Estimating the Sensitivity of Ultra-Wideband Cryogenic IF-LNAs to Input Mismatch by Noise Wave Measurement

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***Abstract*— The noise performance of cryogenic LNAs is usually evaluated using a single parameter: its noise temperature. In this work we present a simple experimental method to measure a complete set of noise parameters, expressed as noise waves, which allow an intuitive evaluation of the effect on the sensitivity of the mismatch at the input of cryogenic LNAs. This method is applicable to broadband LNAs and only requires knowledge of the input return loss of the amplifier and the noise power measured with an electrically long short-circuited line connected at its input. This is particularly useful for the case of LNAs used in the IF of cryogenic heterodyne receivers with not perfectly matched SIS or HEB mixers.**

***Keywords*— Cryogenic Low Noise Amplifiers, High Sensitivity, Noise Parameters, Noise Waves, Millimeter Receivers, SIS Mixers.**

I. Introduction

THE trend of modern radio astronomy receivers is to achieve larger instantaneous bandwidths and better sensitivities [1]. In such wide bands, matching of the mixer and the LNA becomes complicated. Traditionally, noise temperature has been the main indicator used to evaluate the quality of an LNA at cryogenic temperature. However, this parameter does not completely characterize the sensitivity degradation produced by the mismatch of the impedance presented at its input. To evaluate this, we have selected a full set of four noise parameters using the input noise wave representation proposed in [2]. This representation has the advantage of providing an easy and intuitive interpretation of the noise degradation as a function of the reflection coefficient presented at the input by direct inspection of its parameters. This formulation can be considered the noise analogue of the familiar S-parameters.

In this communication we propose a method to measure this set of noise parameters which is applied to a 4-20 GHz cryogenic LNA developed in Yebes. This method requires a simpler experimental setup and less computation than other attempts to measure the noise parameters of an LNA at cryogenic temperature [3], [4].

II. Input noise waves

The input noise wave representation was proposed by Meys [2] in 1978 and considers two partially correlated noise waves at the input of the LNA, one going into the amplifier, A_n, and another emerging from it, B_n, as depicted in Fig. 1. Wave B_n gets reflected at the source and interacts with A_n to produce the complete noise contribution at the input of the LNA, A_{ns}, given by

$$A_{ns} = A_n + \Gamma_S B_n \tag{1}$$

where Γ_S represents the reflection coefficient of the source.

Taking the square modulus of (1) and following the notation proposed by Meys, the total noise power at the input of the LNA can be expressed in units of temperature as

$$T_{ns} = T_a + |\Gamma_S|^2 T_b + 2T_c|\Gamma_S|\cos(\phi_S + \phi_c) \tag{2}$$

where $|\Gamma_S|$ and ϕ_S are the modulus and phase of the reflection coefficient of the source impedance, and T_a, T_b, T_c and ϕ_c are the four noise parameters of the Meys noise wave representation, which we will refer to as noise wave parameters. T_a is the noise temperature measured using a matched load at the source and represents the non-correlated part of the wave going into the amplifier, commonly referred to as the effective noise temperature. T_b represents the non-correlated part of the noise wave emitted from the LNA towards the source. And finally, the correlated part of the noise waves is characterized by parameters T_c and ϕ_c. Parameters T_b, T_c and ϕ_c contribute to produce a change in the noise temperature of the LNA, modulated by the input mismatch as expressed in (2). This set of noise parameters is completely equivalent to other noise representations into which they can be easily transformed [5].

III. Experimental Procedure

We present a method to measure the noise wave parameters T_a, T_b, T_c and ϕ_c of an LNA at cryogenic temperature. This method is inspired by [2] and based on the simplification of expression (2) when a lossless short-circuit ($|\Gamma_S| = 1$) is used as the source of the amplifier depicted in the schematic of Fig. 1

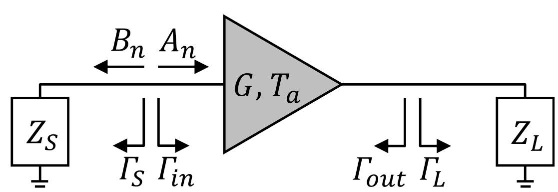

Fig. 1. Representation of a noisy linear two-port LNA using the input noise wave representation considering two partially correlated noise waves.

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$$T_{ns} = T_a + T_b + 2T_c \cos(\phi_s + \phi_c) \quad (3)$$

where T_{ns} is a sinusoidal function of frequency with an average value of $T_a + T_b$ and a peak-to-peak value of $4T_c$. To experimentally implement this procedure, the short-circuit presented at the input of the LNA must be low loss and sufficiently electrically long to allow the correct evaluation of the envelope of the sinusoid described by (3) which will be used to determine the average and peak-to-peak values of T_{ns}.

The electrically long short-circuited line was fabricated in-house by soldering a fitted brass cylinder to one end of an 80 mm piece of 0.141 mil low loss coaxial line (Microcoax UT-141C-LL) connecting the internal and external conductors (Fig. 2). The other end of this coaxial line was terminated in a male 2.92mm connector. The physical length of this line was selected to produce a period in T_{ns} of approximately 1 cycle/GHz in the 4-20 GHz band of the cryogenic LNA used to demonstrate this method (Section IV). This periodicity proved to be adequate to allow the correct evaluation of the envelope of T_{ns}.

Three cryogenic measurements are required to obtain T_{ns} and therefore the four noise wave parameters: a) the gain (G) and noise temperature of the LNA measured with a matched source (T_a) using a variable temperature load as described in [6], b) the S_{11} of the amplifier, and c) the total output noise power of the LNA when loaded at its input with the electrically long short-circuited line (T_{out}). This output power measurement is transformed into noise temperature at the input of the amplifier, T_{ns}, using

$$T_{ns} = \frac{|1 - \Gamma_S \Gamma_{in}|^2}{G} T_{out} \quad (4)$$

where Γ_S is the reflection coefficient of the short-circuited line and Γ_{in} is the input reflection coefficient of the LNA which is assumed equals to its S_{11}. The term $|1 - \Gamma_S \Gamma_{in}|^2$ in (4) accounts for the mismatch between the source and the input of the LNA. As described, the average value of the envelopes of T_{ns} allows to obtain T_b by subtraction of the previously measured value of T_a, while T_c is one fourth of the peak-to-peak value of the envelopes of T_{ns}. The fourth parameter, ϕ_c, can be obtained by feeding the results for T_a, T_b and T_c into (3) and fitting the value of ϕ_c that minimizes its difference with the measured value of T_{ns}.

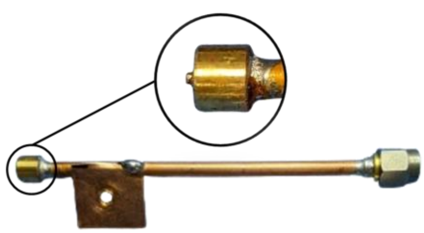

Fig. 2. Photograph and detail of the in-house fabricated electrically long short-circuited line.

The experimental setup used for the proposed method consists of a noise-receiver-equipped (opt. 029) Keysight N5247A PNA-X interfaced with an experimental cryostat and the previously described short-circuited line.

The PNA-X is used to measure cryogenic noise power and cryogenic one-port S-parameters of the LNA and the electrically long short-circuited line. A SOLT calibration of this instrument for S-parameter measurement is done using an electronic calibration module (Agilent N4693-6001) at room temperature. The length and loss variation of the stainless-steel line used to interface the inside and the outside of the cryostat is calibrated by measuring a cryogenically cooled flush short located inside the cryostat. The S_{11} of the LNA is characterized by terminating its output with a matched load and measuring the reflection at its input. The reflection coefficient of the short-circuited line, Γ_S, was carefully measured obtaining a value of the magnitude better than 0.4 dB within most of the 4-20 GHz band.

All measurements are conducted consecutively in the same calibration plane with the same experimental setup and using a PID temperature controller (Lake Shore 336) to reduce temperature variation of DUTs.

IV. Results

To illustrate the proposed method, a 4-20 GHz cryogenic LNA[1] designed and fabricated at Yebes was characterized experimentally at 7 K. Fig. 3 illustrates the measured results for the total output power, T_{out}, and noise temperature, T_{ns}, of the LNA loaded at its input with the electrically long short-circuited line. The results for the four noise wave parameters are depicted in Fig. 4, together with their modeled results. These simulated values were obtained from the complete CAD model of the cryogenic LNA, generated using Keysight ADS software in the same way as described in [6], where the noise contribution of the transistors is included using Pospieszalski's model [7].

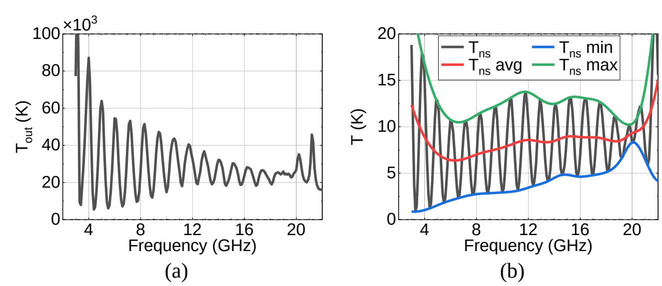

Fig. 3. Experimental results at 7 K for (a) T_{out} and (b) T_{ns} of the 4-20 GHz cryogenic LNA developed at Yebes when terminated with the electrically long short-circuited line. T_{ns} is plotted together with the extracted values of its average and envelopes.

[1]This LNA was developed under the ESO Technology Development Programme aiming at fulfilling the requirements of the ALMA Wideband Sensitivity Upgrade.

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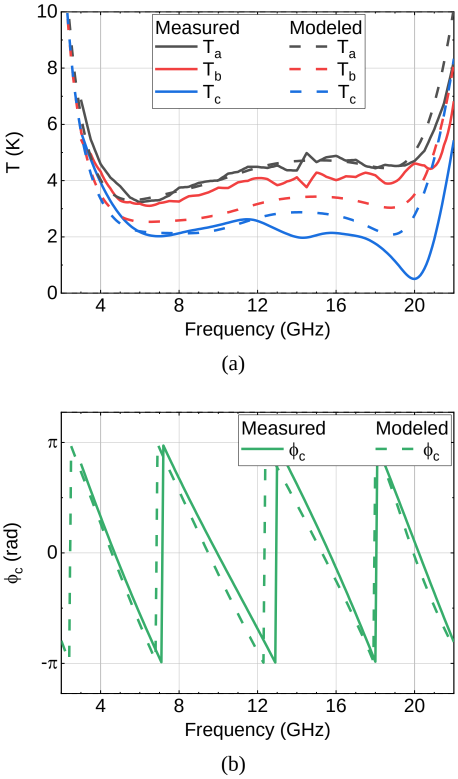

Fig. 4. Experimental (solid) and modeled (dashed) results for (a) T_a, T_b, T_c and (b) ϕ_c of the 4-20 GHz cryogenic LNA from Yebes at 7 K. Note that T_a is the noise temperature measured using a matched input load.

Agreement between measured and modeled noise wave parameters is very good for T_a in the whole band, and up to 12 GHz in the case of T_c. Parameter T_b is offset from modeled values, which could be justified due to loss in the experimental short-circuited line.

Parameters T_a and T_b have a similar flat evolution within the frequency band. The parameter responsible for the description of the magnitude of the correlation, T_c, presents an evident minimum at 20 GHz caused by the low ripple amplitude of T_{ns} at this frequency (see Fig. 3(b)). It is interesting to point out that, for this experiment, the noise temperature that emerges from the input of the LNA, T_b, is lower than its 7 K physical temperature.

V. Method Limitations

The proposed method is only applicable if the LNA complies with some restrictions. First, the LNA must be unconditionally stable for it to be possible to measure its output power without breaking into oscillation when loaded with a short-circuit. Second, it must be wideband in order for a ripple to form in T_{ns} that allows the correct evaluation of its envelope without requiring an excessively long short-circuited line. And third, the LNA gain should be high enough to ensure that the noise contribution of the PNA-X noise receiver is negligible relative to the value of T_{out}. Additionally, gain must also be constant between the three consecutive cooldowns required for the evaluation of the noise parameters. This gain variation has been estimated to be lower than 0.15 dB for the measurement setup used, and according with simulations, this may produce errors lower than 10% on T_b and lower than 5% on T_c.

Finally, another identified potential limitation of the method is the unknown reflection coefficient of the PNA-X noise receiver (Γ_L in the circuit depicted in Fig. 1) which has repercussions on the approximation of Γ_{in} by the S_{11} of the LNA and on the possible formation of standing waves at the output of the amplifier. For $\Gamma_{in} \approx S_{11}$ to be true, the S_{12} of the amplifier and/or the Γ_L of the PNA-X must be approximately zero. Regarding the formation of output standing waves, it should be noted that in the proposed experimental setup Γ_{out} adopts its worst possible value for a given LNA, since the input load is a short-circuit and therefore $\Gamma_S \approx$ -1. In this scenario any possible deviation of Γ_L from a matched load would have the effect of producing a standing wave pattern on the output of the LNA. Both contributions, $\Gamma_{in} \approx S_{11}$ and standing wave formation, have been studied concluding that even a poor $|\Gamma_L|$ of -15 dB would only translate into a variation of about 10% in T_b and 5% in T_c, for the values of $|S_{21}| >$ 30 dB and $|S_{12}| <$ -50 dB of the tested LNA.

VI. Alternative Method

An alternative method to obtain T_b, T_c and ϕ_c for a known T_a has also been developed. In this case, instead of using the envelope of T_{ns}, three instances of non-linear equation (3), corresponding to different lengths of short-circuited line (0, 80 and 160 mm), are numerically solved simultaneously at each frequency point. This can be expressed as

$$\begin{aligned} &T_{ns,k} = T_a + T_b + 2T_c \cos\left(\phi_{s,k} + \phi_c\right) \\ &k = 1,2,3 \end{aligned} \quad (5)$$

where $T_{ns,k}$ is the input noise of the LNA loaded with the corresponding short-circuited line and $\phi_{s,k}$ the phase of each line. The results obtained using this method are shown in Fig. 5 as individual points. A considerable level of dispersion can be appreciated at frequencies where all instances of T_{ns} in (5) have similar values. Fig. 5 also compares these results with the ones obtained with the previous method (solid lines), showing an overall good agreement. Although this new method has the advantage of allowing a direct extraction of parameter ϕ_c, it requires more measurements and produces noisier results making it less experimentally appealing and therefore only used in this study to corroborate the proposed method.

VII. Conclusions

A simple method for measuring the noise parameters of LNAs at cryogenic temperature has been presented and demonstrated. The measured noise parameters are based on the

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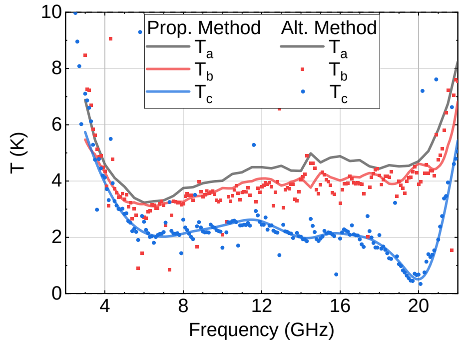
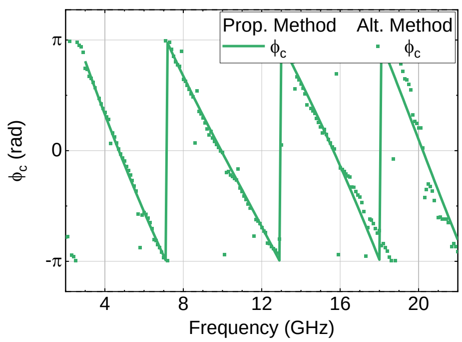


(a)



(b)

Fig. 5. Results for (a) T_b, T_c and (b) ϕ_c obtained using the alternative (discrete points) and proposed (solid lines) methods at 7 K.

input noise wave representation proposed by Meys. These parameters provide a direct and intuitive interpretation of the sensitivity degradation produced by the source mismatch, making them a useful tool for the evaluation and selection of amplifiers for a wide range of low noise applications such as the IF chain of radio astronomy receivers. This set of experimental noise parameters can also be transformed into any other representation, as for example T_{min}, Γ_{opt} and r_n, which allow to generate a complete experimental Touchstone S-parameter file of a cryogenic LNA. The proposed method has the advantage of requiring a simple experimental setup and only one additional cryogenic measurement beyond those usually made to characterize this kind of devices, i.e. noise temperature and S-parameters.

This method has been applied to a broadband 4-20 GHz cryogenic LNA showing good agreement between experimental and modeled results. Confidence in these results has been provided through corroboration by an alternative method. The limitations of the proposed experimental procedure, along with possible sources of measurement error, have been analyzed. These uncertainties have been studied in the context of this amplifier and have been found to be similar to those obtained in the measurement of the noise temperature of cryogenic LNAs [6], [8].

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