A Reduced Uncertainty Method for Gain over Temperature Measurements in an Anechoic Chamber

Vince Rodriguez and Charles Osborne
MI Technologies
Suwanee, GA, USA
vrodriguez@mitechnologies.com

***Abstract*—P Gain over Temperature (G/T) is an antenna parameter of importance in both satellite communications and radio-astronomy. Methods to measure G/T are discussed in the literature [1-3]. These methodologies usually call for measurements outdoors where the antenna under test (AUT) is pointed to the “empty” sky to get a “cold” noise temperature measurement; as required by the Y-factor measurement approach [4]. In reference [5], Kolesnikoff et al. present a method for measuring G/T in an anechoic chamber. In this approach the chamber has to be maintained at 290 kelvin to achieve the “cold” reference temperature. In this paper, a new method is presented intended for the characterization of lower gain antennas, such as active elements of arrays. The new method does not require a cold temperature reference, thus alleviating the need for testing outside or maintaining a cold reference temperature in a chamber. The new method uses two separate “hot” sources. The two hot sources are created by using two separate noise diode sources of known excess noise ratios (ENR) or by one source and a known attenuation. The key is that the sources differ by a known amount. In a conventional Y-factor measurement [4], when the noise source is turned off, the noise power is simply the output attenuator acting as a 50 ohm termination for the rest of the receive system. But by using two known noise sources, the lower noise temperature source takes the place of T-cold in the Y-factor equations. The added noise becomes the difference in ENR values. An advantage of this approach is that it allows all the ambient absorber thermal noise temperature change effects to be small factors, thus reducing one of the sources of uncertainty in the measurement. This paper provides simulation data to get an approximation of the signal loss from the probe to the antenna under test (AUT). Another critical part of the method is to correctly define the reference plane for the measurement. Preliminary measurements are presented to validate the approach for a known amplifier attached to a standard gain horn SGH) which is used as the AUT.**

I. INTRODUCTION

It follows Maxwell’s Equations that accelerating charges radiate. Since atoms contain charges and vibrate proportional to temperature, materials must also radiate proportional to temperature. This radiation is evenly distributed across the frequency band up to approximately 300GHz. The power of this radiation in watts is given by the following equation:

$$P_n = kT_nB \tag{1}$$

where P_n is the thermal noise power in watts, k is Boltzmann’s constant ($1.38\cdot10^{-23}$ J/K/Hz), T_n is the temperature in Kelvin and B is the bandwidth in Hz. It is common to refer to the noise temperature of a system. This noise temperature is not the actual ambient temperature in K, but the temperature at which a resistor heated to that given temperature will radiate that equivalent noise power.

II. BACKGROUND THEORY

In general terms when an antenna is receiving it will receive power related to the noise power in the ambient. The noise will arrive at the antenna from all directions and it will be related to the ambient temperature at the location of the noise sources around the antenna (see Figure 1).

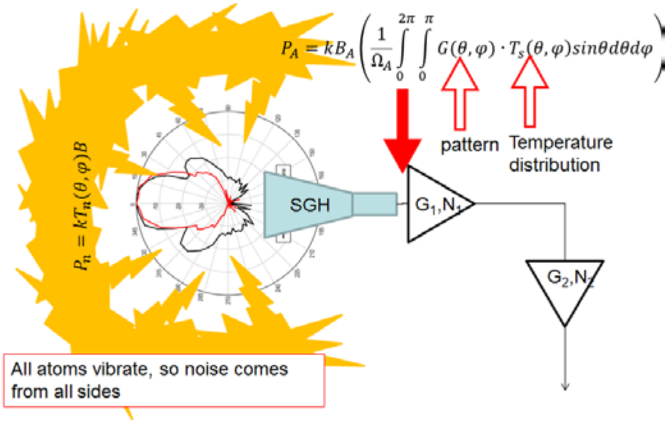

Figure 1. General case of an antenna receiving in an environment. The noise arrives from all sides, but is dependent on the temperature at the location of the sources.

In this paper, for the method used to measure the G/T it is assumed that the temperature in the anechoic chamber is constant. Furthermore, as it is described below, the noise sources will operate at much higher noise temperatures than the typical chamber environment. Making the assumption that the chamber has a constant temperature the equation in Figure 1 that describes the power at the antenna gets reduced to the following form which is the same as (1):

$$P_A = kB_AT_A \tag{2}$$

where P_A is the power at the antenna port, B_A is the antenna bandwidth, and T_A is the temperature sensed by the antenna. T_A is the same as T_n provided that the background noise source is constant across the antenna solid angle [1]. In a system with active and passive components, the power received by the antenna will get amplified (or attenuated, negative gain) in a series of stages and passive components such as resistors, will add their own noise per equation (1).

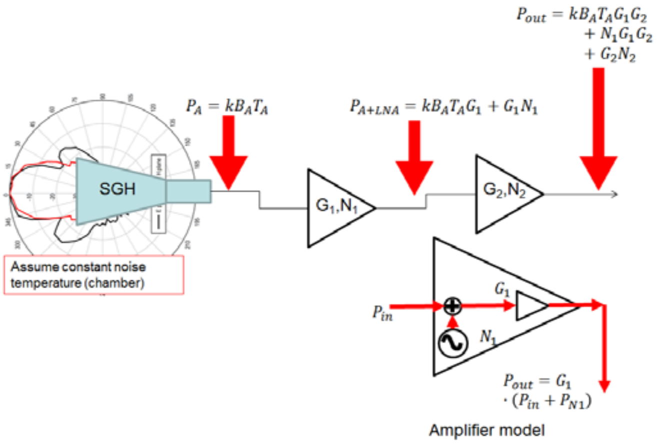

Figure 2. The noise received by the antenna is amplified in the different stages. The amplifier model used, assumes that the internal noise in the amplifier is amplified by the ideal amplifier stage.

In Figure 2 the thermal noise received by the antenna is given by (2). That noise is subsequently amplified in the different stages and the output power related to the noise is given by

$$P_{out} = kB_AT_AG_1G_2 + N_1G_1G_2 + G_2N_2 \tag{3}$$

Now, the system noise, the noise introduces in the amplifier stages is given by the noise temperature of the stages, hence

$$P_{System} = kT_{Sys}B \tag{4}$$

Using (4) on the noise contributions of the system, it derives that

$$T_{Sys} = + \frac{N_1G_1G_2}{kB} + \frac{N_2G_2}{kB}\frac{G_1}{G_1} \tag{5}$$

From (5) we can derive the noise temperature for each stage as

$$T_{Sys} = T_1 + \frac{T_2}{G_1} \tag{6}$$

From this we arrive to the equation for gain over temperature where gain *G* is the gain of the antenna in the system, the gains of the amplifiers (or the losses) are accounted in the noise temperature of each stage.

$$\frac{G}{T} = \frac{G}{T_A+T_{Sys}} \tag{7}$$

The equation can be made more general by adding the noise contribution due to the physical temperature of the antenna and the noise contribution from the physical temperature of the transmission lines

$$T_{antenna} = T_A + \left(\frac{1}{\eta} - 1\right)T_{Phys} \tag{8}$$

where η is the antenna efficiency and T_{phys} is the physical temperature of the antenna in K. For each section of transmission line its noise temperature related to its losses and length is given by:

$$T_{TL} = \left(\frac{1}{e^{-2\alpha l}} - 1\right)T_{phys} \tag{9}$$

where l is the length and α is the attenuation constant of the transmission line. Now that we have defined the Gain over temperature a method for measuring this parameter must be described.

III. HOW TO MEASURE G/T

The approach to measure the G/T follows the Y-factor measurement described in [4]. In reference [6] the noise figure is the signal to noise ratio into the stage divided by the signal to noise ratio at the output of the stage.

$$F = \frac{\left(\frac{S_{in}}{N_{in}}\right)}{\left(\frac{S_{out}}{N_{out}}\right)} = \frac{SNR_{in}}{SNR_{out}} \tag{10}$$

Reference [6] shows that the noise figure *F* can be written in terms of the noise temperature of the device T_e and the standard temperature T_o of 290K.

$$F = \frac{T_e}{T_0} + 1 \tag{11}$$

Y factor measurements require the use of a noise source with a pre-calibrated ENR, the ENR s defined as:

$$ENR = \frac{\left(T_S^{ON} - T_S^{OFF}\right)}{T_0} \tag{12}$$

where T_S^{OFF} is the physical temperature of the device in K. The ENR is used to compute the noise temperature of the noise source at a given frequency. The Y factor is a ratio of two different noise levels. Traditionally the procedure has been to turn the noise source on and then off and use those noise levels to get the Y factor. Hence the Y factor is given by

$$Y = \frac{N^{ON}}{N^{OFF}} = \frac{T^{ON}}{T^{OFF}} \tag{13}$$

The procedure calls for a calibration in which the Y factor of the receiver is measured [4]. From this calibration the noise temperature of the receiver can be calculated.

$$T_{rx} = \frac{\left(T_S^{ON} - Y_{rx}T_S^{OFF}\right)}{(Y_{rx} - 1)} \tag{14}$$

Where the subscript *rx* indicates the receiver. The measurement can be done in the device under test (DUT) and then (6) can be rewritten as

$$T_{Sys} = T_{DUT} + \frac{T_{rx}}{G_{DUT}} \tag{15}$$

Hence the DUT noise temperature can be obtained and the gain of the DUT can be obtained from the measurement itself since

$$G_{DUT} = \frac{\left(N_{Sys}^{ON} - N_{Sys}^{OFF}\right)}{\left(N_{rec}^{ON} - N_{rec}^{OFF}\right)} \tag{16}$$

And then with the G_{DUT} and T_{DUT} the Gain over temperature can be computed. The procedure is similar for antennas. If the antenna can be removed from the active network the standard procedure in [4] can be follow for the amplifiers. In this paper, we look at a methodology that can be used for antennas that have integrated active components, or for antenna array elements. The method is intended to provide a figure for the noise of an integrated amplifier into the antenna, the noise sensed by the antenna when deployed will be different than the noise in the anechoic chamber.

The critical factor in doing the G/T measurement approach is that it allows a system level measurement of performance to be done aggregating antenna gain, noise figure, distributed losses, and matching effects in situ. In practice, most real antenna installations will not see ambient thermal radiation in all directions leading to slightly better performance than indicated. But by using T-cold of at least 3000 Kelvin in this two-noise-source approach that measurement difference can be minimized.

IV. PROCEDURE FOR ANTENNAS

Figure 3 shows the basic test layout for the proposed method to measure G/T. The figure shows the use of two sources as opposed to a single source being turned on and off.

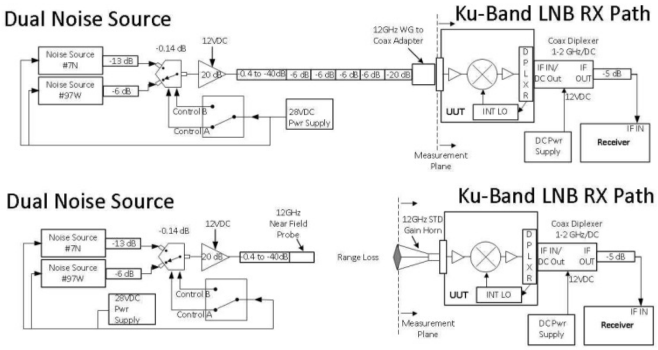

Figure 3. A view of the basic block diagram of the G/T measurement.

For the procedure equation (13) is changed to the following form

$$Y = \frac{N_2^{ON}}{N_1^{ON}} = \frac{T_2^{ON}}{T_1^{ON}} \tag{17}$$

Where the subscript 1 and 2 indicate the noise source 1 and noise source 2. Source 1 and source 2 are diode noise sources with known ENR. These sources differ by a known amount as well. Hence in this methodology the noise source with the lower noise temperature takes the place of the cold source in the standard Y factor method [4]. Figure 3 also shows a LNA that can be switched in line with the noise sources. A 30dB LNA will allow the noise source 1 to have its noise amplified this should make the internal noise of the LNA negligible. The sources are chosen such that the ENR of source 2 is higher than source 1. These high noise temperatures can be used to take into account the losses between the output of the LNA and the input of the DUT to allow sufficient signal to noise to measure the y factor and to calculate the noise figure. The use of these two "hot" sources minimizes the effects of ambient temperature changes as long as both are greater than 10 dB above the ambient thermal noise the system sees. The noise introduced by the components from the ambient temperature, as described in equations (8) and (9), is negligible when compared to the equivalent noise temperatures of the sources.

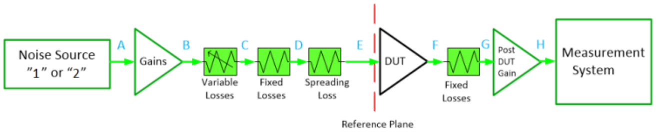

Figure 4. Line Diagram

Referring to Figure 4, at point "A" source 1 is 1,000 Kelvin and source 2 is 10,000 Kelvin are alternately switched into the system. As this noise passes through the LNA the noise is increased by the LNA gain plus its own noise contribution (5.5 dB noise figure = 740 Kelvin). If the amplifier has a gain of 30dB, the noise now becomes 1,740,000 Kelvin for source 1, and 10,740,000 Kelvin equivalent for source 2, at point "B". If the sum of all the fixed and variable losses between "B" and "E" is 30 dB, the noise power input to the DUT at "E" is reduced by a factor of 1,000. This leaves source 1 = 1,740 Kelvin at the input of the DUT. However, the attenuators and cables add their own thermal noise, but source 1 dominates the noise. Source 2 is 10 dB more noise, also dominating the noise contribution of the attenuators and cables.

T-Hot at "E" is 1,740,000 / 1,000 = 1,740 Kelvin. If compared to ambient T-Cold this leaves only an ENR = 10 LOG (1740 / 290) =7.8dB a usable amount of noise to make the measurement. If the losses can be set or held to no more than 30 dB the ENR is close to the original 15 dB ENR out of the noise source. But by using two sources, the difference in source ENR is the critical parameter.

In an anechoic chamber the absorber completely surrounds the receive antenna's field of view. Increasing the gain of the antenna only causes it to see a smaller area of absorber, making received noise power constant unless something of higher physical temperature is in the antenna field of view. However the noise source when turned on illuminates the room with 10,000 Kelvin noise. The absorber reradiates only a small portion of that power. Only the portion of this noise collected by the receive antenna affects the output noise power. This loss between feed and DUT is what must be characterized in a normal single source T-Hot/T-cold measurement. In dual source mode only the difference between the sources is critical.

Another noise contributor is the receive power measuring system itself. If the DUT gain is low, the receive system's own noise power will affect the noise power reading during T-Hot to T-cold measuring. If the receive noise power measuring system has a 24 dB noise figure its own noise floor is -150 dBm/Hz. Mixer losses further degrade this to -136 dBm/Hz for an equivalent noise figure at point "H" of approximately [-174 – (-136)]= 38 dB noise figure. Post DUT gain of 30 dB divides this down so that the effect at "G" is only 6,309 / 1000 = 6.3 Kelvin added noise. This adds less than 0.1 dB to the Post DUT LNA's noise figure of 5 dB, resulting in 5.1 dB noise figure at "G" looking toward the measurement system receiver. System losses of 5dB in cable and switch loss add directly to the noise figure. So at "F" looking toward the measurement system the noise figure becomes 5.1+5dB = 10.1 dB. This is 2700 Kelvin equivalent. If DUT gain is below 20 dB the receive system noise begins to contribute to an error term which the DUT gain has to overcome. At 10 dB gain the error term becomes exponentially larger. At 30 dB DUT gain the term becomes small (See Figure 9). Working between the unknowns caused by system losses and noise figures increasing with frequency, knowing the DUT gain *a priori* becomes important to stay above the noise floor, and below any gain compression effects.

A. *Deriving Losses*

In this part of the measurement the normal range configuration is calibrated by using a power meter after the source switch at test point “B”. The Common port of the switch goes to the feed Open Ended Waveguide (OEW) probe. The Noise Source is connected to the other port. Power is measured at all available points over the frequency range of interest. A Low Noise Amplifier of known gain and noise figure is also used to bridge the DUT to OEWG probe input switch. This allows the known Noise Figure of the LNA to dominate the link budget equations and overcome any second stage contribution of noise which may show up in the DUT noise figure. It can be used similar to a standard gain horn as a way of comparing DUT gain and Noise Figure when used in one of the calibration signal paths. Adding a 3 dB attenuator ahead of the LNA should add 3 dB to the noise figure. This is another good cross check of system dynamic range. Working through the system by substitution using the source and attenuators the loss contribution over frequency of each subsystem part can be derived and recorded for future use.

B. *Linearity*

Noise Figure can’t be measured accurately if any of the components are being driven into compression when the noise source is turned ON. The resulting measurements will indicate noise figure readings lower than if no compression was present. A noise source is a broadband signal which can have more total power than might be assumed in a narrowband comparison in the receiver or spectrum analyzer. The total power in the receiver is measured. Then a signal generator output is increased until the receiver approximately matches the power reading for the noise source. The signal generator level is increased by 10 dB and measured to check for compression. If more than 0.05 dB compression is present, the operating point should be changed by changing attenuation/gain and feed probe spacing, until this measurement runs with no compression. The LNA’s output can be attenuated if mixer compression is occurring. But minimal attenuation should be used to ensure good signal to noise ratios are achieved with no effect on the noise figure. The preliminary measurements shown in the present paper are centered on finding this no-compression region

C. *Temperature*

It is important to have a stable ambient temperature to reduce amplifier gain changes during the measurements. Most noise sources do warm up slightly due to current in the diode and associated circuitry. At least 30 minutes is recommended for the sources to stabilize. This is usually more important for the wired calibration, since room ambient dominates when the two feeds are far enough apart to make the noise source noise power not be seen above the room noise. Using a switch with at least 40 dB of isolation, both noise sources can be left on continuously eliminating the effects of warm up. As previously mentioned, if both the noise source T-Hot source 1 and T-Hot source 2 are insufficient to maintain good signal to noise in this measurement, the gain of the LNA after the switch (point A to point B) must be used as a power amplifier for the noise source. A 40 dB gain LNA for example will increase a 15 dB ENR (10,000 Kelvin) noise source to become a 55 dB (100 Million Kelvin equivalent) ENR source. If followed by 10 dB of system losses this becomes 10 Million Kelvin or 45 dB ENR equivalent. The goal is to balance system gains and losses to not be in compression, while maximizing signal to noise and measurement accuracy, as the preliminary measurements will demonstrate.

D. *Accuracy*

Measurement accuracy is proportional to the attention to detail in noise figure measurements. Each component between noise source and LNA normally has specifications with associated ± errors. Without refining these numbers at spot frequencies the worst case numbers quickly exceed the measured noise figure. The noise source is typically ±0.7 dB specified error compared to the label value. It can be much better if temperature is held constant and accumulated small losses can be compensated by comparison to a known noise figure LNA measured in place of the DUT. And seldom do all errors fall on the same side of a worst case. It is much more common to see a more random distribution of errors leading to RMS being commonly used to derive the expected error function. Using the variable attenuators it is possible to cross check some system measurements, multiple ways to be sure operation is within the linear range. The cover of [4] shows the plot in Figure 5.

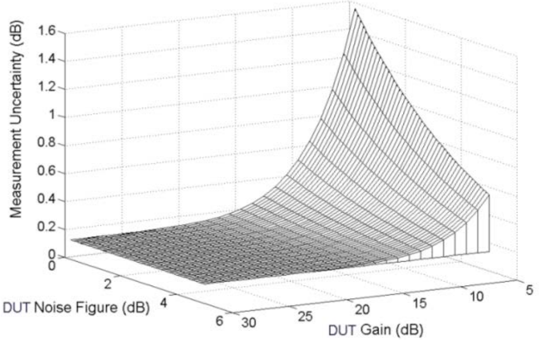

Figure 5. Plot from the cover of reference [4] showing uncertainty versus the DUT characteristics. (courtesy of Keysight)

This basically shows that measurement uncertainty increases for low gain LNAs and low noise figures (under 2 dB). That’s why a known noise figure and gain LNA may be necessary in the test system itself to insure calibration accuracy prior to placing the DUT/LNA combination inline. Return loss interactions add additional uncertainty which can change with small changes in connector or cable lengths.

V. NUMERICAL RESULTS FOR SPACE LOSS

One of the keys to this procedure is to account for the losses. The loss between the OEWG probe and the AUT is critical. For the preliminary results a standard gain horn (SGH) is being used as the AUT. The OEWG and SGH are modeled at a separation of 5λ and 10λ. Where λ is the free space wavelength at 10.2 GHz, thus, the separation is 12.696 cm at 5λ and 29.391 cm at 10λ . Even at the shorter separation of 5λ as the OEWG radiates it covers the entire aperture of the SGH. This can be seen in Figure 6.

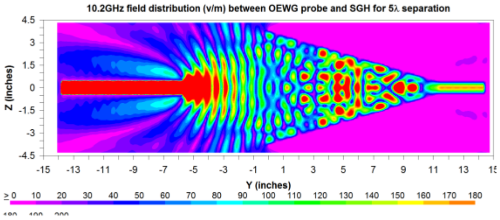

Figure 6. Field distribution of the OEWG probe radiating at a distance of 5λ from the aperture of the SGH.

The coupling between the OEWG and the SGH is shown in Figure 7. This coupling is basically the loss between the OEWG port and the SGH port.

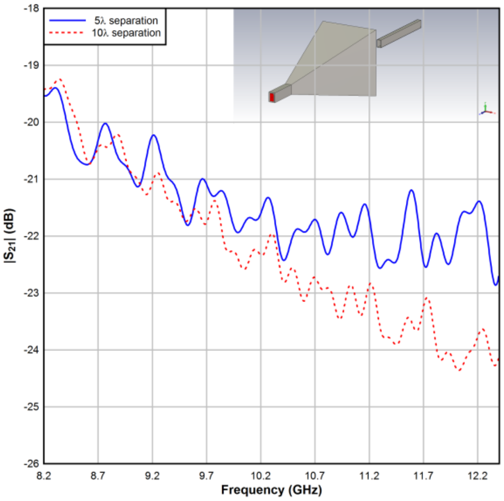

Figure 7. The coupling between the OEWG and the SGH at two distances. The OEWG is radiating while the SGH is receiving. The numerical model geometry is shown in the upper right corner of the plot.

The coupling at 12.17 GHz is -21.50 dB for the 5λ separation between the aperture of the OEWG and the aperture of the SGH. While for a separation of 10λ the coupling is computed as -23.92 dB.

VI. Preliminary Measurements

In this section preliminary measurements are presented. At the time of submitting the present paper the measurement performed are related to achieving the required linearity in the system described in part *B* of Section IV. For these preliminary measurements an anechoic range was not available so a bench-top setup was used for proof of concept. Figure 8 shows the test setup.

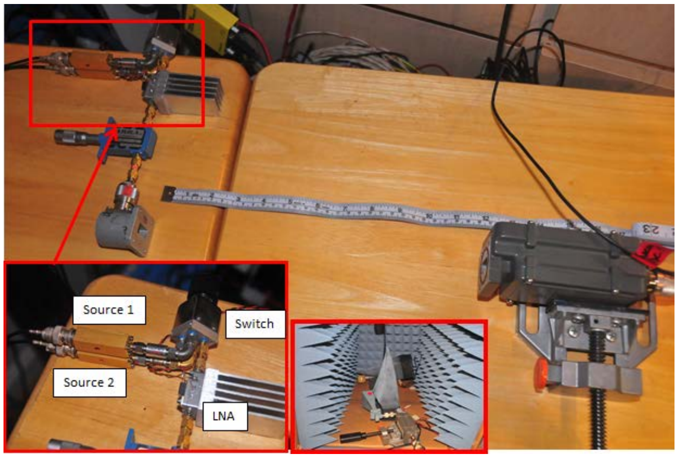

Figure 8. Test set up for preliminary measurements. The test area was surrounded by anechoic material during the radiated tests**.**

As it can be seen in Figure 8, the preliminary test setup is not ideal. Future work has to be done to repeat some of the measurements in a more typical range.

As stated above, most of the preliminary measurements were centered on achieving linearity. Figure 9, shows the results of adjusting the gain/losses in the system by adjusting the attenuator connected to the output of the LNA in Figure 8. Figure 9 shows the noise figure versus the total gain on the system.

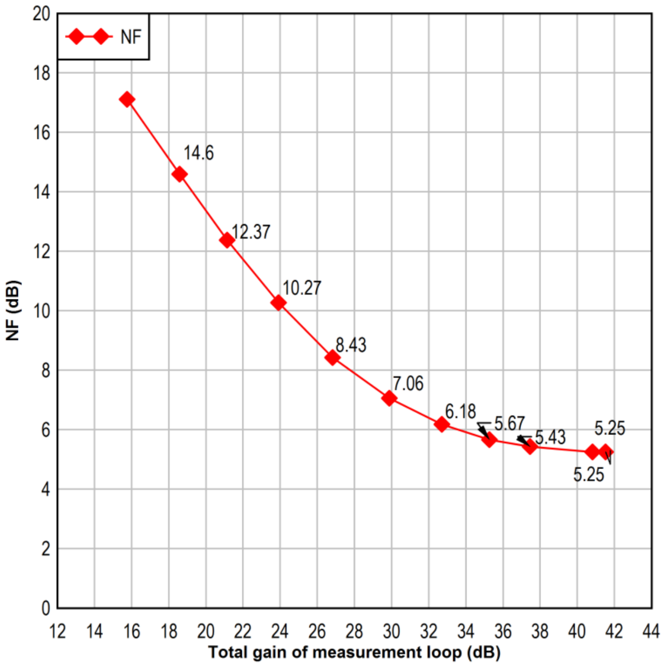

Figure 9. Noise figure measured for different levels of gain to achieve linearity.

The plot shows the different measurements conducted to find the range of gain that will allow measurements to be performed in the linear region of the equipment. The system gain prior to the DUT was adjusted and the noise power received was measured for both noise sources. A small adjustment to the gain was done and the procedure was repeated. These measurements were continued until the ratio between the noise measurements for both sources was constant as the gain was adjusted. The plot shows that indeed adjusting the gain (by reducing the attenuation on the system) to balance the losses the levels can be moved to the linear region and then small changes in gain do not affect the NF measured. A change of 3.38dB on the gain gave only a change of 0.18dB, and the change from 40.83 to 41.52 showed no change on the measured NF of 5.25dB.

At the input to the Device Under Test the gains and losses following the two noise sources equate to an input noise temperature of 49,554 Kelvin and 23,228K, calculating the ENR for each source (assuming a room temperature of 300K) using equation (12) The difference in ENR between the noise sources, the ENR equivalent, is 3.29 dB. At the DUT output the measured change between the output power for each noise source was 2.00 dB. The difference between input and output ratios was 1.29 dB which is the noise figure of the antenna/LNB combination. Using (11) The NF of 1.29 dB NF can be converted into its equivalent T_{DUT} of 680 Kelvin which provides the T for the G/T calculation.

The gain of the antenna is derived from comparison to a standard gain horn, or spherical approximations. In this case subtraction of the Gain minus system noise temperature provides the dB/Kelvin.

Future work is planned to look at calibration of the losses by switching to a CW signal and measuring its level with the receiver.

Having a known G/T reference sample of the UUT also allows confirmation of the system settings and results on a comparable basis similar to a standard gain horn in typical antenna measurements.

VII. CONCLUSIONS

The use of the difference in ENR between two noise sources to derive the Y-factor, provides a way of improving accuracy in G/T and Noise Figure measurements in reducing the dependancies on room ambient temperature control and its subsequent noise temperature effects. In a system with such an amount of non-linear components it is extremely important to be sure that the system is operating in the linear region. Future work is needed to improve the calibration of the losses in the system and to provide

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