Performance of NoiseTech's Cryogenic Impedance Generators (C-IG0160C)

Application Note 002

NoiseTech Microwaves Ltd.

Making noise parameter testing accessible.

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Contents

1 Introduction

Cryogenic low-noise amplifiers (Cryo-LNAs) are key receiver components in ultra-sensitive systems such as radio telescopes, satellites, and quantum computing. These LNAs are capable of achieving exceptionally low noise temperatures, in the order of just 1 or 2 K. With noise temperature this low, measurement of Cryo-LNA noise performance is difficult and subject to systematic errors such as those due to noise source uncertainties in the range of 7 to 20 K (0.1-to-0.3dB uncertainty in noise source ENR) [1,2]. Clearly such large uncertainties make accurate characterization of Cryo-LNAs difficult. To overcome this problem, cold-attenuator method is commonly used [3]. With this method, an attenuator is placed in the cryogenic dewar at the input to the LNA. The attenuator loss reduces the amount of noise source uncertainty and improves the Cryo-LNA noise-figure measurement accuracy.

The recent trend is to equip radio telescopes with phased-array feeds to achieve wider field of view by creating multiple simultaneous beam and improve the telescope field of view and survey speed. A great example of such a system is the Green Bank Telescope cryogenic phased array feed [4]. Developments of phased-array feeds however create a new Cryo-LNA characterization problem. For proper noise matching Cryo-LNAs to phased-array-feed elements, the Cryo-LNAs have to be designed such that their optimum reflection coefficients for minimum noise, Γ_{opt}, equaled the active reflection coefficient of the antenna array, Γ_{act} [5–7]. The theory on determining Γ_{act} has been well developed, however the measurement of Cryo-LNA noise parameters and in particular Γ_{opt} is problematic.

2 Background: room-temperature noise-parameter measurement

A noise factor (or equivalently a noise figure) of a device is a common metric for representing the amount of signal-to-noise-ratio (SNR) degradation due to noise generated by the device [8]. While noise factors are commonly used, they are not invariant quantities of the associated devices and are affected by how the devices are embedded into larger systems. To model noise factor dependence on the embedding, noise parameters are used [9]. There are four noise parameters: minimum noise factor, F_{min}, equivalent noise resistance, R_n, and optimal signal-source admittance for minimum noise, $Y_{opt} = G_{opt} + jB_{opt}$, which can be also represented by Γ_{opt}. The noise parameters are related to the noise factor of a device by

$$F = F_{min} + \frac{R_n}{G_s}\left[(G_s - G_{opt})^2 + (B_s - B_{opt})^2\right] \tag{1}$$

where $Y_s = G_s + jB_s$ is the signal-source admittance.

Measurement of noise parameters involves driving the device with a few signal sources having different Y_s (or equivalently reflection coefficients Γ_s), determining F for each Y_s, and then solving for the four noise parameters using these results [10]. There have been several methods developed of selecting signal-source admittances Y_s for measuring the noise parameters of a device [10–19]. Clearly there is an infinite number of Y_s that can be selected for this purpose and some of such Y_s may not be optimum for extracting noise parameters and may result in very long measurement time. Thus a selection of well-placed Y_s, rather than selecting a large number of Y_s admittances for high redundancy, is desirable to reduce measurement time while maintaining adequate accuracy and measurement uncertainty [12,14,17,20]. [10,20] removed any restrictions on how Y_s pattern covers the Smith chart and instead performed a rigorous theoretical analysis of the system of equations, which are solved to extract the noise parameters, that showed that four Smith-chart regions of Y_ss guarantee a diagonally dominant system of equations and thus guarantee a solution. These four regions are dependent on identified scaling coefficients and can be modified to suite various measurement requirements and device stability conditions. NoiseTech identified the flexibility and performance of the work in [20] as key components to NoiseTech's line of impedance generators and cryogenic impedance generators.

3 Cryogenic noise-parameter measurement

Standard method, discussed in Section 2, of measuring noise parameters involve large mechanical tuners. These cannot be placed in the dewar due to their size, the number of communication lines, thermal load, and dependence of mechanical parts on ambient temperatures. Long-line methods of measuring noise parameters

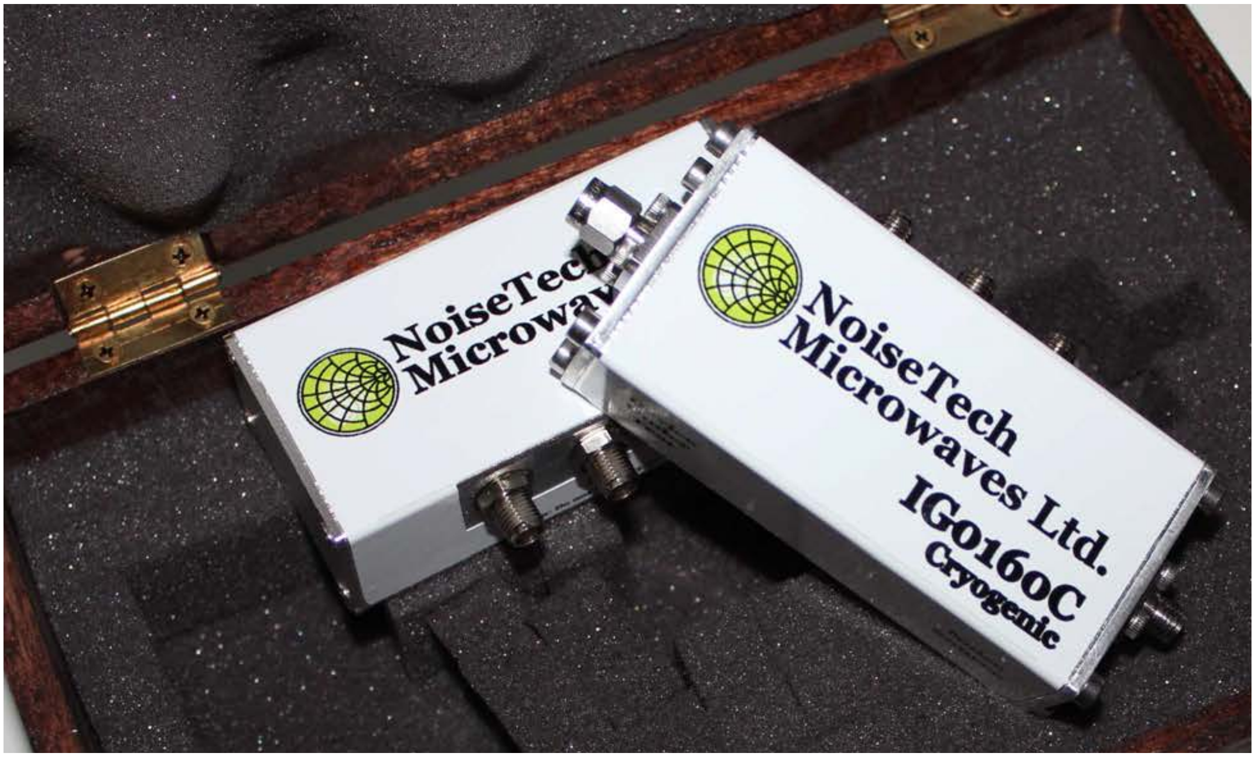

Figure 1: NoiseTech's C-IG0106C cryogenic impedance generator.

require very long and very low loss coaxial cables, which also cannot be placed inside a standard cryogenic cooler. When placing these components outside the dewar, the noise temperature measurement uncertainty becomes over an order of magnitude larger than the measured quantities. The cold-attenuator method with room-temperature tuner can no longer be used as the attenuator will make impedances generated by the tuner all appear near $50\,\Omega$ making noise parameter extraction prone to errors. Without the attenuator noise-source uncertainty and noise-source temperatures being much larger then the noise temperature of the LNA make cryogenic noise-parameter measurements susceptible to additional errors.

NoiseTech's cryogenic impedance generators (C-IG0160C), shown in Fig. 1, solve this problem. The impedance generators consist of two parts. One part is located at the room temperature is used for communicating with the host computer system. The other part, i.e. the RF part of the impedance generator, is compact and fits in small space inside dewars. The cold attenuator is attached on the noise-source side of the cryogenic impedance generator. The communication between the two parts is accomplished over just three low-frequency control lines.

As described in [10], the extraction of four noise parameters requires a system of four linearly independent equations based on (1) for a set of four different Y_s. The linear independence is a strong function of Y_s that are presented at the LNA input with impedance generators or impedance tuners. However, certain regions on Smith chart lend themselves to guaranteed diagonally dominant system of equations and a solution. The four regions, labeled as regions A, B, C and D, are identified in Fig. 2(a). These represent a symmetric subset of all possible regions. Other region configurations are also possible [10, 20]. NoiseTech impedance generators make use of these regions to reduce the impedance generator size by avoiding the generation of impedances that are do not result in linear independent equations. As the result, NoiseTech's impedance generators are compact and ultra repeatable (RMS repeatability <-80dB), where the repeatability, R, is a dB representation $\mathrm{R}\equiv 20\times\log|S_{old}-S_{new}|$ of the difference between initial S-parameters, S_{old}, for one impedance generator state and new S-parameters, S_{new}, measured after the impedance generator has been returned to the same state. Fig. 2(b) shows the effective impedances generated by the C-IG0160C cryogenic impedance generator at frequencies between 100 MHz and 6GHz and for 15 different temperatures between 15K and 345K. The effective impedance overlaps very well with optimum symmetric impedance regions.

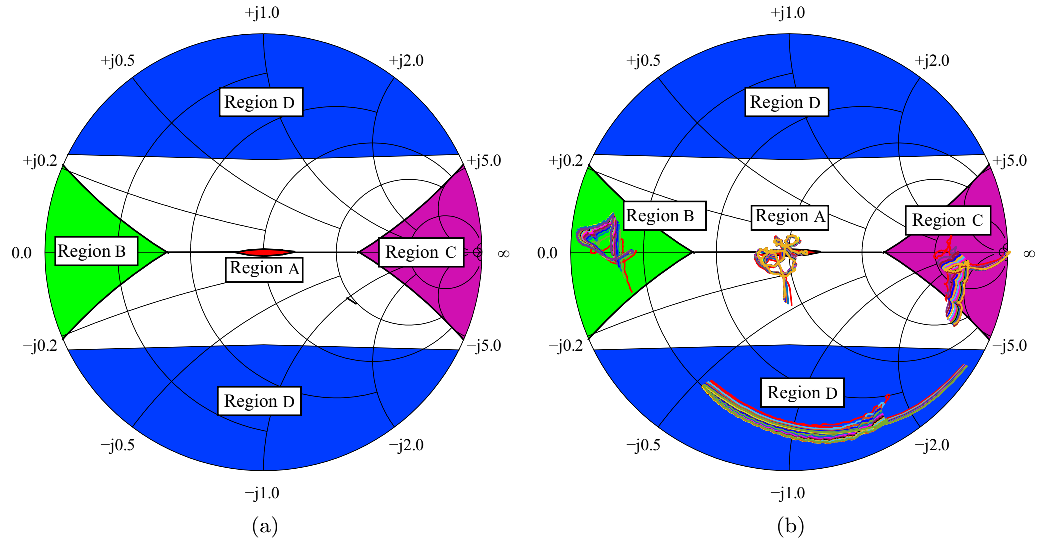

Figure 2: (a) A one subset of regions that result in linear independent diagonally dominant system of equations. (b) Effective reflection coefficients at the output of impedance generator.

Further region adjustment algorithm employed during noise-parameter extraction improves the diagonal dominance of the resultant system equation making noise parameter extraction more accurate.

The measured repeatability of the cryogenic impedance generator at 345K and 15K is shown in Fig. 3 for three temperatures. Repeatability of mechanical impedance tuners and solid-state impedance generators is the key performance metric that determines their suitability for noise parameter measurement. As shown in [21], tuner repeatability accounts for a significant uncertainty in such measurements and therefore is one of the key performance metrics to be considered when selecting method of generating Y_s for measuring noise parameters. The measurement results in Fig. 3 show outstanding repeatability with over 20dB improvement over mechanical impedance tuners.

4 Advantages of NoiseTech's approach

Minimizing the number of source admittance measurements for accurate noise parameter determination is advantageous for reducing measurement time and simplifying the procedure. A 4-point method from [10, 20] does not require a least-squares method of solving the linear system of equations because it is not over determined like other methods. The [10, 20] pattern-selection procedure outlines four distinct admittance regions that can be used for noise parameter measurements. It also allows for the change of scale factors that modify the size and position of regions A-D while accommodating diagonal dominance requirements. The scaling factors can also be used to extend impedance generator frequency coverage [20]. NoiseTech's method chooses Y_s that are less sensitive to measurement uncertainty while still being guaranteed to produce a linearly independent set of noise equations. This in turn reduces the size of impedance generators as they only required for generating specific Y_s. Time saved by reducing the number of Y_s states can be used to reduce uncertainty by averaging the solutions produced by the four Y_s states.

The highlights of the NoiseTech impedance generators are:

– The generated Y_s result in linearly independent measurements.

– Wideband impedance generators produce Y_s that remained within the regions described in [10, 20] with one such region configuration shown in Fig. 2.

–A drawback to mechanical tuners is that the Y_s patterns change with frequency. This drawback is avoided by NoiseTech impedance generators, which are designed to have their output reflection coefficients remain with this the required regions over wideband of frequency.

–Compact size, very low power consumption, simple communication requirement permit use inside of

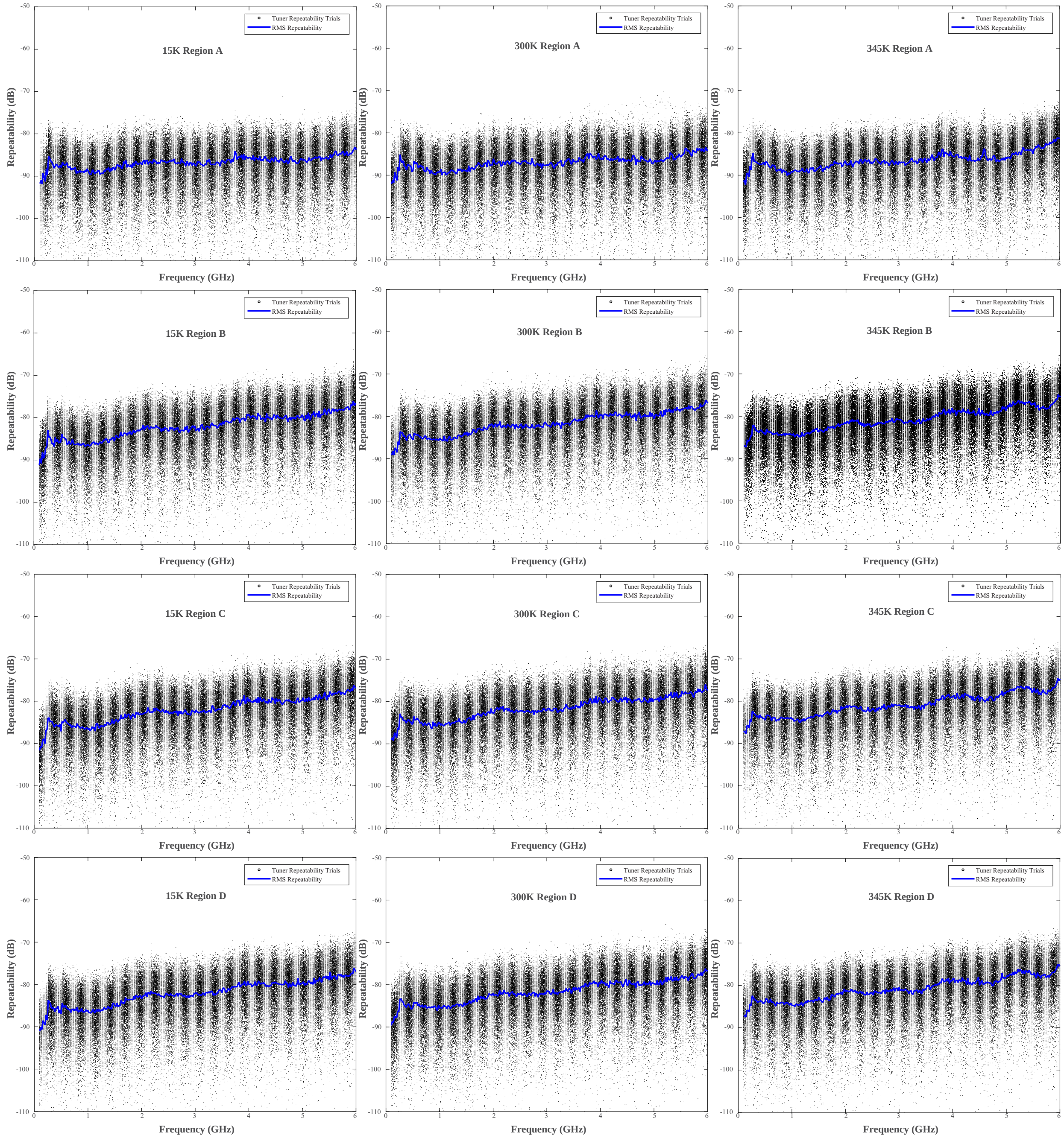

Figure 3: Repeatability of the cryogenic impedance generator at 15K, 300K, and 345K.

cryogenic dewars and other confined spaces.

−Solid-state design results in outstanding repeatability reducing its influence on measurement errors.

5 Conclusion

Compact impedance generators developed by NoiseTech demonstrate excellent repeatability at both elevated temperatures of 345K and down to cryogenic temperatures of 15K. These tuners are the first cryogenic tuners on the market.

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