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A Noise-Temperature Measurement System Using a Cryogenic Attenuator

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This article describes a method to obtain accurate and repeatable input noise-temperature measurements of cryogenically cooled low-noise amplifiers using a commercial noise-figure meter in conjunction with a cryogenic attenuator co-located with the amplifier under test. The calibration techniques used also are discussed.

I. Introduction

Accurate and rapid noise-temperature measurements are critical to the modeling and development of high electron mobility transistor (HEMT) cryogenically cooled amplifiers. Four different techniques have been used in the laboratory to make noise-temperature measurements of cryogenically cooled amplifiers, and each of these is described below. Following this, the cryogenic pad method, the method most often used by the Cryogenics–Electronics Front-End Equipment Group at JPL, is described. Although the cryogenic pad and noise-figure meter are not in and of themselves new, combining them provides an elegant, simple, and quick solution to equivalent input noise-temperature and gain measurements.

A basic piece of equipment needed for cryogenic noise measurements is a cryogenic test-bed capable of cooling the amplifier under test to its operational temperature (typically 15 K or less). The test-bed, shown schematically in Fig. 1, consists of a vacuum housing, a two-stage Gifford–McMahon helium refrigerator, and very low loss input and output RF transmission lines. These lines are copper-plated thin-wall stainless steel to provide low insertion loss and low thermal leakage from the outside room temperature to the internal 15-K environment.

II. Measurement Methods

The following methods for obtaining noise temperature data all employ similar measurement techniques. All of the methods described below use the Y-factor method for obtaining noise temperature data. This method involves taking the ratio of output noise powers when two different input thermal noise powers are presented to the amplifier. The two different noise powers presented to the input of the amplifier can involve the use of a load whose temperature can be varied or two different loads whose respective temperatures are significantly different. This change in load temperature gives a corresponding change in noise power measured at the output of the low-noise amplifier (LNA). The methods differ in their techniques for producing the two different input noise powers, usually designated T_h and T_c.

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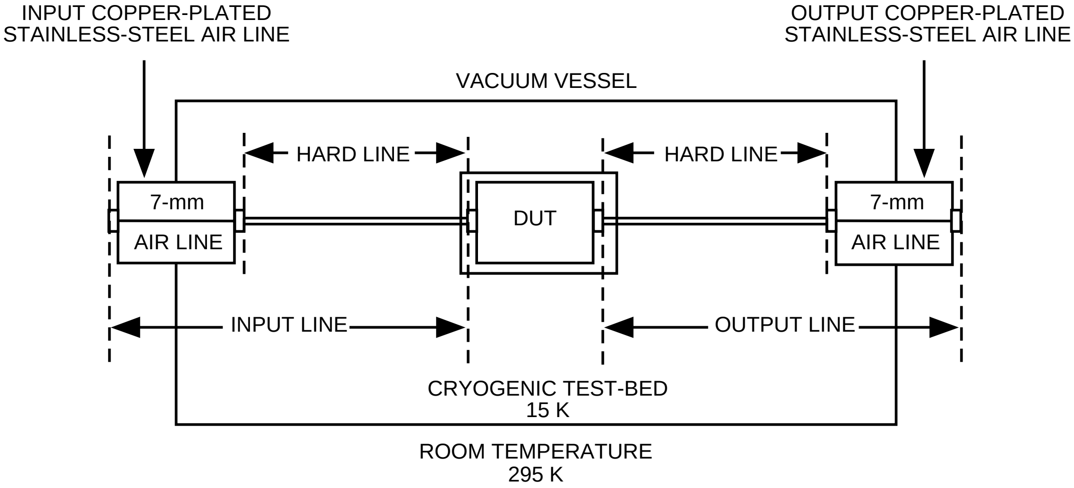

Fig. 1. The cryogenic test-bed with 7-mm coaxial air line input and output.

The effective input noise temperature of a device under test (DUT), T_e, is determined by the following equation:

$$T_e = \frac{T_h - Y\ T_c}{Y - 1} \tag{1}$$

where T_h and T_c are the noise temperatures of the hot and cold noise sources and Y is the ratio of the output powers obtained from the DUT when each of the source temperatures is applied.

A. Method I: Standard Hot and Cold Loads

This straightforward method involves switching the DUT input between two separate terminations that are at widely different, known physical temperatures. This method, shown in Fig. 2, has a large number of difficulties associated with achieving accurate noise measurement. One reason is that the impedances presented to the DUT by the hot and cold paths usually differ significantly from each other. Also, the long-term repeatability of insertion loss and impedance match of the noise source switch is crucial to accurate results. The commonly limited bandwidths of practical cold loads require custom equipment. Still another difficulty is the slow speed of obtaining data due to the mechanical switch. This last limitation is a serious liability when many repetitive measurements need to be made, as when transistor bias settings are being adjusted for optimum performance on a multiple-stage amplifier. This method is still accurate and often is used when many repetitive measurements are not necessary.

B. Method II: Noise-Figure Meter With Noise Diode

The simplest method for making noise-temperature measurements of active devices, such as amplifiers, is to use a commercial noise-figure meter in conjunction with a calibrated diode noise source. A block diagram of this method is shown in Fig. 3. This is the standard method used to measure room-temperature transistor amplifiers, and it works very well with DUTs that have an input noise temperature between the “off” (cold) and “on” (hot) noise temperatures presented by the diode noise source—that is, between 300 kelvins and thousands of kelvins. However, as the equivalent input noise temperatures of microwave HEMT amplifiers have dropped to temperatures below 50 K for room-temperature amplifiers, and lower still for cryogenic amplifiers, the errors provided by this approach are excessive. Another significant shortcoming with this approach is that the diode noise-source impedances in the off and on states are significantly different from each other. This causes a wide variation in the values of input noise temperatures

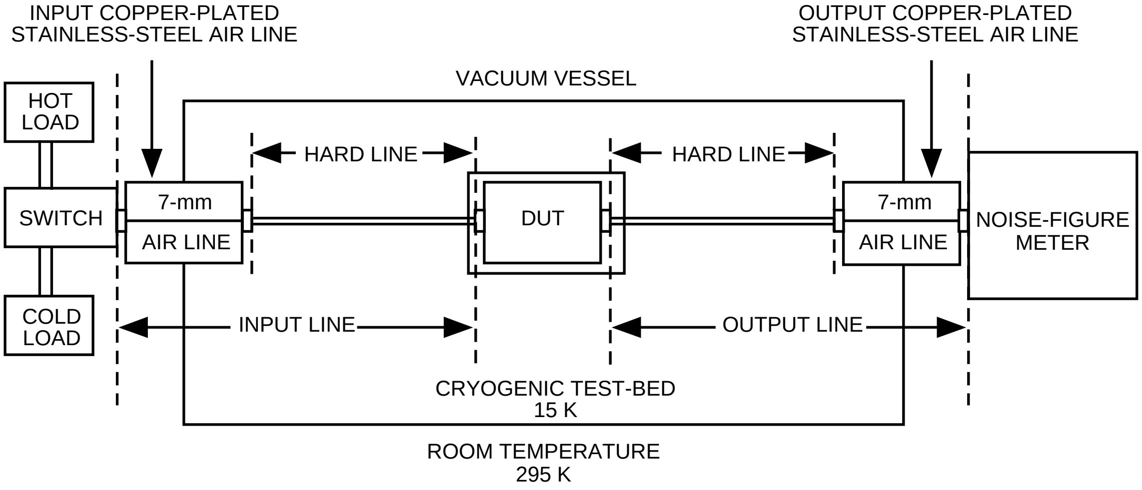

Fig. 2. The external hot–cold load measurement system.

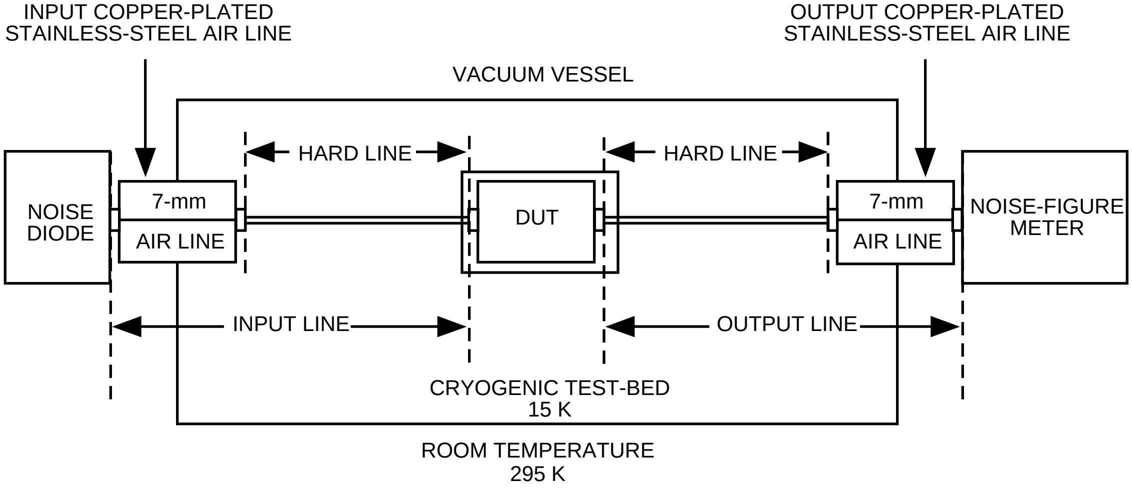

Fig. 3. Standard noise diode measurement with a noise-figure measurement system.

measured as a function of frequency, as can be seen in Fig. 4. The data plotted as noise temperature in kelvins without a cryogenic pad clearly show the effect of these noise diode impedance changes on noise-temperature measurements. This is due not only to the variations in noise diode source impedance between the off and on states but also to the "pulling" of the DUT's input noise temperature by these source impedance changes. In practice, it is difficult to achieve less than a 1- to 2-K variation from one frequency point to another when measuring a 3- to 10-K amplifier. In Fig. 4, the noise diode without a cryogenic attenuator trace not only has peak-to-peak variations higher than the cryogenic attenuator trace, but there also is an offset from the correct noise-temperature value. These errors due to mismatch are very difficult to calibrate.

C. Method III: Hot and Cold Loads in the Test-Bed

A third method, shown in Fig. 5, overcomes many shortcomings of the standard hot–cold load method by using one thermal noise source only in the cryogenic environment along with the DUT (this eliminates many input transmission line calibration difficulties) and attaching a controllable heater to it. When no heat is applied, the load functions as the cold load at a temperature nearly equal to that of the

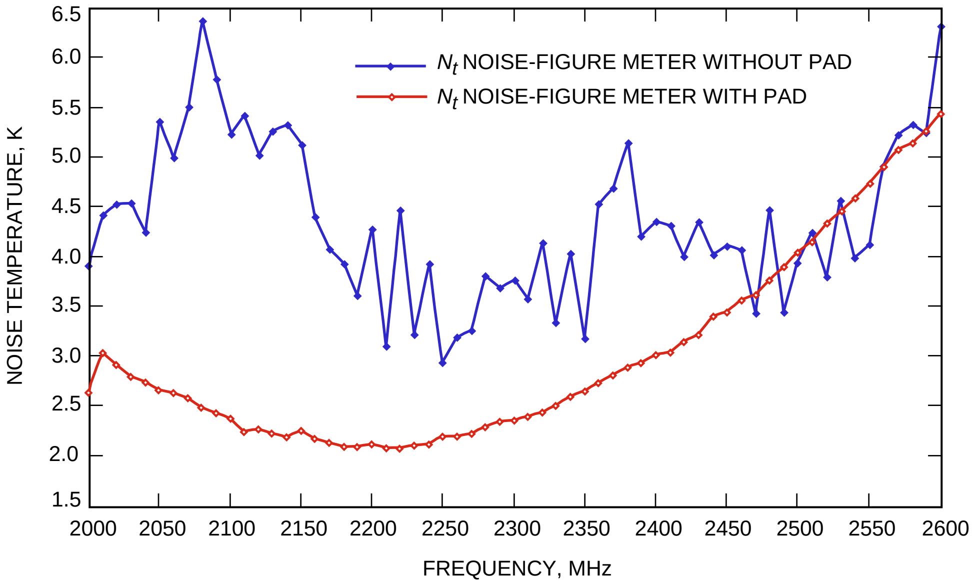

Fig. 4. A comparison of S-band amplifier module noise measurements using a noise-figure meter with and without a cryogenic pad.

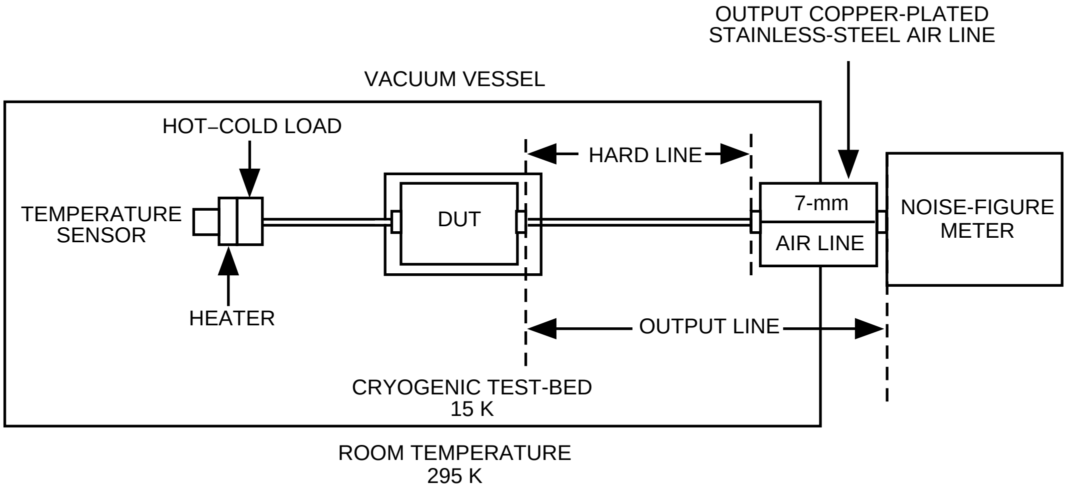

Fig. 5. Diagram of the internal hot–cold load measurement system.

refrigerator. Heat is applied to switch the load to a higher temperature. The repeatability problems of the mechanical switch in method I are eliminated, but the slow measurement time remains. One challenge of this approach is to ensure that the impedance change of the thermal load from the cold to the hot temperatures is acceptably small. Another challenge is to ensure that the heater does not heat the input to the amplifier.

D. Method IV: Cold Sky and Ambient Aperture Load

The method that is still the standard for measuring ultra-low-noise amplifiers is the cold sky–ambient aperture load method. Charles Stelzried and Robert Clauss developed this method at JPL for calibrations of low-noise receivers [1,2]. This method uses a calibrated test feedhorn, with a very low side-lobe pattern to minimize ambient noise pickup from the ground, placed at the room-temperature input of the LNA. A radiometer as shown in Fig. 6 is used to measure the power ratio between the sky and an ambient aperture load placed over the feedhorn. This method is accurate for frequencies in the “microwave window” (from

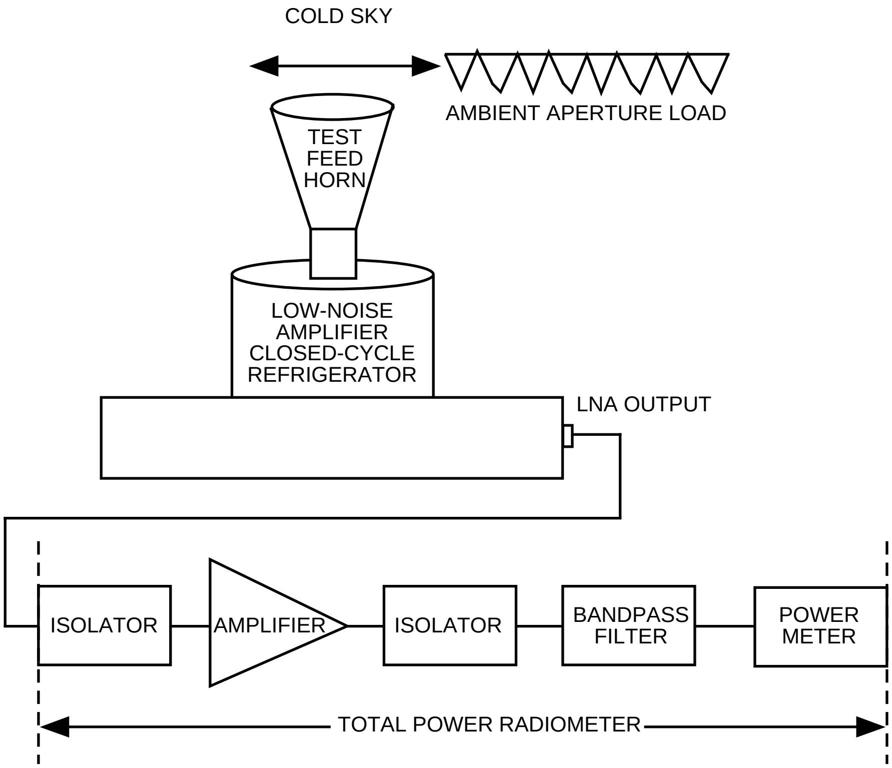

Fig. 6. The cold sky–ambient aperture load noise measurement system.

about 1 to 12 GHz) where atmospheric weather effects are small, but it must be done outdoors where the sky is unobstructed. This method also has the advantage of measuring a "system" noise temperature, which is a measurement of the operating noise temperature when the LNA package is installed in an antenna.

E. Method V: Noise-Figure Meter With a Cryogenic Attenuator

The last method, the cryogenic pad technique shown in Fig. 7, is the method most often employed by the Cryogenics–Electronics Front-End Equipment Group for measuring amplifier modules and will be described in the remainder of this article. In this technique, a cold load is provided when the diode noise source is off. In this state, the source noise temperature applied to the DUT is equal to the physical temperature of the cryogenic pad (about 15 K) plus a small contribution (about 3 K) from the ambient temperature noise diode as attenuated by the cryogenic input transmission line and a 20-dB cryogenic attenuator. Turning the 9000-K noise diode on provides the hot load. The noise power then is attenuated by the cryogenic attenuator and, to a very small extent, by the cryogenic input transmission line, resulting in a source noise power at the DUT input of about 90 K. These cold and hot load temperature levels of 18 and 90 K nominally are, from the point of view of measurement error, very satisfactory for the measurement of DUTs having less than 50-K input noise temperatures. This method was first developed and used by Sander Weinreb and Anthony Kerr at the National Radio Astronomy Observatory (NRAO). The method has some advantages over the other methods described. One advantage is that no mechanical switches are needed; hence, rapid measurement speed is possible. A second advantage is that the off-to-on impedance changes of the diode noise source are reduced almost to insignificance by the 20-dB cryogenic pad. Thirdly, insertion loss of the transmission line connecting the cryogenic attenuator and the outside diode noise source contributes much smaller errors. At JPL, this cryogenic attenuator method has been combined with a high-quality commercial noise figure meter. The commercial noise-figure meter provides the necessary wide-frequency-range tunable receiver and power

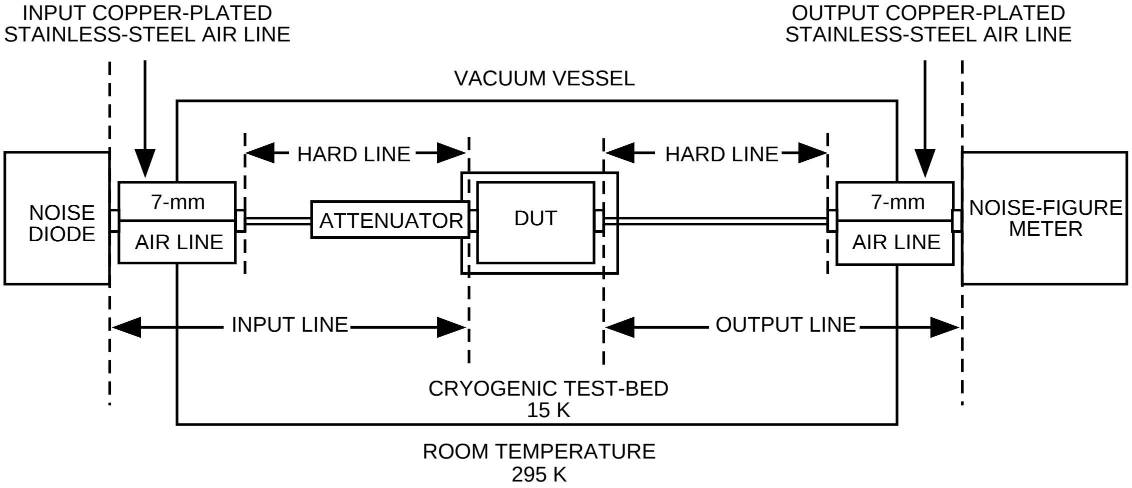

Fig. 7. The noise-figure meter with a cryogenic attenuator noise-measurement system.

meter that follow the DUT and the object-oriented graphically programmed computer-based controllers to implement a noise-temperature measurement system for cryogenic amplifiers covering the frequency range of 10 MHz to 50 GHz.

III. De-embedding

The term "de-embedding" refers to the procedure by which the true hot and cold noise power levels that appear at the input connector of the DUT from the noise diode, input transmission line, and cryogenic attenuator are determined. The information that must be obtained to perform the de-embedding is (1) the excess noise ratio (ENR) of the noise diode, (2) the insertion loss and physical temperature profile of the input and output test-bed transmission lines when the test bed is at normal operating temperature (15 K), and (3) the attenuation and VSWR of the cryogenic attenuator when at normal test-bed operating temperature (15 K). All this information is needed across the frequency range of interest. These items are entered into the computer controller and are used to correct the raw noise-figure meter (NFM) output data.

The first step in the above process is to determine the ENR of the noise diode. The noise diode manufacturer often supplies these calibration data. The second step is to make the test-bed input and output lines as symmetrical as possible with respect to the insertion loss and phase of components from the ambient temperature to cryogenic temperature ends. This symmetry greatly facilitates de-embedding. This is accomplished by careful measurement and matching of components making up these lines, such as semirigid cables, waveguides, adapters, vacuum windows, etc. Then, when symmetrical input and output transmission lines are achieved, the input and output transmission lines are connected together in the test-bed. If the input and output connectors are non-mating, then a low-loss through section such as a coaxial air line or waveguide is used. This input line–output line circuit then is measured for insertion loss over the frequency bands of interest, using a vector network analyzer. These data are stored for later manipulation. The test-bed then is cooled to operating temperature and the insertion-loss measurement repeated. The insertion loss for the input and output lines is assumed to be one-half of this measured value of the cascade of the two lines

The third step is to measure the insertion loss of the cryogenic pad by inserting it between these known input and output lines and repeating the above measurements at both room temperature and cryogenic operating temperature.

From the above information, the actual value of the noise power presented to the DUT with the noise diode off and on can be calculated for the frequencies of interest. The NFM then calculates the corrected noise temperature and gain.

IV. Noise-Measurement Procedure

The DUT is placed in the cryogenic test-bed and connected to the output port of the cryogenic attenuator. The system is cooled to its normal operating temperature of 15 K, and a DC bias is applied to the DUT. The NFM is calibrated per the manufacturer's procedure involving attachment of the noise source directly to the microwave equipment behind the test-bed. The noise source then is attached to the test-bed input transmission line, and the NFM input is connected to the output transmission line. The de-embedded data are entered into the NFM via the computer controller; then the corrected noise temperature of the DUT is calculated by the NFM. An example of corrected input noise-temperature data for a 2-GHz amplifier is shown in Fig. 8.

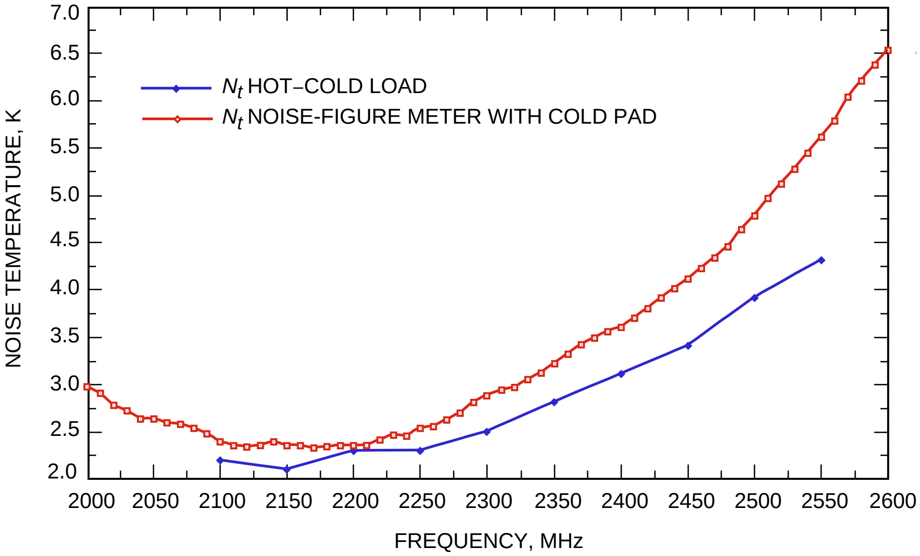

Fig. 8. A comparison of noise-temperature data obtained by the internal hot–cold load method and the noise-figure meter with cold pad.

V. Error Analysis

The following is a brief explanation of the measurement inaccuracies and their magnitudes. The equations used are from [3]. Errors in the measurement of effective input noise temperature result primarily from errors in measured values of (1) the attenuator and input line losses, L_{pad}, (2) the attenuator physical temperature, T_p, and (3) the noise source excess-noise ratio (ENR). The excess noise ratio is defined as

$$ENR = 10 \log \left(\frac{T_h}{290} - 1 \right) \tag{2}$$

The measurement error of L_{pad} typically is ±0.05 dB using the Hewlett Packard (HP)8722D Vector Network Analyzer with Option 400 (four samplers), the 7-mm Calibration Kit HP85050C, and cables HP85132F. Measurement errors for T_{physical} typically are ±0.25 K using a calibrated Lakeshore Cryogenics Thermometer Model 819 in conjunction with a DT-470 diode sensor. The ENR calibration table accuracy for a 15.00-dB ENR HP346A noise source is ±0.1 dB. These values were obtained from [4–6].

Equation (1) can be used to estimate the maximum error in a measurement of T_e given the above component measurement errors. Values for T_h and T_c in Eq. (1) are obtained from the following equations:

$$T_h = \frac{T_{\text{nd on}}}{L_{\text{pad}}} + T_p \left(1 - \frac{1}{L_{\text{pad}}}\right) \tag{3}$$

where $T_{\text{nd on}}$ is the thermal noise temperature, in kelvin, of the diode in the on state, L_{pad} is the total loss of the cryogenic attenuator and cryogenic low-loss input line (in ratio), and T_p is the physical temperature of L_{pad}; and

$$T_c = \frac{T_{\text{nd off}}}{L_{\text{pad}}} + T_p \left(1 - \frac{1}{L_{\text{pad}}}\right) \tag{4}$$

where $T_{\text{nd off}}$ is the thermal noise of the diode in the off state, which is its physical temperature in kelvins.

In the measurement of a typical 2- to 2.6-GHz (S-band) HEMT LNA module, the following values are obtained: a typical Y-factor of 8.1 dB, which has a ratio value of 6.457, assuming negligible uncertainty in this relative measurement; a typical T_p temperature measurement of 12 K with an uncertainty of ± 0.25 K; a typical T_{amb} temperature measurement of 295 K with an uncertainty of ± 0.25 K, a loss measurement of 20 dB with an uncertainty of ± 0.05 dB, and an ENR of 15 dB with an uncertainty of ± 0.1 dB. Another source of error, which was pointed out to the author by R. Clauss, is the effect of the DUT's impedance match on the loss in dB value of the attenuator. From [7], and from conversations with T. Otoshi, we get the following formula:

$$\text{pad error max in dB} = 20 \log(1 \pm [R_1 \times R_g]) \times \frac{1 \pm [S_{22} \times R_l]}{1 \pm [R_g \times R_l]} \tag{5}$$

where R_1 is the magnitude of the reflection coefficient of the attenuator on the load, DUT side; R_g is the magnitude of the reflection coefficient of the noise diode (generator) side; S_{22} is the magnitude of the reflection coefficient of the attenuator on the noise diode side; and R_l is the magnitude of the reflection coefficient of the load.

Table 1 contains typical values for each parameter obtained in the measurement of a 2-K S-band HEMT LNA and the typical tolerances assigned to each parameter (as discussed above). The resultant error in T_e from each of these parameter tolerances is calculated in the right-hand column. Notice that the attenuator loss as a function of DUT match and noise diode ENR error is the largest source of error in the noise-temperature measurement, followed by the relatively equal error contributions from the cryogenic attenuator physical temperature and Y-factor measurements. Adding these six sources of error gives a worst-case error for T_e from all causes of ± 1.34 K.

VI. Conclusion

A method of making accurate input noise-temperature measurements of low-noise cryogenic amplifiers using a cryogenic attenuator in a cryogenic test-bed in conjunction with a commercial noise-figure meter and associated diode noise sources has been described. The advantages of this method for laboratory measurements are simplicity, accuracy, and speed of measurement. The data taken with this method agree well with those taken with hot and cold load techniques as shown in Fig. 5 but are obtained much faster and do not display the peak-to-peak ripple caused by the standard hot–cold load method. The system in current configuration allows for gain and noise-temperature measurements to be made from 10 MHz to 50 GHz.

Table 1. Sources of error in the measurement of effective input noise temperature, T_e, of a DUT.

Parameter	Nominal value	Tolerance	Resultant error in T_e, K
Noise diode ENR	15.0 dB	±0.1 dB	±0.39
Cryogenic attenuator loss	20.0 dB	±0.05 dB	±0.16
Cryogenic attenuator physical temperature	12.0 K	±0.25 K	±0.25
Y-factor	8.1 dB	±0.05 dB	±0.23
Noise diode physical temperature	295 K	±0.25 K	±0.01
DUT return loss mismatch	−10 dB	±10 dB	±0.30
Total errors			±1.34

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