Understanding the ENR Calibration of ELVA Noise Source in the Extended W Band (70-116 GHz)

J.D. Gallego, I. López, C. Diez González, I. Malo

IT-CDT 2016-9

Observatorio de Yebes
Apdo. 148 19080 Guadalajara
SPAIN
Phone: +34 949 29 03 11
Fax: +34 949 29 00 63

Change Record

Revision	Date	Affected Paragraphs(s)	Reason/Initiation/Remarks
A	2016-05-15	All	First Issue

TABLE OF CONTENTS

Introduction

Diode noise sources are very convenient components in a noise measurement setup since they can be switched on an off automatically under the control of Noise Figure Meters. Even when other types of noise sources (hot/cold thermal loads) are used for measurement, noise diodes can still be very useful for the receiver calibration needed when simultaneous gain measurement and second stage correction are performed. Very few commercial diode noise sources are available for millimeter wave W band (75-110 GHz), and the only one which was specified by the manufacturer[1] to cover the extended W band (70-116 GHz) could be located and procured. The extended W band is of great importance in some radio astronomy receivers because of the scientific interest in some molecular lines outside of the standard band, in particular CO line at 115 GHz.

The ENR calibration provided by the manufacturer shows a set of data points spaced 1 GHz with a with a significant amplitude ripple of up to 2 dB peak to peak (see appendix III) This raised some concerns about the possibility of errors which would appear when interpolating between calibration points. This problem is even more severe when using old models of Noise Figure Meters (HP 8970 B), since then the maximum number of ENR calibration points is 35 due to the limited memory available for the table. The total number of calibration points provided by the manufacturer in the band is 49. The work presented in this report was motivated by the need to investigate the reliability of the calibration and its accuracy and to gain some insight on the causes of the ENR ripple and its stability.

Measurement system

The following instruments were used for the calibration and characterization of the noise source:

- ELVA-1 IMPATT Noise Source mod. ISSN-10 s/n 14-15-W with integral isolator
- HP 8970 B Noise Figure Meter (NFM)
- E 8257 B PSG Analog Signal Generator opt 1EU (high output power) (Used as Local Oscillator)
- WR10MixAMC Down Converter (special order from VDI optimized for noise measurement)
- QuinStar isolator mod. QIF W00000 s/n 17911014002 (used at receiver input)
- QuinStar waveguide switch mod.QWM W 00000 s/n 17911013001 (4 port)
- Flann Microwave W band 20 dB pyramidal horn mod. 27240-20 s/n 234008
- LNF-LNR65_115WB s/n 016Z Low Noise W band Preamplifier
- Conical Ambient/LN2 loads made with 10mm thick flat microwave absorber foam
- N 5247 A PNA-X Vector Network Analyzer
- N 5261 A Millimeter Head Controller
- 2 x N 5250CX10 Frequency Extender Module (110 GHz, 1mm connector)
- W 281 C / W 281 D WR10 waveguide to 1mm connector adapters
- W11644 A WR10 Waveguide Calibration Kit for PNA

In addition, an HTBasic program was developed with a convenient procedure for data acquisition. For the calibration the HP 8970 B NFM is used only as a relative power meter and no previous calibration of the receiver is needed. The external LO (E 8257 B) is commanded by the NFM at the desired frequency and the NFM receiver is tuned to the IF.

[1] ELVA-1, Millimeter Wave Division, St Petersburg, Russia.

The system is configured for double side band, so it is sensitive to the two 4 MHz bands centered in the LO frequency and separated by two times the selected IF frequency. Note that the HP970 B can only handle frequencies up to 99.999 GHz because hardware limitations of the LED display. To circumvent this problem the system is cheated and the desired frequency is divided by 10 for all the W band related functions. That means that a frequency of 105 GHz will appear in the display of the NFM as 10.5 GHz. The same is applied to the graphics and calibration tables used or generated by the HTBasic program and to the frequency commands send to the LO. The multiplying factor of the LO has to be configured taking into account this and the harmonic generated by the down-converter (x4). The IF frequency initially selected was 250 MHz, since this value minimizes the noise of the down-converter.

Calibration of the Diode Noise Source

The process of calibration was carried out by comparison of the measured power of the diode noise source in on and off states with the values obtained with ambient and liquid nitrogen (LN2) absorbers in front of a short pyramidal horn. The values of the internal attenuators (RF and IF) of the NFM are auto ranged for the highest power value (noise diode on) at each frequency and kept with the same value for the other power measurements at the same frequency to avoid possible calibration errors.

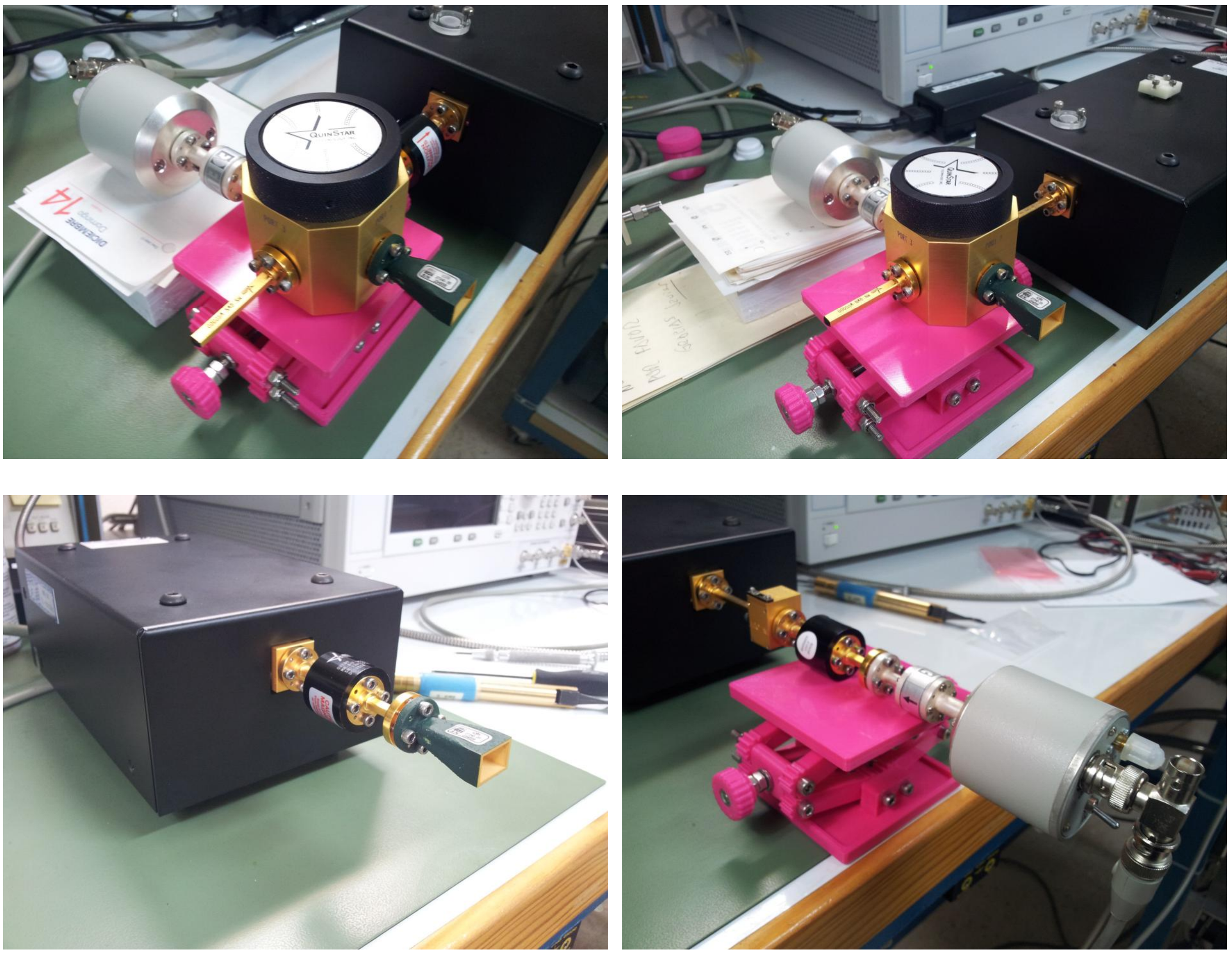


Figure 1: Different configurations used for the calibration of the noise source. In the upper row a waveguide switch is used to connect either the horn or the noise source with or without an isolator at the input of the down-converter. The bottom row shows the configuration with input isolator (no WG switch) with and without the LNF preamplifier.

The different configurations used for the calibration and the results obtained are presented in figures 1 and 2. In the results shown in figure 2, it can be seen that the results acquired with the different configurations agree quite well and the ripple is repetitive. The agreement with the original ELVA calibration is good in some zones (75-80 GHz and 95-105 GHz) but not in all the frequency range. However, the pattern of fine grain higher and lower peaks seem to agree quite well.

The reasons for the disagreement between the ELVA and Yebes calibration are not understood at this time. They could be related with non-linearity (compression) of the ELVA power meter or with spurious responses to the sub-harmonics of the LO. To this respect, the down-converter used in the Yebes setup is believed to be very clean, since it was optimized by VDI for undesired spurious responses in the band below the -40 dBc level.

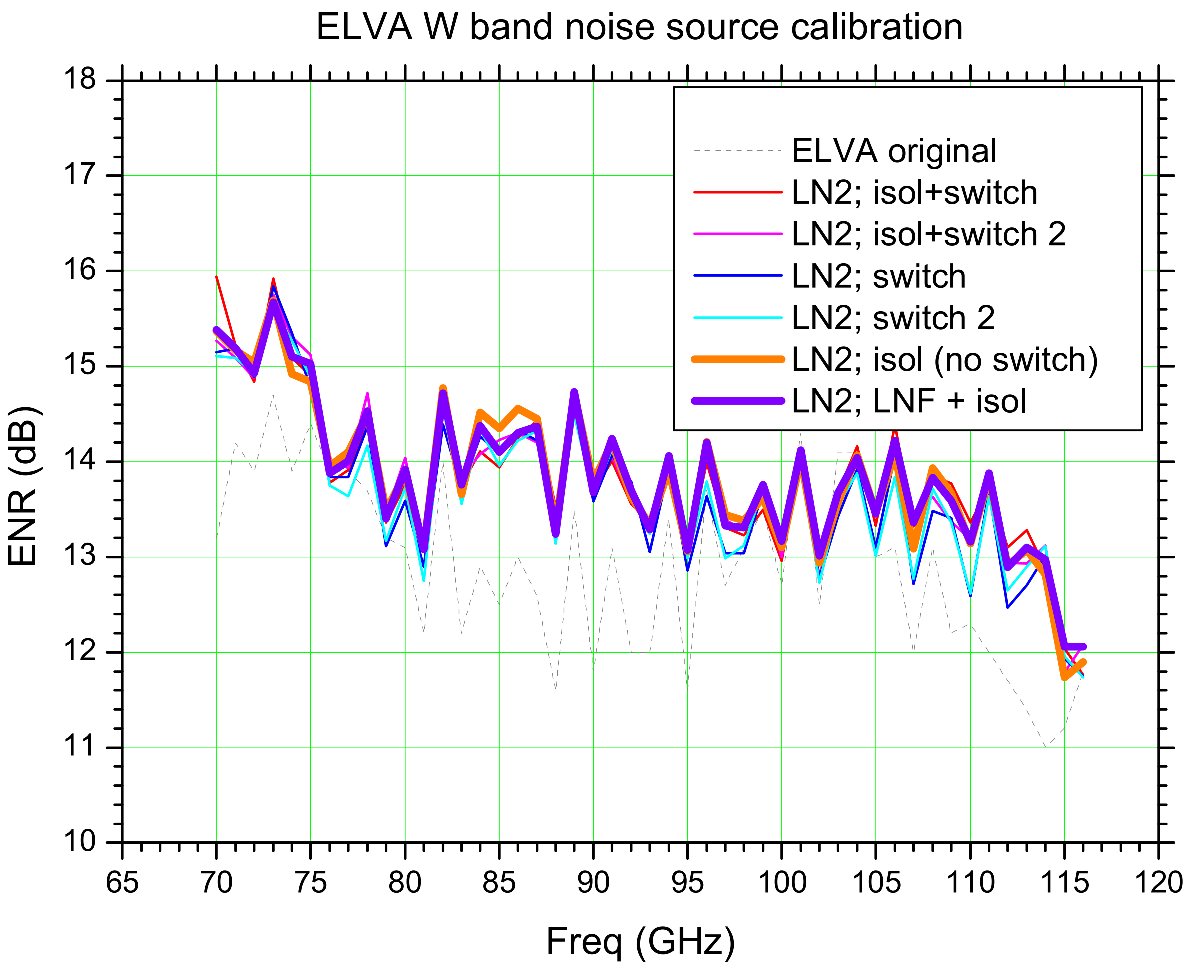


Figure 2: ENR calibration results obtained with the different configurations of figure 1. Two runs of the calibrations with the WG switch are presented for checking the repeatability. The measurement finally used is the thick violet line (no WG switch, LNF preamplifier and isolator), which is believed to be more accurate due to the lower system noise temperature. The original calibration provided by ELVA is presented in the same graph as a discontinuous line for comparison. The data is sampled at 1 GHz intervals with an IF frequency of 250 MHz (DSB mode).

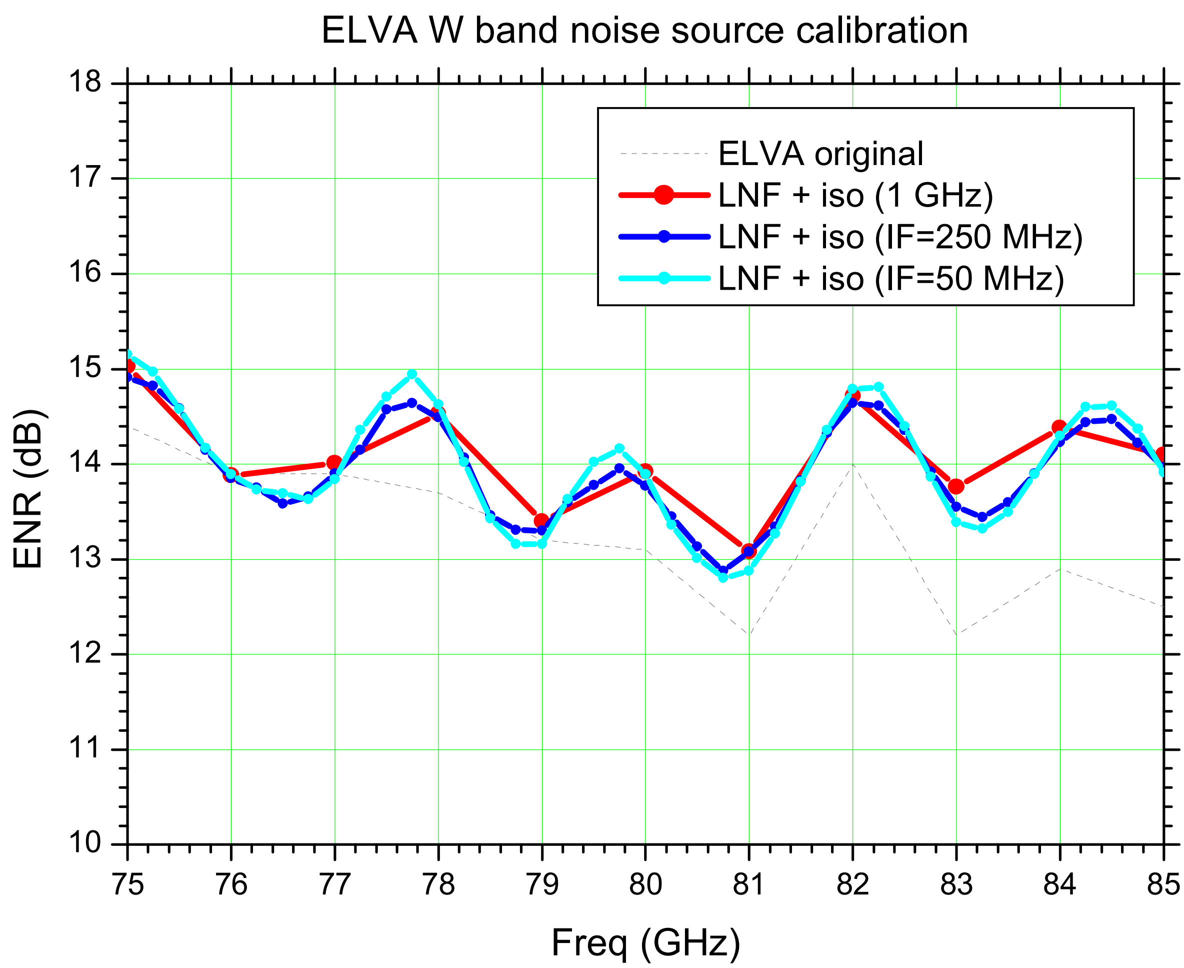
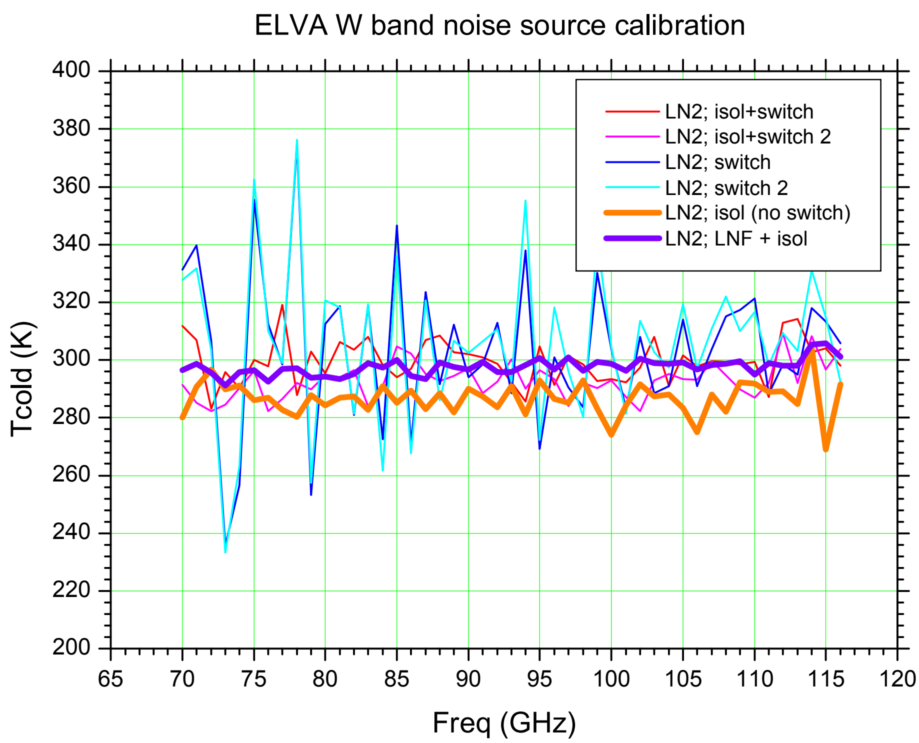


Figure 3: Detail of the 75-85 GHz range to resolve the ENR calibration ripple. The Yebes and original ELVA calibration with 1 GHz frequency steps from figure 2 are presented in the red and discontinuous grey lines. Two new measurements with 250 MHz frequency steps are presented in the blue and cyan lines. The blue line is acquired with a 250 MHz IF frequency (same as in figure 1) and the cyan with a 50 MHz IF. Note that the measurement with lower IF (cyan, 50 MHz) presents more pronounced peaks (the higher IF has the effect of smoothing the curve). With the 250 MHz frequency steps the ripple pattern is totally resolved and it becomes clear that there is an inherent ripple in the ENR of the source which has to be taken into account.

A new set of measurements with higher frequency resolutions were taken to resolve more clearly the ripple pattern. The results shown in figure 3 confirm that the ripple with a frequency of ~2GHz is present and that interpolation of ENR data with frequency spacing between calibration points of more than 1 GHz would be questionable.

In addition to the ENR, the calibration process provides measurements of the noise temperature of the system and the temperature of the diode noise source in the off state. These data is presented in figure 4. The ripple appearing in the temperature of the noise diode is a good indicator of the quality of the measurement. The best results (appendix III) are obtained for the configuration with a low noise preamplifier and an isolator at the input.



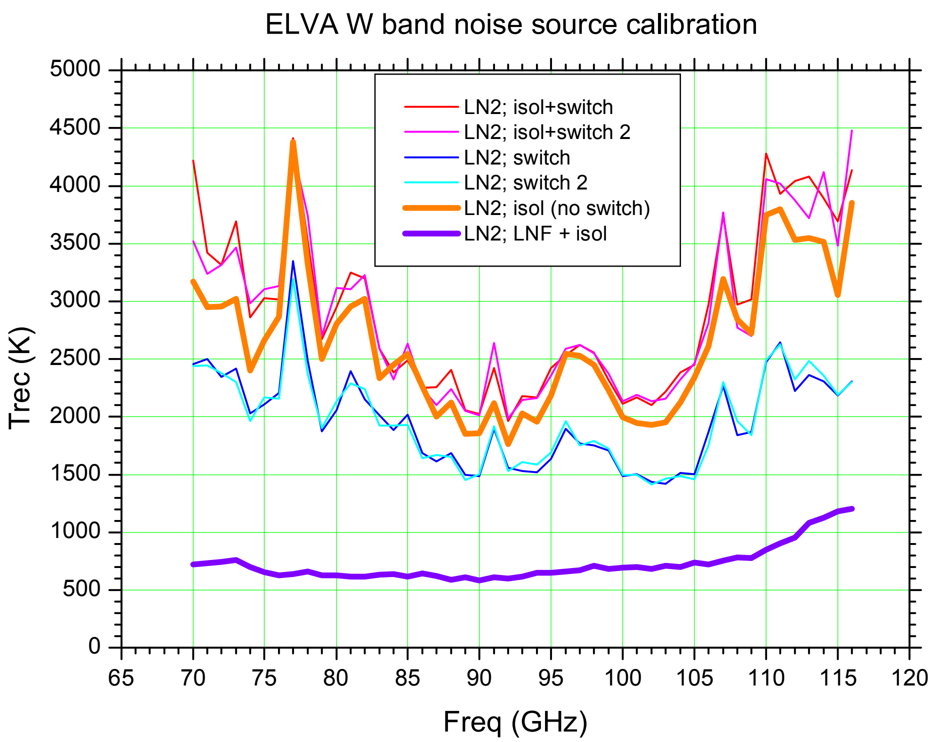


Figure 4: Measured diode noise source off temperature (up) and system temperature (down) corresponding to the configurations presented in figure 1. The thick violet line (no WG switch, LNF preamplifier and isolator) yields the lower system temperature and the less intense ripple in the off state temperature (as expected).

Measurement of S parameters of system components

The estimation of the accuracy of the ENR obtained requires knowledge of the magnitude of the reflection coefficient of all the noise sources involved and of the input of the receiver. In theory, if the complex reflection coefficients are known, they could be used for correcting the power measurements and obtaining a better accuracy but in practice this possibility is quite problematic to implement. For example, it would be very complicated to achieve exactly the same position of the ambient and LN2 absorbers relative to the horn for the measurements of reflection coefficient and for the noise power and minute deviations would cause large phase variations (although the magnitude will not change significantly).

Figures 5 and 6 show the reflection coefficient of the noise diode and of the hot/cold loads. The variation of the reflection of the diode is quite small, making it suitable for the measurement of low noise preamplifiers. Figures 7 and 8 present the measured S parameters of the isolator and preamplifier used.

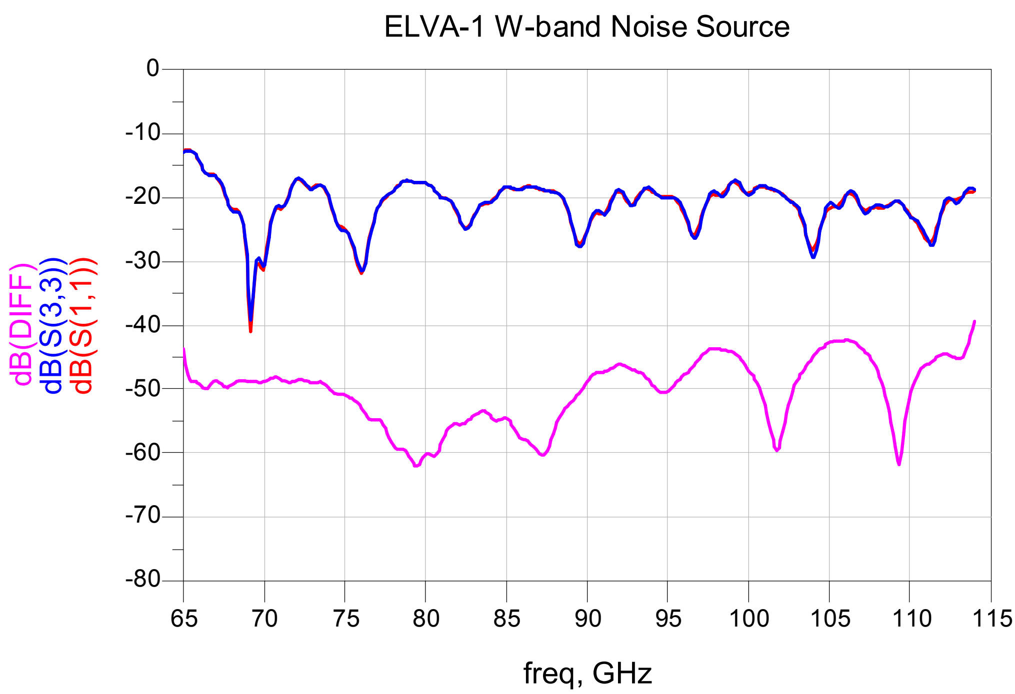


Figure 5: Measured reflection coefficient of ELVA diode noise source in the on (blue) and off (red) states. The two plots appear almost identical. The magnitude of the vector difference between on and off is presented in cyan. Note that the variation is very small (but measurable) due to the presence of the built in isolator.

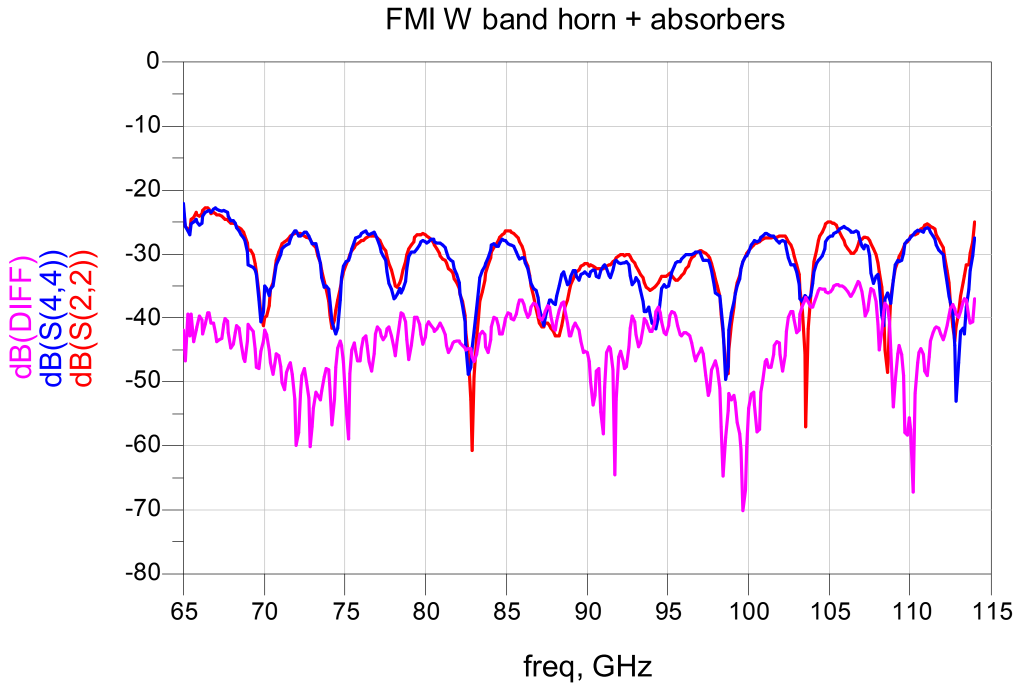


Figure 6: Measured reflection coefficient of the horn and absorbers used for the calibration (red=small cone, blue=large cone). The reflection coefficient is dominated by the discontinuities at the waveguide port and at the end of the horn. The contribution of the absorber cones is below the -35 dB level.

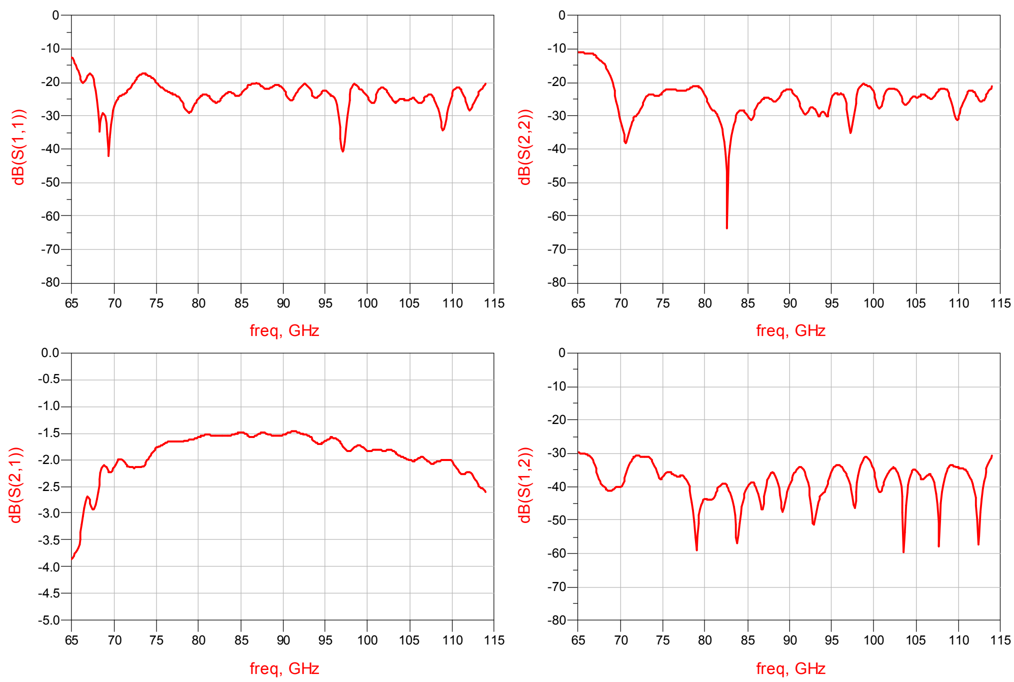


Figure 7: Measured S parameters of QuinStar isolator mod. QIF W00000 s/n 17911014002 used at receiver input.

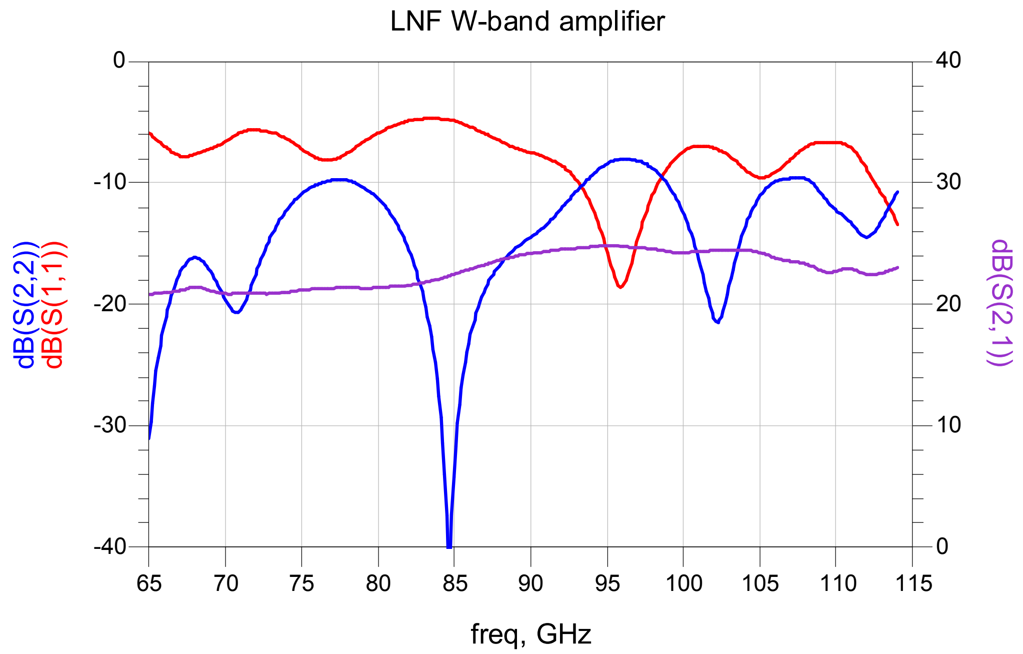


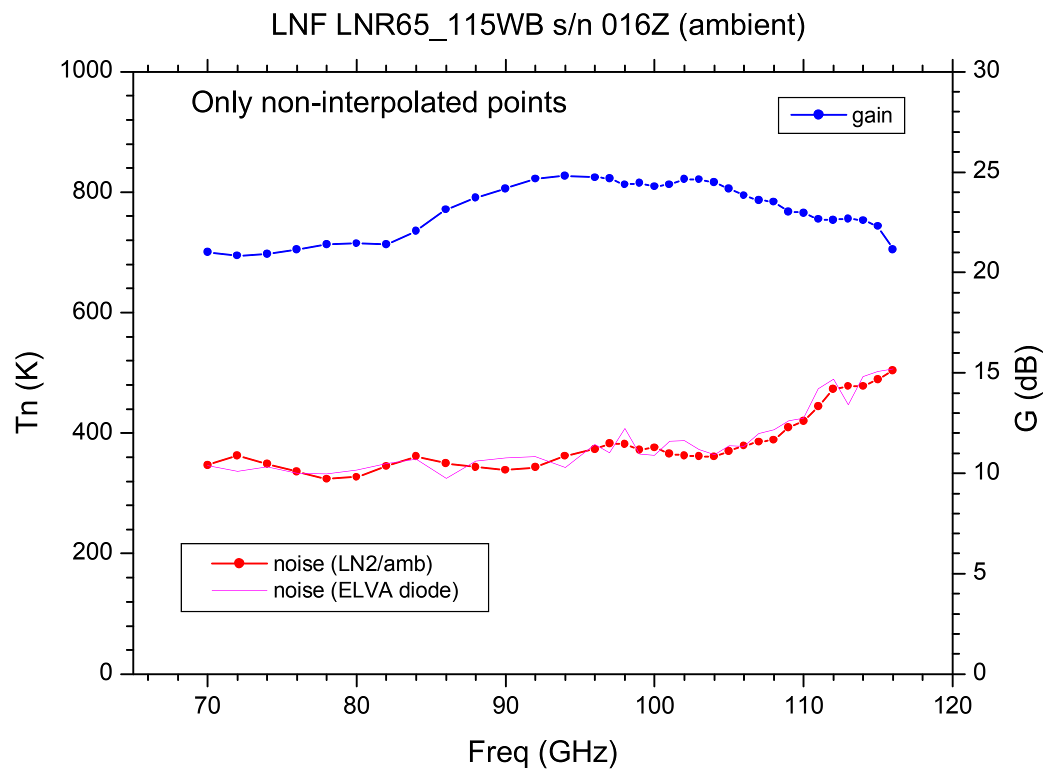
Figure 8: Measured S parameters of LNF-LNR65_115WB s/n 016Z Low Noise W band Preamplifier

Error estimation

The accuracy of the value of the ENR measured can be estimated by the Monte Carlo method [1], [2]. The calculation is performed using a MathCAD file specially developed for his case as shown in appendix I. For the configuration with LNF preamplifier and input isolator the estimation yield **an accuracy of ±0.17 dB** with a coverage factor of 2 (2σ, level of confidence of 95%). This value is quite similar to the specification of precision coaxial microwave noise sources in the low bands (<26 GHz). The reason for this good accuracy is a) the small change of reflection coefficient between hot and cold calibration loads (-35 dB) and b) the low system noise temperature. Using totally independent hot and cold loads with similar reflection coefficients (-25 dB) but random phases would yield a much higher error.

Low Noise Amplifier measurement

In order to check the calibration of the ENR in the normal environment it was decided to perform the complete calibration-measurement process with the standard program used to control the HP 8970 B NFM. To accomplish this, the ENR values obtained in the calibration were used to fill the internal table of the NFM. As only 35 values could be introduced, it was decided to fill the beginning of the table (up to 96 GHz) with 2 GHz steps and the following part, until 116 GHz, with 1 GHz steps. The calibration of the NFM can only be performed using its internal ENR table. However, the program uses is own independent ENR table for the measurements which resides in the computer disk. This table is not memory limited, ant it was filled completely with 1 GHz frequency steps for the data points.



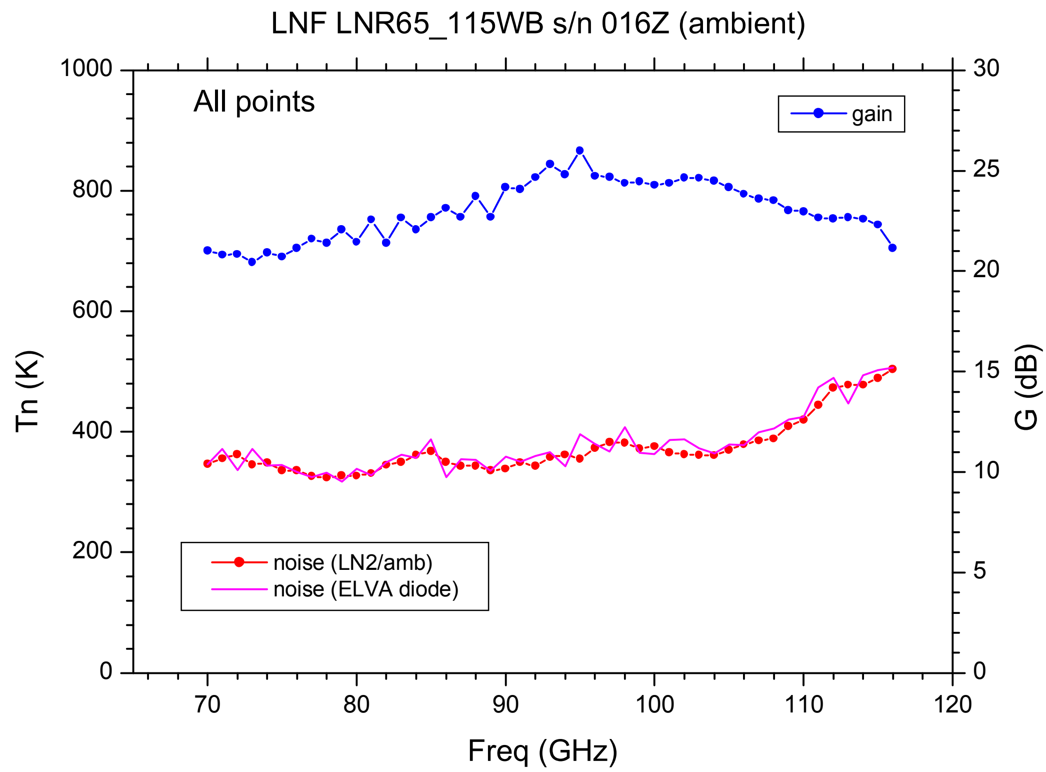


Figure 9: Measurement of gain and noise of LNF-LNR65_115WB s/n 016Z. Calibration is always performed with the ELVA noise source. The measurements obtained with hot/LN2 absorbers and with ELVA noise diode are shown for comparison. The graph on the TOP present only the data at the frequencies present in the NFM calibration table. The BOTTOM graph uses interpolation on the ENR calibration table to obtain the missing points. Note the additional gain ripple in the 70-96 GHz range.

The results of figure 9 show an excellent agreement between the measurements with the hot/cold loads and with the ELVA noise diode. The bottom graph also show the gain ripple which appears when the ENR data of the calibration table with 2 GHz frequency spacing is interpolated to obtain 1 GHz spacing. Then, a non-existent gain ripple appears as an artifact. The ripple does not appear in the noise measurement because the ENR table used for the measurement was in the computer and contained data spaced 1 GHz.

Finally, a comparison of the measured gain obtained with the HP 8970 B NFM and with the Vector Network Analyzer PNA-X is presented in figure 10. The agreement between measurements is almost perfect, confirming the no saturation of the amplifier in the VNA measurements and the good calibration of the system in NFM measurements.

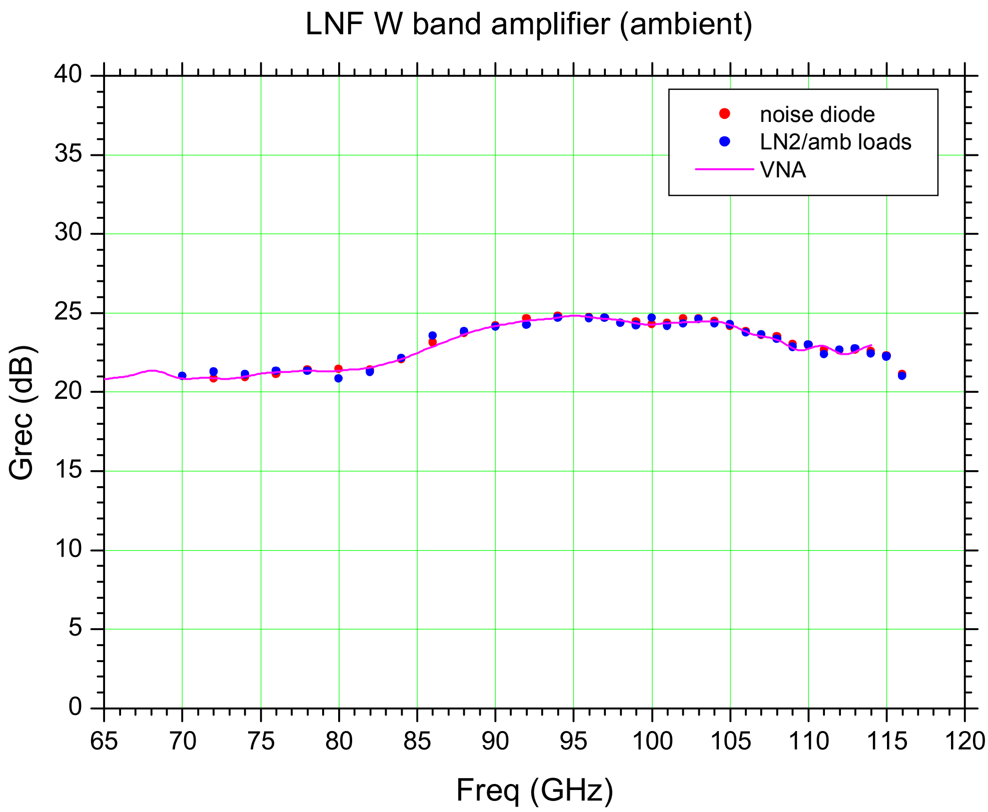


Figure 10: Comparison of gain measurements obtained with Noise Figure Meter and with Vector Network Analyzer.

Conclusions and recommendations

- The ELVA-1 W band noise source presents a **ripple in ENR** with a frequency of **~2 GHz**. which may cause significant errors in measurements, specially if the calibration table used contains points separated by more than 1 GHz
- **Avoid interpolation** of the ENR calibration table: measure only at the frequency data points existent in the ENR calibration table.
- If a HP 8970 B NFM is used there is only space for **35 points** in the internal calibration table. This is not sufficient for sweeping with 1 GHz steps in W band. It is better to use 2 GHz steps
- If DSB mode is used (default), measure with the same IF which was used for the ENR calibration. 250 MHz is recommended.

References:

[1] Gallego, JD; Pospieszalski, MW; " Accuracy of noise temperature measurement of cryogenic amplifiers, NRAO Electronics Division Report,1-31,1992

[2] Juan Daniel Gallego, Juan Luis Cano, "Estimation of Uncertainty in Noise Measurements Using Monte Carlo Analysis," *RadioNET FP7 1st Engineering Forum Workshop "Low Noise Figure Measurements at Cryogenic and Room Temperature"*, Chalmers University of Technology, April 2009. .

APPENDIX I:

ENR ERROR IN CALIBRATION WITH LN2 AND AMBIENT LOADS

$dB \equiv 1$ $Hz \equiv sec^{-1}$ $MHz \equiv 10^{6} \cdot Hz$ $K \equiv 1$ $T_0 \equiv 290$ $Nsd \equiv 2$ (number of standard deviati for error calculation)

Noise diode data:

$ENR := 15 \cdot dB$	ENR of noise diode source to be calibrated
$\Gamma dmaxdB := -16 \cdot dB$	Worst case reflection coefficient
$\Gamma difdB := -40 \cdot dB$	Worst case change in reflection coefficient
$Tdoff := 297 \cdot K$	Ambient temperature of noise diode

Hot and cold loads for calibration:

$Thot := 297 \cdot K$	Temperature of hot load
$\Delta Thot := 1 \cdot K$	Error in temperature measurement
$Tcold := 78 \cdot K$	Temperature of cold load
$\Delta Tcold := 1 \cdot K$	Error in temperature measurement
$\Gamma hcmaxdB := -25 \cdot dB$	Worst case reflection coefficient of hot and cold loads (mainly due to horn; fixed)
$\Gamma hcdifdB := -35 \cdot dB$	Worst case change in reflection coefficient between hot and cold loads (absorber)

Receiver parameters:

$Trec := 1200 \cdot K$	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)
$B := 4 \cdot MHz$	Bandwith of receiver filter
$t := 0.4 \cdot sec$	Integration time of receiver
$\Delta G := 0.01$	Error in gain from hot to cold measurement (detector in NFM)

$mean\left(\overrightarrow{(10 \cdot \log(G))}\right) = -20.059$

$Nsd \cdot stdev\left(\overrightarrow{(10 \cdot \log(G))}\right) = 0.132$

$max\left(\overrightarrow{(10 \cdot \log(G))}\right) = -19.827$

$min\left(\overrightarrow{(10 \cdot \log(G))}\right) = -20.303$

measured gain (in dB)

$mean(Trecm) = 1220.7$

$Nsd \cdot stdev(Trecm) = 48.9$

$max(Trecm) = 1310$

$min(Trecm) = 1143.7$

measured receiver noise temperature

$mean(Thdm) = 9270.6$

$Nsd \cdot stdev(Thdm) = 321.7$

$max(Thdm) = 9862.7$

$min(Thdm) = 8749.3$

mesured noise diode ON temperature

$mean(Tcdm) = 296.8$

$Nsd \cdot stdev(Tcdm) = 36.4$

$max(Tcdm) = 334.6$

$min(Tcdm) = 258.2$

mesured noise diode OFF temperature

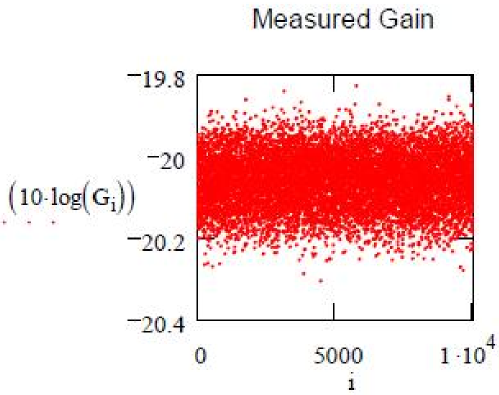
$mean(ENRdBm) = 14.905$

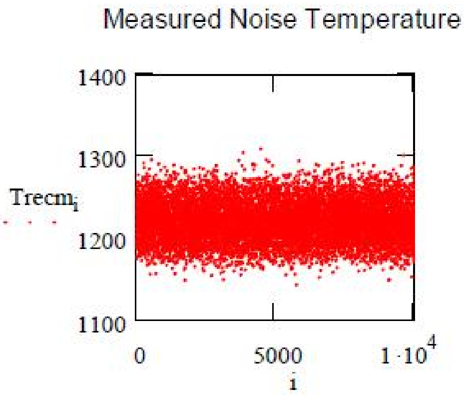
$Nsd \cdot stdev(ENRdBm) = 0.165$

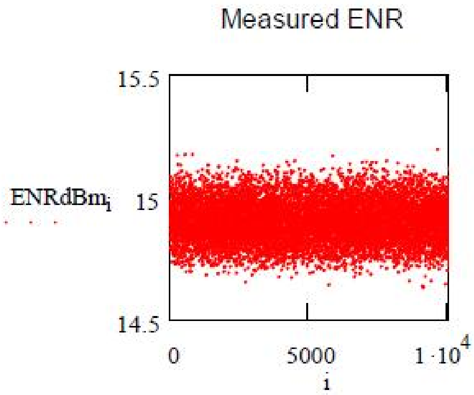
$max(ENRdBm) = 15.197$

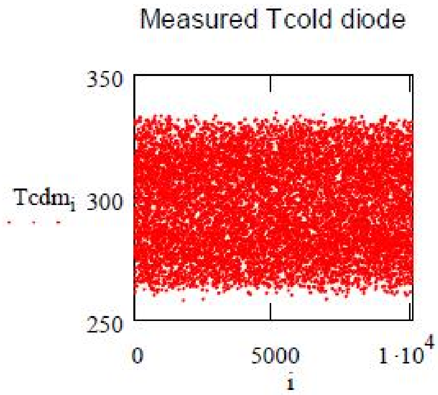
$min(ENRdBm) = 14.635$

measured ENR of noise diode


Measured Gain
−19.8
−20
−20.2
−20.4
(10·log(G_i))
0
5000
1·10^4
i


Measured Noise Temperature
1400
1300
1200
1100
Trecm_i
0
5000
1·10^4
i


Measured ENR
15.5
15
14.5
ENRdBm_i
0
5000
1·10^4
i


Measured Tcold diode
350
300
250
Tcdm_i
0
5000
1·10^4
i

APPENDIX II:

ENR Calibration of ELVA-1 noise source mod. ISSN-10 s/n 14-15-W

```
NOISE AND GAIN MEASUREMENT ENR_cal_Wband.bas SYS:350 CAL:  3 May 2016

TIME: 13:57:18  DATE: 11 May 2016 Tampli=  Tamb= NOT AVAIABLE

DATA STORED IN FILE:     C:\HPBASIC\NOISE_mix\DATA\M_213.TXT


RF ATT: +20, +10,   0 dB
LNF016Z + ISOLATOR
NO BIAS DATA AVAILABLE

Tmean=   665.76 K   Tmin=   580.54 K   Tmax=   846.32 K   Delta=   265.78 K
Gmean=     5.42dB   Gmin=     2.65dB   Gmax=     7.36dB   Delta=     4.71dB
Tcold=   296.00 K                                NdB Table=    11
```

F	ENR	Thot	Tcold	Phdiod	Pcdiod	Phot	Pcold
7.000	15.38	10312.07	296.49	42.35	32.02	32.00	30.97
7.100	15.19	9873.93	298.64	42.81	32.68	32.66	31.64
7.200	14.93	9316.15	295.58	42.38	32.51	32.50	31.48
7.300	15.67	10980.94	291.26	43.75	33.27	33.28	32.29
7.400	15.10	9674.11	295.72	43.26	33.09	33.08	32.02
7.500	15.03	9533.62	296.49	43.51	33.23	33.21	32.10
7.600	13.88	7383.93	292.57	42.16	32.76	32.76	31.60
7.700	14.01	7592.42	296.86	41.81	32.37	32.35	31.21
7.800	14.53	8527.23	297.17	42.33	32.52	32.50	31.39
7.900	13.40	6636.32	293.84	42.10	33.14	33.13	31.98
8.000	13.92	7442.10	294.26	42.64	33.22	33.22	32.07
8.100	13.08	6184.79	293.41	41.73	33.00	32.99	31.82
8.200	14.72	8897.39	295.09	43.65	33.47	33.46	32.29
8.300	13.76	7190.93	298.97	43.37	34.12	34.09	32.94
8.400	14.38	8240.44	297.28	44.21	34.43	34.41	33.27
8.500	14.10	7751.04	299.92	44.56	34.95	34.91	33.74
8.600	14.30	8106.19	294.50	44.99	35.30	35.29	34.16
8.700	14.37	8220.90	293.41	45.78	35.92	35.92	34.76
8.800	13.24	6420.37	299.11	44.78	35.81	35.78	34.57
8.900	14.73	8912.26	297.59	46.06	35.87	35.84	34.66
9.000	13.68	7061.03	296.63	45.60	36.20	36.19	34.96
9.100	14.24	7990.90	299.47	44.63	34.88	34.85	33.67
9.200	13.70	7095.65	295.87	45.86	36.52	36.50	35.31
9.300	13.29	6476.57	295.72	45.55	36.65	36.64	35.47
9.400	14.06	7687.22	298.22	46.09	36.65	36.63	35.50
9.500	13.07	6176.64	300.62	45.53	36.97	36.94	35.81
9.600	14.20	7918.08	296.73	46.69	37.18	37.16	36.06
9.700	13.33	6542.25	300.80	45.45	36.75	36.72	35.63
9.800	13.31	6510.99	296.21	45.32	36.76	36.75	35.70
9.900	13.76	7187.06	299.50	45.64	36.60	36.57	35.49
10.000	13.17	6311.83	298.67	45.09	36.60	36.58	35.51
10.100	14.12	7783.25	296.40	45.92	36.61	36.59	35.53
10.200	13.01	6098.00	300.40	44.59	36.19	36.16	35.08
10.300	13.67	7043.58	299.00	45.06	36.21	36.18	35.14
10.400	14.04	7658.31	298.71	45.71	36.49	36.47	35.41
10.500	13.46	6729.27	299.15	44.57	35.99	35.97	34.95
10.600	14.22	7968.45	296.70	45.06	35.74	35.73	34.69
10.700	13.36	6578.47	298.28	43.92	35.49	35.47	34.47
10.800	13.83	7304.32	298.67	44.10	35.36	35.34	34.37
10.900	13.59	6933.12	299.63	43.60	35.05	35.02	34.05
11.000	13.16	6300.63	295.04	41.83	33.86	33.85	32.94
11.100	13.88	7377.17	299.00	41.97	33.59	33.56	32.70
11.200	12.89	5938.09	298.10	41.20	33.80	33.78	32.96
11.300	13.10	6220.36	297.95	41.47	34.23	34.22	33.48
11.400	12.97	6051.44	305.36	40.98	33.98	33.95	33.23
11.500	12.06	4967.06	305.84	39.37	33.21	33.17	32.49
11.600	12.06	4961.87	301.16	37.17	31.05	31.03	30.36

APPENDIX III:

ELVA-1 noise source mod. ISSN-10 s/n 14-15-W original data

MEASURED DATA:

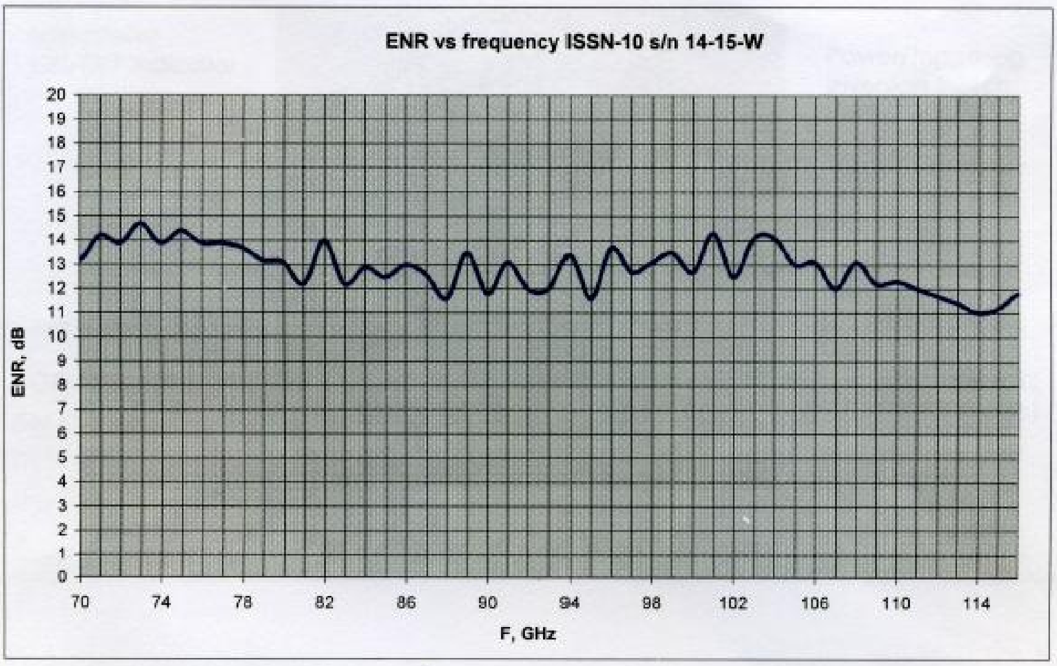


Fig.1. ENR vs. Frequency.

F. GHz	ENR. dB	F. GHz	ENR. dB	F. GHz	ENR. dB	F. GHz	ENR. dB	F. GHz	ENR. dB
70	13.2	80	13.1	90	11.8	100	12.7	110	12.3
71	14.2	81	12.2	91	13.1	101	14.3	111	12
72	13.9	82	14	92	12	102	12.5	112	11.7
73	14.7	83	12.2	93	12	103	14.1	113	11.4
74	13.9	84	12.9	94	13.4	104	14.1	114	11
75	14.4	85	12.5	95	11.6	105	13	115	11.2
76	13.9	86	13	96	13.7	106	13.1	116	11.8
77	13.9	87	12.6	97	12.7	107	12	117	11.5
78	13.7	88	11.6	98	13.1	108	13.1	118	10.7
79	13.2	89	13.5	99	13.5	109	12.2		

Tab.1. ENR vs. frequency.