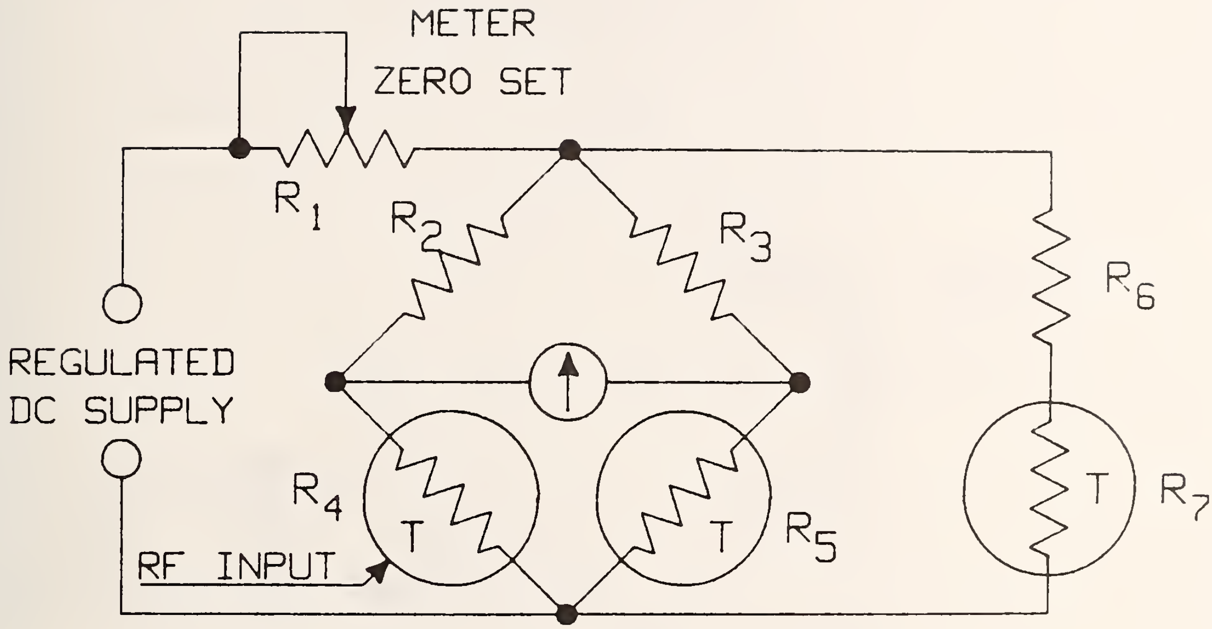

Figure 4.2.4 Unbalanced thermistor bridge. Initial balance is obtained with meter set at zero. Temperature compensation is achieved with external thermistor R_7.

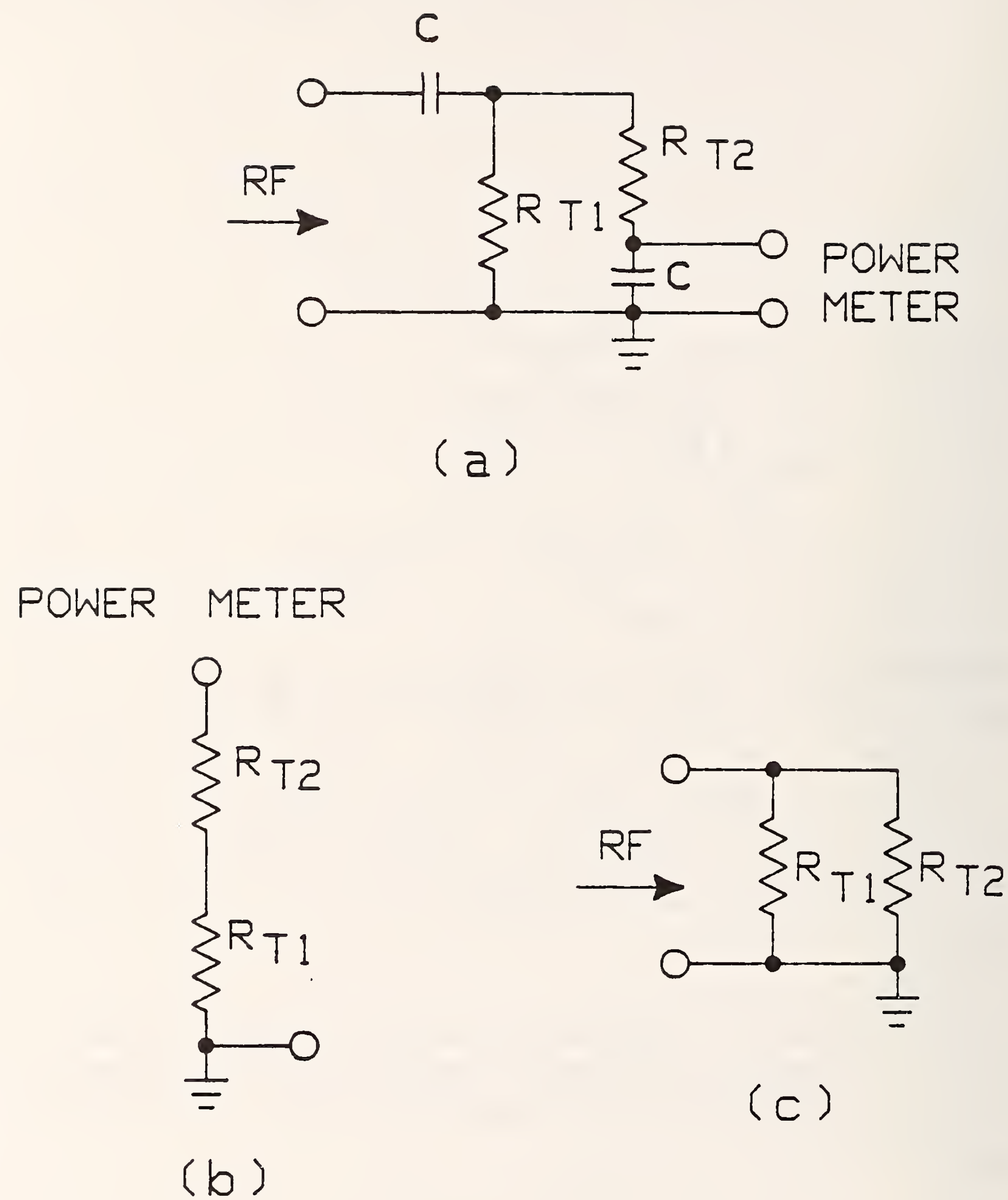

Figure 4.2.5 Dual-element thermistor mount:

(a) Actual circuit.
(b) Dc and low-frequency equivalent circuit.
(c) Rf and high-frequency equivalent circuit.

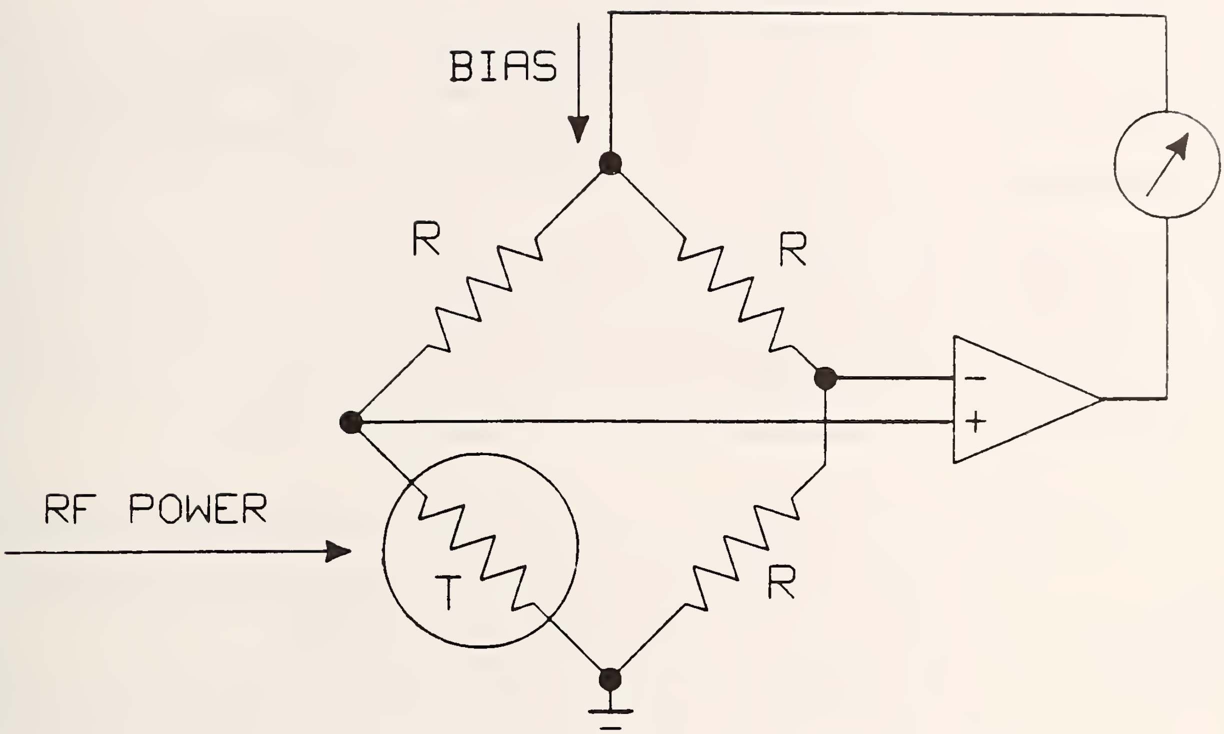

Figure 4.2.6 Simplified diagram of a self-balancing Wheatstone bridge.

from the amplifier provides self-balancing as shown in figure 4.2.6 [2]. Figure 4.2.7 is a simplified diagram of a bridge circuit in which a second bolometer bridge provides temperature compensation. Both bridges are self-balanced through amplified feedback [2].

Although linearity of the thermistor response is relatively greater at levels of rf, mw and mmw power above 4 mW, sensitivity decreases in this region, especially at higher operating temperatures, as seen in figure 4.1.1 (b). Changes in resistance per milliwatt are smaller than those at power levels below approximately 4 mW.

Mismatch uncertainties occur when values of line and load impedances become dissimilar. These impedance mismatches reduce the power absorbed by the sensor and, in an unbalanced bridge, a 2:1 resistance change can cause an uncertainty of up to 0.5 dB [1].

Manually balanced bridges provide excellent sensitivity for the measurement of low power (less than 2 mW) but require considerable time for the frequent adjustments necessary to balance the bridge. They have, however, long been used in standards laboratories where high accuracy is important. Characteristics of manually balanced bolometer bridges are:

(1) bolometer operation at a single value of resistance, which provides a dynamic range of about 20 dB and presents closely matching impedances to rf, mw, and mmw power sources;

(2) measurement of substituted dc power with suitable accuracy and correlation directly with known voltage and resistance standards; and

(3) slow measurement, which also requires calculation of the results of each power measurement [1].

Automatically balanced bridges eliminate all operations required for the manually balanced bridges, except for the zero adjustment for initial balance. A diagram of this type of bridge is shown in figure 4.2.8. Positive feedback, from a differential amplifier placed across the bridge, is temperature-sensitive, depending on the resistance of the thermistor. Negative feedback, across the other side of the bridge which contains a tuned circuit, is frequency-sensitive and reaches a minimum value at the resonant

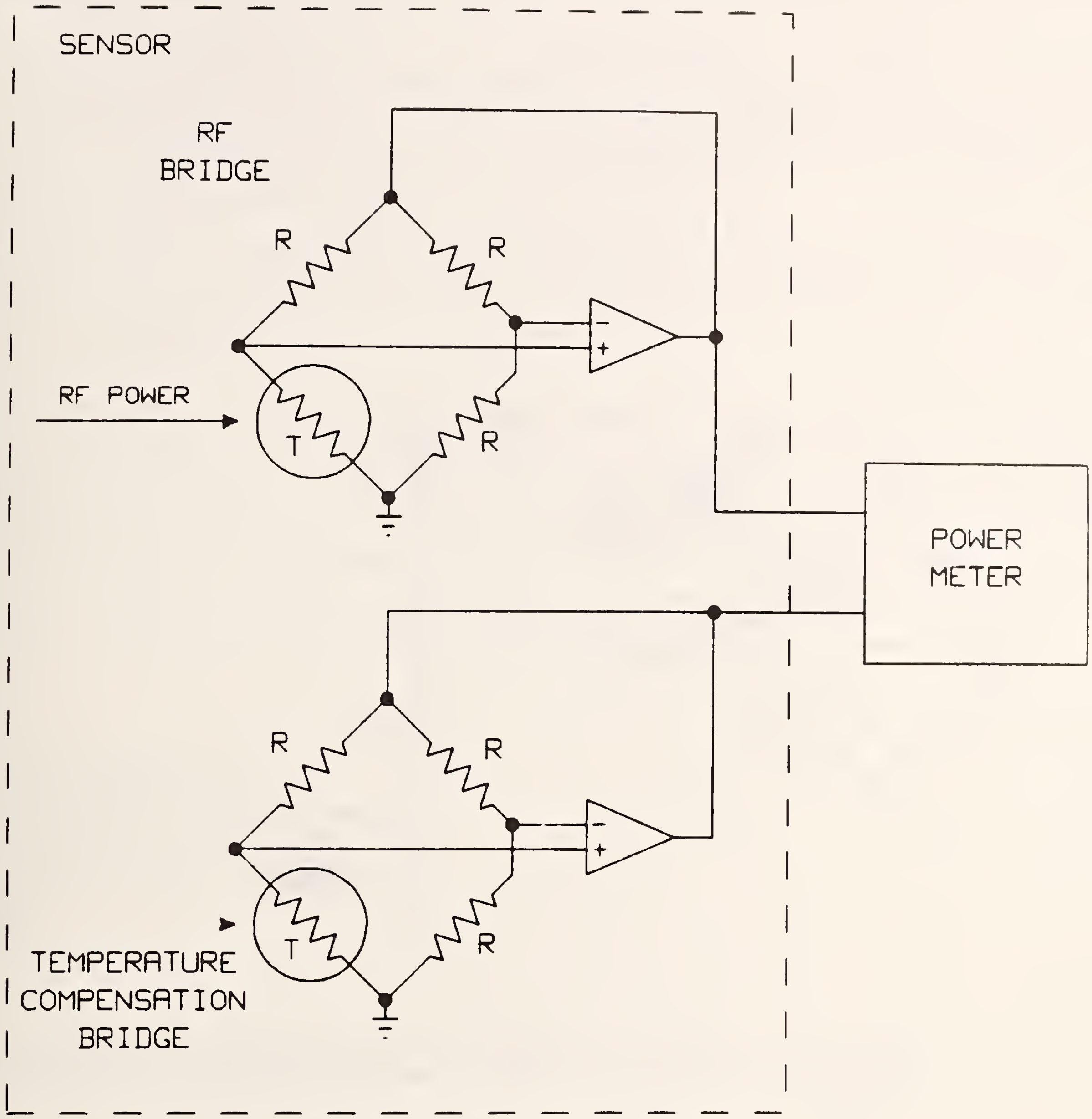

Figure 4.2.7 Simplified diagram of a temperature-compensated bridge circuit in which a second bridge provides temperature compensation.

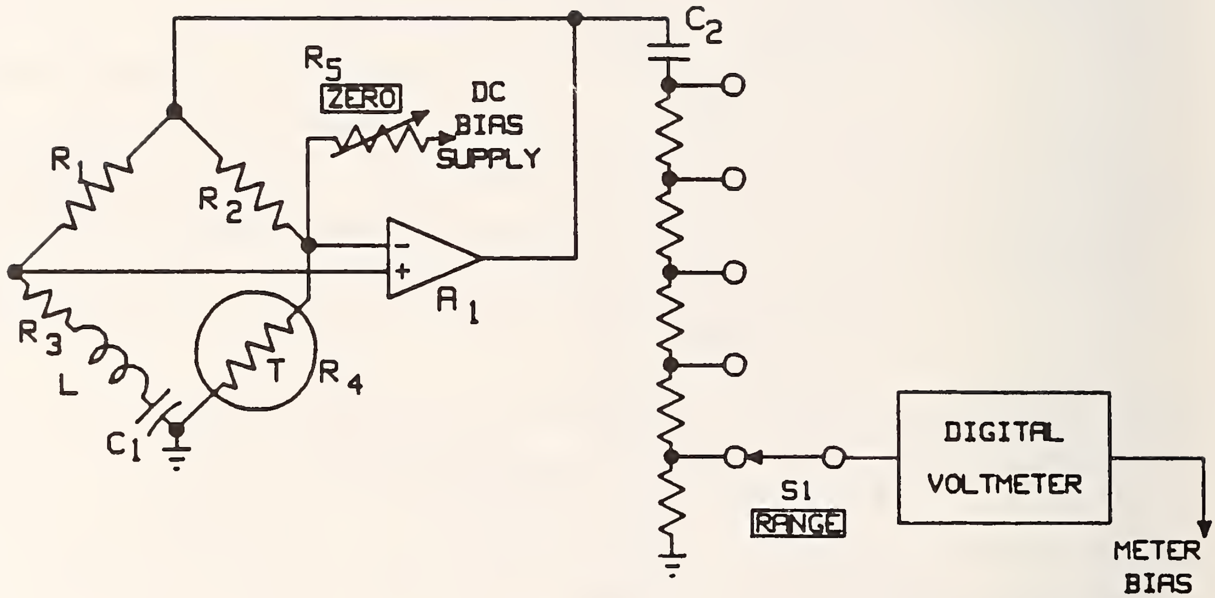

Figure 4.2.8 Simplified diagram of an automatic power meter showing bridge, tuned circuit, feedback mechanism, and metering system.

frequency of the tuned circuit. Characteristics of the automatically balanced bolometer bridge are:

(1) rapid measurement with no need for auxiliary instruments;

(2) constant value of bolometer operating resistance, which provides a suitable impedance match at all power levels within the dynamic range of the instrument; and

(3) lack of temperature compensation, which may obscure measurements on the low-scale setting due to interference from ambient temperature changes.

Bolometer mounts for manual and automatic bridges may be: (1) tunable, (2) fixed and tuned, or (3) broadband and untuned. They are typically coaxial for frequencies up to 18 GHz, and waveguide structures for frequencies above 18 GHz. The coaxial mounts are untuned, and their bolometer elements usually present 200 Ω to the bridge. The tunable waveguide bolometer mounts are typically tuned manually for each frequency of interest.

5.0 System Calibration

Reference Standard Calibration System

The Unit Under Test (UUT) must be measured against a reference standard power measurement system. The following procedure for setting up and calibrating the reference system must be performed prior to testing any parameters of the UUT. The procedure spans the range of power levels from 0.5 to 10 mW and typically has three parts, one for each of three consecutive frequency bands within the frequency range of interest. Part 1 covers the calibration procedure for the frequency range from 10 to 100 MHz. Part 2 contains the calibration procedure for the power level range from 0.5 to 10 mW and the frequency range from 100 MHz to 18.0 GHz and Part 3 is the calibration procedure for the frequency range from 18.0 to 26.5 GHz.

The power measurement system basically consists of two units: a Wheatstone bridge which contains a bolometer sensing element and external instrumentation. Two equal resistors form two arms of the bridge and a third resistor is equal to the operating resistance of the bolometer. Only the bolometer sensor is external to the meter, but it functions as the fourth arm of the bridge within the power measurement system.

The theory of power measurement presented in Section 4.2 is based on the principle of dc substitution. There are two steps. Initially, a single source of dc voltage is applied to the bridge from a regulated voltage source, (see figure 4.2.1). This is the total power on the bridge at this time. No rf power is allowed to impinge on the thermistor sensor in this step. Since this power is dc rather than rf power, Ohm's law may be used to calculate the dc value by measuring the dc voltage, V_1, as shown in figure 5.1, and dividing the voltage by the operating resistance, R_T, of the thermistor.

In the second step, rf power is allowed to impinge on the thermistor with no other changes in the circuit. As rf power is applied to the bolometer, its resistance decreases (if the element is a thermistor). The bridge circuit detects this unbalanced condition and increases the dc bridge current. The new voltage, V_2, increases to restore a balance of bridge power. This change in dc power is equal (ideally) to the rf power dissipated in the bolometer element. (In practice they are not equal because of dc-rf substitution errors [6]). The equivalent value of rf power is calculated

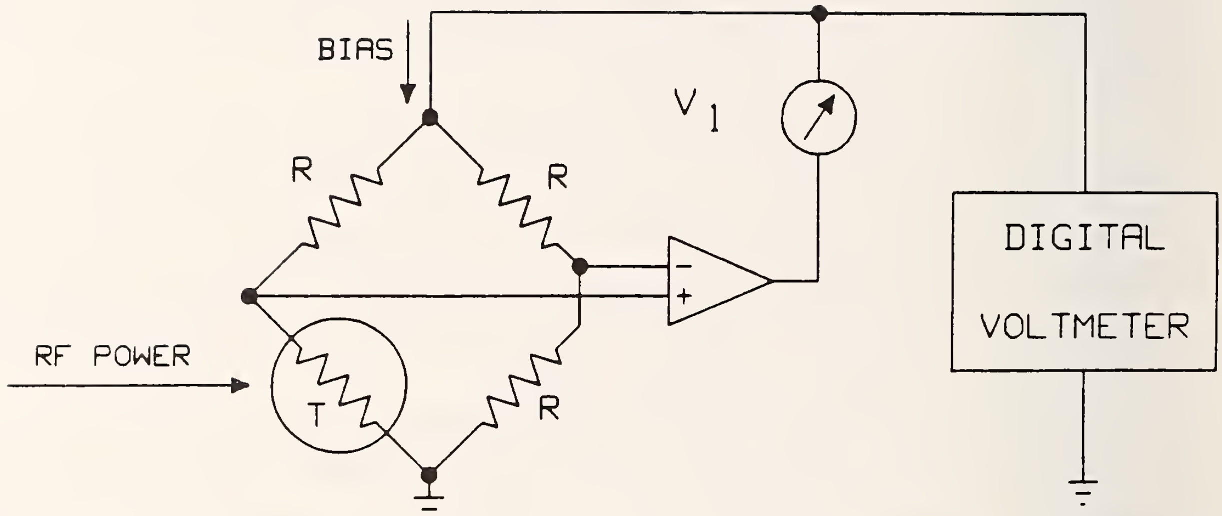

Figure 5.1 Basic power measurement system showing thermistor bridge and digital voltmeter.

using the value of the substituted dc power and the appropriate bolometer calibration factor for the frequency of interest.

System calibration may be obtained with several types of equipment specifically designed for this purpose. A typical configuration is shown in figure 5.1.1. This system[1] is based on the assumption that power levels about the measurement reference plane are equal across this plane. A calibration factor from an NIST-calibrated reference standard is transferred to an internal power sensor with a typical loss of 0.5-1.0 percent in transfer. This is done for 109 NIST-traceable frequencies [18]. The output power level of this standard equals the input power level to the reference power sensor across the measurement reference plane.

This system is used to determine the accuracy of the internal power sensor. The latter then becomes the standard for evaluating the calibration factor of the bolometer sensor in a UUT.

5.2 System Calibration Method

5.2.1 Part 1: (10-100 MHz)

The system is connected as shown in figure 5.2.1. The signal source is set at the lowest frequency, 10 MHz, with a minimum rf output level. A bias dc voltage, V_1, in millivolts, (as read on the DVM) is placed on the reference sensor to establish an operating point within its linear response region with no rf input from the signal source to the power measurement system. When rf power is applied to the reference sensor from the signal source at a level of zero dBm (1 mW), the bridge becomes unbalanced and the DVM indicates a new dc voltage, V_2, in millivolts. The values of V_1 and V_2 are read and recorded.

These two voltage values are squared and the difference between these squared terms is divided by the operating resistance (Section 4.1) of the sensor. The result is the dc-substituted power, P_{dc}, measured by the reference sensor of the standard. P_{dc_1} is the value of P_{dc} for Part 1, where

[1]When manufacturers' trade names are used to specify certain types of equipment, this does not imply endorsement by the National Institute of Standards and Technology. Similar products by other manufacturers may have equal or better quality.

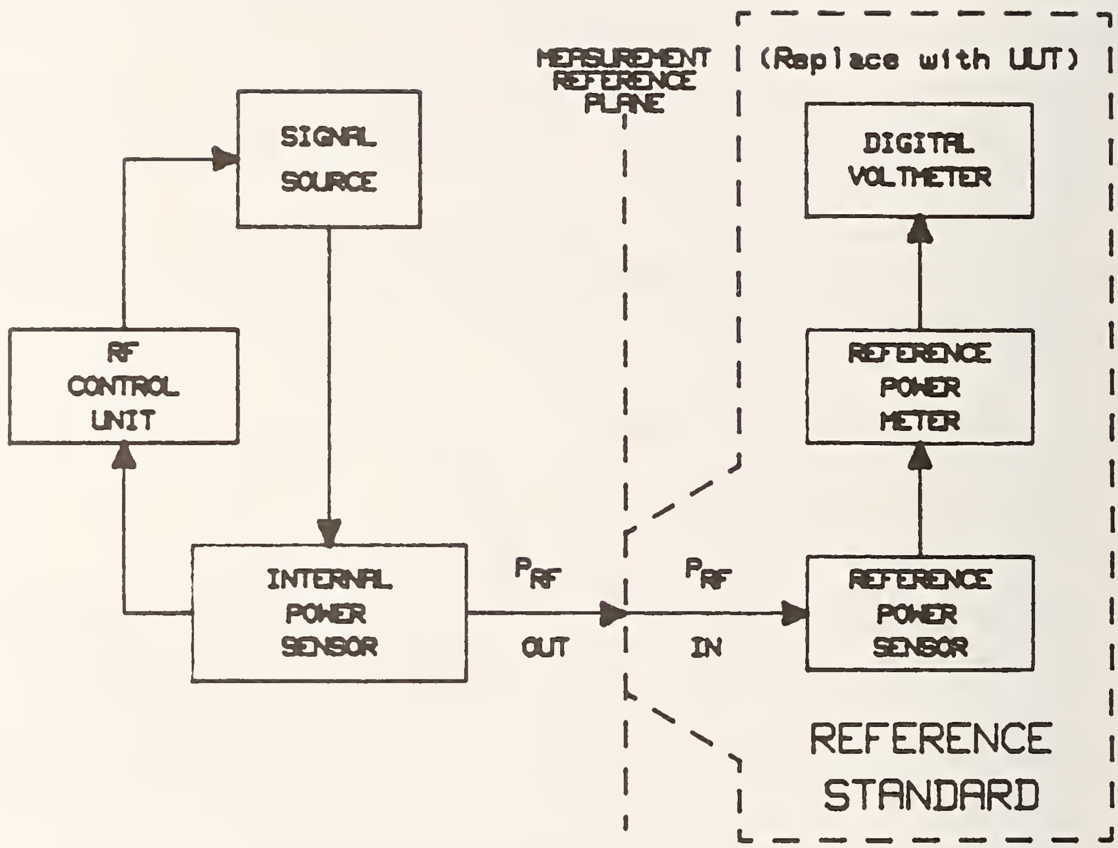

Figure 5.1.1 Typical calibration system for a reference standard.

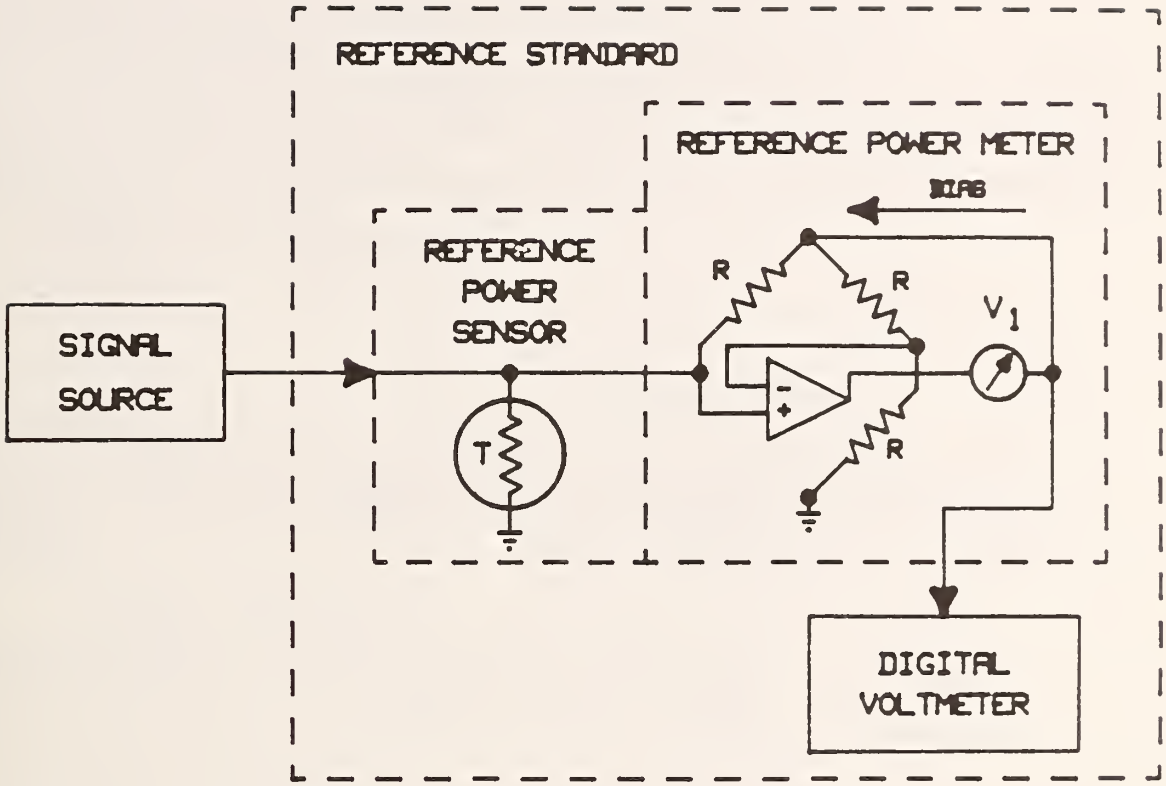

Figure 5.2.1 Typical test setup for a system calibration procedure for the frequency range of 10 to 100 MHz.

$$P_{dc_1} = \frac{V_1^2 - V_2^2}{200} \times 10^3 \quad [\mathrm{mW}], \tag{5.1}$$

when V_1 and V_2 are in millivolts.

A further calculation converts the dc substituted power to rf power, P_{rf_1}, through the use of the bolometer calibration factor, K_1, where K_1 is the calibration factor of the reference standard bolometer sensor at the frequency of interest. It is provided by the manufacturer of the sensor.

$$P_{rf_1} = \frac{P_{dc_1}}{K_1} . \tag{5.2}$$

The values of P_{dc_1} and P_{rf_1} are recorded. Table 5.2.1 presents the recorded data in a useful format. This procedure is repeated at typical frequencies of 50 MHz and 100 MHz.

Table 5.2.1 System calibration data for the frequency range from 10 to 100 MHz

Signal Source	Ref. Standard	DVM		Calculated Values	
Frequency (MHz)	CAL Factor (K_1)	V_1 (mV)	V_2 (mV)	P_{dc_1} (mW)	P_{rf_1} (mW)
10					
50					
100					

5.2.2 Part 2: (0.1-18.0 GHz)

An rf transfer standard with its own control unit is used for this frequency range. This control unit contains the bolometer bridge and controlled-temperature source for stabilizing the bolometer mount. The control unit is

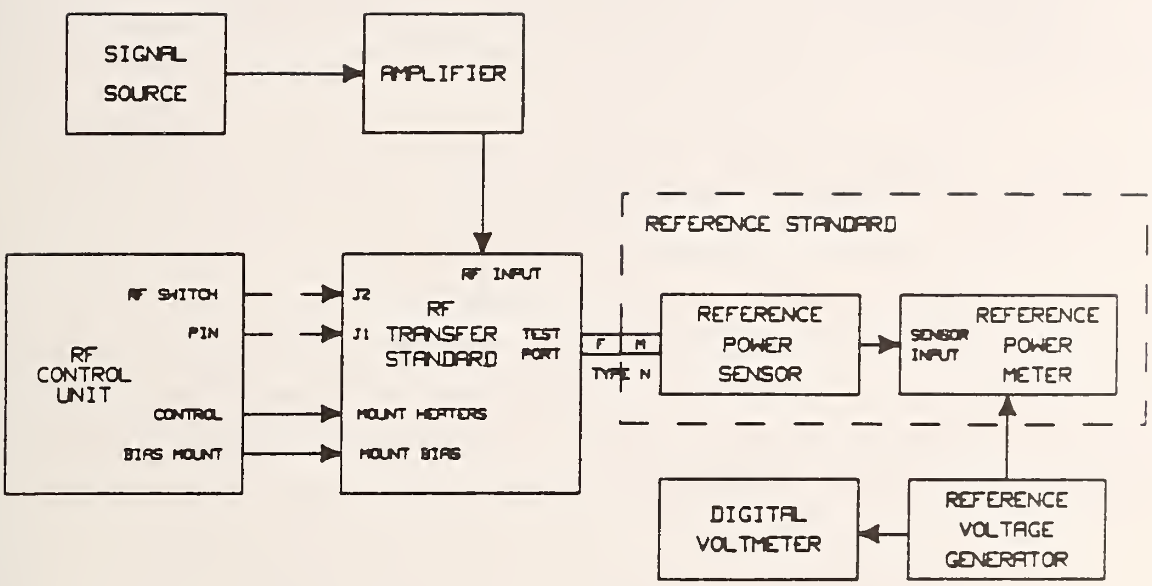

Figure 5.2.2 Typical test setup for a calibration procedure for the frequency range of 0.1 to 18.0 GHz.

connected to the rf transfer standard as figure 5.2.2 indicates. The rf control unit is maintained in the frequency-locked condition by supplying sufficient rf output power level from the signal source.

The voltage applied to the rf transfer standard by the reference voltage generator, through the reference standard, is measured on the DVM first with the rf control unit turned off, V_1, and then with the control unit turned on, V_2. The dc-substituted power, P_{dc}, measured by the rf transfer standard is calculated by taking the difference between the squares of these voltage values and dividing by the operating resistance (Section 4.1). For this frequency range, or Part 2, P_{dc} is designated as P_{dc_2} and is calculated as follows:

$$P_{dc_2} = \frac{V_1^2 - V_2^2}{200} \times 10^3 \text{ [mW]} . \tag{5.3}$$

P_{dc_2} is linearly related to the calibration factor, K_2, of the internal power sensor of the transfer standard and to the value, P_{dc_1}, of the reference standard measured in Part 1. A value of K_2 is given by the manufacturer, but the actual calibrated value of K_2, is

$$K_{2_{calc}} = K_1 \left(\frac{P_{dc_2}}{P_{dc_1}}\right), \tag{5.4}$$

which is recorded together with the value of K_2 given by the manufacturer, $K_{2_{mfr}}$. A useful format for recording these values is given in table 5.2.2. $K_{2_{calc}}$ is determined for each frequency of interest and represents the new calibration (CAL) factor to be used for the rf power transfer standard. If these new CAL factors agree with those given by the manufacturer, no change is necessary. If the CAL factors differ from those given by the manufacturer, the newly determined values must be used.

Dc-substituted power is provided in this frequency range by the rf control unit at 0.5 mW and for 1 mW to 10 mW in 1-mW steps. The rf control unit provides stability of these power levels with an accuracy of ±0.1 percent. In order to do this the output power level of the rf signal source at the rf input of the rf transfer standard must be sufficient to drive a PIN diode attenuator in the rf transfer standard. This controls the signal level stability by holding this level in a locked condition. The bridge balance meter on the control unit will initially deflect to the local oscillator (LO) region but will return to the center position at zero. This zero position is an indication of the locked condition and therefore signifies that the output level of the rf signal source is sufficient to maintain a stable power level of 10 mW at the rf output of the rf transfer standard [18]. Nominal values of 10 μW, 0.5 mW, 1 mW and 10 mW are useful levels of P_{dc_2} at each frequency for determining the calibration factor. The PIN attenuator allows for nominal values of 10 μW.

To maintain this stable level, the output power level of the signal source must be greater than +10 dBm (10 mW) at the rf input to the rf transfer standard to counteract a loss of several decibels in rf power level which occurs within the rf transfer standard. A nominal value for the level of output power at the signal source could be +13 dBm (20 mW). This requires the use of a high quality amplifier.

An amplifier gain of 40 dB is typically used for the signal source in this frequency range from 0.1 to 1.0 GHz. The output level of the signal source should be -20 dBm for this frequency range in order to provide an input to the rf power transfer standard (through the amplifier) of approximately +20 dBm (100 mW). However, the maximum power input to the rf transfer standard must not exceed +23 dBm (200 mW). Once this output level has been set on the signal source, no change should be necessary for this frequency range. The proper level of operation is indicated by the return to the locked position for each selected value of dc substituted power on the rf control unit.

An amplifier gain of 20 dB is used for the signal source frequency range from 2 to 18 GHz. The output level of the signal source should therefore be set at zero dBm for this frequency range to provide an input to the rf power transfer standard (through the amplifier) of approximately +20 dBm (100 mW).

Repeat the above procedure for a useful range of frequencies such as 0.5, 1.0, 2.0, 4.0, 7.0, 8.2, 10.0, 12.4, 15.0 and 18.0 GHz.

Table 5.2.2 System calibration data for the frequency range from 0.1 to 18.0 GHz

Signal Source	Ref. Standard	DVM		Nominal Value	Calculated Values	
Frequency (GHz)	CAL Factor (K_2)	V_1 (mV)	V_2 (mV)	P_{dc_2} (mW)	P_{dc_2} (mW)	P_{rf} (mW)
0.1				0.01 0.5 1.0 5.0 10.0		
0.5						
1.0						
2.0						
4.0						
7.0						
8.2						

Table 5.2.2. (Cont.)

Signal Source Frequency (GHz)	Ref. Standard CAL Factor (K_2)	DVM		Nominal Value	Calculated Values	
		V_1 (mV)	V_2 (mV)	P_{dc_2} (mW)	P_{dc_2} (mW)	P_{rf} (mW)
10.0						
12.4						
15.0						
18.0						

5.2.3 System Calibration Method, Part 3: (18.0-26.5 GHz)

The system is connected as shown in figure 5.2.3. For frequencies above 18 GHz, a waveguide transmission line is used rather than a coaxial line. The reference-power transfer standard is inserted into the waveguide structure, which is then manually tuned for each frequency of interest during calibration. Settings for tuners T_1, T_2, T_3 and T_4, for each frequency of interest, are provided by the manufacturer of the power meter measurement system. Tuner settings for a typical waveguide power transfer standard are given in Appendix 14.3.

The bias voltage, V_1, in millivolts, which is applied to the reference-power transfer standard from the reference power meter (indicated in figure 5.2.1), establishes an operating point for the linear response of the internal power sensor of the transfer standard.

The voltage, V_2, in millivolts, from the signal source is then measured, and the dc substituted power for this frequency range, P_{dc_3}, is determined by the difference between V_1 squared and V_2 squared, divided by the sensor's operating resistance (Section 4.1), where

$$P_{dc_3} = \frac{V_1^2 - V_2^2}{200} \times 10^3 \text{ [mW]} . \tag{5.5}$$

Values of the calibration factor, K_3, of the reference-power standard for each frequency of interest are provided. These are determined at a standards laboratory.

The rf power, P_{rf}, is then calculated by dividing P_{dc_3} by the calibration factor, K_3, for each frequency of interest as follows:

$$P_{rf} = \frac{P_{dc_3}}{K_3} . \tag{5.6}$$

All values are recorded, as formatted in table 5.2.3, and this procedure is repeated for suggested additional frequencies, at suitable intervals, such as 20, 22, 24, 25 and 26.5 GHz.

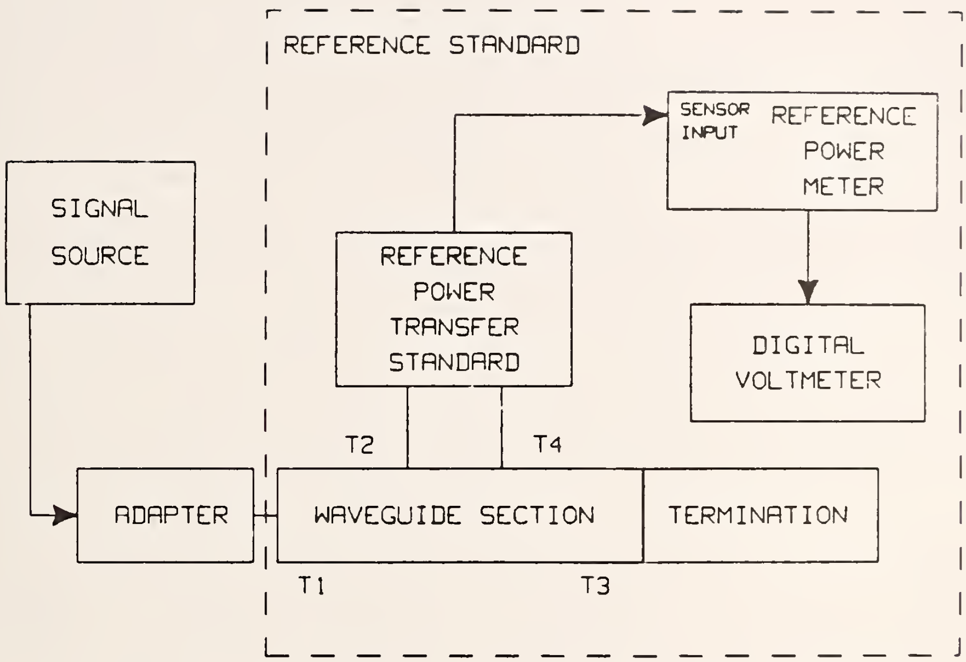

Figure 5.2.3 Typical test setup for a system calibration procedure for the frequency range of 18.0 to 26.5 GHz.

Table 5.2.3 System calibration data for the frequency range from 18.0 GHz to 26.5 GHz

Signal Source Frequency (GHz)	Ref. Standard CAL Factor (K_3)	DVM		Calculated Values	
		V_1 (mV)	V_2 (mV)	P_{dc_3} (mW)	P_{rf} (mW)
18.0					
20.0					
22.0					
24.0					
25.0					
26.5					

6.0 Evaluation of Power Measurement Capabilities

6.1 General

The measurement parameter of interest is rf, μw, or mmw power. The power range of interest commonly used for many industrial and military applications is 10 μW to 10 mW. It is necessary not only to determine whether a power meter can measure these powers accurately, but also to verify that these measurements are obtainable throughout the frequency ranges for which the instrumentation is required. They must also be obtainable within specified limits of long-term stability, operating temperature, and response time. Extension of the power measurement capability to 5 W and overload protection for the power meter are also of interest. In addition, other characteristics of the total instrumentation must be considered if the final measurement results are to contain validity. Characteristics of subsystems of the total instrumentation which contribute to the precision and reliability of final results must also be studied. These subsystems are: (1) the metering subsystem; (2) the internal power reference; and (3) the power sensor. Figures 6.1.1 [3] and 6.1.2 (after [2]) are block diagrams of power meters showing types of power meter subsystems.

Evaluation of power meter performance must include such characteristics as: (1) ranges of frequency and power; (2) operating temperature; (3) stability; (4) response time; (5) power sensor calibration factor; (6) extended power measurement; (7) overload protection; (8) parameters of the internal power reference, and (9) parameters of the power sensor. Summaries of techniques are described and block diagrams illustrating these procedures are presented here, together with some typical measurement results. All measurement procedures must be preceded by the system calibrations described in Section 5.

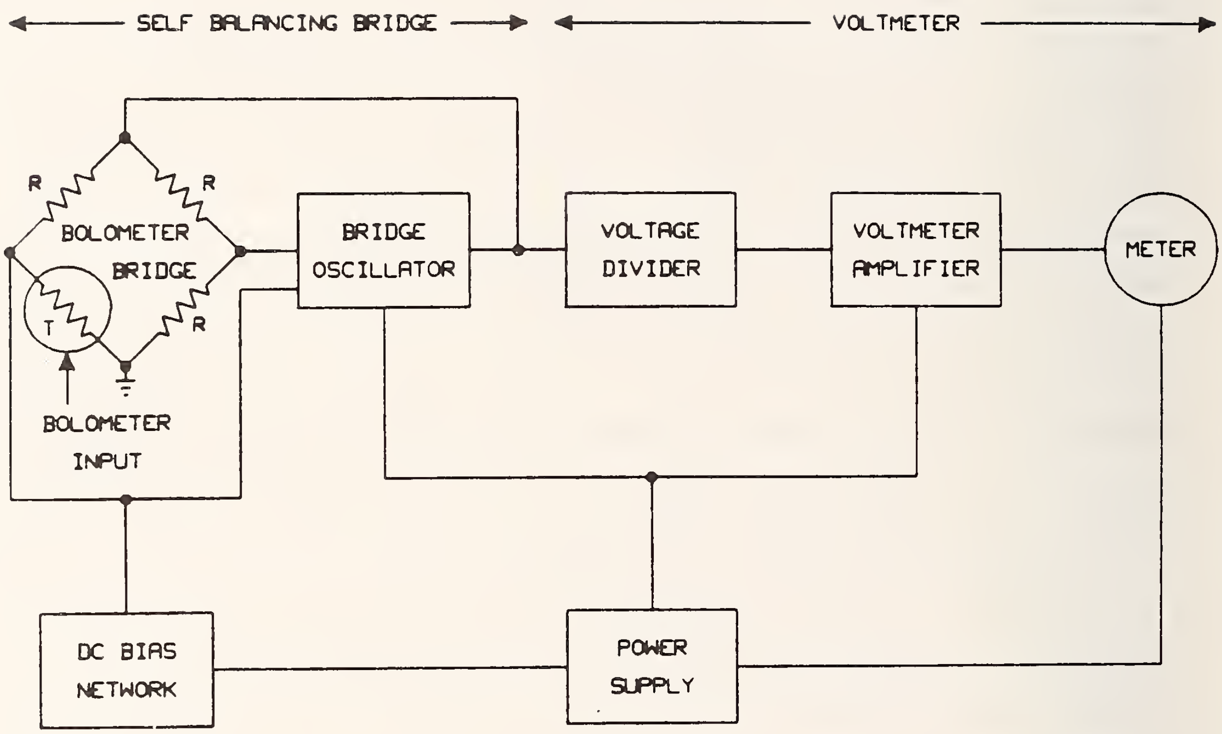

Figure 6.1.1 Block diagram of a power meter illustrating the subsystems.

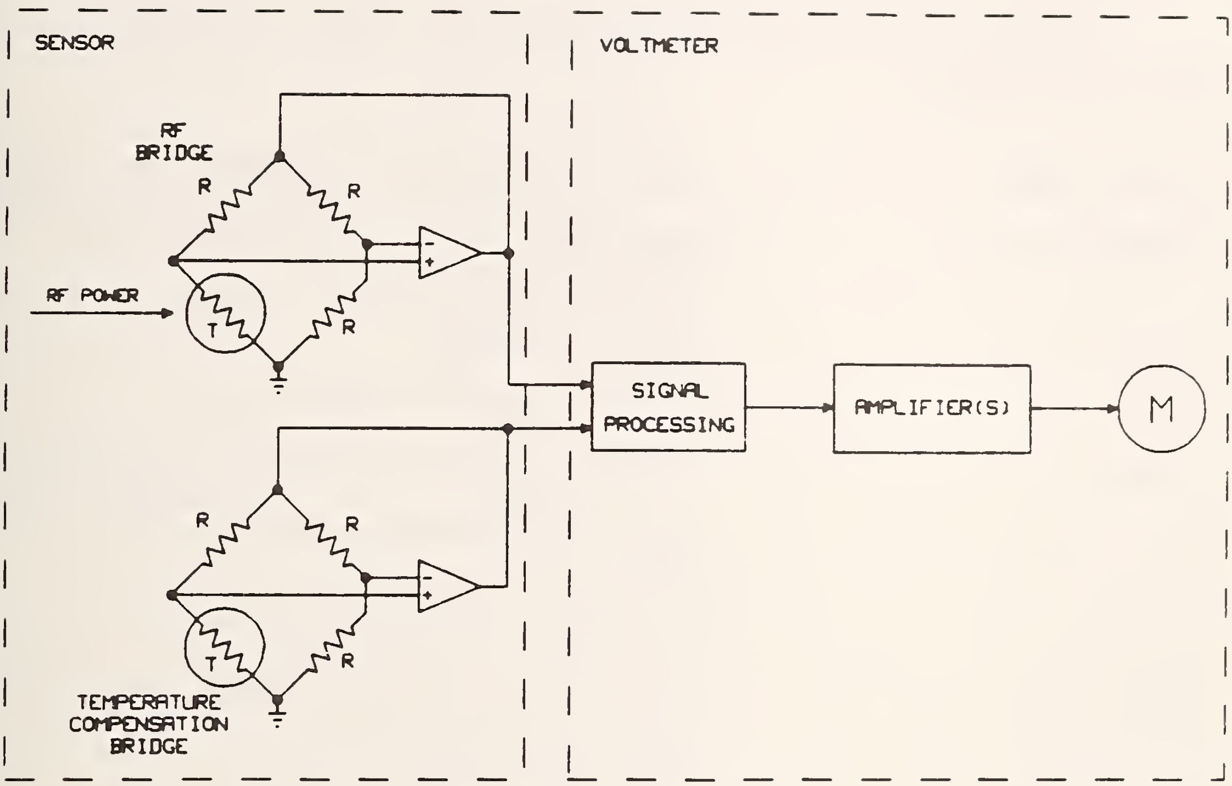

Figure 6.1.2 Simplified diagram of a temperature-compensated power meter illustrating the subsystems.

6.2 Initial Conditions

The controls of the UUT and the signal source must be set to the appropriate positions prior to conducting the performance tests.

6.2.1 Unit Under Test

Perform the following typical settings for each of the controls on the UUT in this order:

SENSOR INPUT	Connect sensor cable to SENSOR INPUT port
ON/OFF SWITCH	Set to ON (Allow one hour warm-up)
RANGE	Set to AUTORANGE
ZERO	Press to zero the meter display
POWER REF	Connect sensor cable to REF OSCILLATOR port
CAL FACTOR	Enter into power meter the CAL Factor for 50 MHz
CAL ADJUST	Adjust until meter reads 1.000 mW
SENSOR INPUT	Connect sensor cable to SENSOR INPUT port
CAL FACTOR	Enter into power meter the CAL Factor for frequency of interest

6.2.2 Signal Source

Set the controls on the typical signal source as follows:

ON/OFF SWITCH	ON
FREQUENCY	To frequency of interest
AM	OFF
FM	OFF
PM	OFF
AUTOMATIC LEVEL CONTROL	Internal
OUTPUT RANGE ATTENUATOR	Maximum attenuation
OUTPUT RANGE VERNIER	Maximum attenuation
RF OUTPUT SWITCH	OFF
LEVEL MODE SELECTOR	LEVEL
FREQUENCY REFERENCE	Internal

6.3 Performance Tests

6.3.1 Frequency Range and Power Range

The ranges of frequency and power are measured initially before any other performance tests. The typical frequency range is specified as 10 MHz to 26.5 GHz and the power range is 10 μW to 10 mW.

6.3.1.1 Part 1:(10-100 MHz)

After the system calibration of Section 5.2.1 for the frequency range 10 MHz to 100 MHz is performed and the initial conditions of Section 6.2 are met, the UUT is connected as shown in the test setup of figure 6.3.1.1 to measure the frequency range from 10 to 100 MHz and the power range from 10 μW to 10 mW at each frequency of interest.

The values of frequency, dc-substituted power, P_{dc_1}, and CAL factor, K_1, of the reference sensor, determined in the calibration of Section 5.1, Part 1, are recorded in table 6.3.1.1 in both watts and decibels.

A frequency of 10 MHz and an rf output power (RFOP) of 1 mW are selected on the signal source. Attenuation of 20 dB applied to the signal source output provides an input power level of 10 μW to the UUT. A set of calibrated attenuators is required here. (These are calibrated by the manufacturer or a calibration laboratory such as NIST.)

The appropriate value of K_1 must be entered into the UUT for each frequency of interest. This must be recorded together with the power indicated on the UUT, P_{UUT}. A useful tabular format is given in table 6.3.1.1.

Actual values of attenuation at the power meter input may vary slightly from the nominal value of 20 dB and these data are provided by the manufacturer for each attenuator. The attenuator should be calibrated by a calibration laboratory such as NIST, prior to use in this test. Therefore, each power measurement made by the UUT must be corrected for any variations in the calibrated results from the nominal value. These corrected measurements, P_{UUT_C}, are recorded in table 6.3.1.1. The correction factor is the result when the difference between calibrated and nominal attenuation values is divided by the nominal attenuation value.

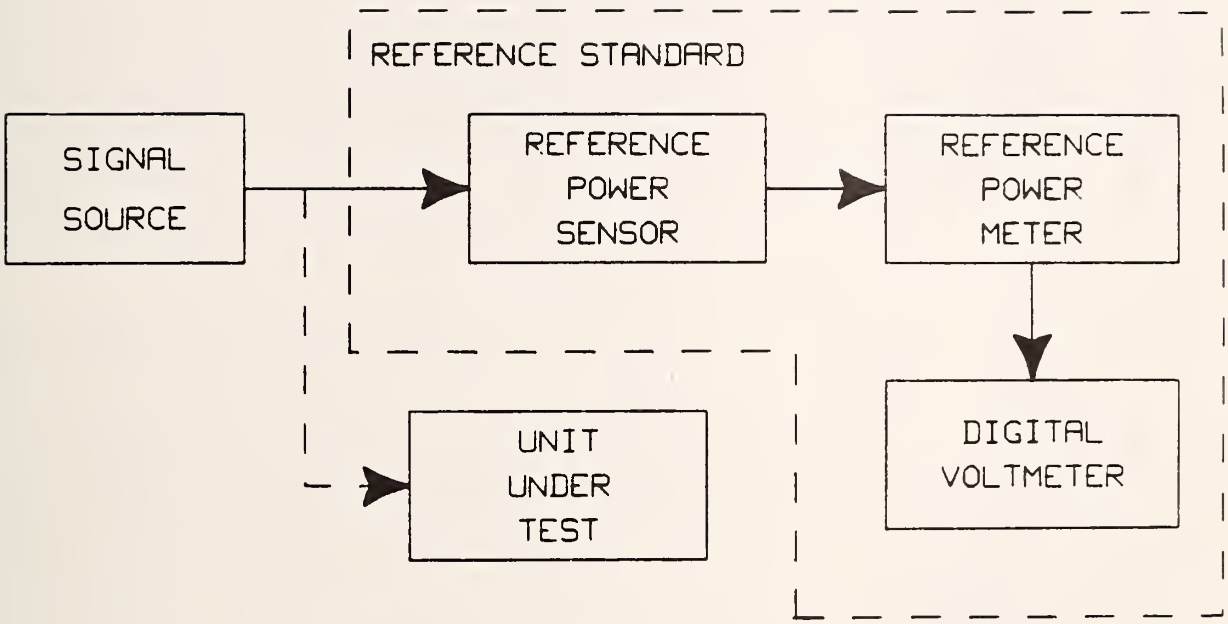

Figure 6.3.1.1 Typical test setup for measurement of frequency range and power range of the Unit Under Test (UUT) from 10 to 100 MHz.

Table 6.3.1.1 Data for determining frequency range and power range of the Unit Under Test (UUT) from 10 to 100 MHz

Signal Source			Reference Sensor		Attenuator	UUT					CAL Factor
						Power Input	Power Measured				
					Attenuation (corrected)		(displayed) (P_{UUT})		(corrected) (P_{UUT_c})		($K_{UUT\,calc}$)
Freq. (MHz)	RFOP (mW)	RFOP (dBm)	P_{dc} (mW)[1]	K_1	(dB)	(mW)	(mW)	(dBm)	(mW)	(dBm)	
10 50 100	1	0				10 μW					
10 50 100	10	10				100 μW					
10 50 100	1	0				1 mW					
10 50 100						10 mW					

The bolometer calibration factor of the UUT, K_{UUT}, is determined as follows:

$$K_{UUT} = K_1 \left(\frac{P_{UUT_c}}{P_{dc_1}}\right). \qquad (6.1)$$

This value is also recorded in the table, and the procedure is repeated for each frequency of interest while maintaining the input power level of the UUT at 10 μW.

For a power input to the UUT of 100 μW the signal source output level is increased to 10 mW.

Upon removal of the attenuator the signal source output levels of 1 mW and 10 mW equal the input power levels to the UUT. Each of these changes in power level input to the UUT are followed by the measurement sequence described above at each frequency of interest.

6.3.1.2 Part 2:(0.1-18.0 GHz)

The system calibration described in Section 5.2.2 for the frequency range from 0.1 to 18.0 GHz must be performed and the initial conditions of Section 6.2 must be met. The UUT is then connected in the test configuration of figure 6.3.1.2 to measure this frequency range over the power range from 10 μW to 10 mW at each frequency of interest. Comparison of figures 5.2.2 and 6.3.1.2 shows that the measurement configuration differs from the calibration configuration only where the UUT and its level-setting attenuator replace the reference standard of the former configuration.

The values of frequency and the CAL factor of the reference power sensor of the calibration procedure, K_1, and the calibration factor of the rf transfer standard, K_2, determined in the calibration of Section 5.2.2, are read from table 5.2.2 and recorded in table 6.3.1.2 at this time. The values of dc substituted power, P_{dc_2}, of the rf control unit, are also recorded from Section 5.2.2 in watts or decibels. The sensor CAL factor of the UUT from the manufacturer, $K_{UUT_{mfr}}$, is also entered in table 6.3.1.2. The power of 10 μW applied to the UUT is obtained by insertion of a calibrated

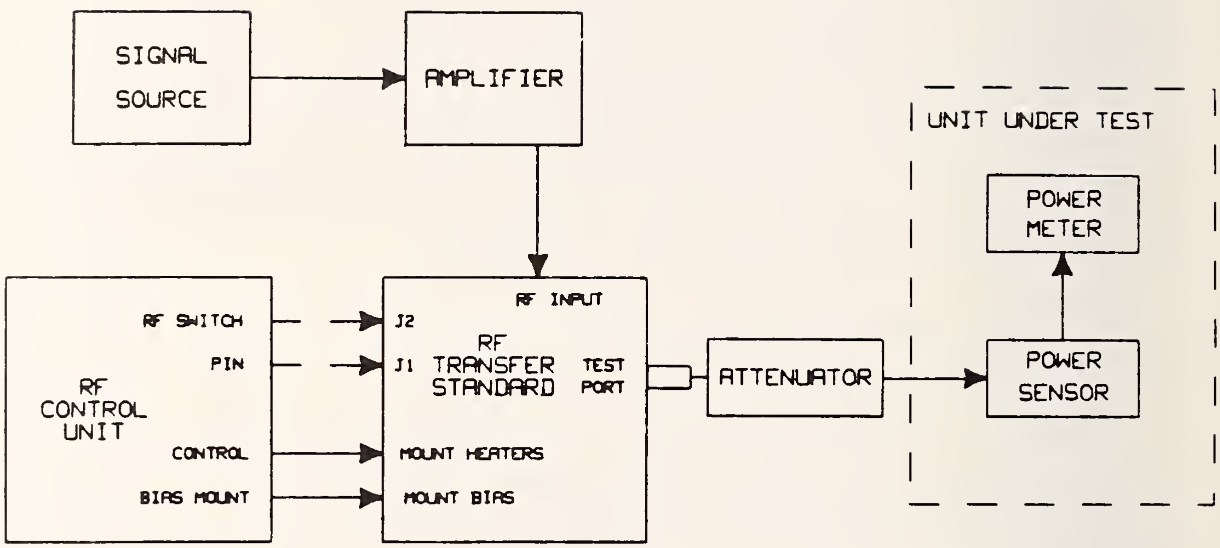

Figure 6.3.1.2 Typical test setup for measurement of frequency range and power range of the Unit Under Test (UUT) from 0.1 to 18.0 GHz.

Table 6.3.1.2 Data for determining frequency range and power range of the Unit Under Test (UUT) from 0.1 to 18.0 GHz

Source Generator Frequency (GHz)	Ref Power Sensor (K_1)	Rf Power Transfer Standard CAL Factor (K_2)	Rf Control Unit Dc Subst Power (P_{dc_2})	UUT CAL Factor (K_{UUTmfr})	$P_{UUT_{meas}}$			
					10 (μW)	10 (μW)	1 (mW)	10 (mW)
0.1								
0.5								
1.0								
2.0 Gen #1								
2.0 Gen #2								
4.0								
8.2								
10.0								
12.4								
15.0								
18.0								

20-dB attenuator between the rf transfer standard and the UUT and then setting the power output from the transfer standard at 1 mW.

Any variations in attenuation from the nominal 20-dB value are given by the manufacturer of the attenuator or the calibration laboratory and must be incorporated into the final power measurement, $P_{UUT_{meas}}$, as discussed in Section 6.3.1.1.

After each frequency of interest has been selected and the power measured and recorded as described above, the power input to the UUT is brought to 100 μW with an output of 10 mW from the signal source. The procedure is repeated through the same range of frequencies.

The 20-dB attenuator is removed and power levels of 1 mW and then of 10 mW are applied to the UUT for measurement through the same frequency ranges given above.

6.3.1.3 Part 3:(18.0-26.5 GHz)

After the system calibration described in Section 5.2.3 for the frequency range from 18.0 to 26.5 GHz is performed, and the initial conditions of Section 6.2 are completed, the UUT is connected in the test configuration shown in figure 6.3.1.3. Measurements on the UUT can then be performed over this frequency range and over the power range from 10 μW to 10 mW at each frequency of interest. The values of frequency, equivalent dc power, P_{dc_3}, and sensor CAL factor, K_3, from table 5.2.3 are recorded in table 6.3.1.3 at this time. A frequency of 18.0 GHz is selected on the signal source at an output power level of 1 mW. The calibrated 20-dB attenuator is inserted between the source output and the UUT to provide a calibrated input to the UUT of 10 μW. The waveguide tuners T_1, T_2, T_3 and T_4 are adjusted for maximum power transfer to the UUT. The value of K_3 is entered into the UUT for each frequency of interest. The power level displayed on the UUT (P_{UUT}) is read and recorded in table 6.3.1.3. The calculated value of the UUT power sensor calibration factor, $K_{UUT_{calc}}$, is obtained as follows:

$$K_{UUT_{calc}} = K_3\left(\frac{P_{UUT}}{P_{dc_3}}\right). \tag{6.2}$$

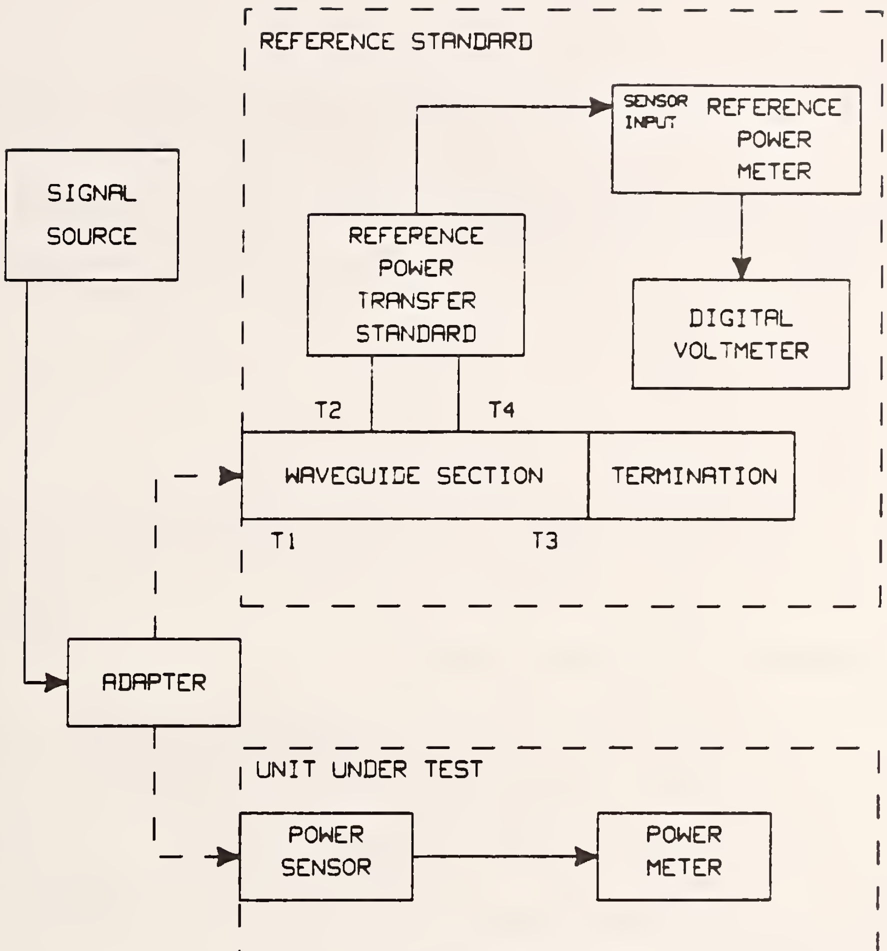

Figure 6.3.1.3 Typical test setup for measurement of frequency range and power range of the Unit Under Test (UUT) from 18.0 to 26.5 GHz.

This value of $K_{UUT_{calc}}$ is recorded in table 6.3.1.3. The actual power levels of the UUT, P_{UUT}, are recorded for each input power level of interest; useful levels are approximately 10 μW, 0.5 mW, 1 mW and 10 mW. The stepsare repeated for each frequency and power of interest.

Table 6.3.1.3 Data for determining frequency range and power range of the (UUT) from 18.0 to 26.5 GHz

Source Generator Frequency (GHz)	Ref Sensor CAL Factor (K_3)	Ref Sensor P_{dc_3}	UUT P_{UUT}	UUT $K_{UUT_{calc}}$	$K_{UUT_{mfr}}$
18.0					
20.0					
22.0					
24.0					
25.0					
26.5					

6.3.2 Power Sensor Calibration Factor

The calibration factor $K_{UUT_{mfr}}$ of the UUT power sensor, given by the manufacturer, is a nominal value, but an exact value $K_{UUT_{calc}}$ must be calculated, with the system reference standard and the power measurements of the UUT, $P_{UUT_{meas}}$, over the specified ranges of frequency and power.

A typical specification for the calibration factor of the UUT would require a value between 85 % and 100 % within ± 1%, or between +1 and -1 dBm, within ±0.01 dB.

The system calibration is performed as given in Section 5, and the initial conditions of the UUT, signal generator and all other required equipment are set.

The frequency and power ranges of the UUT are verified according to the performance tests for these parameters. Figures 6.3.1.1, 6.3.1.2 and 6.3.1.3 show the test configurations for their respective frequency ranges.

The calibration procedures of Section 5 yield the values of the dc-substituted power of the reference standard, P_{dc_n}, for n = 1, 2 and 3 for three frequency ranges, as well as the values of the reference standard power sensor calibration factors, K_n. The power sensor calibration factor of the UUT may be calculated as shown below by use of an algebraic ratio of power measured by the UUT to that of the dc substituted power of the reference power sensor. This ratio is then multiplied by the calibration factor of the reference power sensor to give the calculated value of K_{UUT}. Since the system for each frequency range used for the calibration of the reference standard is the same as that used for the power measurement of the UUT, then $K_{UUT_{calc}}$ holds the same relationshipto $P_{UUT_{meas}}$ as that between K_n and P_{dc_n}. This is calculated as follows:

$$K_{UUT_{calc}} = K_n\left(\frac{P_{UUT_{meas}}}{P_{dc_n}}\right), \tag{6.3}$$

which is expressed as a percent if the units of K_n are in percent. The final step is the calculation of the difference in percent between $K_{UUT_{calc}}$ and $K_{UUT_{mfr}}$, as follows:

$$\Delta K_{UUT}\ (\%) = \frac{K_{UUT_{calc}} - K_{UUT_{mfr}}}{K_{UUT_{calc}}} \times (100). \tag{6.4}$$

A value of 100 percent is assigned to the highest positive value of $K_{UUT_{mfr}}$ and the lesser values are obtained in percent with magnitudes scaled accordingly.

If $K_{UUT_{mfr}}$ is expressed in decibels, then it is desirable to convert $K_{UUT_{calc}}$ (in percent) to decibels, and the following conversion can be applied:

$$K_{UUT_{calc}}\ (\mathrm{dB}) = 10 \log K_{UUT_{calc}}\ (\%). \tag{6.5}$$

All readings must be recorded. A useful format is given for each frequency range in tables 6.3.2.1, 6.3.2.2 and 6.3.2.3.

Table 6.3.2.1 Power sensor calibration factors of the Unit Under Test (UUT) for the frequency range from 10 to 100 MHz

Source Frequency	Ref. Sensor CAL Factor	DVM		CAL Value	UUT			Cal Factor Difference	
(MHz)	(K_1)	V_1 (mV)	V_2 (mV)	P_{dc} (mW)'	$P_{UUT_{meas}}$	$K_{UUT_{mfr}}$	$K_{UUT_{calc}}$	Limits (± %)	Actual (± %)
10									
50									
100									

Table 6.3.2.2 Power sensor calibration factors of the Unit Under Test (UUT) for the frequency range from 0.1 to 18.0 GHz

Source Frequency (GHz)	Ref Sensor CAL Factor (K_2)	RF Control Unit DC Subst Power (P_{dc_2}) (mW)	UUT			CAL Factor Difference	
				CAL Factor			
			$P_{UUT_{meas}}$	$K_{UUT_{mfr}}$	$K_{UUT_{calc}}$	Limits (± %)	Actual (± %)
0.1							
0.5							
1.0							
2.0							
4.0							
7.0							
8.2							
10.2							
12.4							
15.0							
18.0							

Table 6.3.2.3 Power sensor calibration factors of the Unit Under Test (UUT) for the frequency range from 18.0 to 26.5 GHz

Source Frequency (GHz)	Ref Sensor CAL Factor (K_3)	DVM		CAL Value P_{dc_3} (mW)	UUT			Cal Factor Difference	
		V_1 (mV)	V_2 (mV)		$P_{UUT_{meas}}$ (mW)	$K_{UUT_{mfr}}$	$K_{UUT_{calc}}$	Limits (± %)	Actual (± %)
18.0									
20.0									
22.0									
24.0									
25.0									
26.5									

6.3.3 Operating Temperature Effects

It is important to verify the behavior of the power meter and sensor under specified environmental conditions. There are several parameters of the environment which could affect power measurement, but the only significant effect is that from temperature. A typical specification is the requirement that the power meter and power sensor meet all other operating requirements over the temperature range from 0°C to 55°C.

The internal initial conditions of the UUT are set and the test configuration of figure 6.3.3 is used. This setup is contained within the environmental test chamber. The power meter's internal reference oscillator is used as the signal source. Since this test is independent of frequency, the single frequency of 50 MHz of the reference oscillator provides sufficient stability to observe any changes in performance.

The output level of 1 mW of the reference oscillator is attenuated by 20 dB before entering the sensor in order to observe any changes in power measurement down to 10 nW on the 10 μW scale.

Power measurements are made at suitable temperature increments. Any changes in readings within 10 nW are recorded, along with the percent of change, in a format such as that shown in table 6.3.3.

Table 6.3.3 Data for determining the operating temperature effects on the Unit Under Test (UUT)

Frequency (MHz)	Temp (°C)	CAL Factor for 50 MHz (K_{UUT})	Power Level (μW)	Power Change (nW)	Percent Change
	0 23 37 45 50 55		10		

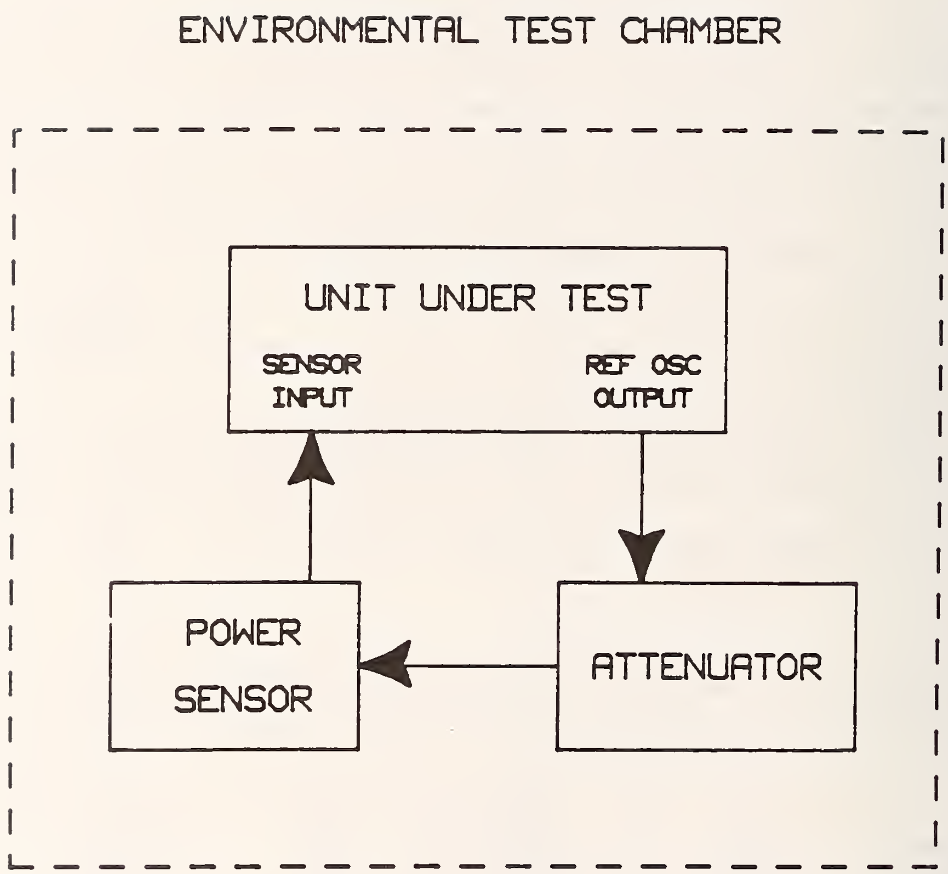

Figure 6.3.3 Typical test setup for measurement of operating temperature effects on the Unit Under Test (UUT).

6.3.4 Response Time

Response time of the power meter is defined as the time required for the indication to reach 90 percent of its final or steady state value (Section 2.1.16). The reading must begin at zero, and arrive at 90 percent of the final value in a specified time interval. The specified response time is typically 10 s or less on the most sensitive scale, and 2 s or less on any other scale setting.

The internal initial conditions of the UUT are set. The test configuration of figure 6.3.4 is used. A signal source frequency of 100 MHz is convenient although this test is independent of frequency. The UUT power sensor is connected to the rf output of the signal source which is set at -20 dBm, and the most sensitive setting of the UUT indication is selected. A suitable timing device with a range of 0-60 s is required.

The power readings of the UUT are recorded in a format such as that shown in table 6.3.4. The rf power of the signal source is turned off. Then both this rf output and the timing device are turned on simultaneously. At t = 10 s the power level on the UUT, ${}^{P}UUT_{t}$, is read and recorded, in both decibels and watts. At t = 60 s the final power level of the UUT, ${}^{P}UUT_{f}$, is read and recorded in table 6.3.4 in both decibels and watts.

The values of 90 percent of the final power levels are calculated and recorded in decibels and watts. The differences in 90 percent of the final power readings and the associated readings at the appropriate time intervals are calculated and recorded in the Δ Reading column. These values are calculated as (0.9 ${}^{P}UUT_{f}$ - ${}^{P}UUT_{t}$) both in dB and mW. These Δ readings can be compared with the values expected to meet the response time specifications.

A similar procedure is followed with rf power output levels of -10, 0, and +10 dBm, with timed intervals of 2 s.

These tests may be performed at additional frequencies of 1.0 and 10.0 GHz (or other frequencies as desired).

6.3.5 Long-Term Instability (Drift)

Power meter response time is measured in seconds or smaller units and is indicative of the UUT's short-term characteristics. The long-term stability [4] (or long-term instability or drift) of the steady-state value is

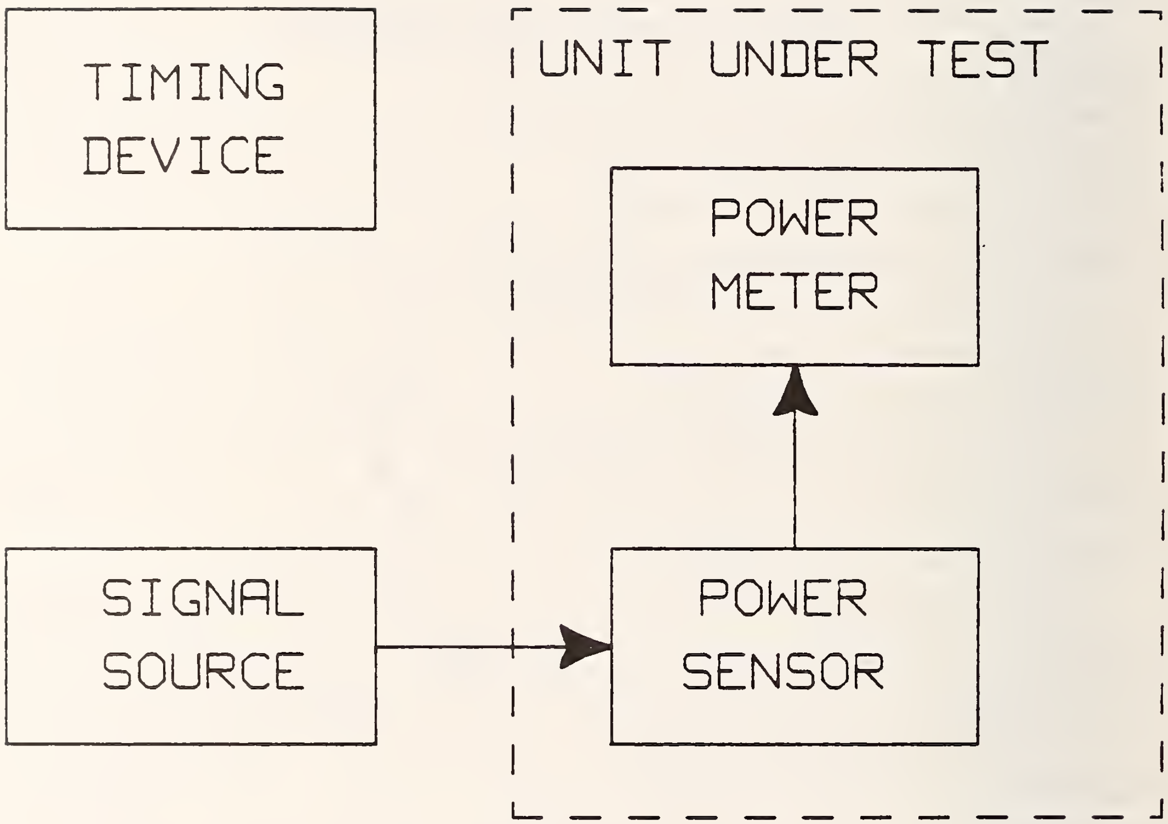

Figure 6.3.4 Typical test setup for measurement of response time of the Unit Under Test (UUT).

Table 6.3.4 Data for determining the response time of the Unit Under Test (UUT)

Signal Source			UUT Response Time									
Frequency (GHz)	RFOP		Power Sensor CAL Factor (K_{UUT})	P_{UUT_f} Final Reading		Specifd Time Intervl t	Reading at t sec (P_{UUT_t})		90 % of Final Reading (0.9 P_{UUT_f})		Δ Reading (0.9 P_{UUT_f} - P_{UUT_t})	
	dBm	mW		(dBm)	(mW)	(sec)	(dBm)	(mW)	(dBm)	(mW)	(dB)	(mW)
0.1	-20	0.01	100			10						
	-10	0.1				2						
	0	1.0				2						
	+10	10.0				2						
1.0	-20	0.01				10						
	-10	0.1				2						
	0	1.0				2						
	+10	10.0				2						
10.0	-20	0.01				10						
	-10	0.1				2						
	0	1.0				2						
	+10	10.0				2						

defined as the maximum acceptable change in a power measurement in 1 h for a constant input rf power, constant ambient temperature, and constant line voltage [4].

Since this test is independent of frequency, the 50 MHz frequency of the UUT reference oscillator can be used as a constant signal source for testing long-term instability.

The temperature compensation function built into bolometer mounts is designed to eliminate drift in the power sensor due to ambient temperature changes. This test also includes a preliminary waiting period of 15 min to further protect the power sensor from ambient temperature changes.

The initial internal calibration of the UUT is completed first. The CAL factor for 50 MHz of the UUT power sensor, K_{UUT}, is calculated from eq (6.3) and recorded in table 6.3.2.1. It is included here. However, since drift is indicated solely by a change in power level, this may be determined as a difference in the indicated values rather than in the calculated values. Then the UUT is inserted into the test configuration shown in figure 6.3.5. A 20-dB attenuator between the reference oscillator and the power sensor attenuates the 1-mW power output from the reference oscillator to 10 μW.

A series of six power readings are taken at 10-min intervals and re-corded in a format such as that presented in table 6.3.5. The units of any changes in power indication are usually nanowatts. The change in power can be calculated in percent for the various time intervals. These power changes can be recorded and compared with the allowable values as stated by the UUT drift specification.

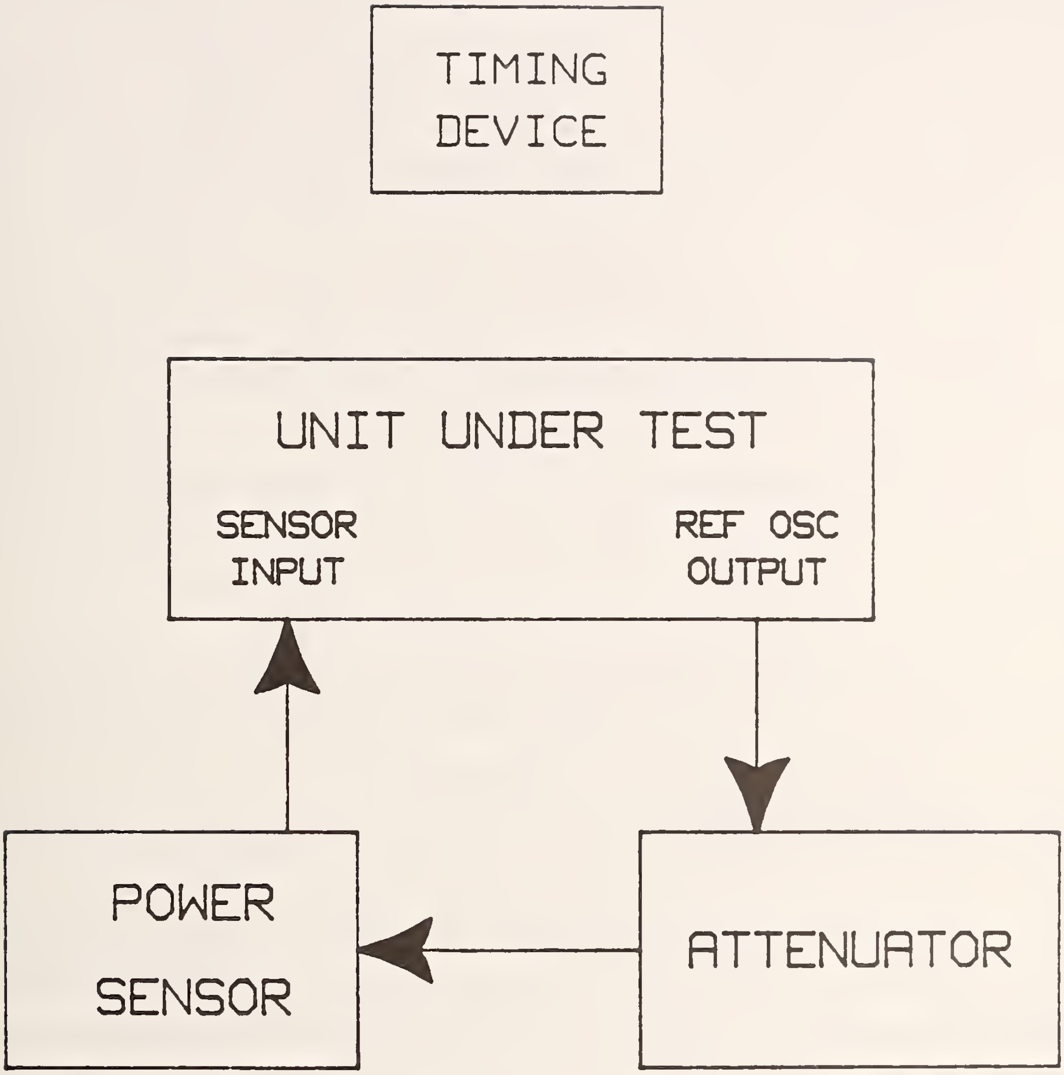

Figure 6.3.5 Typical test setup for measurement of long-term instability (drift) of the Unit Under Test (UUT).

Table 6.3.5 Data for determining the long-term instability (drift) of the (UUT)

Frequency (MHz)	Time (Min)	Power Sensor CAL Factor for 50 MHz (K_{UUT})	Power Level (μW)	Change in Power (nW)	Power Level Change (%)
50	0				
	10				
	20				
	30				
	40				
	50				
	60				

6.3.6 Display Functions

The metering subsystem transfers the power or energy output of the bolometer bridge with suitable amplification to, typically, a controlled digital display. The features of automatic zero, zero carryover, autoranging and display provide proper control of zero indication, and versatility in selection of scale factors and units of measurement.

The following power meter display features must all be evaluated: (1) automatic zero; (2) zero carryover; (3) autoranging, which eliminates resetting the readout to zero for each scale of sensitivity level, and (4) functions of the display such as resolution and annunciators for different types of units of measurement.

6.3.6.1 Automatic Zero

A typical specification for performance of the automatic zero capability requires that a value of zero within ±1% of full scale be automatically displayed on each sensitivity range setting after the initial value is selected on the most sensitive range.

When the display of the UUT is manually set to zero on the 10 μW range, any change in the least significant digit (LSD) from reading to reading (Δ LSD) must not exceed 100 nW typically. These units must be recorded accurately for each sensitivity scale, as formatted in table 6.3.6.1. Readings should be taken at least three times at any sensitivity and the results examined to determine whether the UUT meets the desired specifications. These readings could be taken until three reproducible values are obtained or the average of three readings could be calculated, to see if the specifications are being met.

Table 6.3.6.1 Data for testing the automatic zero of the Unit Under Test (UUT)

Range	Reading				Δ LSD	
	1st	2nd	3rd	Average	Max. Deviation (full scale)	Limits
1. Most sensitive						
2. Next most sensitive						
3. Next most sensitive						
4. Next most sensitive						
5. Least sensitive						

6.3.6.2 Zero Carryover

Zero carryover is defined in Section 2.1.22 and its performance test is described in [4] as follows:

"4.11.3. Zero Carryover. For multirange instruments only, normally zeroed on the most sensitive range, state maximum acceptable deviation from zero indications for any range switch setting, expressed in percent of full scale."

The procedure following initial internal calibration of the UUT requires setting the zero of the meter on the most sensitive scale. Several readings of this display should be taken and any variation of the LSD in the digital display should be noted in table 6.3.6.2. To calculate percent of full scale, divide the value of the any deviation of the average reading from nominal value by the full scale reading, keeping the units consistent, and multiply this ratio by 100.

The procedure is repeated for each range but the initial setting of the zero of the meter should not be repeated. The function of this test is to evaluate the carryover of the zero to each additional range selected.

Table 6.3.6.2 Data for determining the zero carryover of the Unit Under Test (UUT)

Range	Reading				Δ LSD	
	1st	2nd	3rd	Average	Max. Deviation (% full scale)	Limits
1. Most sensitive						
2. Next most sensitive						
3. Next most sensitive						
4. Next most sensitive						
5. Least sensitive						

6.3.6.3 Autoranging

The autoranging capability of a power meter refers to the automatic switching of readout through several ranges for any given measurement. This feature can be evaluated with a single frequency such as 100 MHz from the signal source. The test configuration is shown in figure 6.3.6.3. The test is performed by a manual increase in the power output level from the signal source over a suitable range such as that from -30 dBm to +10 dBm while the readings displayed on the UUT are observed, to see that the instrument

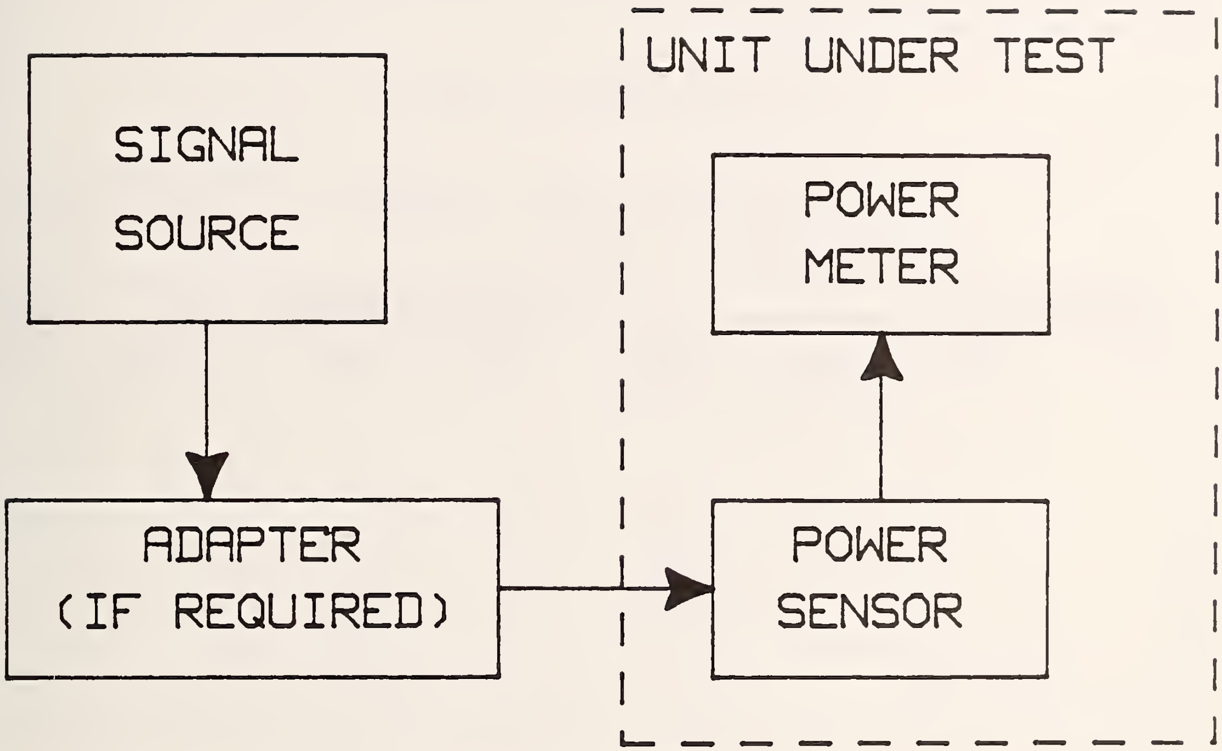

Figure 6.3.6.3 Typical test setup for testing of the autoranging, display, and annunciator capabilities of the Unit Under Test (UUT).

automatically selects the appropriate range and indicates the appropriate power level. The reading in decibels is recorded for each power level setting in a table such as that shown in table 6.3.6.3. The equivalent reading in watts is also recorded for each range. The evaluation is completed by repeating the procedure over the range from +10 dBm down to -30 dBm.

The automatic selection of each range in sequence may be interrupted at any range as needed. If the power output of the signal is then increased, an OVERRANGE annunciator should be activated. This activation should be recorded in the Overrange column together with the power level at which this occurs. This power level should be compared with the specifications provided for the UUT for this capability.

Table 6.3.6.3 Data for determining the autoranging capability of the Unit Under Test (UUT)

Signal Source		UUT Indicated Ranges										
Frequency (MHz)	RFOP (dBm)	1 Mode		2 Mode		3 Mode		4 Mode		5 Mode		Over-range
		dB	watt	dB	watt	dB	watt	dB	watt	dB	watt	
100	-30											
	-20											
	-10											
	0											
	+10											
	0											
	-10											
	-20											
	-30											

6.3.6.4 Display

Display characteristics include digital or analog format, or both, and annunciators typically indicate either decibels or watts as selected.

The test configuration of figure 6.3.6.3 is suitable for this test. A single frequency, usually 0.1 GHz, is applied to the UUT, with either decibels or watts selected on the UUT. A minimal rf output level is selected for the source signal. This is increased incrementally while the number of digits displayed on the UUT is observed for each range of power level. All observations are recorded including all digits displayed at each level. A useful format for recording these data is given in table 6.3.6.4.

The test procedure is repeated with the UUT set in the alternate mode. In the watt mode the UUT display is typically required to indicate values out to hundreds of nanowatts in the performance test for long-term instability (drift). Therefore, when the UUT scale is set on 10 μW, the display must show three digits to the least significant decimal place in this mode to indicate hundreds of nanowatts.

Table 6.3.6.4 Data for testing the display of the Unit Under Test (UUT)

Signal Source		UUT No. of Power Level Display Digits			
Frequency (GHz)	RFOP (dBm)	Range	Decibel Mode	Watt Mode	Analog Yes/No
		1			
		2			
		3			
		4			
		5			

6.3.6.5 Annunciators

The display usually includes annunciators for both watts and decibels. In the watt mode these typically illuminate the ranges in mW, or 10^{-3} W; or μW, or 10^{-6} W. The decibel mode normally indicates dBm, or dB, or dBr (relative dB).

The test configuration of figure 6.3.6.3 is used to evaluate the annunciator capability. A single frequency, usually 0.1 GHz, is applied to the UUT from a signal source. Rf output levels, from -30 dBm to +10 dBm on the signal generator, are applied to the UUT, which is set on the decibel scale. Each display is observed and recorded in a format such as that of table 6.3.6.5.

While in the decibel mode, one may observe the dBr function. The dBr annunciator is illuminated, and +10 dBm is entered in the UUT as a reference level. Then the rf output from the signal generator is decreased in steps, while the display in dBr is observed and recorded.

Next, watts are selected and the test is repeated. The watt mode annunciator units (mW or 10^{-3} W, for example) are observed, and readings are also entered in table 6.3.6.5.

Table 6.3.6.5 Data for testing the annunciators of the Unit Under Test (UUT)

	UUT Annunciators				
	Decibel Mode			Watt Mode	
Required Annunciators	dBm	dB	dBr	mW	μW
mW or 10^{-3} W					
μW or 10^{-6} W					
dBm					
dB					
dB relative					

6.3.7 Internal Power Reference Source

Power meters are generally provided with an internal power reference source. This is necessary as a known source of power to verify and adjust the sensitivity of the power sensor. This power reference source is used in open-loop power measurements made with thermocouple or diode sensors, but not with thermistor bolometer mounts, which are closed loop measurements. However, all instruments allow for any type of power sensor. This source is an oscillator of single frequency and power level. It is permanently installed by the manufacturer and is not adjustable. It is required in order to verify the calibration factor of non-thermistor bolometer mounts. The stability of the internal power reference must be verified at the necessary operating temperature range of the instrument and for a typical time period of one year.

The impedance of this internal source is a function of frequency and standing wave ratio (SWR) and hence is determined only for a specific SWR. Detailed procedures follow for testing the performance of this source.

6.3.7.1 Internal Oscillator Frequency

The frequency of the internal reference oscillator may be evaluated with the test configuration shown in figure 6.3.7.1. This frequency, usually 50 MHz, is measured on a frequency counter. The results are recorded in a table such as table 6.3.7.1 and compared with those allowed by the specifications for this test.

Table 6.3.7.1 Data for determining oscillator frequency of the internal power reference source of the Unit Under Test (UUT)

UUT Ref Oscillator Specified Frequency (MHz)	Frequency Counter Reading (MHz)
50.0	

6.3.7.2 Internal Reference Power

The internal power reference source is typically required to provide 1 mW at the frequency of the internal reference oscillator.

The reference oscillator port of the UUT is connected to the reference standard as shown in figure 6.3.7.2. The reference oscillator is not turned on at this time. The dc voltage, V_1, in millivolts is read on the DVM of the reference standard and recorded in table 6.3.7.2. The reference oscillator of

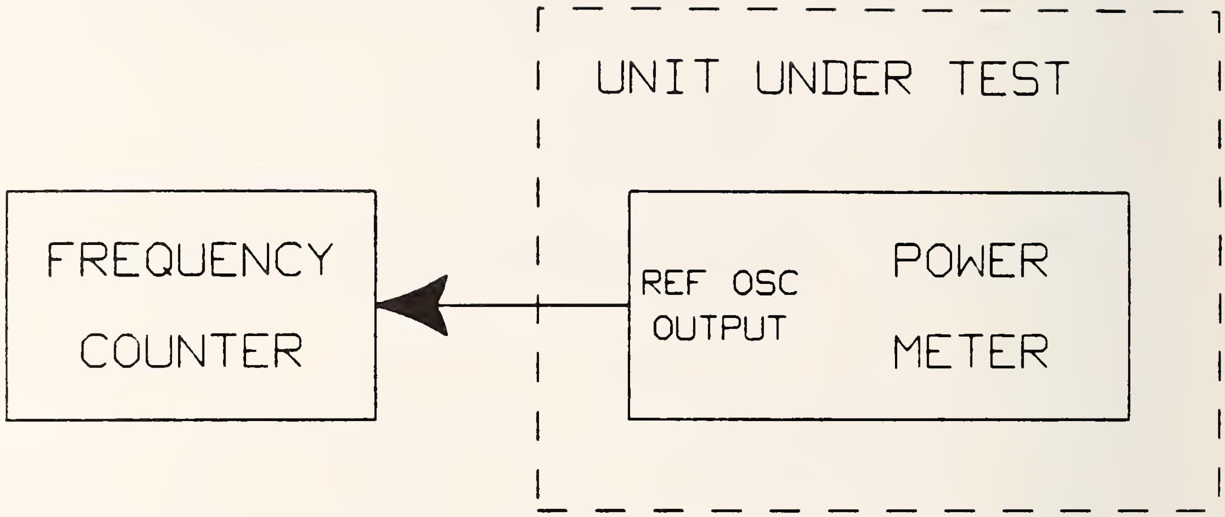

Figure 6.3.7.1 Typical test setup for measurement of the frequency of the internal power reference source of the Unit Under Test (UUT).

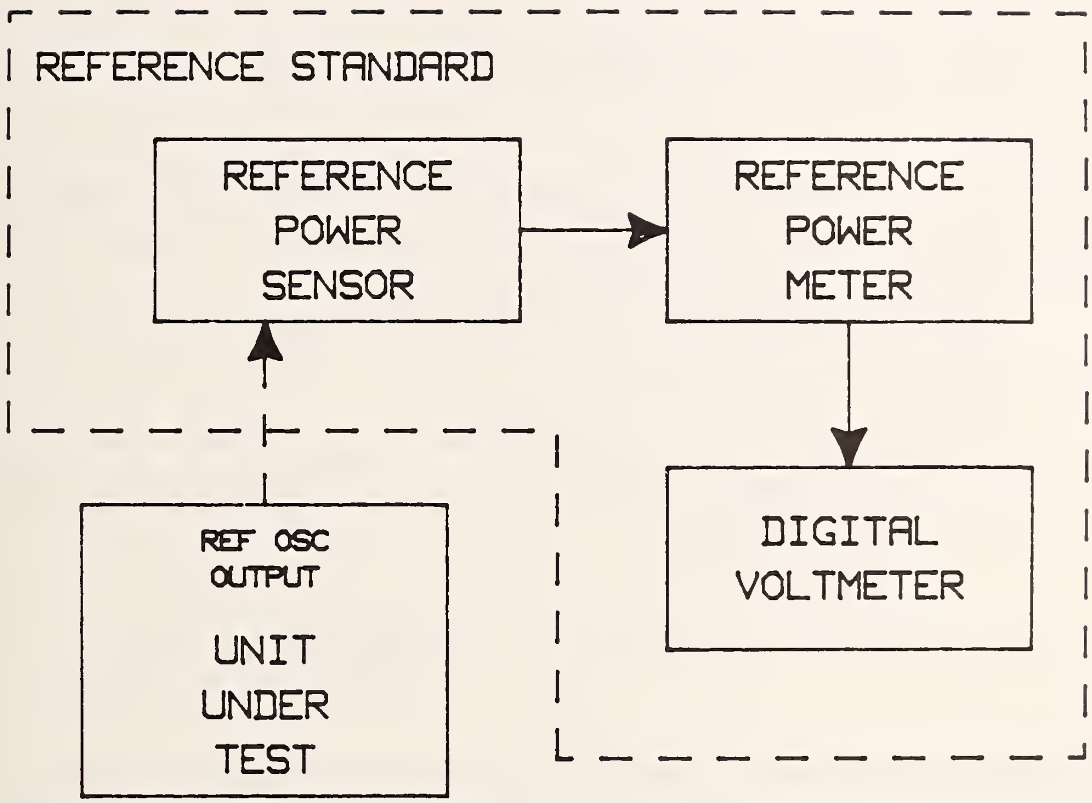

Figure 6.3.7.2 Typical test setup for measurement of the output power level of the internal power reference source of the Unit Under Test (UUT).

the UUT is then turned on and a similar voltage reading, V_2, is obtained in millivolts and recorded in table 6.3.7.2. A resolution of 10 μV should be attainable for each reading.

The rf power output of the reference oscillator is then calculated as follows:

$$P_{dc} = \frac{V_1^2 - V_2^2}{200} \times 10^3 \text{ [mW] (as in eq. 5.1);} \tag{6.6}$$

$$P_{rf} = \frac{P_{dc}}{K_1} \text{ [mW] (as in eq. 5.2),} \tag{6.7}$$

where P_{dc} is the dc substituted power, K_1 is the power sensor CAL factor of the reference standard, (from table 5.2.1), and P_{rf} is the measured output power of the reference oscillator of the UUT.

Three independent sets of readings are recorded in a format such as that presented in table 6.3.7.2.

An average of these three readings, $P_{rf_{avg}}$, is also calculated and recorded. The difference between $P_{rf_{avg}}$ and the manufacturer's value of 1 mW is calculated as follows:

$$\text{Power difference in percent} = \pm \frac{P_{rf_{avg}} - 1 \text{ mW}}{1 \text{ mW}} \times 100. \tag{6.8}$$

This value is then recorded in table 6.3.7.2 and compared with the allowable difference as stated in this specification of the UUT.

Table 6.3.7.2 Data for determining the output power of the internal power reference source of the Unit Under Test (UUT)

Frequency (MHz)	Ref Power Sensor CAL Factor (K_1)	DVM		Calculated Values			
		V_1 (mV)	V_2 (mV)	P_{dc} (mW)	P_{rf} (mW)	Prfavg (mW)	P_{diff} (+%)
50.0							

6.3.7.3 Internal Power Stability

A typical specification for stability of the internal power reference source requires that the frequency and output level remain within ±1.2 percent of the values supplied by the manufacturer, for a period of one year over the temperature range specified. The difference between the specified values and the measured values can be calculated. Equation (6.8) may be used to determine the difference in percent of the long-term stability of the power output level. A similar calculation for long-term stability of the frequency of the internal standard is as follows:

$$\text{Percent Drift} = \pm \frac{\text{Frequency measured (MHz)} - 50\text{ MHz}}{50\text{ MHz}} \times 100. \qquad (6.9)$$

A useful format for this information is provided in table 6.3.7.3.

Table 6.3.7.3 Data for determining the output power stability of the internal power reference source of the Unit Under Test (UUT)

UUT Specified Power Reference		Measured Power Reference		Difference in %	
Frequency (MHz)	Output Level (dBm)	Frequency (MHz)	Output Level (dBm)	Freq.	Output Level
50.0					

6.3.7.4 Internal Source Impedance

The impedance of the internal power reference source is a function of frequency, so a specified value is valid at one specific frequency. The purely resistive value of impedance is achievable only in the dc case. At all other frequencies inductive and capacitive reactance components create values of impedance which are complex numbers and vary with frequency and location on a transmission line. Since the internal power reference source is used to calibrate the power meter sensors, it is designed to have specific electrical characteristics so that it does not introduce additional errors during the calibration of the power meter. The power reference source in a typical power meter provides a fixed output of 1.00 mW at 50.000 MHz. Furthermore the power reference source is constructed so that the characteristic impedance at the output port is designed as a purely resistive 50-Ω impedance. A useful method [19] for evaluation of uncertainty limits for the internal source impedance follows.

Assumptions for a transmission line at radio and ultra-high frequencies are:

(1) the line has low losses; hence, resistance R is small;

(2) distributed circuit parameters are discrete constants based on a unit length of line.

With these assumptions, the following approximations may be made:

$$R \ll \omega L, \tag{6.10a}$$
$$G \ll \omega C, \tag{6.10b}$$

where R, L, C, and G are the resistance, inductance, capacitance and conductance per unit length of line, respectively. Based on these inequalities, the following approximations are valid:

$$Z = R + j\omega L \approx j\omega L, \tag{6.11a}$$
$$Y = G + j\omega C \approx j\omega C. \tag{6.11b}$$

Then the characteristic impedance of the line, Z_o, may be defined and approximated as

$$Z_o = [(R + j\omega L)/(G + j\omega C)]^{1/2} \approx (L/C)^{1/2}. \tag{6.12}$$

Similarly, the propagation constant, γ, may be expressed as

$$\gamma = \alpha + j\beta, \tag{6.13}$$

where α = the attenuation constant in nepers per unit length and β = the phase constant in radians per unit length.

The general transmission line equations may be written for a line of length, ℓ, and termination Z_ℓ as

$$V_x = V_\ell \cos \beta x + jI_\ell Z_o \sin \beta x \tag{6.14a}$$
$$= V_\ell \cos \beta x + j(V_\ell/Z_\ell)Z_o \sin \beta x,$$

and

$$I_x = I_\ell \cos \beta x + j(V_\ell/Z_o)\sin \beta x. \tag{6.14b}$$

Since voltmeters and ammeters read magnitude without regard to phase, the magnitudes of the voltage and current on a transmission line at a point, x, become

$$|V_x| = V_\ell[(\cos^2 \beta x + (Z_o/Z_\ell)^2 \sin^2 \beta x)]^{1/2} , \tag{6.15a}$$

$$|I_x| = I_\ell[(\cos^2 \beta x + (Z_\ell/Z_o)^2 \sin^2 \beta x)]^{1/2} . \tag{6.15b}$$

When $\sin \beta x = 1$, V_x is a maximum.

Then $$V_{x_{max}} = V_\ell(Z_o/Z_\ell), \tag{6.16a}$$

and $$I_{x_{max}} = I_\ell(Z_\ell/Z_o). \tag{6.16b}$$

Similarly, when $\sin \beta x = 0$, V_x and I_x are minimum.

Then $$V_{x_{min}} = V_\ell, \tag{6.17a}$$

and $$I_{x_{min}} = I_\ell. \tag{6.17b}$$

A useful parameter for impedance evaluation is the voltage standing wave ratio, VSWR. This is defined as the ratio of maximum to minimum voltage on a transmission line at a specific frequency [3] and is given by

$$\mathrm{VSWR} = V_{max}/V_{min} \tag{6.18a}$$

and $$\mathrm{ISWR} = I_{max}/I_{min}. \tag{6.18b}$$

Then using eq (6.16a, 6.17a), eq (6.18a) becomes

$$\mathrm{VSWR} = Z_o/Z_\ell, \qquad (\text{for } Z_o > Z_\ell) \tag{6.19a}$$

and using eq (6.16b, 6.17b), eq (6.18b) becomes

$$\mathrm{VSWR} = Z_\ell/Z_o \qquad (\text{for } Z_o < Z_\ell) . \tag{6.19b}$$

The value of the VSWR of the internal power reference source at the specified frequency is given by the manufacturer. The upper and lower limits of uncertainty in Z_ℓ may be calculated with the use of eq (6.19a, 6.19b). The following example illustrates this procedure.

Given: $Z_\ell = R_\ell = 50\ \Omega$

and VSWR = 1.05 at 50 MHz.

To find: (a) $Z_{\ell_{max}}$ where $Z_\ell > Z_o$

and (b) $Z_{\ell_{min}}$ where $Z_o > Z_\ell$.

Then: (a) $Z_{\ell_{max}} = (\mathrm{VSWR})\ (Z_o) = (1.05)(50\ \Omega) = 52.50\ \Omega$

(b) $Z_{\ell_{min}} = (\mathrm{VSWR}/Z_o) = 47.62\ \Omega$

The nominal value of the impedance of the internal power reference source (as stated by the manufacturer) should be recorded. A useful format is shown in table 6.3.7.4.

Calculate the limiting values of the internal power reference source impedance as shown above and record these values in table 6.3.7.4. These values can then be compared with the specification of this test. A possible alternate method is the use of an rf impedance bridge to measure the power reference source impedance. The bridge must be characterized at the frequency of interest.

Table 6.3.7.4 Data for determining the impedance limits of the internal power reference source of the Unit Under Test (UUT)

Frequency (MHz)	Impedance (Ω)	VSWR	Calculated Limits	
			Lower (Ω)	Upper (Ω)
50.0		1.05		

6.3.8 Power Sensors

6.3.8.1 Sensor Voltage Standing Wave Ratio (VSWR)

The following maximum values of voltage standing wave ratio (VSWR) are typical specifications over the listed frequency ranges and for the power range specified in Performance Test 6.3.1.

Frequency	VSWR
10 MHz-14 GHz	1.4
14-18 GHz	1.5
18-26.5 GHz	1.6

6.3.8.1.1 Part 1: (10-100 MHz)

After the initial calibration procedures are completed, the equipment is connected as shown in figure 6.3.8.1.1 for the frequency range of 10-100 MHz.

A dual channel power meter is used in this test. This contains two separate measurement channels, A and B. Since these channels are independent of each other, each may be calibrated according to the methods for calibration of a UUT described in Section 6.3.1.1 for 10 to 100 MHz, in Section 6.3.1.2 for 0.100 to 18.0 GHz, and in Section 6.3.1.3 for 18.0 to 26.5 GHz.

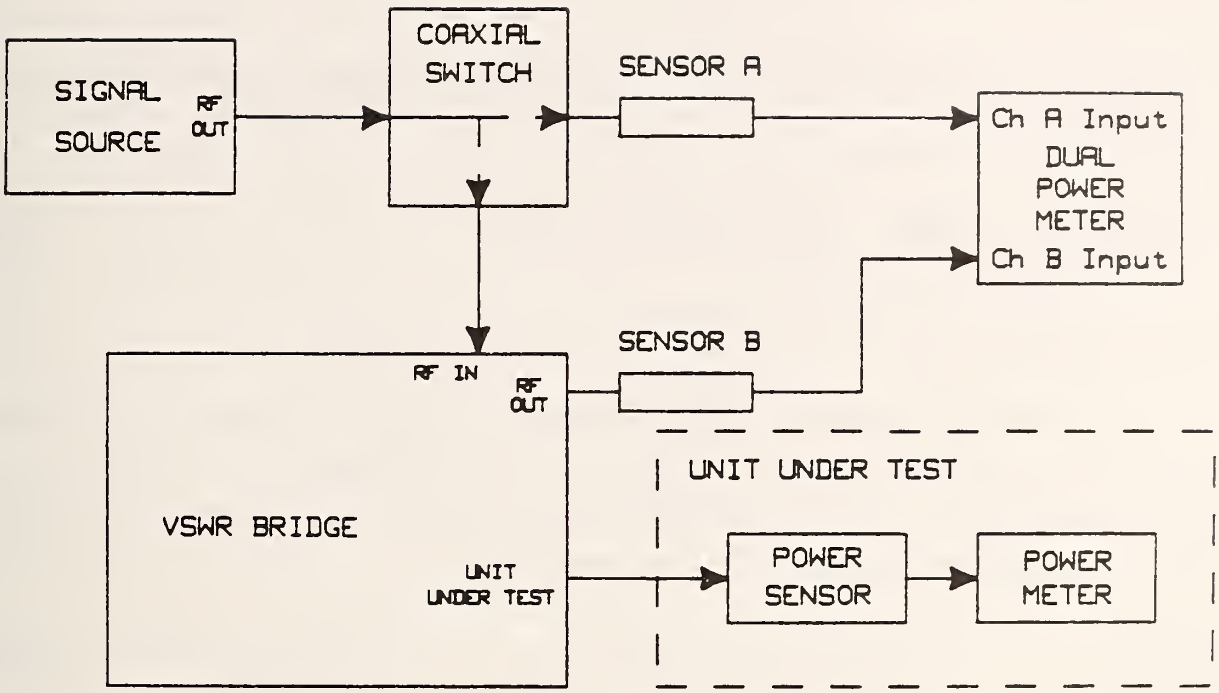

Figure 6.3.8.1.1 Typical test setup for measurement of power sensor VSWR of the Unit Under Test (UUT) for the frequency range from 10 to 100 MHz.

From eq (6.18a) VSWR = V_{max}/V_{min} ·

In addition, $V_{max} = V_i + V_r$ (6.20a)

and $V_{min} = V_i - V_r$, (6.20b)

where V_i and V_r are the incident and reflected voltages on the transmission line [3].

Therefore, $\text{VSWR} = |(V_i + V_r)/(V_i - V_r)|.$ (6.21)

However, VSWR cannot be measured but must be calculated from values of the reflection coefficient, Γ. Γ is defined in Section 2.1.16, which is paraphrased here, as the ratio of the reflected wave, in volts, to that of the incident wave in volts [3], as follows:

since $\Gamma = V_r/V_i$, (6.22)

then, from eq (6.21), $\text{VSWR} = (1 + |\Gamma|)/(1 - |\Gamma|).$ (6.23)

The use of a VSWR bridge, as figure 6.3.8.1.1 indicates, requires the characterization of this bridge for VSWR as a function of frequency over the frequency range of interest. Since VSWR cannot be measured directly but must be calculated from values of Γ, these must be known for each frequency of interest. They are determined from the power measurements on both Channels A and B of the dual channel power meter. The square roots of these power terms provide the values in volts from which to calculate Γ.

Loads with known VSWR must be used to determine the characteristic curve of the bridge. The transfer function of the VSWR bridge typically is linear with frequency over the desired VSWR range. However, a direct reading in VSWR is not available from the VSWR bridge, and the readings are not constant as the frequency is varied. Therefore, a bridge calibration factor is necessary for each test frequency.

The characterization of the bridge shows that a calibration factor (M_{bridge}) must be applied to the readings on power sensor B to determine the true reflection coefficient of the load being measured. To obtain the necessary characteristic curve of the VSWR bridge, standard reference mismatch loads with known values of VSWR and $|\Gamma|$ are connected in sequence to the test port of the VSWR bridge. They provide fixed reference points on this curve. A power level of incident power, P_i, of +13 dBm (20 mW) on Channel A is set with the signal source rf output power level at the three suggested frequencies of 10 MHz, 50 MHz and 100 MHz (for this frequency range). Then the ratio of the known reference value of $|\Gamma|$ to the square root of the power of reflected power, P_r, at power sensor B (with P_i held constant at 20 mW) is taken as a multiplication factor, M_{bridge}. This is shown in the following set of equations.

In general, $$|\Gamma| = \left(\frac{P_r}{P_i}\right)^{1/2}. \qquad (6.24)$$

However, for the bridge,

$$|\Gamma| = K_{bridge} \left(\frac{P_r}{P_i}\right)^{1/2}, \qquad (6.25)$$

where K is a bridge factor selected for the frequency of interest from the bridge characteristic curve described above.

Since P_i is held constant, (6.26)

$$|\Gamma| = M_{bridge} \, (P_r)^{1/2}. \qquad (6.27)$$

Since values of Γ and P_r are known, M_{bridge} can be determined for each frequency of interest as follows:

$$M_{bridge} = \frac{|\Gamma|}{(P_r)^{1/2}} = \frac{K_{bridge}}{(P_i)^{1/2}} . \tag{6.28}$$

Channel A is selected with the external coaxial switch shown in figure 6.3.8.1.1. The frequency of the signal source is set to 10 MHz at an rf power of +13 V dBm (20 mW), as measured on power sensor A of the dual channel power meter. This value, P_A, is recorded in a table such as table 6.3.8.1.1.

Then the external coaxial switch position is changed to the RF IN port of the VSWR bridge and the RF OUT port is connected to power sensor B of the dual power meter. The UUT is also connected to the VSWR bridge at the test port. The value of power measured by power sensor B, P_B, is also recorded in table 6.3.8.1.1.

The value of the UUT reflection coefficient, Γ_{UUT}, may be calculated as follows:

$$|\Gamma_{UUT}| = (M_{bridge})\,(P_B)^{1/2}, \tag{6.29}$$

and then is recorded in table 6.3.8.1.1.

The VSWR of the power sensor of the UUT may be calculated as follows:

$$VSWR_{UUT} = \frac{1 + |\Gamma_{UUT}|}{1 - |\Gamma_{UUT}|} . \tag{6.30}$$

This is also recorded in table 6.3.8.1.1.

The reading P_A of power sensor A may vary by ±1 dB due to variations in the signal source output level. Line losses may also contribute to variations in power sensor measurements.

Compensation to M_{bridge} values for variations in P_A are made as follows:

$$M'_{bridge} = M_{bridge}\,[(20\text{ mW})/P_A]^{1/2}. \tag{6.31}$$

The value of M'_{bridge} should be used when the signal source output level is other than +13 dBm (20 mW).

This procedure is repeated for frequencies of the signal source set at 50 MHz and 100 MHz using the appropriate values of M_{bridge} for these frequencies.

Table 6.3.8.1.1 Data for determining the power sensor VSWR of the Unit Under Test (UUT) for the frequency range from 10 to 100 MHz

Signal Source		SWR Bridge Multiplier		Dual Power Meter		Calculated Values	
Frequency (MHz)	RFOP (dBm)	(M_{bridge})	Compensated M_{bridge} (M'_{bridge})	P_A (mW)	P_B (mW)	$\lvert \Gamma_{UUT} \rvert$	$VSWR_{UUT}$

6.3.8.1.2 Part 2: (0.1-18.0 GHz)

In this procedure the VSWR of the UUT power sensor is obtained by the use of a dual directional coupler. The UUT power sensor is connected as a load to the TEST port of the dual directional coupler (see figure 6.3.8.1.2.). The coupler should be calibrated by the manufacturer for the frequencies of interest to determine the actual coupling factors. This will prevent the introduction of significant uncertainties into this measurement from the coupler. These coupling factors apply to specific dual directional couplers. No two couplers have identical values. Typical values in table 6.3.8.1.2 are included for information only and are not to be used in actual measurements. Couplers should be identified by serial number to allow consistent use in the test set-up and to prevent confusion in the application of specific coupling factors. Figures 14.1.a and 14.1.b in Appendix 14.1 are plots of coupling factors for a typical coaxial coupler for two ranges of frequencies. Figure 6.3.8.1.2 shows that the power sensor of Channel A on the dual power meter senses the incident power, P_i, in the dual directional coupler with respect to the TEST port

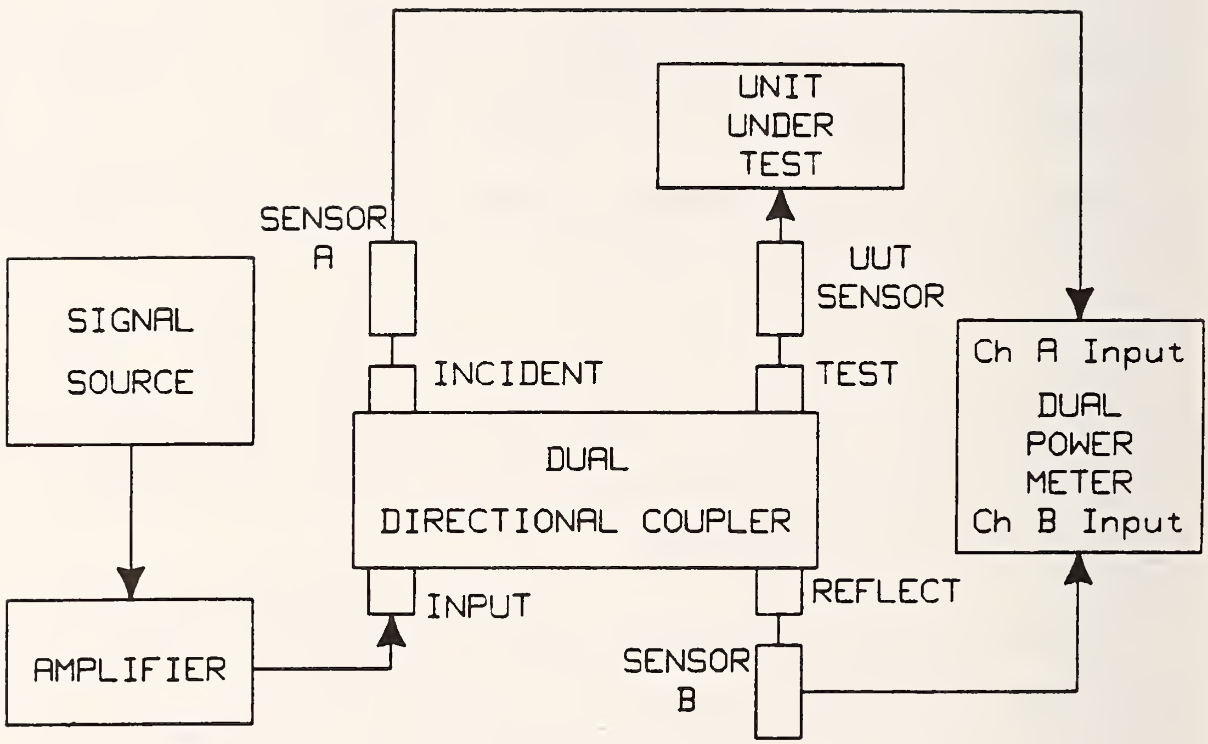

Figure 6.3.8.1.2 Typical test setup for measurement of power sensor VSWR of the Unit Under Test (UUT) for the frequency range from 0.1 to 18.0 GHz.

($P_{i_{test}}$) and that the power sensor of Channel B on the dual power meter senses the reflected power, P_r, in the dual directional coupler with respect to the TEST port, ($P_{r_{test}}$). The values of the forward coupling factor, C_F, and the reflected coupling factor, C_R, for each dual directional coupler at each frequency of interest should be tabulated in table 6.3.8.1.2 in decibels for future reference. Each of these typical coupling factors is also given as a ratio in table 6.3.8.1.2. An example of the conversion of units is as follows:

Given: $C_F = 22.50$ dB (for 100 MHz).

$$r = P_2/P_1$$

$$P_1 = 1 \text{ unit}$$

Since, $22.50 = 10 \log r$, by definition,

then, $\log r = 22.50/10$

and,

$$r = 10^{2.25} = 177.83. \tag{6.32}$$

Then,

$$P_2 = (r)(P_1) = 177.83\ P_1\ . \tag{6.33}$$

The VSWR of this load is determined in a procedure of several steps. First the power is measured at the incident and reflected ports of the dual directional coupler on Channels A and B of a dual power meter. The calibration factors of these sensors of the dual power meter for the frequencies of interest are then included to give values of actual power at the incident and reflected ports of the directional coupler. Then these values are translated to the TEST port of the coupler by applying the coupling factors of the incident and reflected ports with respect to the TEST port. These twice-modified values are the actual values of the incident and reflected power applied to the UUT power sensor at the TEST port. Finally, they are used to calculate the reflection coefficient, Γ, and VSWR of the UUT power sensor.

The equipment is connected as shown in figure 6.3.8.1.2 after the completion of all the calibration procedures just described. The following steps compose the measurement procedure:

1. Set the rf output level of the signal source to +10 dBm and record this frequency and output level in table 6.3.8.1.2.

2. Record in table 6.3.8.1.2 the calibration factors of the dual power meter sensors. These are K_A of the power sensor of Channel A and K_B of the power sensor of Channel B for each appropriate frequency.

3. Measure the power, P_A, of Channel A and the power, P_B, of Channel B on the dual power meter and record these values in table 6.3.8.1.2.

4. Calculate the corrected value, P_{A_c}, of P_A to include K_A and calculate the corrected value, P_{B_c}, of P_B to include K_B for the appropriate frequency, as follows:

$$P_{A_c} = (P_A)(K_A), \tag{6.34a}$$

$$P_{B_c} = (P_B)(K_B), \tag{6.34b}$$

and record these values in table 6.3.8.1.2.

5. Calculate the value of P_i as follows:

$$P_{i_{test}} = (P_{A_c})\ (C_F), \tag{6.35a}$$

and record this value in table 6.3.8.1.2.

6. Calculate the value of $P_{r_{test}}$ as follows:

$$P_{r_{test}} = (P_{B_c})\ (C_R), \tag{6.35b}$$

and record this value in table 6.3.8.1.2.

Table 6.3.8.1.2 Data for determining the power sensor VSWR of the Unit Under Test (UUT) for the frequency range from 0.1 to 18.0 GHz.

Signal Source		Dual Directional Coupler				Dual Power Meter							UUT Power Sensor Calculated Values			
Frequency	RFOP	Typical CF		Typical CR												
(GHz)	(dBm)	(dB)	r	(dB)	r	K_A	K_B	P_A	P_B	P_{A_c}	P_{B_c}	P_i	$P_{i_{test}}$	$P_{r_{test}}$	$\lvert\Gamma_{UUT}\rvert$	VSWR
0.1	+10	22.50	177.83	22.70	186.21											
0.5		19.34	85.90	19.55	90.16											
1.0		19.29	84.92	19.69	93.11											
gen #1																
2.0		19.52	89.54	20.03	100.69											
gen #2																
2.0		21.21	132.13	21.94	156.31											
6.0		20.14	103.28	21.13	127.92											
10.0		20.49	111.94	21.72	148.59											
14.0		20.39	109.40	21.91	155.24											
18.0		20.49	111.94	21.70	147.91											

7. Repeat the procedure with the appropriate dual directional coupler and signal source for frequencies of 0.5, 1.0, 2.0, 6.0, 10.0, 14.0, and 18.0 GHz.

8. Calculate the values of reflection coefficient, and VSWR of the UUT power sensor, for all measurements just performed, where, from eq (6.24),

$$\Gamma_{UUT} = [(P_r)/(P_i)]^{1/2},$$

and, from eq (6.30),

$$VSWR = \frac{1 + |\Gamma_{UUT}|}{1 - |\Gamma_{UUT}|} .$$

9. Record these values in table 6.3.8.1.2.

6.3.8.1.3 Part 3: (7.0-26.5 GHz)

The frequency range from 7.0 to 26.5 GHz is specific for the use of waveguide directional couplers with the appropriate adapters. This frequency range includes the frequencies of 7.0 to 18.0 GHz which are included in Section 6.3.8.1.2. However, all the measurements of Section 6.3.8.1.2 are made with coaxial dual directional couplers, while all of Section 6.3.8.1.3 measurements require waveguide directional couplers and appropriate adapters.

The following procedures must be completed before performance tests are made:

(1) System calibration procedure for this frequency range. (Section 5.2.3).

(2) Initial internal calibration procedure of the UUT. (Section 6.2.1).

(3) Initial conditions of the signal source (Section 6.2.2).

(4) Frequency range and power range performance tests. (Section 6.3.1.3).

The performance test for the VSWR of the power sensor in this frequency range is performed with a waveguide reflectometer using the appropriate waveguide directional couplers for the frequency ranges of interest.

The equipment is connected according to figure 6.3.8.1.3. A frequency of 7.0 GHz is set on the signal source with an rf power of +10 dBm. The power sensors on channels A and B on the dual power meter measure incident power, P_i, and reflected power, P_r.

Since the magnitude of the reflection coefficient, $|\Gamma|$, is used to calculate values of VSWR, the value of $|\Gamma|$ of the UUT, $|\Gamma_{UUT}|$, must be determined. By definition $|\Gamma|$ is proportional to the ratio of reflected voltage to incident voltage in a transmission line, where the load is purely resistive [3].

Thus, by definition, in terms of power,

$$|\Gamma| = C\left(\frac{P_r}{P_i}\right)^{1/2} . \tag{6.36}$$

The proportionality factor, C, may be determined from the measurements of P_i and P_r of a load whose impedance is, ideally, a known value and is purely resistive. A short circuit (sc) termination is useful here because we can assume $|\Gamma| = 1$. The values of $P_{i_{sc}}$ and $P_{r_{sc}}$ are recorded in table 6.3.8.1.3.

$$\text{Then} \quad 1 = C_{sc}\left(\frac{P_{r_{sc}}}{P_{i_{sc}}}\right)^{1/2} , \tag{6.37}$$

$$\text{or} \quad C_{sc} = \left(\frac{P_{i_{sc}}}{P_{r_{sc}}}\right)^{1/2} . \tag{6.38}$$

The termination is then replaced by the UUT and $P_{i_{UUT}}$ and $P_{r_{UUT}}$ are measured on channels A and B respectively and recorded in table 6.3.8.1.3.

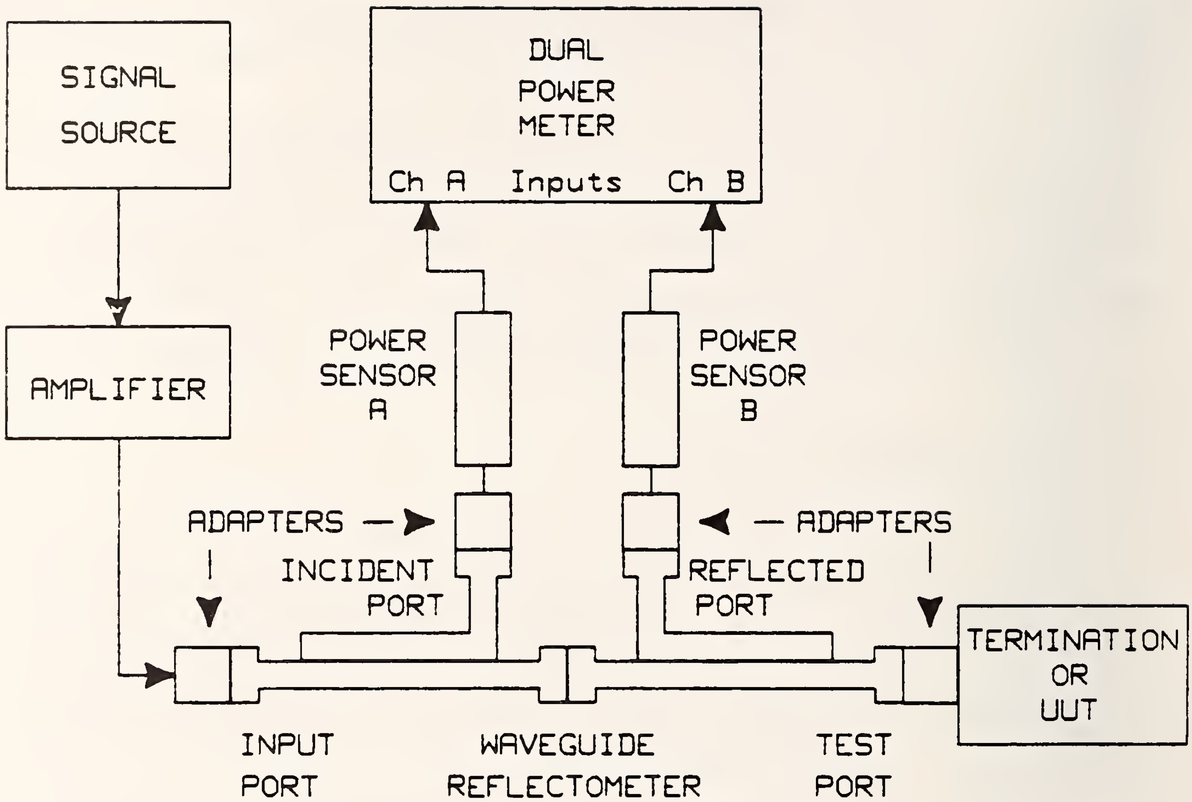

Figure 6.3.8.1.3 Typical test setup for measurement of power sensor VSWR of the Unit Under Test (UUT) for the frequency range from 7.0 to 26.5 GHz.

Table 6.3.8.1.3 Data for determining the power sensor VSWR of the Unit Under Test (UUT) for the frequency range from 7.0 to 26.5 GHz

Source Generator		Wave-guide	Dual Power Meter		UUT		Calculated Values	
Frequency (GHz)	Level (dBm)	Band (WR)	$P_{i_{sc}}$ (mW)	$P_{r_{sc}}$ (mW)	$P_{i_{UUT}}$ (mW)	$P_{r_{UUT}}$ (mW)	$\lvert \Gamma_{UUT} \rvert$	VSWR
7.0	+10	112						
10.0		112		-				
8.2		90						
12.4		90						
10.0		90						
12.4		90&75						
12.4		62						
18.0		62						
12.4		62						
15.0		62&75						
18.0		42						
26.5		42						

Solving for $|\Gamma_{UUT}|$, we have

$$|\Gamma_{UUT}| = C_{sc} \left(\frac{P_{r_{UUT}}}{P_{i_{UUT}}} \right)^{1/2} , \tag{6.39}$$

$$|\Gamma_{UUT}| = \left(\frac{P_{r_{UUT}}/P_{i_{UUT}}}{P_{r_{sc}} / P_{i_{sc}}} \right)^{1/2} . \tag{6.40}$$

This value is recorded in table 6.3.8.1.3.
The value of VSWR is then calculated from eq (6.30) as follows:

$$VSWR = \frac{1 + |\Gamma_{UUT}|}{1 - |\Gamma_{UUT}|}$$

and recorded in table 6.3.8.1.3.

6.3.8.2 Sensor Operating Resistance

The operating resistance of coaxial power sensors is not easily measured but can be calculated. The rf impedance of these coaxial power sensors (typically 50 Ω) must be considered rather than the dc resistance (usually 200 Ω, as discussed in Section 4.1). Vector components of the operation impedance are involved at all frequencies.

Since the bolometer mount impedance varies with given values of VSWR, it may be calculated from a knowledge of the values of VSWR which are obtained for different frequencies. The relationship of VSWR to impedance is shown in figure 6.3.8.2 for a given value of VSWR. As the values of VSWR increase:

(a) The upper limit of the impedance will increase proportionally to VSWR.

(b) The lower limit of the impedance will decrease in inverse proportion to VSWR at a relatively slower rate.

These uncertainty limits which were derived in Section 6.3.7.4 may be determined in the following way:

IMPEDANCE OR ADMITTANCE COORDINATES

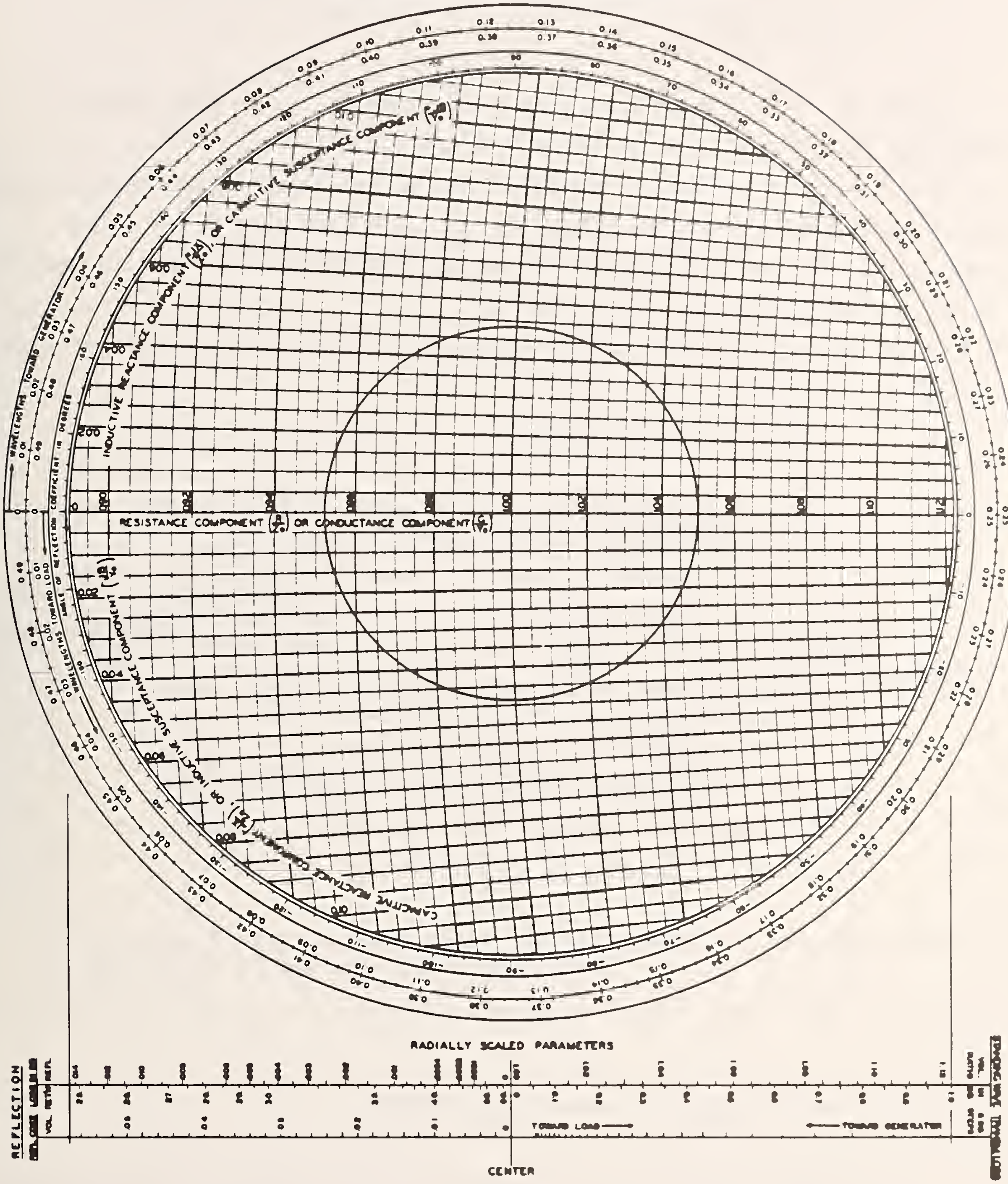

Figure 6.3.8.2 Relationship of VSWR to impedance at microwave frequencies for a value of VSWR of 1.05.

(a) To find an upper limit of impedance multiply impedance times VSWR: (50 Ω)•(VSWR).

(b) To a lower limit of impedance divide impedance by VSWR: (50 Ω)/(VSWR).

The value of impedance inscribed on the sensor by the manufacturer is recorded in a format such as table 6.3.8.2.

The limits of operating impedance can be determined from the VSWR measurements performed in Sections 6.3.8.1.1, 6.3.8.1.2 and 6.3.8.1.3. The appropriate values of frequency ranges and VSWR (SWR) are found in Section 6.3.8.1 and recorded in table 6.3.8.2.

Upper and lower limit values of operating impedance are entered in table 6.3.8.2.

Table 6.3.8.2 Data for determining the sensor operating resistance of the Unit Under Test (UUT)

Power Sensor		Frequency Range (MHz)	VSWR	Inscribed Operating Resistance (Ω)	Calculated Impedance Limits	
Model No.	Serial No.				Lower (Ω)	Upper (Ω)

6.3.9 Extended Power Measurement Capability

The system calibration procedures with the proper initial conditions on the signal source and the UUT are performed first. Then the equipment is connected as shown in figure 6.3.9. A typical frequency of 10 MHz is selected

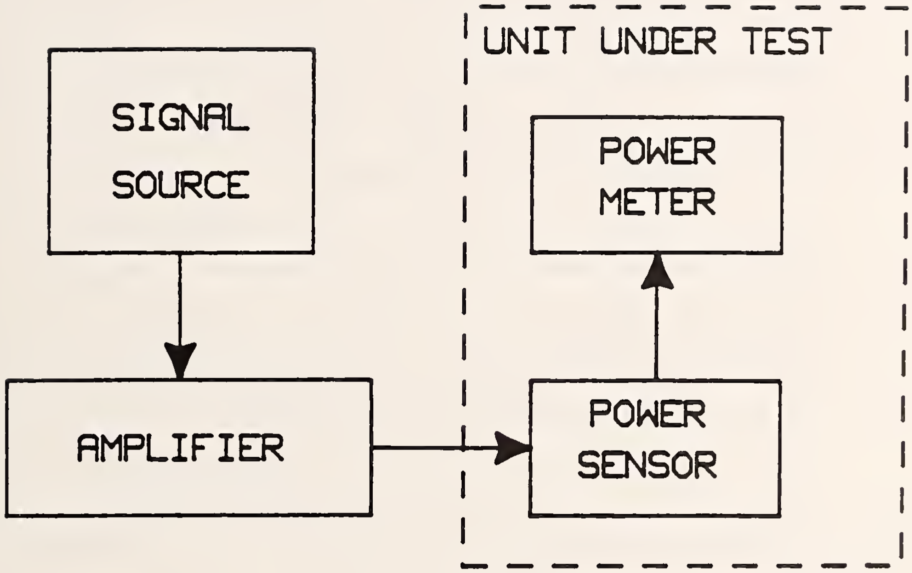

Figure 6.3.9 Typical test setup for measurement of extended power capability of the Unit Under Test (UUT).

Table 6.3.9 Extended power measurement data from the Unit Under Test (UUT)

Signal Source Frequency (GHz)	Amplifier Output (nominal) (W)	UTT P_{UUT} Indicated (mW)
0.05		
0.1		
0.5		
7.0		
8.2		
10.0		
12.4		
15.0		
18.0		

on the signal source and the rf power is increased until the amplifier output matches the specified level for the power sensor.

The UUT power reading should be recorded in table 6.3.9 which provides a suggested format for recording the UUT power measurements at all frequencies of interest between 10 MHz and 18.0 GHz. Since thermistors and barretters have limited capacity for handling power measurements, it may be necessary to reduce the input power level with the insertion of a calibrated attenuator or a power divider. Several types of these are available [3].

6.3.10 Meter Overload Protection

Typical overload protection capability is stated in the manufacturer's specifications, but it is important to determine the true protection capability of a power meter within specified limits of overloads applied to the input connector of the UUT. A customary limit for an overload of average power is 100 mW. A typical limit for a sudden increase in the energy creating an overload is 10 μJ/pulse or 5 W peak.

The performance test to determine the protection capabilities for these overloads requires equipment such as (1) a pulse generator of variable range; (2) amplifiers to cover the frequency range from 10 MHz to 18.0 GHz; (3) a timing device capable of measuring 5 or more minutes, and (4) an oscilloscope with a range from dc to 300 MHz.

After the initial calibration of the UUT, the equipment is connected according to figure 6.3.10. Initially the amplifier is connected directly to the oscilloscope to set the pulse generator to produce a pulse with a duration of 2 μs, a peak amplitude of 15.8 V and a repetition rate of 10 kHz.

The value of the pulse peak amplitude of 15.8 V satisfies the requirement of 5 W peak, which is calculated as follows:

Given: $P = 5$ W peak

$R = 50\ \Omega$

for $$P = \frac{V^2}{R}\ [W], \qquad (6.41)$$

then, $$V = (PR)^{1/2} = \left[(5)(50)\right]^{1/2} = 15.8\ [V]. \qquad (6.42)$$

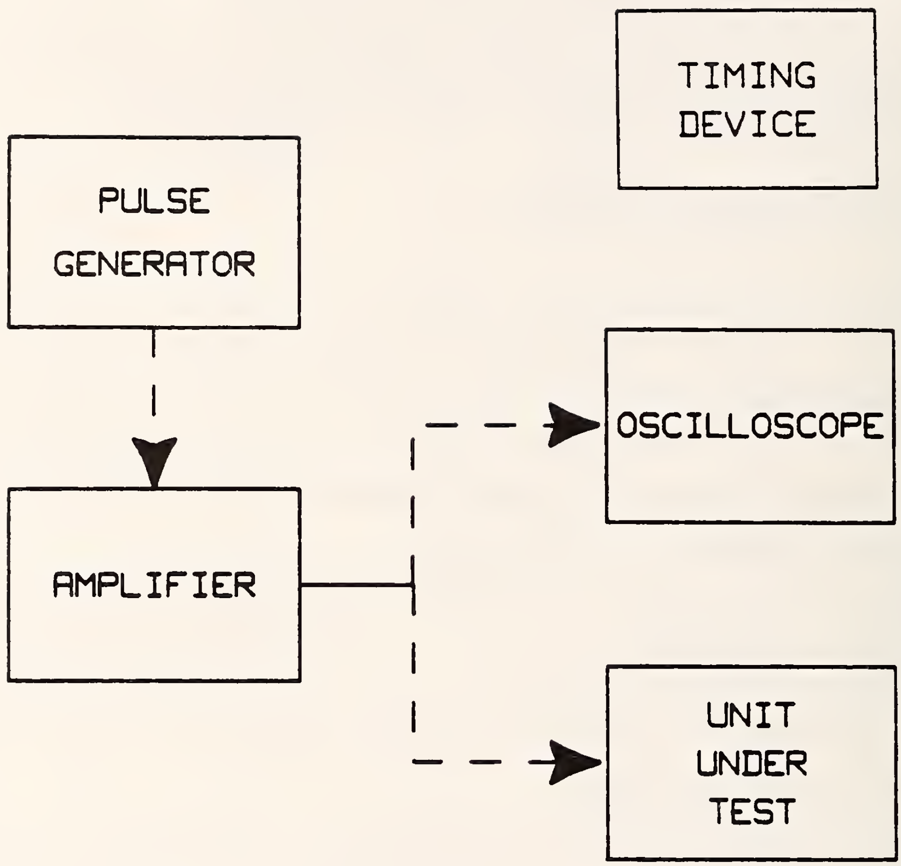

Figure 6.3.10 Typical test setup for measurement of overload protection capability of the Unit Under Test (UUT).

The pulse duration of 2 μs with the peak amplitude of 5 W satisfies the requirement of an input to the UUT of 10 μJ of energy, calculated as follows:

$$\text{Energy} = (5\ \text{W})\ (2\ \mu\text{s}) = 10\ [\text{W}\cdot\mu\text{s, or }\mu\text{J}]\ . \tag{6.43}$$

The repetition rate of 10000 pulse/s satisfies the requirement of 100 mW (0.1 W) of average power, calculated as follows:

$$\text{Average Power} = \frac{10\ (\text{W}\cdot\mu\text{s})}{100\ \mu\text{s}} = 0.1\ [\text{W average}]. \tag{6.44}$$

The pulse generator is then turned off. The amplifier is removed from the oscilloscope and connected to the UUT. The timing device and pulse generator are then turned on simultaneously, and the pulse input is applied to the UUT through the amplifier. At the end of 3 min, the timing device and pulse generator are turned off simultaneously.

Any visible adverse effects on the UUT are recorded in table 6.3.10.

The system calibration for the frequency range from 10 to 100 MHz is completed, followed by all performance tests for this frequency range. All results are recorded in table 6.3.10.

The overload protection test is repeated and the system calibration procedure for the frequency range from 0.1 to 18.0 GHz is completed. Performance tests in this frequency range are then carried out at 0.5 and 2.0 GHz. All results are recorded in table 6.3.10.

Table 6.3.10 Overload protection data from the Unit Under Test (UUT)

Unit Under Test				
Frequency (GHz)	Indications	Other Effects	Performance Tests (Pass/Fail)
0.10			
0.50			
2.0			

7.0 Calculation of Results

It is generally more efficient to obtain calculated results from measurements while the measurements are in progress. This increases the awareness of any anomalies and the opportunity to verify the validity of results. Sample data sheets are provided with each measurement procedure in this document, with columns arranged in the sequence of the test procedure steps, and labeled with the names and units of the required intermediate measurements or calculations. The progression in an orderly fashion across the data sheet to the final column of results is designed to facilitate the testing, documentation, analysis and review of the power meter's evaluation.

8.0 Estimation of Measurement Uncertainty

Measurement uncertainty is composed of several uncertainties arising from various sources throughout the system. Total measurement uncertainty of the instrument under test must be determined by evaluation of the contributions of uncertainties arising from individual sources within the system. These individual uncertainties affect the total measurement uncertainty in varying degrees. Their contributions are analyzed and the total uncertainty determined.

8.1 Uncertainties Due to Impedance Mismatches

When a source transmits power to a load, at least two impedance values are present in this system. These are: (1) Z_g, the impedance of the source (or a generator) and, (2) Z_ℓ, the impedance of the load. Each of these impedances is a complex number, having both magnitude and phase angle. The available power from the source is designated P_g and the power received by the load is P_ℓ. In the ideal case, maximum power is transferred to the load when Z_ℓ is equal to Z_g^*, the complex conjugate of Z_g. In reality, however, there is never a perfect match between the impedances of the source and the load. Reflections of electromagnetic fields occur at the load and some of the forward wave is reflected back to the source. The energy of these waves are voltages and currents which are complex values with both magnitude and phase angle. At microwave frequencies a more convenient parameter than voltage is used: the complex reflection coefficient, Γ, with magnitude of ρ, and phase angle, ϕ. Γ is defined in Section 2.1.16. When Γ is expressed in terms of voltage it is the ratio of the reflected voltage to the incident or forward voltage, and hence is dimensionless. When Γ is expressed in terms of power, ρ is squared since $P = V^2/Z$ from Ohm's law. The phase angle ϕ, is typically not known, so only ρ is measurable. Γ then is expressed as $|\Gamma|$. Γ is also defined in terms of Z_g and Z_ℓ and designated Γ_g and Γ_ℓ respectively. The characteristic impedance, Z_o, typically $50 + j0\ \Omega$ for a coaxial line, appears in these definitions. The reflection coefficient Γ_g, at the generator or source, is defined as

$$\Gamma_g = \frac{Z_g - Z_o}{Z_g + Z_o}, \tag{8.1}$$

and similarly the reflection coefficient at the load, Γ_ℓ, is defined as

$$\Gamma_\ell = \frac{Z_\ell - Z_o}{Z_\ell + Z_o}. \tag{8.2}$$

The ratio of P_g to P_ℓ is termed the conjugate mismatch loss, which is designated here as Z_g*ML. In general,

$$Zg^*ML = 10 \log \frac{P_g}{P_\ell} = 10 \log \frac{|1 - \Gamma_g \Gamma_\ell|^2}{(1 - |\Gamma_g|^2)(1 - |\Gamma_\ell|^2)} \quad [dB]. \tag{8.3}$$

This ratio cannot be less than 1 since P_g is either equal to or greater than P_ℓ [20].

When Γ_g and Γ_ℓ do not equal to 0

$$P_\ell = P_g \frac{(1 - |\Gamma_g|^2)(1 - |\Gamma_\ell|^2)}{|1 - \Gamma_g \Gamma_\ell|^2}. \tag{8.4}$$

If Z_ℓ equals Z_g^*, then Γ_ℓ equals Γ_g^*, P_ℓ equals P_g and P_ℓ is maximum. In the general component form, $Z_\ell = R_\ell + jX_\ell$ and $Z_g^* = R_g - jX_g$, so that in this case $R_\ell + jX_\ell = R_g - jX_g$. The real terms R_g and R_ℓ are equal in magnitude, while the reactive terms are equal but opposite in sign, so that this combination of Z_g^* and Z_ℓ is purely resistive.

If there are no reflections from the source, $\Gamma_g = 0$, and

$$P_\ell = P_g (1 - |\Gamma_\ell|^2) \tag{8.5}$$

In reality, there are reflections at the source also. These occur when power reflected from the load returns to the source and is re-reflected by the source back toward to the load. Then Γ_g does not equal 0, and $Z_g{}^*ML$ is modified by an "interaction factor," designated $| 1 - \Gamma_g\Gamma_\ell |^2$ [4].

When a transmission line is terminated in Z_o, then $Z_\ell = Z_o$ and $P_\ell = P_o$. There are no reflections at the load, so $\Gamma_\ell = 0$. When the source is reflective, Γ_g does not equal zero, so that

$$P_\ell = P_g \, (1 - | \Gamma_g |^2) \, . \tag{8.6}$$

Thus, for the general case, eq (8.3) holds.

If only the magnitudes of the complex variables Γ_g and Γ_ℓ are measurable, the uncertainty, U_m, due to impedance mismatches can only be defined within limits. U_m in dB can be expressed as

$$U_m = 10 \log (1 \pm | \Gamma_g\Gamma_\ell |)^2 \text{ [dB]}. \tag{8.7}$$

U_m reaches a maximum, $U_{m\ max}$, when the product $| \Gamma_g\Gamma_\ell |$ is positive and real. Thus:

$$U_{m\ max} = 10 \log (1 + | \Gamma_g\Gamma_\ell |)^2 \text{ [dB]}. \tag{8.8}$$

The magnitude of $U_{m\ max}$ will always be a positive number but can never exceed 20 log 2 or 6 dB.

A minimum value of U_m, $U_{m\ min}$, occurs when the product $| \Gamma_g\Gamma_\ell |$ combines with 1 exactly out of phase (negative, real). Thus:

$$U_{m\ min} = 10 \log (1 - | \Gamma_g\Gamma_\ell |)^2 \text{ [dB]}. \tag{8.9}$$

$U_{m\ min}$ is always negative, and its magnitude is greater than the magnitude of $U_{m\ max}$, but usually by a very small amount [2].

If the mismatch uncertainty limits are given in percent deviation of U_m from a magnitude of 1, rather than in decibels, this may be expressed as

$$U_m\ (\%) = 100\ [(1 \pm |\Gamma_g\Gamma_\ell|)^2 - 1]. \tag{8.10}$$

If the term in parentheses is expanded, eq (8.10) becomes,

$$U_m\ (\%) = 100\ [(1 \pm 2|\Gamma_g\Gamma_\ell| + |\Gamma_g|^2|\Gamma_\ell|^2) - 1]\ . \tag{8.11}$$

The product $|\Gamma_g\Gamma_\ell|$ is usually less than 0.1 and $|\Gamma_g|^2|\Gamma_\ell|^2$ is negligible, so eq (8.11) may be written as:

$$U_m\ (\%) \approx 100\ (\pm 2|\Gamma_g\Gamma_\ell|)$$

$$\approx \pm 200|\Gamma_g\Gamma_\ell|. \tag{8.12}$$

Equation (8.12) provides a useful approximation to the maximum and minimum limits of the mismatch uncertainty, U_m.

8.2 Uncertainties Due to Power Sensor

The efficiency, η, of a device is the ratio of the useful output power to the input power. In the case of a thermistor mount, η may be expressed as

$$\eta = \frac{\text{rf power absorbed by bolometer}}{\text{net power delivered to bolometer mount}}\ .$$

The output power is the equivalent dc or low frequency power, P_{sub}, that is substituted by the bolometer unit. The power P_ℓ, delivered to the load, is designated P_s for power delivered to sensor. Similarly Γ_ℓ is designated Γ_s, the reflection coefficient of the sensor. Thermistor sensors however, experience some losses internally due to differences in heating effects and spatial distributions of the rf and dc power within the sensor material [3]. These substitution losses are frequency-dependent. Therefore, a more realistic expression of sensor efficiency is the effective efficiency, η_e. This is defined in Section 2.1.12 for bolometer units as "the ratio of the substitution power, P_{sub}, to the total rf power dissipated within the sensor." [4] The effective efficiency, η_e, may be expressed as

$$\eta_e = \frac{P_{sub}}{P_s} . \tag{8.13}$$

P_{sub} is usually measured and P_s is calculated from P_{sub}/η_e. Since P_{sub} is frequency-dependent, η_e is also.

The sensor is a load, and mismatch losses between the source and the sensor occur in the same fashion as those for the general loads discussed in Section 8.1. The mismatch loss factor at the sensor is designated as $(1 - |\Gamma_S|^2)$.

A method for measuring the effective efficiency of uncalibrated thermistor mounts or other power sensors is described by Russell [21]. This measurement method uses a six-port network analyzer. One or more thermistor mounts of known efficiency are connected to the measurement port of the six- port network analyzer and used to generate a system constant, K_a, for each frequency of interest. The calculation of K_a includes the known effective efficiency of the standard mount, its reflection coefficient, and the system reflection coefficient. K_a relates the available power, P_{dc}, at the standard mount to the dc power, P_i, measured at the incident sidearm port of the six-port network. The value of K_a remains constant over an extended period of time if the network is not changed in any way. Several connections are made to each known power standard mount in turn and the averages and standard deviations are computed for each frequency. These data are stored. Then the uncalibrated mounts are connected to the measurement port and the values of P_{dc} are obtained for these mounts. The effective efficiency of each mount under test is then calculated using the new measurements and the values of K_a for the appropriate frequencies.

The combined values of mismatch loss and effective efficiency are contained in a term more frequently used than η_e. This is the calibration factor, K_S, which appears as K_1, K_2 or K_3 (depending on the frequency range of interest) in Sections 5 and 6. The definition of K_S from Section 2.1.11 is:

$$K_S = \frac{P_{sub}}{P_i} = \eta_e (1 - |\Gamma_S|^2) . \tag{8.14}$$

The measurement of K_s is usually determined by a reference standard laboratory and is supplied by the manufacturer of the sensor [2]. Since η_e is specific for each sensor at each frequency of interest, the values of K_s which are provided by the manufacturer for each specific sensor should be used with the appropriate frequencies.

8.3 Uncertainties Due to Power Meter Instrumentation

The power meter instrumentation contributes uncertainties which arise from various sources within the meter. Instrument uncertainty can be caused by nonlinearities in circuits, imprecise attenuators used for various range displays, and uncertainties in amplifier gain. These are combined in an uncertainty term provided by the manufacturer within designated limits.

Power sensor uncertainty and instrument uncertainty are not easily separated. A procedure for determining this combined uncertainty is given as follows:

Select the appropriate calibration factor, K_n, of the reference power sensor where n = 1, 2 or 3 depending on the frequency range of interest.

Enter K_n into the power meter (UUT). (The UUT power measurements ($P_{UUT_{meas}}$) for the frequencies of interest are tabulated in Sections 6.3.1.1, 6.3.1.2, and 6.3.1.3. These values of $P_{UUT_{meas}}$ will be similar to the value of Pdc_n.)

Solve for the calculated value of the power reading of the UUT ($P_{UUT_{calc}}$) as follows:

$$P_{UUT_{calc}} = \frac{Pdc_n}{K_n} \quad . \tag{8.15}$$

The UUT measurement uncertainty is then calculated as the difference, in percent, between the power actually measured by the UUT and the calculated value of the power applied to the UUT.

$$\text{Measurement uncertainty in percent} = \frac{P_{UUT_{calc}} - P_{UUT_{meas}}}{P_{UUT_{calc}}} \times 100. \qquad (8.16)$$

8.4 Uncertainties Due to Internal Reference Oscillator

The reference oscillator, which is used with thermocouple or diode sensors, but not with thermistor mounts, may contribute an uncertainty in power output which must be specified by the manufacturer. The reference oscillator also has a reflection coefficient due to any mismatch at the operating frequency. Since the reference frequency is low in relation to the typical measurement frequencies, this reflection coefficient contributes a mismatch uncertainty factor of approximately ±1.2 % [2]. Thermistor detection is free of these two sources of error because thermistors are closed-loop devices and do not require a reference power level, as discussed in Section 6.3.7.

8.5 Thermocouple Effects at Lead-Sensor Interface

The connections of the two thermistor leads to the thermistor oxide material may form thermocouples when the bias current is an alternating current. Since the temperature of the thermistor material is maintained at approximately 100°C above room temperature, or about 125°C, and if both contacts have slightly different temperatures, this thermocouple effect produces a dc current. This current may add to or subtract from the dc current in the meter. The uncertainty in power measurements due to this effect usually does not exceed 0.3 μW. It may be eliminated for low-level power measurements with a dc supply with reversible polarity for the dc substitution power. The reversal of the dc polarity provides the sum and difference of the substitution and thermoelectric powers [2].

A power meter for measuring power at rf, mw and mmw frequencies has been developed which eliminates lead errors associated with the bridge leads [22]. The Wheatstone bridge in this meter is not self-balancing. A current is passed through the bolometer mount while voltage is sensed across it, so the resistance of the bolometer is defined at the dc terminals of the mount. This reference plane eliminates the effect of bridge lead resistance that could otherwise introduce uncertainties, particularly in the case of long leads.

8.6 Digital Readout Uncertainty

This uncertainty is the ±½ count uncertainty in the least significant digit of a digital display. It may be canceled if the difference between two power readings is required, or it could be additive, in the worst case, making an uncertainty of ± 1 count maximum [2]. The units of the least significant digit are usually nanowatts as discussed in Section 6.3.5 when those of the measured power are microwatts. The percent of uncertainty would then equal approximately ± 0.1%.

8.7 Offset Voltage Uncertainty

Uncertainty in power measurements can be introduced by the offset voltage, which forces the meter to read zero when no rf, μw or mmw power is sensed. The zero setting is made on the most sensitive range as specified by the manufacturer. The uncertainty contribution from this source may be ± 0.5% when the measured power, P_m, is 50 μW and full scale equals 100 μW [2].

8.8 Zero Carryover Uncertainty

An additional uncertainty can occur when the zero carryover mechanism, which is designed to eliminate manual resetting of the zero point when changing display scales, operates with different offsets on different scales. The uncertainty from this source is typically ± 0.2% [2].

8.9 Short-Term Instability

A source of uncertainty is noise, or short-term instability. This is usually specified as a change in meter indication over an interval such as one minute, for constant input power, constant temperature and constant line voltage [4]. The uncertainty contribution from this source is approximately ± 0.05% [2].

8.10 Long-Term Instability

Long-term instability, (also known as long-term stability or drift [4]), is specified for a period of one hour, with constant input power, constant temperature and line voltage [4]. The drift is usually caused by changes in the zero-settings of the display scales. On high ranges, this effect is insignificant. For low scales with their increased sensitivity this can introduce uncertainty. The warm-up interval specified by the manufacturer should be observed. In addition, if the zero is reset immediately prior to a reading, these effects can be eliminated.

When the rf power is low, a constant-current source may be used in order to avoid large uncertainties in the substituted power. This can be a resistor whose value is approximately 100 times that of the bridge resistance. Any changes in load impedance will then be approximately one percent or less. Accuracies of 5 percent or better have been obtained in this manner with a 50-Ω single thermistor bridge at powers from 1 to 100 mW [23].

8.11 Total Measurement Uncertainty

Total uncertainty is calculated from all the sources discussed above. The power delivered to a load, P_ℓ, is less than the ideal ($\Gamma_g = 0$) source power, P_g, by the mismatch uncertainty factor, U_m, where

$$U_m = \frac{|1 - \Gamma_g\Gamma_\ell|^2}{1 - |\Gamma_\ell|^2} \tag{8.17}$$

from eq (8.3).

The net power at the sensor is converted from rf power to the equivalent dc or substituted power, P_{sub}, but in the process P_{sub} is modified by η_e of the sensor and the magnitude of the mismatch loss between the sensor and the source. The uncertainty in the sensor mismatch is expressed as

$$U_s = \frac{1}{\eta_e\,(1 - |\Gamma_s|^2)}\ , \tag{8.18}$$

which is an uncertainty only if η_e and $|\Gamma_s|$ are unknown.

With the substitution of eq (8.14), eq (8.18) becomes

$$U_s = \frac{1}{K_s} \, . \tag{8.19}$$

Finally, this twice-modified power from the generator reaches the power meter instrumentation where further modifications occur to the power measurement, due to imperfections in range-changing attenuators, amplifiers, and any reference oscillator mismatch. These effects are multiplicative and multiply P_{sub} as cascaded amplifiers multiply gain. They are represented by the multiplicative factor, m, [2] which appears in eqs (8.20, 8.21) below.

The sum of the uncertainties introduced by zero offset, zero carryover, noise and drift is additive algebraically to the power meter reading.

8.11.1 Worst Case Uncertainty

Worst case uncertainty, U_{wc}, considers maximum values, algebraically added, of the deviation of a power measurement, P_m, from an established reference or ideal value, P_g, of power at the generator. This ideal value would be the maximum value, $P_{g\,max}$, that P_m could achieve if measured at the generator. Consequently, using the power meter reading, P_m, this becomes

$$P_{g\,max} = \frac{(\text{mismatch uncertainty})\,(P_m - \text{offset}_{max})}{(K_{s\,min})\quad(m_{min})} \tag{8.20}$$

and

$$P_{g\,min} = \frac{(\text{mismatch uncertainty})\,(P_m - \text{offset}_{max})}{(K_{s\,max})\quad(m_{max})} . \tag{8.21}$$

U_{wc} for P_m may also be shown as:

(1) an absolute differential in power:

$$U_{wc} = (P_g\ max + |P_g\ min|) - P_m; \tag{8.22a}$$

(2) or as a fractional deviation:

$$U_{wc} = \frac{P_g\ max + |P_g\ min|}{P_m}; \tag{8.22b}$$

(3) or as a percent of P_m:

$$U_{wc} = \frac{P_g\ max + |P_g\ min|}{P_m} \times 100; \tag{8.22c}$$

(4) or a deviation in dB from P_m:

$$U_{wc} = 10 \log [P_g\ max + |P_g\ min|)/P_m]. \tag{8.22d}$$

If all of the uncertainties are expressed in decibels or in percent, they are all algebraically additive [2].

8.11.2 Root-Sum-Square (RSS) Uncertainty

Root-sum-square (RSS) uncertainty is a more realistic method of uncertainty assessment than worst case uncertainty. It is based on the assumption that most of the uncertainties of power measurements, even though systematic rather than random, are independent of each other. And therefore can be combined as independent variables.

This method specifies the changes of each component of uncertainty in fractional form, as the ratio of the change of the component to the component itself. Each ratio is then squared, the sum taken and the square root of the whole obtained.

8.11.3 Calculation of Total Measurement Uncertainty

The total measurement uncertainty of the power meter (UUT) is composed of the sum of the uncertainties contributed by:

(1) the power sensor uncertainty and the instrument uncertainty (which cannot be easily separated), as discussed in Sections 8.2 and 8.3;

(2) the calibration factor uncertainty that is measured and recorded in Performance Tests 6.3.2.1, 6.3.2.2, and 6.3.2.3;

(3) the reference oscillator uncertainty (in power measurements with nonthermistor mounts) due to a difference in power level from 1 mW which is measured and recorded in Performance Test 6.3.7.2, and

(4) the reference oscillator uncertainty (in power measurements with nonthermistor mounts) due to mismatch (discussed in Section 8.4);

(5) the thermocouple effects at the lead-sensor interface when applicable (Section 8.5);

(6) the digital readout uncertainty when applicable (Section 8.6).

The offset factor includes:

(7) the uncertainty in zero offset voltage (Section 8.7);

(8) zero carryover uncertainty (Section 8.8);

(9) short-term instability (noise) (Section 8.9);

(10) long-term instability (drift) (Section 8.10).

The appropriate calibration factor uncertainties must be read from their respective tables and entered in table 8.11.1. The total measurement uncertainty is then calculated at each frequency and recorded in table 8.11.1. The resultant total measurement uncertainty is valid only for the specific instrument under test with its associated power sensor or sensors at the frequencies used during calibration.

8.12 Uncertainty Analysis of Power Measurements for known VSWR values

The limits of uncertainty in values of power measurements at a load may be determined for specific frequency ranges if the VSWR at the source (or generator) is known for those ranges. The reflection coefficient of the source, Γ_g, is determined without a load because the presence of the device whose power is to be measured constitutes a load.

Table 8.11.1. Total measurement uncertainty

	Measurement Uncertainties										
					Reference Oscillator		Zero Functions				
Frequency (GHz)	U_m (± %)	CAL Fctr. * (± %)	Meter Instr. (± %)	Pwr. Sensor (± %)	*Level (± %)	**U_{mro} (± %)	Offset (± %)	Carryover (± %)	Noise (± %)	Drift (± %)	***Total (± %)
0.01											
0.05											
0.10											
0.50											
1.00											
2.00											
4.00											
7.00											
8.20											
10.00											
15.00											
18.00											
20.00											
22.00											
24.00											
25.00											
26.50											

*The reference oscillator uncertainty due to a difference in power level from 1 mW measured at 50 MHz must be included at all measurement frequencies when thermocouple or diode sensors are used.

**The reference oscillator uncertainty due to mismatch is specified by the UUT manufacturer and must be entered here when thermocouple or diode sensors are used.

***The total (worst case) measurement uncertainty is the algebraic sum of the individual uncertainties tabulated in this table. The RSS determination of total measurement uncertainty can be used if desired.

Step 1: To determine Γ_g:

Given,

Source VSWR (Worst Case)	Frequency Range
1.06	0.01 - 8.0 GHz
1.10	8.0 - 18.0 GHz

Since, from eq (6.23),

$$(VSWR)g = \frac{1 + |\Gamma_g|}{1 - |\Gamma_g|} \tag{8.23}$$

then, $$|\Gamma_g| = \frac{(VSWR)_g - 1}{(VSWR)g + 1}. \tag{8.24}$$

For the frequency range of 0.01 - 8.0 GHz,

$$|\Gamma_g| = \frac{1.06 - 1}{1.06 + 1} = \frac{0.06}{2.06} = 0.029. \tag{8.25}$$

For the frequency range of 8.0 - 18.0 GHz,

$$|\Gamma_g| = \frac{1.10 - 1}{1.10 + 1} = \frac{0.10}{2.10} = 0.048. \tag{8.26}$$

Step 2: To determine Γ_ℓ:

Example: Assume a value for the VSWR at the load, $(VSWR)_\ell$, of 1.10.

Since, from eq (6.23),

$$\frac{1 + |\Gamma_\ell|}{1 - |\Gamma_\ell|},$$

then,

$$|\Gamma_\ell| = \frac{(VSWR)_\ell - 1}{(VSWR)_\ell + 1} = \frac{1.10 - 1}{1.10 + 1} = \frac{0.10}{2.10} = 0.048$$

Step 3: To determine the power measurement uncertainty in percent:

From eq (8.12), $U_m\ (\%) = \pm\ 200\ |\Gamma_g \Gamma_\ell|$.

Typical values of uncertainty in power measurement are calculated for the two solutions of Γ_g given above. Nine values of VSWR of the load are assumed for each value of Γ_g. These uncertainties are tabulated in table 8.12.1.

Table 8.12.1 Calculated values of typical power measurement uncertainty in percent for known VSWR values.

Frequency (GHz)	Source		Load		Uncertainty
	VSWR	$\lvert \Gamma_g \rvert$	VSWR	$\lvert \Gamma_\ell \rvert$	$\pm 200 \lvert \Gamma_g \Gamma_\ell \rvert$
0.01-18.0	1.06	0.029			
			1.00	0	0
			1.10	0.048	0.28
			1.20	0.091	0.53
			1.30	0.130	0.75
			1.40	0.167	0.97
			1.50	0.200	1.16
			1.60	0.231	1.34
			1.70	0.259	1.50
			1.80	0.286	1.66
			1.90	0.310	1.80
8.0 - 18.0	1.10	0.048			
			1.00	0	0
			1.10	0.048	0.46
			1.20	0.091	0.87
			1.30	0.130	1.25
			1.40	0.167	1.60
			1.50	0.200	1.92
			1.60	0.231	2.22
			1.70	0.259	2.49
			1.80	0.286	2.75
			1.90	0.310	2.98

9.0 Summary

The importance of power measurements is described. Differences in methods of measurement at low and high frequencies are presented. The theory of conversion of high-frequency energy to heat in a sensing material is presented. Various common types of sensors are described. Tests to determine the performance of power meters are presented, together with suggested formats for recording results. Sources of uncertainty in measurements are analyzed, and the relative contribution to total instrument uncertainty from each source is presented. Measurements which are made with a heat-sensitive sensor are shown as typical results with this method of detection.

10.0 Conclusions

The use of energy conversion principles for the detection of high-frequency power and its conversion to a dc or low-frequency power permits the use of the instrumentation currently available for power measurement in the low-frequency region. These techniques have been developed and refined over the past years. They provide power measurements which are reproducible within calculable limits of uncertainty and which are acceptable for most purposes. More sophisticated techniques of measurement are available but are usually reserved for higher precision.

The tests presented in this report are sufficient to evaluate the performance of power meters currently in use over the specified frequency range. Confidence in the test results is based on an understanding of the principles of detection, conversion and quantification of power embodied in the thermistor sensor method.

As technology such as communications requires higher frequencies than those of today, new methods of power measurement will require similar but more precise energy conversion methods in order to use the existing power measurement instrumentation described here.

11.0 Acknowledgments

The authors wish to express their appreciation to John D. Smilley, Galen H. Koepke, and John T. Stanley for their constructive evaluation of this document and recommendations for enhancement of the procedures involved in power meter performance assessment; to John P. Wakefield and Manly P. Weidman for their valuable technical guidance; and to Neil T. Larsen, whose extensive work in this field has provided authoritative suggestions and source material.

Special acknowledgment is accorded to James R. Major for valuable contributions in mathematical derivations and circuit design and graphics.

The development and optimization of the test setups and verification of the measurement procedures by Richard L. Ehret greatly enhanced their reliability for reproducibility of results.

Shirley Deeg of the NIST Information Office provided invaluable professional publication management. Terry Yenser and Sharon Huntoon contributed many hours of patient preparation of this document. Darwin Miner and Dean Eicher of MASC Graphic Support Services provided professional graphic support in all facets of the art work.

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14.0 Appendices

Appendix 14.1

Calibration Results for Typical Coaxial Dual Directional Couplers

a. Frequency Range: 0.05 to 2.0 GHz.
b. Frequency Range: 2.0 to 18.0 GHz.

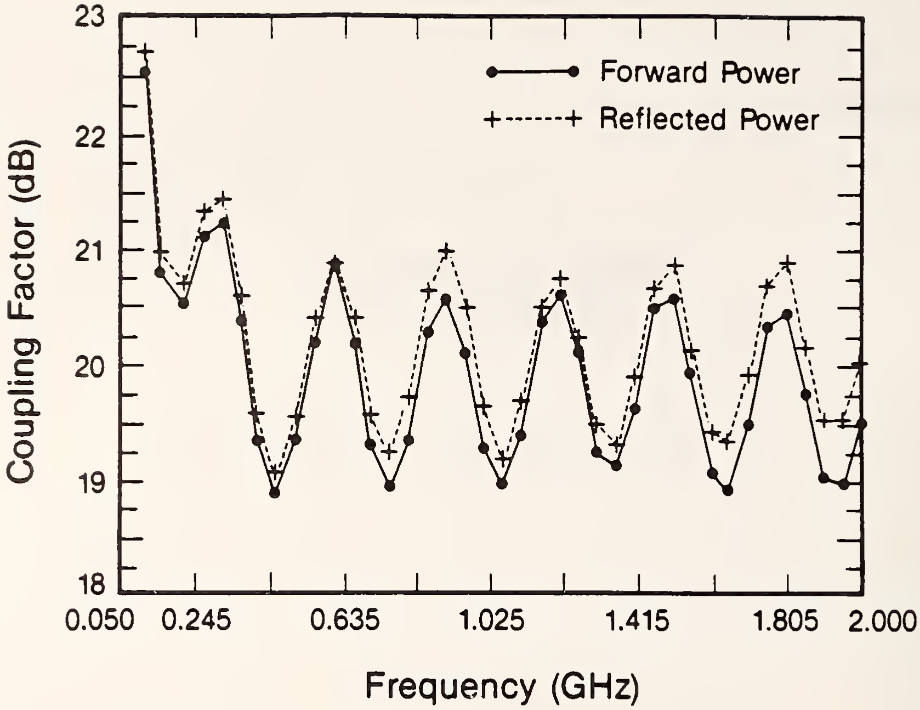

Figure 14.1.a. Plots of forward and reflected coupling factors of a typical coaxial dual directional coupler in dB with respect to the OUTPUT Port for the frequency range of 0.05 to 2.0 GHz.

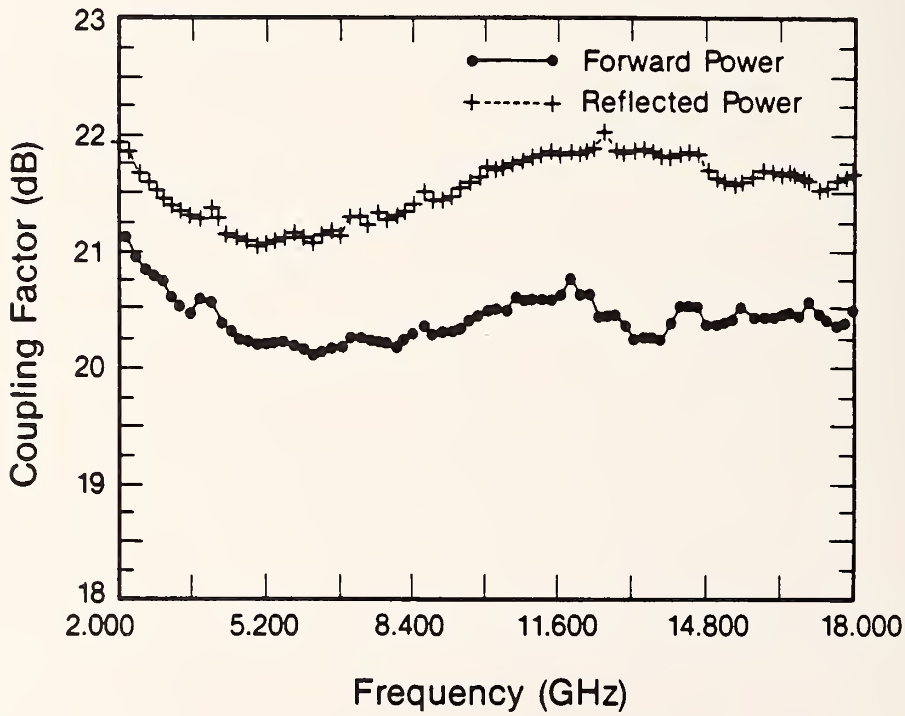

Figure 14.1.b. Plots of forward and reflected coupling factors of a typical coaxial dual directional coupler in dB with respect to the OUTPUT Port for the frequency range of 2.0 to 18.0 GHz.

Appendix 14.2

Calibration Factors for a Typical Reference Power Standard

14.2.1 K_1 (0.01-0.10 GHz).
14.2.2 K_2 (0.10-18.0 GHz).
14.2.3 K_3 (18.0-26.5 GHz).

Table 14.2.1 Values of calibration factor K_1 for a typical reference power standard for the frequency range from 0.01 to 0.10 GHz [13]

Frequency (GHz)	CAL Factor K_1
0.010	0.9388
0.03	0.9900
0.050	0.9905
0.100	0.9877

Table 14.2.2 Values of calibration factor K_2 for a typical reference power standard for the frequency range from 0.10 to 18.0 GHz [13]

Frequency (GHz)	CAL Factor K_2	Frequency (GHz)	CAL Factor K_2	Frequency (GHz)	CAL Factor K_2
0.100	0.9842	4.0	0.9598	10.0	0.9041
0.500	0.9831	5.0	0.9538	11.0	0.8977
1.000	0.9781	6.0	0.9442	12.0	0.8901
1.150	0.9753	7.0	0.9235	12.4	0.8947
2.0	0.9659	8.0	0.9116	14.0	0.8926
3.0	0.9643	9.0	0.9039	15.0	0.8817
				16.0	0.8860
				17.0	0.8776
				18.0	0.8616

Table 14.2.3 Calibration data for a typical reference power standard measured by the National Institute of Standards and Technology for the frequency range from 18.0 to 26.5 GHz*

Frequency (GHz)	Reflection Coefficient (Γ)		Effective Efficiency (η_e)		CAL Factor (K_3)	
	Sample 1	Sample 2	Sample 1	Sample 2	Sample 1	Sample 2
18.0	0.198	0.121	0.982	0.975	0.943	0.961
20.0	0.019	0.115	0.976	0.971	0.976	0.958
22.0	0.090	0.158	0.976	0.971	0.968	0.947
24.0	0.107	0.127	0.978	0.971	0.967	0.955
25.0	0.078	0.073	0.977	0.967	0.971	0.962
26.5	0.086	0.121	0.977	0.966	0.970	0.952

* Sample values from bolometer mounts calibrated at NIST.

Appendix 14.3
Tuner Settings for a Typical Waveguide
Rf Power Transfer Standard

Table 14.3 Tuner settings for a typical waveguide rf power transfer standard for the frequency range from 18.0 to 26.5 GHz**

Frequency (GHz)	Tuner Setting (micrometer reading)			
	T_1	T_2	T_3	T_4
18.0	0.243	0.050	0.146	0.069
19.0	0.335	0.051	0.336	0.045
20.0	0.415	0.041	0.360	0.039
21.0	0.389	0.046	0.379	0.040
22.0	0.426	0.395	0.395	0.042
23.0	0.151	0.052	0.399	0.039
24.0	0.181	0.061	0.157	0.047
25.0	0.193	0.042	0.162	0.048
26.0	0.202	0.039	0.188	0.055
26.5	0.200	0.049	0.194	0.052

**NIST laboratory calibration.

NBS-114A (REV. 2-80)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET (See instructions)	1. PUBLICATION OR REPORT NO. NIST/TN-1310	2. Performing Organ. Report No.	3. Publication Date December 1988

4. TITLE AND SUBTITLE

Performance Evaluation of Radiofrequency, Microwave, and Millimeter Wave Power Meters

5. AUTHOR(S)

Eleanor M. Livingston, Robert T. Adair.

6. PERFORMING ORGANIZATION (If joint or other than NBS, see instructions)

National Institute of Standards and Technology
~~NATIONAL BUREAU OF STANDARDS~~
DEPARTMENT OF COMMERCE
WASHINGTON, D.C. 20234

7. Contract/Grant No.

8. Type of Report & Period Covered

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS (Street, City, State, ZIP)

10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

Measurement techniques are described for the evaluation of the electrical performance of commercially available radiofrequency (rf), microwave (mw) and millimeter wave (mmw) power meters which use bolometric power sensors and typically operate from 10 MHz to 26.5 GHz for an average power range of 10 μW to 10 mW with appropriate attenuation for higher power ranges.

Power measurements at dc and low frequencies are relatively straightforward since voltage, current, and impedance are discrete entities from which values of power may be calculated through the use of Ohm's law. For radio, microwave and millimeter wave frequencies, however, these become complex, interactive, distributed parameters. Impedance mismatch, leakage, and nonlinear responses must also be considered. The principle of the bolometric method of measurement of rf, mw and mmw power is presented.

Techniques are described for analysis of: ranges of frequency and power, operating temperature, stability, response time, calibration factor, extended power measurement, overload protection, and characteristics of the internal power reference source. Some automated methods are discussed. Block diagrams of test setups are presented.

Sources of uncertainty in the bolometric method are analyzed.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

bolometer; dc substitution; microwave power; millimeter wave power; power measurement; radiofrequency power; temperature compensation; thermistor; uncertainty.

13. AVAILABILITY

☒ Unlimited
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☒ Order From Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.
☐ Order From National Technical Information Service (NTIS), Springfield, VA. 22161

14. NO. OF PRINTED PAGES

158

15. Price

U.S. DEPARTMENT OF COMMERCE
National Institute of Standards and Technology
(formerly National Bureau of Standards)
325 Broadway
Boulder, Colorado 80303-3328