

Amplifier Noise Measurements at NIST

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Abstract—We have recently measured the noise characteristics of two low-noise commercial amplifiers in the 2.0–4.0 GHz frequency range. The tests were part of a program to develop and validate measurement methods for a noise-figure development service. Measured noise figures were about 0.5 ± 0.04 dB. We present the results and the accompanying uncertainties. We also describe the measurement method and summarize the many checks that were used to validate the method.

I. INTRODUCTION

THE MICROWAVE Metrology Group of the United States National Institute of Standards and Technology (NIST) is developing a measurement service for amplifier noise figures. As a test of the measurement methods for this service, we have measured the noise characteristics of two low-noise commercial amplifiers in the 2.0–4.0 GHz frequency range. This paper summarizes the measurement methods and noise parameterization used, presents the results and uncertainties of the measurements on the two amplifiers, reports the checks performed to verify the procedures and results, and discusses differences from other methods and parameterizations. All measurements on the amplifiers were performed through adapters, and we present results for both the amplifiers alone and for the amplifier-adaptor combinations.

II. TECHNICAL BACKGROUND

There are many different sets of parameters used to characterize the noise characteristics of amplifiers. The set we use [1], [2] is based on an S -parameter matrix representation of the amplifier as a linear two-port (see Fig. 1)

$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = S \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} + \begin{pmatrix} \hat{b}_1 \\ \hat{b}_2 \end{pmatrix} \quad (1)$$

where \hat{b}_1 and \hat{b}_2 are due to noise sources within the two port. If we separate \hat{b}_2 into two pieces—one that is correlated with \hat{b}_1 and one which is not— $\hat{b}_2 = \alpha \hat{b}_1 + \hat{b}_{2,0}$, then the noise parameters can be defined as

$$\begin{aligned} T_a &= \frac{1}{G_{21}} \langle |\hat{b}_{2,0}|^2 \rangle \\ T_{\text{rev}} &= \frac{\langle |\hat{b}_1|^2 \rangle}{1 - |S_{11}|^2} \\ \beta &= -S_{11}^* - \frac{\alpha(1 - |S_{11}|^2)}{S_{21}} \end{aligned} \quad (2)$$

where the intrinsic gain has the form

$$G_{21} = \frac{|S_{21}|^2}{1 - |S_{11}|^2}. \quad (3)$$

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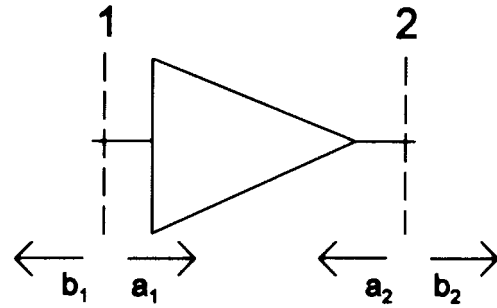


Fig. 1. Notation for (1).

Since β is complex, there are four independent real noise parameters in (2). The relationship between this set of parameters and the IEEE set is given in [2].

In terms of the four noise parameters of (2), the effective input noise temperature of the amplifier is given by [2]

$$\begin{aligned} T_e &= \frac{T_a + T_{\text{rev}} |\Gamma'_1 - \beta|^2}{1 - |\Gamma'_1|^2} \\ \Gamma'_1 &= \frac{\Gamma_1 - S_{11}^*}{1 - S_{11} \Gamma_1} \end{aligned} \quad (4)$$

where Γ_1 is the reflection coefficient of the source connected at plane 1. The output noise temperature from the amplifier, at plane 2, is related to T_e and the input noise temperature T_1 through the available-power gain A_{21}

$$\begin{aligned} T_{\text{out}:2} &= A_{21}(T_1 + T_e) \\ A_{21} &= \frac{G_{21}(1 - |\Gamma'_1|^2)}{1 - |\Gamma_{2i}|^2} \end{aligned} \quad (5)$$

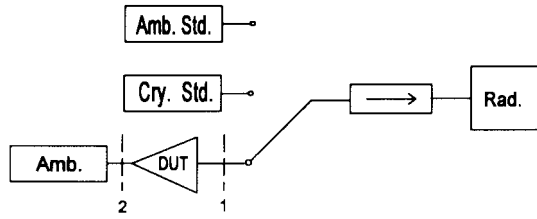
where Γ_{2i} is the reflection coefficient at plane 2 looking back toward the amplifier. By combining (3)–(5), we obtain the expression for the output noise temperature from the amplifier in terms of the four noise parameters, the reflection coefficients, and the S parameters

$$T_{\text{out}:2} = G_{21} \frac{T_1(1 - |\Gamma'_1|^2) + T_a + T_{\text{rev}} |\Gamma'_1 - \beta|^2}{(1 - |\Gamma_{2i}|^2)}. \quad (6)$$

III. MEASUREMENTS

A. Procedures

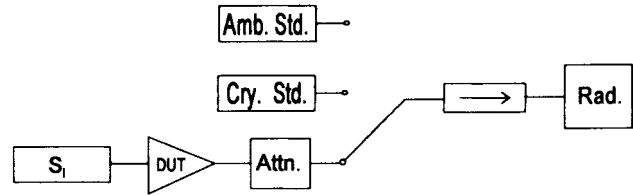
The relevant reflection coefficients and S parameters were all measured by conventional means, using a vector network analyzer (VNA). The intrinsic gain G_{21} of the device under test (DUT) could also be determined from VNA measurements. However, we would then have to assume that it is stable over the time period comprising both VNA and noise power measurements. We prefer instead to determine G_{21} along with the noise parameters from the noise power measurements and (6). As a check, we compared the value of G_{21} obtained from


 Fig. 2. Configuration for direct measurement of T_{rev} .

the VNA measurements to the value obtained from the noise measurements. In principle, (6) can be used to determine all the noise parameters from multiple measurements of $T_{\text{out};2}$ using different source reflection coefficients (and hence different values of Γ_1'). The particular set of noise parameters we have chosen, however, lends itself to a somewhat different approach. Since T_{rev} has been defined to correspond to the noise temperature of the reverse radiation from the input port of the amplifier, it can be measured directly by traditional radiometric methods. The configuration is depicted in Fig. 2. An ambient load is connected to the output port (plane 2), the noise temperature is measured at plane 1, looking into the input port of the amplifier, and T_{rev} is obtained by correcting for the small amount of the power from the ambient load at plane 2 which propagates back to plane 1. For the amplifiers we tested, the correction for the bleed-through power from the ambient load is negligible (<0.01 K).

Having measured T_{rev} directly, we are left with G_{21} , T_a , and β to be determined. That requires (at least) four independent measurements. We use six different sources to provide some redundancy: a cryogenic source with small reflection coefficient and five ambient standards—a matched load and a short in each quadrant of the Smith chart. The general configuration is shown in Fig. 3, where S_i refers to the six different sources used. Additional redundancy is provided by the fact that we use a calibrated radiometer rather than relying on the measurements on the amplifier to set the scale of the radiometer response. For each of the six sources, the output temperature was measured 35 times in succession for 1/6 s each time. The three remaining parameters are then determined by linear least-squares fits of (6) to the measurement results, where the function to be minimized is the unweighted sum of the residuals $\sum [T_i(\text{meas}) - T_i(\text{calc})]^2$. The fitting is done in two steps: First, β and G_{21} are determined by a fit to differences of measured output temperatures, and then T_a is determined by a fit to all the data, with β and G_{21} fixed at their fitted values. This sequential fitting procedure is used in order to study the behavior of the individual noise parameters; it also facilitates the linearization of the fit. In future measurements, we intend to use more sophisticated fitting routines and to weight the residuals by the inverses of the variances ($1/\sigma_i^2$). As a matter of nomenclature, we shall refer to the approach just described as the “direct- T_{rev} ” method of noise parameter measurement since its distinguishing feature is the direct measurement of T_{rev} .

An additional complication arises in these measurements due to the fact that the amplifiers tested had K connectors, whereas the radiometer and noise sources had GPC-7 connec-


 Fig. 3. Measurement configuration for determination of noise parameters other than T_{rev} .

tors. Consequently, all measurements on the amplifiers were made through adapters (3.5 mm to GPC-7). Thus, the DUT depicted in Figs. 2 and 3 represents the amplifier with adapters, and we obtain the noise parameters for that combination. In order to obtain the noise temperatures to use in obtaining the noise parameters of the amplifier alone, we refer to Fig. 4 and use

$$\begin{aligned} T_2 &= \alpha_{21}T_1 + (1 - \alpha_{21})T_{\text{amb}}, \\ T_3 &= \frac{T_4 - (1 - \alpha_{43})T_{\text{amb}}}{\alpha_{43}} \end{aligned} \quad (7)$$

where α_{ji} is the ratio of available power at the output (j) of the adapter due to a given available power at the input (i). It is measured using the technique described in [3]. The adapter on the output of the amplifier has little effect on the noise figure since its noise power is small compared with the amplified input noise, but the adapter on the input side of the amplifier has a significant effect, as will be seen in the results presented below.

B. Uncertainty Analysis

We evaluate two types of uncertainties [4], [5]—type-A, which are evaluated by statistical methods, and type-B, which are estimated by other means and usually correspond to traditional systematic uncertainties. In all cases, the uncertainties we quote will be the expanded (2σ) standard uncertainties, corresponding approximately to a 95% confidence level. The type-A uncertainties were determined in the fitting procedure. Type-B uncertainties arose from the following sources [6]–[8]:

Temperature of Cryogenic Standard	± 1.6 K
Ambient Standard	± 0.23 K
Reflection Coefficient	
(Real or Imag. part)	± 0.0016 (GPC-7)
	± 0.005 (3.5 mm)
Available-Power-Ratio of Adapter,	
α_{adapt}	± 0.005
Radiometer Linearity (Y factors)	± 0.001
Radiometer Isolation Error	
(40 dB isolation)	± 0.3 K
Connector Loss Variability	± 0.003 dB
Mismatch Variations across	
Detector Passband	± 0.003 .

The uncertainties are independent and are added in quadrature. Typical values for the resulting uncertainties in the NIST noise

TABLE I
RESULTS FOR EFFECTIVE INPUT NOISE TEMPERATURE AND NOISE FIGURE. UNCERTAINTIES CORRESPOND TO 2σ

DUT	f (GHz)	T_{e0} (K)	$T_{e,min}$ (K)	NF_0 (dB)	NF_{min} (dB)
AMP1+adpt.	2.0	42±5	34±10	0.58±0.06	0.49±0.13
	3.0	34±3	32±5	0.49±0.04	0.45±0.07
	4.0	37±3	36±5	0.52±0.04	0.50±0.07
AMP1	2.0	36±11	17±16	0.50±0.15	0.25±0.22
	3.0	30±6	27±6	0.43±0.08	0.39±0.09
	4.0	30±6	28±5	0.42±0.08	0.41±0.07
AMP2+adpt.	4.0	43±4	41±3	0.60±0.05	0.57±0.04
AMP2	4.0	36±6	33±6	0.50±0.08	0.47±0.07

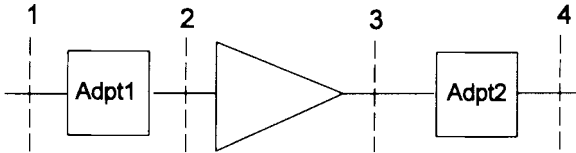


Fig. 4. Reference planes for amplifier with adapters.

parameters are (AMP1, 4 GHz)

$$T_{rev} = 38.0 \text{ K} \pm 3.3 \text{ K},$$

$$T_a = 38.2 \text{ K} \pm 3.5 \text{ K},$$

$$\beta = (-0.372 \pm 0.040) + j(0.027 \pm 0.078).$$

C. Results

The results of the measurements of the noise characteristics of the two amplifiers, with and without adapters, are given in Table I. The table contains the results and uncertainties for the effective input noise temperature for a reflectionless source (T_{e0}), the minimum effective input noise temperature ($T_{e,min}$), the noise figure for a reflectionless source (NF_0), and the minimum noise figure (NF_{min}). The equations relating T_{e0} and $T_{e,min}$ to the NIST noise parameters can be found in [2]. The other traditional parameters, such as Γ_{opt} , were also computed but are not presented here.

A few features of the results warrant comment. The first point is that the two amplifiers are indeed low noise, with minimum effective input temperatures around 30 K, corresponding to minimum noise figures of approximately 0.4 to 0.5 dB. The expanded uncertainties for the amplifier-adapter combination are 3 K in T_{e0} (for good cases) and 0.04 dB in NF_0 . This should be indicative of the uncertainty that can be achieved for an amplifier whose connectors match those of the cryogenic standard and radiometer. Correcting for the effect of the adapter increases the uncertainty to 6 K (0.08 dB) for the results for the amplifier alone. The major contributors to the uncertainty are the temperature of the cryogenic primary standard and, when required, the corrections for adapter effects.

IV. CHECKS AND VERIFICATIONS

Checks were performed on hardware, software, and methods. The hardware validation comprised checks of system linearity, stability, and harmonic response, accuracy of reflec-

tion coefficient measurements, and validation of the primary standards. The results for the gains of the amplifiers obtained from the fits were checked by direct VNA measurements of the scattering parameters of the amplifier. The methods and software were checked by comparing the results obtained above (the direct- T_{rev} method) to the results obtained using four different measurement and calculational methods, which we will call

- 1) manual method,
- 2) adapter method,
- 3) corrected Y -factor method,
- 4) full-fit method.

The manual method begins with a direct measurement of T_{rev} , as described in the *Procedures* subsection above. A sliding short is then connected to the input of the DUT and adjusted to yield first the maximum output temperature and then the minimum. The difference between the maximum and minimum temperatures (along with the corresponding Γ 's) can be used to determine β from (6). Finally, T_a and G_{21} are determined by measuring the output temperatures for two low-reflection input sources of different noise temperatures. This manual method constitutes the most useful check of our software and procedures because it provides direct, intuitive measurements of the noise parameters and because the calculational approach is very different from that of the method adopted and described in the *Procedures* subsection above.

The second method used as a check was the adapter method. This consisted of performing the analysis with the adapters considered as part of the standard and the radiometer, rather than as part of the DUT. It was effected by a different choice of reference planes. The results for the noise parameters of the amplifiers alone should not be affected by this change, and indeed, they were not. This serves as a consistency check of the software and analysis as well as a check of the reflection coefficient measurements.

The third check method was a Y -factor method for T_{e0} , which is similar to the approach used traditionally by noise-figure meters but corrected to account for mismatch and for reflections from sources. (The specific form for the corrections will be derived and presented elsewhere.) This approach constitutes a useful check because the mathematics is very different from our chosen formulation. In addition, it provides insight and information on the magnitude of the error that a

typical noise-figure meter could make. As an example, the simple Y -factor approach assumes reflectionless sources. If the cryogenic source has a reflection coefficient $\Gamma_{\text{cry}} = 0.077$, then for $T_{e0} = 36.1$ K, there is a 3.9 K correction due to the nonzero source reflection. The values obtained for T_{e0} from this method agreed with the T_{e0} obtained above.

The final approach used to check the overall results was to discard the direct measurement of T_{rev} and perform a fit for all four noise parameters plus the intrinsic gain using the data from the measurements of output noise temperature for the six different input sources (one cryogenic, five ambient). The software for this approach is similar to that used for the direct- T_{rev} method, except that now T_{rev} is determined from the fit, and the information from the direct measurement of T_{rev} is not used. The results obtained in this manner were consistent with those of the direct- T_{rev} method, but the fitting uncertainty was larger. The increase in the fitting uncertainty is to be expected since in this approach, we do not use the information from the direct measurement of T_{rev} .

V. DISCUSSION AND SUMMARY

Four ambient standards, one cryogenic (or hot) standard, and an uncalibrated radiometer are sufficient to measure the four noise parameters plus the gain of an amplifier. It is common practice to use additional sources in order to provide redundancy and improve accuracy [9], [10]. NIST uses additional ambient sources but also measures the scattering parameters of the DUT, directly measures the reverse radiation from the DUT, and uses a calibrated radiometer. The additional information provides a check of DUT stability and permits us to properly quantify the measurement uncertainties, providing uncertainty estimates valid for any source reflection coefficient [11].

A disadvantage of the direct- T_{rev} method is that it demands metrology skill in low-temperature measurements (since T_{rev} is typically a cryogenic temperature for a low-noise amplifier). In addition, measurement of T_{rev} requires that the input port of the DUT be connected to the radiometer, and thus, the connections of the two DUT ports must be interchanged, either manually or by additional switches.

To summarize, NIST has developed and tested a procedure for measuring the noise parameters of microwave amplifiers. If the primary NIST noise standards can be used (GPC-7, Type N, WR-90, WR-62, WR-42, WR-28), the measurement uncertainty (95% confidence level) for noise parameters such as T_{e0} , $T_{e,\text{min}}$, and T_{rev} is about 3 K under favorable circumstances. This was demonstrated on two low-noise amplifiers operating between 2 and 4 GHz. Amplifiers with other connectors must be measured through adapters, and the errors depend strongly on the accuracy with which the adapters can be characterized. For an amplifier with 3.5-mm connectors, the uncertainties of T_{e0} , $T_{e,\text{min}}$, and T_{rev} rose to about 6 K for favorable cases. A crucial consideration in these initial measurements was validation of the system, methods, and software. Many consistency checks were performed, and several alternative measurement and computational schemes were used to verify the measurements.

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