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# Comparison of Noise Measurement Results with Three Different Cryogenic Variable Temperature Loads

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# Change Record

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# 1. Introduction

This report presents the comparison of the results obtained with three different cryogenic variable temperatures loads of the type used for noise temperature measurements of cryogenic amplifiers. The device tested was 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. We consider the comparison meaningful in the 2-14 GHz range in which the amplifier noise is low and the gain is high. Two of the loads used have been assembled and calibrated recently using exactly the same procedure and are used in a servo controlled mode to stabilize the temperatures of the chip using the integrated sensor and heater. The third one is an old prototype unit which was originally used in open loop mode (no temperature control) with a regular power supply for the heater and a 4-wire Ohm capable precision multimeter for sampling the sensor. This prototype unit cannot be used with the temperature controller because, due to an accidental ESD arcing event, there is a conduction path between the sensor and the heater (the temperature controller requires a totally floating sensor for proper operation).

The two newer loads are used at temperatures of 25 and 45 K and the time required for thermal stabilization is around 15-30 seconds (from cold to hot or hot to cold). The older load was used with a) no power applied (≈14 K) and b) with the maximum voltage estimated for safe operation (≈51K with 20 V). The sensitivity of the PTC resistor used for sensing the chip temperature is reduced very fast at low temperature and that makes unreliable its use below 20 K. For this reason, the temperature of the old load in the “off” state was always obtained from a calibrated diode sensor attached to the box and not from the integrated sensor. In all the cases the temperature of the amplifier measured was stabilized at 15 K with an independent control loop.

# 2. Variable temperature cryogenic loads

All the heated loads are built with the same chip design described in [1]. For the measurements reported here they were fitted with identical 2.92 mm male connectors which could be directly attached to the input of the amplifier. An additional tuning in YHL 201 was made using 250 µm width gold ribbon.

The photo of a connectorized load is shown in figure 1. Figure 2 shows the reflection for the loads at room and cryogenic temperature up to 50 GHz.

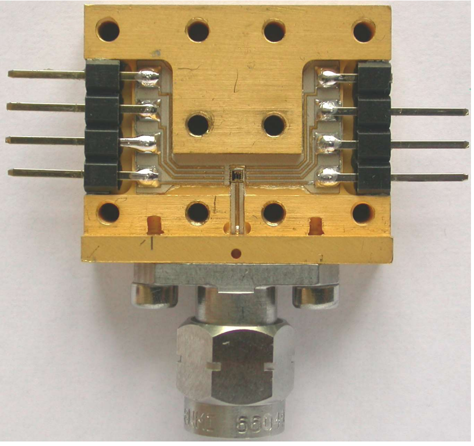

**Figure 1:** Example of a load mounted in a test fixture. Sense and power lines are connected to the left and right side of the chip, respectively. A 50 ohms line connects the chip to the RF connector (bottom).

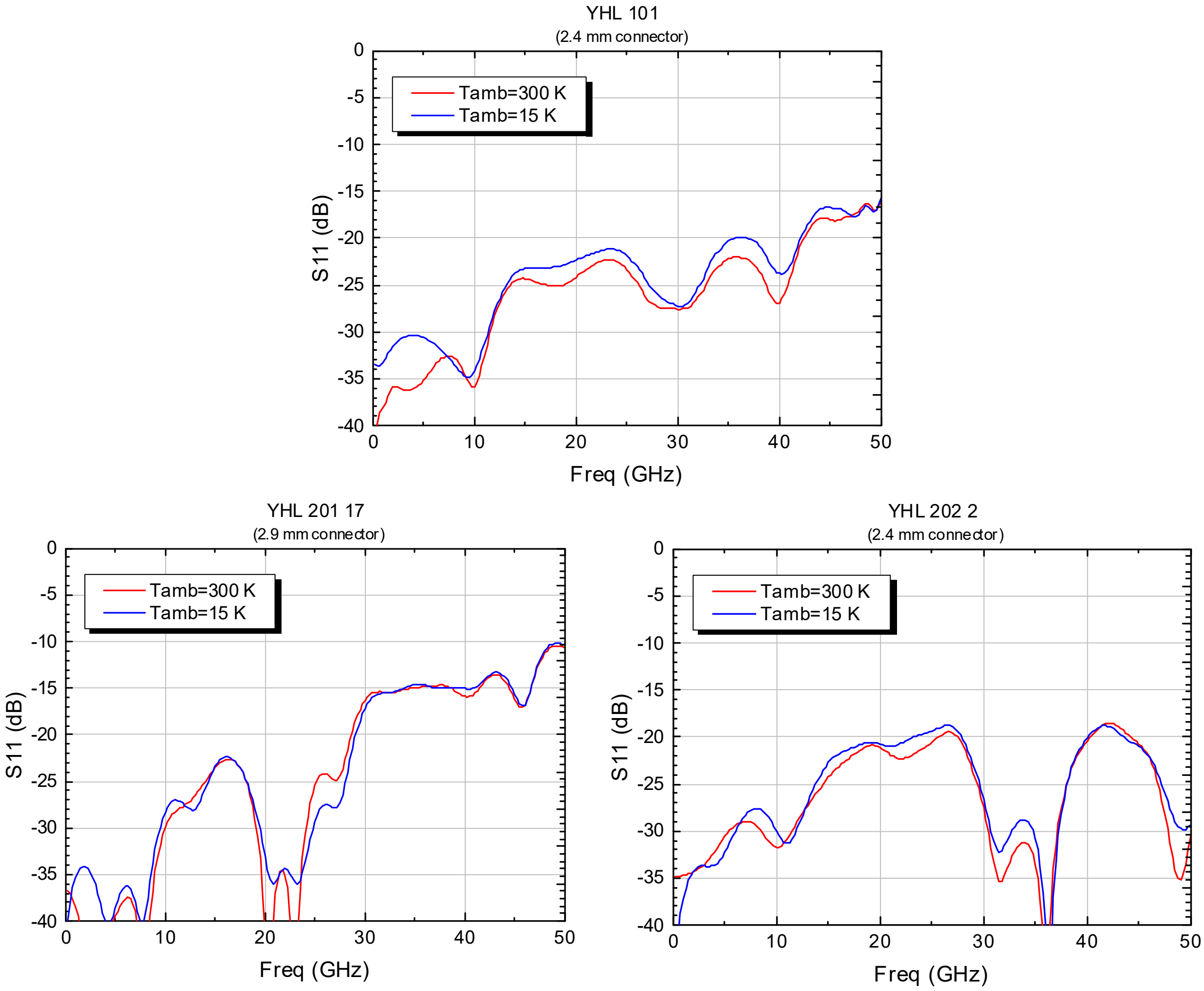

**Figure 2:** Reflection of the different loads at room (red) and cryogenic (blue) temperature. Note that YHL 201 was only tested using 2.9 mm connectors.

There are some subtle differences between the loads which are summarized in table I. Note that the thermal resistance (power needed for a temperature increment) is different in each unit.

## Table I

*Differences of the heated loads. Tc and Th are the physical temperatures used for the cold and hot states, P@Th is the power dissipated in the heater to obtain Th and Rth is the estimated thermal resistance (from the heather to the thermal sink) at Th.*

| s/n | Box | Input circuit | Tc (K) | Th (K) | P (mW) @ Th | Rth (K/W) @ Th |
|---|---|---|---|---|---|---|
| **YHL 201** | Brass | Quartz (In#290) | 25.0 | 45.0 | ~400 | ~75 |
| **YHL 202** | Brass | Quartz (epoxy) | 25.0 | 45.0 | ~625 | ~48 |
| **YHL 101** | Brass | Duroid (epoxy) | 13.7 | 51.3 | ~400 | ~94 |

The on–chip PTC sensors were calibrated by measurements of their resistance while cooling or heating the cryostat. It was found more adequate to use a controlled heating procedure (1K/min) for data acquisition, since the system cools too fast when below 50K and then there are large temperature gradients within the different components. Figure 3 presents the calibration data acquired during cooling and heating of the last two heated loads. Note that the sensitivity drops quite abruptly below 50 K and almost vanish at 4 K. The sensitivity at high temperature (slope of the R-T curve) is slightly different in the two units.

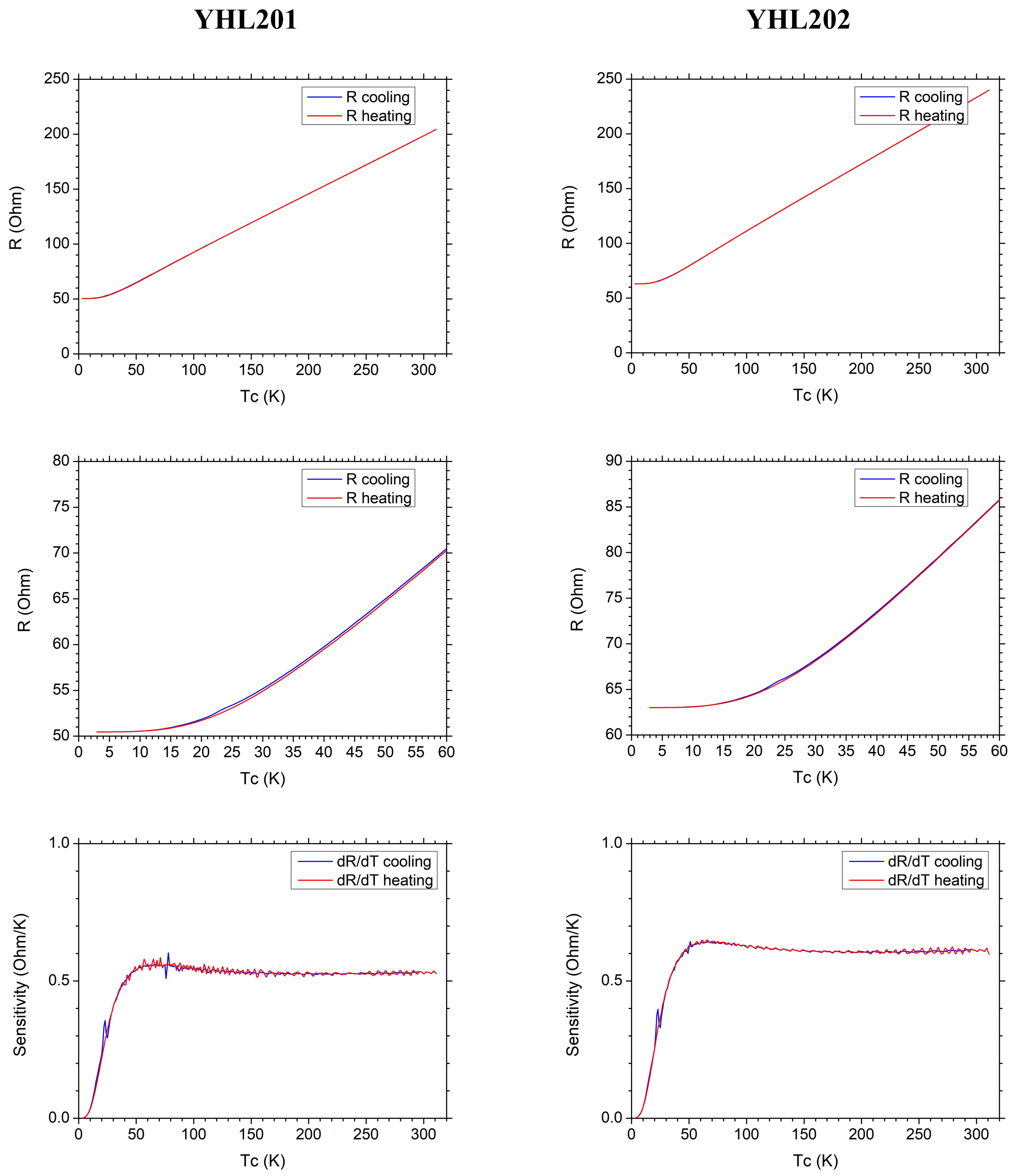

**Figure 3:** Calibration curves (R vs. T) and sensitivity (dR/dT vs. T) of the PTC sensors integrated in two of the heated loads. There is a small discrepancy of the curves obtained during heating and cooling which can be explained by the different speeds of the cooling and heating procedures (see text).

# 3. Concerns related to calibration

The precise knowledge of the temperature of the 50 Ohm termination is critical for the accuracy of the noise measurements [1]. As the calibration is based on the comparison of resistance readings of the chip PTC sensor with the temperature reading of a diode sensor attached to the box of the heated load, an experiment with two sensors (one in the bottom and other on the top of the box) was carried out to check the uniformity of the temperature. The two diode sensors were previously calibrated respect to a common standard to avoid additional uncertainties. Figure 4 shows the results of this experiment. Note that, even if we restrict the data to the heating curves, temperature differences of ±0.2 K are found for temperatures below 50 K. This could be, in absence of other effects, a limit of the accuracy of the calibration.

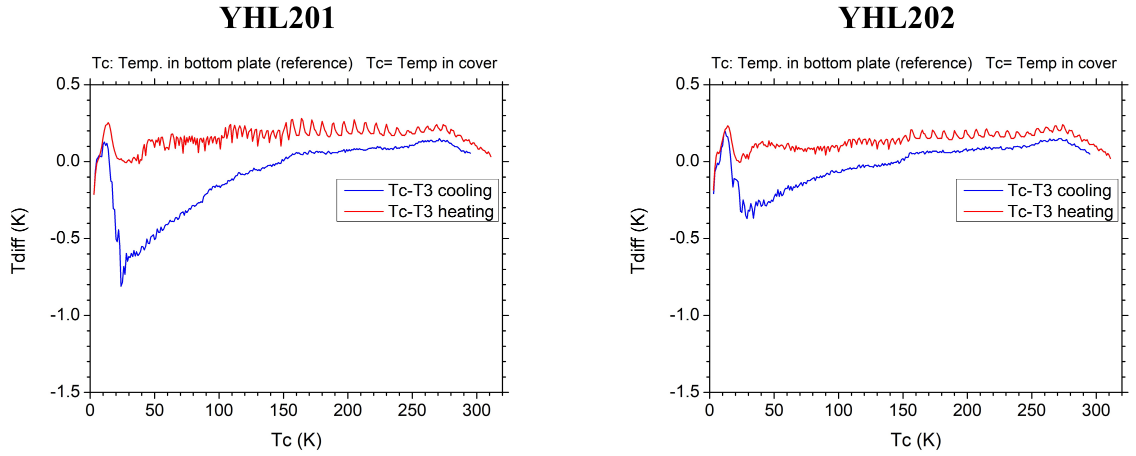
**YHL201** **YHL202**

**Figure 4:** Temperature difference of two diode sensors attached to the heated load (top and bottom). The temperature gradient observed in the box sets a limit to the confidence in the calibration of the heated load sensor.

Other problem which is neglected when using the on-chip PTC sensor is the self-heating effect. The resistance is measured in a 4-wire ohm configuration applying a constant current of 1 mA[1] [2]. The power dissipation depends on the temperature, but it is in the ~0.05-0.25 mW range. The temperature rise on the chip will depend on how much of this power is transferred by conduction and how much is radiated to the surroundings.

One way to quantify the importance of self-heating is to measure the resistance of the PTC sensor as a function of the current used for the measurement. The self–heating should manifest as a dependence of the measured resistance with the power dissipated (proportional to the current squared). The temperature controller does not allow changing the current, but it can be done with a precision source/measure unit[2]. The results of this experiment on a heated load[3] are presented in figure 5.

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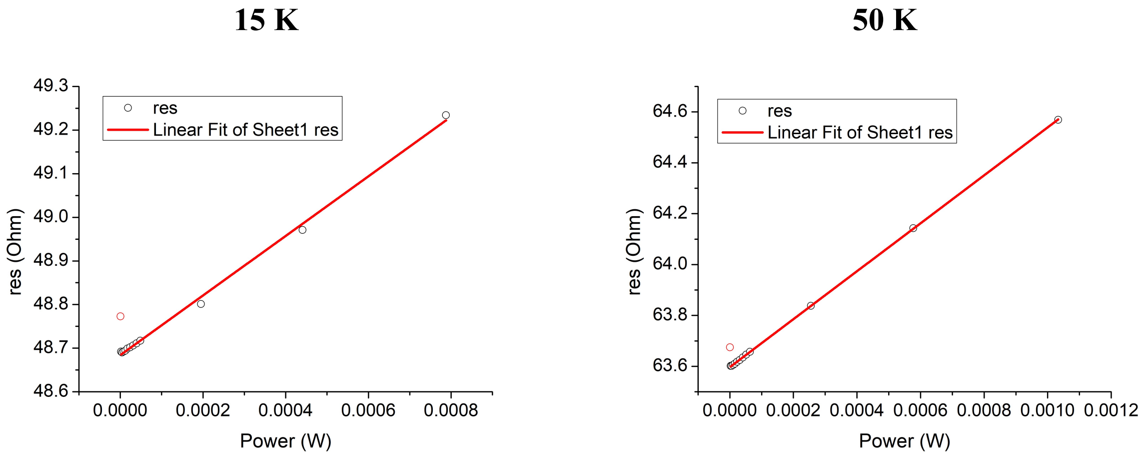
[1] The value of 1 mA of current applies for the LS 336 temperature controller as well as for the HP 34401 A multimeter used for 4-wire measurement of the resistance.

[2] The instrument used for this measurement was a Keysight B2912A.

[3] The heated load mentioned here was a different module which was accidentally damaged in other experiment. However, its characteristics are very similar to YHL201 and YHL202.


15 K

50 K

**Figure 5:** Sensor resistance of a heated load module as a function of the self dissipated power, showing a clear linear dependence. The highest point of power corresponds to a current of 4 mA.

If we assume a perfect (cero thermal resistance) thermal contact between the PTC sensor and the semiconductor chip, all the heat dissipated in the sensor would be transferred to the chip and the temperature rise will be the same in both. The effect of this increment of temperature on the noise measurements is easy to analyze (assuming all the components in the chip at the same temperature). The calculations for this effect are developed in appendix I. There it is shown that for the particular case of a 7 K noise temperature amplifier the noise value measured would be ~0.5 K higher.

However, there are strong indications that the thermal contact of the PTC with the chip is far from perfect. Using the data of figure 3 and the calibration table of the sensor (R vs. T), one can estimate the thermal resistance between the sensor and the thermal sink. As an example (see data in the appendix I) at ~50 K and with a sensor current of 1 mA (P=63.6 μW), the temperature increment is ~0.11 K, yielding an estimated thermal resistance of $1.7\times10^3$ K/W. This value is much higher than any of the thermal resistances shown in table I. The conclusion is that the thermal contact between the sensor and the chip is far from perfect and this may have some impact on the accuracy of the measurements. The problem of having a high thermal resistance between the sensor and the chip is that then it is more susceptible to perturbation by other effects like coupling to thermal radiation of the surroundings.

Other indication of the poor coupling between the PTC sensor and the chip was based on noise temperature measurements. The experiment consisted in measuring the output noise power with and without the 1 mA sensor excitation. Although the experiment was not very rigorous, the noise increment was not detected.

# 4. Measurements

The measurements presented in Table II and figure 6 correspond to these devices and instruments:

| | |
|---|---|
| - Cryogenic amplifier: | Y214G 1032 1 (at Tamb=15 K) |
| - Noise figure analyzer: | N8975B s/n MY57471501 |
| - Preamplifier: | U7227C s/n MY56030243 |
| - PNA-X: | N5247A s/n US51370529 (with opt 029) |
| - Calibration Noise Source: | 346A s/n 2814A01243 |
| - Cryostat | Sumitomo RDK 415D (4K) |
| - Temperature Controller: | Lake Shore 336 |

**Table II**

*Noise temperature of the amplifier Y214G 1032 1 (at Tamb=15 K) measured with the three different loads. Tn is the average noise in the 2-14 GHz band. The instrument used (PNA-X or NFA) and the values of the hot and cold temperatures are also given. The increment respect to the lowest noise temperature appears in the last column.*

| **Heated Load s/n** | Tc (K) | Th (K) | Tn (K) | ΔTn (K) |
|---|---|---|---|---|
| **YHL 201 (PNA-X)** | 25.0 | 45.0 | 6.22 | +0.10 |
| **YHL 201 (NFA)** | 25.0 | 45.0 | 6.12 | +0.00 |
| **YHL 202 (PNA-X)** | 25.0 | 45.0 | 6.68 | +0.56 |
| **YHL 202 (NFA)** | 25.0 | 45.0 | 6.60 | +0.48 |
| **YHL 101 (PNA-X)** | 13.7 | 51.3 | 7.51 | +1.39 |
| **YHL 101 (NFA)** | 13.7 | 51.3 | 7.50 | +1.38 |

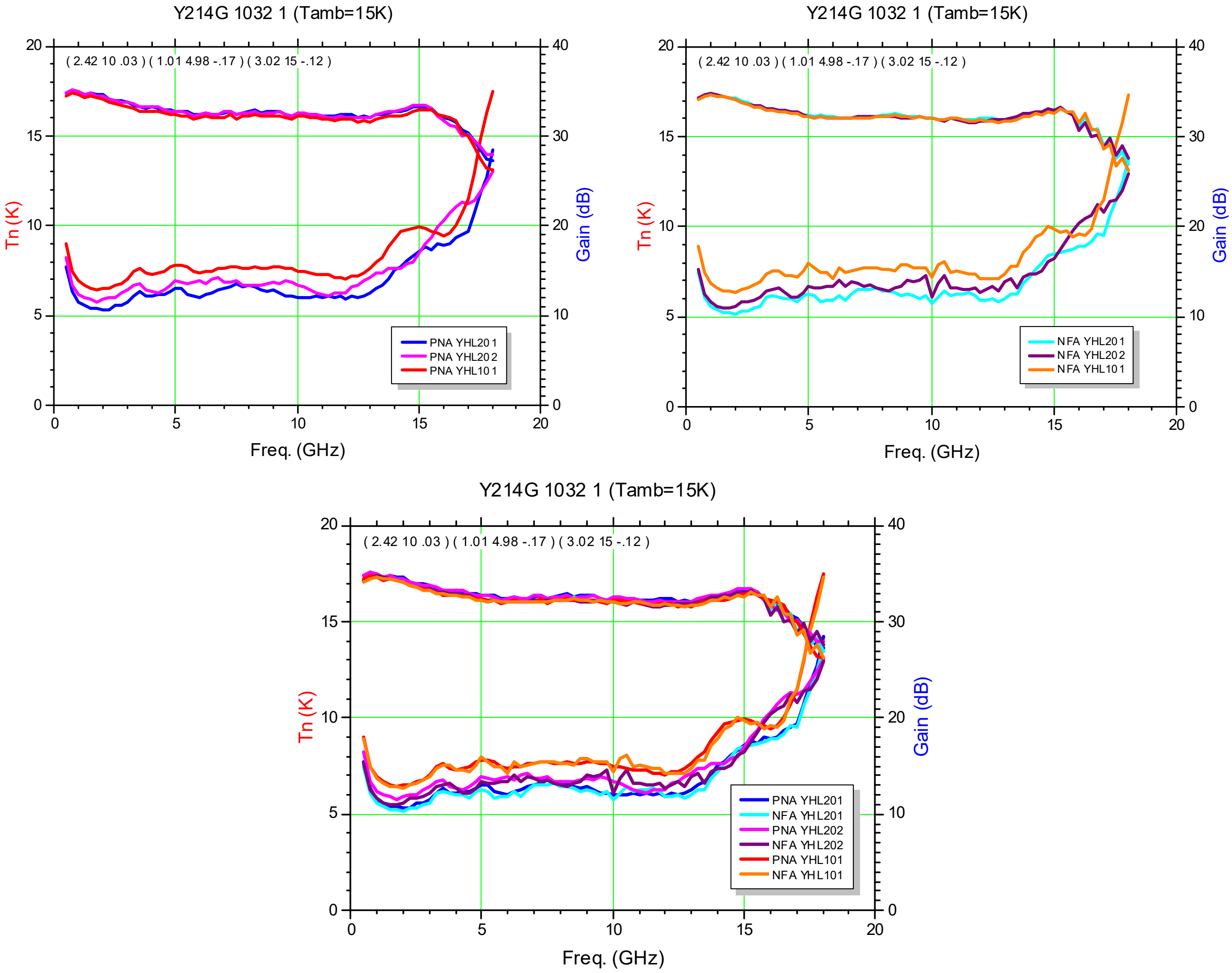


**Figure 6:** Noise and gain results at cryogenic temperature for amplifier Y214G 1032 measured with the PNA (top left) and the NFM (top right). The complete set of measurements is also shown (bottom).

# 5. Conclusions

The noise temperature measurements of a wide band amplifier obtained with three different cryogenic heated loads have been compared. Two of them were recently built and calibrated and were operated with a PID controller used to stabilize the temperature. The third one was an early prototype with some electrical deficiencies which could only be operated in open loop.

The results obtained show some differences in the noise ripple in the band which can be explained by the different output reflection coefficient of each load.

The difference of average noise temperature obtained in the 2-14 GHz band with the two newer loads is ~0.5 K. This discrepancy is not higher than the estimated absolute accuracy of the measurements (±0.6 K from [1]), although we expected better agreement. The result with the older load was worse, with a discrepancy of ~1.4 K respect to the best of the new ones. The reasons for this are not understood, although the electrical problems of the chip (communication between the sensor and the heater) may play a role.

We started suspecting on possible problems related with the determination of the temperature of the 50 Ohm termination with the PTC sensor. Very small errors in this parameter may greatly compromise the accuracy of the noise measurement.

To gain insight into the problem, the effect of self-heating of the PTC sensor was considered. In this process we got strong evidence that there may be a high thermal resistance between the sensor and the chip. This opens the possibility of a poor coupling of the sensor to the real temperature of the termination and some (difficult to quantify) coupling to the surrounding thermal radiation. More work may be needed to clarify this issue.

# 6. References

[1] J. D. Gallego, R. Amils, C. Diez González, I. López, I. Malo, “Using Keysight PNA-X and NFA Noise Receivers for Noise Temperature Measurements with Cryogenic Variable Temperature Loads”, CDT Technical Report 2019-17. http://www1.oan.es/reports/doc/IT-CDT-2019-17.pdf

[2] “User’s Manual Model 336 Temperature Controller”, Lake Shore Cryotronics, Inc., Rev. 2.0 P/N 119-048 25 July 2017, p 7. https://www.lakeshore.com/docs/default-source/product-downloads/336_manual0ebc9b06cbbb456491c65cf1337983e4.pdf?sfvrsn=2e8633a3_1

# 7. Appendix I

MathCAD file with an example of the calculation of the effect of self-heating of the integrated PTC sensor of the heated load on the noise temperature measurements. This example assumes a perfect (cero thermal resistance) thermal contact between the sensor and the semiconductor chip. It is consider that all the heat dissipated is transferred to the chip and the temperature rise will be the same in both. Note that due to the facts exposed in section 3 (high thermal resistance between the sensor and the thermal sink) this situation appears to be highly unrealistic. However, since the calculation procedure is straightforward and the values obtained are useful for estimating the order of magnitude of the errors involved, it has been considered interesting to include these results.

# ERROR IN NOISE TEMPERATURE DUE IN HEATED LOAD CAUSED BY SENSOR CURRENT HEATING

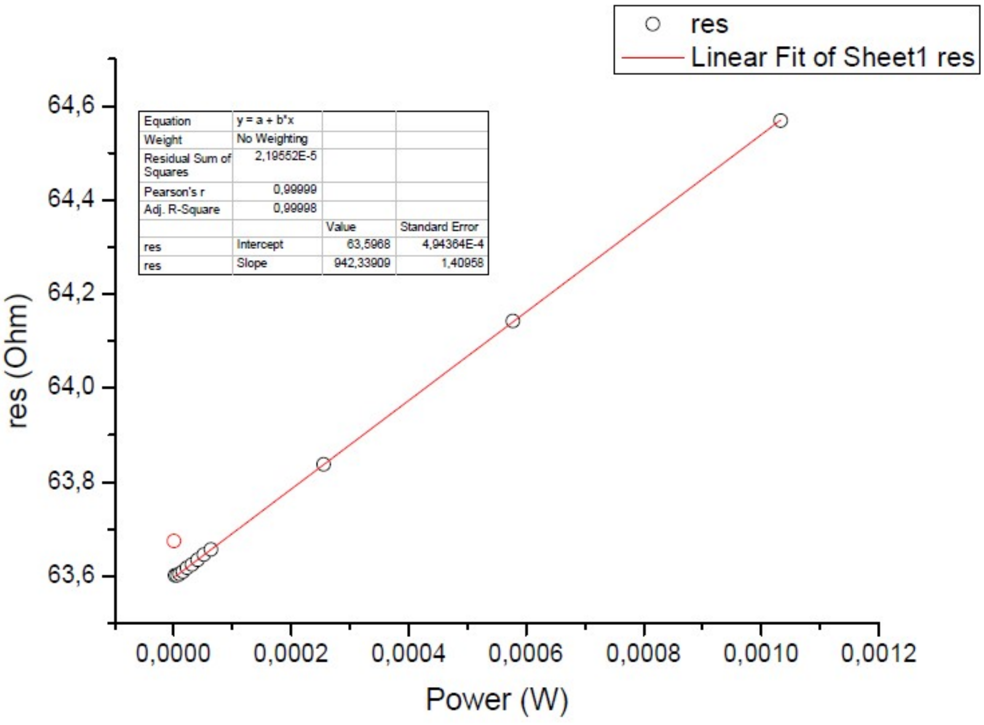
The resistance of the heated load sensor is measured by applying a 1mA current (nominal) and measuring the voltage. This current could, in principle, can increase the temperature of the heated load respect to the value calibrated (by measurements of temperature with an independent diode sensor outside of the box). The following values have been determined by measurements of the resistance at different currents with a SMU (the value at 0 mA has been extrapolated):

| | | | |
|---|---|---|---|
| 0 mA | 48.648 Ohm | 13.753 K | |
| 1 mA | 48.103 Ohm | 14.103 K | ΔTc_1 = 0.350 K |
| 4 mA | 49.234 Ohm | 17.842 K | ΔTc_4 = 4.089 K |
| 0 mA | 63.597 Ohm | 51.349 K | |
| 1 mA | 63.657 Ohm | 51.458 K | ΔTh_1 = 0.109 K |
| 4 mA | 64.569 Ohm | 53.097 K | ΔTh_4 = 1.748 K |

(The conversion from resistance to temperature was performed using the calibration table of the sensor)

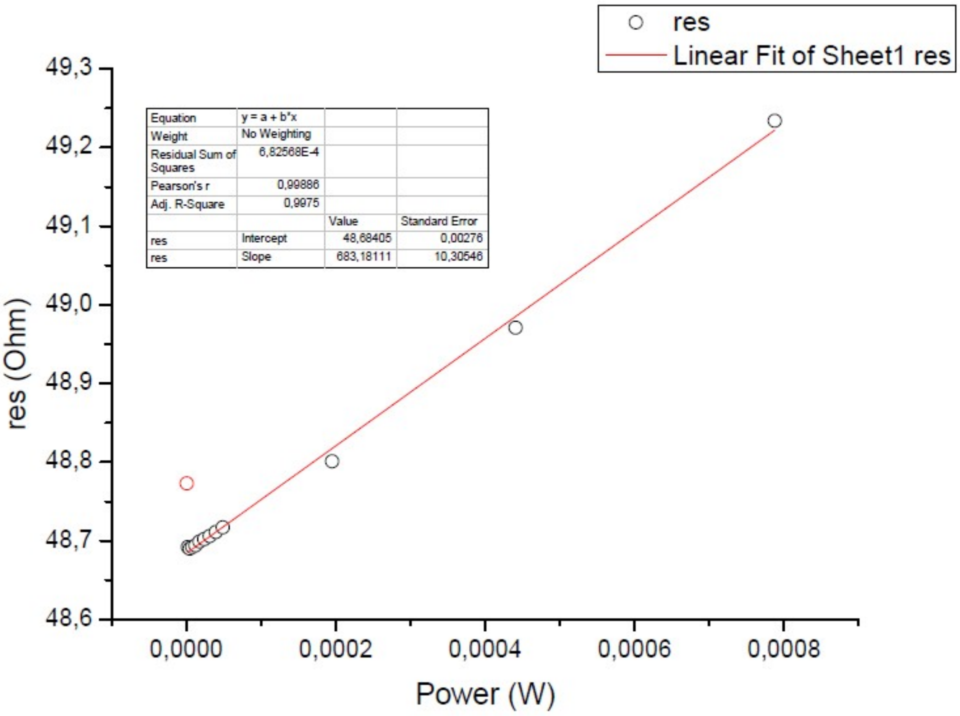
This means that the SENSOR MAY BE HOTTER than it is assumed and this causes an error in the value of the noise temperature obtained in the measurement.

In the following calculation we will assume that the 50 Ohm termination (noise generator) will be also heated by the sensor current. Note that the current of the multimeter for the Ohms scale used is 1 mA.



| | | | |
|---|---|---|---|
| Equation | y = a + b*x | | |
| Weight | No Weighting | | |
| Residual Sum of Squares | 2,19552E-5 | | |
| Pearson's r | 0,99999 | | |
| Adj. R-Square | 0,99998 | | |
| | | Value | Standard Error |
| res | Intercept | 63,5968 | 4,94364E-4 |
| res | Slope | 942,33909 | 1,40958 |

Measured resistance vs power applied to sensor @ Tbox = 50 K



| | | | |
|---|---|---|---|
| Equation | y = a + b*x | | |
| Weight | No Weighting | | |
| Residual Sum of Squares | 6,82568E-4 | | |
| Pearson's r | 0,99886 | | |
| Adj. R-Square | 0,9975 | | |
| | | Value | Standard Error |
| res | Intercept | 48,68405 | 0,00276 |
| res | Slope | 683,18111 | 10,30546 |

Measured resistance vs power applied to sensor @ Tbox = 15 K

## Effect in noise calculation

$$Y = \frac{(Tn + Th)}{(Tn + Tc)} \qquad (1)$$

$$Tn = \frac{Th - Y \cdot Tc}{Y - 1} \qquad (2)$$

Real value of Tn $Tn := 7$

## For I=1 mA

Values of the temperatures calibrated $Th\_0 := 51.349$ $Tc\_0 := 13.753$

Values of real temperatures at 1 mA: $Th\_1 := 51.458$ $Tc\_1 := 14.103$

Y factor measured: $Y := \frac{Tn + Th\_1}{Tn + Tc\_1}$ $Y = 2.77$

Value of Tn calculated $Tn\_c := \frac{Th\_0 - Y \cdot Tc\_0}{Y - 1}$ $Tn\_c = 7.486$

Error in measured noise temperature: $Tn\_c - Tn = 0.486$

## For I=4 mA

Values of the temperatures calibrated $Th\_0 := 51.349$ $Tc\_0 := 13.753$

Values of real temperatures at 1 mA: $Th\_1 := 53.097$ $Tc\_1 := 17.842$

Y factor measured: $Y := \dfrac{Tn + Th\_1}{Tn + Tc\_1}$ $Y = 2.419$

Value of Tn calculated $Tn\_c := \dfrac{Th\_0 - Y \cdot Tc\_0}{Y - 1}$ $Tn\_c = 12.739$

Error in measured noise temperature: $Tn\_c - Tn = 5.739$

## Derivation of a general formula for the error in noise measurement:

Th is the hot temperature for I=0 mA (value obtained in the calibration with an external sensor)

ΔTh is the hot temperature increment of the chip when applying measurement current

Tc is the cold temperature for I=0 mA (value obtained in the calibration with an external sensor)

ΔTc is the cold temperature increment of the chip when applying measurement current

Tn is the noise temperature (true value)

Tn_meas is the noise temperature measured

ΔTn is the error in noise temperature

The value of Y measured is:

$$Y = \frac{Tn + (Th + \Delta Th)}{Tn + (Tc + \Delta Tc)}$$

The value of the noise temperature obtained in the measurement is:

$$Tn\_meas = \frac{Th - Y \cdot Tc}{Y - 1}$$

Substituting the value of Y:

$$Tn\_meas = \frac{Tc \cdot Tn - Th \cdot Tn + Tc \cdot \Delta Th - Th \cdot \Delta Tc}{Tc - Th + \Delta Tc - \Delta Th}$$

The error in Tn is:

$$\Delta Tn = Tn\_meas - Tn = \frac{Tc \cdot Tn - Th \cdot Tn + Tc \cdot \Delta Th - Th \cdot \Delta Tc}{Tc - Th + \Delta Tc - \Delta Th} - Tn$$

Simplifying and grouping terms adequately:

$$\Delta Tn = \frac{\Delta Tc\cdot(Tn + Th) - \Delta Th\cdot(Tn + Tc)}{(Th + \Delta Th) - (Tc + \Delta Tc)}$$

Note that ΔTh and ΔTc give opposite sign errors in Tn !

$$\Delta Tn(Tn, Th, \Delta Th, Tc, \Delta Tc) := \frac{\Delta Tc\cdot(Tn + Th) - \Delta Th\cdot(Tn + Tc)}{(Th + \Delta Th) - (Tc + \Delta Tc)}$$

## Verification of the formula

Real value of Tn $Tn := 7$

## For I=1 mA

Values of the temperatures calibrated $Th := 51.349$ $Tc := 13.753$

Values of real temperatures at 1 mA: $Th\_1 := 51.458$ $Tc\_1 := 14.103$

$\Delta Th := Th\_1 - Th$ $\Delta Tc := Tc\_1 - Tc$

$\Delta Th = 0.109$ $\Delta Tc = 0.35$

$$\Delta Tn(Tn, Th, \Delta Th, Tc, \Delta Tc) = 0.486$$

## For I=4 mA

Values of the temperatures calibrated $Th := 51.349$ $Tc := 13.753$

Values of real temperatures at 4 mA: $Th\_1 := 53.097$ $Tc\_1 := 17.842$

$\Delta Th := Th\_1 - Th$ $\Delta Tc := Tc\_1 - Tc$

$\Delta Th = 1.748$ $\Delta Tc = 4.089$

$$\Delta Tn(Tn, Th, \Delta Th, Tc, \Delta Tc) = 5.739$$