	NOISE SOURCES COMPARISON AROUND THE EUROPE **FINAL REPORT**	
	Author: Sergio Mariotti	Revised by: A. Orfei, J.D. Gallego	Date: Sept. 14th 2010

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NOISE SOURCES COMPARISON AROUND THE EUROPE
FINAL REPORT

INTRODUCTION

It's well known that the correct way to furnish an experimental measure is to provide both the observed value and its associated uncertainty.

For the low noise amplifiers, the improvement of the technology and the cryogenic cooling has produced a decreasing of the input Noise Temperature down to few times the theoretical quantum limit $h\nu/2$, while the associated uncertainty isn't affected by any reduction.
It isn't rare a case we quote the noise temperature of an LNA as Te = 10 +/-20 K.

The causes that generates and propagates the Uncertainty are well described and discussed in [1] and [2].
Here's a summary of that causes and typical values for the travelling LNA measured by a typical mod. 346C Noise Source [3]

	[dB]
Uncertainty related to the LNA Noise Figure [strongly dependent on U(ENR)]	0.20
Uncertainty related to Instrument Noise Figure	0.004
Uncertainty related to LNA Gain Measurement	0.01
Uncertainty related to ENR	0.15
Overall (RSS) Uncertainty on Noise Figure (1 σ)	**0.25**

In this case, the NF of the LNA is NF = 1.7 dB +/-0.25 dB or 139 +/-26 K (1σ).
It's evident that the strongest cause of U(Te) is the U(ENR).
The most obvious questions is how the U(ENR) can be reduced?
Before to answer, it's necessary give the answer to another question: What is the minimum theoretical limit of U(ENR) ?
The answer may be found in [4] and in [5], and may be summarised as follow:
ENR is determined by the help of a radiometric chain. At the input a relays switch sequentially three arms of the chain, the cold standard, the hot standard and the unknown noise source.

U(ENR) is the resultant propagation of many causes of uncertainty but the most significant are:
The uncertainty of the temperature of the cold noise source U(Tcold)
The uncertainty of the spar of the arms of radiometric chain used for comparison U(sij) .

1

Given the most accurate values obtainable from commercial Network Analyzer operated by a very skilled operators, a Noise Generator may be calibrated with U(ENR) = +/-0.055 dB (1 σ) at 18 GHz.

For more than 20 years, the hp/Agilent most accurate Noise Generators, mod. HP346 had U(ENR) quoted +/-0.15 dB (1 σ). In the hp/Agilent documents, for the mod. HP346 has been wrote that:
the vector method to reduce the U(ENR) was known but not applied [6]
the uncertainty was quoted at 1 σ instead the more common adopted value 2 σ [7].

In Year 2003, a join workgroup of Institute of Radioastronomy and University of Tor Vergata has lowered the uncertainty of their own Noise Generators by application of the most accurate vector method known [5]. The uncertainty reached was U(ENR) = +/-0.055 dB (1 σ) at 18 GHz.
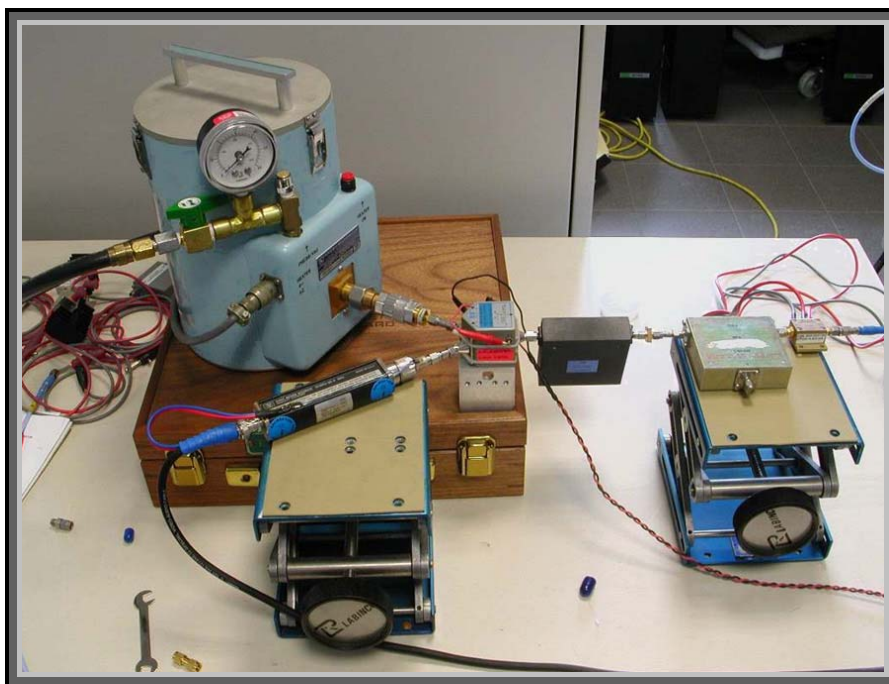
1 In house Noise Source calibration with secondary standard

In year 2004 Agilent started to sell a more accurate Noise Generator, the model series SNS N400x, the related Uncertainty was quoted: U(ENR) = +/-0.06dB (1σ) .

Despite of the uncertainty has been strongly reduced and the theoretical limit has been almost reached, the value of 0.055 dB cannot be considered a "small" value. Note that realistically, a U(ENR)= 0.055 dB once propagated, produces a U(NF) = 0.09 dB (+/-7 K at 1 σ or +/-14K at 2 σ) [3] .

What action can be taken in order to further improve the uncertainty?
As suggested by [8] and [9] the only possible action is a comparison. The inter-laboratory comparison by itself doesn't further reduces the uncertainty but it enhances the differences and should suggest some corrective actions, especially for the values farther from the mean.

COMPARISON

The inter-laboratory comparison is not a re-calibration. By itself doesn't change the ENR of the compared Noise Sources. The differences in readings occurring at each laboratory will not be cleared.

Only once this document has been read, each laboratory will have the freedom to apply corrections to ENR. In any case, each correction should be applied with great precaution and cautiousness.

The canonical way to do a comparison is a comparison of a travelling standard.
An Input Noise Temperature Standard (an LNA with a standard Noise Temperature) doesn't exist. Te of LNA is every time dependent on ambient temperature , bias supply and even on the reflection coefficient of the source. But if the travelling LNA will be measured at known ambient temperature, biased by a very stable power supply and close on well matched load , its Te can be considerate stable enough around the travel.

The comparison is more accurate as smaller is Te of the LNA. So a cryogenic comparison, in principle, should be preferred to a room temperature comparison [10].
But practically speaking, a balancing of the Pros & Cons must be done:

	Cryo LNA comparison	Room temperature LNA comparison
Man power required	week (s) (-)	hours (+)
Accuracy	best (+)	high (…)
Sensitivity to how the setup is arranged	more (-)	less (+)
Sensitivity to U(ENR)	less (+)	more (-)
Easy to do	less (-)	more (+)
Probability to find candidate laboratories	less (-)	more (+)

Due to that reasons, a room temperature comparison has been preferred.

Frequencies:
Often the frequency boundaries comes at 18 GHz, 26.5 GHz, 40 GHz, 50 GHz, 67 GHz …
The best seller Noise Generators covers the very popular bandwidth 10 MHz-18 GHz.
Of course, higher frequencies are also very important for radio astronomy.
It has been chosen a frequency range 16…26.5 GHz for the following reasons:
- The high end of the bandwidth (say 18 or 26.5GHz) is probably affected by greater uncertainty or errors than the low end of the bandwidth . A comparison is probably more meaningful at the high end of the bandwidth.
- 16…26.5GHz has been chosen because step over the 18 GHz boundary. In this way, even the laboratories that are arranged up to 18 GHz may takes advantage of the comparison.

Reflection coefficient and impedance matching:

The LNA has been impedance matched as well as possible, but it cannot be regarded as a well matched device.

As higher is the product of the reflection coefficient (ρNS * ρLNA) as higher is the ripple of the Te curve over frequency.

It is request to the laboratories to perform two measurements, one placing a selected low VSWR, ferrite isolator in front of the LNA and the other one without that circulator. All the measurements made with the circulator will be compared all together, as well as the measurements performed without the circulator.

Comparing the two obtained measurement traces, it's possible distinguish if the ripple is mainly due to mismatch errors or due to ENR differences.

Drift:

Since a drift on gain and noise temperature may occur during the measurement session , a measurement of the "thru" is requested both at the beginning and at the ending of the measurement session. If an important drift will be seen , the Te data file will be corrected.

Room temperature:

The handling of the Noise Source and LNA as well as the solar light coming trough a window, as well as the vicinity of an heater or air conditioning changes the physical temperature of the LNA and consequently it's Te.

For this reason a proper shield form heat/cold sources is required , as well a period of time long enough to reach the thermal equilibrium (5 minutes).

Aging check:

At INAF-IRA the LNA has been measured both at the beginning and one year later at the end of the campaign. Differences on Te was smaller than +/- 2 K except for frequencies greater than 26.3 GHz where the difference was slowly increasing with the frequency up to 10K .

DATA PROCESSING

The data files coming from each one laboratory have been analyzed.

Not all data set are organized on the requested way.

Some data are 50 MHz spaced while other are 100 MHz spaced. One data set is 500 MHz spaced.

This difference has involved a small complication on the processing but does not affects the comparison.

Most data set contains Noise Temperature and Insertion Gain while two data set contains NF (dB) only. This small lack does not affect the comparison.

Some data set do not include the "initial" and "final" zero traces. It has been assumed that the drift was negligible.

Where possible, the drift has been evaluated. For all data set both the Noise and Gain drifts were negligible.

Since the data set have been collected at different physical temperatures, a correction has been applied in order to normalize the actual Noise Temperature. The experimental found law $\frac{\Delta Te}{\Delta Tamb} = +0.5 \ K/°C$ has been applied.

Two families of Cartesian graphic have been plotted: the case without input isolator (NO_CIRCULATOR) and the case with the isolator in front of the LNA (YES_CIRCULATOR).

As it may be seen, the spread is very large. Also it's difficult to understand the whole traces.

A selective analysis is much more indicative. Three kind of analysis has been performed:

- The effect of the mismatch loss is analyzed and discussed.
- the actual Noise Temperature trace is compared to the mean value (calculated at every frequency along the points coming from each Noise Generator).
- Traces performing similar behaviour has been looked for, grouped, analyzed and discussed.

What kind of mean?

The most known method to estimate the mean value of a number of samples is the calculation of the arithmetic average, accomplished by +/- the standard deviation.

An alternative method, widely used at NIST, is the computation of the median accomplished by +/- the MAD [11] . For uniformly and normal distributed samples, the average and median are coincident, as well as the standard deviation and the MAD.

But in the case that few samples fall far outside the distribution law, the median better filters away the farther samples. Even the MAD, rather than the standard deviation, better filters the rare and farther samples. So the median method is more robust than the average one.

RESULTS

Impedance Mismatch effects

A mismatch error should generates a ripple on the frequency domain representation of the trace.
The mismatch error is as large as the trace `NO_CIRCULATOR` shows more ripple than the trace `YES_CIRCULATOR`.

The mismatch effect has been summarized on the next table:

| ORGANISATION	NOISE GENERATOR	Mismatch error (difference on the ripple)	Freq. range
INAF-IRA	HP 346C +10 dB	absent	**16-26.5**
INAF-IRA	HP 346	n/a	16-18
Uni Cantabria	HP 346C K01	**strong**	**16-26.5**
Uni Cantabria	HP 346C K01+10 dB	absent	**16-26.5**
Uni Manchester	SNS N4002	small	**16-26.5**
Yebes	HP 346C+10dB	absent	**16-26.5**
Yebes	NC 346KA+10dB	absent	**16-26.5**
Yebes	SNS N4002	small	**16-26.5**
Astron	HP 346ª	n/a	16-18
Astron	SNS N4000	n/a	16-18
Fraunhofer IAF	SNS N4000	n/a	16-18
Fraunhofer IAF	SNS N4002	absent	**16-26.5**

Charts
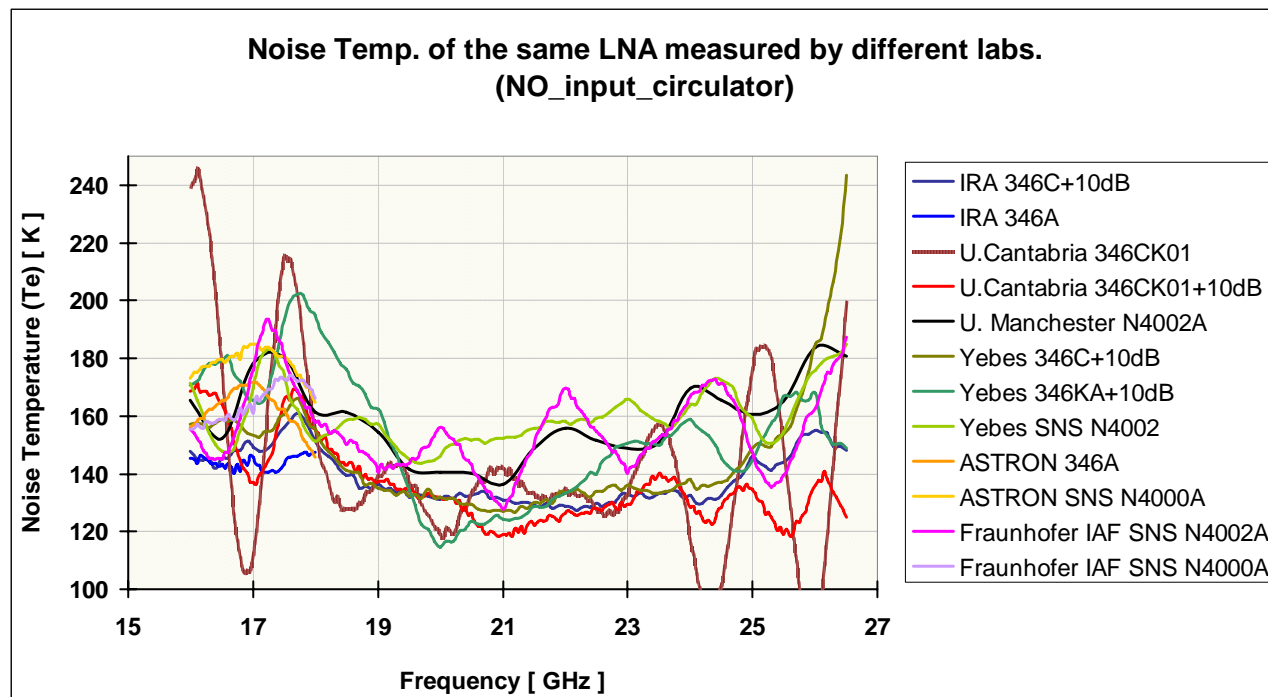
2 Noise Temperature of same LNA measured by different labs (NO_input_circulator)
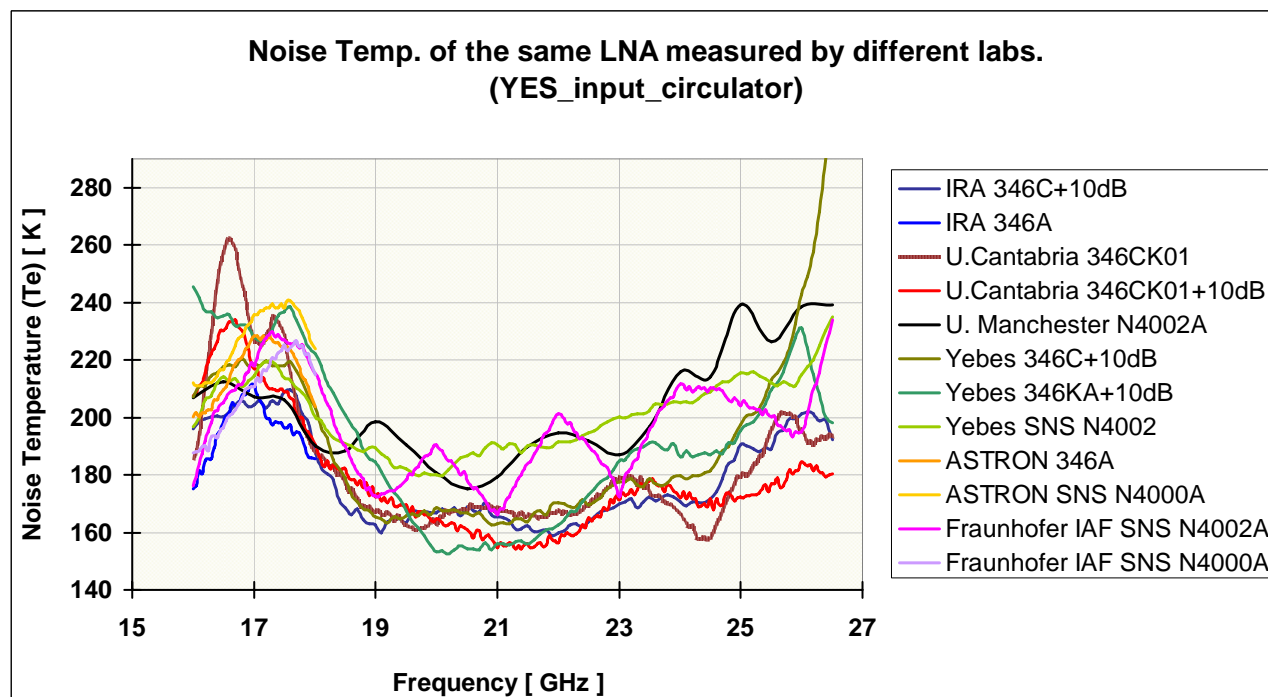
3 **Noise Temperature of same LNA measured by different labs (YES_input_circulator)**

**Noise Temp. of the same LNA measured by different labs. (YES_input_circulator, 16...18 GHz only)**
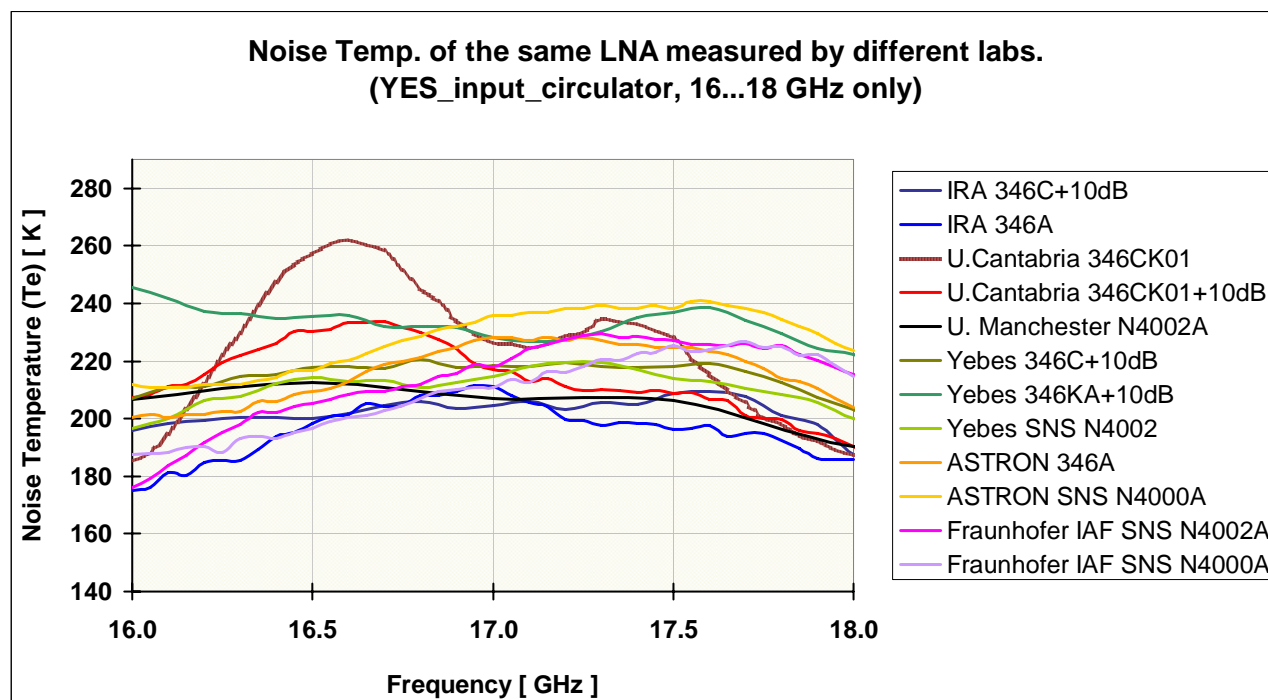
4 **Noise Temperature of same LNA measured by different labs (YES_input_circulator, 16...18 GHz only)**

Even if the different colours may help the trace identification, the whole traces are not the best way to compare different measures because is confusing.

A good way to compare each measurement is a plot of every measurement compared with the "mean" of the measurements. As discussed before, the median value, rather the average , better describe the "most probable mean".
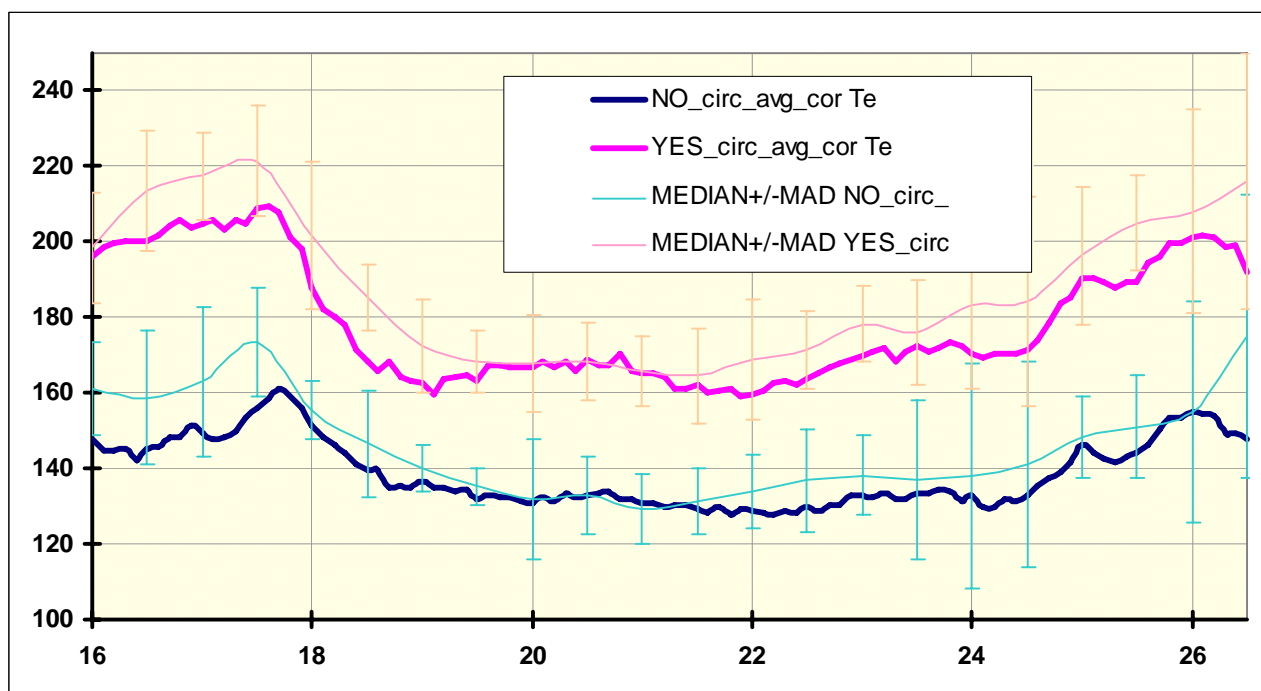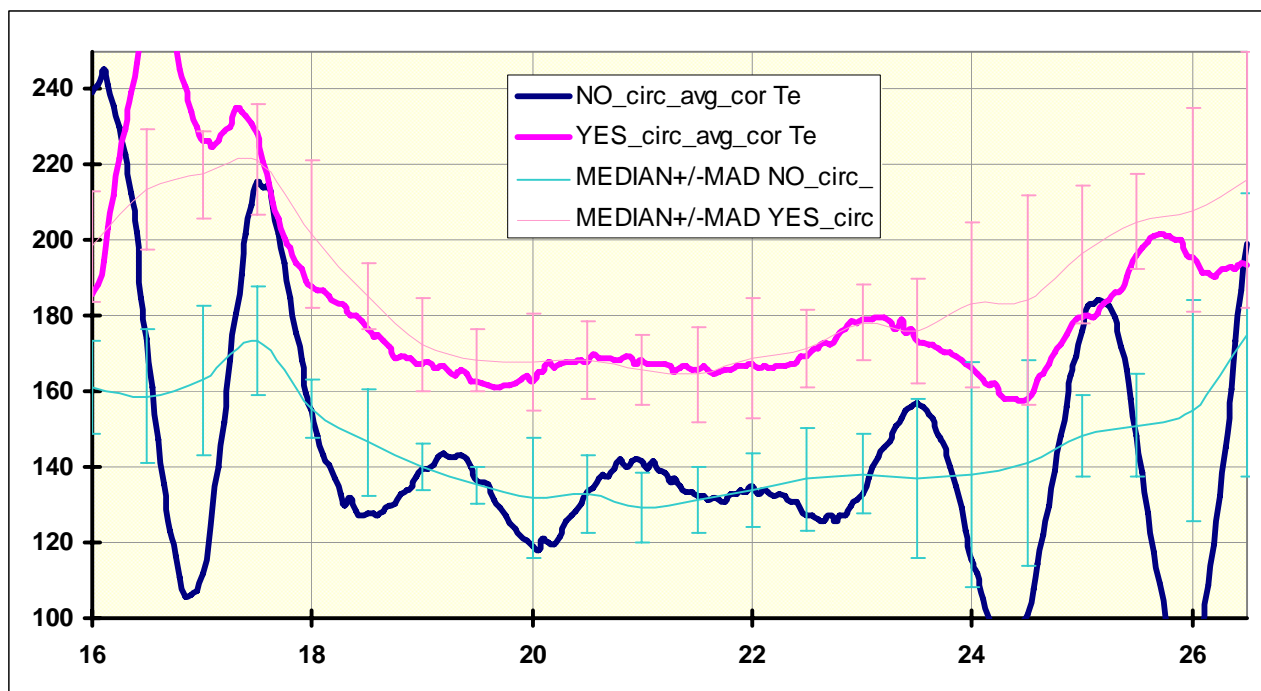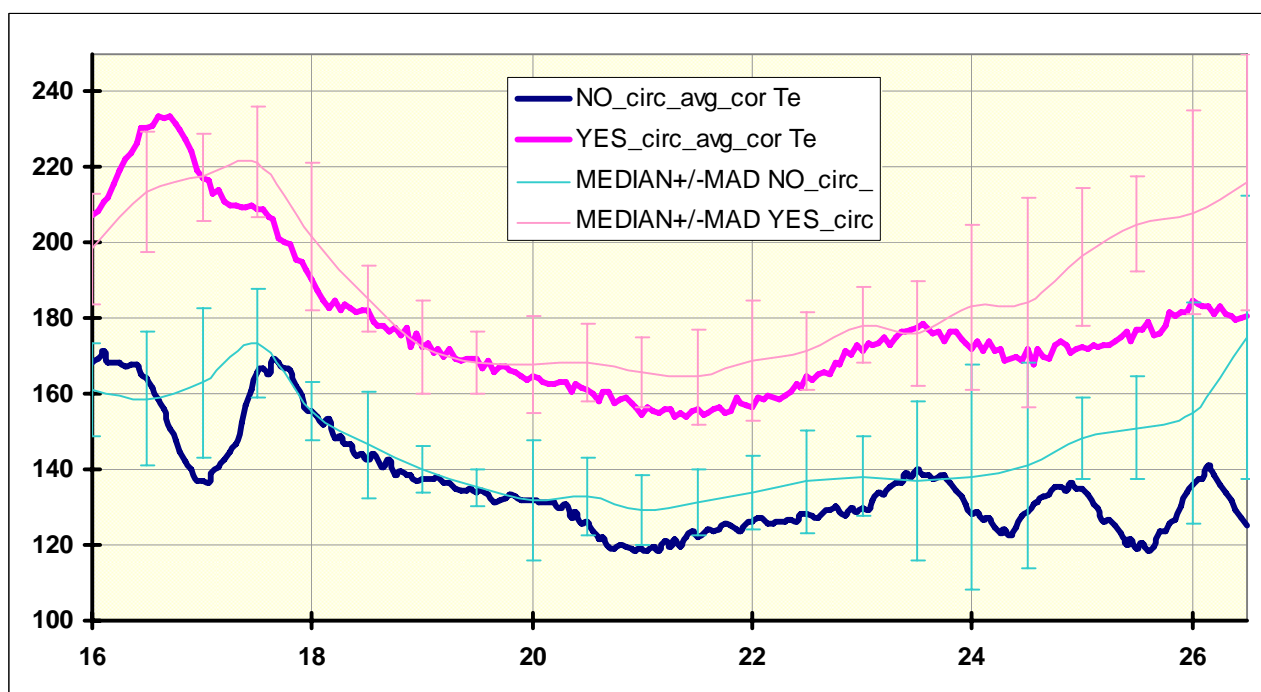
5 INAF-IRA , HP 346C+10 dB attenuator
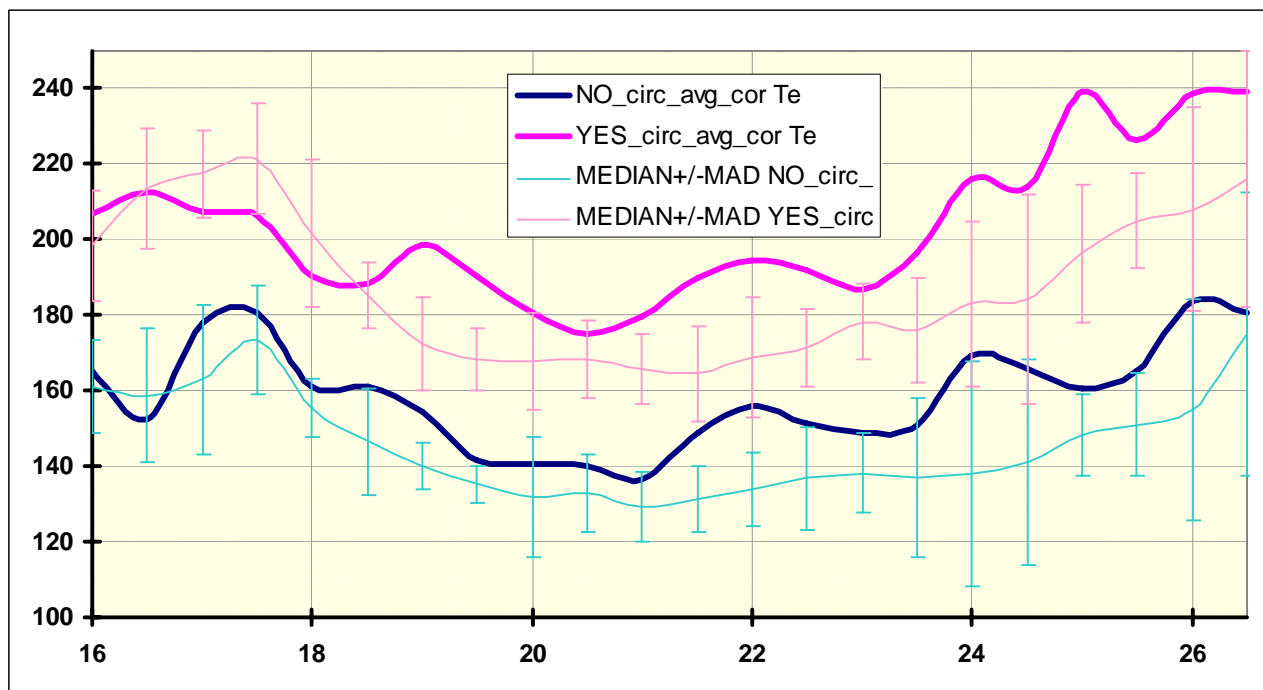

6 INAF-IRA , HP346A
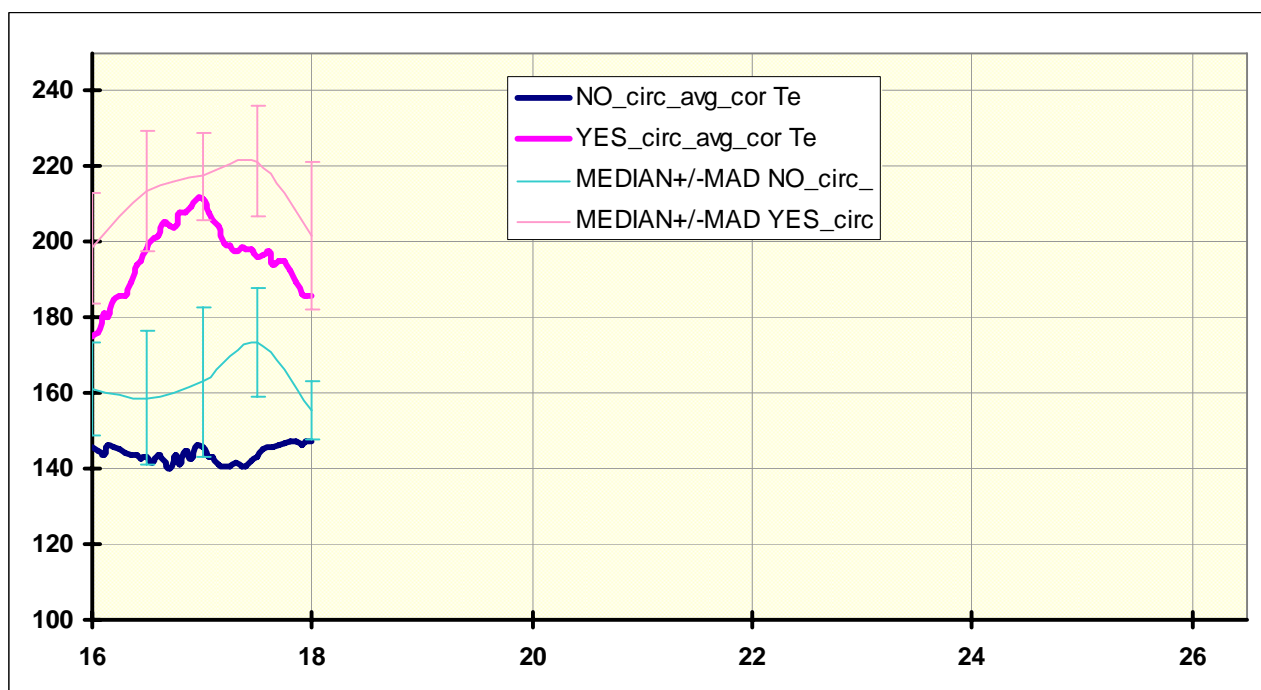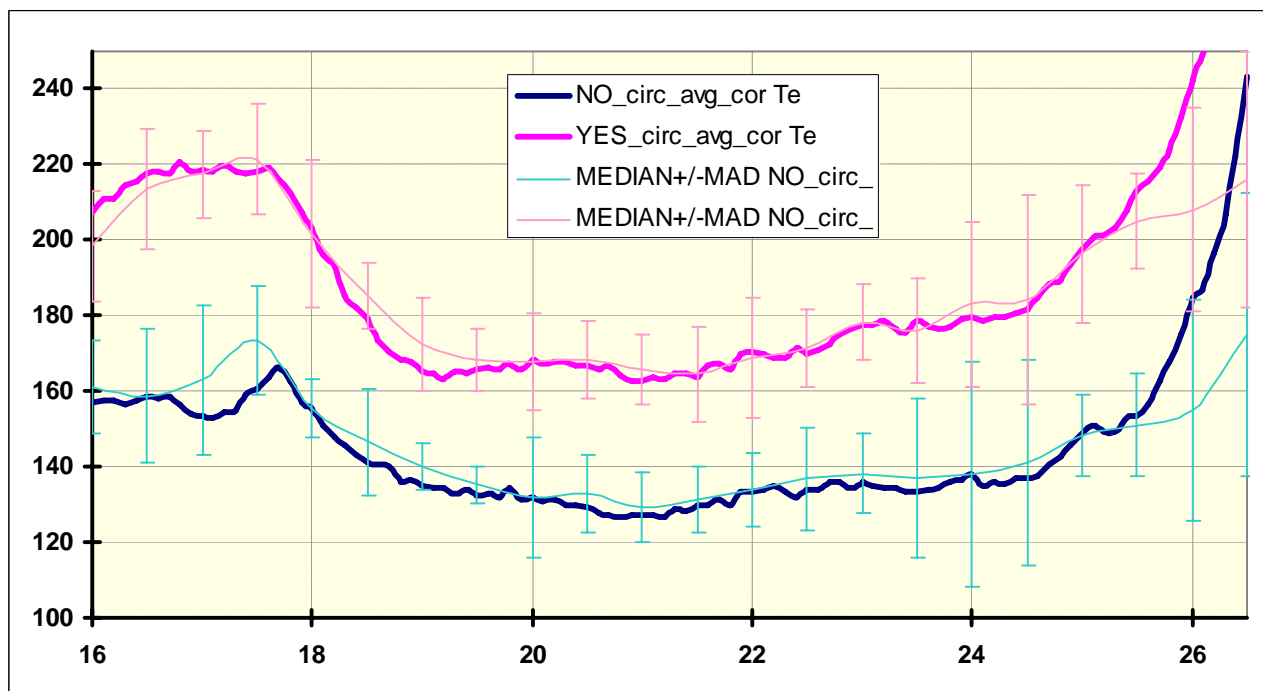
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7 University of Cantabria, HP346CK01
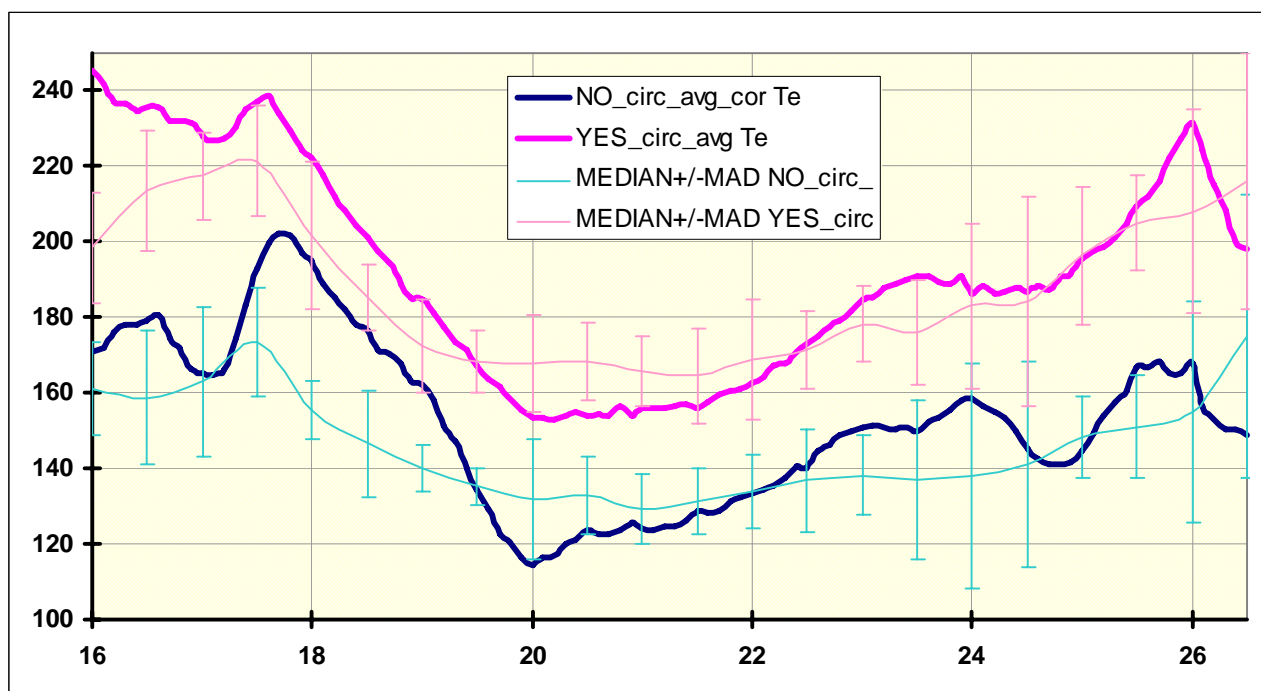

8 University of Cantabria, HP346CK01+10dB Attenuator

9 University of Manchester, SNS N4002A

10 Centro Astronomico de Yebes , HP346C+10dB Attenuator

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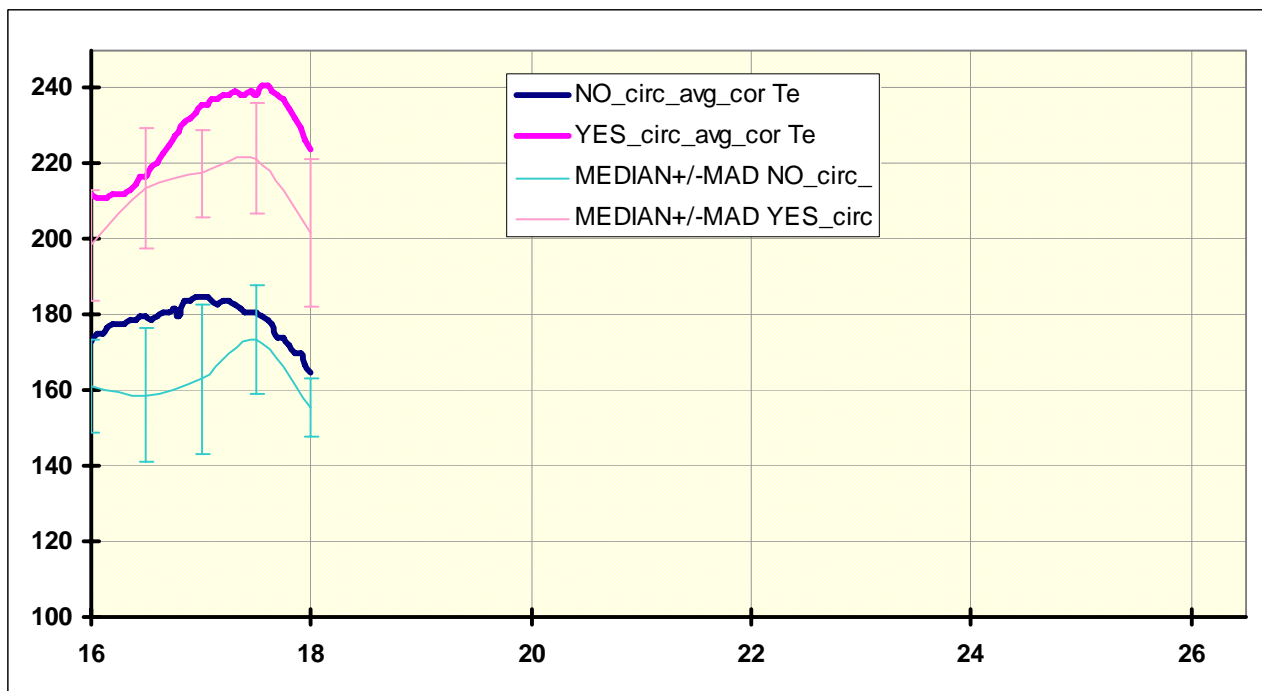
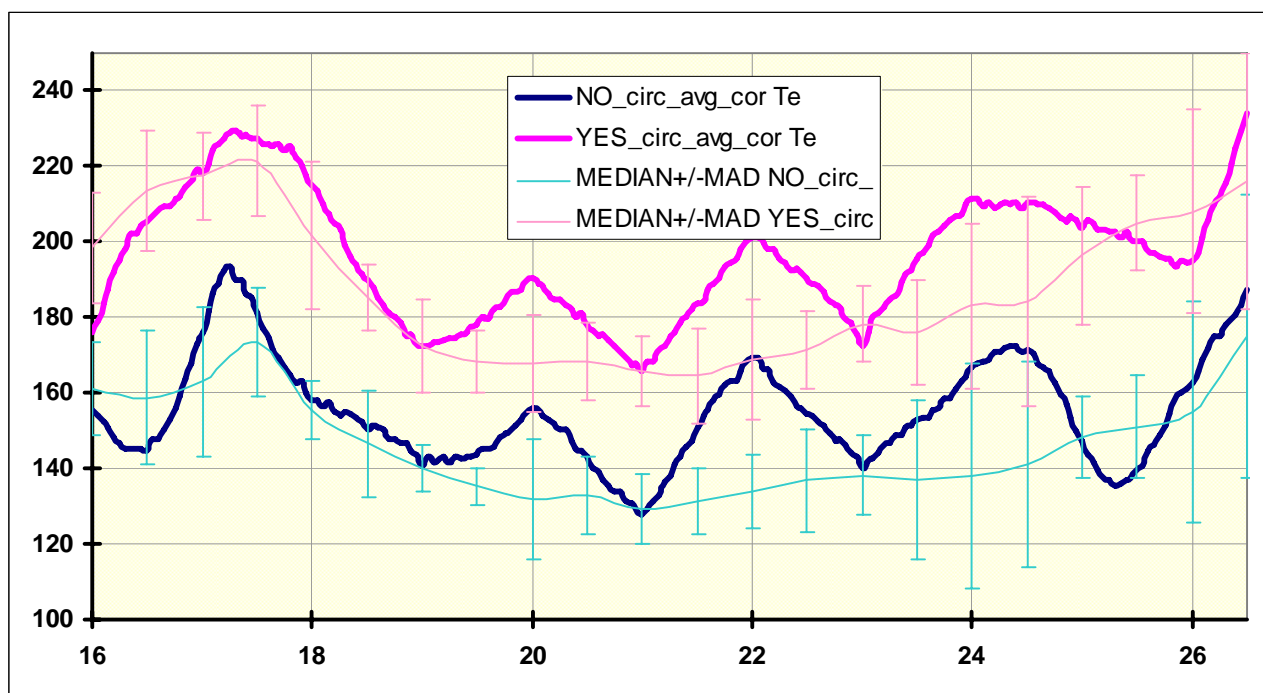**11 Centro Astronomico de Yebes, NC346KA+10dB Attenuator**
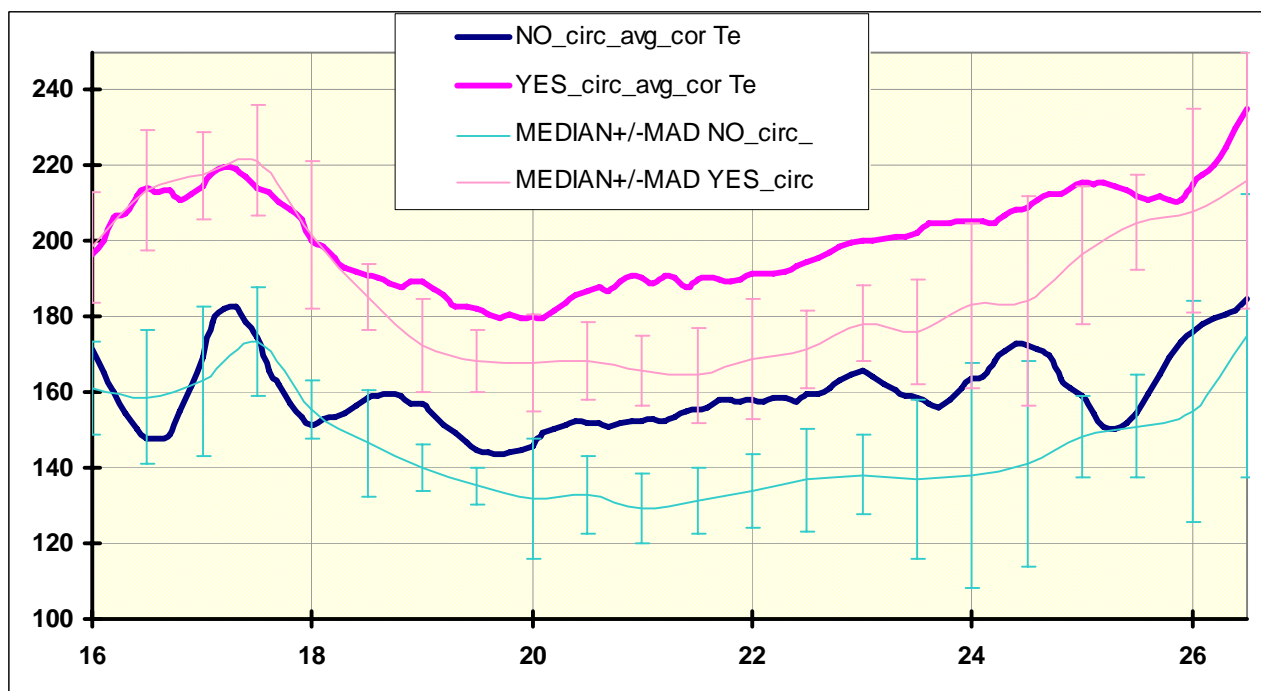
12 Centro Astronomico de Yebes, SNS N4002A
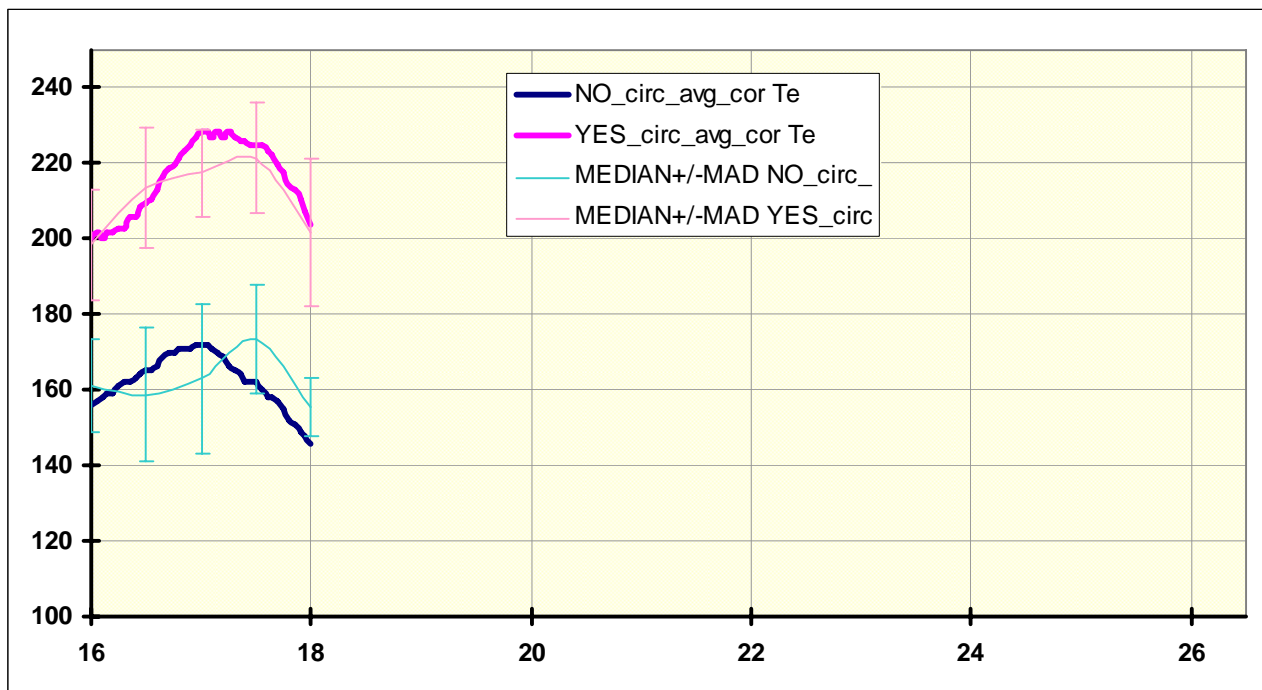
13 Astron, HP346A

14 Astron, SNS N4000A

15 Fraunhofer IAF, SNS N4002A

16 Fraunhofer IAF, SNS N4000
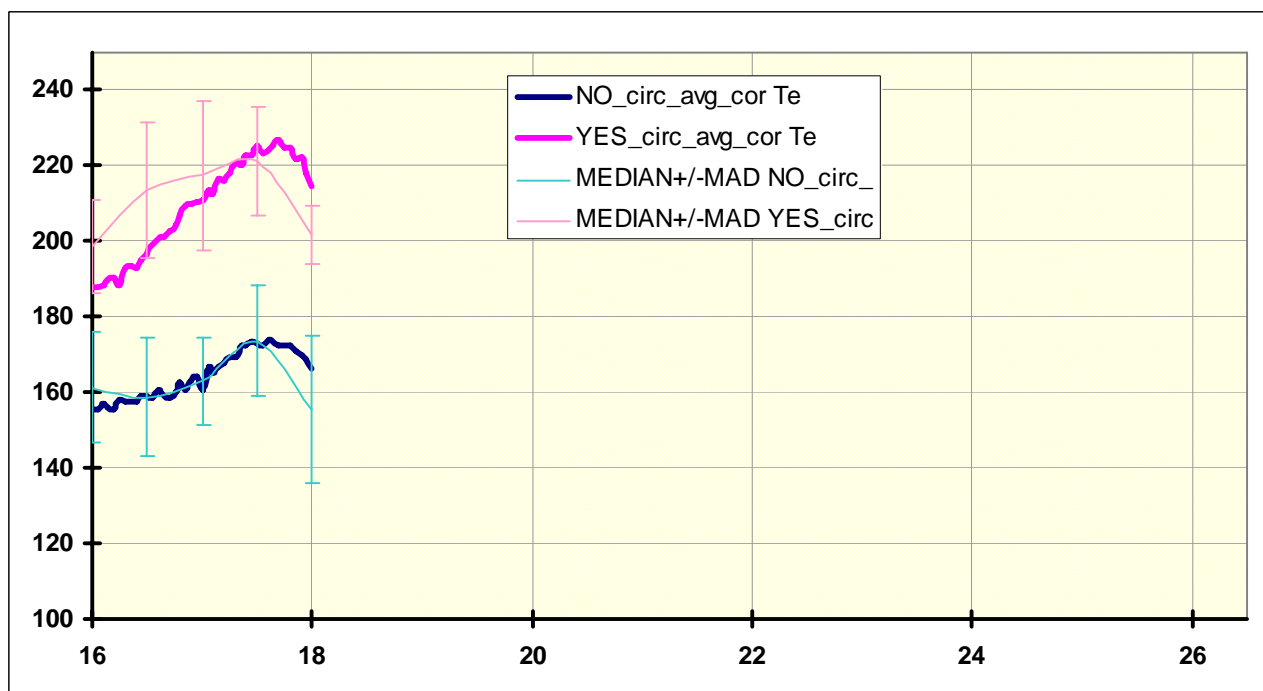
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Trace behaviour, similarities and noise generators summary

In the following table the behaviour of the compared noise generators and the uncertainty labelled by the factory are summarized

ORGANISATION	NOISE GENERATOR	Date	Freq. range	Similar behaviour	Uncertainty u(ENR)
INAF-IRA	HP 346C +10 dB	03/09/2009	**16-26.5**	■ CM	+/- **0.06** [1]
INAF-IRA	HP 346	17/08/2009	16-18		+/- 0.12
Uni Cantabria	HP 346C K01	20/07/2009	**16-26.5**		+/- **0.06** [2]
Uni Cantabria	HP 346C K01+10dB	20/07/2009	**16-26.5**	■ CM	+/- **0.06** [2]
Uni Manchester	SNS N4002	30/10/2009	**16-26.5**	○	+/- **0.06**
Yebes	HP 346C+10dB	30/11/2009	**16-26.5**	■ CM	+/- 0.12
Yebes	NC 346KA+10dB	30/11/2009	**16-26.5**		+/- 0.12
Yebes	SNS N4002	30/11/2009	**16-26.5**	○	+/- **0.06**
Astron	HP 346A	20/04/2010	16-18	CM	+/- 0.12
Astron	SNS N4000	20/04/2010	16-18		+/- **0.06**
Fraunhofer IAF	SNS N4000	25/05/2010	16-18	CM	+/- **0.06**
Fraunhofer IAF	SNS N4002	25/05/2010	**16-26.5**	○	+/- **0.06**
INAF-IRA	HP 346C +10 dB	08/06/2010	**16-26.5**	Repeatibility check	
INAF-IRA	HP 346	08/06/2010	16-18	Repeatibility check	

Where:
[1]   Uncertainty reduced by in-house calibration
[2]   K01 stands for 1GHz…50GHz 2.4mm coax connector.
■   the behaviour of the traces is similar among themselves
○   the behaviour of the traces is similar among themselves
CM   the trace is closer to median value

It has been looked for the most similar curves. In the following two graphics are plotted le closest curves because the number of similar families of curves is two.

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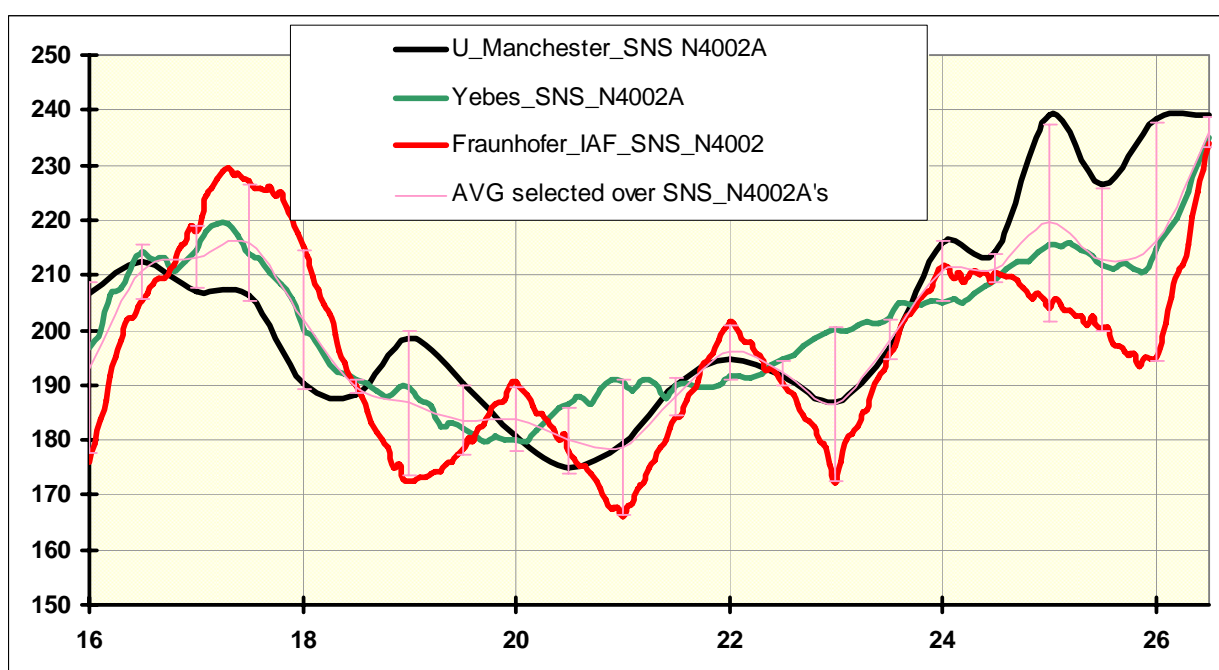| Author: Sergio Mariotti	Revised by: A. Orfei, J.D. Gallego	Date: Sept. 14th 2010

As it may be seen in the following charts, the measurements performed by laboratories that involves the *mod. NC346C + 10 dB attenuator* are closer among themselves.

Also measurements performed by laboratories that involves the *SNS N4002* are among themselves. But the two families are different among themselves.

It may be suspected that the differences may be imputed to differences in the original calibration procedures at Agilent factory.
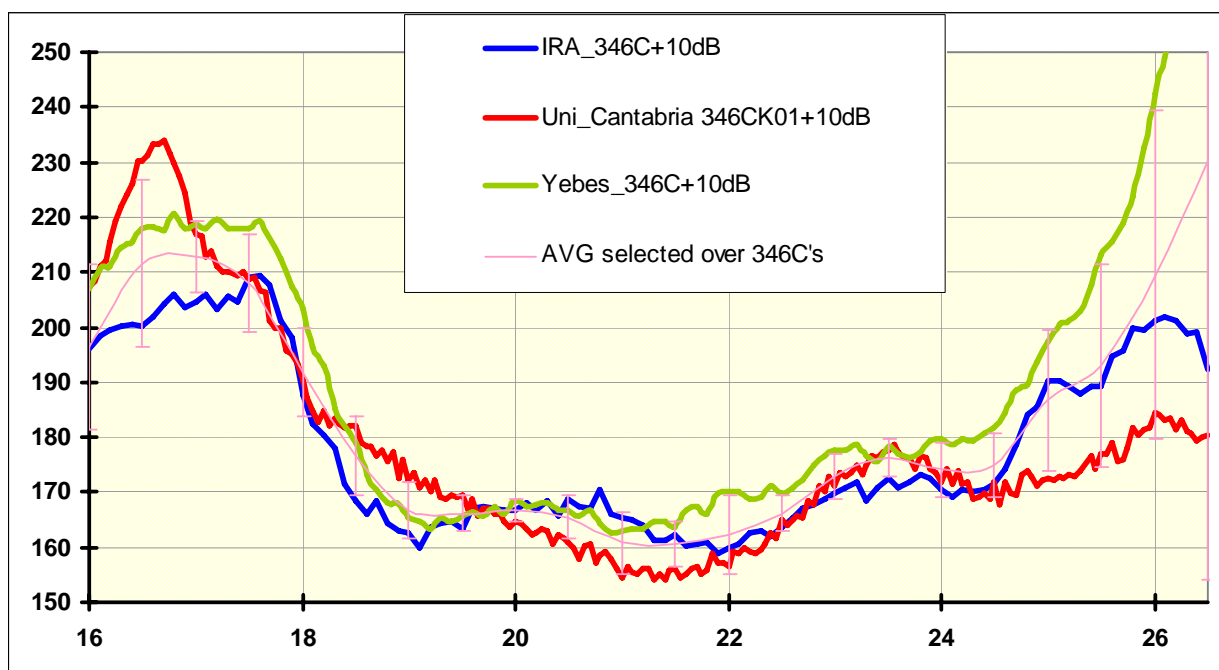
17 Measurements performed with Noise Generators mod. 346C+10 dB Attenuator by different labs

18 Measurements performed with Noise Generators SNS_N4002A by different labs

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ENR TABLE CORRECTION

For laboratories like to correct their ENR table in order to reduce the distance from the average or median, a method is described.

It's important to write in an explicit way that this operation is conceptually a mistake for two reasons:

- A metrological mistake. The calibration of a Noise Source by the knowledge of Te of LNA is same as the calibration of a pocket rule by comparing to the length of a table desk (while the right way is the contraire).

- A mathematical mistake. It isn't a rigorous method, it's just s an approximation. The reason is because for a rigorous calculation it should be necessary to know and take into account for the noise temperature of the Noise Figure Meter (the Calibration data), while those data are unknown.
  However since the LNA gain is high enough, the Noise Temperature of the Noise Figure Meter is strongly masked, so accepting a small error, the Noise contribution of the noise figure analyzer may be neglected. In any case, even if it's an approximation the method is converging, so the error will be reduced and there is no risk of overcorrection.

But if the difference of ENR is suspected to be very large, a corrective action is perhaps better than do nothing. So, if the preceding simplification is accepted, the actual measured Noise Temperature is:

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

The similar equation form may be written for the value we would read, the corrected Noise Temperature ($T^c e$)

$$T^c e = \frac{T^c h - Y \cdot Tc}{Y - 1} \qquad (2)$$

Now , let perform the ratio,

$$\frac{T^c e}{Te} = \frac{Th - Y \cdot Tc}{T^c h - Y \cdot Tc} \qquad (3)$$

Solving for the corrected hot temperature $T^c h$,

$$T^c h = \frac{Th - Y \cdot Tc}{\dfrac{Te}{T^c e}} + Y \cdot Tc \quad (4)$$

Finally the new, corrected ENR value is:

$$ENR^c = 10 \cdot \log(\frac{T^c h - To}{To}) \qquad (5)$$

Or , if the operator prefers the advantages of the small correction for $Tc \neq To$, even if formally different by the ENR definition, we get:

$$ENR^c = 10 \cdot \log(\frac{T^c h - Tc}{290}) \qquad (5 \text{ bis})$$

Where:
Te = Input Noise Temperature of the LNA (the actual Noise Temperature)
Th = Hot Noise Temperature generated by the Noise Generator (the actual value)
To = 290 K, The standard temperature
Y = The Y factor .
$T^c e$ = Input Noise Temperature of the LNA (the wanted value)
$T^c h$ = Hot Noise Temperature generated by the Noise Generator (the wanted value)
ENR = The Excess Noise Ratio (the actual value)
ENR^c = The Excess Noise Ratio (the wanted value)

Note that the variables Te and $T^c e$ should not only be considered alone, but also their ratio $\dfrac{Te}{T^c e}$ has a physical meaning.

The knowledge of the variable Y is required but probably was not recorded at the time of measurement. It doesn't matter because the Y factor may be calculated offline by solving the (1) for Y and combining the (5) or the (5bis)

$$Th = To + To \cdot 10^{\frac{ENR}{10}} \qquad (6)$$

$$Y = \frac{Te + To + To \cdot 10^{\frac{ENR}{10}}}{Te + Tc} \qquad (7)$$

In order to help users, who want correct their ENR table, a MS Excel file is provided. The user should input, frequency by frequency, the actual ENR, the actual Te and the spreadsheet will calculate the ENR corrected that produce the median Te.

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CONCLUSIONS:

The Noise Temperature measurement of a travelling LNA has shown strong differences among laboratories. Assuming as the major cause of uncertainty on Noise Temperature the uncertainty of ENR , the spread of the data is much larger than the expected.

Many of the Noise Sources were "lowest uncertainty type", so there is no room for improvements involving the factory.

The only way to further reduce the uncertainty of the ENR is the calibration with a cryo-load that acts as a primary or secondary metrological standard. This is especially thru for the millimetre wave frequencies where the uncertainty is greater.
Because the cryo loads are very expensive (50000 – 100000 €) a join or consortium is suggested for the purchase, as well as a sharing in the use.
Perhaps the best way would be a common European Centre for Noise Source Calibration that involve metrological standard cold-loads as shown in the following pictures.

Noise/Com Cold Load	Maury Microwave Cold Load

In any case, each laboratories that believe its ENR is wrong, has the freedom to correct it by using the algorithm provided.

ACKNOWLEDGEMENTS

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