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THE NBS SWITCHING RADIOMETERS

National Bureau of Standards
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Boulder, Colorado 80303

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An error analysis for the Dicke radiometers used by the National Bureau of Standards (NBS) in their WR90 and WR62 waveguide noise calibration services for sources with noise temperatures above 1000 kelvin is discussed. A list of measurement frequencies currently available in the WR90 and WR62 bands is presented.

Key words: error analysis; microwave; noise; radiometer.

1. INTRODUCTION

The material presented in this report was extracted from notes presented at a Noise Seminar conducted in 1970, and represents the "state of the art" at that time.

1.1 What Is Measured?

The measurement of noise sources is usually made by comparing a "standard" noise source with an "unknown noise source." The comparison is made by a radiometer. There are many types of radiometers and each has its own advantages and disadvantages. For comparing microwave noise sources that have outputs above room temperatures with standards above room temperature, a switching type of radiometer is one of the types employed at NBS [1,2]. The "standard noise source" and "unknown noise source" in this case is the NBS Reference Standard and the NBS Working Standard respectively during the initial comparison, after which the noise output of the NBS Working Standard is known and has a specified accuracy. For the next step the "standard noise source" is the NBS Working Standard and the customer's noise source is the "unknown noise source." For convenience when discussing comparisons the "standard noise source" and "unknown noise source" are consistently referred to as standard and unknown respectively, and the level of comparison can be judged by what noise source is used as the standard.

At NBS the reference noise standard is used to determine the output of three working standards. Each customer's noise source is measured using two of the three working standards. The noise source submitted for calibration is compared to the working standard, and the comparison relates the difference in noise power output between these two items through a difference attenuation measurement. Since the noise power is related to effective noise temperature, T_{ne}, of the item by

$$P_{noise} = kT_{ne}B \tag{1}$$

(where k is Boltzmann's constant and B is the limiting bandwidth of the system), it is established practice to report to the customer the value of the effective noise temperature of the output of the noise source calibrated. The effective noise temperature [2], T_{ne}, is proportional to the power emerging from the output port of a noise source when it is connected to a nonreflecting load. The noise temperature, T_n, of the noise source (generator) is analogous to the available power from a generator [3] and is obtained when corresponding reflection coefficients for generator and load are complex conjugates of each other. The relationship between the noise temperature and effective noise temperature is

$$T_{ne} = (1 - |\Gamma|^2)T_n, \tag{2}$$

where Γ is the magnitude of the reflection coefficient of the customer's noise source (generator). For this comparison, that is between customer's noise source and the working standard, the radiometer input port is adjusted to have a reflection coefficient magnitude less than 0.01.

The noise output of a noise source can also be reported in terms of excess noise ratio, ENR. The excess noise ratio, expressed in decibels, is calculated from the effective noise temperature using the equation

$$ENR = 10 \log_{10} \frac{T_{ne} - T_o}{T_o} ,$$

where T_o is 290 K, which is an arbitrary standard temperature [4].

This measurement process can only accommodate continuously operated noise sources and has not been adapted to measuring pulsed gas-discharge noise sources for three reasons: 1) pulsed noise sources are very unstable even in the pulsed mode of operation (this problem is further compounded by the feature that their noise output varies widely depending upon where and for how long in the pulse the noise is sampled); 2) there is no common or universally accepted pulsing rate and gating characteristic used by the manufacturers of automatic noise figure meters; and 3) pulsed noise sources generally have shorter useful lives.

Using calibrated noise sources, noise figures, noise factors, operating noise temperatures, and effective noise temperatures of devices, components, and systems can be measured by either the Y-factor or other similar techniques [5]. An automatic noise figure meter could be devised that would be quite accurate if it employed a switchable ferrite to simulate a pulse of noise by switching the RF output of a noise source operated in the continuous mode. It should be noted that automatic noise figure meters are at present only relative measuring instruments.

2. ERROR ANALYSIS OF THE SWITCHING RADIOMETER

2.1 The Switching Concept

A switching radiometer is basically a half power radiometer and is often called a Dicke radiometer, since in 1946 Dicke [6] suggested using a switch in the front end of a radiometer (fig. 1a). The name half power arises because only half the power available at the input is available for use by the receiver. This situation results due to the switching process connecting the receiver to the source being observed for half the time and to some reference source for the other half of the time. Dicke constructed a wheel made of an absorbing material and shaped in such a way that, when rotated by a motor in a slotted section of the waveguide, it produced a nearly square wave modulation with close to equal times in and out of the waveguide. If it is assumed

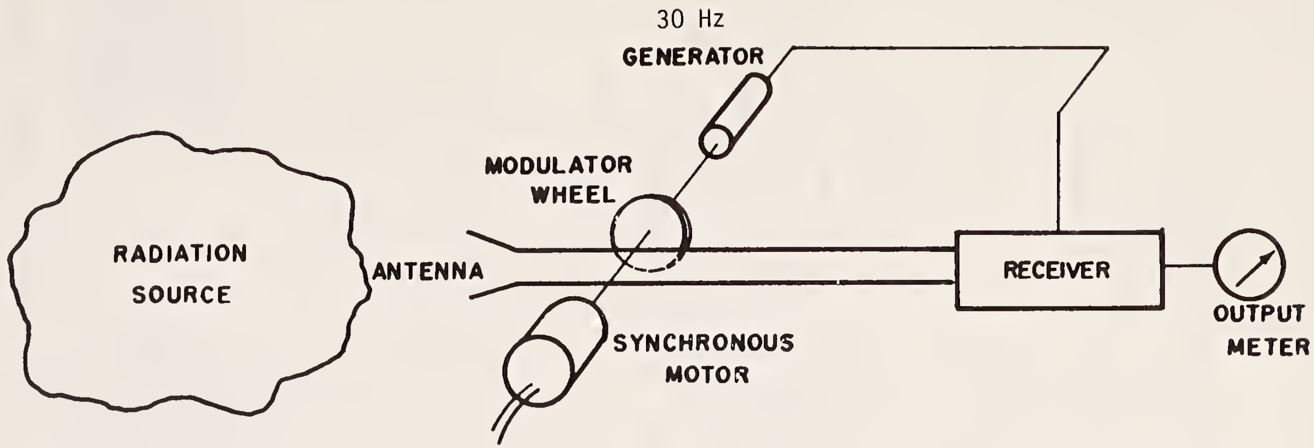
30 Hz
GENERATOR
MODULATOR
WHEEL
RADIATION
SOURCE
ANTENNA
SYNCHRONOUS
MOTOR
RECEIVER
OUTPUT
METER

Figure 1a.

that the wheel and antenna are both nonreflecting, then the effect of the wheel is one of disconnecting the antenna and connecting an equivalent resistance (the absorbing material of the wheel) to the receiver. Note that if the radiation from the wheel and the antenna is the same no change will be noticed on the output meter, while if there is a difference a modulated signal will result and the deflection on the output meter will change. This scheme was adapted for use in the measurement of standards since it is effectively insensitive to gain variations. This type of radiometer, figure 1b, alternately samples power from a known and an unknown noise source by switching repetitively from one to the other. A null-balance is achieved when the power output from both sources is identical.

The NBS radiometer is modified to compare the noise power from an unknown source and a standard source through a single arm of the radiometer (called the comparison arm) as shown in figure 2. The advantage of this modification is that the paths for the noise power from both the standard and unknown noise sources are more nearly identical. This advantage means that an insertion loss measurement of two separate paths (c.f. fig. 1b) need not be made, and the difference between the noise sources will be an attenuation difference measurement instead of an absolute attenuation measurement. Asymmetries in the junction of the arms and time variations in the mismatch of the modulators do not enter into the error analysis.

With a radiometer of this basic design, the signal entering the receiver will have a chopped appearance unless the power from the reference level source and the source on the comparison arm have identical power outputs at the receiver input. Figure 3 illustrates schematically the two different signals seen by the receiver; that is for the conditions of a balance and an unbalance of noise power between the reference and comparison arms. For convenience of drawing the figure it is assumed that the resultant signal is a square wave.

2.2 Fundamentals of Error Analysis

When dealing with measurements of random noise, one important consideration that must be recognized is that there are no passive devices. Devices can be considered passive ONLY when they are either perfect conductors or they are maintained at a physical temperature of absolute zero (0 kelvin). The antithesis is that all devices having a physical temperature above absolute zero are random noise generators; if they have low resistive properties then the noise generation for any arbitrary fixed temperature will be comparatively small and conversely, devices with high resistive properties will generate comparatively larger amounts of noise at the same fixed temperature. This being the case, it is necessary to consider maintaining a constant ambient temperature in order to avoid changes in noise generation from a varying temperature affecting separate devices to different degrees. If noise standards are used that have effective noise temperatures that are well above ambient temperature then this problem is less severe.

With any radiometer the principle of measurement is one of comparing a standard noise source with an unknown noise source. For some applications where only a relative difference needs to be known, the value of the standard is not needed.

Basically an error analysis is a process of trying to determine: 1) what parameters of a measurement process will constitute an error to the final results; 2) how large will be the contribution from the individual components to the total error of each such parameter; 3) how to evaluate each contributing factor; and 4) how to collect the resulting values to arri ve at a meaningful limit to the total error. In the case where a comparison is made between a standard

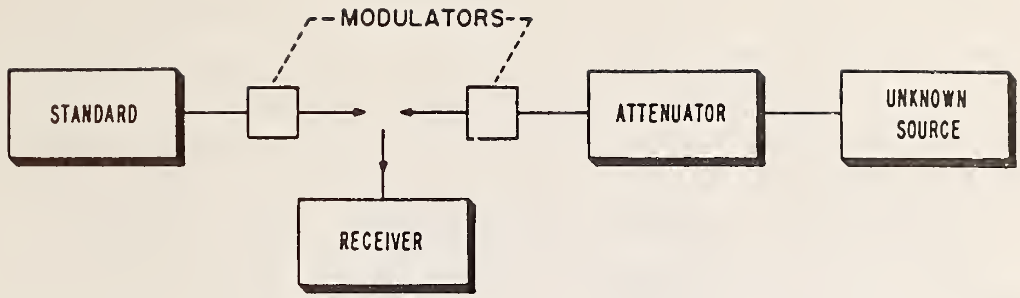

Figure 1b.

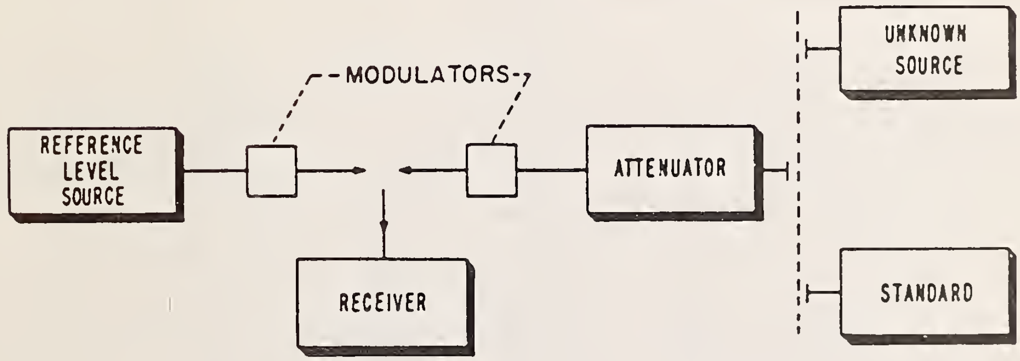

Figure 2.

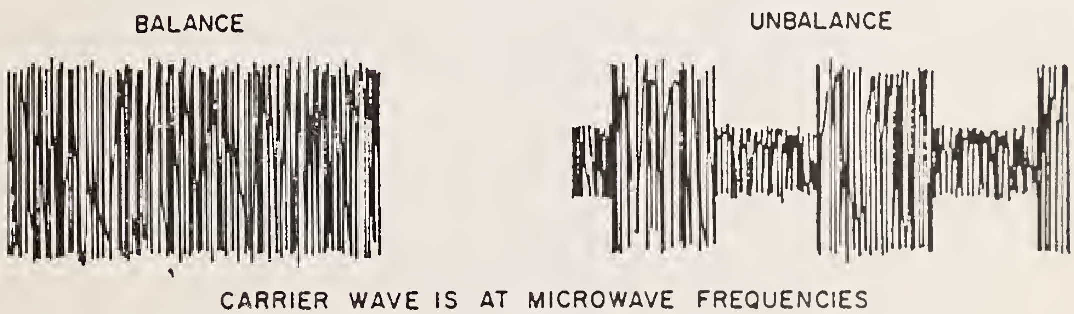

Figure 3.

and an unknown, a condition of balance may be arrived at. This will be a special situation where, at an arbitrary plane of reference, two separate conditions will each produce a balance of the comparator. A mathematical evaluation of what actually happens at this arbitrary plane for a condition of balance can be made. The equation arrived at will be the balance equation for that specific comparator. If we make a partial differentiation of this balance equation, we can identify what parameters need to be examined to evaluate their contribution to the total error of the measurement process. The examination of a parameter must include varying every conceivable variable (e.g., humidity, atmospheric pressure, temperature, power level, frequency, etc.) and any combination of variables that may affect the parameter itself. Where a mathematical equation is arrived at, the equation will describe how the errors will be collected, and this result will give the total systematic error of this measurement process. For the case where random errors are heavily involved, they will need to be collected by a different technique. (The collection of random sources of error will not be treated here since they provide a very small contribution in the noise system to be treated.)

2.3 Error Analysis of a NBS Type Switching Radiometer

Using the simplified diagram of the NBS switching radiometer, figure 2, we can isolate our arbitrary reference plane and determine a balance equation. The arbitrary reference plane will be located immediately before the modulators. For convenience, we will call everything to the left of this reference plane the receiver. Figure 4 shows what must analyzed.

In figure 4 details of the precision attenuator are elaborated to clarify possible contributions to the total error. P_1 is the power entering the input and P_2 the power entering the receiver. In all cases, primed designations indicate that the noise source on the input is the unknown, and correspondingly the unprimed quantities indicate the standard is attached to the input. All Γ's are reflection coefficients and the associated arrow designates which port is considered. T_n is the noise temperature, and T_A is ambient temperature. S_{21} is a term of the scattering matrix and it is proportional to the attenuation of the path [3] from the input plane (plane 1) to our arbitrary reference plane (plane 2). For the condition where the receiver is in balance, $P_2 = P_2'$, where the primes signify that the unknown is attached to the radiometer.

In developing the error analysis it was soon learned that either the attenuator in the comparison arm had to be matched to the line or to avoid this it had to be calibrated with adequate isolation on either side. It was chosen to add the isolation to the attenuator as a convenience to the operator.

A fairly complete analysis of the radiometer is given in the Wells, et al. paper [2]. Using the general eq (11) from the paper

$$P_1 = kT_n\Delta f \frac{(1-|\Gamma_n|^2)\ (1-|\Gamma_1|^2)}{|1-\Gamma_n\Gamma_1|^2} . \tag{3}$$

Note that $P_2 = \eta P_1$, where

$$\eta = \frac{|S_{21}|^2(1-|\Gamma_L|^2)}{|1-S_{22}\Gamma_L|^2(1-|\Gamma_1|^2)} \text{ and } \Gamma_1 = S_{11} + \frac{S_{12}S_{21}\Gamma_L}{1-S_{22}\Gamma_L} . \tag{4}$$

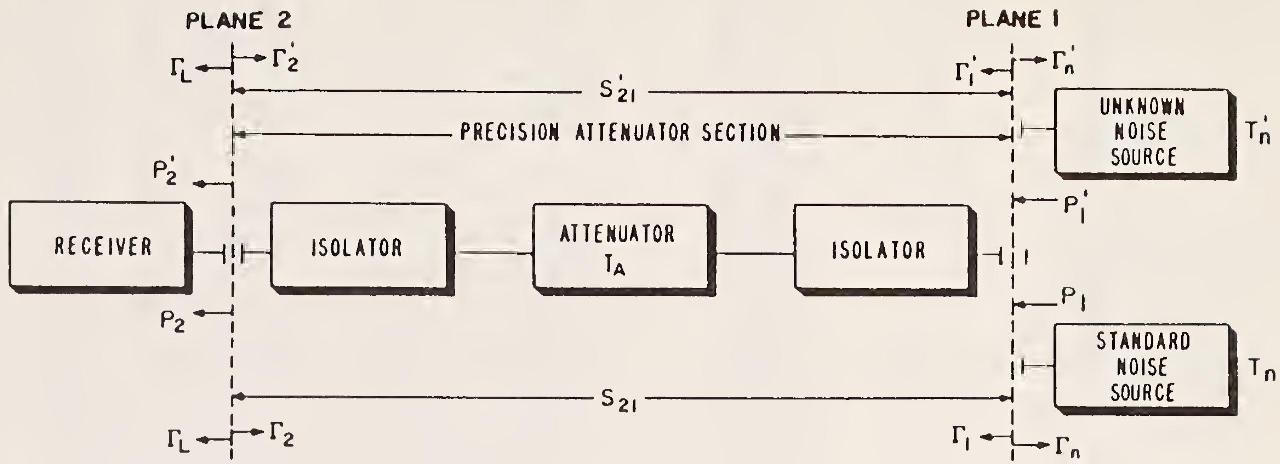
PLANE 2
PLANE 1
Γ_L
Γ_2'
Γ_1'
Γ_n'
S_{21}'
PRECISION ATTENUATOR SECTION
UNKNOWN NOISE SOURCE
T_n'
P_2'
P_1'
RECEIVER
ISOLATOR
ATTENUATOR T_A
ISOLATOR
P_1
P_2
STANDARD NOISE SOURCE
T_n
S_{21}
Γ_L
Γ_2
Γ_1
Γ_n

Figure 4.

Following the development in the paper, and using the definition $T_{ne} \equiv T_n(1-|\Gamma_n|^2)$ (eq (2)) as the effective noise temperature and the conditions of eqs (3) and (4), the following expression is obtained.

$$T'_{ne} = \frac{|(1-\Gamma_2\Gamma_L)\ (1-S'_{11}\Gamma'_n)|^2}{|(1-\Gamma'_2\Gamma_L)\ (1-S_{11}\Gamma_n)|^2}\ T_{ne}-T_A(1-|\Gamma_n|^2)\ \frac{|S_{21}|^2}{|S'_{21}|} \qquad (5)$$

$$+ T_A(1-|\Gamma'_n|^2) + T_{Ae} + T_{re}\ .$$

Due to having adequate isolation on either side of the attenuator, $\Gamma_2 = \Gamma'_2$ and $S_{11} = S'_{11}$. This means that $T_{Ae} = 0$ and $T_{re} = 0$. This modifies eq (5) to

$$T'_{ne} = \frac{|1-S_{11}\Gamma'_n|^2}{|1-S_{11}\Gamma_n|^2}\ T_{ne}-T_A(1-|\Gamma_n|^2)\ \frac{|S_{21}|^2}{|S'_{21}|^2} + T_A(1-|\Gamma'_n|^2). \qquad (6)$$

Differentiating eq (6), an expression is obtained which can be used to determine absolute uncertainties. Since $|\Gamma_n|$ and $|\Gamma'_n|$ are small, the factor $(1-|\Gamma_n|^2)$ will be approximately unity. This gives the approximation for

$$\delta T'_{ne} \simeq \frac{|S_{21}|^2}{|S'_{21}|^2}\ \delta T_{ne} + 0.23(T'_{ne}-T_A)\delta\Delta + \ 1 - \frac{|S_{21}|^2}{|S'_{21}|^2}\ \delta T_A$$

$$+ 2T_A \frac{|S_{21}|^2}{|S'_{21}|^2}\ |\Gamma_n|^2 + |\Gamma'_n|^2\ \frac{\delta|\Gamma_n|}{|\Gamma_n|} + M\ . \qquad (7)$$

$\delta T'_{ne}$ is the error in T'_{ne} or the error obtained in comparing an unknown noise source with a standard noise source. δT_{ne} is the error in the standard noise source. T'_{ne} is the value of the unknown noise source obtained as a result of the measurements and the calculations made using eq (6). T_A is the ambient temperature of the system and particularly the precision attenuator. $\left|\frac{S_{21}}{S'_{21}}\right|^2 = 10^{\Delta/10}$, where Δ is the attenuation difference between the standard and unknown noise sources as measured on the precision attenuator, so $\delta\Delta$ is the error in using the precision attenuator. δT_A is the error to which the absolute value of the ambient temperature is known. $\frac{\delta|\Gamma_n|}{|\Gamma_n|}$ is the error incorporated in measuring the reflection coefficient magnitudes using a tuned reflectometer [7]. M is the error in determining the mismatch, and its maximum is given by

$$M = \left[\frac{(1+|S_{11}\Gamma_n^{'}|)^2}{(1-|S_{11}\Gamma_n|)^2} - 1 \right] \left[T_{ne}^{'} - T_A(1-|\Gamma_n^{'}|^2) \right]. \qquad (8)$$

All the terms in this equation have been discussed with the exception of S_{11}. S_{11} is the same as Γ_1 since the isolator in front on the attenuator provides at least 30 dB isolation.

These equations are applied successively from the first measurements in which the NBS Reference Noise Standard is used to measure the NBS Working Standards; and eventually to the measurements where the NBS Working Standard is used to measure a customer's Laboratory Noise Standard. To facilitate understanding this process and to realize the degradation of the measurement accuracy, an example is presented later using the NBS Reference Standards and radiometers to determine an Error Flow Diagram.

3. THE NBS SWITCHING RADIOMETERS

3.1 The WR90 and WR62 Radiometers

The WR90 and WR62 radiometers are basically the same. As a consequence this description will be based solely on the WR90 radiometer. The description will be used as a basis for determining the accuracy which NBS Working Standards will have.

3.1.1 The WR90 Comparison Radiometer

Figure 5 shows a detailed block diagram of the WR90 radiometer. The comparison arm of the radiometer consists of a reflectometer [7] in series with a calibrated precision attenuator. The waveguide switch after the precision attenuation is part of the reflectometer; it connects the detector and VSWR meter into the circuit for the reflected signal of the reflectometer. Attaching the reflectometer to the radiometer allows the direct measurement of any noise source attached to the input. When the reflectometer is tuned, the radiometer input port is automatically tuned to approximate a nonreflecting load. As far as the error analysis is concerned the presence of the reflectometer adds nothing to figure 4. The calibrated precision attenuator section is removable for calibration by the subcarrier technique to an accuracy of ± 0.005 dB; the attached isolators eliminate the need for matching the attenuator to the line [2]. The attenuator itself is a rotary-vane attenuator that is modified by a gearbox that is permanently mounted to it. The combination provides a fine control of the rotor of the attenuator with no detectable backlash so that a 0.001 degree movement of the rotor is resolvable. The angular movement of the rotor is converted to attenuation values [8] quite easily, thereby providing resolution capability at low attenuation values to 0.0001 dB, and at high attenuation values to 0.001 dB.

The reference arm is composed of two attenuators and the reference level noise source. One attenuator is used to balance the power in the reference arm with that entering the receiver from the comparison arm. The other attenuator is used for the purpose of determining the sensitivity of the receiver by introducing small known changes to the receiver input.

The switching method employed in the WR90 and WR62 radiometers is a mechanically driven pair of modified rotary-vane attenuators. The modification of the attenuators amounts to substituting

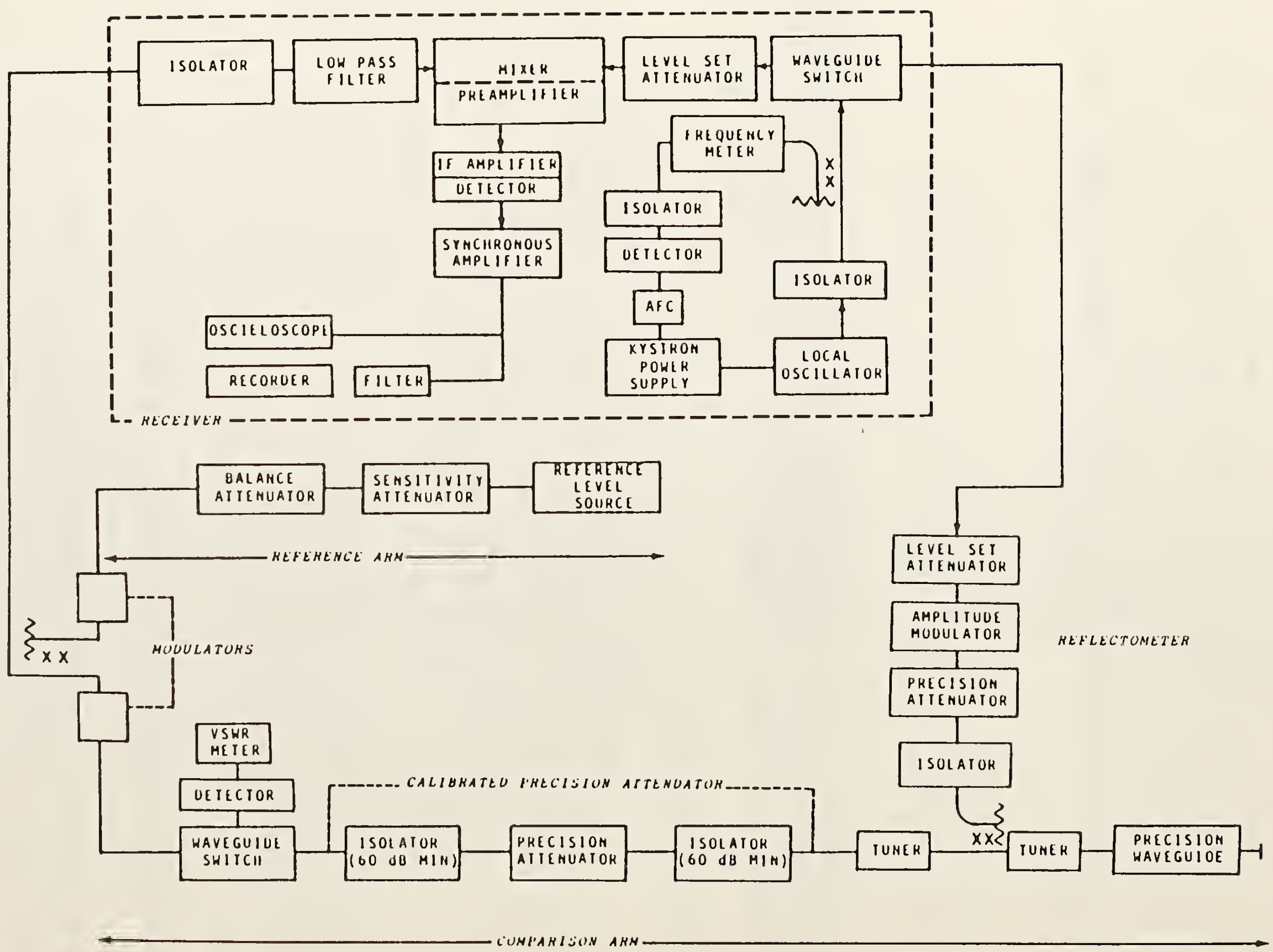
ISOLATOR
LOW PASS FILTER
MIXER
PREAMPLIFIER
LEVEL SET ATTENUATOR
WAVEGUIDE SWITCH
FREQUENCY METER
IF AMPLIFIER
DETECTOR
ISOLATOR
DETECTOR
SYNCHRONOUS AMPLIFIER
ISOLATOR
AFC
OSCILLOSCOPE
KYSTRON POWER SUPPLY
LOCAL OSCILLATOR
RECORDER
FILTER
RECEIVER
BALANCE ATTENUATOR
SENSITIVITY ATTENUATOR
REFERENCE LEVEL SOURCE
REFERENCE ARM
MODULATORS
LEVEL SET ATTENUATOR
AMPLITUDE MODULATOR
REFLECTOMETER
PRECISION ATTENUATOR
ISOLATOR
VSWR METER
DETECTOR
CALIBRATED PRECISION ATTENUATOR
WAVEGUIDE SWITCH
ISOLATOR (60 dB MIN)
PRECISION ATTENUATOR
ISOLATOR (60 dB MIN)
TUNER
TUNER
PRECISION WAVEGUIDE
COMPARISON ARM

Figure 5.

the bearings for a variety more suited to continuous rotation and to replacing the manufacturer's drive mechanism by toothed pulleys and timing belts [1]. The orientation of the vanes of the attenuators is such that they maintain a 90° angular difference; the resulting effect is a switching system where the receiver sees only one arm of the radiometer at a time. The combining junction for the two arms is a directional coupler, and the output of the modulators is a 30 Hz modulation of the rf noise signal.

The signal enters the mixer-preamp via a low pass filter, which limits the bandpass, cutting off higher frequencies of noise power. This prevents undesirable higher harmonics being generated when the signal is beat with the signal from the local oscillator. Both the response and the image components of the intermediate frequency are used. The waveform of the IF is the same as shown in figure 3, except that now the carrier frequency is at 30 MHz. Since the bandwidth of the IF amplifier system is approximately 8 MHz, the assumption is made that the noise spectrum of the microwave noise sources being used is flat over a minimum of 68 MHz, figure 6. This assumption is usually valid. The IF signal is amplified and detected, thereby sending a 30 Hz signal to the synchronous amplifier. The 30 Hz signal is first amplified and then detected synchronously at the rotary-vane switching frequency. The resulting signal looks like a rectified 30 Hz signal which will assume a positive or negative attitude, when the radiometer is unbalanced, and appear to have no signal, when the radiometer is balanced. This type of detection scheme inherently has a very narrow bandwidth. The d-c component is obtained by filtering this signal and displaying the result on a recorder.

Some refinements of the system that have resulted in the better operation are: 1) the local oscillator frequency is stabilized by a servo-control system using phase detection; 2) the filament power supply for the mixer-preamp and IF amplifier is a regulated dc voltage supply; 3) a waveguide switch is included in the local oscillator arm so that local oscillator power can be turned off to prevent overdriving the system when changing from the standard noise source to an unknown noise source, and to use the local oscillator power for the reflectometer, eliminating the need for a separate power source; 4) the mixer-preamp is isolated from the L.O. and the rest of the radiometer's waveguide by a dc block (made from mica); and 5) the whole system is rigidly mounted on a secure base, (fig. 7).

The measurement technique is as follows. An unknown noise source is connected to the radiometer with the precision attenuator set at a calibrated setting. The balance attenuator is adjusted until a null output is observed on the scope and recorder. A sensitivity check may be made by inducing a known change on the sensitivity-balance attenuator with which the recorder is calibrated. After a null is reached the local oscillator power is turned off and the unknown noise source is exchanged for a standard noise source. The local oscillator is turned on and the precision attenuator is readjusted until the null is again achieved. The amount of attenuation that was introduced or removed by adjusting the precision attenuator is directly related to the difference in the output noise power of the standard and the unknown. The resulting value of the effective noise temperature of the noise source to be measured may be calculated by applying the data to:

$$T'_{ne} = (T_{ne} - T_A)10^{\Delta/10} + T_A, \tag{9}$$

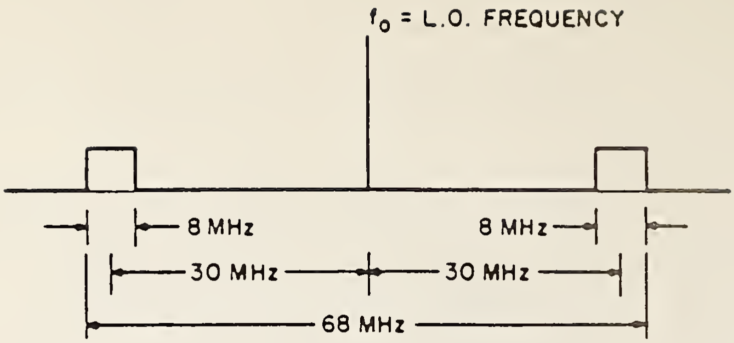

Figure 6.

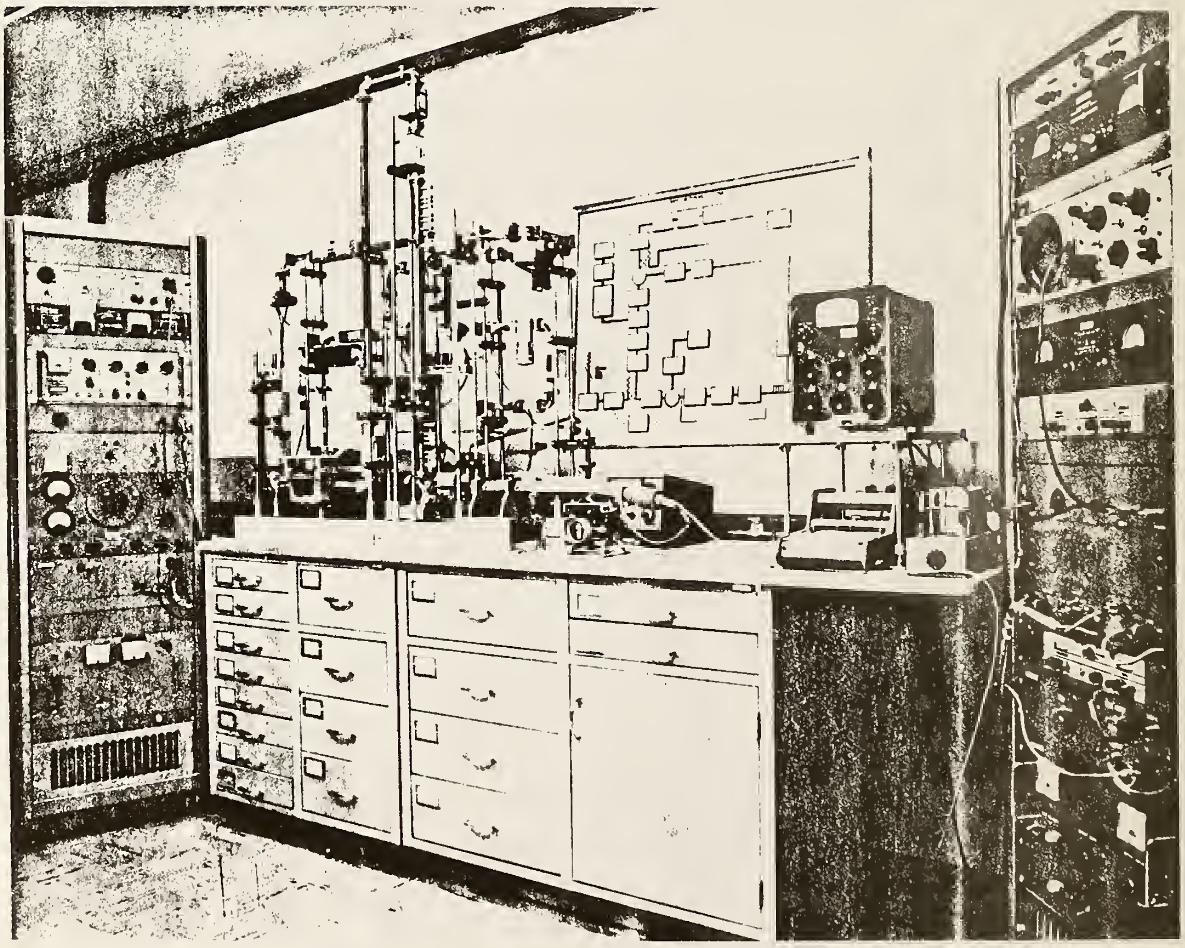

Figure 7.

where T_A is the measure of the ambient temperature of the precision attenuator, Δ is the algebraic difference in attenuation as read on the precision attenuator, and T_{ne} is the effective noise temperature of the standard. It should be clear that this is a reduction of eq (6) when the assumption is made that $|\Gamma_n|$ and $|\Gamma_n'|$ are quite small, and $|S_{21}|^2/|S_{21}'|^2 = 10^{\Delta/10}$.

From this example we can see that the most critical requirement is in having a high quality precision attenuator in the comparison arm. This attenuator must have good resolution, high precision, and an accurate calibration. Further, it will be noted that the only requirement on the "reference level" noise source is that it must be stable over the length of time necessary to observe the difference in output of both the standard and the unknown. The difference between these two noise sources is determined at least five times, and an average of the results is computed and reported to the customer.

3.1.2 Applying the Error Analysis to the WR90 Radiometer

In examining the radiometer, care is taken to assure that no d-c bias exists in the RF detection scheme, no harmonics are generated in the mixer, the L.O. frequency is adequately stable and has minimal noise input, and the synchronous detector is synchronized to the switch.

The ambient temperature is evaluated to determine what value to assign to δT_A. In the NBS lab the ambient temperature varies throughout the room so the temperature is monitored in the vicinity of the precision attenuator. An evaluation was made to determine the difference between the temperature at the monitor and the temperature of the attenuating vane in the precision attenuator. It was found that δT_A is less than 2°C.

An analysis was performed on the built-in reflectometer to ascertain the limits of error in

$\frac{\delta|\Gamma_n|}{|\Gamma_n|}$. A maximum error of 5 percent was found [7].

$\delta\Delta$ contains all errors in determining Δ. These include the limits of error assigned to the attenuator during its calibration process (which include the discrepancy in attenuation values read in the 68 MHz bandwidth of concern), the error in distinguishing a null, and the error due to the operator judgement. The error is less than 0.005 dB. The latter errors are determined by experimentation.

The mismatch error is arrived at by using eq (8) with the measured values obtained. If the receiver uses both the image and response of the IF, then all Γ and S values must be evaluated at the separate IF frequencies. For example, the WR90 Radiometer uses a 30 MHz IF; this means the Γ and S values must be measured at f_o + 30 MH_z and f_o - 30 MH_z. If the values measured are large, then further measurements are necessary to see how Γ and S vary in the bandwidth of concern about both $f_o \pm 30$ MHz. If the values measured are small, they can be averaged to get a value for use in the equations.

The value of δT_{ne} is the limit of error to which the standard being used to perform the calibration is known. For an example, let us assume the NBS Reference Noise Standard is known to approximately ± 4.0 kelvins at 9.6 GHz; this standard is used to measure and evaluate the NBS Working Standards. For an NBS Working Standard that has an effective noise temperature of 11,000 K and a reflection coefficient magnitude of 0.02 we can apply the equations to see that during the process of comparison a degradation takes place and the NBS Working Standards are correspondingly known to approximately ± 109.4 kelvins. This is the applicable value used to determine the limits of error of the unknown interlaboratory standard. If we assume the unknown interlaboratory standard sent for calibration is stable, has a $|\Gamma_n'| \leq 0.02$, and yet has a 100 K different effective noise temperature from the NBS Working Standard then the limit of error will be ± 136.4 kelvins. This example is worked out in table 1 with typical values for a series of comparisons at 9.6 GHz. The same information is included in an Error Flow Diagram in figure 8. This diagram illustrates that each time the radiometer is used a degradation of error results. Note that although the NBS Reference Noise Standard is known to ± 4.0 K, after making a comparison the effect is that ± 43.9 K or 40.1% of the error of the NBS Working Standard is due to the Reference Noise Standard.

Table 1

A. Using the NBS Reference Noise Standard to calibrate an NBS Working Standard (typical values for 9.6 GHz).

$$\delta T_{ne} = 4.0 \text{ K}, \qquad T_A = 24.8°\text{C} = 298 \text{ K}, \qquad \delta T_A = 2 \text{ K},$$

$$|\Gamma_n| \leq 0.07 \qquad |\Gamma_n'| \leq 0.02, \qquad S_{11} = 0.01$$

$$\frac{|S_{21}|^2}{|S_{21}'|^2} = 10^{\Delta/10} = 10^{1.04} = 11, \qquad \frac{\delta|\Gamma_n|}{|\Gamma_n|} = 0.05$$

$$T_{ne}' = 11{,}000 \text{ K} \qquad \delta\Delta = 0.005 + 0.005 = 0.01 \text{ dB (for Working Standard).}$$

$\delta\Delta$ is comprised of the limits of error of the attenuator's calibration (±0.005 dB), and the balance and operator error (when using the Reference Standard these two amount to ± 0.005 dB). Using eq (7)

$$\delta T_{ne}' \simeq 43.9 + 24.6 + 20 + 1.6 + 19.3 = 109.4 \text{ K}$$

B. Using an NBS Working Standard to calibrate a customer's Interlaboratory Standard.

$$\delta T_{ne} = 109.4 \text{ K}, \qquad T_A = 298 \text{ K} \qquad \delta T_A = 2 \text{ K}$$

$$T_{ne}' = 11{,}100 \text{ K (for Customer's Interlaboratory Standard)},$$

$$S_{11} = 0.01, \qquad |\Gamma_n| = |\Gamma_n'| \leq 0.02$$

$$\frac{|S_{21}|^2}{|S_{21}'|^2} = 10^{0.004} = 1.0093, \quad \frac{\delta|\Gamma_n|}{|\Gamma_n|} = 0.05, \ \delta\Delta = 0.005 + 0.002 = 0.007 \text{ dB}$$

(balance and operator error in this case is ± 0.002 dB). Using eq (7)

$$\delta T_{ne}' \simeq 110.4 + 17.4 + 0 + 0 + 8.6 = 136.4 \text{ K.}$$

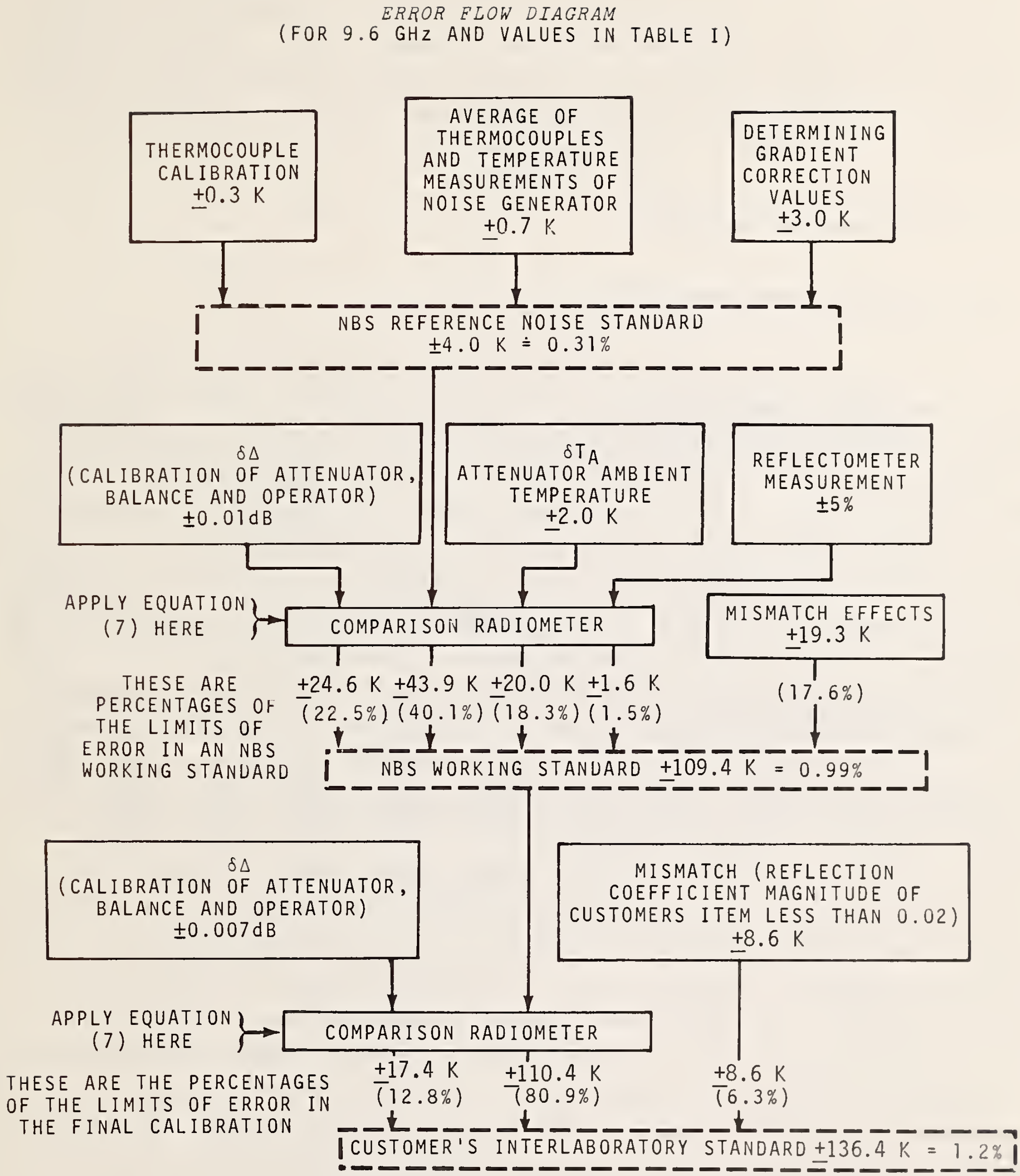
ERROR FLOW DIAGRAM
(FOR 9.6 GHz AND VALUES IN TABLE I)
THERMOCOUPLE CALIBRATION ±0.3 K
AVERAGE OF THERMOCOUPLES AND TEMPERATURE MEASUREMENTS OF NOISE GENERATOR ±0.7 K
DETERMINING GRADIENT CORRECTION VALUES ±3.0 K
NBS REFERENCE NOISE STANDARD ±4.0 K ≐ 0.31%
δΔ (CALIBRATION OF ATTENUATOR, BALANCE AND OPERATOR) ±0.01dB
δT_A ATTENUATOR AMBIENT TEMPERATURE ±2.0 K
REFLECTOMETER MEASUREMENT ±5%
APPLY EQUATION (7) HERE
COMPARISON RADIOMETER
MISMATCH EFFECTS ±19.3 K
THESE ARE PERCENTAGES OF THE LIMITS OF ERROR IN AN NBS WORKING STANDARD
±24.6 K (22.5%)
±43.9 K (40.1%)
±20.0 K (18.3%)
±1.6 K (1.5%)
(17.6%)
NBS WORKING STANDARD ±109.4 K = 0.99%
δΔ (CALIBRATION OF ATTENUATOR, BALANCE AND OPERATOR) ±0.007dB
MISMATCH (REFLECTION COEFFICIENT MAGNITUDE OF CUSTOMERS ITEM LESS THAN 0.02) ±8.6 K
APPLY EQUATION (7) HERE
COMPARISON RADIOMETER
THESE ARE THE PERCENTAGES OF THE LIMITS OF ERROR IN THE FINAL CALIBRATION
±17.4 K (12.8%)
±110.4 K (80.9%)
±8.6 K (6.3%)
CUSTOMER'S INTERLABORATORY STANDARD ±136.4 K = 1.2%

Figure 8.

Figure 9 gives an idea of the accuracy to which two of the four NBS Working Standards are known. The particular two NBS Working Standards have been measured and evaluated at five frequencies and their limits of systematic error have been determined through the process related. It is easily seen that the accuracy improves as the frequency increases across the band. The WR62 NBS Working Standards have comparable curves with comparable values. Since the customer's standard is calibrated against the NBS Working Standard it too will display a similar increase in accuracy across the band although the differences from one end of the band to the other will depend upon the characteristics of the item being measured.

4. WR90 AND WR62 MEASUREMENT SERVICES

4.1 Existing Waveguide Measurement Services

At present two switching systems exist for the measurement of high-temperature sources and they are in the WR90, and WR62 waveguide sizes. The word system is used to include the appropriate NBS Reference Standard, NBS Working Standards, and the radiometric comparator.

Although the systems are constructed in WR90 and WR62 waveguide sizes, the items that can be calibrated by them can be in any of the waveguide sizes whose frequency range overlaps that of one of these systems ... namely, WR112, WR75, and WR51. To measure noise sources in these other waveguide sizes, a waveguide to waveguide transition is required. The transition is analyzed to determine the loss incurred in attaching it to a customer's interlaboratory standard and to determine the additional error it will cause to the calibration of the noise source.

Table 2 is extracted from the NBS Special Publication No. 250 [9] and describes what calibration services of noise sources using the WR90 and WR62 systems are available. Extension of these services to cover frequencies above the normal upper limits of each of the systems is not possible due to problems of multimoding. Extension in a downward direction can be handled as long as the requested frequency is at least 0.15 GHz above the cutoff frequency of the waveguide.

Table 2 identifies the NBS Fee Schedule number, and the output noise power range in both effective noise temperature and excess noise ratio that can be handled by the calibration service. This range of noise power output can be increased easily in an upward direction to cover solid-state type noise sources if the need arises. To extend the range in a downward direction is not as easily accomplished. An indication of accuracy is given in terms of both effective noise temperature and excess noise ratio. The actual accuracy reported is based upon the measurements.

To establish a frequency for regular use in the calibration service takes 3 to 4 months for the necessary preliminaries, primarily reactivating the reference standard and evaluating it at the specified frequency, then measuring and evaluating the working standards (which includes evaluation of the radiometer and calibration of the precision attenuator and cavity wavemeter). Due to this lengthy effort a selection of frequencies have been established in each waveguide size (table 3) to try and cover the frequency band as well as possible and eliminate the need for continually adding frequencies. On occasion the need for a specific frequency will exist either to get the greatest accuracy or to do work at a classified frequency, and NBS will accommodate these needs under fee schedule 4.6.1 as it is able to do so.

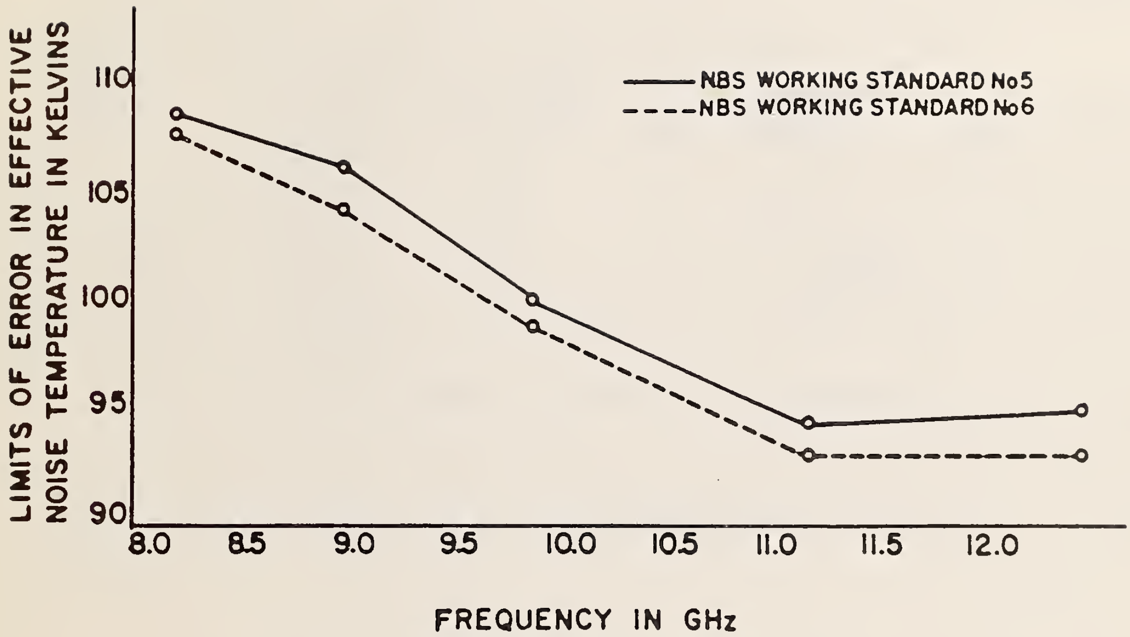
LIMITS OF ERROR IN EFFECTIVE
NOISE TEMPERATURE IN KELVINS
110
105
100
95
90
NBS WORKING STANDARD No5
NBS WORKING STANDARD No6
8.0
8.5
9.0
9.5
10.0
10.5
11.0
11.5
12.0
FREQUENCY IN GHz

Figure 9.

Table 2

EFFECTIVE NOISE TEMPERATURE MEASUREMENTS OF WAVEGUIDE NOISE SOURCES USING THE WR90 AND WR62 SYSTEMS

Service available: Effective noise temperature.

NBS Fee Schedule	Waveguide Size	Effective Noise Temperature Range	Excess Noise Ratio Range
4.6D	WR 62(12.4-18.0 GHz)	700-300,000 K	1.5 to 30 dB
	WR 75(10.0-15.0 GHz)	700-300,000 K	1.5 to 30 dB
	WR 90(8.20-12.4 GHz)	700-300,000 K	1.5 to 30 dB
	WR112(8.20-10.0 GHz)	700-300,000 K	1.5 to 30 dB

Special Calibration

		Source Impedance		Limits of Error	
Waveguide Size	Waveguide Flange	VSWR	Reflection Coefficient Magnitude	Effective Noise Temperature	Excess Noise Ratio
WR 62(12.4-18.0 GHz)	UG-419/U	< 1.2	< 0.09	± 150-200 K	± 0.06-0.08 dB
WR 75(10.0-15.0 GHz)	Cover type	< 1.2	< 0.09	± 175-225 K	± 0.07-0.09 dB
WR 90(8.20-12.4 GHz)	UG-39/U	< 1.2	< 0.09	± 150-200 K	± 0.06-0.08 dB
WR112(9.20-10.0 GHz)	UG-51/U	< 1.2	< 0.09	± 175-225 K	± 0.07-0.09 dB

Limits of error for waveguide noise sources are estimated for effective noise temperatures of approximately 11,000 K.

Table 3

FREQUENCIES AVAILABLE FOR CALIBRATION IN THE WR90 & WR62 BANDS

WR90 in GHz	WR62 in GHz
8.2	12.4
9.0	13.5
9.5	14.0
9.8	15.0
10.0	16.0
10.2	16.5
10.5	17.0
11.2	18.0
11.8	
12.4	

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An error analysis for the Dicke radiometers used by the National Bureau of Standards (NBS) in their WR90 waveguide noise calibration services for sources with noise temperatures above 1000 kelvin is discussed. A list of measurement frequencies currently available in the WR90 and WR62 bands is presented.

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

error analysis; microwave; noise; radiometer

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