A 279-381 GHz SIS Receiver For the new APEX Telescope

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Abstract—**We present a 279-381 GHz fixed-tuned double sideband (DSB) receiver based on superconductor-insulator-superconductor (SIS) junction mixer. This receiver has been installed and is under commissioning at the new Atacama Pathfinder EXperiment (APEX) 12 m submillimetre telescope located on Chajnator, at an altitude of 5100 m on the Atacama Desert, in Northern Chile. The cryostat is equipped with two channels; one is currently installed and is the one described here. The second channel is for a 210-280 GHz sideband separating SIS mixer that will be installed fall of 2005. A full characterization of the receiver performance was done, the measured system noise temperature (uncorrected) is 30-50 K corresponding to about 2-3 quantum noises across the full frequency band with the IF from 3.8 to 7.6 GHz. Measurements of the mixer saturation and receiver stability are presented. Finally, we will describe the control system that allows operating the receiver remotely and automatically tuning any given frequency in less than 5 minutes.**

Index Terms—**Superconductor-Insulator-Superconductor (SIS) junction, radial E-probe, bias-T.**

I. INTRODUCTION

The Atacama Pathfinder EXperiment (APEX) submillimeter telescope [1] is a collaboration between the Max Planck Institute for Radioastronomy (MPIfR) (in collaboration with Astronomisches Institute Ruhr Universitet Bochum (RAIUB)), Onsala Space Observatory (OSO) and the European Southern Observatory (ESO) to construct a single dish antenna on the high altitude site of Llano Chajnantor at an altitude of 5100 m on the Atacama Desert on the Atacama Large Millimeter Array (ALMA) site, in Northern Chile. This site is believed to be one of the best for sub-millimeter wave observations. The antenna is a prototype antenna of the ALMA, but with improved surface accuracy (down to 14 μm rms) to allow higher frequency operation. Another difference with the ALMA antennas is the presence of 2 Nasmyth cabins to accommodate more instruments. APEX is planned to have both heterodyne and continuum instruments, covering the frequency range (230 GHz–1.5 THz). The cassegrain cabin will contain the bolometer arrays, the cabin A will contain single pixel heterodyne receivers and the cabin B will accommodate the heterodyne arrays. The telescope is in the final installation phase (Fig. 1).

The work presented here is done for APEX band 2, covering the frequency range 275-370 GHz with the center frequency at approximately 345 GHz. The receiver described in this paper is double sideband (DSB) and will be used as a first light facility receiver for the APEX telescope and will be the first instrument available to the astronomical community. This development aims also as a base for a future sideband-separating mixer (2SB) that will be installed in the final facility receiver together with 3 other channels (230 GHz, 450 GHz and 1.3 THz).

Fig. 1. View of the Apex telescope.

II. RECEIVER OVERVIEW

A. Cryostat

The receiver is equipped with 2 channels (Fig. 2 and Fig. 3). The first is for the APEX band 2, 275-370 GHz, which is double sideband (DSB), and is currently being installed and tested. The second channel is for APEX band 1, 210-280 GHz sideband separation (2SB). That mixer will be installed end of 2005 while all optics is in the Dewar already.

The mixer uses superconductor-insulator-superconductor

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(SIS) junctions using Niobium technology. The mixer chip is mounted in a full-height waveguide mixer block. The cryostat window is a 5 mm HDPE window with linear corrugations. The infrared material is 10 mm of PPA30 material [2]. The optics inside the receiver consists of a flat and an ellipsoidal mirrors (Fig. 4). The input is a corrugated horn [3]. The IF output of the mixer is connected to a 4-8 GHz isolator followed by a 2-stage 4-8 GHz LNA sitting on the 4 K plate; the second 2-stage LNA with its respective isolator is placed on the 12 K plate. The cold amplification is about of 45 dB.

The receiver RF operating range actually is 279 - 381 GHz limited by the Gunn oscillator tuning range (95-125 GHz). The mixer itself has a broader bandwidth 260-385 GHz.

The cryostat is a hybrid closed-cycle system using 2 independent helium systems, a Gifford Mac-Mahon 2-stage refrigerator, together with a Joule-Thomson refrigerator previously used in the SEST telescope. The 2-stage gives a temperature of about 70 K and 15 K for the outer shields. The Joule-Thomson circuitry cools the helium gas further where it condensates with a slight overpressure (about 4.5 K). The cooling takes usually about 12-15 hours.

Fig. 2. View of the receiver after installation in the Apex telescope.

B. *Receiver optics*

The optics of the telescope consists of 11 mirrors, the main dish, the sub-reflector, 4 mirrors in the cassegrain cabin and 5 mirrors in the cabin A. The first mirror after the Nasmyth flange is rotating along the elevation axis in order to select different instruments placed in the Cabin A. The second mirror is also rotating (Fig. 2) and it allows selecting the channel of the receiver. At present, we have 2 channels in the receiver, and for the final facility receiver, a 6-channel system will be built. The last 2 cold mirrors are inside the cryostat. Figure 3 shows the inner part of the receiver with the optics for the 2 channels.

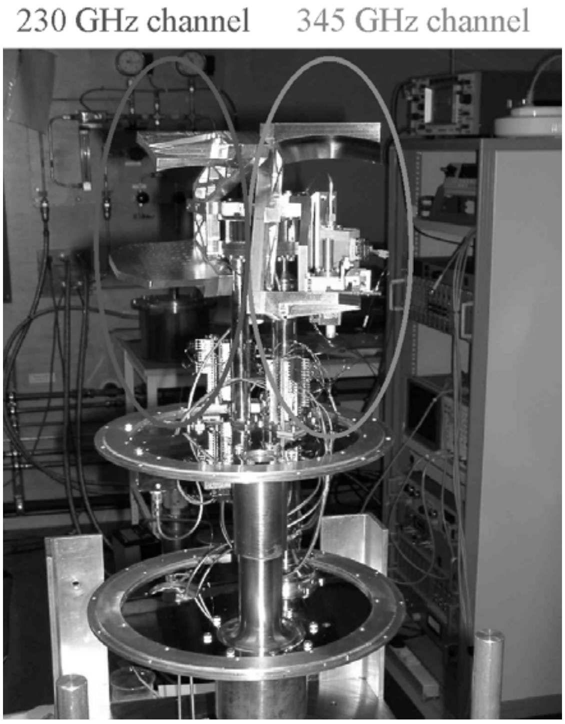

Fig. 3. View of the inner part of the cryostat.

Fig. 4 shows the Gaussian beam propagation inside the receiver cold optics. The 4 K cold plate can be seen together with the mixer bracket with the mixer block, the 4-8 GHz isolator and the LNA.

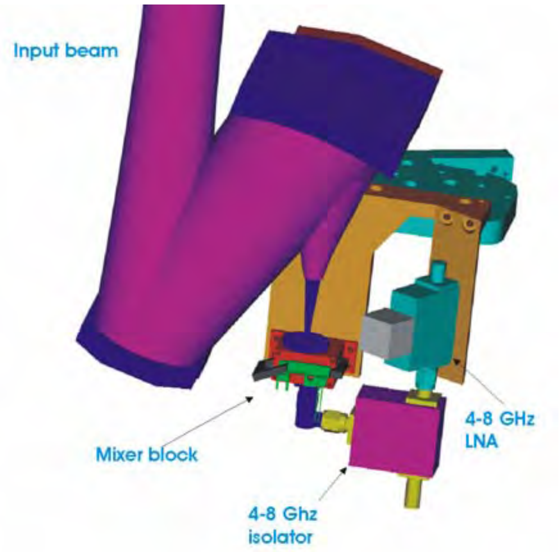

Fig. 4. Receiver optics inside the cryostat for the 345 GHz channel.

C. *Mixer Design*

1) *Mixer layout*

The mixer design is based on a novel waveguide-to-microstrip transition with an integrated wideband bias-T [4]. The novelty of this probe comes from the fact that it couples the input waveguide signal to the SIS junction via a radial probe [5] (see Fig. 5) while having an isolated port at the opposite side of the substrate where the IF signal can be extracted and DC current can be injected to bias SIS junctions or suppress Josephson current. This design is optimized for a full-height waveguide, therefore with reduced RF losses and easier machining, which are important advantages becoming especially crucial for mm and sub-mm frequency waveguide components with extremely small dimensions and high losses. The waveguide dimensions chosen for the mixer are 380 x 760 μm^2. The mixer chip uses a 65 µm thick crystalline quartz substrate. The microstrip RF chokes 1 and 2 in the Fig. 5 are of a hammer type to minimize space. The thin-film superconducting microstrip lines used for the SIS integrated tuning circuitry are placed on 400 nm layer of SiO_2 sputtered on top of the RF choke 2, which acts as the ground for the tuning circuitry

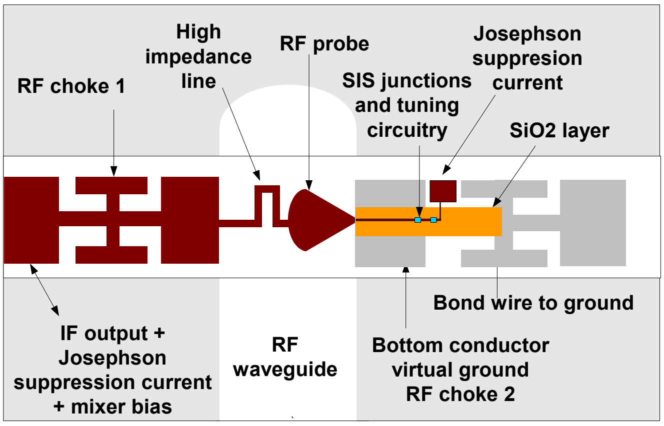

Fig. 5. Mixer chip layout.

2) *Josephson effect suppression*

One of the main motivation to use this novel layout for the mixer chip was to have an additional port available to apply a DC current through the wiring superconducting lines as demonstrated in [6]. This current creates a localized magnetic field parallel to the plane of the SIS junction and therefore suppresses the Josephson effect. The standard solution to suppress the Josephson effect in SIS junctions is to use external solenoids, usually employing a superconducting wire. For the sideband separating [7] or balanced mixers, that we intend to have for the final version of the APEX telescope heterodyne receiver, the SIS junctions will be at a very close distance (typically about 1 mm spacing). Thus, using exclusively superconducting coils to suppress the Josephson effect would not provide an independent suppression of the Josephson current in adjucent SIS junctions simultaneously.

The main advantage of the used type of Josephson suppression circuit is its compactness as it uses the existing superconducting lines from the SIS integrated tuning circuitry. Unfortunately, first results on the suppression of the Josephson effect using the control line indicated that we couldn't reach the first null in the sin(x)/x dependence of the Josephson current. A field higher than 60 Gauss is required to reach that null, or according to our measurements a current over 50 mA is required. The highest current that we could apply before a part of the superconducting circuitry switched to the normal state was between 20 and 40 mA depending on the chip. This limit is due to weak points in the design where a very narrow line (4 µm) goes through different steps in height, where its thickness is probably very little; therefore the critical current at those points is reduced. Our future designs will take into account this fact so the control line can work as expected.

One solution was to use a pair of permanent magnets that create a magnetic field strong enough to get closer to a minimum and then to use the control line to fine-tune the magnetic field. However, for the installation of the receiver we used an external solenoid (from a commercial relay), thermally decoupled from the mixer block, with iron-made magnetic concentrators. The required current to get to the first null was about 3-4 mA only. The solenoid resistance is about 200 Ohms; therefore power dissipation was not an issue.

3) *Mixer chip design*

Three different chip designs were fabricated differing in the probe RF impedance (either 30 Ohm or 60 Ohm). The calculations of the probe impedance were done using High Frequency Structure Simulator (HFSS) [8]. To tune out the junction capacitance, the first design uses a single junction with a parallel inductive line whereas the other designs use twin junctions scheme where two SIS junctions are connected through a short inductive line [9, 10]. The remaining resistive part is matched to the RF probe by a $\lambda/4$ transformer. Mixer design parameters are described in more details in [11].

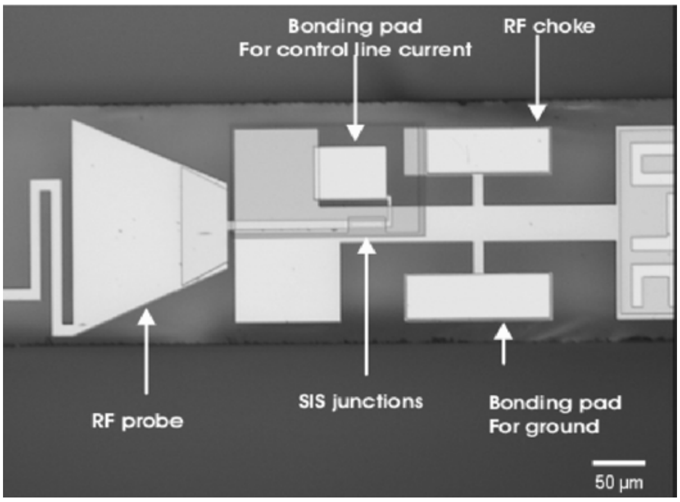

Fig. 6. Optical microscope view of a chip using an RF probe of 30 Ohm impedance

4) SIS fabrication

The SIS junctions were fabricated by in-house process using Chalmers MC2 clean room facility and dedicated cluster sputter tool. The Nb-AlOx-Nb SIS junctions are designed to have an area of 3 μm^2 and with a normal state resistance Rn = 7 Ω. The chips were fabricated on a 65 μm thick crystalline quartz substrates glued on a 250 μm 1” square substrate. The process flow for the SIS chips was based on Nb/Al-AlOx/Nb trilayer technique [12], which proved to provide the most reproducible properties of the SIS junctions. The yield is higher than 85 %, with Rn having the specified value and with deviations of less than 10 %. The actual area of the junctions was somewhat smaller (2.4 μm^2) implying a critical current density Jc of 9 kA/cm^2. The sub-gap to normal resistance ratio is typically of 20-25 at 4.2 K.

5) Mixer block

The mixer block was fabricated using Copper-Tellurium alloy and the split-block technique to facilitate machining. The mixer chip is placed in a 130 μm-deep channel milled in one half of the mixer block. The probe was designed to be slightly offset so that the mixer sits in the bottom of that channel and there is 65 μm air-gap above the quartz substrate. Therefore the other half of the mixer block doesn’t need to have a channel and this eases the fabrication. The chip size is 1 mm x 200 μm x 65 μm. A very thin layer of gold (2 μm) is plated onto the mixer block to allow wire-bonding. The IF circuit integrated in the mixer block comprises a bias-T and 20 Ohm-to-50 Ohm IF transformer on an alumina substrate, which is placed on the same half of the mixer block. Three bond wires connect the mixer chip to the circuitry on the alumina substrate. The DC circuitry for the SIS biasing is placed on the backside of the mixer block half. The mixer block also includes a transition from rectangular to circular waveguide.

D. The 4-8 GHz cryogenic LNA

Nowadays, radio telescope receivers typically employ IF amplifiers with 1 GHz bandwidth. But with the increasing interest for sub-mm observations, larger bandwidths are required for broader spectral line and continuum observations of extragalactic sources. The selected IF band was 4-8 GHz and a 4-8 GHz LNA was developed in GARD group [13]. This LNA uses commercial GaAs HEMTs and when measured at a cryogenic temperature of 12 K, gives gain of 26 dB and a noise temperature of 5 K with a total power consumption of 12 mW (optimized for the best noise performance). With the power consumption minimized to 4 mW, the amplifier has 24 dB gain and the noise temperature degrades only to 6 K. Figure 7 shows measurements for 12 pieces of this LNA showing consistency of the performance. raise

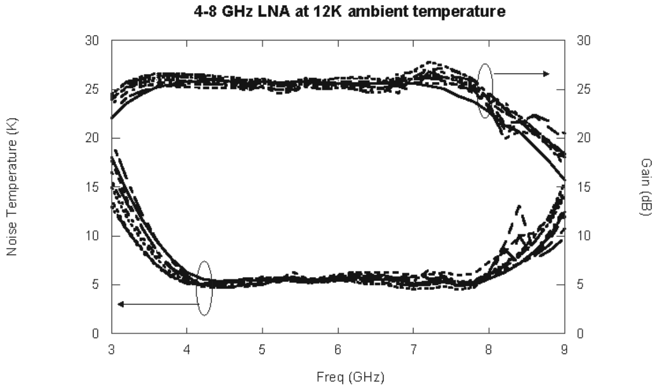

Fig. 7. Performance of series of 12 LNA, 4-8 GHz.

E. The local oscillator

Figure 8 shows the LO chain. The local oscillator incorporates mechanically tunable Carlstrom Gunn oscillator for 96 to 125 GHz. It can be tuned down to 95 GHz if necessary. The output power is typically above 30 mW. The Gunn is Phased-Locked with a reference signal of 400 MHz. The self-biased tripler is from Virginia Diodes, giving a typical output power of 0.5-2 mW. The LO uses a conical feed-horn with refocusing lens and a flat mirror; LO signal is injected through a 12 μm Mylar beam splitter giving about 1-2 % coupling.

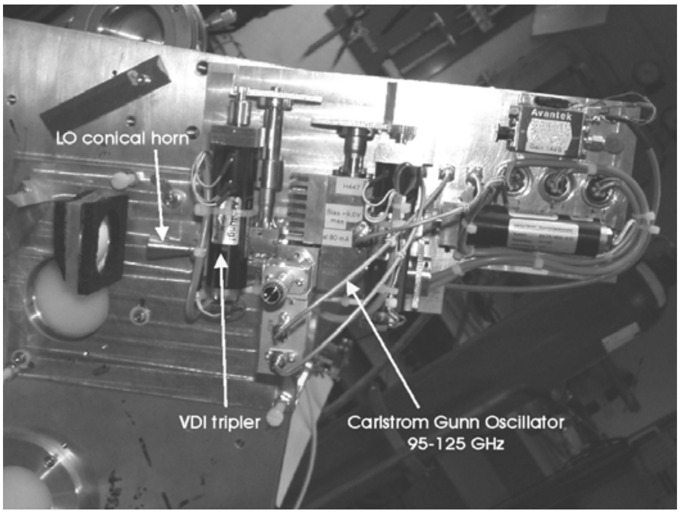

Fig. 8. LO source comprising a Gunn oscillator and a tripler.

III. Receiver Performance

A. Noise temperature measurement in lab

Noise temperature measurements were performed with the Y factor technique using a hot (293 K) and cold load (77 K) in front of the input window. Fig. 9 shows the uncorrected noise temperature achieved for different mixer blocks with different junctions when measured in a laboratory test Dewar. We used a BWO LO for frequencies between 220–380 GHz. Results show a noise temperature of 30-50 K across almost all of the frequency range, increasing to 60 K at the high frequency end for 2 mixers. Two different wafers were produced and the junctions selected were completely randomly chosen within these wafers. Having so repeatable results ensures that the design is remarkably insensitive to small differences in the mixer blocks dimensions and to the junction's parameters.

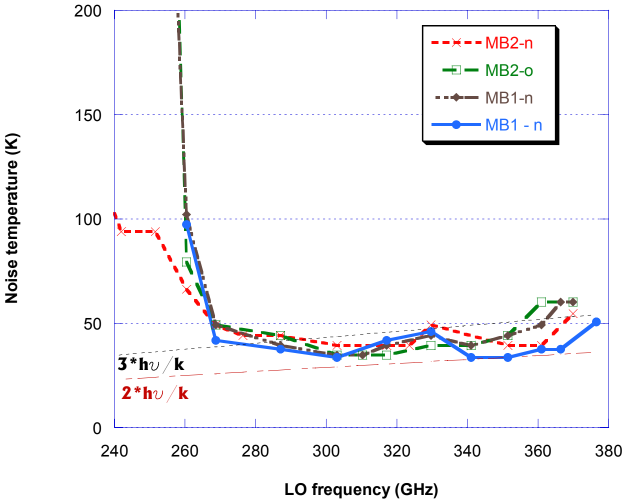

Fig. 9. Uncorrected receiver noise temperature for 4 mixer blocks with twin junctions measured in a lab test cryostat.

The mixer block MB1-n, the lowest curve in the Fig. 9, was selected to be installed in the First Light receiver.

B. *IF noise temperature*

Fig. 10 shows an example of noise temperature measurement across the IF band at an LO frequency of 351 GHz corresponding to a signal frequency centered at 345 GHz, which is the rest frequency of the rotational transition 3-2 of CO, one of the most important lines in our frequency range. The noise temperature is reasonably flat for an IF band of 3.8-7.6 GHz, not far from the designed IF band of 4-8 GHz.

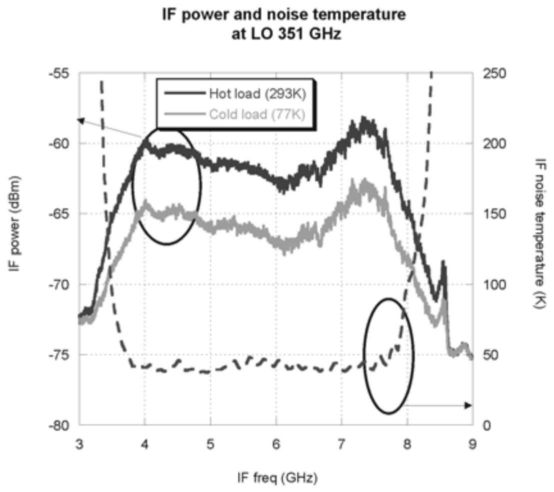

Fig. 10. Measured uncorrected noise temperature for the receiver across the IF band at 351 GHz.

C. *Receiver saturation*

The saturation was measured using two different techniques. The first one uses a variable temperature load. The temperature of the load can be varied from –30 C to +100 C and the IF output power is recorded for various input load temperatures. At the lower frequency end (LO of 290 GHz) where the saturation is expected to be highest, it appears to be no noticeable saturation; there is about 1.5 % saturation. The accuracy of this method is mainly set by the accuracy of the load temperature measurements. Multiple temperature sensors are used across the load. Apart from the temperature sensors accuracy (± 0.3 K), gradients of temperature are limiting the accuracy. Very roughly the saturation error is given by $\Delta T*2$ %, so an error of 1 K in the hot load physical temperature measurement translates into 2 % added error.

The second method uses a scheme described by A. R. Kerr et al. [14] using a weak CW test signal introduced through a beam splitter while the receiver input is switched between liquid nitrogen and room temperature loads. The CW signal incremental gain compression can then be measured and through the calculations the large signal gain compression is estimated. A summary of the results using the CW signal method is given in the following table:

LO freq	Incremental gain compression	Large signal gain compression
291 GHz	5.4 %	3 % ± 2 %
300 GHz	4.7 %	2.8 % ± 2 %
318 GHz	3.3 %	1.7 % ± 2 %
351 GHz	3 %	1.5 % ± 2 %

Here the accuracy is limited by how well we can resolve the peak value, which is ± 0.1 dB, corresponding to an error of ± 2 %. Therefore, both methods are consistent in that the saturation values are lower than 5 % and are within the measurement error, which is of about ± 2 %.

D. *Receiver stability*

The total power receiver stability was measured, using a set up with 600 MHz filter centered at 6 GHz. Depending on the measurement data, the Allan time [15] varies from 30-100 seconds. Fig. 11 shows example of the measured data.

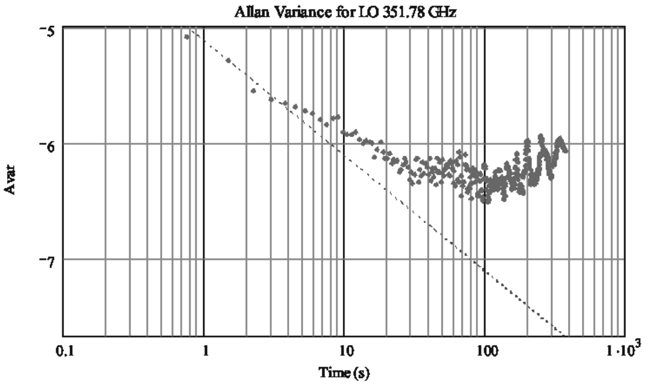

Fig. 11. Example of Allan stability measurements.

IV. CONTROL SYSTEM

The receiver was designed to be entirely remotely operated, and thus the tuning procedure to be fully automated. with the entire tuning procedure to be done remotely through a computer. The tuning is based on the use of tuning tables. First the local oscillator is set using rough values in tuning tables, the PLL is locked and then the tuning motor is adjusted to have the Gunn bias to the optimum value. After that the SIS is biased to its optimum value. The mixer performance is quite insensitive to small variations of tuning values. The magnetic coil current is set to a value close to 15 mA, which is about the 4th minima in the Josephson current versus coil current relation. We need to go that high because the twin junctions behave SQUID-like and therefore it is much more sensitive to the applied magnetic field. Possible small differences between the two junctions make the use of the first minima more difficult.

Fig. 12. View of the receiver control system, together with a test notebook.

A newly developed SIS bias supply provides bias to the mixer within the requited -10 to +10 mV range with accuracy of setting better than 5 μV. To decrease interferences and the effect of grounding loops the mixer is biased by a floating power supply. Setting to a given voltage is done via digital output module in the control rack that sends a pulse TTL signal. This signal goes through an opto-coupler to three cascaded 4 bits counters, which are forming 12-bit word. This word is then fed to a 12-bit DAC set in bipolar mode (-5 to +5 V). Each successive pulse increases (or decreases) the DAC output with 2.4 mV. A 3 K and 10 Ohm resistors circuitry inside the mixer block forms a voltage divider, which provides the -10 to +10 mV DC voltage bias range on the SIS junction.

V. CONCLUSION

A 279-381 GHz SIS receiver was designed, built, tested and installed on the APEX Telescope in Northern Chile. The receiver noise temperature as measured in the labs is between 30-50 K across the entire frequency range. The IF band is from 3.8-7.6 GHz. The receiver saturation was measured to be less than 5 %, and the receiver total power Allan variance time was measured to be between 30 and 100 seconds for a BW of 600 MHz. Installation on the APEX telescope in Atacama Desert, Chile, was made in April 2005, with the planned technical and scientific commissioning in May-June 2005. The receiver should be available to the astronomical community from September 2005. Future development is to combine two of these DSB mixers to produce a sideband separation mixer. ACKNOWLEDGMENT

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