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Using Keysight PNA-X and NFA Noise Receivers for Noise Temperature Measurements with Cryogenic Variable Temperature Loads

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1. Introduction

This report describes the comparison of the results obtained with different configurations used for the measurement of a wide band cryogenic amplifier of about 7 K noise temperature (noise figure 0.10 dB) and 32 dB of gain in the 0.5-18 GHz frequency range. Obtaining good accuracy in this type of measurements is a challenge which exceeds the capability of commercial noise figure measurement equipment used in a conventional way and special methods should be used. The "cold attenuator" method allows taking advantage of the standard procedures used in noise figure meters with switched diode noise sources in a very convenient way, but the calibration of the noise source presents some difficulties. A better absolute accuracy can be obtained using a cryogenic load at variable temperature connected directly to the input of the amplifier but then the measurements are much slower and the stability of the measurement system becomes a critical factor for obtaining good results. This report describes the results obtained and the lessons learned in the attempt to use the Keysight PNA-X and the NFA noise receivers for accurate measurements of an amplifier with a cryogenic heated load and the comparison with previous results obtained with a cryogenic attenuator.

2. Variable temperature cryogenic load

The cryogenic variable temperature load used for these measurements is based on a metamorphic GaAs chip which contains a temperature stable high frequency 50 Ohm NiCr termination, a 1 KOhm NiCr heating resistor and a resistive PTC temperature sensing element. The chip is mounted on a gold plated brass chassis fitted with a 2.92 mm coaxial connector. The module is thermally connected to the cold plate of the refrigerator by a copper braid. More details of this device can be found in [3] and [4].

The temperature of the termination can be controlled by the power dissipated in the heating resistor. For our measurements the hot and cold temperatures used were 45 and 25 K respectively. A PID temperature controller (Lake Shore model 336) was used for the cryogenic temperature measurement and control [6]. The resistance of the PTC sensing element was measured with a 4-wire configuration and converted to temperature using a table stored in the instrument. Prior to a measurement session, the possible offset in the resistance (typically a few mOhms) was determined by taken a measurement of the sensor at the coldest temperature achievable with the cryostat (typically 3-4 K) with no power applied and comparing with a calibrated diode sensor attached to the chassis. The calibration table stored in the instrument was corrected for this small offset.

The Lake Shore 336 controller has two independent PID control loops. One was used for stabilizing the temperature of the cryogenic amplifier (DUT) (typically at 15 K) and the other for controlling the temperature of the input termination (25-45 K). The temperature of the amplifier was controlled by heating resistors attached to the cold plate and with a diode sensor in the body of the amplifier. The input termination was controlled with the on-chip heating resistor and the PTC sensing element. Typically a maximum power of ≈0.625 W was dissipated in the chip to raise its temperature to 45 K. However, the LS 336 is only prepared to drive heating resistors in the 25-100 Ohm range, and an external 100 Ohm 50 W resistor was connected in parallel with the chip to overcome this difficulty. The maximum current of the controller was limited to 210 mA to avoid a too high voltage (>20 V) in the heater terminals which could permanently damage the chip by internal arcing in the bridges. The time needed to change the temperature from 25-45 K or from 45-25 K and to stabilize to better than 0.03 K is 15 sec. Figure 1 presents some pictures of the heated load chip, the cold plate of the cryostat and the temperature controller.

Figure 1: Up left: photo of the variable temperature cryogenic termination chip. Up right: photo of the cold plate of a cryostat with a cryogenic amplifier and a variable temperature load module connected to the input. Down: Photo of the Lake Shore 336 cryogenic temperature controlled used.

3. PNA-X noise receiver

The PNA X used for these measurements was model N5247A (10 MHz to 67 GHz) with option 029 (high-accuracy noise figure). This option incorporates a dedicated noise receiver which can be switched in port 2 and a tuner which can be inserted internally in port 1. The option 029 of PNA-X is conceived for measurements with the cold source method up to 50 GHz as described in [1]. Unfortunately this method cannot be easily applied for measurements of cryogenic amplifiers inside a cryostat with adequate accuracy. Instead, for our heated load measurements, we use the Y-factor method employing the PNA-X receiver as a tunable precision noise power meter. The characteristics of the receiver required for this type of measurement are: and high instantaneous bandwidth, low noise, perfect linearity (no saturation) and excellent stability.

The maximum instantaneous bandwidth which can be selected in the receiver is 24 MHz. This value is much larger than what can normally be found in noise figure meters (typically 4 MHz in old models and up to 8 MHz in the last generation). The advantage of using such a large bandwidth is that the integration time can be reduced while keeping a low fluctuation in the noise power measurement. The integration time per point used in our measurements is typically ≈0.25 sec. This corresponds to 1000 averages (the integration time cannot be selected directly).

Three different gain settings (low, medium and high) can be used in the PNA-X noise receiver. Figure 1 presents the measurement of the noise temperature (and noise figure) for the three gain settings.

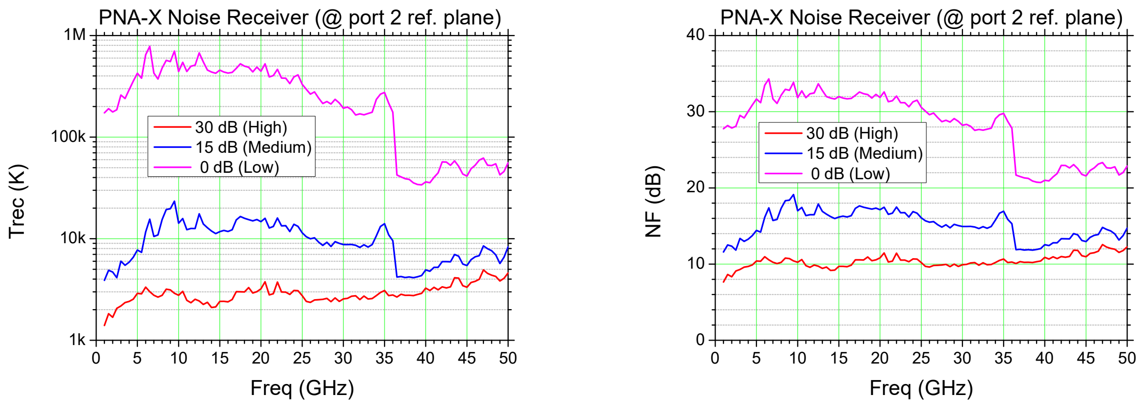

Figure 2: Measured receiver noise temperature (left) and noise figure (right) of the PNA-X noise receiver for its three gain settings (as measured with a 346C K01 noise source).

Regarding the linearity, the PNA-X with the maximum gain setting may easily enter in the compression regime and care should be taken to avoid that condition. This is particularly delicate in the high gain (30 dB) position when wideband amplifiers are connected to the input. In our case, for the measurement of the 32 dB cryogenic amplifier with the heated load, the measurement could be performed in the high gain setting without saturation. An attempt to add a 10 dB external amplifier to reduce the noise temperature of the PNA-X resulted in triggering the warning of “excessive noise power” (possible compression), so finally the measurement was taken without any preamplifier.

The stability of the PNA-X noise receiver is good, and since it has a switchable filter bank instead of a YIG pass band filter for spurious responses removal, the possible hysteresis when changing frequency is not a problem. Figure 3 presents an example of the results obtained measuring a thru just after calibration and three hours later in a temperature stable environment. Figure 4 shows the type of connection to the cryostat containing the cryogenic amplifier and the variable temperature load. The flexible cable used has the undesired effect of increasing the receiver noise and deteriorating the stability.

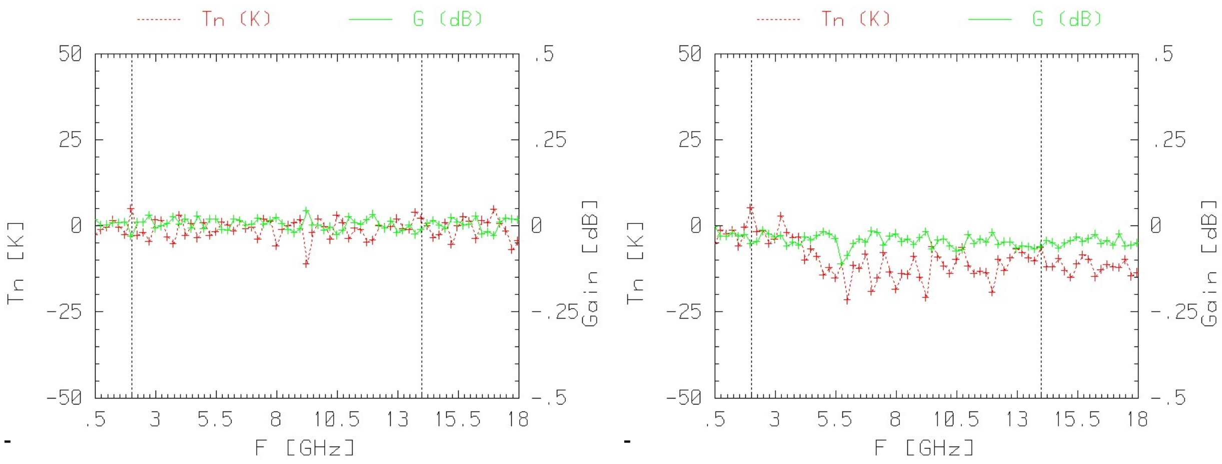

Figure 3: Stability of the PNA-X noise receiver. Measurement of a thru connection just after calibration (left) and after 3 hr in a stable environment (right). Calibration performed with a 346A noise source directly connected to port 2,

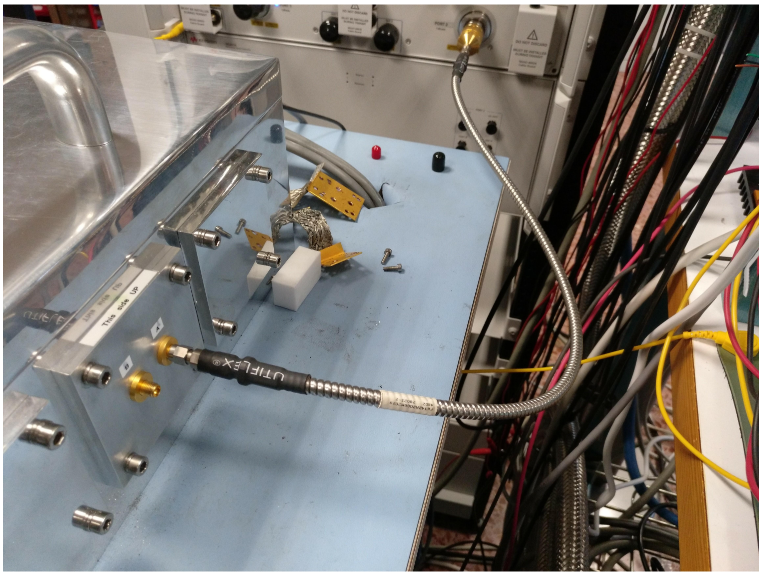

Figure 4: Connection of the PNA-X receiver to the cryostat output using a flexible cable (2.92 mm connectors UTIFLEX type).

4. NFA N8975B Noise Figure Analyzer

The NFA 8975B is based on the Keysight X Series Signal Analyzer platform and its internal architecture is the same of a classical spectrum analyzer. In fact, it can be used as a swept spectrum analyzer and even as an IQ analyzer with the firmware provided by the manufacturer. The frequency range for noise figure is from 10 MHz to 26.5 GHz. The instrument includes a non-removable YIG filter (preselector) in the signal path to reject non desired mixer responses. YIG filters are known to be peculiar regarding stability and hysteresis [2]. This is not very important when using a diode noise source since then the instrument is sequentially tuned at each frequency point and the ON/OFF power readings are taken without changing the frequency of the YIG. However, when using a thermal noise source this method is not practical, because it takes quite long to change the temperature of the load and the most convenient procedure is to acquire the power measurements at all frequencies with the load at one temperature and after that repeat the acquisition with the input load at a different load temperature. With this method is critical to have a very repeatable gain of the system between consecutive frequency sweeps, and the possible changes of the YIG filter are a big concern.

Figure 6 shows a simplified block diagram of the RF section. The instrument is provided with a low noise external preamp (U7227C, G=20-30 dB, NF=2-5dB) which can be used to reduce the noise of the receiver in the case of low gain DUTs. The preamplifier is connected to a USB port for biasing and to transfer calibration data and error conditions to the main instrument. Care should be taking with the output RF cable **(minimum bend diameter = 20 cm!)** to avoid permanent damage or degradation. This preamplifier was always used for our measurements as shown in figure 5.

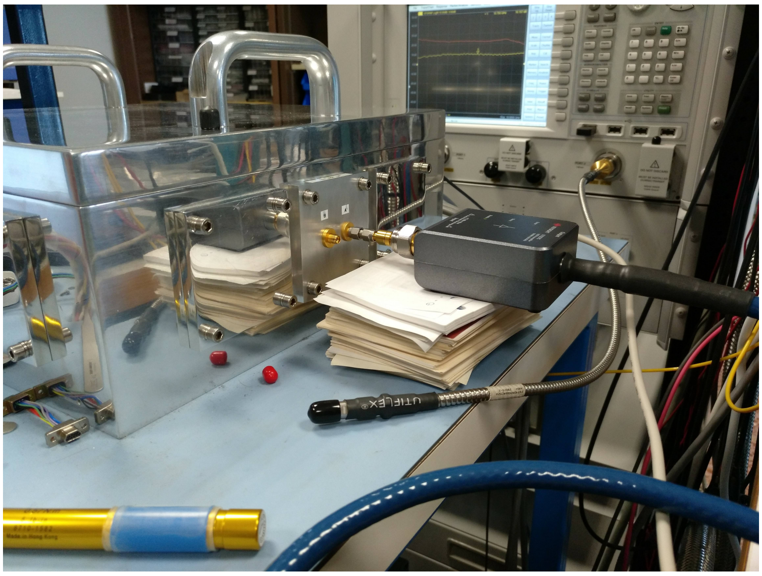

Figure 5: Connection of the external preamplifier of the NFA to the cryostat output.

The internal attenuator of the NFA can be changed from 0 to 40 dB in 4 dB steps. This attenuator is useful for detecting compression of the internal preamp (if used). A change in the attenuator requires re-calibration since it affects gain and noise figure of the receiver. For noise figure measurements the most useful values are from 0 to 8 dB because larger values increase the noise figure in excess and then it is more advantageous removing the internal preamplifier. The internal preamplifier gain is typically ≈30 dB with a noise figure of 9-12 dB (from Keysight Service Guide). Note that the YIG preselector is only used for high frequencies (>3.6 GHz). For frequency higher than 3.6 GHz there are two different sub-bands (which use different mixer and LO arrangements) inside the instrument with a breakpoint of 13.6 GHz.

The maximum selectable instantaneous bandwidth of the system for noise figure measurements is 8 MHz. We used an integration time of 0.5 sec/point to obtain sufficiently low fluctuations in power measurements.

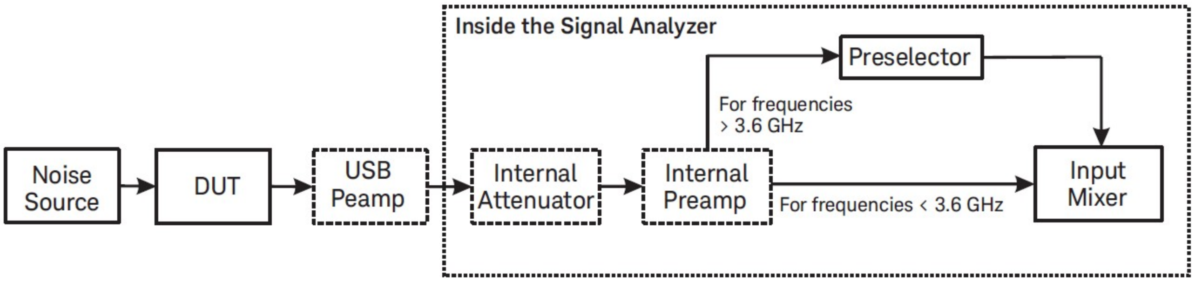

Figure 6: Block diagram[1] of the Keysight NFA 8975B Noise Figure Analyzer with an external optional USB preamplifier connected to the input.

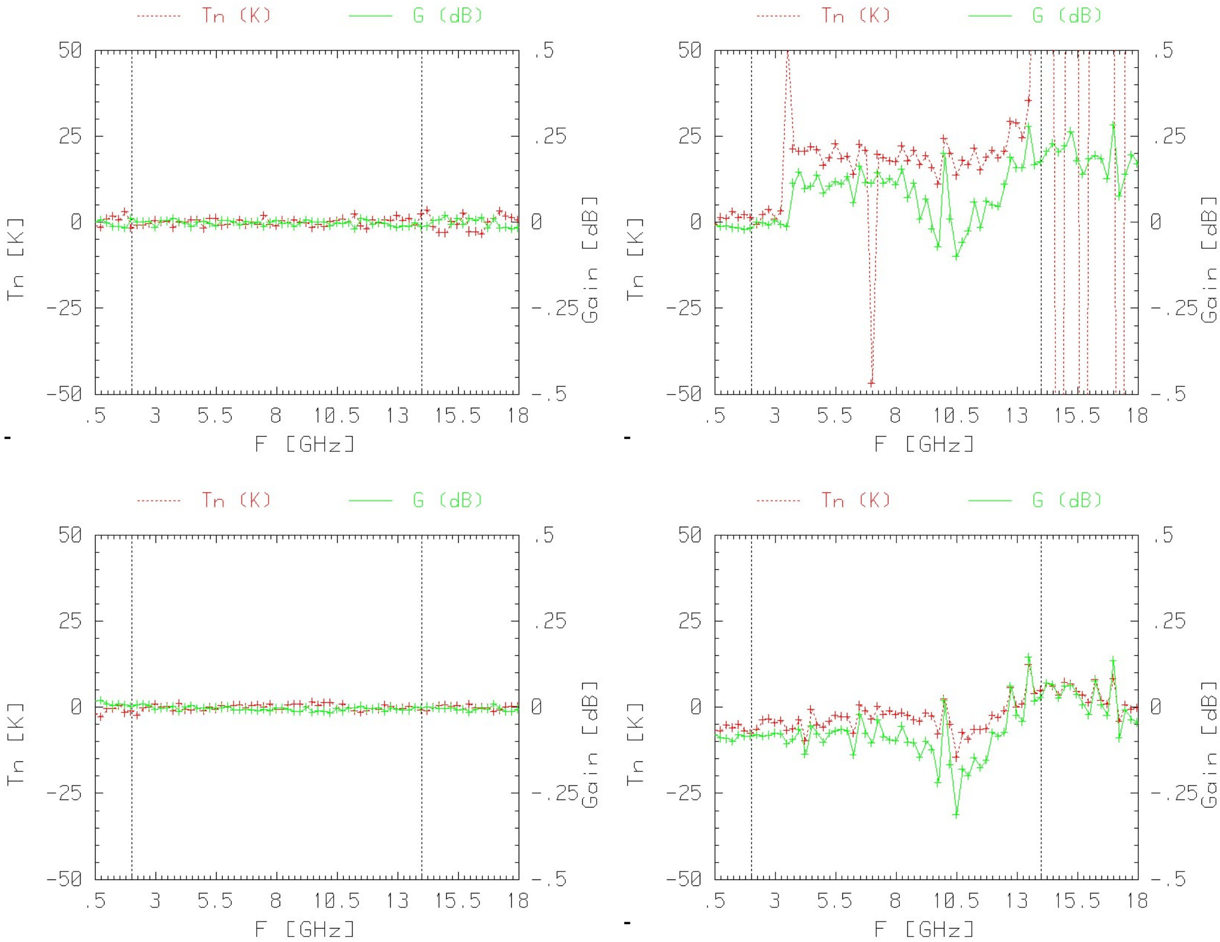

Figure 7: Stability of the NFA noise figure analyzer with external USB preamplifier and internal preamplifier OFF (up) and ON (down). Measurement of a thru connection just after calibration (left) and after 3 hr in a stable laboratory environment (right). Calibration performed with a 346A noise source directly connected the input of the external USB preamplifier.

[1] Reproduced from figure 2-15 of "N9069C Noise Figure Measurement Guide" Keysight manual, page 41.

The stability of the system was checked in the same way as in the PNA-X in two different configurations, with and without the internal preamplifier. It is extremely important for the stability to warm up the system for several hours and to maintain a stable ambient temperature in the laboratory. The automatic alignments should be turned OFF, especially between calibration and measurements and during the measurement. Otherwise the stability will deteriorate considerably. Figure 7 shows examples of the stability of the system as measured with a thru connection with/without the internal preamplifier. The effect of the YIG filter drift is clearly visible for frequencies greater than 3.6 GHz.

The NFA 8975B can be used configured with many combinations of internal and external (USB) preamplifiers and step attenuators. The best combination (in general) is the one which provides the lowest noise without gain compression. The lowest noise is obtained with the two preamps on and with 0 dB attenuator but with this it is easy to get into compression for wideband amplifiers of more than 10dB gain measured with a 5 dB ENR noise source. However, for the special configuration used in our measurements with the cryogenic heated load, the situation is quite different and it has been experimentally found that the two preamplifiers can be kept on without saturation. In practice, the lack of compression can be easily checked by comparing noise measurements with different values of attenuation or by removing the internal preamp. Details of this will be given in the measurement section. In case of excessive noise power the NFA generates errors which can be observed in the screen or captured by controlling programs.

5. Software for noise measurements

Two HTbasic computer programs, one for each instrument, were prepared for the data acquisition with the variable temperature cryogenic load and the PNA-X/NFA. In the case of the PNA-X, the only possibility for Y factor type measurement is using an external controller. The NFA has a manual mode which could, in principle, be used for this type of measurements, but the program makes the task much easier and convenient, reduces the chances of operator errors and adds the possibility of using a frequency dependant cold temperature (Tcold). Some of the main features of the programs are:

- The calibration of the instrument is stored in the computer disk. The last calibration can be recovered in case of computer crash.
- Unlimited length of ENR files.
- ENR frequency interpolation.
- PNA-X/NFA is simply used as a relative power meter. Calibration calculations are performed by the program. The information on the correction applied is available to the user.
- The complete frequency sweep is performed first with the noise source ON and later with the noise source OFF. The same sequence is used for calibration and measurement (to minimize hysteresis effects in YIG filter).
- Implementation of options for measurements with thermal hot/cold load (cryogenic), cold attenuator and standard noise diode.
- Automatic control of the temperature of the thermal load (using Lake Shore 336 controller), with adequate waiting time for stabilization.
- Option for the calibration of the ENR, Thot and Tcold of an unknown noise source using other noise diode or hot/cold calibration loads.
- Results (graphs and tables) are automatically stored in sequential files in the computer disk.

- Control of a multiplexer (34970A) for recording amplifier bias data with each measurement.

6. Measurements

The measurements presented correspond to these devices and instruments:

- Cryogenic amplifier: Y214G 1032 1 (at Tamb=15 K)
- Heated Load: YHL 201 17 Cal1
- Cryogenic Attenuator: YATF 102-15 (System 1020-3)
- Noise figure analyzer: N8975B s/n MY57471501
- Preamplifier: U7227C s/n MY56030243
- PNA-X: N5247A s/n US51370529 (with opt 029)
- Noise Source: 346A s/n 2814A01243
- Cryostat Sumitomo RDK 415D (4K)
- Temperature Controller: Lake Shore 336

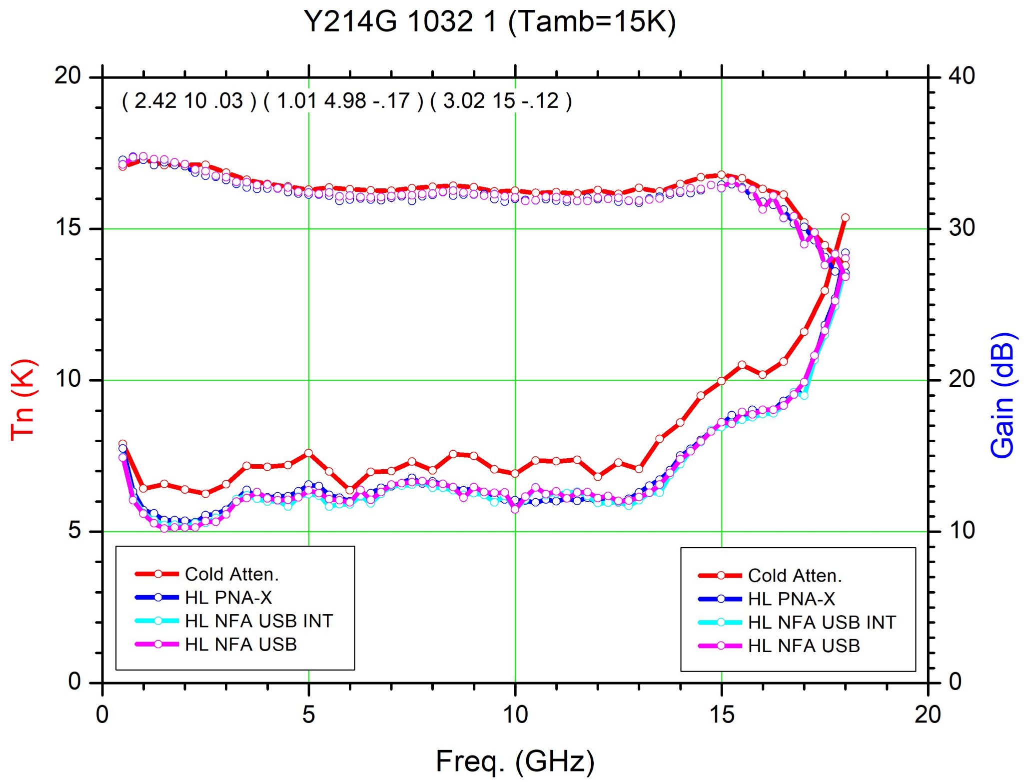

Figure 8: Comparison of the results of the noise temperature and gain of the amplifier Y214G 1032 1 (at Tamb=15 K) measured by the different methods. The measurements with the cold attenuator[2] are clearly higher.

Figure 8 presents the comparison of the results obtained in this test for the different configurations used for the heated load with previous measurements obtained with the cold

[2] The cold attenuator measurement was obtained in a different cryostat (system 1020-3) and with a different Noise Figure Analyzer (NFA N8975A with noise source SNS N4002A). This system was described in [5].

attenuator method [5]. The agreement of the PNA-X and the NFA is good in general and the values obtained with the cold attenuator are clearly higher (≈1K). We believe that there is a problem either in the calibration of the ENR of the cold attenuator or in its physical temperature. The values obtained with the NFA with and without internal preamp also agree well, demonstrating that there is no compression in the receiver. The noise curves obtained with the heated load are very smooth; although the one from the PNA-X looks more "clean" (this is not clearly seen with all the curves plotted in the same graph). We believe that this may be caused by the non-repeatability of the YIG filter.

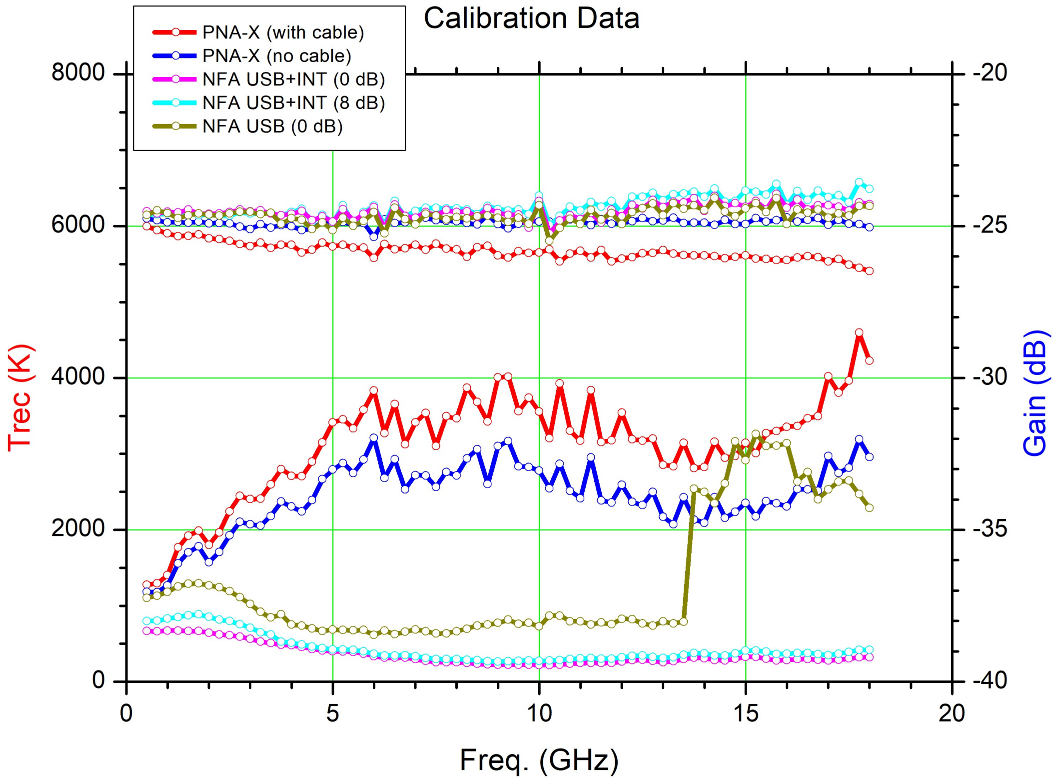

Figure 9: Calibration data (noise temperature and gain) of the PNA-X with/without input cable and of the NFA with different configurations of preamp and attenuators.

Figure 9 presents the calibration data of the PNA-X and the NFA in the different configurations. The contribution of the cable to the noise and gain of the PNA-X is clearly appreciable. The noise can go up to 4000 K in the high end of the band. The NFA with the two preamps (external and internal) shows a remarkably good noise temperature. The addition of the 8 dB attenuator degrades slightly the noise temperature. Removing the internal preamplifier raises the noise even more and then the band switching at 13.6 GHz becomes evident. For that band the noise becomes similar to the PNA-X.

Note the "glitches" in the gain curves of the NFA at approximately 6 and 10 GHz. These features also appear very often in noise temperature measurements and are more pronounced when the system drifts. We believe that they could be related with YIG filter issues.

The impact of the noise temperature of the instrument in the measurement of the DUT (amplifier) can be better appreciated in figure 10, which shows the correction (Trec/Gamp) subtracted to the system noise temperature to obtain the DUT noise temperature. For the

PNA-X the value is roughly 2 K in the middle of the band while for NFA with external and internal preamplifiers is in the 0.15K range. It is desirable to keep this correction low, since this will minimize any error introduced by gain measurements errors or drift in the instrument gain between calibration and measurement.

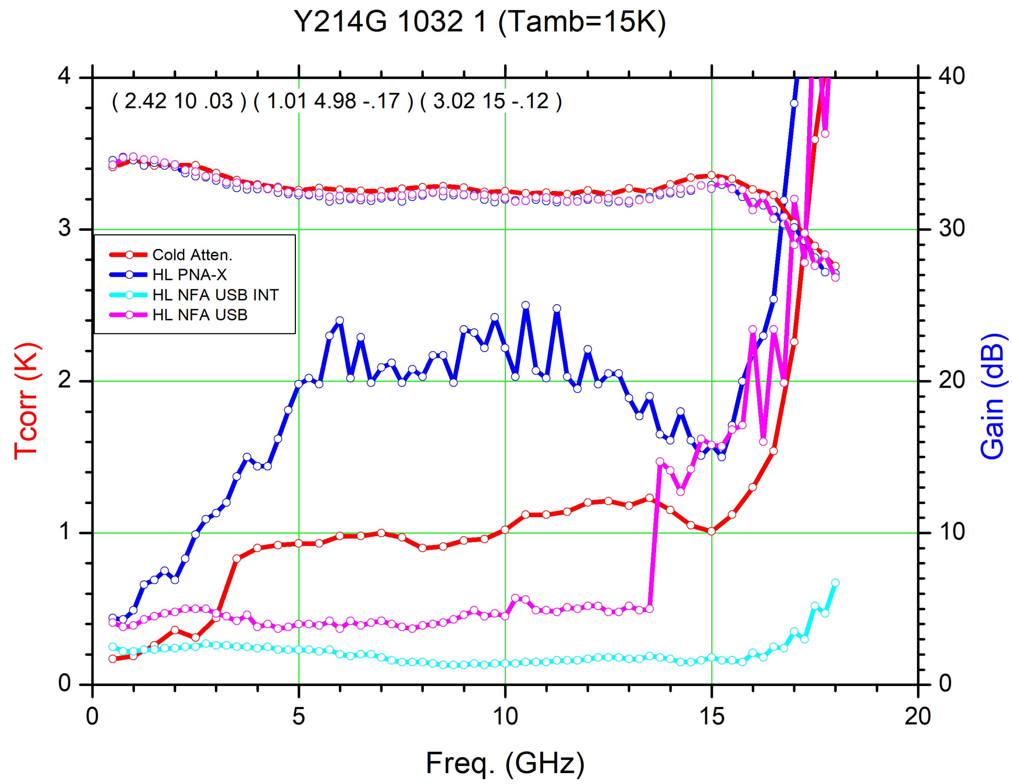

Figure 10: Noise temperature correction applied to obtain DUT data in figure 8 for the different configurations used.

7. Repeatability of measurements

Figure 11 presents the results of the repeatability of the noise and gain measurements. It can also be appreciated the superior "smoothness" and the absence of glitches in the PNA-X noise curves. There is also an effect of ripple in the gain measured with the NFA at freq>16 GHz which may be related with the input reflection of the external amplifier.

Some of the noise curves taken with the PNA-X show higher noise (up to 1K more at some frequencies). It is interesting to note that the highest noise values were obtained just after a calibration, and subsequent measurements yield progressively lower values until they converge with the values obtained by the NFA. We suspect that this may be an effect introduced by the flexible cable used, which needs to "accommodate" after being flexed for connecting the calibration noise diode. Appendix 1 presents an example of a calculation of this effect with

Despite the fact that the curves do not appear very smooth, the measurements obtained with the NFA show good repeatability (with and without the internal preamp).

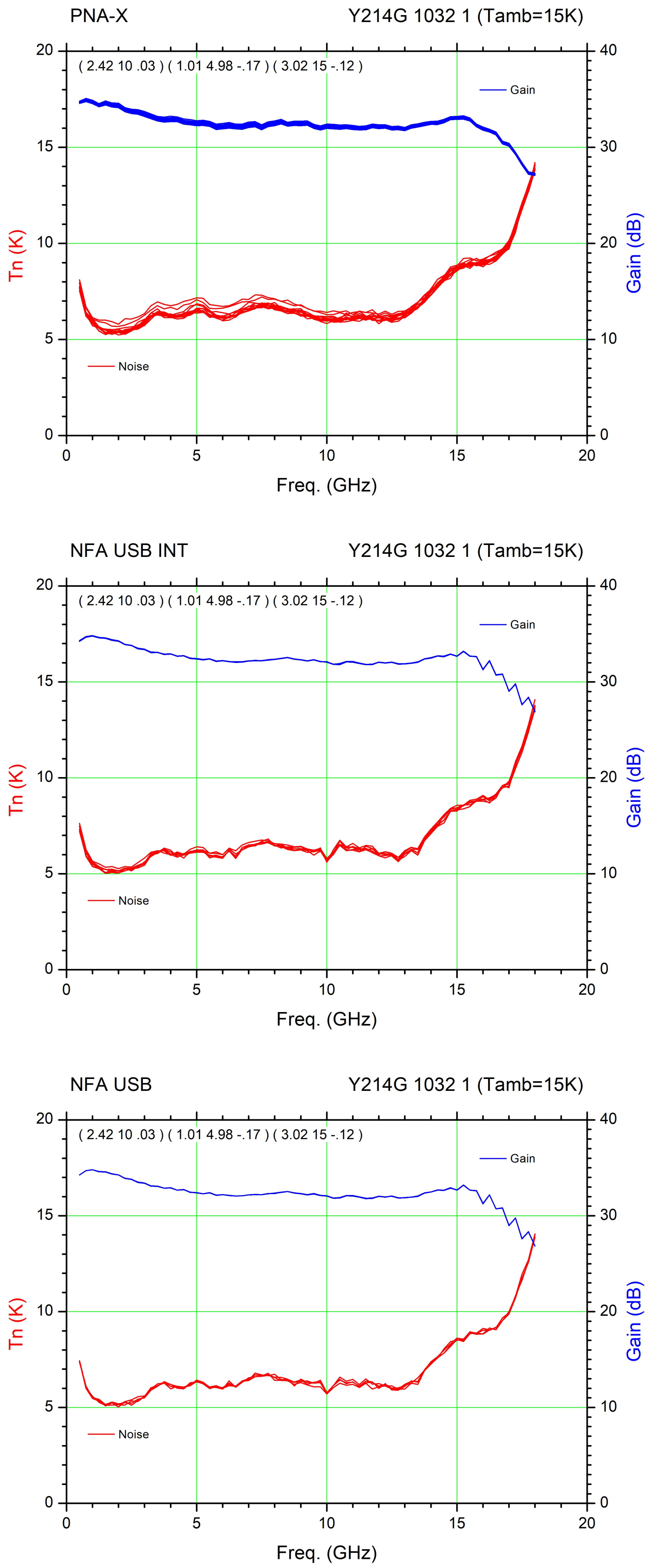

Figure 11: Comparison of the repeatability of noise and gain measurements with the PNA-X and the NFA with/without internal preamplifier.

8. Accuracy estimation

The accuracy of the measurements can be estimated by the Monte Carlo method [8]. An example of the results of this type of calculation with the parameters assumed for PNA-X is presented in Appendix II. The accuracy estimated in this case is ±0.8 dB for the gain and ±0.6 K for the noise temperature (at 2σ). The same values are applicable, in principle, to the NFA, since the error is dominated by the effect of the accuracies of the hot/cold loads. However, there are some parameters with a very important effect which may not be adequately taken into account in the calculation. For example, any variation of gain between the hot and cold measurement will have a great impact in the final error (0.1 dB will produce 1.3 K of error). Other important factor is the uncertainty in the cold load (0.5 K error in its physical temperature will yield 1.2 K error in the noise temperature).

9. Conclusions

Both the PNA-X and the NFA receivers can be used for noise measurements of cryogenic wideband amplifiers with variable temperature loads with good results.

With the models available in our laboratory, the PNA-X receiver covers the 10 MHz-50GHz range, while the NFA only the 10-MHz to 26.5 GHz.

The NFA can be used with the external (USB) and internal preamplifiers without saturation. In these conditions the receiver noise temperature is quite low and the correction needed to determine the noise of the amplifier is small. However, the noise curves obtained are not totally smooth.

The PNA-X internal preamplifier is optimized up to 50 GHz and, as a side effect, the noise at lower frequency cannot be very good. The compression regime can be easily reached and it is not easy to use additional preamplifiers to further reduce the system noise. The corrections needed to obtain the temperature of the amplifier are larger than in the NFA. The noise curves obtained are very smooth.

The PNA-X has to be connected by a coaxial cable to the cryostat. The variations of the cable may be the cause of some repeatability problems found in the measurements.

The maximum instantaneous noise bandwidth of the PNA-X is 24 MHz and the one of the NFA is 8 MHz. That makes possible to make frequency sweeps faster in the PNA-X than in the NFA.

10. References

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11. Appendix I

MathCAD file with an example of the effect of variation of gain and noise temperature of the receiver in the measurement of noise of a cryogenic amplifier with PNA-X.

Effect of change in GAIN and NOISE of measurement system in noise temperature measurements with heated load

The change in the gain and noise temeperature of the measurement receiver between calibration and measurement changes the value of the measurements taken with heated load

$Trec := 4000$ $\Delta GdB := 0.50$ Change in GAIN: (G_mea - G_cal)

$\Delta Trec := 100$ Change in Trec: (Trec_mea - Trec_cal)

$Thmea := 45$ $Tcmea := 25$ $Tamp := 7$ $GampdB := 30$

CALCULATION

$\Delta G := 10^{\frac{\Delta GdB}{10}}$ $\Delta G = 1.122$ $Gamp := 10^{\frac{GampdB}{10}}$ $Gamp = 1 \times 10^{3}$

$Phmea := [Gamp \cdot (Thmea + Tamp) + (Trec + \Delta Trec)] \cdot \Delta G$ $Phmea = 6.295 \times 10^{4}$

$Pcmea := [Gamp \cdot (Tcmea + Tamp) + (Trec + \Delta Trec)] \cdot \Delta G$ $Pcmea = 4.05 \times 10^{4}$

$Y := \frac{Phmea}{Pcmea}$ $Tsys := \frac{Thmea - Y \cdot Tcmea}{Y - 1}$ $Tsys = 11.1$

$Gdut := \frac{Phmea - Pcmea}{Thmea - Tcmea}$ $GdutdB := 10 \cdot \log(Gdut)$ $GdutdB = 30.5$

$Tdut := Tsys - \frac{Trec}{Gdut}$ $Tdut = 7.535$

12. Appendix II

MathCAD file with an example of the calculations of the noise and gain measurement errors for the case of the PNA-X.

ERROR IN NOISE MEASUREMENTS FOR HEATED LOAD METHOD

$dB \equiv 1 \quad Hz \equiv sec^{-1} \quad MHz \equiv 10^{6} \cdot Hz \qquad K \equiv 1 \qquad Nsd \equiv 2$ (number of standard deviations for error calculation)

Noise source for calibration:

$ENRc := 5.1 \cdot dB$	ENR of calibration noise source
$\Delta ENRc := 0.13 \cdot dB$	Error in ENR of calibration noise source
$\Gamma cmaxdB := -23 \cdot dB$	Worst case reflection coefficient
$\Gamma cdifdB := -50 \cdot dB$	Worst case change in reflection coefficient
$Tamb := 297 \cdot K$	Ambient temperature of calibration noise source
$\Delta Tamb := 3 \cdot K$	Error in ambient temperature of calibration noise source

Noise source for measurement:

$Tcryo\_h := 45 \cdot K$	Temperature of heated load
$\Delta Tcryo\_h := 0.2 \cdot K$	Error in temperature measurement
$Tcryo\_c := 25 \cdot K$	Temperature of non heated load
$\Delta Tcryo\_c := 0.2 \cdot K$	Error in temperature measurement
$\Gamma mmaxdB := -20 \cdot dB$	Worst case reflection coefficient of load (no change with temperature)

Receiver parameters:

$Trec := 4000 \cdot K$	Noise temperature of receiver for mached load
$Tiso := 297 \cdot K$	Temperature of input isolator
$\Gamma rmaxdB := -20 \cdot dB$	Input reflection of receiver (worst case)
$B := 24 \cdot MHz$	Bandwith of receiver filter
$t := 0.25 \cdot sec$	Integration time of receiver
$\Delta Gc := 0.15$	Error in gain form calibration to measurement (attenuator in NFM)
$\Delta G := 0.001$	Error in gain from hot to cold measurement (detector in NFM)

Amplifier parameters:

$S11dB := -5 \cdot dB$	Input reflection of amplifier
$S12dB := -50 \cdot dB$	Reverse transmision of amplifier
$S21dB := 32 \cdot dB$	Gain of amplifier
$S22dB := -10 \cdot dB$	Output reflection of amplifier
$Tdut := 7 \cdot K$	Noise temperature of amplifier

Monte Carlo calculations:

$$Gmeas_i := \frac{(N2M_i - N1M_i)\cdot(THC - TCC)}{(N2_i - N1_i)\cdot(Thm_i - TCM)}$$

$\text{mean}\left[\overrightarrow{(10\cdot\log(Gmeas))}\right] = 31.992$

$Nsd\cdot\text{stdev}\left[\overrightarrow{(10\cdot\log(Gmeas))}\right] = 0.806$

$\max\left[\overrightarrow{(10\cdot\log(Gmeas))}\right] = 32.949$

$\min\left[\overrightarrow{(10\cdot\log(Gmeas))}\right] = 31.092$

measured gain of amplifier (in dB)

$$YC_i := \frac{N2_i}{N1_i} \qquad Trmeas_i := \frac{THC - YC_i\cdot TCC}{YC_i - 1}$$

$\text{mean}(Trmeas) = 4.064\times 10^3$

$Nsd\cdot\text{stdev}(Trmeas) = 158.114$

$\max(Trmeas) = 4.33\times 10^3$

$\min(Trmeas) = 3.826\times 10^3$

measured receiver noise temperature

$$YM_i := \frac{N2M_i}{N1M_i} \qquad Tsysmeas_i := \frac{THM - YM_i\cdot TCM}{YM_i - 1}$$

$\text{mean}(Tsysmeas) = 9.611$

$Nsd\cdot\text{stdev}(Tsysmeas) = 0.801$

$\max(Tsysmeas) = 11.029$

$\min(Tsysmeas) = 8.455$

mesured system noise temperature

$$Tdutmeas_i := Tsysmeas_i - \frac{Trmeas_i}{Gmeas_i}$$

$\text{mean}(Tdutmeas) = 7.032$

$Nsd\cdot\text{stdev}(Tdutmeas) = 0.644$

$\max(Tdutmeas) = 8.087$

$\min(Tdutmeas) = 6.137$

measured amplifier noise temperature