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Vector Corrected Noise Temperature Measurements

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***Abstract* – A new one-port technique for measuring noise temperature is presented that uses receiver noise parameters for error correction. Improved accuracy in one-port measurements of noise temperature made with commercial systems is demonstrated without using isolators. Equations for correcting mismatch errors are developed as part of the available vector noise temperature equation. Results, presented for a C-band solid-state cold noise source and a pair of microwave solid-state noise diodes, are shown to be in good agreement with radiometric measurements of the same sources.**

***Index Terms*— Enhanced scalar method, mismatch error, radiometer method, scalar method, noise, noise parameters, noise temperature, noise temperature measurement, noise temperature measurement errors, vector method.**

I. INTRODUCTION

The National Institute of Standards and Technology (NIST) in Boulder, Colorado performs highly specialized measurements of diode-based and tube-based noise transfer standards. NIST uses automated radiometer systems to make precision one-port noise temperature measurements [1]. These radiometers are custom designed and require the use of isolators between the device under test (DUT) and any system pre-amplifier to prevent the varying reflection coefficients of the DUT and calibration standards from affecting the gain and noise performance of the pre-amplifier. The inclusion of these isolators in the radiometer system, while essential, fundamentally limits the frequency of operation of the system to the in-band frequency of the isolators.

In previous works, it has been shown that accurate one-port noise temperature measurements can be performed using commercial systems. In 2001, results were presented that showed enhanced one-port noise temperature measurement capabilities [2]. In that work, three different measurement methods were used to demonstrate the varying degrees of obtainable measurement accuracy by use of commercial noise measurement equipment. In 1997, the Wireless and Microwave (WAMI) Research Group at the University of South Florida (USF) used a noise figure meter and a solid-state noise source for calibration to characterize FET-based cold noise sources and obtained good agreement with NIST radiometer measurements [3].

In this work, a new method of performing one-port noise temperature measurements with a commercial noise parameter measurement system is presented. The system used is fundamentally a one-port noise temperature measurement-based system that is geared to extract two-port noise parameters. The new technique uses the receiver noise parameters extracted by the noise measurement system to make one-port measurements and is known as the *vector method.* The vector method addresses the specific shortcomings of the scalar methods in a way different from the radiometer method as presented in [2]. The vector method does not use isolators like the enhanced scalar and radiometer methods to minimize mismatch errors. This exclusion of isolators in the vector measurement system allows the user to attain a wide frequency range of applicability of the instrumentation. Like the radiometer method, the vector method provides correction for *source mismatch error*. However, the vector method also provides correction for *receiver mismatch error*. The process of correcting for both source and receiver mismatch errors to provide a more accurate measurement of noise temperature is known as a vector measurement and is described in detail herein.

II. ONE-PORT NOISE TEMPERATURE MEASUREMENT ERRORS

A. Source Mismatch Error

The simplest of the one-port methods for measuring noise temperature discussed in this work is the scalar method. It requires only a noise figure meter and a noise diode for noise figure meter calibration before DUT measurement. However, due to its broad theoretical assumptions, it is the least accurate of the methods. One of these assumptions is that the DUT, off noise diode, and on noise diode all are impedance matched to the noise figure meter. In almost all cases, this assumption is not correct and is a source of error. Thus source mismatch error occurs when at least one of either the off noise diode, the on noise diode, or the DUT is not matched to the noise figure meter subsequently affecting the delivered power.

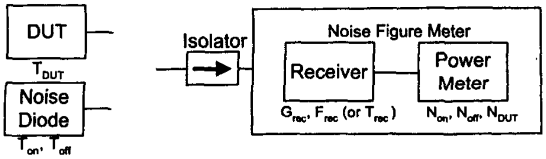

Fig. 1 Scalar one-port noise temperature measurement system with isolation to minimize mismatch error.

B. Receiver Mismatch Error

The noise receiver's gain and noise temperature are functions of the impedance presented to the noise figure meter. The scalar method assumes that the gain and noise temperature of the noise figure meter are both constant versus the source (DUT or noise diode) that is connected to the noise figure meter. This is true only if all of the sources present the same impedance to the noise figure meter. However, this is not the case since in most instances the DUT, off noise diode, and on noise diode all have different impedances. These differences in impedance cause errors due to the changes in noise figure meter gain and noise temperature versus the source that is connected to the noise figure meter. This is known as receiver mismatch error. Receiver mismatch error can occur only where source mismatch error exists, however source mismatch error can exist without receiver mismatch error.

III. Error Minimization and Correction

A. Error Minimization

The errors that plague the scalar method and compromise its accuracy can be substantially minimized to provide reasonable measurement results. This can be accomplished by inserting an isolator that is closely matched to the noise figure meter into the measurement setup as seen in Fig. 1. The isolator minimizes the source mismatch error by presenting a matched impedance to the noise figure meter for all sources. The receiver mismatch error is minimized due to the isolation between the noise figure meter and the sources (DUT and noise diode). The enhanced scalar and radiometer methods utilize isolators in this fashion to improve measurement accuracy.

B. Error Correction

The radiometer method employs error correction in addition to error minimization to provide improved accuracy over the scalar methods. The radiometer method corrects for source mismatch error. Expressions for mismatch factors and available power ratios between the radiometer receiver and the sources (DUT and noise diode) can be used to modify the scalar noise temperature equation to give a corrected radiometer noise temperature equation [1], [2].

The vector method provides correction for source and receiver mismatch errors. This is accomplished by quantifying the following: (a) the mismatch between the sources (DUT and noise diode) and the receiver, (b) the receiver's noise temperature versus source impedance, and (c) the receiver's gain versus source impedance. Correcting for source mismatch error, a source mismatch factor can be expressed for the vector measurement system seen in Fig. 2 as

$$M_s(\Gamma_X) = \frac{1-|\Gamma_X|^2}{|1-\Gamma_{rec}\Gamma_X|^2} \quad , \tag{1}$$

where Γ_X and Γ_{rec} are the reflection coefficients of the DUT (X) and the receiver. Correcting for receiver mismatch error requires all four noise parameters of the receiver to be characterized. With the calibration setup of Fig. 3, receiver characterization is accomplished using a commercial noise parameter measurement system. After a series of calibrations is performed as outlined in [4], the noise measurement system calculates the following receiver parameters used in this work: $F_{min,rec}$, $\Gamma_{opt,rec}$, $R_{n,rec}$, $k_B B G_0$, and Γ_{rec}. The receiver's gain can be can be written as

$$G_{rec}(\Gamma_X) = G_0 \cdot M_s(\Gamma_X) \quad , \tag{2}$$

where G_0 is the input matched ($\Gamma_X = 0$) receiver gain. The receiver noise temperature is defined as [5], [6]

$$T_{rec}(\Gamma_X) = T_{\min,rec} + \frac{4T_o R_{n,rec} G_{opt,rec}|\Gamma_X - \Gamma_{opt,rec}|^2}{(1-|\Gamma_X|^2)(1-|\Gamma_{opt,rec}|^2)} \quad (\mathrm{K})\,. \tag{3}$$

Using $F_{min,rec}$ in dB and $\Gamma_{opt,rec}$ we obtain

$$T_{\min,rec} = T_o(10^{\frac{F_{\min,rec}}{10}} - 1) \quad (\mathrm{K}) \tag{4}$$

$$G_{opt,rec} = \frac{1}{Z_o} \cdot \frac{1-|\Gamma_{opt,rec}|^2}{|1+\Gamma_{opt,rec}|^2} \quad (\mathrm{mhos})\,, \tag{5}$$

where $G_{opt,rec}$ is the receiver's optimum noise conductance, Z_o is the characteristic (reference) impedance, and T_o = 290 K.

IV. Vector Noise Temperature Measurements

Fig. 2 shows a vector one-port noise temperature measurement system. The detected noise power, N_X, at the power meter can be written as

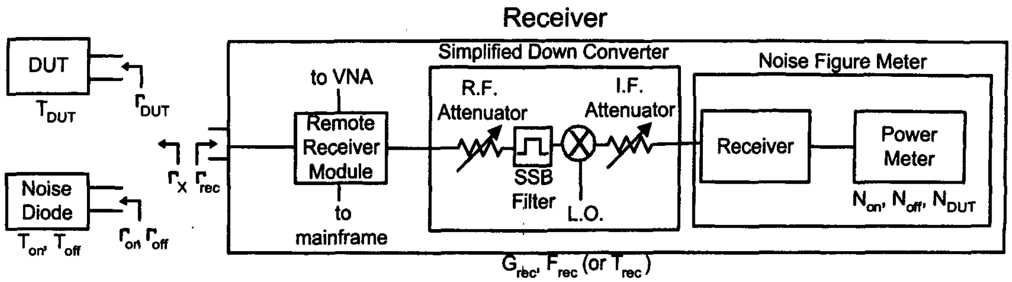

Fig. 2 Vector one-port noise measurement system.

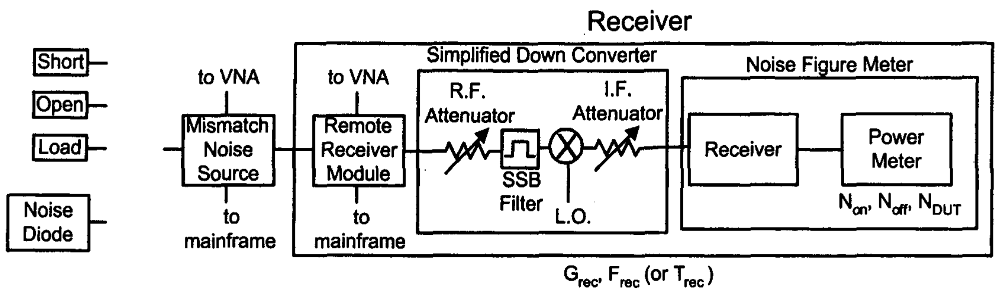

Fig. 3 Calibration setup of vector one-port noise measurement system.

$$N_X = k_B \cdot B \cdot G_{rec}(\Gamma_X) \cdot \left[T_X + T_{rec}(\Gamma_X)\right] \quad \text{(W)}, \quad (6)$$

where k_B and B are respectively Boltzmann's constant and the noise measurement bandwidth. By substituting DUT for X, using Equation (2) to expand Equation (6), and solving for T_{DUT}, the available vector noise temperature T^V_{DUT} can be expressed as

$$T^V_{DUT} = \frac{N_{DUT}}{k_B B G_0 \cdot M_s(\Gamma_{DUT})} - T_{rec}(\Gamma_{DUT}) \quad \text{(K)}, \quad (7)$$

where N_{DUT} and Γ_{DUT} are respectively the measured system noise power with the DUT connected to the receiver of Fig. 2 and the measured DUT reflection coefficient. These values are measured by the noise parameter measurement system when a DUT is connected to the receiver and a noise measurement is performed.

V. RESULTS AND COMPARISONS

A C-Band synthetic cold source (SCS) was used as a cold DUT. Measurements were made in the frequency range from 3.5 to 4.4 GHz with frequency steps of 50 MHz. The SCS operates on the principle that the reverse noise emerging from the input of a HEMT exhibits a synthetic cold temperature [7]. The SCS was simultaneously matched for noise and gain and was calibrated against a liquid-nitrogen cold load via a symmetrical switch to an automated radiometer.

Fig. 4 illustrates the degree of accuracy that is obtainable with the scalar, enhanced scalar (with 25 dB isolation), radiometer (with 25 dB isolation), and vector methods versus the manufacturer's data provided for the C-band SCS. Both the noise figure meter-based (NFM) radiometer and vector methods track the manufacturer's radiometer data very well. NIST's noise figure radiometer (NFRAD) data are also plotted and in most instances show reasonable agreement.

Fig. 5 shows measured noise temperature results for solid-state noise source #1. Both vector and NFM radiometer (with 25 dB isolation) methods agreed reasonably well with NIST's NFRAD data and the manufacturer's noise temperature, from the noise source excess noise ratio (ENR) and reflection coefficient. Areas where the vector method differs from the manufacturer's noise temperature may suggest where the noise source (ENR) is out of calibration. It should be noted that a new and separate solid-state noise source was used solely for calibration in all vector measurements and assumed to be an accurate reference. Error bars on the manufacturer's curve are based on the typical +/- 0.2 dB ENR uncertainties of a coaxial noise source calibration.

Good agreement, as seen in Fig. 6, was also obtained between the vector method and NIST's NFRAD method when solid-state noise source #2 was measured. A new and separate solid-state noise source was used for calibration in the vector measurements. The measurement range of NFRAD was limited by the frequency bands of the isolated radiometers and cryogenic standards used at NIST.

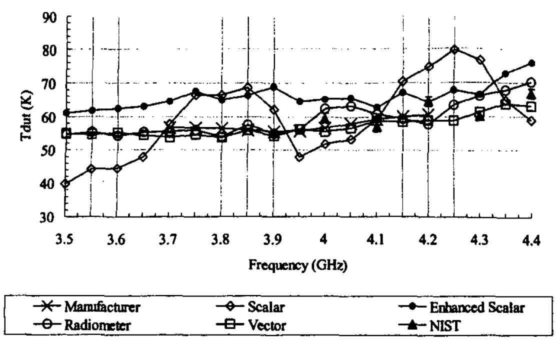

Fig. 4 Synthetic cold source data with scalar, enhanced scalar and NFM radiometer measurements performed at Raytheon Andover, vector measurements performed at Agilent Technologies North Billerica, and NIST measurements performed in Boulder, CO using NIST's NFRAD. Error bars are for a ±1.4 K NIST measurement uncertainty.

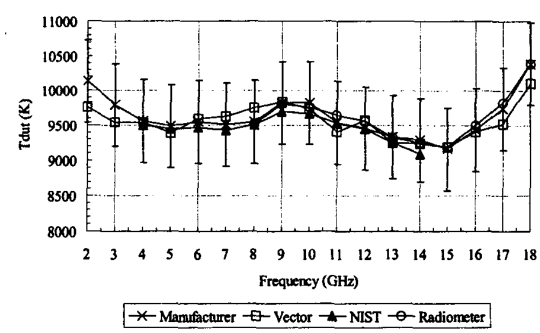

Fig. 5 Solid-state noise source #1 data with vector measurements performed at Agilent, NFM radiometer measurements performed at NIST, and NIST measurements performed in Boulder, CO using NIST's NFRAD. Error bars around the manufacturer's values are for a ±0.2 dB DUT ENR uncertainty.

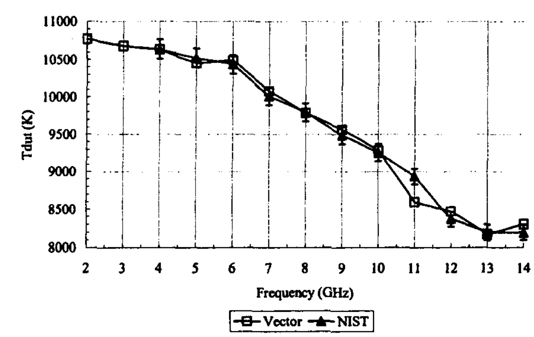

Fig. 6 Solid-state noise source #2 data with vector measurements performed at Agilent Technologies North Billerica and NIST measurements performed in Boulder, CO using NIST's NFRAD. Error bars are for a 1.2% NIST measurement uncertainty.

VI. CONCLUSIONS

The vector method uses commercial systems and is capable of producing accurate measurement results. This is substantiated when vector measurement results for a given DUT are compared against and validated with the results of well established one-port noise temperature measurement methods such as the radiometer method used by NIST's NFRAD and the NFM radiometer method that uses commercial systems. It also compares well with manufacturer's data. The vector method, unlike the other methods, does not rely upon isolators to minimize the effects of mismatch errors, but instead uses equations to provide correction for both source and receiver mismatch errors. The absence of isolators in the vector measurement system is conducive to a broader measurement band, which is limited only by the measurement equipment in the system.

Integration of this new measurement technique into the software of commercial noise parameter systems would provide an easy and accurate way of performing broadband one-port noise temperature measurements. One key application of this new method would include the ability to assess the accuracy of a commercial noise measurement system when noise source transfer standards with history traceable to a national calibration laboratory such as NIST are measured.

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