MEASUREMENTS OF PERFORMANCE OF InP AND GaAs VLBI X BAND CRYOGENIC AMPLIFIERS (WP 2000 & 3000, ESA CONTRACT 14297/00/SW)

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TECHNICAL NOTE
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3 INTRODUCTION

This report corresponds to Work Packages 2000 and 3000 of the ESA contract "Development of a state of the art cryocooled X-band low noise amplifier". The goal of Work Package 2000 is to measure two prototypes of VLBI amplifiers available in the Centro Astronomico de Yebes. One of them (S/N YXV 001) was built with GaAs HEMT devices in all three stages, while the other (S/N YXV 005) has ETH InP devices in the first and second stage and GaAs in the third. The measurements were done according with the description given in WP1000 unless otherwise specified. The bias point of these amplifiers was originally optimized for minimum noise. As the specifications of this project asked for some values of IP3 and compression, the amplifiers were measured at several bias points, with the aim to obtain information on the trade-off of improved linearity and the other characteristics. The goal of WP3000 is to analyze the results of WP2000 as well as other recent experience with InP and GaAs devices to determine which devices are best suited for the application requested in this project.

4 BIAS POINTS

The bias points referred in the rest of this report are summarized in table I. It was identified that the main parameter affecting the compression and intermodulation was the drain current of the third stage. For this reason, it was decided to take measurements at several values of this parameter. Note in table I that only the drain current of the third stage is changed between different bias points of the same amplifier at the same physical temperature.

TABLE I

Bias points used in the measurements.

Amplifier S/N	Temp. (K)	Bias ref.	V_{d1}	I_{d1}	V_{d2}	I_{d2}	V_{d3}	I_{d3}
YXV 001 (GaAs)	297	LOW-A	3.00	10.0	3.00	10.0	3.00	10.0
		MED-A	3.00	10.0	3.00	10.0	3.00	15.0
		HIGH-A	3.00	10.0	3.00	10.0	3.00	20.0
	14	LOW-C	3.00	5.0	3.00	5.0	3.00	5.0
		MED-C	3.00	5.0	3.00	5.0	3.00	10.0
		HIGH-C	3.00	5.0	3.00	5.0	3.00	15.0
YXV 005 (InP)	297	LOW-A	1.30	10.0	1.30	10.0	3.00	10.0
		MED-A	1.30	10.0	1.30	10.0	3.00	15.0
		HIGH-A	1.30	10.0	1.30	10.0	3.00	20.0
	14	LOW-C	0.50	2.0	0.50	2.0	3.00	5.0
		MED-C	0.50	2.0	0.50	2.0	3.00	10.0
		HIGH-C	0.50	2.0	0.50	2.0	3.00	15.0

5 NOISE MEASUREMENTS

5.1 Ambient temperature

The amplifiers were measured at ambient temperature outside the cryostat with both noise figure measurement systems (350 and 1020). As the noise source and the systems differ, the results are slightly different. Figure 1 presents a comparison of the measurements of the amplifiers in the two systems at the original optimum bias. Table II presents the comparison of the relevant data of these measurements. The average noise temperature and minimum and maximum gain were obtained in the original band of the amplifier (8.1-9 GHz), shown by vertical markers in figure 1. The noise temperature and gain measured at 8.4 GHz are presented in table II for convenience. Table III presents some details of the measurement system. Note that an isolator is used in system 1020 but not in the 350. This is because the preamplifier used in system 1020 has a worse input match. The isolator is not used in system 350 (older) for historical reasons, and to keep the measurements compatible with previous ones. As the receiver noise temperature is frequency dependent, the range of values for the 7-10 GHz band is presented in the table. Note that the noise sources used for ambient and cryogenic measurements are different, as explained in [1]. The mode used in the measurements by default is DSB. Figure 2 presents a comparison of measurements in SSB and DSB modes, showing no significant differences in the results. Finally, figure 3 and table IV present measurements of the amplifiers in system 1020 at three different bias points. The noise degradation at high bias is negligible at ambient temperature.

TABLE II

Comparison of noise and gain measurements at ambient temperature in the two systems.

Amplifier S/N	System	Temp. (K)	Bias ref.	T_{min} (K)	T_{avg} (K)	$T_{8.4}$ (K)	G_{min} (dB)	G_{max} (dB)	$G_{8.4}$ (dB)
YXV 001 (GaAs)	1020	297	LOW-A	78.98	80.63	79.27	31.97	33.83	33.04
	350	297	LOW-A	73.23	75.01	74.99	31.61	33.69	33.19
YXV 005 (InP)	1020	297	LOW-A	91.60	95.69	94.69	34.45	34.91	34.58
	350	297	LOW-A	84.90	87.50	85.42	34.40	35.14	35.05

TABLE III

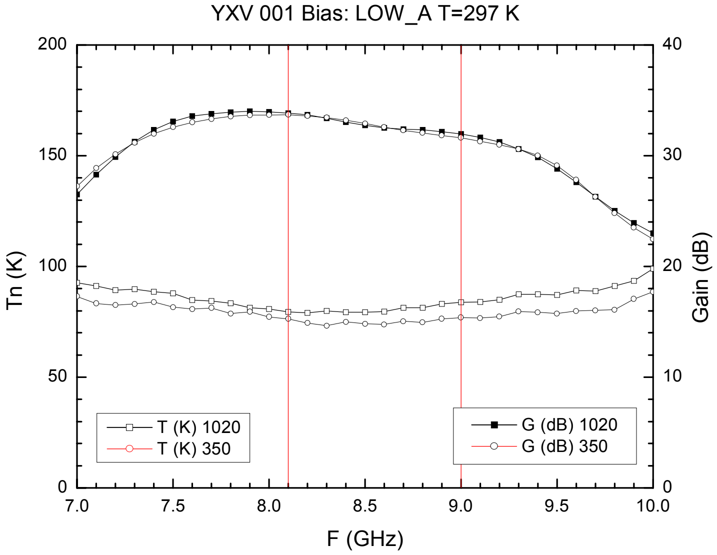
Details of 1020 and 350 systems used for ambient temperature measurements outside the cryostat.

System	Noise Source (SN)	Receiver Noise Temperature (K)	Input Isolator
1020	HP 346 A S/N: 3318A05234	395-430	YES
350	HP 346 A S/N: 2614A01243	195-225	NO

TABLE IV

Comparison of noise and gain measurements at ambient temperature for different bias in 1020 system.

Amplifier S/N	System	Temp. (K)	Bias ref.	T_{min} (K)	T_{avg} (K)	$T_{8.4}$ (K)	G_{min} (dB)	G_{max} (dB)	$G_{8.4}$ (dB)
YXV 001 (GaAs)	1020	297	LOW-A	78.98	80.63	79.27	31.97	33.83	33.04
	1020	297	MED-A	78.93	80.87	79.67	32.21	34.11	33.26
	1020	297	HIGH-A	78.99	80.86	78.99	32.27	34.16	33.30
YXV 005 (InP)	1020	297	LOW-A	91.60	95.69	94.69	34.45	34.91	34.58
	1020	297	MED-A	92.10	95.72	92.10	34.63	35.12	34.76
	1020	297	HIGH-A	91.77	95.69	93.18	34.60	35.13	34.73



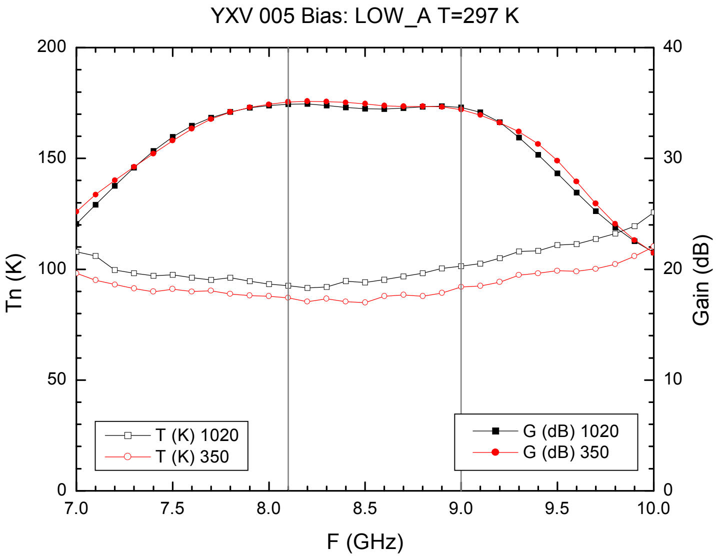


Figure 1: Comparison of noise and gain measurements at ambient temperature outside the cryostat in 350 and 1020 systems. Vertical markers are located at 8.1 and 9 GHz to show the original band of the two amplifiers. Both are biased for minimum noise.

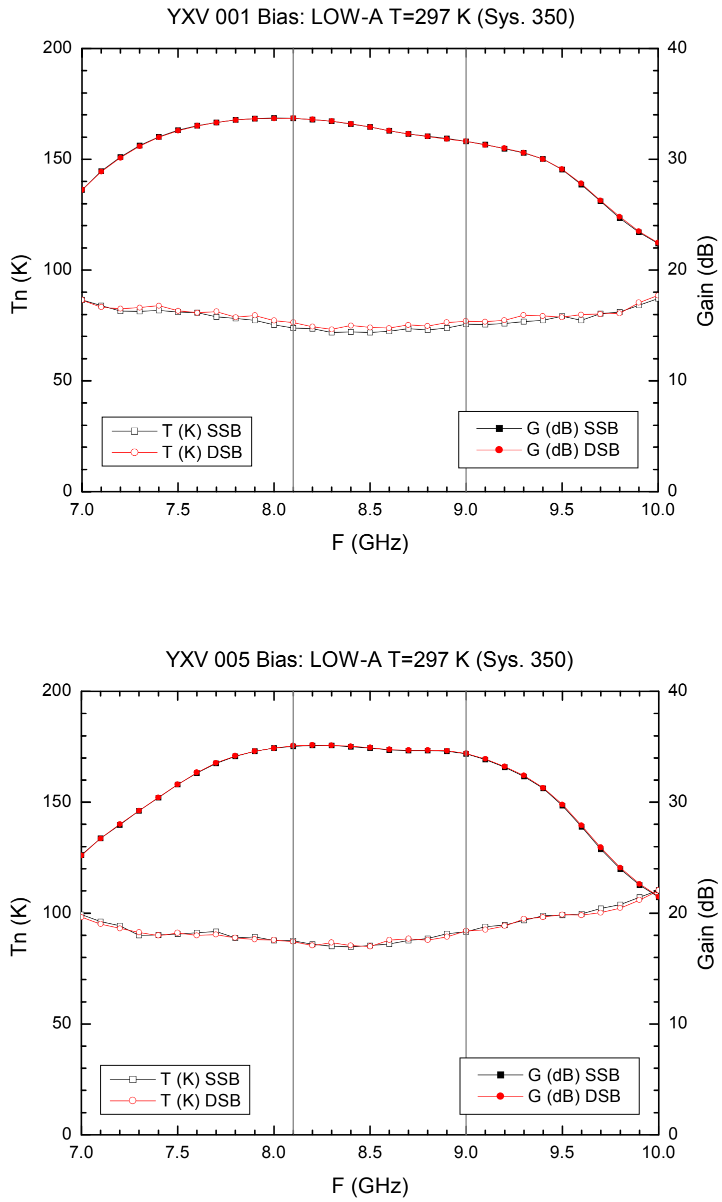
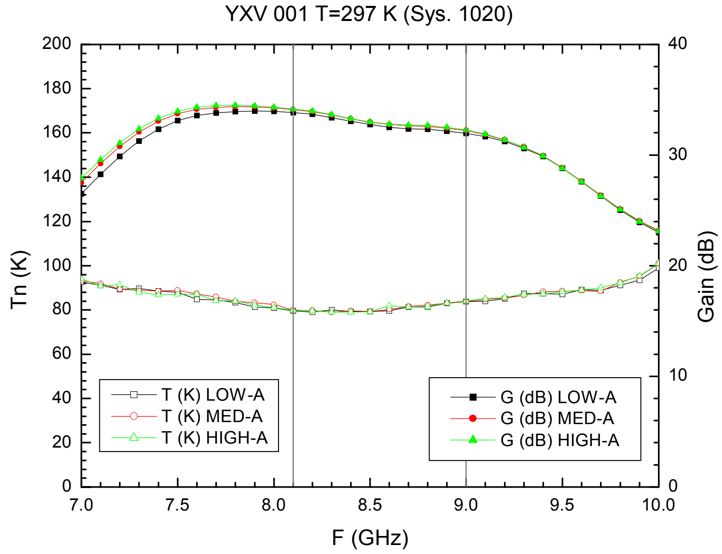


Figure 2: Comparison of noise and gain measurements at ambient temperature outside the cryostat in SSB and DSB modes in system 350. Vertical markers are located at 8.1 and 9 GHz to show the original band of the two amplifiers. Both amplifiers are biased for minimum noise. The calibration for the SSB measurement was done immediately before measurement in each case.



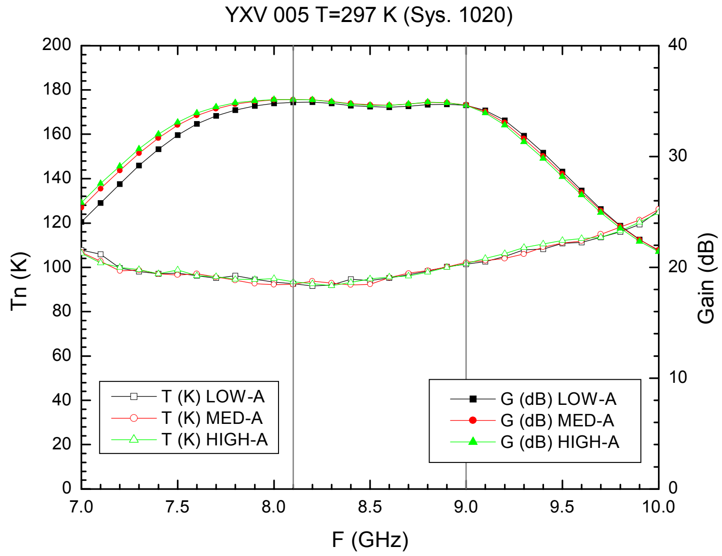


Figure 3: Comparison of noise and gain measurements at ambient temperature outside the cryostat in DSB mode in system 1020 for several bias points. Vertical markers are located at 8.1 and 9 GHz to show the original band of the two amplifiers.

5.2 Cryogenic temperature

The amplifiers were measured at cryogenic temperature (14 K) in the two systems (350 and 1020). As the noise source and the systems differ, the results are slightly different. Figure 4 presents a comparison of the measurements of the amplifiers in the two systems at the original optimum bias (LEDs off). Table V presents the comparison of the relevant data of these measurements. The average noise temperature and minimum and maximum gain were obtained in the original band of the amplifier (8.1-9 GHz), shown by vertical markers in figure 1. The noise temperature and gain measured at 8.4 GHz are presented in table V for convenience. Table VI presents some details of the measurement system. Note that an isolator is used in system 1020 but not in the 350. This is because the preamplifier used in system 1020 has a worse input match. The isolator is not used in system 350 (older) for historical reasons, and to keep the measurements compatible with previous ones. As the receiver noise temperature is frequency dependent, the range of values for the 7-10 GHz band is presented in the table. Note that the noise sources used for ambient and cryogenic measurements are different, as explained in [1]. The mode used in the measurements by default is DSB. Figure 5 presents a comparison of measurements in DSB and in SSB modes, showing no significant differences in the results. For the SSB measurements the frequency sweep is from 8.3 to 8.6 with 0.01 GHz of resolution, and no fine grain details are found. The best results of the InP amplifier were obtained when it was cooled with bias LOW-C on and LEDs off. However, this amplifier showed some histeresis with light. If the LEDs were switched on, the noise temperature raised immediately about 0.7 K. After switching the LEDs off, the noise decreases slowly toward the initial value, but after several hours, the noise still was 0.4 K higher than the initial dark value. However, if the amplifier is heated to room temperature, and cooled again in darkness, the initial values of noise temperature are obtained. Finally, figure 6 and table VII present measurements of both amplifiers in system 1020 at the two different bias points. The noise degradation at high bias is about 0.4 K for the InP amplifier, but only 0.15 K for the GaAs amplifier.

TABLE V

Comparison of noise and gain measurements at cryogenic temperature in the two systems.

Amplifier S/N	System	Temp. (K)	Bias ref.	T_{min} (K)	T_{avg} (K)	$T_{8.4}$ (K)	G_{min} (dB)	G_{max} (dB)	$G_{8.4}$ (dB)
YXV 001 (GaAs)	1020	14	LOW-C	8.44	8.64	8.51	33.13	34.05	33.68
	350	14	LOW-C	8.96	9.33	9.26	32.64	34.16	33.38
YXV 005 (InP)	1020	14	LOW-C	3.52	3.69	3.57	35.21	35.78	35.42
	350	14	LOW-C	3.87	4.01	3.92	35.69	36.03	35.82

TABLE VI

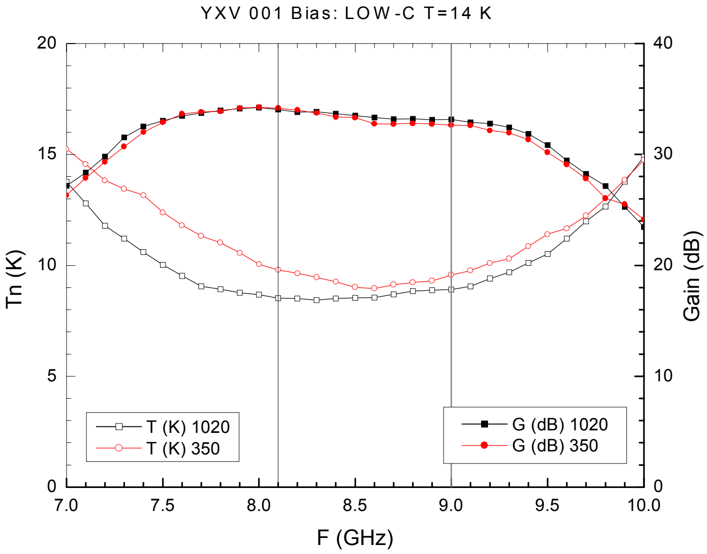
Details of 1020 and 350 systems used for cryogenic temperature measurements in the cryostat.

System	Noise Source (SN)	Receiver Noise Temperature (K)	Input Isolator
1020	HP 346 C S/N: 3328A04589	490-515	YES
350	HP 346 C S/N: 2339A00946	250-320	NO

TABLE VII

Comparison of noise and gain measurements at cryogenic temperature for different bias in 1020 system.

Amplifier S/N	System	Temp. (K)	Bias ref.	T_{min} (K)	T_{avg} (K)	$T_{8.4}$ (K)	G_{min} (dB)	G_{max} (dB)	$G_{8.4}$ (dB)
YXV 001 (GaAs)	1020	14	LOW-C	8.44	8.64	8.51	33.13	34.05	33.68
	1020	14	HIGH-C	8.58	8.80	8.60	33.47	34.41	34.07
YXV 005 (InP)	1020	14	LOW-C	3.52	3.69	3.57	35.21	35.78	35.42
	1020	14	HIGH-C	3.85	4.06	4.01	33.54	34.68	34.09



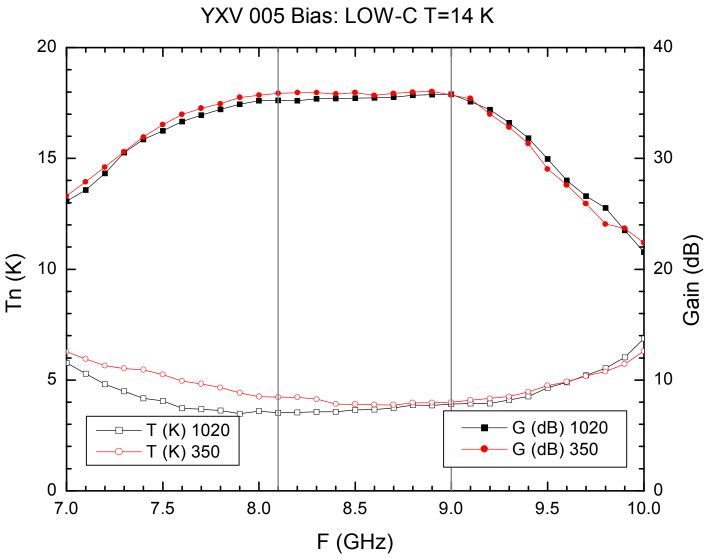
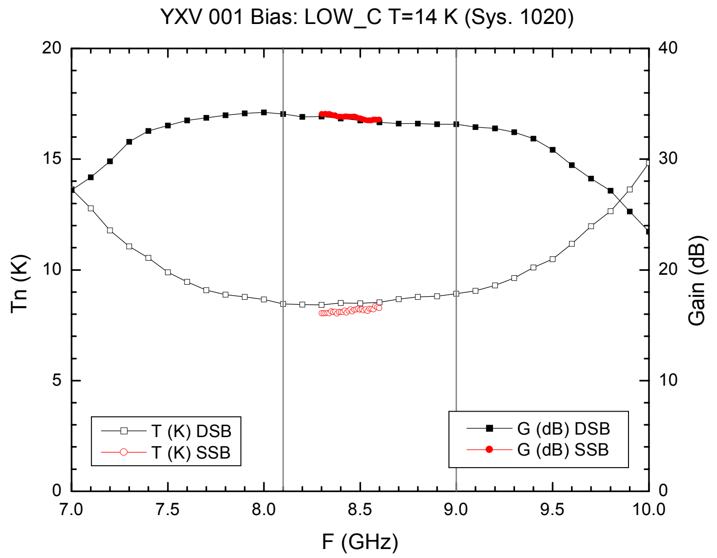


Figure 4: Comparison of noise and gain measurements at cryogenic temperature in 350 and 1020 systems. Vertical markers are located at 8.1 and 9 GHz to show the original band of the two amplifiers. Both are biased for minimum noise with LEDs off.



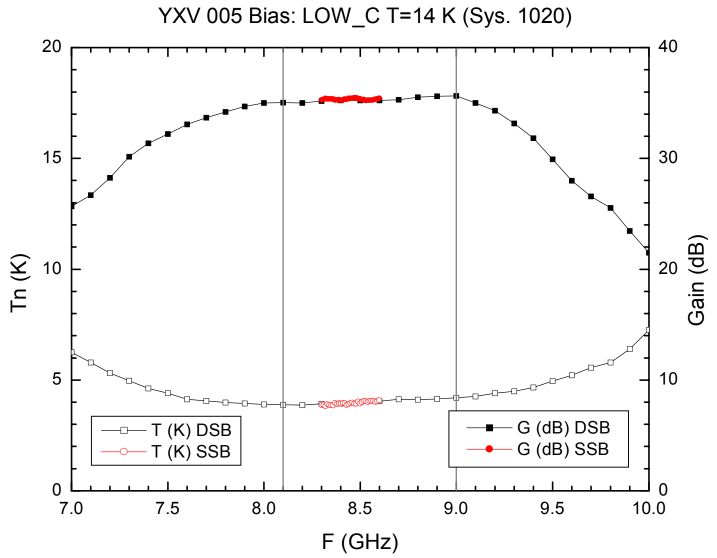
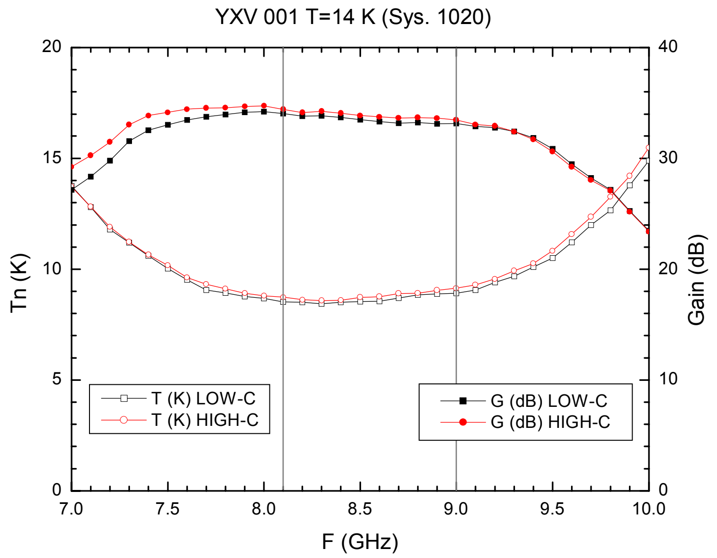


Figure 5: Comparison of noise and gain measurements at cryogenic temperature in SSB and DSB modes in system 1020. Vertical markers are located at 8.1 and 9 GHz to show the original band of the two amplifiers. Both amplifiers are biased for minimum noise. The calibration for the SSB measurement was done immediately before measurement in each case.



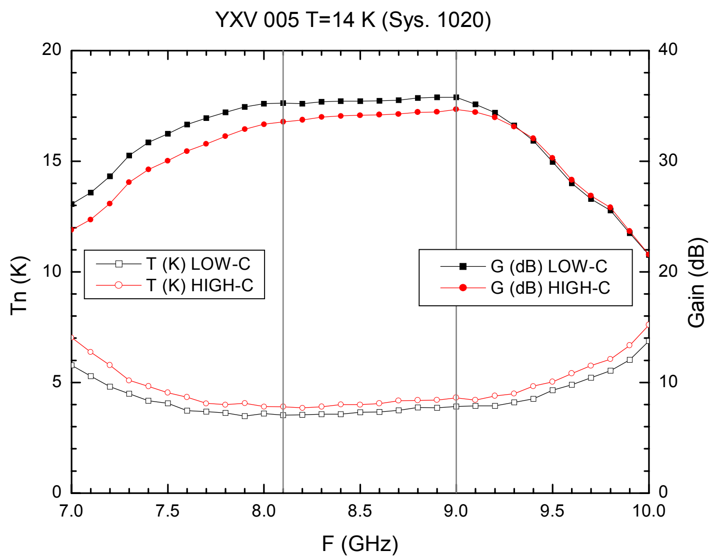


Figure 6: Comparison of noise and gain measurements at cryogenic temperature in DSB mode in system 1020 for different bias points. Vertical markers are located at 8.1 and 9 GHz to show the original band of the two amplifiers.

6 GAIN AND REFLECTION MEASUREMENTS

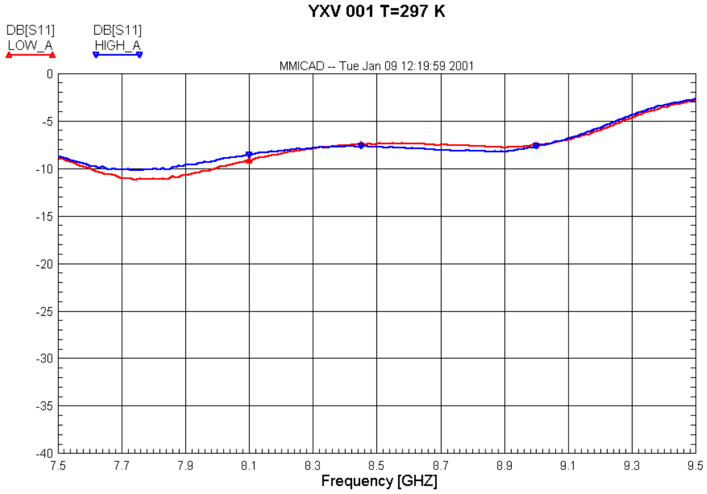
6.1 Ambient temperature

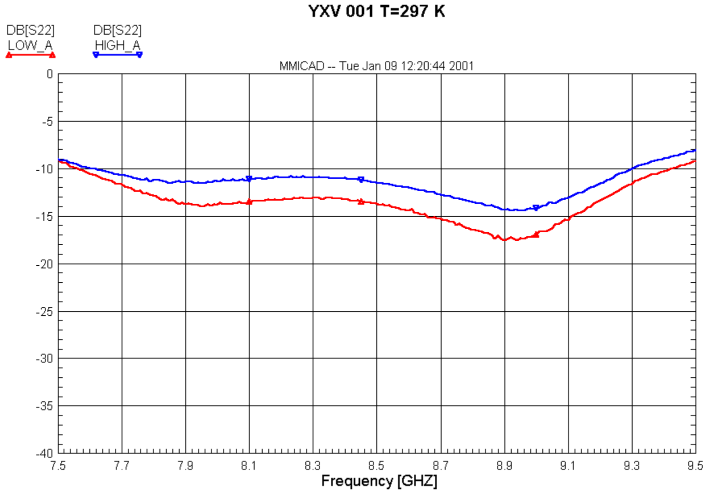
The amplifiers were measured at ambient temperature outside the cryostat at several bias points with the Scalar Network Analyzer (SNA) and with the Vector Network Analyzer (VNA) as explained in [1]. Only the VNA measurements (more accurate) are presented in this report, but the agreement with the SNA measurements is quite good. Figures 7 and 8 present the measurements of input reflection (S11) output reflection (S22) and gain of amplifiers YXV001 and YXV005 at two bias points (LOW_A and HIGH_A). Table VIII presents the numeric values of the same parameters in the 8.4-8.5 GHz band. The values for S11, S22 and S21 given in the table are for the worst case in the band. The main change observed at the high bias point is that the output reflection coefficient becomes worse.

TABLE VIII

Comparison of gain and reflection measurements at ambient temperature for different bias points. S11 and S22 are the worst case reflection in the band. S12 is the average gain and ΔS21 the maximum gain variation in the band. Band is from 8.4 to 8.5 GHz.

Amplifier S/N	System	Temp. (K)	Bias ref.	S11 (dB)	S22 (dB)	S21(dB)	ΔS21(dB)
YXV 001 (GaAs)	VNA	297	LOW-A	-7.42	-13.28	33.00	0.21
	VNA	297	HIGH-A	-7.67	-11.00	33.32	0.20
YXV 005 (InP)	VNA	297	LOW-A	-8.90	-13.33	34.78	0.04
	VNA	297	HIGH-A	-8.96	-10.57	34.96	0.02





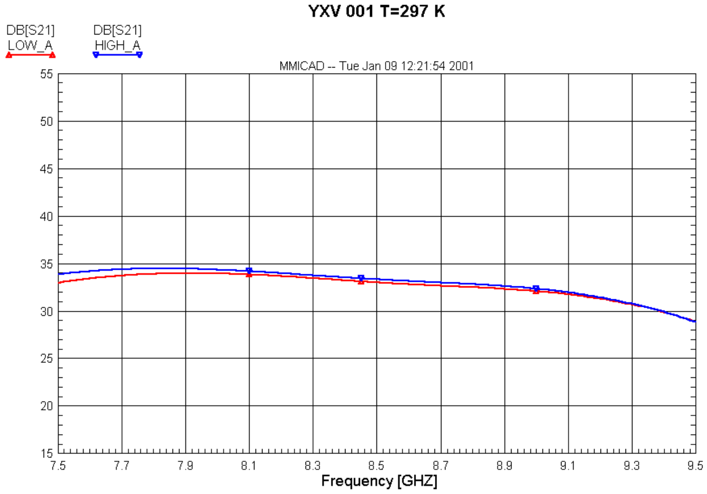


Figure 7: Input and output reflection and gain of amplifier YXV001 at ambient temperature measured with the Vector Network Analyzer outside the cryostat. Data is presented for two different bias points (LOW_A and HIGH_A). Markers are located at 8.1 and 9 GHz to show the original band of the amplifier.

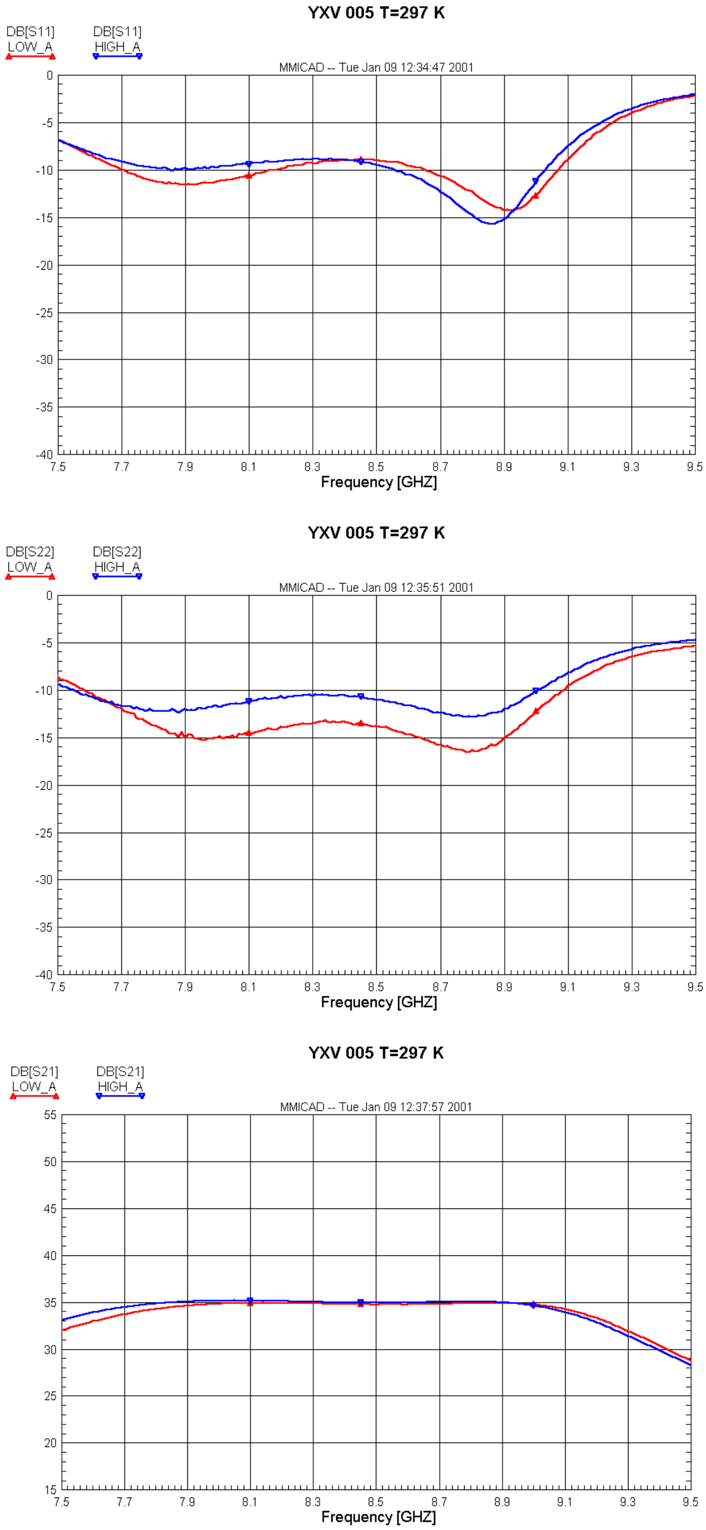


Figure 8: Input and output reflection and gain of amplifier YXV005 at ambient temperature measured with the Vector Network Analyzer outside the cryostat. Data is presented for two different bias points (LOW_A and HIGH_A). Markers are located at 8.1 and 9 GHz to show the original band of the amplifier.

6.2 Cryogenic temperature

The amplifiers were measured at cryogenic temperature in cryostat 350 with the Scalar Network Analyzer (SNA) and in cryostat 1020 with the Vector Network Analyzer (VNA) as at several bias points. Only the VNA measurements (more accurate) are presented in this report. The agreement with the SNA measurements is not as good as in ambient temperature measurements due to the effect of the transitions and cables. In the VNA measurements presented in this report the effect of the input and output transitions (stainless steel cables) is de-embedded by post processing the data with MMICAD program. This was done by taking measurements of the stainless steel transition S parameters at ambient temperature and storing the data in computer files. Then, the measurements of the amplifier were "corrected", assuming no change in the transitions from ambient to cryogenic temperature. The input of the amplifier is connected directly to one of the transitions, but the output needs an additional semi-rigid, U-shaped, cooper cable. The shape of the output cable makes very difficult for our system to measure its S parameters. Besides, as it is made out of copper, the loss will change when cooled, and the de-embedding will not be valid. For these reasons, the output cable was not de-embedded. Instead, a time domain gate was applied to remove the perturbation in the output reflection introduced by the output cable and other residual effects not completely corrected with the de-embedding. The accuracy of the measurements taken in this way is very hard to estimate. Instead, the validity of this procedure has been checked by comparing measurement of one amplifier outside the cryostat with measurements inside the cryostat at ambient temperature. Figure 9 presents the comparison with the post-processed data. The small offset in S21 and S22 is due to the losses of the copper cable at the output of the amplifier not taken into account in the de-embedding. Figures 10 and 11 present the measurements of input reflection (S11) output reflection (S22) and gain of amplifiers YXV001 and YXV005 at two bias points (LOW_C and HIGH_C). The data of these figures has been de-eembeded, and corrected with the gate in the time domain. Table IX presents the numeric values of the same parameters in the 8.4-8.5 GHz band. The values for S11, S22 and S21 given in the table are for the worst case in the band. As in ambient temperature measurements, the main change observed is in the output reflection coefficient.

TABLE IX

Comparison of gain and reflection measurements at cryogenic temperature for different bias points. S11 and S22 are the worst case reflection in the band. S12 is the average gain and ΔS21 the maximum gain variation in the band. Band is from 8.4 to 8.5 GHz.

Amplifier S/N	System	Temp. (K)	Bias ref.	S11 (dB)	S22 (dB)	S21(dB)	ΔS21(dB)
YXV 001 (GaAs)	VNA	14	LOW-C	-7.91	-13.38	33.45	0.13
	VNA	14	HIGH-C	-8.26	-10.72	33.96	0.04
YXV 005 (InP)	VNA	14	LOW-C	-10.33	-14.53	35.72	0.05
	VNA	14	HIGH-C	-11.05	-17.80	34.66	0.09

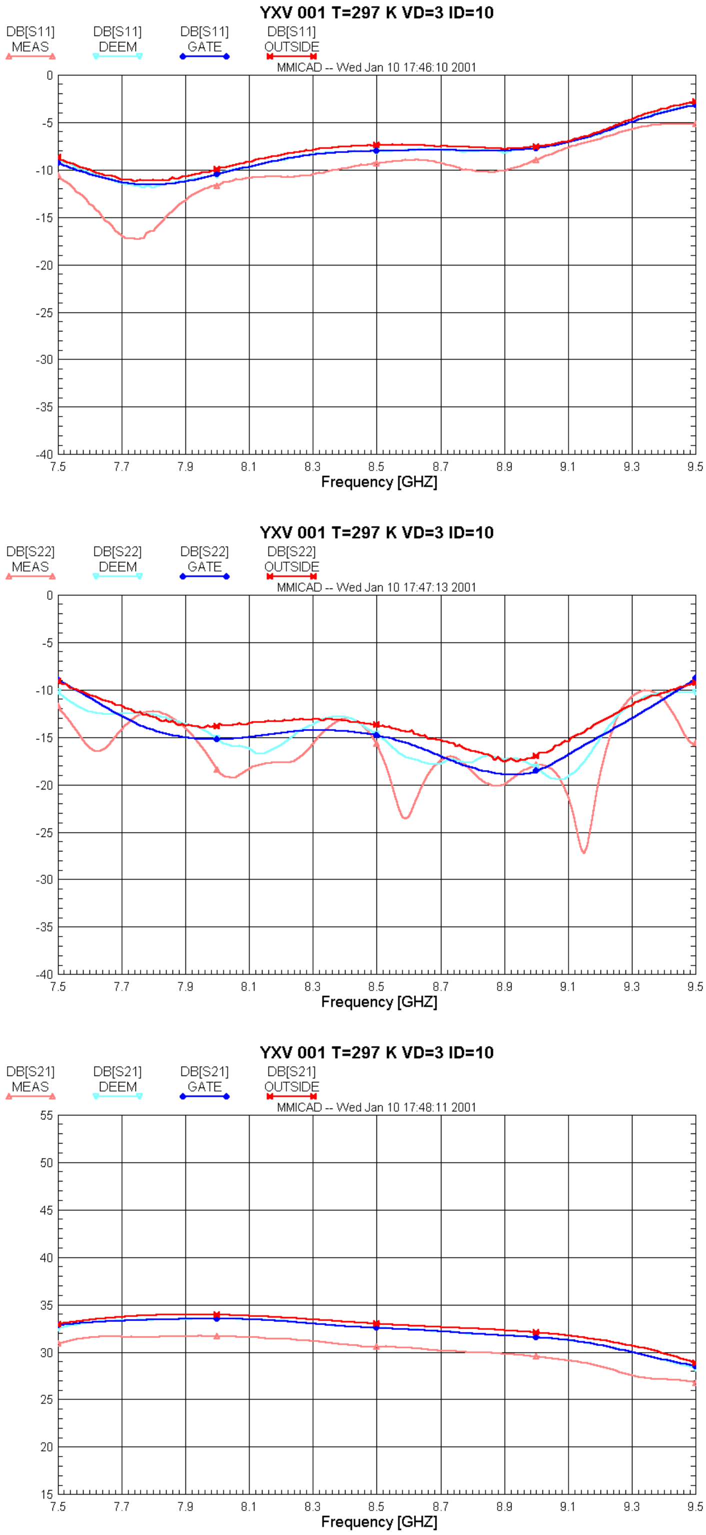
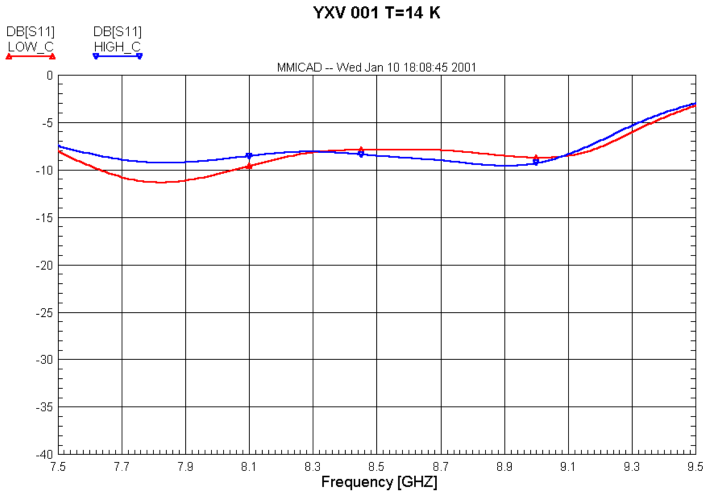
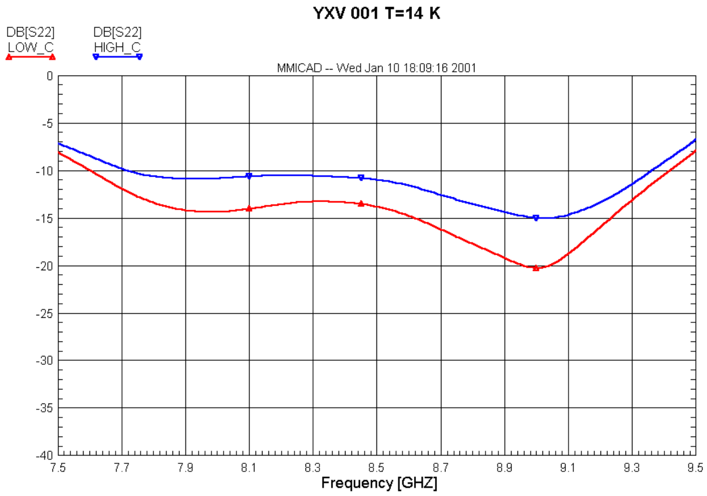


Figure 9: Input and output reflection and gain of amplifier YXV001 at bias LOW_A and at ambient temperature measured with the Vector Network Analyzer in the cryostat and outside (for validation of the de-embedding method). *MEAS*: measured in cryostat. *DEEM*: de-embedded of stainless steel transitions. *GATE*: de-embedded with gate in the time domain. *OUTSIDE*: measured outside the cryostat.





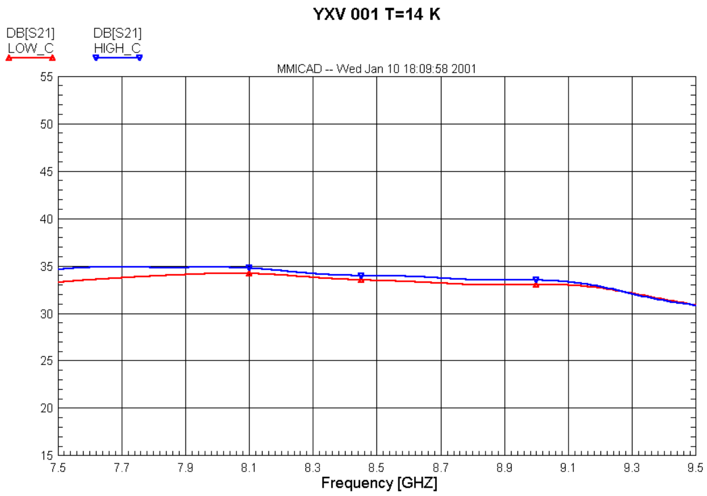


Figure 10: Input and output reflection and gain of amplifier YXV001 measured with the Vector Network Analyzer at cryogenic temperature. Data is presented for two different bias points (LOW_C and HIGH_C). Markers are located at 8.1 and 9 GHz to show the original band of the amplifier.

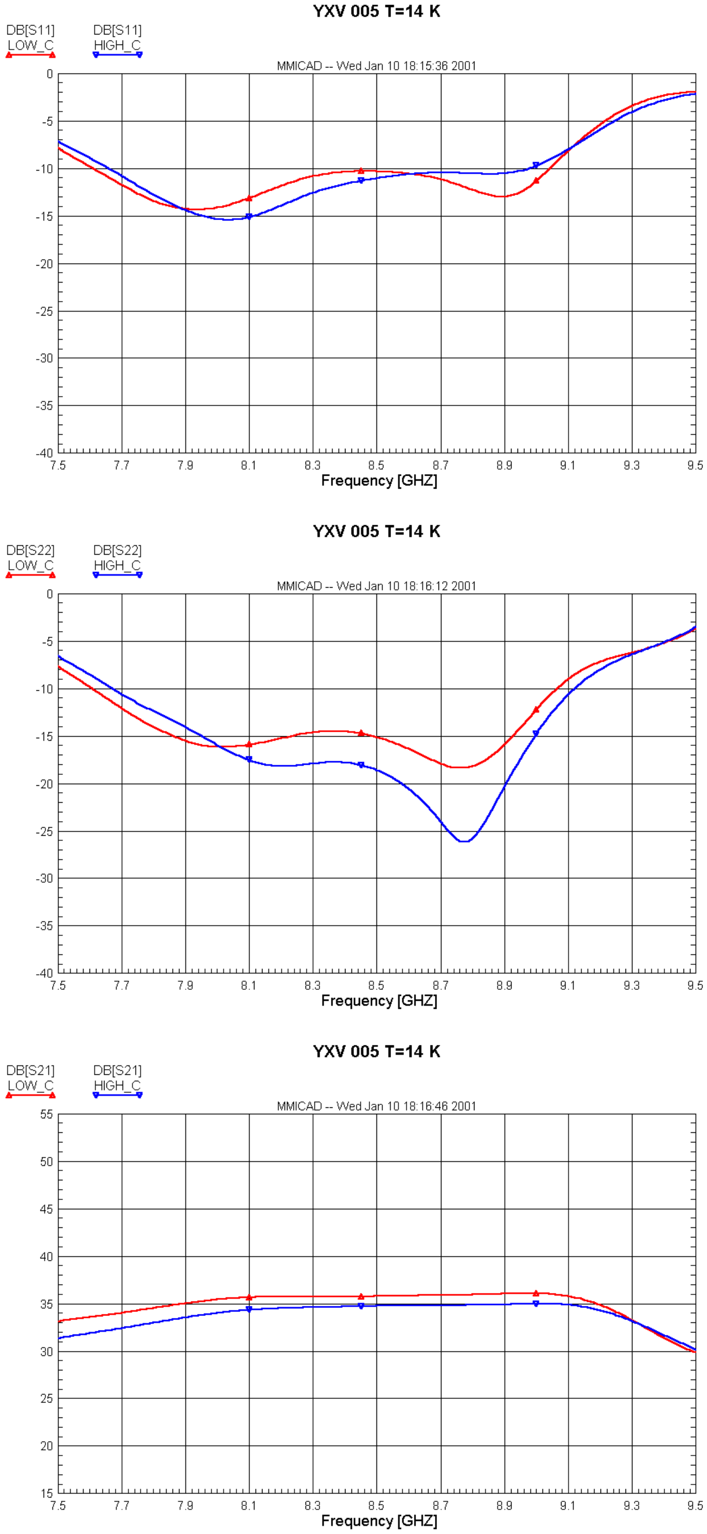


Figure 11: Input and output reflection and gain of amplifier YXV005 measured with the Vector Network Analyzer at cryogenic temperature. Data is presented for two different bias points (LOW_C and HIGH_C). Markers are located at 8.1 and 9 GHz to show the original band of the amplifier.

7 LINEARITY AND MAXIMUM INPUT MEASUREMENTS

7.1 Compression (P_{1dB})

The 1dB compression point was measured in cryostat 350 with The Scalar Network analyzer (SNA). The measurements were done at 8.45 GHz. The loss of the output cable (Cu) and stainless steel transitions were measured and taken into account and its value is given in table X. The value of P_{1dB} of the table is already corrected for the loss. The loss at 14 K was estimated assuming the same loss of stainless steel transitions measured at ambient temperature and dividing the loss in the cooled Cu cable (in dB) by 5. The response observed in YXV 005 (InP) at cryogenic temperature was anomalous, as it is shown in the example of figure 12. The reason of the anomaly is not known, but does not seem to be related with the use of InP devices in the first and second stage. It could be due to a peculiar effect of the batch of Mitsubishi GaAs devices used in this amplifier. The same response was found in other amplifier built with the same device in the output stage (YXV 003). However, other amplifier for a different band (YCF 2014) built only with InP devices from ETH was tested and showed normal (not anomalous) compression. However, with the InP device in the output stage, the value of P_{1db} is quite low (~-9 dBm), due to the low bias used in these devices. LED illumination did not have a significant effect in the anomalies observed. The missing data for YXV 005 at cryogenic temperature in table X is due to anomalous compression.

TABLE X

Compression (P_{1dB}) measurements at different bias points and temperature (Freq: 8.45 GHz).

Amplifier S/N	System	Temp. (K)	Bias ref.	Loss (dB)	P_{1dB} (dBm)
YXV 001 (GaAs)	350	297	LOW-A	1.00	2.44
	350	297	MED-A	1.00	6.11
	350	297	HIGH-A	1.00	7.95
YXV 001 (GaAs)	350	14	LOW-C	0.62	-4.20
	350	14	MED-C	0.62	2.30
	350	14	HIGH-C	0.62	5.79
YXV 005 (InP)	350	297	LOW-A	1.00	1.49
	350	297	MED-A	1.00	5.11
	350	297	HIGH-A	1.00	7.40
YXV 005 (InP)	350	14	LOW-C	0.62	-4.91
	350	14	MED-C	0.62	-
	350	14	HIGH-C	0.62	2.96

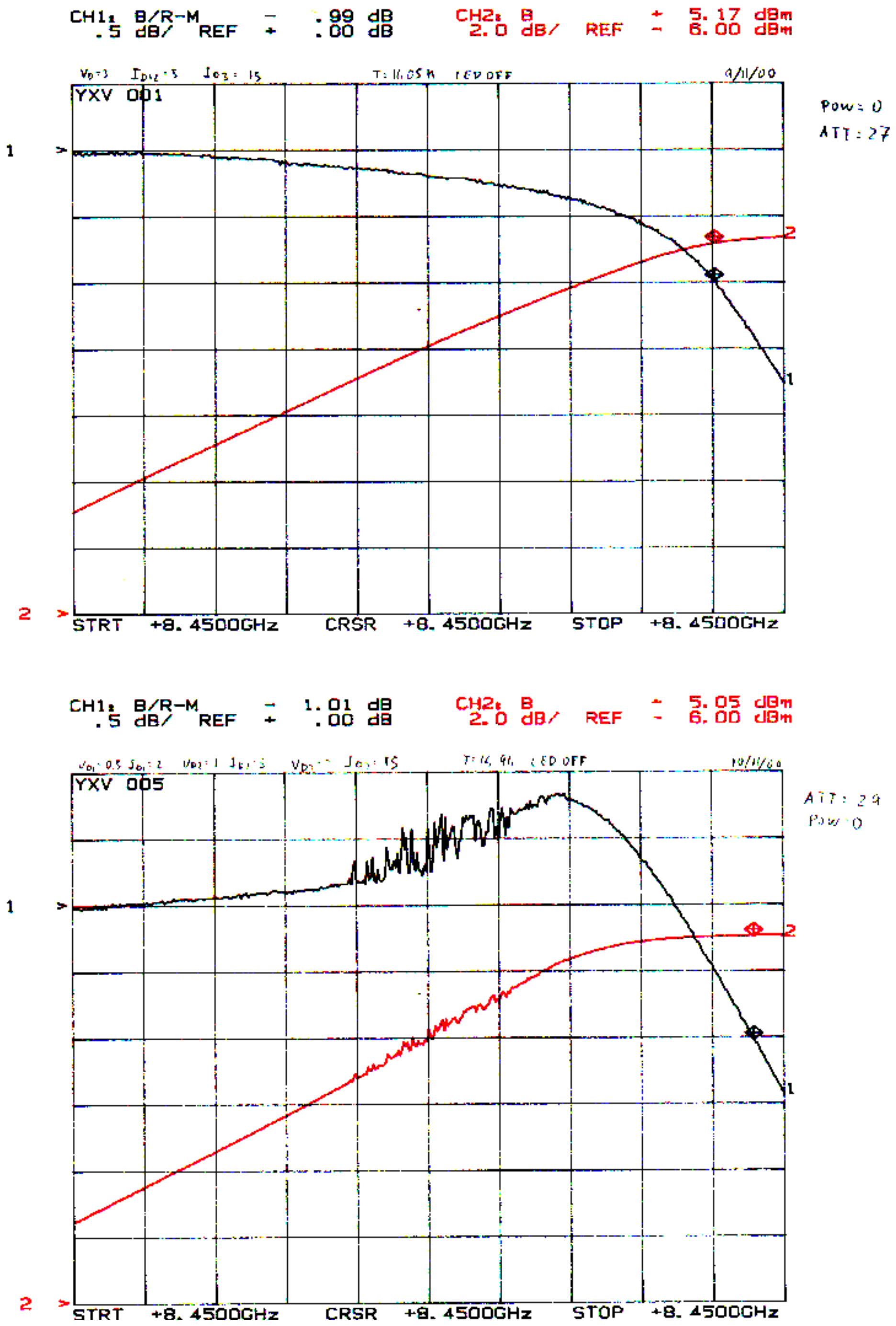


Figure 12: Example of normal and anomalous compression. Normal compression (up) is shown for amplifier YXV001 at cryogenic temperature and bias HIGH_C. Anomalous compression (down) is shown for amplifier YXV005 at cryogenic temperature biased at Vd1=0.5 Id1=2 Vd2=1 Id2=5 Vd3=3 Id3=15. This special bias has been chosen to exaggerate the anomalous effects. LED illumination did not have a significant effect in the anomalies.

7.2 Intermodulation (IP3)

The intermodulation was measured in cryostat 350 with the Scalar Network analyzer (SNA). The measurements were done at 8.45 GHz, with a suppression of third order products of approximately 30 dB. The value of 40 dB mentioned in [1] turned out to be too low, because the intermodulation products were too close to the spectrum analyzer noise level. The loss of the output cable (Cu), stainless steel transitions, and cable from the cryostat to the Spectrum Analyzer were measured and taken into account and its total value is given in table XI. The value of IP3 of the table is corrected for the loss. The loss at 14 K was estimated assuming the same loss of stainless steel transitions measured at ambient temperature and dividing the loss in the cooled Cu cable (in dB) by 5. Note that the difference (IP3 - P_{1dB}) is smaller than 10, especially at cryogenic temperature. Then, the standard rule of thumb for the estimation of IP3 from P_{1dB} can not be used.

TABLE XI

Intermodulation IP3 measurements at different bias points and temperature (Freq: 8.45 GHz).

Amplifier S/N	System	Temp. (K)	Bias ref.	Loss (dB)	IP3 (dBm)
YXV 001 (GaAs)	350	297	LOW-A	3.00	11.6
	350	297	MED-A	3.00	15.2
	350	297	HIGH-A	3.00	16.8
YXV 001 (GaAs)	350	14	LOW-C	2.62	0.0
	350	14	MED-C	2.62	5.2
	350	14	HIGH-C	2.62	9.2
YXV 005 (InP)	350	297	LOW-A	3.00	9.6
	350	297	MED-A	3.00	14.0
	350	297	HIGH-A	3.00	16.0
YXV 005 (InP)	350	14	LOW-C	2.62	3.0
	350	14	MED-C	2.62	5.2
	350	14	HIGH-C	2.62	9.0

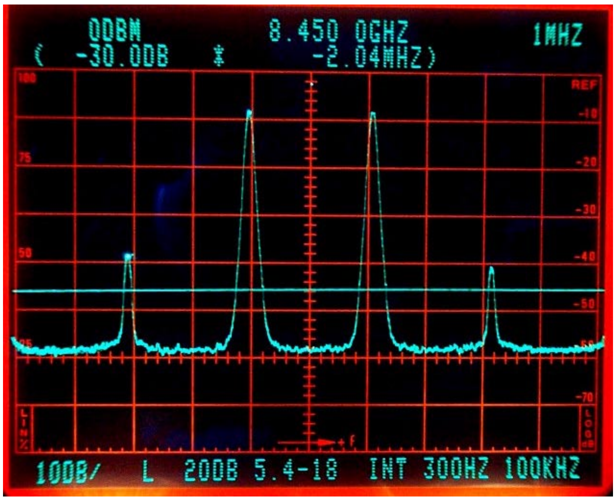


Figure 13: Example of a typical measurement of IP3.

7.3 Maximum input

As stated in the definition of measurements [1, WP1340], the maximum input without damage was checked by injecting a power level of 0 dBm (8.45 GHz) at the input of the amplifier during at least 1 minute. The test was carried out in the two amplifiers (YXV001 and YXV005) in system 350. The injection of the power was performed in the setup for compression measurements, and the noise was measured before and after with a different setup (with the cold attenuator at the input). No significant difference in the noise temperature or other sign of degradation was found.

8 GROUP DELAY MEASUREMENTS

8.1 Ambient temperature

The group delay has been measured outside the cryostat as defined in WP1400. A time domain gate of 5 ns (1.5 m in air) centered in the main response has been used to smooth the measurement. The slope of the delay has been obtained by numerical differentiation of the delay data. The results for amplifiers YXV001 and YXV005 are presented in table XII and figure 14.

TABLE XII

Comparison of group delay measurements (ambient) at different bias points (8.4-8.5 GHz).

Amplifier S/N	System	Temp. (K)	Bias ref.	Delay ripple (ps pp)	Delay slope (ps/MHz max.)
YXV 001 (GaAs)	VNA	297	LOW-A	10.3	0.20
	VNA	297	HIGH-A	5.6	0.25
YXV 005 (InP)	VNA	297	LOW-A	6.0	0.33
	VNA	297	HIGH-A	3.3	0.22

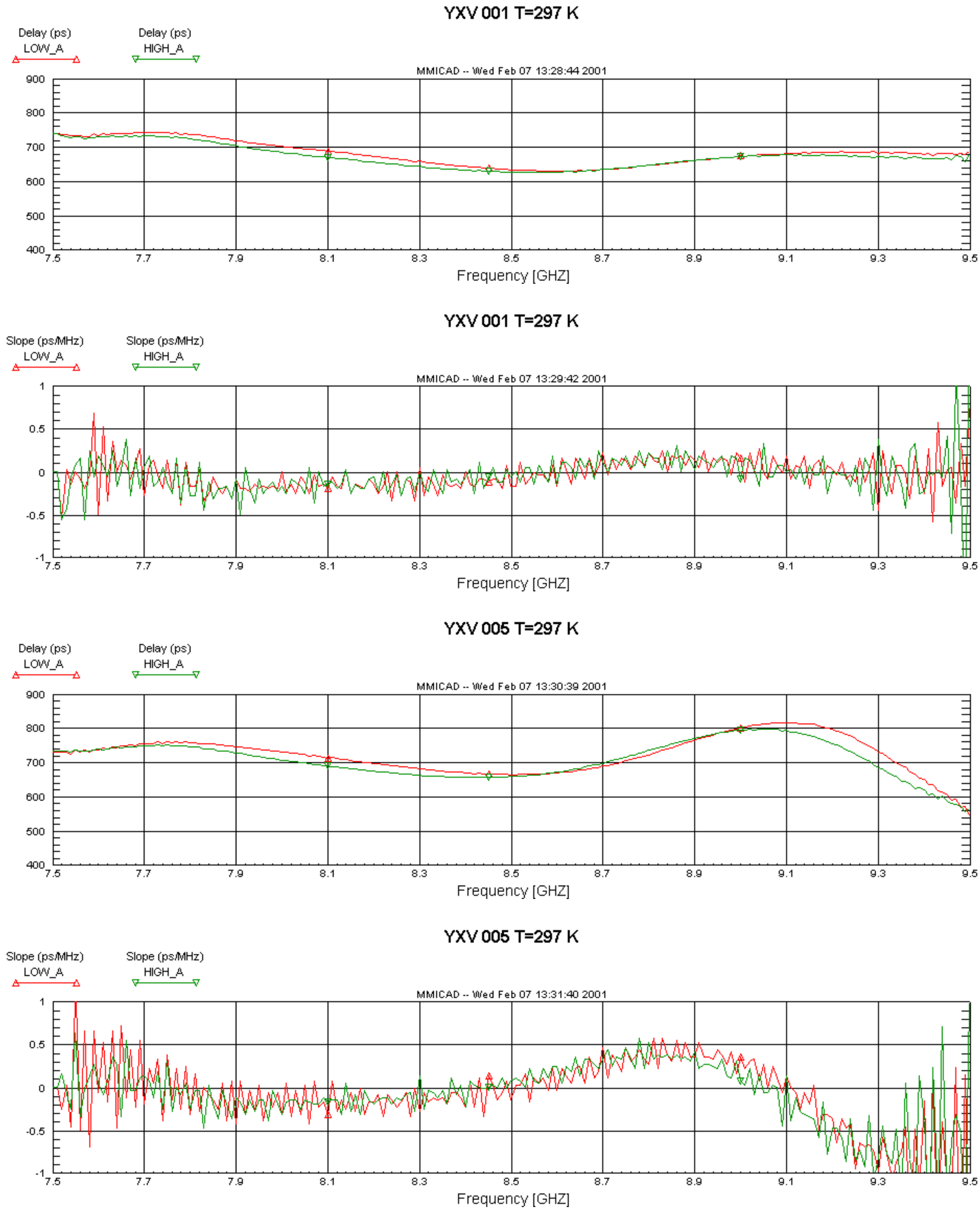


Figure 14: Measurements of delay in ps and slope of the delay in ps/MHz of amplifiers YXV001 and YXV005 at two different bias points and at ambient temperature outside the cryostat. The absolute value of the delay of these measurements is correct, since the calibration of the Vector Network Analyzer was done at the same reference plane of the connection of the amplifier.

8.2 Cryogenic temperature

The group delay at cryogenic temperature has been measured with the amplifier in cryostat 1020 as defined in WP1400. The S parameters were de-embedded of the effect of stainless steel input lines and hermetic transitions. A time domain gate of 5 ns (1.5 m in air) centered in the main response has been used to smooth the measurement. However, as in the measurement of the cryogenic S parameters the effect of the flexible cable at the output of the amplifier has not been de-embedded. For this reason, the absolute value of the delay is the sum of the delay of the amplifier and of the output cable. The slope of the delay has been obtained by numerical differentiation of the delay data. The results for amplifiers YXV001 and YXV005 are presented in table XIII and figure 15.

TABLE XIII

Comparison of group delay measurements (cryogenic) at different bias (8.4-8.5 GHz).

Amplifier S/N	System	Temp. (K)	Bias ref.	Delay ripple (ps pp)	Delay slope (ps/MHz max.)
YXV 001 (GaAs)	VNA	297	LOW-C	5.3	0.16
	VNA	297	HIGH-C	19.5	0.33
YXV 005 (InP)	VNA	297	LOW-C	9.1	0.30
	VNA	297	HIGH-C	4.7	0.19

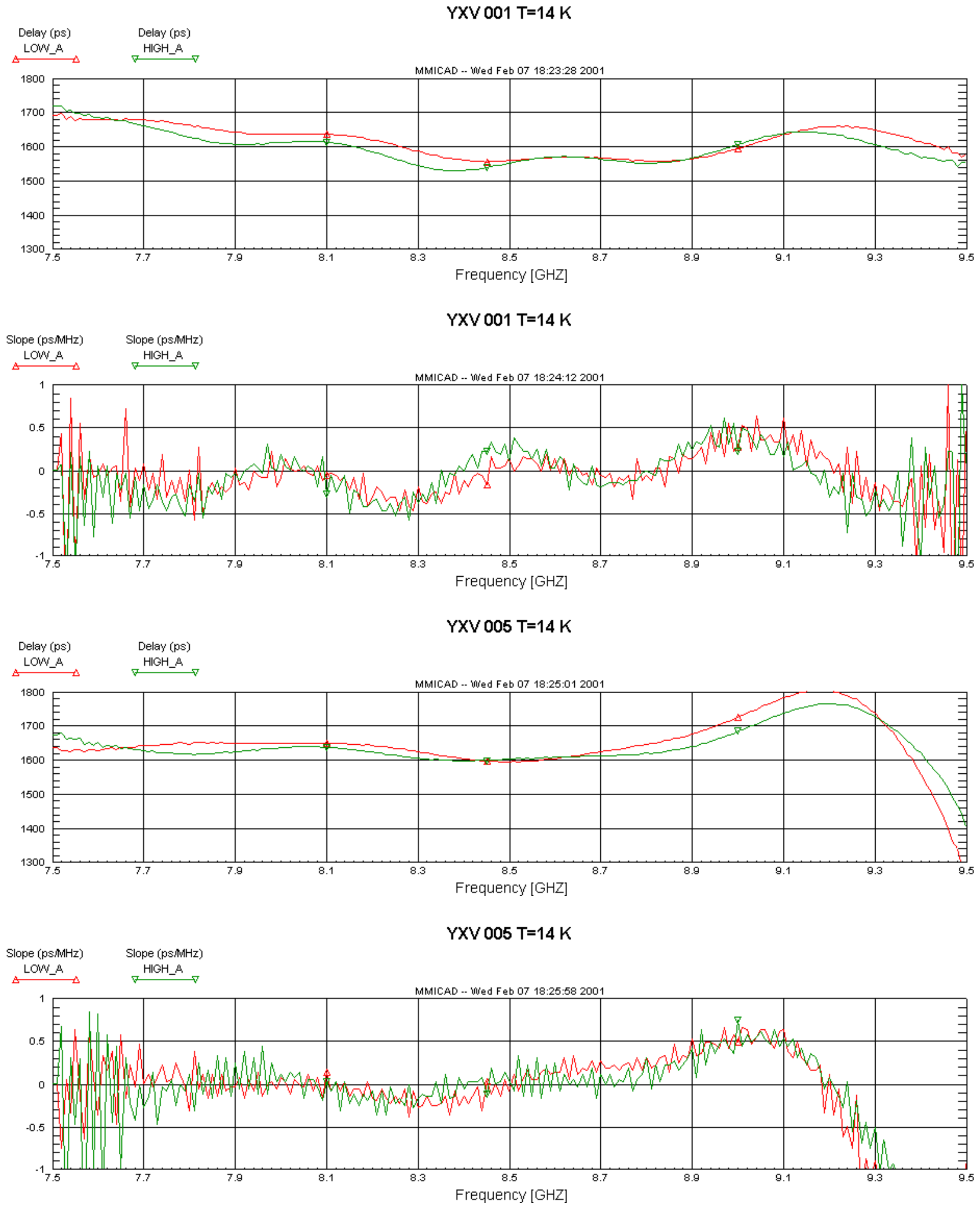


Figure 15: Measurements of delay in ps and slope of the delay in ps/MHz of amplifiers YXV001 and YXV005 at two different bias points and at cryogenic temperature in cryostat 1020. The absolute value of the delay of these measurements includes the delay of the flexible cable at the output of the amplifier.

9 GAIN STABILITY MEASUREMENTS

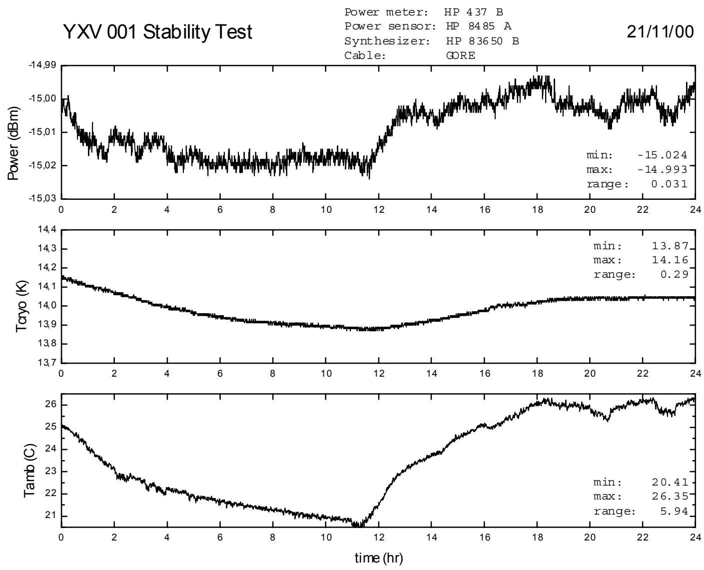
9.1 Long term stability

The long term gain stability was measured in a 24 hour period with the amplifier cooled at cryogenic temperature in system 1020 using a synthesizer at the input (HP 83650 B) and a power meter at the output (HP 437 B + HP 8485 A). This measuring system was suggested by ESOC and tested in our laboratory. The stability and the resolution of the measurement system were better than with the system based in the Scalar Network analyzer proposed in WP 1500 initially. The power level at the output of the amplifier was set to approximately –15 dBm to avoid compression. The stability of the measurement system was checked in an independent measurement without the amplifier and was found to be ±0.01 dB with a variation in ambient temperature of ±2.95° C. The results of the measurements of the amplifiers are presented in table XIV and in figure 16.

TABLE XIV

Long term gain stability measurements. Values of ΔTcryo, ΔTamb and ΔG given are peak to peak.

Amplifier S/N	**System**	**Temp. (K)**	**Bias ref.**	**ΔTcryo (K pp)**	**ΔTamb (K pp)**	**ΔG (dB pp)**
CALIBRATION (no amplifier)	-	-	-	-	5.90	0.019
YXV 001 (GaAs)	1020	14	LOW-C	0.29	5.94	0.031
YXV 005 (InP)	1020	14	LOW-C	0.50	4.28	0.028



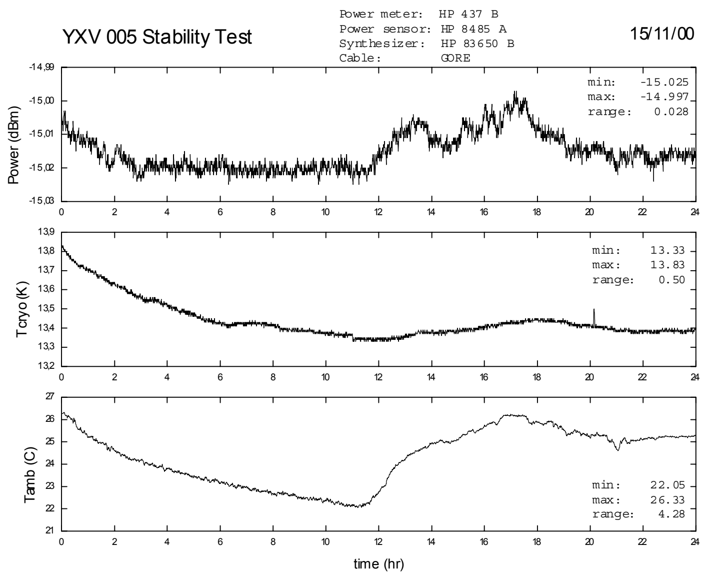


Figure 16: Measurements of long term gain stability in a 24 hours period at cryogenic temperature. Both amplifiers were biased for minimum noise. The measurements of the cryogenic and the ambient temperature are presented in the same graph for comparison.

9.2 Short term stability

The short-term gain stability was measured at ambient and cryogenic temperature in system 1020 as described in WP1510. The power level was set to obtain approximately –20 dBm at the output of the amplifier, to avoid compression. A total of 50 spectrums were averaged for each measurement. Each scan is comprised of 201 points and its duration was 85.2 seconds approximately. The total integration time was 71 minutes. Data of phase fluctuation was taken in the same set of measurements. The data presented has been calibrated taking into account the fluctuations of the measuring system, obtained in a separate measurement with the same power level in the detector. The value of the calibration is presented in the graphics with the calibrated measurements for comparison. The measured spectrums are presented in figures 17 and 18. Table XV presents the values of the parameters of the functions fitted to the measurements. The values of and b in the table correspond with the fitting of spectrums of the form presented in the following formulas:

$$g(f) = b \cdot \left(\frac{1 \cdot Hz}{f} \right)^a$$

$$\Phi(f) = d \cdot \left(\frac{1 \cdot Hz}{f} \right)^c$$

Were g(f) is the spectral density of normalized gain fluctuations and Φ(f) is the spectral density of phase fluctuations (not normalized), with dimensions of $Hz^{-½}$ and $deg \cdot Hz^{-½}$ respectively. The fitting range was selected from 0.1 to 0.9 Hz.

TABLE XV

Short term gain and phase stability measurements.

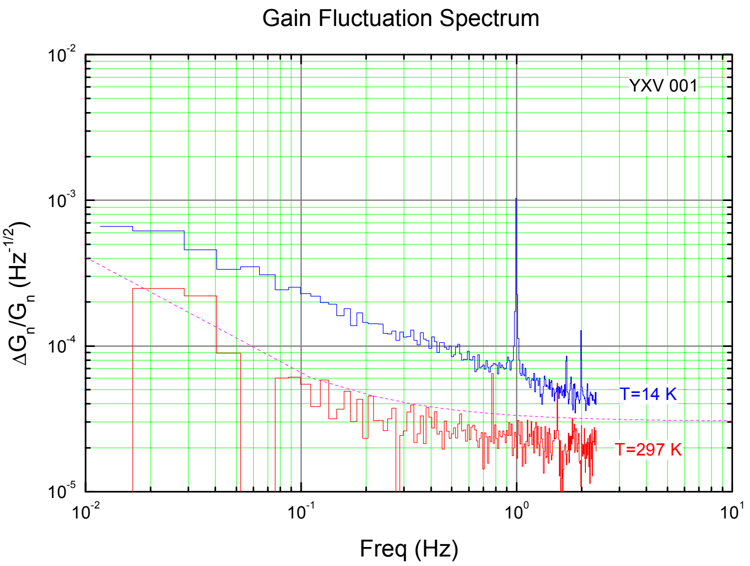
Amplifier S/N	System	Temp. (K)	Bias ref.	a	b (ΔG/G @1 Hz) $Hz^{-1/2}$	c	d (ΔΦ @1 Hz) $deg \cdot Hz^{-1/2}$
YXV 001 (GaAs)	1020	297	LOW-A	0.34	$2.1 \cdot 10^{-5}$	0.25	$0.8 \cdot 10^{-3}$
		14	LOW-C	0.57	$6.2 \cdot 10^{-5}$	0.58	$2.7 \cdot 10^{-3}$
YXV 005 (InP)	1020	297	LOW-C	0.59	$3.0 \cdot 10^{-5}$	0.50	$1.3 \cdot 10^{-3}$
		14	LOW-C	0.52	$4.5 \cdot 10^{-5}$	0.52	$2.9 \cdot 10^{-3}$

It is of some practical interest to relate the value of the spectrum of phase fluctuations obtained in this way with the value which will be measured in a spectrum analyzer in dBc (assuming dominant phase noise). With the approximation of small angles, (Φ(f)<<1 rad.):

$$L(f) = \frac{1}{2} (\Phi_{rad}(f))^2$$

Where L(f) is the spectral density of power in one sideband divided by the total power of the signal, with dimensions of Hz^{-1}, and $\Phi_{rad}(f)$ is Φ(f) expressed in $rad \cdot Hz^{-½}$. The values obtained for the worst case of our measurements (YXV 005 @ 14 K) are approximately:

-66 dBc @ 0.01 Hz
-79 dBc @ 0.1 Hz
-88 dBc @ 1 Hz



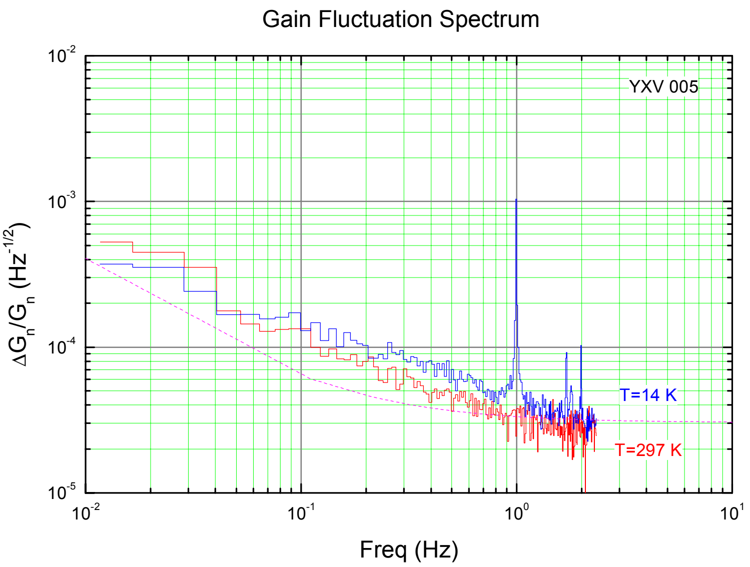
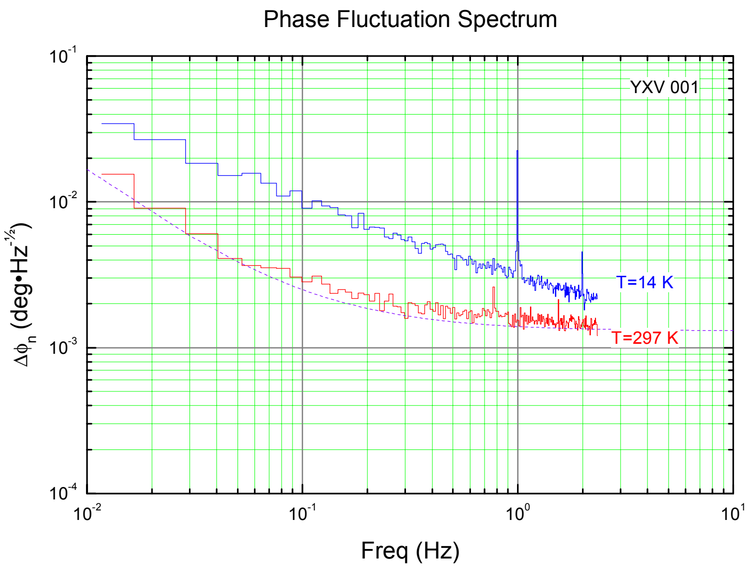


Figure 17: Measurements of short-term gain stability (normalized gain fluctuations) for amplifiers YXV001 and YXV005. The lines appearing at 1 Hz at cryogenic temperature are due to the cycle of the refrigerator. The lines appearing in the ambient temperature measurement of YXV001 are probably related with mechanical vibrations of the vacuum pump of the system. The dashed line is the spectrum of normalized gain fluctuations of the measuring system. The amplifier measurements are corrected for this effect.



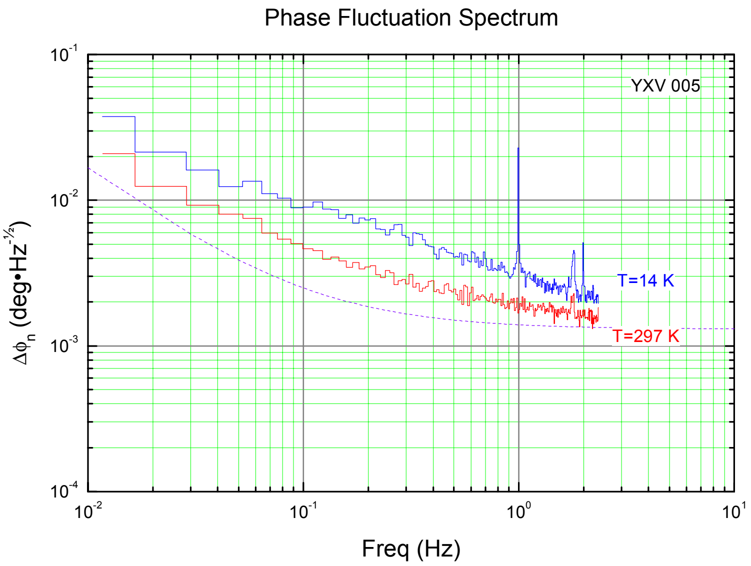


Figure 18: Measurements of short term phase stability (phase fluctuations) for amplifiers YXV001 and YXV005. The lines appearing at 1 Hz at cryogenic temperature are due to the cycle of the refrigerator. The lines appearing in the ambient temperature measurement of YXV001 are probably related with mechanical vibrations of the vacuum pump of the system. The dashed line is the spectrum of normalized phase fluctuations of the measuring system. The amplifier measurements are corrected for this effect.

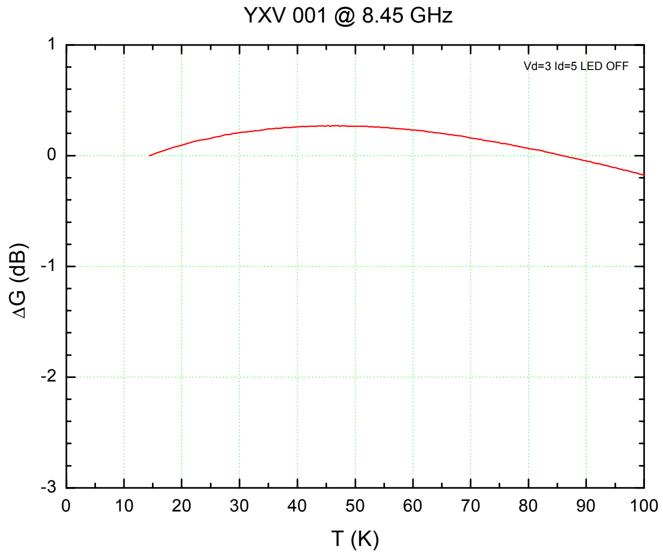
9.3 Gain variation with temperature

There is a variation in the method used for this measurement with respect to the description in [1]. In the discussion with ESOC, it was agreed to measure the gain variation with temperature in the noise measurement setup, to obtain simultaneously the data of noise variation with temperature. The idea was to use the heating resistors with low power to raise slightly the cryogenic temperature (~5 K), and to measure the amplifier at the temperature obtained. However, when this procedure was tried in the cryostat, it was found that the heat needed to change the cryogenic temperature introduced important temperature gradients in the cold plate. As the difference between the amplifier and the attenuator was quite large (3.5 K), we suspected that the value of temperature read in the sensor was not representative of the real temperature of the attenuator element. As the gain and noise measurements are strongly dependent on the accuracy of the temperature of the attenuator, the values obtained by this method were considered not reliable. In consequence, a different method was used to measure the gain variation with temperature. The setup used is exactly the same described for the long-term stability measurement (HP 83650 B synthesizer and HP 437 B power meter). The variation of temperature was obtained switching off the refrigerator. In these conditions, it took two hours to raise the temperature to 100 K. The power level was set to obtain approximately –15 dBm of power at the output. Table XVI presents the values obtained in the gain variation wit temperature for the two amplifiers at cryogenic temperature. This value has been computed using the variation measured between 14 and 26 K. Figure 19 presents the gain variation in the 14-100 K range. There is not clear explanation for the weird (non-monotonic) behavior of YXV 001. This kind of behavior has been observed for other amplifiers at temperatures below 100 K, and is dependent on the properties of the devices.

TABLE XVI

Gain variation with temperature measurements.

Amplifier S/N	**System**	**Temp. (K)**	**Bias ref.**	**ΔG/ΔT @14K (dB/K)**
YXV 001 (GaAs)	1020	14	LOW-C	0.015
YXV 005 (InP)	1020	14	LOW-C	-0.009



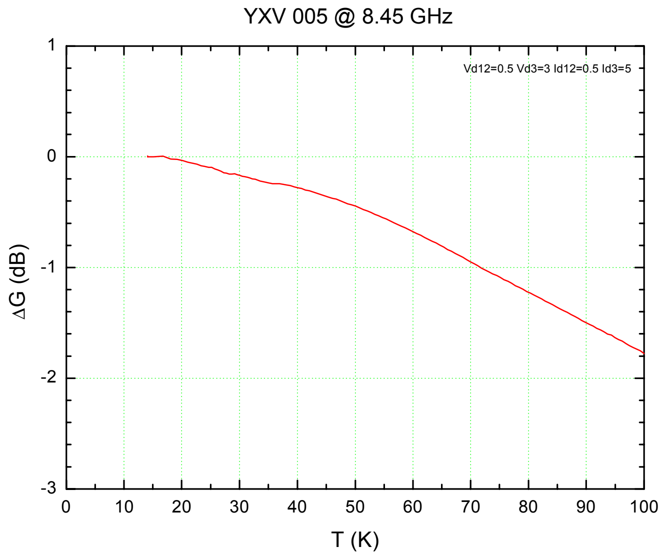


Figure 19: Measurements of gain variation with temperature of amplifiers YXV001 and YXV005 in the range from 14 to 100K. The amplifiers are biased for minimum noise at cryogenic temperature.

10 COMPARISON WITH THE SPECIFICATIONS

Table XVII presents the comparison of the specifications with the results obtained in the measurements. All the data is for cryogenic temperature with the exception of noise temperature, which is given at ambient and cryogenic temperature. All the cryogenic data is given for the optimum bias for noise (LOW-C) with the exception of 1dB compression and IP3 intermodulation given for high bias in the 3rd stage (HIGH –C). The use of this bias point has little impact in the other measurements, with the exception of output reflection.

TABLE XVII

Comparison of specifications with measurements.

	SPEC (8.4-8.5 GHz)	YXV 001 (GaAs)		YXV 005 (InP)		REMARKS
		measured	bias	measured	bias	
Noise Temp. (Cryogenic)	<6 K @ 15 K Tamb (InP) <9 K @ 15 K Tamb (GaAs)	9.3 K	LOW-C	4.0 K	LOW-C	Measured in sys. 350 Average in 8.1-9 GHz
Noise Temp. (Ambient)	<80 K @ 300 K Tamb	73 K	LOW-A	85 K	LOW-A	Measured in sys. 350 Average in 8.1-9 GHz
Gain	33 dB min	33.5 dB	LOW-C	35.7 dB	LOW-C	Measured with VNA (Sys 1020)
Gain flatness	1 dB pp max	0.13 dB pp	LOW-C	0.05 dB pp	LOW-C	Measured with VNA (Sys 1020)
Gain slope	± 0.1 dB/MHz max	≈0.001 dB/MHz	LOW-C	≈0.001 dB/MHz	LOW-C	Measured with VNA (Sys 1020)
Gain var. with temp.	± 0.05 dB/K max. @15 K	0.015 dB/K	LOW-C	-0.009 dB/K	LOW-C	Measured with Power Meter
24 h. gain stability	0.4 dB in 24 hours	0.03 dB/24 h	LOW-C	0.03 dB/24 h	LOW-C	Measured with Power Meter
Group delay ripple	100 ps pp max.	5 ps pp	LOW-C	9 ps pp	LOW-C	Measured with VNA (Sys 1020)
Group delay slope	10 ps/MHz max.	0.2 ps pp	LOW-C	0.3 ps pp	LOW-C	Measured with VNA (Sys 1020)
Input reflection	<-17.7 dB (with isolator) <-7.0 dB (no isolator)	-7.9 dB	LOW-C	-10.3 dB	LOW-C	Measured with VNA (Sys 1020)
Output reflection	<-17.7 dB (with isolator) <-11.7 dB (no isolator)	-13.4 dB	LOW-C	-14.5 dB	LOW-C	Measured with VNA (Sys 1020)
Output 1 dB compression	+5 dBm	+5.8 dBm	HIGH-C	+3.0 dBm	HIGH-C	Measured with SNA (Sys. 350)
Output IP3	+15 dBm	+9.2 dBm	HIGH-C	+9.0 dBm	HIGH-C	Measured with Spectrum Analyzer

11 CONCLUSIONS OF MEASUREMENTS

11.1 Analysis of performance of YXV001 (GaAs) and YXV005 (InP)

From the data of table XVII, it is clear that the main problems to meet the desired specifications are the input and output reflection, IP3 and P_{1dB}. The cryogenic noise performance obtained with InP devices is better than with GaAs, as expected. On the other hand, the capability to handle large signals without distortion is clearly improved for high bias, and this is better handled with GaAs devices, because the optimum bias of InP devices for minimum noise is usually very low. The use of InP HEMTs in the first stage is necessary to obtain the best noise performance. The noise contribution of the device of the second stage to the total noise is still noticeable. The difference between a GaAs and an InP HEMTs in the second stage is expected to be on the order of 0.3 K (estimation from model). However, if an InP device in the second stage is biased low, it could be easily saturated for a power level of +5 dBm at the output of the amplifier (desired value of P_{1dB}). The P_{1dB} of the InP devices is about –9 dBm when biased for optimum noise, but could be increased up to +4 dBm with a much higher bias (values estimated from measurements of a two stage amplifier for the 4-8 GHz band with two stages of InP HEMTs). Using these values as estimation, and assuming 11 dB of gain per stage, it seems that InP devices can be used (with some risk) in the second stage of the amplifier if its bias is set to a high value. However, the model of the InP devices has never been obtained for such a high bias

The third stage of the two amplifiers tested was a GaAs HEMT in both cases. The anomalies observed in the compression at cryogenic temperature in one of the amplifiers (YXV 005) are probably related only with a particular behavior of the batch of GaAs devices used[1], and not with the use of InP in the other stages. The reason for this supposition is that in the development of these amplifiers it was detected a tendency to oscillate in some of these devices, which was solved adding some microwave absorber material in the box. The anomaly observed could be a similar effect, produced only at high power levels. The tendency to oscillate was observed only with some devices manufactured by Mitsubishi, and it is expected that other devices (for example Fujitsu HEMTs) could solve the problem. Mitsubishi devices were used because its cryogenic noise performance is excellent and its price is very low, but we believe that Fujitsu devices could be used in the third stage without any penalty in noise.

The input and output reflection coefficients measured are higher than the specification in both prototypes tested. The value of -17.7 dB (SWR=1.3) is difficult to obtain without isolators. The input and output reflection coefficients are dependent on the design of the matching networks, the devices used and the bias point. From experience in other designs, we estimate that even with an additional effort in the characterization of the devices and several iterations of designs, it will be difficult to obtain less than -10 dB (SWR=1.92) at the input and less than -15 dB (SWR=1.43) at the output. However, with isolators, it will be easy to obtain less than –20 dB (SWR=1.22).

11.2 Experience from other projects.

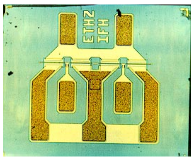
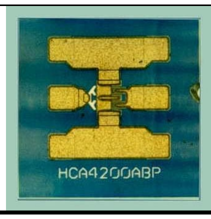
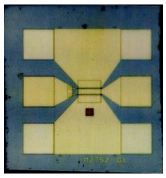
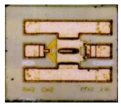
11.2.1 InP devices

A number of InP devices have been tested for the development models prepared for FIRST. The priority in FIRST is to obtain a very low noise in a wide band (4-8 GHz) with very low power dissipation. The results obtained allow the identification of the devices with better noise performance. The devices presented in tabe XVIII are only those with the best performance and reliability. Only devices made by TRW and ETH are presented. TRW devices are made with 0.1 μm and ETH with 0.2 μm gate length. The theory states that devices with a shorter the gate length have better noise temperature and high frequency gain. However, from the practical point of view, may not be better to not use devices with too short gate length, because they are more sensitive to ESD damage, more prone to oscillate, and have worse short term stability.

[1] Mitsubishi MGFC4418D lot. GL010D-VA06680

TABLE XVIII

Results of some InP devices tested for FIRST in the 4-8 GHz band.

	ETH 200×0.2 μm	**TRW (big) 200×0.1 μm**	**ETH 150×0.2 μm**	**TRW (small) 200×0.1 μm**
Avg. Noise Temp.(Cryogenic)	~5.5 K	~5.0 K	~4.6 K	~4.0 K
Gain	~11 dB/stage	~13 dB/stage	~13.5 dB/stage	~14 dB/stage
Power dissipated	1.25 mW/stage	1.25 mW/stage	1.1 mW/stage	1.5 mW/stage
ΔG/G @1 Hz	7×10^{-5} $Hz^{-1/2}$	2×10^{-5}- 1.4×10^{-4} $Hz^{-1/2}$	$<6\times10^{-5}$ $Hz^{-1/2}$	-
Reliability	Non passivated Poor pad adhesion	Good! Oscillations? Baseline for FIRST	Non passivated	Very small size Difficult to bond
Availability	YES	?	YES	?
Picture				

The ETH device included in amplifier YXV 005 tested for this work is of the type ETH200×0.2 μm, but from an older batch. The performance of devices of the batch presented in table XVIII was worse.

ETH has given permission for using their devices for this application. TRW-JPL have been consulted, but no answer has been obtained yet. With the present constraints and availability, the ETH150×0.2 μm seems to be best choice to obtain better noise temperature. The layout and dimensions of these devices are different from those of the original YXV amplifier design, but it is expected to perform reasonably well without modifications. It is interesting to note that there is a version of this device with an experimental passivation, although its performance is slightly worse.

11.2.2 GaAs devices

Cryogenic GaAs amplifiers have been built in our laboratory over many years for several Radio Astronomy observatories. Many units of C-band amplifiers have been built using Fujitsu and Mitsubishi devices. The experience with those is that, in general, Fujitsu devices of the type FHR02X are very repetitive from batch to batch and require higher bias to obtain minimum noise. Mitsubishi devices suffer from poorer repeatability from batch to batch and sometimes show some tendency to oscillate without control at cryogenic temperature often related with discontinuities in the DC curves. In our previous work, Mitsubishi devices have been used quite often because of its superior noise performance in selected batches, its lower power dissipation and its lower cost. However, for the present application, it may be an important advantage to have a higher optimum bias, and for this reason, devices of the type of the FHR02X are recommended. The FHR02X is an old device (It has been in the market for more than 10 years). Newer versions of pseudomorphic HEMT devices made by Fujitsu with better room temperature performance, like the FHX13X, do not have the advantages of the FHR02X and have a behavior similar to Mitsubishi devices or even worse (some of them have very low optimum bias).

11.2.3 Present and future availability

Tables XIX and XX show a selection of our database with the GaAs and InP devices in stock in our laboratory of interest for this project. The last column shows the number of devices at the time of writing this report. The column labeled "date" shows the date of arrival of the devices.

The recommended GaAs devices for this project are T-008, T-009, T-013 and T-022.

The recommended InP devices for this project are T-036 and T-044.

TABLE XIX

GaAs devices in stock in our laboratory.

CODE	P/N	MFR.	BATCH	DATE	DEVICES
T-005	MGFC 4404	Mitsubishi	A320 30-13	-	4
T-006	FHX04X	Fujitsu	9310-HCE8-4	-	3
T-008	FHR02X	Fujitsu	9045-HAF142	-	5
T-009	FHR02X	Fujitsu	9312-HCS136-5	-	1
T-013	FHR02X	Fujitsu	HCN 409-7	08/01/1996	17
T-014	MGFC 4417 D	Mitsubishi	GL010-D-VA11710	10/04/1996	4
T-015	FHX13X	Fujitsu	HHN 375-15	30/05/1997	1
T-016	MGFC 4417 D03	Mitsubishi	GL010D-VA11710	20/06/1997	56
T-017	MGFC 4418 D03	Mitsubishi	GL010D-VA06680	20/06/1997	55
T-018	FHX13X	Fujitsu	HHN 411-01	09/12/1997	21
T-022	FHR02X	Fujitsu	HCN Z05-01	30/03/1998	10
T-034	MGFC 4418 D03	Mitsubishi	GL010D-VA06680	25/06/1999	100
T-037	MGFC 4419G-A13	Mitsubishi	GL050Z-VA033130	30/09/1999	34
T-038	FHX13X	Fujitsu	HHN-417-06	30/09/1999	25

TABLE XX

InP devices in stock in our laboratory.

CODE	P/N	MFR.	BATCH	DATE	DEVICES
T-023	TRW 160	JPL-TRW	-	04/05/1998	32
T-026	ETH 200	ETH	-	19/06/1998	11
T-030	TRW 160	JPL-TRW	4017-018	18/03/1999	18
T-031	TRW 160	JPL-TRW	4017-023	18/03/1999	8
T-032	TRW 160	JPL-TRW	4017-020	18/03/1999	17
T-033	TRW 160	JPL-TRW	4017-027	18/03/1999	21
T-035	ETH 200	ETH	(Measured)	06/07/1999	27
T-036	ETH 200	ETH	(Not measured)	06/07/1999	33
T-039	TRW 200	JPL-TRW	HCA-4200-ABP	11/02/2000	45
T-040	ETH 200	ETH	991005/HO	17/04/2000	22
T-042	TRW 200	JPL-TRW	4044-041	27/11/2000	30
T-043	ETH 150	ETH	Passivated	01/12/2000	19
T-044	ETH 150	ETH	Not passivated	01/12/2000	19

The future availability of any GaAs or InP device is uncertain. The FHR02X GaAs HEMT proposed has been in the market for more than 10 years, but can be discontinued at any time. New versions from Fujitsu have a better noise and lower power dissipation, but are expected to be worse for the linearity. Mitsubishi devices usually are in the market only for one or two years. Then new devices replace them. InP devices are experimental, and are expected to be in continuous evolution while the developing groups keep their interest. ETH is committed in the development of InP devices for FIRST, and for IRAM in the coming 2-3 years (in separate contracts). They have given their approval to use their devices for this application. TRW-JPL is committed for the development of InP technology for FIRST-PLANK in the coming 2-3 years. They have been consulted to use their devices for this application, but no answer has been received yet. In any case, the long-term availability of any GaAs or InP device is not certain. It is recommended to build a number of amplifiers sufficient for the required application and for spares while the devices last.

11.3 Use of isolators at Input or Output

As the input and output reflection required may be difficult to obtain, Cryogenic Isolators made by PAMTECH[2] have been acquired to be used if required. From the manufacturer data, the input and output reflection is better than –23.7 dB (SWR=1.14), the isolation better than 25 dB, and the insertion loss less than 0.15 dB. This performance was measured at 77 K, and may deviate slightly at 15 K. The main problem with the use of isolators is the increment in the noise temperature due to the loss added at the input of the amplifier. The increment of noise temperature is given by:

$$\Delta T = (L - 1) \cdot (T_{iso} + T_{amp})$$

Where L is the value of the insertion loss (linear), T_{iso} is the physical temperature of the isolator, and T_{amp} the noise temperature of the amplifier. For L=0.15 dB, T_{iso}=15 K and T_{amp}=4 K the value obtained is:

$$\Delta T = 0.67 \cdot K$$

This value is very high, and it will be advantageous to avoid the use of the input isolator. However, the required performance in the input reflection can not be guaranteed with the present design without it.

[2] PAMTECH model XTE 1218K

12 REFERENCES

[1] J. D. Gallego and I. López Fernández, "Definition of Measurements of Performance of X Band Cryogenic Amplifiers," Technical Note ESA/CAY-01 TN01, July 2000.

[2] J. D. Gallego, I. López Fernández, "Measurements of Gain Fluctuations in GaAs and InP Cryogenic HEMT Amplifiers," Technical Report C.A.Y. 2000-1, February 2000.

13 SYMBOLS, ABBREVIATIONS AND ACRONYMS

$\Phi(f)$	*Spectral density of phase fluctuations (not normalized)*
Cu	*Cooper*
DSB	*Double Side Band*
ESD	*Electrostatic discharges*
ETH	*Swiss Federal Institute of Technology, Zurich*
g(f)	*Spectral density of normalized gain fluctuations*
$G_{8.4}$	*Gain at 8.4 GHz*
GaAs	*Gallium Arsenide*
G_{max}	*Maximum Gain*
G_{min}	*Minimum Gain*
I_d	*Drain current*
InP	*Indium Phosphide*
IP3	*Third Order Interception Point*
IRAM	*Institute for Millimeter Wave Radio Astronomy*
JPL	*Jet Propulsion Lab.*
LED	*Light Emitting Diode*
MFR	*Manufacturer*
P/N	*Part Number*
P_{1db}	*1 dB compression point*
pp	*Peak to peak*
S/N	*Serial Number*
SNA	*Scalar Network Analyzer*
SSB	*Single Side Band*
SWR	*Standing Wave Ratio*
$T_{8.4}$	*Noise Temperature at 8.4 GHz*
T_{amb}	*Ambient Temperature*
T_{av}	*Average Noise Temperature*
T_{cryo}	*Cryogenic Temperature*
T_{min}	*Minimum Noise Temperature*
V_d	*Drain Voltage*
V_g	*Gate Voltage*
VLBI	*Very long Baseline Interferometry*
VNA	*Vector Network Analyzer*