DEFINITION OF MEASUREMENTS OF PERFORMANCE OF X BAND CRYOGENIC AMPLIFIERS

Juan Daniel Gallego
Isaac López Fernández

TECHNICAL NOTE
Document Reference: ESA/CAY-01 TN01

TECHNICAL REPORT C.A.Y. 2000-4
July 2000

INTRODUCTION

This report corresponds to Work Package 1000 of the ESA contract “Development of a state of the art cryocooled X-band low noise amplifier”. The goal of this Work Package is to define all the measurements needed to characterize the performance of the amplifiers. The description will distinguish between room temperature and cryogenic measurements. A description of the hardware used (implementation) and details of the calibration will also be given.

DESCRIPTION OF THE LABORATORY EQUIPMENT

1.1 Cryostat 350

This cryostat was the first built in our laboratory, and has been used for the cryogenic noise measurements in all the previous projects for frequencies from 1 to 12 GHz. It is based in a CTI 350 cryocooler and compressor. The cooling time from room temperature to 15 K is seven hours. The system can be heated fast (2 hours) using the four resistors installed in the cryostat. A cryogenic thermometer with four sensors, selected by a rotary switch, allow monitoring the temperature in several points. The coaxial transitions are made with 0.141” cables with stainless steel outer conductor, BeCu inner conductor, and TEFLON dielectric. The vacuum transitions are made with commercial SMA feedtroughs (Radiall R125 753). There is a DC block (NARDA 4568) and a 15 dB attenuator (NARDA 4779-15) permanently installed in one of the lines and calibrated for cold attenuator noise measurements. Other two coaxial lines are available for reflection and gain measurements. Connector savers (male to female SMA) protect some of the most critical connectors. The equipment associated with this cryostat is listed in table 1.

TABLE I

Equipment associated with cryostat 350

Model	Description	Remarks
Lake Shore 818	Cryogenic Thermometer	RS 232 interface
DT 470 DI 13	Cryogenic Temperature Sensors	±1 K accuracy in 2-100 K range
CAY	FET Power Supply	Feedback power supply, four stages
HP 8970 B	Noise Figure Meter	
HP 8971 B	Noise Figure Test Set	Used with NFM (10 MHz-18 GHz)
HP 8340 B	Synthesized Sweeper	Used with NFM (10 MHz-26.5 GHz)
HP 346 A	Noise Source	Used with NFM (ENR 5 dB, 0.01-18 GHz)
HP 346 B	Noise Source	Used with NFM (ENR 14 dB, 0.01-26.5 GHz)
HP 8757 A	Scalar Network Analyzer	
HP 8350 B	Sweeper Main Frame	Used with SNA
HP 83595 A	Sweeper Plug in	Used with SNA (10 MHz-26.5 GHz)
HP 11667 B	Power Divider	Used with SNA (10 MHz-26.5 GHz)
HP 85027 B	Directional Bridge	Used with SNA (10 MHz-26.5 GHz)
HP 85027 B	Detectors	Used with SNA (10 MHz-26.5 GHz)
HP 34970 A	Data Acquisition / Switch Unit	Used to read bias data
HP 34908 A	40 Channel Multiplexer	Used to read bias data
HP VECTRA	Computer	Controller for cryogenic noise measurements

1.2 Cryostat 1020

This cryostat is the last built in our laboratory, and has been prepared to make possible high frequency measurements (>12 GHz) as well as for measurement of cryogenic S parameters of chip devices using a special test fixture and a TRL calibration. However it is also usable for noise measurements at the same frequencies as cryostat 350. It is based on a CTI 1020 cryocooler and compressor. It incorporates a controller for the vacuum pump and the vacuum valve, making simpler the operation, and reducing the risk of some of the most common operational errors. The cooling time from room temperature to 15 K has been reduced to four hours. The system can be heated fast (1-2 hours) using the four resistors installed in the cryostat. A cryogenic thermometer with four sensors, selected by a multiplexer, allow monitoring the temperature in several points. There are two sets of coaxial transitions available: a) low loss (for noise measurements up to 26 GHz) and b) air lines for S parameter measurements up to 40 GHz. The low loss lines a) are of the same type as the transitions used in the CTI 350 cryostat. Some of the components have been improved, and the connector savers eliminated, making possible operation up to 26 GHz. These transitions are made with 0.141” cables with stainless steel outer conductor, BeCu inner conductor, and TEFLON dielectric. The vacuum transitions are selected commercial SMA feedtroughs (Radiall R125 753). There is a DC block (NARDA 4568) and a cascade of a 10 dB plus 6 dB attenuators (NARDA 4778-6 and 4778-10) permanently installed in one of the lines and calibrated for cold attenuator noise measurements. The air lines b) are completely built in our laboratory using inner and outer conductor made of stainless steel tubes, without any solid dielectric. These lines were conceived to allow operation up to 40 GHz and to avoid phase variations during cooling due to dielectric changes. The vacuum transitions are made with glass beads of the type used for K (2.92 mm) connectors. The equipment associated with this cryostat is listed in table 2

TABLE 2

Equipment associated with cryostat 1020

Model	Description	Remarks
Lake Shore 208	Cryogenic Thermometer	RS 232 interface, internal multiplexer
DT 470 DI 13	Cryogenic Temperature Sensors	±1 K accuracy in 2-100 K range
CAY	FET Power Supply	Feedback power supply, four stages
HP 8970 B	Noise Figure Meter	
HP 8971 C	Noise Figure Test Set (modified)	Used with NFM (10 MHz-26.5 GHz)
HP 83650 B	Sweep Signal Generator	Used with NFM (10 MHz-50 GHz)
HP 346 A	Noise Source	Used with NFM (ENR 5 dB, 0.01-18 GHz)
HP 346 B	Noise Source	Used with NFM (ENR 14 dB, 0.01-26.5 GHz)
HP 8510 C	Vector Network Analyzer	
HP 83651 A	Sweep Signal Generator	Used with VNA (45 MHz-50 GHz)
HP 8517 A	S parameter Test Set	Used with VNA (45 MHz-50 GHz)
HP 6626 A	Precision Quad Power Supply	For HEMT devices DC characterization
HP 34970 A	Data Acquisition / Switch Unit	Used to read bias data
HP 34908 A	40 Channel Multiplexer	Used to read bias data
HP VECTRA	Computer	Controller for cryogenic noise measurements
HP VECTRA	Computer	Controller for VNA measurements

1.3 Other equipment

Other instruments necessary for the measurements are presented in Table 3. Other small items (connectors, cables, isolators, attenuators) will used as required, but are not presented in Table 3

TABLE 3

Other microwave equipment used in amplifier measurements

Model	Description	Remarks
HP 437 B	Power Meter	
HP 8485 A	Power Sensor	50 MHz-26.5 GHz
TEK 494 AP	Spectrum Analyzer	10 KHz-21 GHz
HP 8494 B	Precision Step Attenuator	11 dB, 1 dB step, DC-18 GHz
HP 8495 D	Precision Step Attenuator	70 dB, 10 dB step, DC-26.5 GHz
1909D2	MAURY sliding short	SMA connector, stability tests
1909C2	MAURY sliding short	SMA connector, stability tests
MT 7118 A	MAURY cryogenic load LN2	7 mm connector
2659A	MAURY ambient load	7 mm connector
AFS3 0400-1200	MITEQ Low Noise Amplifier	4- 12 GHz preamplifier for noise measurements
JS4 0800-2600	MITEQ Low Noise Amplifier	8- 26 GHz preamplifier for noise measurements
HP 8349 B	Microwave Amplifier	2-20 GHz amplifier for signal generators

PERFORMANCE OF CRYOSTAT INPUT LINES

One of the main problems for the measurement of cryogenic amplifiers is the need of transitions to introduce and to extract the signal in the cryostat. Ideally the transitions should be of very low loss and low reflection, and at the same time should have low thermal conductivity and be vacuum tight. As these requirements are in contradiction, a compromise should be reached for its design. Losses in the input lines are a severe problem for noise measurements. Reflections in the lines and in the hermetic transitions limit the accuracy of reflection measurements and cause ripples in gain measurements.

Other important problem found in cryogenic measurements is the variation of losses of the transitions and other components with temperature. One good feature of the stainless steel lines used in these cryostats is that the electrical conductivity changes very little with temperature. The attennuators and DC-blocks have also been chosen with stainless steel bodies, and selected for small changes with temperature. The variation of losses in the stainless steel lines, attenuators and DC-blocks used in the systems have been checked and found negligible within the errors of the measurements. As a result, the calibration of losses in the lines and attenuation can be done at room temperature. This is not true for other coaxial copper cables used to make connections inside the dewar (for example to connect the output of the amplifiers to the output line). In our experience, copper semi-rigid cables reduce their loss by a factor of 5 (in dB) from ambient to 15 K.

Figure 1 presents the insertion and reflection losses of the three types of cryogenic transitions available in the refrigerators. Markers are located at 1, 2, 4, 8 and 12 GHz. Transition A of cryostat 350 show the best reflection performance in the band of interest (8.4 GHz).

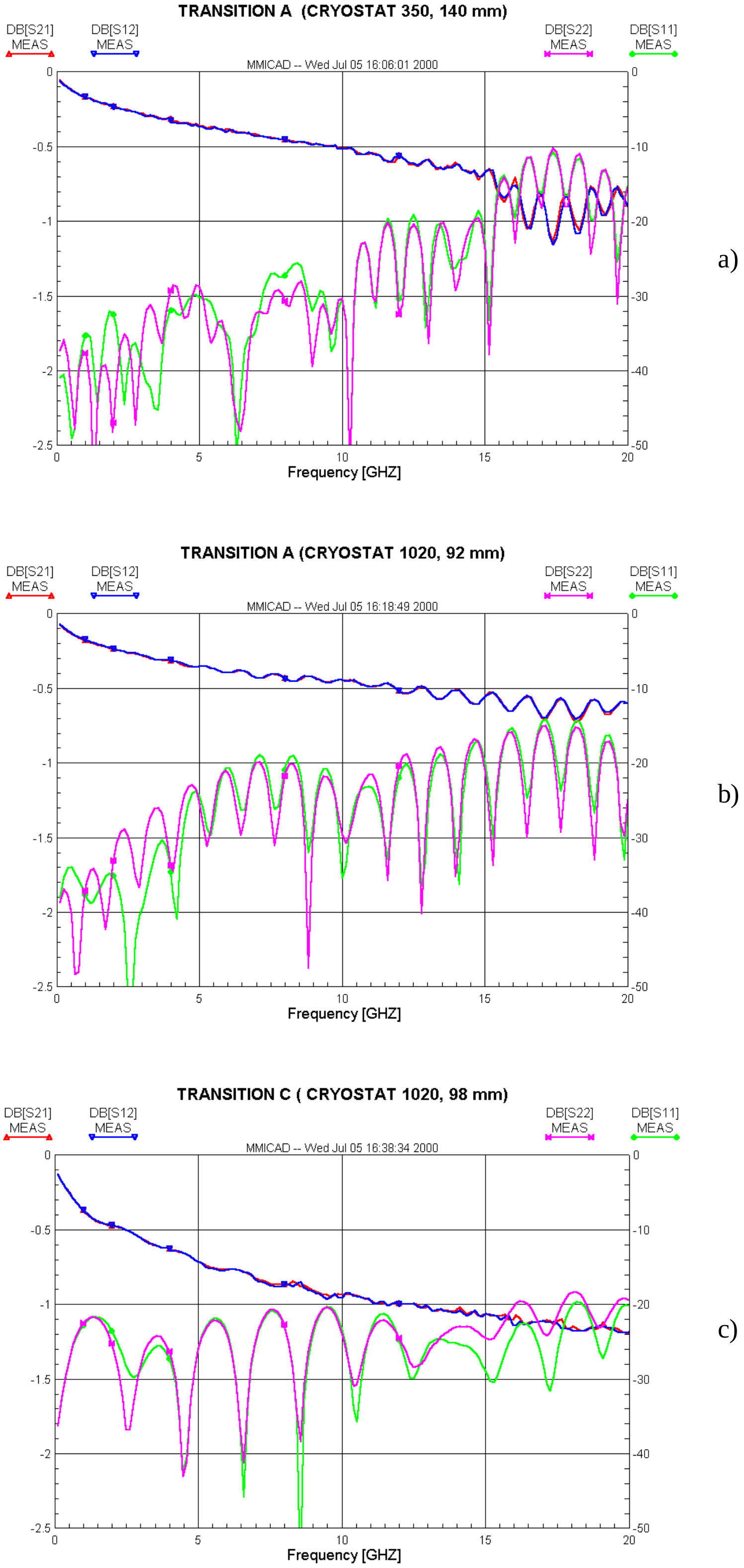


Figure 1: Insertion and reflection loss of the three types of coaxial transitions available: a) transition A of cryostat 350 (stainless steel .141” cables with TEFLON, L=140 mm), b) transition A of cryostat 1020 (stainless steel .141” cables with TEFLON, L=92 mm) and c) transition C of cryostat 1020 (special stainless steel air lines, L=98 mm)

WP1100 NOISE

WP1110 Definition of noise measurement method

The description of noise measurements will be treated with detail, since the main goal of the project is to obtain an amplifier with the lowest possible noise. The theory and details of the noise measurements can be found in the literature (see [1], [2], [3], [4], [5], [6]). Several methods have been proposed in the past for the measurement of amplifier noise:

Room temperature methods:

- Hot/ cold loads
- Diode noise sources

Cryogenic temperature methods:

- Hot/cold loads
- Diode noise sources
- Variable temperature cryogenic load
- Diode noise source and cold attenuator

In general, the Y factor method with two independent hot and cold loads is used for metrology grade measurements at ambient temperature. Usually one of the loads is at ambient temperature or in a stabilized oven and the other is in Liquid Nitrogen [7]. The advantage of this method is the inherent accuracy of the calibration of the noise sources, as only its physical temperature need to be known. This method is often used for calibration of diode noise sources rather than for measurement of microwave amplifiers. Its inconvenience is due to the difficulty to perform swept measurements and to the errors caused by the change of impedance from hot to cold loads (important for devices with moderate or high input reflection coefficient [8], [9]).

The room temperature noise measurements of this contract will be performed with the HP 8970 Noise Figure Meter System [5], [6] and the noise source will be a HP 346 A diode [10]. There are two of these sources in our laboratory, and a comparison between the two can be made if necessary. The HP346 A is the recommended source for DUT´s of low noise and whose gain is especially sensitive to small changes in source impedance. This is achieved including an internal 10 dB attenuator to reduce the ENR and the change in reflection coefficient. A MITEQ preamplifier (4-12 GHz) will be used in the Noise Figure Meter to reduce the system noise. The band for the measurements will be from 7 to 10 GHz, with steps of 100 MHz, to obtain a clear view of the amplifier tuning. There is an X band isolator available to put at the input of the MITEQ preamplifier (X-320, 8-12 GHz), but it will limit the band at low frequency, and will not be used unless is strictly needed. The Noise Figure Measurement System will be used in DSB (Double Side Band) mode [6]. In this mode, the YIG preselector is not used, and the measurements represent an average of two side bands, 4 MHz wide, located symmetrically around the LO frequency, with a separation of 25 MHz of the LO frequency selected (IF=25 MHz). This method is good for wide band amplifiers, as the one object of this contract. Otherwise, the SSB (Single Side Band) mode must be used. Our experience with the Noise Measurement System suggest to use DSB mode when possible, because drift and histeresis in the YIG filter can cause some problems in the calibration.

For cryogenic noise measurements, the effect of the transitions in very difficult to de-embed, since the temperature distribution of the lines is not well known, and their contribution to the noise of the system is often bigger than the noise temperature of the amplifier. For this reason, measurements of modern cryogenic amplifiers with noise sources connected to the room temperature side of the cryostat are almost useless. Switched cryogenic loads [11], variable temperature cryogenic loads [12] and diode noise diodes with cryogenic attenuators [8] have been proposed to avoid this problem. The goal of the three methods is to make the system less sensitive to the Dewar transitions or even to avoid them. The method with the cooled attenuator is the most convenient for swept measurements with a Noise Figure Meter. As in room temperature noise measurements, two different cryogenic loads can provide a better absolute accuracy, but only in the case of devices very insensitive to changes in the input impedance. With a variable temperature load, devices sensitive to input impedance variations can be measured with good accuracy and the calibration is based on measurements of the physical temperature of the load. However this method is very time consuming, and not adequate for swept measurements. As the realization of swept measurements was considered fundamental when tuning an amplifier, the cold attenuator method was chosen by our laboratory for routine cryogenic amplifier measurement long time ago. The repeatability of the measurements have been checked with amplifiers used in telescopes for years, and then measured in our laboratory obtaining results within ±0.2 K of the original measurement (checked with L and C band amplifiers of 3 to 6 K). The absolute accuracy of the measurements is more complex to estimate [8], but it is approximately ±1.4 K, and it is dominated by the calibration of the cryogenic thermometer used to sense temperature of the attenuator.

Figure 2 presents the block diagram of the cold attenuator measurements. The noise diode is located outside the cryostat, and there is a DC-block and an attenuator inside the cryostat. The function of the DC block is not to isolate the inner conductor of the coaxial lines for DC, but to reduce the heat arriving to the attenuator through the coaxial line. If a DC block is not included, the inner part of the attenuator is hotter than its body, and the temperature sensed is not correct. This effect gives noise measurements too pessimistic. The value of the attenuator is a compromise to obtain sufficient ENR to have low fluctuations in the measurements for a reasonable integration time, and a contribution of the losses in the lines low enough. The combination of the DC-block and the attenuator were calibrated with the HP 8510 Vector Network Analyzer, and the losses and reflection are presented in figure 3. The Excess Noise Ratio (ENR) of the noise sources used in each cryostat is presented in figure 4. Note that the HP 346 Noise Source is different for cryostat 350 and cryostat 1020.

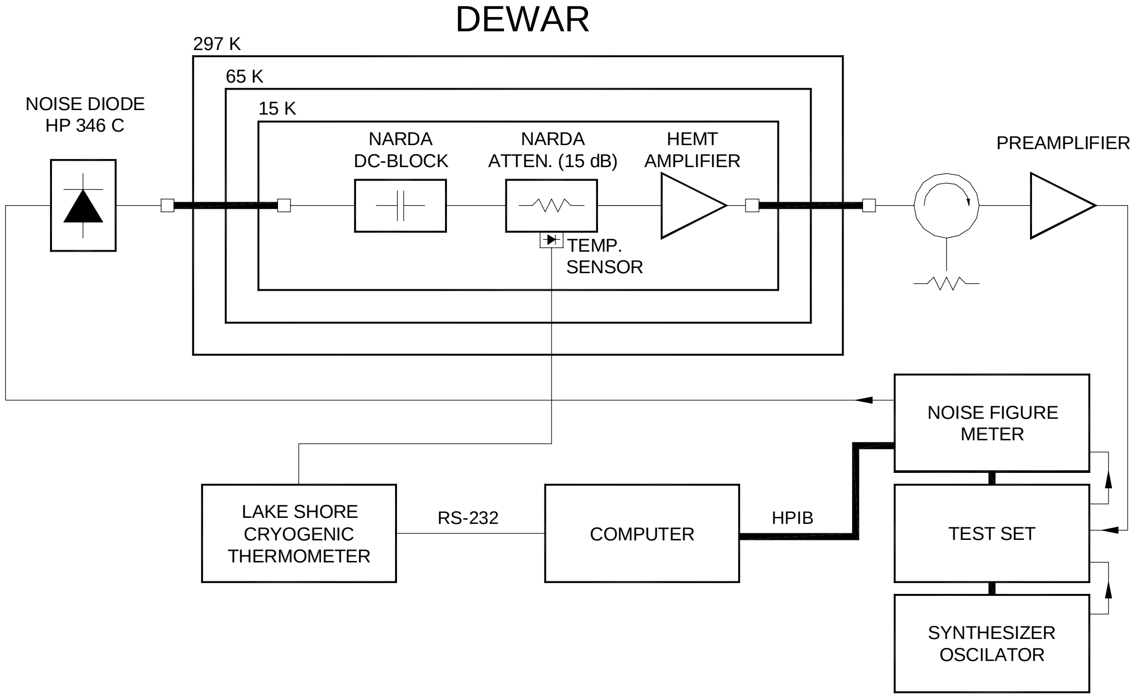


Figure 2: Block diagram of cryogenic noise measurements with the cold attenuator method.

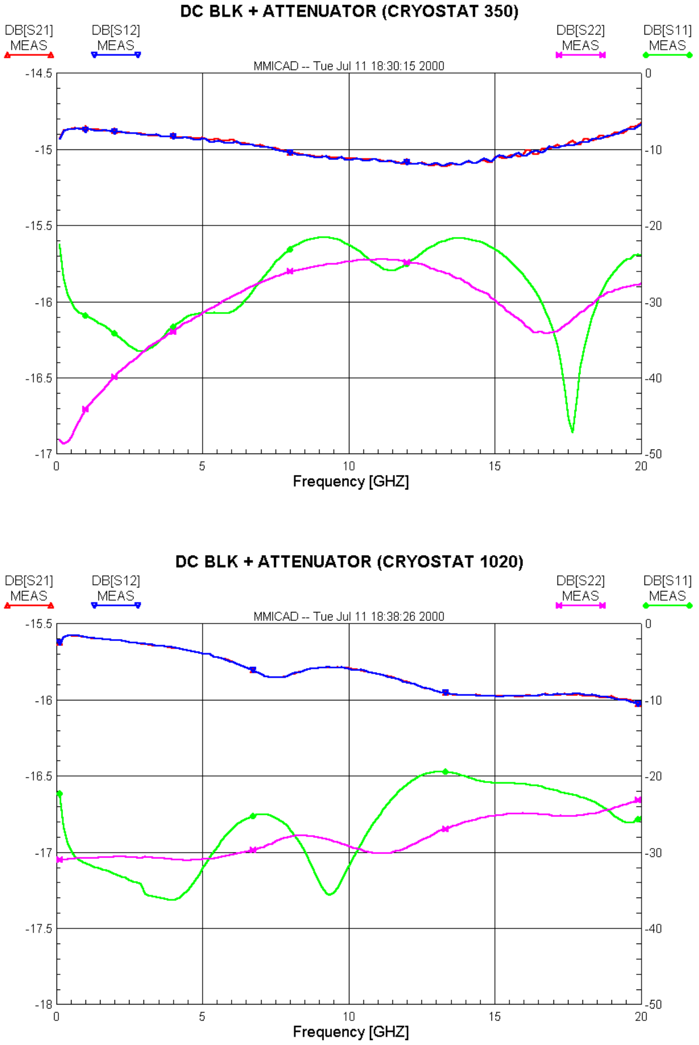


Figure 3: Insertion and reflection loss of the DC-block and the attenuator of the two cryostats (350 up and 1020 down). Port 1 is connected to the DC-block input and port 2 to the attenuator output.

In the cold attenuator method implemented in our laboratory, there is a computer controlling the Noise Figure Meter with software specially developed for cryogenic measurements. Calibration tables with values of ENR of the different noise sources and losses of the lines and attenuator are stored in files. The equivalent temperature presented to the amplifier with the noise source off and on is computed for each frequency based on the data of the tables and the actual cryogenic temperature, and is sent to the Noise Figure Meter prior to the measurement. The cold temperature is calculated taking into account the contributions of the input lines (supporting the temperature gradient) and the DC-block and attenuator. For the part of the input lines supporting a temperature gradient, a linear temperature distribution can be assumed. Then, the equivalent temperature at the end of the segment is [13] [14]:

$$T_{e2} = \frac{T_{e1}}{L} + \left(1 - \frac{1-\frac{1}{L}}{L'}\right) \cdot T_2 - \left[\frac{1}{L} - \frac{1-\frac{1}{L}}{L'}\right] \cdot T_1 \qquad (1)$$

Were T_{e1} is the equivalent temperature at the input of the segment, L is the total loss of the segment and T_1 and T_2 the physical temperatures at each end. L´ can be calculated as:

$$L' = \frac{10\cdot\log_{10}(L)}{10\cdot\log_{10}(e)} = \frac{L(dB)}{10\cdot\log_{10}(e)} \cong 0.23036\cdot L(dB) \tag{2}$$

In the case of a segment of line at uniform temperature, or for an attenuator, the equivalent temperature at the output is:

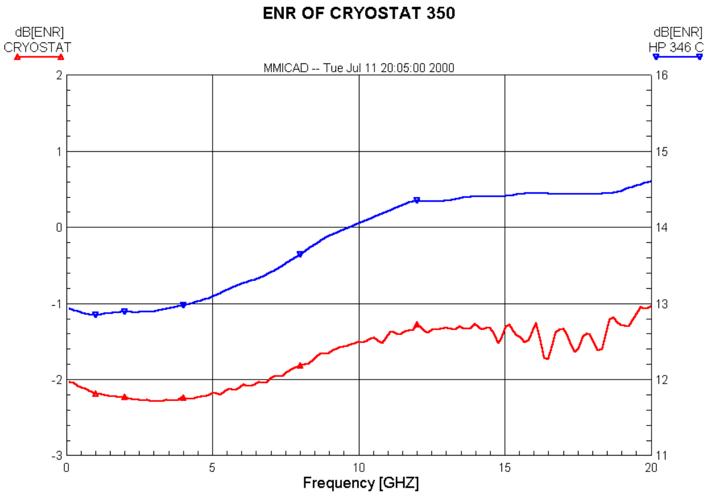
$$T_{e2} = \frac{T_{e1}}{L} + \left[1 - \frac{1}{L}\right]\cdot T \tag{3}$$

Were T is the physical temperature and the meaning of the other symbols is the same as in (1). The value of the cold temperature at the input port of the amplifier can be can be obtained chaining the results of (1) and (3) for the configuration used in each cryostat. Then, the equivalent temperature with the noise source on can be obtained form the Excess Noise Ratio.

$$ENR(dB) = 10\cdot\log_{10}\frac{T_{on} - T_{off}}{290\cdot K} \tag{4}$$

Were T_{on} and T_{off} are the equivalent temperatures at the output of the attenuator with the noise source on and off. The ENR of the cryostat can be calibrated using a receiver and ambient and LN2 loads as in [8] or calculated subtracting the total insertion loss of the lines and the attenuator for the ENR of the diode noise source given by the manufacturer. In our experience, if the losses are carefully measured, the value obtained by calculation is better, since our equipment is not the most adequate for calibration with ambient and LN2 loads (drift, reflections...). The calibration of the ENR of figure 4 was obtained in this way.

The values of T_{off} and T_{on} at 8.4 GHz are typically 22 and 216 K for the cryostat 350 cooled to 14 K . If all the losses are considered concentrated in the attenuator, theses values change only ~0.15 K . Appendix I present a MathCAD file for the computation of the effect of lines with losses with a temperature gradient.



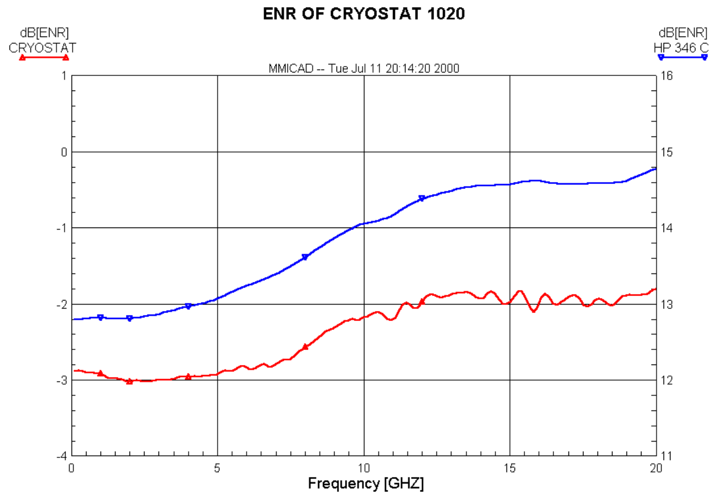


Figure 4: Excess Noise Ratio of the noise sources of the two cryostats. Curves labeled “cryostat” are for the HP 346 C noise sources (different in each cryostat) connected to the corresponding transitions, DC-blocks and attenutors. The ENR of each noise source as calibrated by the manufacturer is presented in the same graph for comparison (note the offset in the scale).

The error in the noise temperature and gain measurements obtained with the cold attenuator measurements can be estimated using a Monte Carlo simulation of the measurements as described in [8]. A MathCAD file to perform the calculation has been prepared and is presented in Appendix II. The results for a cryogenic amplifier similar to what is expected from this contract (Tn=4 K G=30 dB) appear in Table 4. The main source of error is the calibration of the diode temperature sensor used to measure the temperature of the attenuator. The precision of this sensor is ±1K, and this causes an error of the same magnitude in the noise temperature measured. The next factor in importance is the calibration of the noise diode and the losses in the attenuator. The table also present the total contribution of all the other error sources like reflection effects, second stage contribution, gain variations and fluctuations due to finite integration time. The error in the gain measured with this method is obtained the simulation too, and it is ±0.7 dB. For comparison, the error in noise temperature measurements for an amplifier at room temperature (Tamb=297 K) of Tn=90 K and G=30 dB, measured with the HP 346 A noise diode is ±13K.

TABLE 4

Error budgets for noise measurements with the cold attenuator method.
(See text and Appendix II for details)

SOURCE OF ERROR	CONTRIBUTION
Calibration of Noise Source	0.77 K
Calibration of cold attenuattor	0.54 K
Calibration of temperature sensor	1.00 K
All other	0.34 K
TOTAL:	**1.40 K**

WP1120 Implementation of noise measurements

The measurements at ambient temperature will be done outside the cryostat with the Noise Figure Meter System described above and the HP 346 A Noise Source. Noise temperature and gain of the amplifier will be measured simultaneously. Noise temperature will be corrected for receiver contribution. The optimum bias for minimum noise of the amplifier will be investigated

The measurements at cryogenic temperature will be performed in the cryostat 350 with the instruments listed above and using the cold attenuator method described previously. Noise temperature and gain of the amplifier will be measured simultaneously. Noise temperature will be corrected for receiver contribution. The optimum bias for minimum noise of the amplifier will be investigated, as well as the effect of LED illumination on the HEMTs.

WP1130 Calibration of noise measurements

Calibration of the noise sources, attenuators and transitions have been already stored in files in the two computers used to control the noise figure meters. This calibration will be available for the measurements of cryogenic gain and noise temperature of the amplifiers of this contract. Prior to the measurement, the Noise Figure Meter must be calibrated to make possible gain measurements and correction of measurement system noise. Typically this self-calibration is done once a day in a measurement session, or when the frequency range or mode of the system is changed. The self-calibration must be redone too if there is an important change in ambient temperature (>5 K) since last calibration. These calibrations are stored in volatile memory in the Noise Figure Meter, and can not be re-used.

WP1200 GAIN AND REFLECTION

WP1210 Definition of gain and reflection measurement method

The gain and reflection of cryogenic amplifiers can be measured with the Scalar Network Analyzer HP 8757 A using the configuration presented in Figure 5. The linearity of this equipment is very good, and the accuracy is limited by other factors, like calibration errors, effects of multiple reflections and noise. The frequency range covered by the instrument in its present configuration is from 10 MHz to 26.5 GHz. It is always necessary to include a fixed attenuator at the output of the generator to reduce the power to a level low enough to avoid the saturation of the amplifiers measured. Unfortunately, the attenuator limits the dynamic range of the measurements. This adverse effect is particularly important for measurements of low reflection coefficients. The reason is that the sensitivity of the wide band detectors used is limited to –55 dBm. In practice, for simultaneous measurement of reflection and gain of amplifiers, it is interesting to use the “alternate sweep” feature of the system with two different power levels in the signal generator. The higher power can be used in the sweep corresponding to the acquisition of reflection data, were a slight saturation of the last stage of the amplifier is allowable and does not change the input reflection performance. For the sweep corresponding to the acquisition of the gain data, a lower power must be selected, to avoid any saturation of the amplifier. The variation of the output power between the two sweeps can be made up to 15 dB.

The use of the reference channel for normalization of the measurements with a sample of the power of the generator has some important advantages. For example, the output power of the generator can be changed, and the calibration will remain valid. In addition, the output match of the generator is improved [15], although this is not important when an attennuator is used at the output of the generator. The saturation of the amplifier can be easily detected by the reduction in gain, and the 1 dB compression point can be measured, since the detectors are calibrated for absolute power measurements too.

The calibration of the system for reflection measurements is performed using the average of a short and an open circuit connected to the output of the directional bridge. The transmission is calibrated connecting a short line (thru). In both cases the calibration mark the 0 dB reference. The use of two standards for the calibration of reflection allows reducing the ripple caused by multiple reflections during calibration [15].

The accuracy of reflection measurements is dependent on the directivity and output match of the directional bridge. The value of the reflection coefficient measured can be expressed as:

$$\Gamma_m = D + \frac{\Gamma}{1 - \Gamma \cdot \Gamma_b} \tag{5}$$

Where Γ is the actual reflection coefficient, D is the directivity and Γ_b is the output math of the reflection bridge. All them are complex numbers with unknown phase in practice. For the reflection bridge used in X band, the directivity is -35 dB and the reflection match is -15 dB. When used in combination with cryostat transitions, these values are degraded by the additional reflection in the lines. Taking the value of -25 dB (cryostat 350) for the worst case reflection in X band, then the directivity is reduced to -23 dB and the output match to -13 dB. Figure 6 presents the error limits calculated for the two cases as a function of the return loss to be measured. For high reflection coefficient, the test port match dominates the error, while for low reflection the main contribution is from the directivity. It can be seen in these curves that the reflection bridge can appreciate return losses of up to 25 dB with acceptable accuracy, but no more than 15 dB can be measured for a device inside the cryostat 350 due to the effect of the transitions.

Other limiting factor for reflection measurements is the limited sensitivity of the reflection bridge detector. In our experience, for an amplifier of the type to be measured in this contract, and with the power level adequate to avoid adverse effects of saturation, the detector noise limits the maximum measurable reflection loss to 16 dB. To obtain the maximum sensitivity in the reflection measurements, it is necessary to use the AC mode of the SNA (carrier modulated at 27.777 KHz instead of CW). In this mode the sensitivity is improved by 5 dB, and the stability of the system (drift of the calibration) is better. The maximum allowable power at DUT input to avoid saturation is –37 dBm.

The accuracy of transmission measurements with the SNA depends on the reflection coefficients of the detector and source used (Γ_d, Γ_b), as well as the S parameters of the DUT. The insertion gain is defined as the ratio of the power measured with the DUT to the power measured during calibration:

$$G = \left| \frac{(1-\Gamma_b \cdot \Gamma_d)\cdot S_{21}}{(1-S_{11}\cdot\Gamma_b)(1-S_{22}\cdot\Gamma_d) - S_{12}\cdot S_{21}\cdot\Gamma_b\cdot\Gamma_d} \right|^2 \qquad (6)$$

As in the case of the reflection, the phase of the parameters is unknown, and the error can be calculated finding the extremes of (6). In the case of amplifiers, the product $S_{12}S_{21}$ can be neglected, and it is easier to find the maximum and minimum of previous expression. For the system used with $|\Gamma_b|\approx$-20 dB, $|\Gamma_d|\approx$-17 dB, and for a typical amplifier with $|S_{11}|\approx|S_{22}|\approx$-10 dB the error is ±0.7 dB. When the effect of the transitions (25 dB of reflection) is included, the system is degraded to $|\Gamma_b|\approx$-16 dB, $|\Gamma_d|\approx$-14 dB, and the error is ±1.2 dB.

The Scalar Network Analyzer is a very convenient instrument for cryogenic amplifier testing because it can be used not only for gain and reflection tests, but for 1 dB compression and for testing the unconditional stability in a very simple and effective way. Other important feature of the SNA is the easy routing of cables (detectors only need DC cables), and easy calibration. When used in the DC (non-modulated) mode, the SNA has very wide band sensitive CW detectors. The detectors are calibrated only up to 26.5 GHz, but can detect power at much higher frequencies (at least to 50 GHz). A very good test to check the unconditional stability of the amplifier is to connect a sliding short at the input and a SMA tee at the output with a sliding short in one port and a SNA detector to the other. Then, the two sliding shorts are slowly moved, and no power should be detected in any position. If power is detected, the amplifier is oscillating, and it is not unconditionally stable. When an oscillation is detected, a spectrum analyzer can be used to measure the frequency of oscillation.

When the accuracy of the SNA or its sensitivity is not sufficient, a Vector Network Analyzer should be used. The VNA HP 8510 C is a very sensitive and accurate instrument, but is not as easy to use and to calibrate, and it is reserved for measurements in which its special characteristics are really needed. When calibrated with HP 85052 B using the sliding load technique, the VNA has an effective directivity better than -45 dB and a source and load match better than –31 dB in X-band [16]. This reduces the errors in the measurement of reflection and transmission coefficients of amplifiers to negligible quantities (±0.15dB in transmission and less than ±1dB in reflection for reflection loss up to 25 dB). The noise floor of the system is very low too, and reflection loss up to 50 dB can be easily detected with the system configured to avoid saturation (10 dBm Source Power, 30 dB internal attenuator, -32 dBm @ 8 GHz in the test port). For measurements inside the cryostat, the time domain gating technique can be used to avoid the effect of the limitation imposed by the reflection in the vacuum transition. This technique has been used for cryogenic measurements of isolators with low input and out put reflection with good results [17].

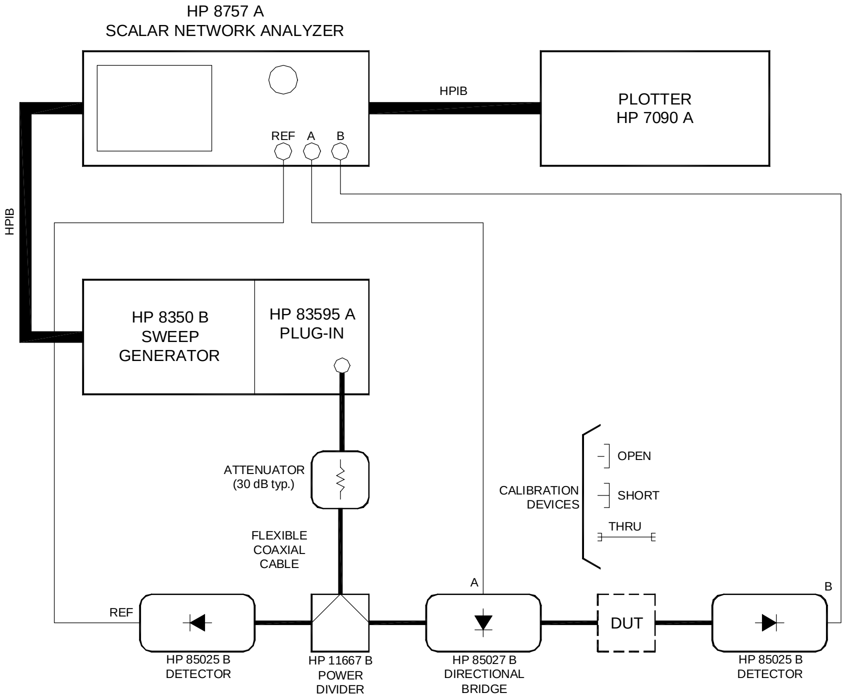


Figure 5: Configuration used in the Scalar Network Analyzer for the simultaneous measurement of transmission and reflection. The measurement of the reference channel (REF) allows changes in the output power of the generator keeping the calibration valid.

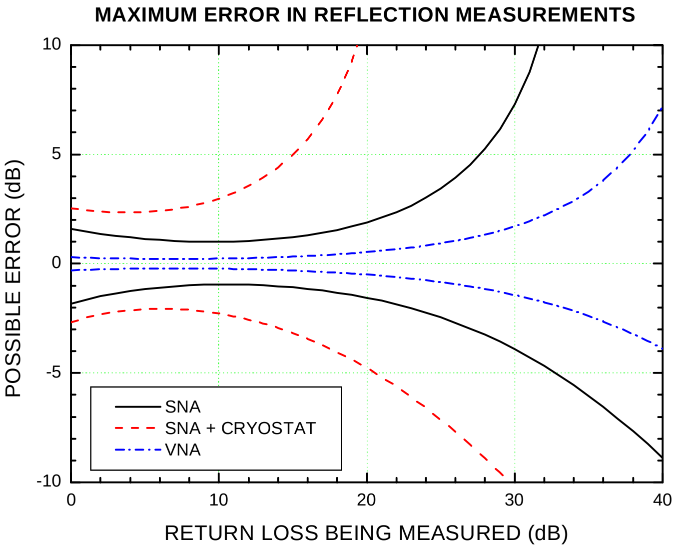


Figure 6: Error limits in measurement of reflection coefficient with the Scalar Network Analyzer and Vector Network Analyzer. The continuous curves are for the SNA reflection bridge as specified in X band (directivity=35 dB, test port match=15 dB). The dashed curves are for the bridge including the effect of the cryostat transitions (directivity=23 dB, test port match=13 dB). The dash-dot curves are for the Vector Network Analyzer as specified in X band (directivity=45 dB, test port match=31 dB)

WP1220 Implementation of gain and reflection measurements

Gain and reflection measurements will be taken with the Scalar Network Analyzer in AC mode, with the configuration shown in figure5. The amplifier will be measured outside the cryostat at room temperature and inside cryostat 350 at cryogenic temperature. The DC bias will be the optimum determined in noise measurements. The Scalar Network Analyzer will also be used in DC mode for unconditional stability test with sliding shorts at input and output as described above.

If more accuracy is needed in reflection measurements, the Vector Network analyzer will be used. For cryogenic measurements with the VNA will be carried out in cryostat 1020 with air line transitions. For measurements inside the cryostat, a time domain gate will be used to avoid the masking effect of the reflections in the vacuum transitions.

Gain variation with temperature at operating temperature will be determined by measurements of gain performed at 15K and 20K.

WP1230 Calibration of gain and reflection measurements

Calibration of the Scalar Network Analyzer will be done with the Open-Short –Thru technique described above. Calibration of the Vector Network Analyzer will be done with the Open-Short-Load-Thru technique with the 3.5 mm connector calibration kit. The reference plane of the VNA will be at the end of its flexible cables. The transmission parameters will be normalized respect to the value of a low loss short “U” cable connected inside the cryostat to correct for the losses of the transitions. The reflection parameters will be normalized respect to the value of a short connected inside the cryostat for the same reason. The “start” and “stop” times of the time domain gate will be chosen to include the response of the amplifier but not the effect of the transitions. The validity of the gate chosen will be checked comparing room temperature measurements inside and outside the cryostat.

WP1300 LINEARITY AND MAXIMUM INPUT

WP1310 Definition of linearity measurements

Two types of linearity measurements will be performed: 1 dB compression and IP3 (Third order two-tone interception point). The first one is a measure of compression, while the second one is a measure of distortion.

The1 dB compression point [18], [20] is the output power measured when the gain of the amplifier has dropped 1 dB below its value for low signals. It will be measure with the Scalar Network Analyzer, using the setup presented in figure 7. The step attenuator can be set in the 0-81 dB range with 1dB steps. The analyzer will be configured for power sweep at a fixed frequency (8.4 GHz). The output power selected in the sweeper will be –5 dBm with a variation of 10 dB per sweep (from –5 to +5 dBm). The attennuator must be approximately set to obtain the 1 dB compression near the end of the sweep. In the SNA, one channel will be set to display the ratio of output power to reference power (B/REF), and the other will present the absolute power detected by B. With the power sweep feature disabled in the sweeper, and with an adequate value of the step attenuator, the channel presenting (B/REF) will be normalized to obtain a value of 0 dB for a power low enough to avoid compression. Then, the power sweep feature will be enabled, and the 1 dB compression will be found in the channel presenting (B/REF) normalized. The output power for this point can be read in the channel measuring the absolute power of B in dBm.

The IP3 (Third order two-tone interception point) [18], [19], [20] will be measured using two signal generators and a spectrum analyzer. The configuration for this measurement is presented in figure 9. The frequency of one of the generators will be selected in the middle of the band, with an offset of a few MHz (typically 2 MHz). Prior to the measurement, the power output of the two generators will be adjusted to obtain the same level at the input of the amplifier. This adjustment will be done without DUT, and with the step attenuator set for the minimum value. Then the step attenuator will be increased, and the DUT connected. The value of the attenuation will be chosen to obtain a clear view of the distortion products, yet being far from saturation. Typically, a suppression of 40 dB below carrier will be taken. The IP3 can be calculated as:

$$IP3(dBm) = \frac{Suppression(dB)}{Order - 1} + P_{out}(dBm) \tag{7}$$

Were Suppression is the level of spurious below carrier, P_{out} is the output power level of the fundamental signal, and Order is the order of the spurious product (in this case 3).

There is a rule of thumb relating IP3 to the 1-dB compression point plus 10 dB. This is only an approximation, and depends on the type of nonlinearly of the device tested.

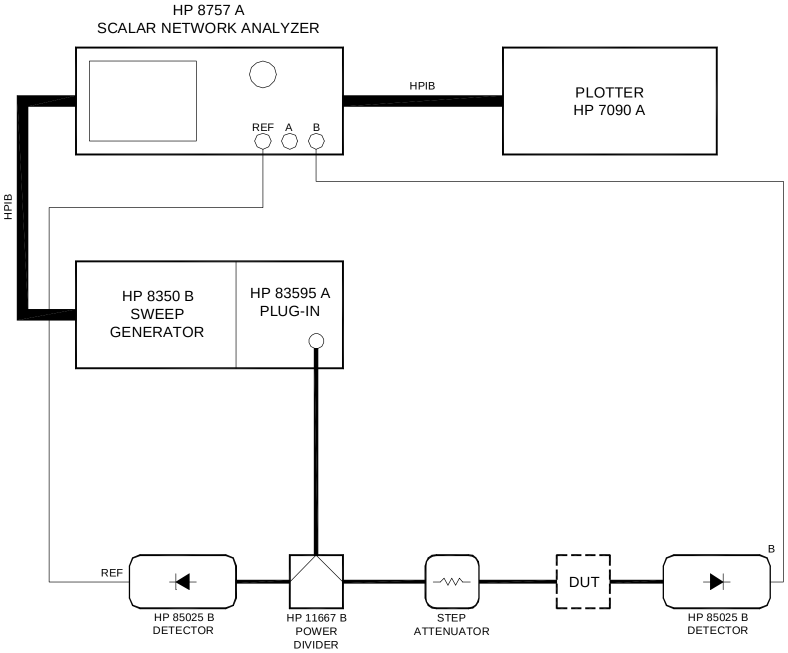


Figure 7: 1 dB compression point setup. The scalar network analyzer is set to a fixed frequency and in the power sweep mode. The DC (non-modulated) mode should be selected.

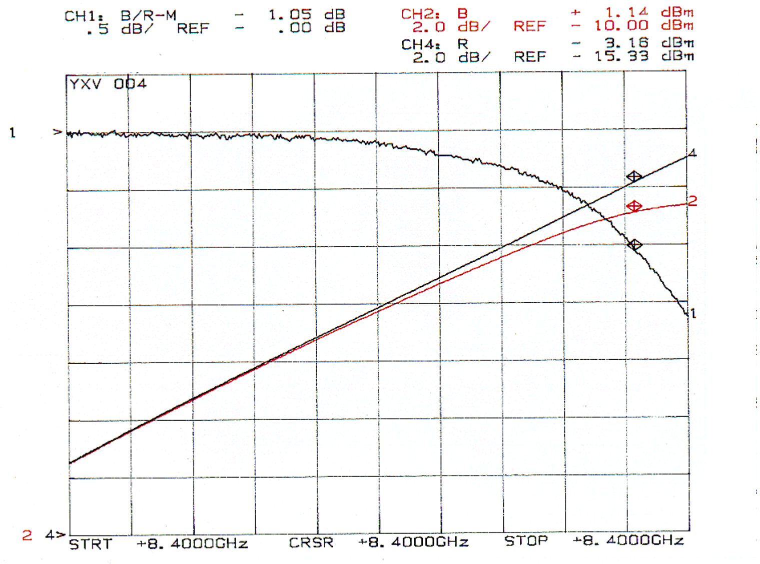


Figure 8: Example of 1 dB compression point measurement. Channel 1 presents (B/REF) normalized and channel 2 present the output power measured by detector B (see figure 7). Channel 4 presents the power of the REF detector.

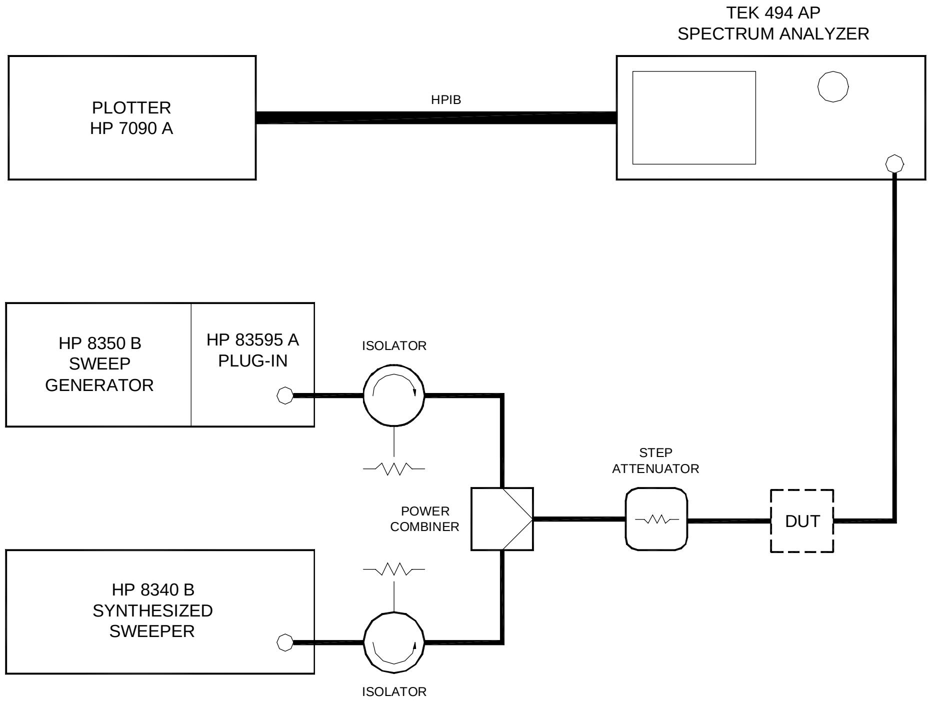


Figure 9: Third order two-tone interception point setup. The power from two CW generators is combined at the input of the DUT. The output power of the two generators is adjusted to obtain the same level at the input of the DUT. The frequency of the two generators is adjusted for a difference of a few megahertz.

WP1320 Implementation of linearity measurements

The1 dB compression point will be measured at 8.4 GHz with the Scalar Network Analyzer in DC mode, with the setup shown in figure 7 and with the equipment configured as explained previously. The amplifier will be measured outside the cryostat at room temperature and inside cryostat 350 at cryogenic temperature. The DC bias will be the optimum determined in noise measurements.

The IP3 (Third order two-tone interception point) will be measured at 8.4 GHz with the setup of figure 9 as explained. The frequency offset of the two signal generators will be 2 MHz (one generator at 8.399 ant other at 8.401 GHz) and the suppression will be set to 40 dB approximately. The amplifier will be measured outside the cryostat at room temperature and inside cryostat 350 at cryogenic temperature. The DC bias will be the optimum determined in noise measurements.

WP1330 Calibration of linearity measurements

For the 1 dB compression point, the channel measuring B/R in the Scalar Network Analyzer must be calibrated (normalized) to obtain a gain of 0 dB at a power level low enough to have negligible compression (high value of the step attenuator). The absolute calibration of the detectors of the SNA is not as good as in dedicated power detectors. Typically the error in the measured power is 1-2 dB. If a good accuracy is needed, the SNA detector should be previously calibrated against a good power meter, and the difference should be introduced as an offset in the SNA. For cryogenic measurements, if the ultimate accuracy is desired, the losses between the output of the amplifier and the input of the detector (cables and transitions) should be determined and taken into account.

For the IP3 (Third order two-tone interception point), the output power of the two signal generators should be adjusted to obtain the same level at the input of the DUT. As in previous case, the amplitude calibration of the Spectrum Analyzer is not as good as the calibration of a power meter, and similar errors to the SNA can be expected. As previously, if the maximum accuracy is necessary, the total losses of the cable connecting the output of the amplifier to the input of the measuring equipment should be taken into account to determine the absolute power level.

WP1340 Maximum input without damage

The specification of the maximum input without damage will be checked by injecting a power level of 0 dBm (8.4 GHz) at the input of the amplifier during at least 1 minute. Previous experience shows that one of the characteristics of the amplifier more sensitive to degradation of the devices is the noise temperature. The method used will be to measure the noise temperature before and after the application of the 0 dBm signal at the input of the amplifier. The test can be performed at room and at cryogenic temperature. However, at cryogenic temperature the amplifier will be measured with the cold attenuator method and it will be necessary to inject a signal level of approximately 15 dB at the input of the cryostat if one wants to make the test in a single cool down. The maximum output power of our signal generator (HP 8340 B) have been checked, and it is 16.7 dBm at 8.4 GHz. If more power is needed to overcome the losses, a HP 8349 B amplifier with an output power in excess of 20 dBm is available in our laboratory.

WP1400 GROUP DELAY

WP1410 Definition of group delay measurements

Group delay is the measurement of the signal transit time through a device. It is defined as the derivative of the phase slope with frequency. In this contract, the group delay will be measured using the HP 8510 Vector Network Analyzer. This instrument computes the group delay from the phase change $\Delta\varphi$ in a specific frequency aperture Δf assuming a linear approximation for the rate of change of phase with frequency [21]. More specifically, the minimum frequency aperture is given by the resolution of the span, and the delay is computed as:

$$t_d = -\frac{\varphi_{n+1} - \varphi_n}{2 \cdot \pi \cdot (f_{n+1} - f_n)} \tag{8}$$

Being φ_{n+1} and φ_n the phase angles of successive points of the scan and f_{n+1} and f_n the frequency corresponding to each point.

A wider frequency aperture results in loss of fine grain variations of group delay. This loss of detail is the reason that in any comparison of group delay data, the aperture used to make the measurement should be taken into account. In selecting the aperture, there is a tradeoff between resolution of fine detail and the effects of noise. The effects of noise can be reduced by increasing the aperture, however, this will trend to smooth out the fine detail. In decreasing the aperture, more fine detail will become visible, but the noise will increase, possibly to the point to obscuring the detail.

For this specific measurement, the criterion for selecting the aperture has been to maintain a phase difference between successive points of at approximately 4° in the band. This can be achieved with a sweep from 7 to 10 GHz and 201 points (Δf=15 MHz). An example of an amplifier measured at room temperature with this method is shown in figure 10.

Simulations of the group delay of the amplifier show a result totally clean and in good agreement with the measurement. The small ripple in the measurement is an instrument effect and it is not real.

The group delay specifications put limit on the ripple and in the maximum slope in the band, but the absolute value is not of interest. The absolute value can be easily obtained at room temperature with a complete SOLT calibration of the VNA, but is not so easy to obtain inside the cryostat, as the calibration of the VNA is done at the end of its flexible cables. If the absolute value of the group delay is not needed, an alternative approach to calibrate the VNA is to use a simple normalization respect to a thru connection, and a gate in the time domain to avoid the ripple due to the effect of multiple reflections. Figure 11 shows the result of this technique on the same amplifier. The agreement with figure 10 is almost complete.

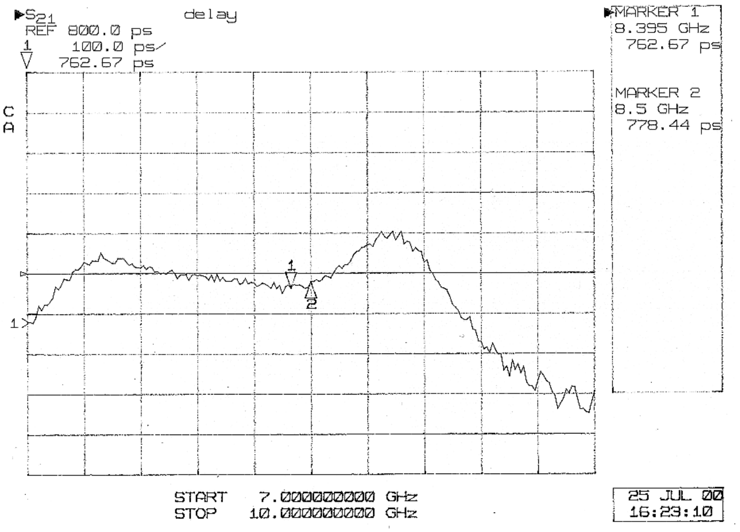


Figure 10: Example of measurement of the group delay of an amplifier taken with the HP 8510 VNA. The calibration is a complete SOLT, and the frequency aperture is 15 MHz. Smoothing is off.

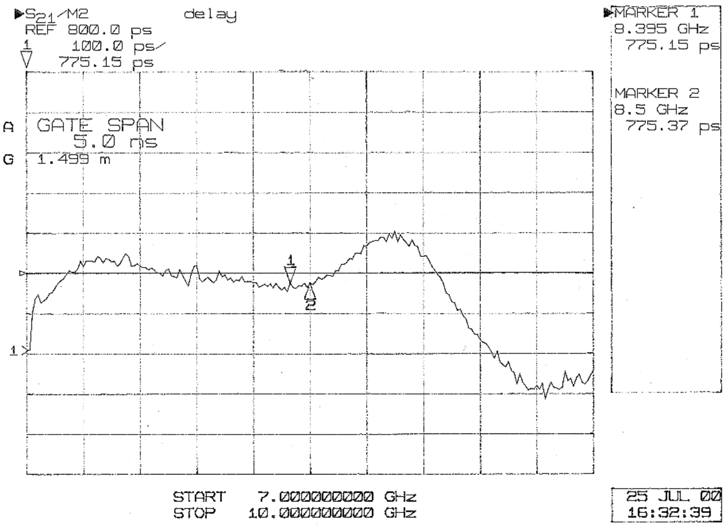


Figure 11: Example of measurement of the group delay of the same an amplifier as in figure 10. In this case the VNA has not been calibrated. A normalization respect to a thru connection has been done and a time domain gate (5 nS) has been used instead.

WP1420 Implementation of group delay measurements

The group delay will be measured with the HP 8510 Vector Network Analyzer In the 7 to 10 GHz range with 201 points. At room temperature the amplifier will be measured outside the cryostat with a complete SOLT coaxial calibration to obtain an absolute measurement of good quality. For cryogenic temperature the cryostat 1020 with the air line transitions will be used. The non–calibrated delay will be normalized respect to a non zero length thru connection, and a 5 ns gate in the time domain centered in the main response will be applied. The DC bias will be the optimum determined in noise measurements. Care should be taken to avoid saturation. A value of 40 dB for the internal attenuattors of the test set should be set if the power of the generator is set to 10 dBm. Otherwise, if the power of the generator is set to 0 dBm, the internal attenuattors of the test set should be set 30 dB.

WP1430 Calibration of group delay measurements

For room temperature, a conventional two port SOLT calibration will be used. For cryogenic temperature the VNA will not be calibrated. Instead, normalization respect to a non zero length thru connection will be used, and a time domain gate of 5 ns, centered in the main transmission response will be applied. The validation of the calibration for cryogenic temperature will be done by comparison of the data taken at room temperature, with data taken with the amplifier inside the cryostat prior to cooling.

WP1500 GAIN STABILITY

WP1510 Definition of gain stability measurements

Two types of gain stability can be considered: long and short term. Only long-term gain stability is specified in the contract. Short-term gain stability is of importance for wide band low noise radiometer receivers of the type used in Radio Astronomy, and it is better characterized by the normalized spectrum of gain fluctuations. Short-term gain stability will be measured only if the contractor estimates that this parameter relevant for the present application.

Long term gain stability, as specified in the contract, will be measured as the total gain variation in a 24 hour period. The main problem anticipated for this measurement will be the variation of gain in the measuring equipment itself. The gain of the amplifier and of the measuring equipment is a function of the ambient temperature. The temperature of our laboratory shows fluctuations (even with air conditioner), and the temperature of the cryostat can show some variations too. The measurements of the gain variation in a 24 hour period will be taken with the Scalar Network Analyzer in cryostat 350 and with the setup of figure 5. Data of the ambient temperature of the room and the cryogenic temperature of the amplifier will be recorded to show a possible correlation of the gain variations measured with temperature. The data will be sampled at regular intervals by the computer used in the cryostat 350. The ambient temperature will be measured with a thermocouple located close to the SNA mainframe. The thermocouple will be connected to the HP 34908 A Multiplexer. The measurements will be sampled with one minute intervals, in order to resolve possible variations due to the on-off cycles of the air conditioner.

Short term gain stability can be measured (if required) with the same system used in [22]. Usually the spectral density of normalized gain fluctuations is used for this characterization. The spectrum is obtained by Fast Fourier Transform of time domain data acquired with the HP8510 Vector Network Analyzer. Several spectrums are averaged to reduce the random fluctuations. Our system allows us to obtain spectrums in the 0.012-2.34 Hz range. The spectrum obtained is usually of the form:

$$S(f) = b \cdot \left(\frac{1 \cdot Hz}{f} \right)^{\alpha} \tag{9}$$

The exponent α is normally very close to 0.5 and the value of b is the parameter used to compare different devices or amplifiers. b is known as the value of the spectral density of normalized gain fluctuations at 1 Hz, and its units are $1/\sqrt{\text{Hz}}$ when α is 0.5. Typical values of b for InP amplifiers are $\sim 10^{-4}$ $1/\sqrt{\text{Hz}}$, but are very dependant of the type of devices used. Figure 12 presents an example of a measurement of gain fluctuations of a cryogenic amplifier

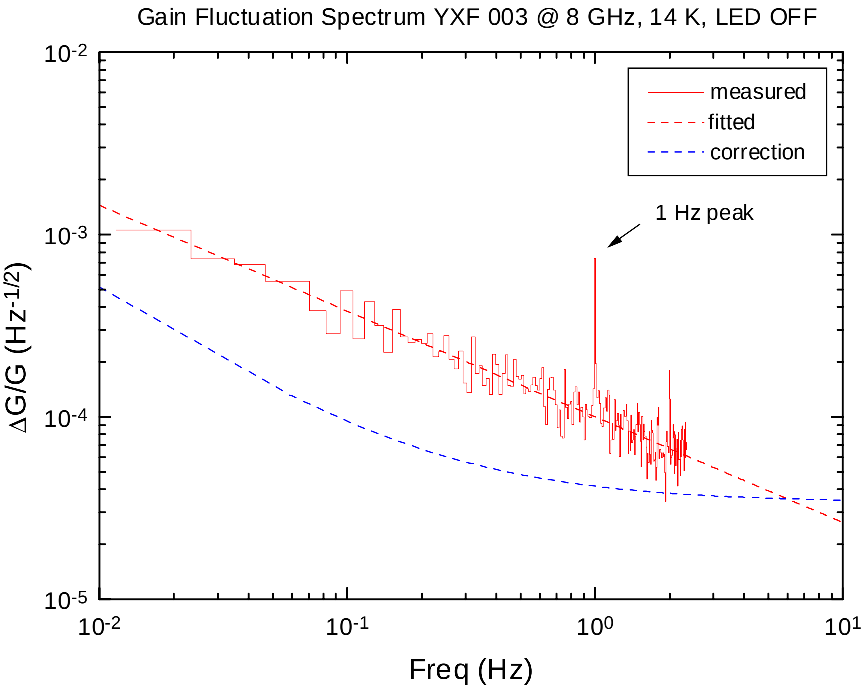


Figure 12: Example of calibrated measurement of the Spectral Density of Normalized Gain Fluctuations of Amplifier YXF 003. The measured data presented has been corrected to eliminate the contribution of system fluctuations. The value of the correction is also shown in the graph as a reference. The peak appearing at 1 Hz is due to the cycle of CTI 1020 refrigerator. A smaller peak at 2 Hz is also visible.

WP1520 Implementation of gain stability measurements

Long term gain stability will be measured only at cryogenic temperature using the Scalar Network Analyzer in cryostat 350 and with the setup of figure 5. Data of the ambient temperature of the room and the cryogenic temperature of the amplifier will be recorded to show a possible correlation of the gain variations measured with temperature. The data will be sampled at 1 minute intervals for a total of 24 hours.

Short-term gain stability will be measured only if the contractor estimates that this parameter relevant for the present application. In this case, the Vector Network Analyzer and the air lines of cryostat 1020 will be used for the measurement. Special care of the configuration of the cryostat is needed to minimize temperature oscillations at 1 Hz. Data will be taken at room and cryogenic temperature. Details of the implementation are given in [22].

WP1530 Calibration of gain stability measurements

For long term gain stability, the Scalar Network Analyzer will be calibrated as described in WP1200.

For short term gain stability, the fluctuations of the system will previously measured and then subtracted as in the data presented in [22].

REFERENCES:

[1] H. Haus, “IRE standards on methods of measuring noise in linear two ports, 1959,” Proc. IRE, vol. 48, pp. 60-68, Jan. 1960.

[2] IRE Subcommittee 7.9 on Noise, “Description of the Noise Performance of Amplifiers and Receiving Systems,” Proc. IRE, vol. 50, pp. 436-442, March 1963.

[3] W. R. Atkinson et al, “Representation of Noise in Linear Two-Ports,” Proc. IRE, vol. 48, pp. 69-74, Jan. 1960.

[4] “Fundamentals of RF and Microwave Noise Figure Measurements,” Hewlett Packard Application Note 57-1.

[5] “Applications and Operation of the 8970A Noise Figure Meter,” Hewlett Packard Product Note 8970A-1.

[6] “Applications and Operation of the 8970B Noise Figure Meter and 8970S Microwave Noise Figure Measurement System,” Hewlett Packard Product Note 8970B/S-2.

[7] “Input Noise Temperature Calibration Equations for Liquid Nitrogen Cooled Precision Cryogenic Termination,” Maury Microwave Technical Note TN-009, March 1968.

[8] J. D. Gallego and M.W. Pospieszalsky, “Accuracy of Noise Temperature Measurement of Cryogenic Amplifiers”, Electronics Division Internal Report No. 285, National Radio Astronomy Observatory, Charlottesville, VA, March 1990.

[9] “Noise Figure Measurement Accuracy,” Hewlett Packard Application Note 57-2.

[10] “Noise Sources 10 MHz to 26.5 GHz (models 346 A/B/C),” Hewlett Packard Technical Data.

[11] S.-K. Pan, A. R. Kerr, M. J. Feldmang, A. W. Kleinsassera, J. Stasiaks, R. L. Sandstroms, and W. J. Gallagher, “An SIS Mixer for 85-116 GHz Using Inductively Shunted Edge-junctions,” IEEE Trans. on MTT 37, pp- 580-592, March 1989.

[12] W. R. McGrath, A. V. Raisänen and P. L. Richards, “Variable Temperature Loads for Use in Accurate Noise Measurements of Cryogenically Cooled Microwave Amplifiers and Mixers,” International Journal of Infrared and Millimeter Waves, vol. 7, no.4, 1986, pp. 543-553.

[13] C.T. Stelzried, ”Temperature Calibration of Microwave Thermal Noise Sources,” IEEE Trans. on MTT 13, pp- 128, January 1965.

[14] C.T. Stelzried, ”Microwave Thermal Noise Standards,” IEEE Trans. on MTT 16, pp- 646-655, September 1968.

[15] “High Frequency Sweept Measurements”, Hewlett Packard Application Note 183.

[16] “Specifications and Performance Verification program”, HP 8510 Network Analyzer System, 08510-10033 Rev. A.02.00

[17] Juan Daniel Gallego, Isaac López Fernández, Carmen Diez González, “Measurement Of Cryogenic Performance Of 4-8 Ghz Pamtech Isolators S/N 108-112,” Technical Report C.A.Y. 2000-2, May 2000.

[18] “General Amplifier Parameters and Performance,” Avantek Application Note M013.

[19] “Spectrum Analysis... Distorsion Measurements,” Hewlett Packard Application Note 150-11.

[20] Thomas S. Laverghetta, “Handbook of Microwave Testing,” Artech House 1981, pp 268-282.

[21] “HP 8510 C Network Analyzer Operating and Programming Manual,” Hewlett Packard.

[22] 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.

APPENDIX I

Math CAD file: cold_att.mcd

APPENDIX II

Math CAD file: nerr2d.mcd