Heterodyne Array Development at the University of Arizona

C. Groppi, C. Walker, C. Kulesa, The University of Arizona

G. Narayanan, The University of Massachussetts

K. Jacobs,U. Graf, R. Schieder , Universitat zu Koeln

J. Kooi, California Institite of Technology

ABSTRACT

Over the past four years, SORAL and its colaborators have been developing two SIS heterodyne array systems for astronomical telescopes: the PoleStar 4 beam arr ay for the 850 GHz atmospheric window, and DesertStar 7 beam array for the 350 GHz atmospheric window. PoleStar was delivered to the AST/RO telescope at the South Pole during the austral summer of 2000, and is now in normal operation. Desert Star is undergoing lab testing and engineering on the Heinrich Hertz Telescope now. We will present an overview of the system designs, techniques for local oscilator multiplexing, bias control, optics, cryogenics and results from system characterization and commissioning. Techniques used in the construction of these arrays are being extended, with the ultimate goal of building fully integrated heterodyne arrays with hundreds of pixels.

PoleStar: An 810 GHz Array Receiver for AST/RO

A 4-pixel array receiver constructed to operate in the astrophysically important 810 GHz atmospheric window was assembled and tested at the Steward Observatory Radio Astronomy Lab (SORAL) and installed on the Antarctic Submillimeter Telescope and Remote Observatory located at the South Pole (AST/RO) at the South Pole (Groppi et al. 2000). The cold, dry conditions at the South Pole, coupled with its relatively high altitude (~10,500 ft.) make it an excellent location for observations at submillimeter wavelengths. AST/RO has a 1.7 m aperture and was designed to take advantage of these conditions (Stark et al 2001). The almost ideal atmospheric conditions and the resulting observing ef cienc y available from the South Pole motivated us to build an 810 GHz

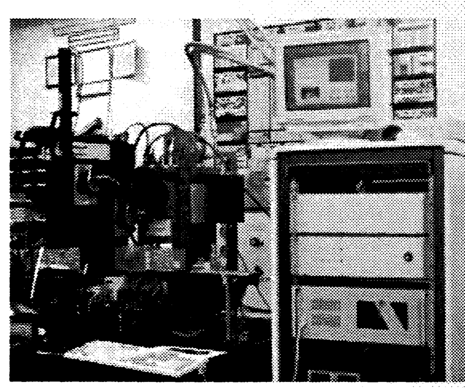

Figure 1: PoleStar in the lab during front-end testing.
All system electronics t into a single transportable equipment rack. A He-Ne laser is mounted on the optics plate here for optics alignment.

array for use on AST/RO. Figure 1 is a photograph of the receiver front-end as it appeared in the lab before deployment.

Pole Star Optical Design

The purpose of the optical system is to re-image AST/RO's focal plane onto a compact 2x2 array of lenses located in the array cryostat and to ef ciently inject local oscillator power into each mixer. Focal plane re-imaging is achieved by a pair of parabolic mirrors and two ats. A quasi-optical LO power divider is used to split the focused LO beam into 4 equal parts. The power dividing is accomplished by two, low-loss, ~50% crystalline quartz beam splitters. Each beam splitter is paired with a at mirror to give the emerging beams the proper horizontal and vertical offsets. After including all loss mechanisms, we estimate that 18% of the incident LO power is in each LO beam at the output of the power divider.

LO diplexing is handled with a 0.5 mil Mylar beamsplitter. A 2x2 array of HDPE lenses then focuses the beams into the mixer feedhorns. Initially, we used a Martin-Puplett interferometer as an LO diplexer, but we later decided to replace it with a simple Mylar beamsplitter. While the MPI theoretically couples 100% of both the LO and sky power, they are very sensitive to misaligned beams. Even a 0.5 degree beam squint can cause 3 dB of loss in both LO and sky power, adding close to 600K of noise (Martin et al. 1977). The Mylar diplexer is not sensitive to mixer squint, and adds very little loss as long as the Mylar thickness is kept small.

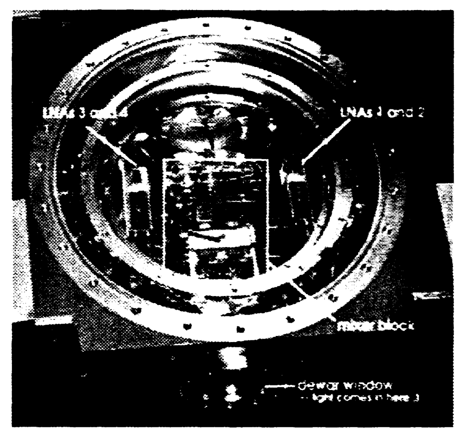

Figure 2: The inside of the PoleStar cryostat.
The 4 L-band Low-Noise IF ampli ers are mounted on the 15K radiation shield, and the mixers, lenses and bias tees are mounted on the 4K working surface.

JPL Local Oscillator

The rst major upgrade to PoleStar was the replacement of the LO chain with whisker contacted multipliers with a state-of-the-art planar diode LO chain with 100 GHz power ampli ers before the rst doubler . This LO chain uses multipliers developed for the Herschel HIFI project, designed and built jointly by JPL and UMass (Mehdi et al. 2003). The source is a 100 GHz Gunn Oscillator from J. Carlstrom. This is followed by two 100 GHz power ampli ers in series, then a 200 GHz doubler , a 400 GHz doubler and an 800 GHz doubler. The multipliers are self biased and tunerless. Measured power output at the operational frequency of 807.3 GHz is in excess of 250 μW. After the LO upgrade, it was possible to saturate all the mixers using only a 0.5 mil Mylar beamsplitter. In addition, the self-biased tunerless operation makes the system much easier to use for the winter-over operators. Figure 3 shows the JPL/UMass LO chain installed on PoleStar.

Cryostat

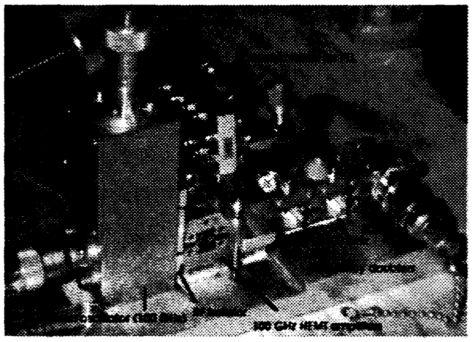

Figure 3: The JPL/UMass LO chain added to PoleStar.
This was added during the Austral summer of 2001. This chain puts out 0.25 mW at 807.3 GHz, enough to saturate all the mixers with a 0.5 mil thick Mylar LO diplexer. This LO chain is based on Herschel HIFI technology, using planar tunerless multipliers and 100 GHz power ampli er modules.

The Pole STAR cryostat (Figure 2) was constructed by Precision Cryogenics and is based on the successful Caltech Submillimeter Observatory (CSO) hybrid design. It uses a CTI model 350 coldhead to cool the outer and inner radiation shields to ~77 and ~12 K, respectively and a 4 liter liquid helium can to maintain the mixers at their operating temperature. This same basic design is used for all AST/RO and CSO receivers. In the single pixel AST/RO receivers, 30.5 mm diameter, Te on coated, crystalline quartz windows are used at 300 and 77 K. Zitex is used as the IR lter on the 12 K radiation shield. With a good vacuum, hold times of ~6 days can be achieved. At 77 K, we use an additional layer of Zitex. For the 300K vacuum window, we use a 0.3 in. thick z-cut crystalline quartz vacuum window with polyethylene anti-re ection coating, and diamond dust coating on the inner surface to reduce thermal load. While polyethylene is not as good an anti-re ection coating as Te on for crystalline quartz, it is easy to apply, robust and inexpensive. This window is based on the design successfully used on the SPARO polarimeter used on the VIPER telescope also at the South Pole (Dotson et al. 1998). This window has virtually no loss at 810 GHz, and dramatically improved the dewar hold time and vacuum compared to earlier windows. With all 4 mixers and ampli ers mounted in the cryostat, the measured hold time is ~3 days.

Mixers

The SIS mixers used in PoleStar were made by KOSMA. Each mixer uses a Potter horn with a circular to half height rectangular waveguide transition to couple radiation to a Nb SIS junction. The junctions achieve low noise (~450 - 650K) performance through the use of an on-substrate Al tuning structure and a x ed waveguide backshort. The mixers have embedded magnets to suppress the Josephson effect. A four-wire bias system is used to ensure stable operation of the mixers. The inductive stub tunes out the capacitance of the SIS junction over the entire operating band, eliminating the need for mechanical backshort and E-plane tuners. Each mixer is extremely compact, with a small, square cross-section allowing easy stacking in recilinear arrays. A novel magnet probe design with a rearmounted electromagnet spool allows the mixers to be packed directly against each other. These mixers are prototype designs for the KOSMA effort to build mixers for Herschel HIFI instrument's band 4. Developments pushed by this effort promise to reduce mixer noise temperatures to below 300K at 800 GHz in the next few years.

Pole Star Array AOS

The Array AOS (aAOS) built by KOSMA provides four independent spectrometer channels, each with ~1 MHz of spectral resolution over a 1 GHz bandwidth. At 810 GHz, these numbers translate to 0.37 and 370 km/s respectively. It uses a single laser, a 4-channel, lithium niobate Bragg cell, and a custom CCD to achieve its performance parameters. The aAOS has been successfully tested on the IRAM 30m and CSO. This spectrometer also bene ts from K OSMA's contribution to the Herschel HIFI instrument, through their contract to provide a multi-channel spectrometer system for the instrument (Schieder et al. 2003).

Pole Star Bias Control Hardware

The SIS junctions, the electromagnets used to suppress quantum-generated mixer noise,and the Low Noise Ampli ers (LN As) all require noise-free, accurate electrical biasing for reliable operation. On single-pixel receivers, providing the appropriate biasing voltages and currents is handled adequately by individual boxes with manual potentiometers and LCD panels on the front. With the advent of array receivers, however, the sheer number of boxes required makes this kind of control impractical. The PoleStar bias system uses proven circuit design used on single pixel receivers at AST/RO and the Heinrich Hertz Telescope. We replace the manual potentiometers in these designs with a Xicor digital potentiometer, and package 4 channels of bias on a single Euro 96 card. These modular 4 channel cards can be plugged into a backplane in a 19" equipment rack, allowing easy extensibility. All digital communications with the bias system are done through a bidirectional optically isolated connection with the control computer. The I^2C bus used for digital communications has a separate clock line. The digital lines, including the clock, are only active when changing a bias setting. The voltages and currents for the SIS junctions, magnets and ampli ers, the total po wer from the 4 channel total power box and the cryostat temperature information are read through a A/D card in the control computer. Signals from the bias system are multiplexed with Burr-Brown analog multiplexers, and read through a single BNC output.The I^2C signals needed by the electronics is generated at the parallel port of an otherwise normal rack mounted PC running the Linux operating system. An Intelligent Instrumentation PCI-20428W multi-purpose Data Acquisition (DAQ) card is used for non-I^2C control of the instrument.

Noise and stability measurements

Figure 4 shows the LO pumped IV curves of each of the three mixers currently functioning as of summer 2003, together with IF power sweeps. The fourth mixer has developed a super short and will be replaced during the Austral summer of 2003-2004. The red curve shows the IF power output when a HOT (290K) load is placed in front of the receiver. The blue curve shows the response with a COLD (77K) load After two seasons of upgrades, PoleStar is now working with noise temperatures close to those measured in the lab at Cologne with an optimized test receiver. After the installation of the new LO system with Mylar diplexer, the crystalline quartz window and properly leveling input power to both the total power box, up/down converter and aAOS, mixer noise temperatures are between 625K and 640K. Even with three pixels, the receiver is almost 15 times faster for mapping than WANDA, the single pixel 810 GHz facility receiver. Receiver stability measurements on Pole STAR were made by monitoring the IF output power of two of the receivers over ~1000 sec. The IF power variation was about 1 part in 1000 over this period.

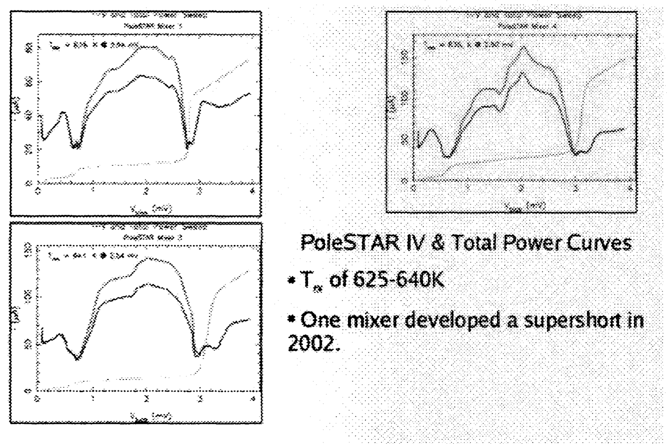

Figure 4: Post-upgrade IV and total power curves from the three functioning mixers.

First Light on AST/RO

Pole STAR was installed on AST/RO during a three week period from mid November to early December 2000. Figure 5 shows spectra taken with PoleSTAR in its latest con gu-ration, with all upgrades. Spectra from the three functioning mixers are shown, also towards NGC 6334. The instrument has been at the South Pole continuously since the Austral summer of 2000.

Lessons Learned

In the process of building, deploying and operating PoleSTAR, we have learned several lessons that we can apply to all our future designs of heterodyne array receivers. Several components in the initial PoleSTAR design did not work as expected, and advances in technology have allowed us to improve receiver performance and reliability. Initially, one of the most pressing problems in developing an array for high frequency operation was the dif culty of obtaining LO po wer. At the time PoleSTAR was deployed, our LO source produced only 40 μW of power. This forced us to use a MPI LO diplexer since we could not afford to waste any LO power. While theoretically capable of delivering 100% of both the LO and sky power, small optical misalignments destroy their performance. While other solutions exist, especially for a x ed tuned receiver (Silicon etalons, meandering waveguide feeds), advancements in LO technology made this problem moot. We have bene ted from the enormous de velopment effort created by work for the Herschel HIFI instrument, which has increased available LO power by almost an order of magnitude since PoleSTAR was deployed. The new, more powerful LO is easier to align and use, is more robust, and the optics simpli cations allo wed for an improvement of more than 500K in receiver noise temperature.

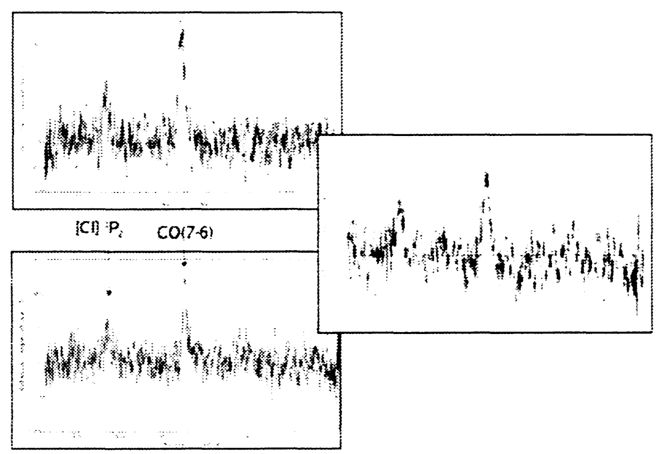

Figure 5: PoleStar spectra after upgrades.
Both [CI] and CO(7-6) are visible in all three spectra, taken during the Austral summer of 2002 toward NGC6334. Since no measurement of beam precession had been done, pointing is not known well for this observation.

PoleSTAR also went through three iterations of vacuum windows before we found one with suitable performance. Anti-re ec-tion coated crystalline (z-cut) quartz has the lowest loss of any material suitable for large diameter vacuum windows. Optimally, Te on is used for the AR coating because its dielectric constant is the closest to the square root of the quartz. At the time of deployment, no company we could nd w ould coat a vacuum window with Te on. We decided to make a window out of high density polyethylene (HDPE), 0.5 in thick with pockets milled out for each beam. A solid window would have unacceptable loss at 810 GHz. By milling pockets leaving a membrane of 2λ thickness behind, the window spanned the 4 in. window aperture, with acceptable loss. While this window did work, it added ~200K to the receiver noise temperature and was subject to cracking. We next tried a window made from ZoteFoam PPA-30 nitrogen blown Te on foam. This low dielectric constant material holds a vacuum, and has very low loss at 350 GHz. No measurements existed at 810 GHz, but the resulting window was very inexpensive and more robust than the HDPE window. We found the loss to be less, but this window still added ~150K to the receiver noise temperature. The loss of a slab of ZoteFoam rises rapidly above 400 GHz, possibly due to scattering off the foam cells. We nally chose a z-cut crystalline quartz window with polyethylene AR coating as discussed in section . This vacuum window cost over $3000 US, but is the only solution that offers good performance at 800 GHz over a 4 in. cryostat window aperture.

Desert Star: a 7 pixel 345 GHz Heterodyne Array Receiver for the Heinrich Hertz Telescope

DesertSTAR is a 7 beam, 345 GHz heterodyne array receiver for the Heinrich Hertz Telescope (HHT) on Mt. Graham, AZ. The instrument uses x ed-backshort Superconductor-Insulator-Superconductor (SIS) mixers with a broadband waveguide probe. Instantaneous bandwidths of 2 GHz can be achieved over the entire 345 GHz atmospheric window. A cryostat with a Joule-Thompson (JT) mechanical refrigerator allows continuous operation and 1.8W of cooling capacity at 4K, and provides the needed temperature stability for low-noise operation. Local Oscillator (LO) distribution is accomplished with a novel phase grating that yields high ef cienc y and power uniformity in a hexagonally symmetric geometry. The computer controlled bias system is an evolution of a proven design that is simple, portable to any computer platform, and readily extensible to over 100 channels. It provides control and monitoring of bias, temperature and vacuum from any X-windows capable machine, and writes an instrument status web page visible with any web browser. The 2 GHz Intermediate Frequency (IF) bandwidth allows the future addition of a wide-band backend optimized for extragalactic observations, with ~1700 km/s of velocity coverage. The system will increase mapping speed at the HHT by a factor of ~16 compared to the current 345 GHz receiver system.

Figure 6: A picture of DesertStar mounted on the right ange of the HHT .
This photograph was taken during an engineering run in June, 2003.

DesertSTAR was designed for use as a facility instrument for the Heinrich Hertz Telescope, located at 10,500 ft. on Mt. Graham in south-eastern Arizona. The telescope is a 10m Cassegrain design with Carbon Fiber Reinforced Plastic (CFRP) primary re ector panels and backup structure. The quadrupod and the subre ector are also CFRP. The CFRP construction provides very good stiffness, plus the temperature stability necessary to operate 24 hours per day (Baars et al. 1999). The surface of the main re ector has an RMS roughness of ~13 μm, measured with holography. DesertSTAR will be mounted on the right Nasmyth platform, bolted directly to the telescope ange. Figure 6 is a photograph of DesertSTAR on the right Nasmyth ange of the HHT during an engineering run in June, 2003. The ange opening itself limits the maximum number of pixels. With the 2Fλ spacing of the pixels in DesertSTAR, the outer beams clear the ange at the 4 ω level. The beams on the sky are 22" FWHM, with 44" center-to-center spacing, arranged in a close packed hexagonal arrangement. This con gu-ration maximizes the number of beams through telescope ange on the HHT , while still preserving ~20 dB isolation between pixels.

Optics

Given that an array receiver is already a very complicated system, we chose to make the optics of DesertSTAR as simple as possible. Experience with the PoleSTAR 810 GHz array has shown that in practice, complex optical circuits are dif cult to implement in practice with array receivers. With an array architecture based on individual mixers mounted in the focal plane, it is dif cult to control the beam boresight to the required tolerances. Other arrays, like CHAMP (Gusten 2000) and SMART (Graf 2000) have gone through great pains to ensure alignment of optical components and mixers. We have chosen to eliminate all optics from the system that require extremely tight tolerances on mixer beam boresight, and minimize the number of lenses and mirrors. The beam from each diagonal horn is matched to the telescope with separate High Density Polyethylene (HDPE) lens mounted directly to the mixer housing, decreasing the chances of mixer squint due to horn-lens misalignment. The beams then re ect off a single, cold 45 at mirror and directly illuminate the at tertiary of the telescope.

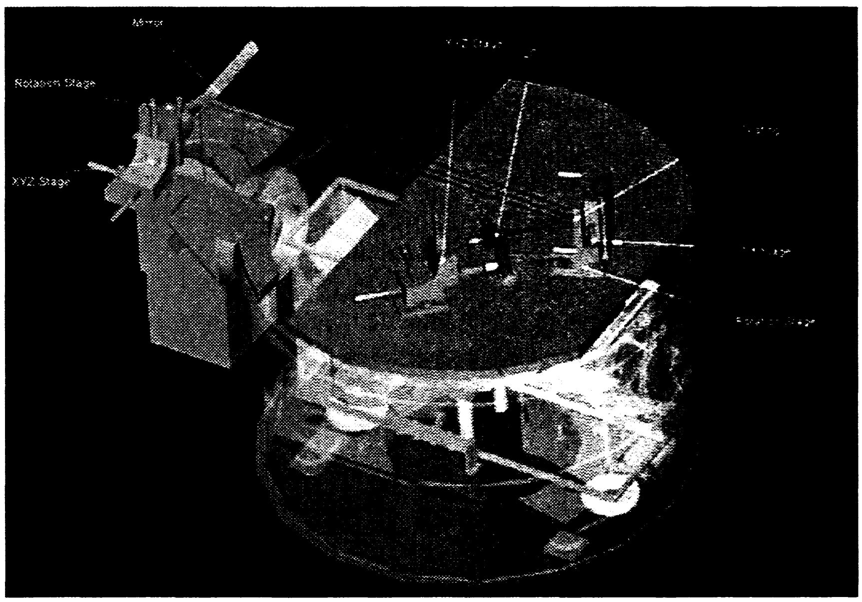

Figure 7: A cutaway CAD drawing of DesertStar.
This shows the LO distribution optics, mixer array and internal at mirror . Since the beam bundle is not crossed anywhere in the system, optics complexity is minimized. Figure courtesy Dathon Golish.

Most designs use a curved mirror to cross the beam bundle at the location of the vacuum window to minimize window size and then use another curved mirror to parallelize expanding beams. We chose to keep the beams parallel throughout at the cost of increased vacuum window size. A new material, ZoteFoam PPA-30, made it possible to construct a 4.5 in. clear aperture vacuum window with extremely low loss and good vacuum properties. ZoteFoam PPA-30 is a closed-cell polyethylene foam blown with dry nitrogen gas. A 1" thick window 8" in diameter (1.75" glue surface, 4.5" clear aperture) is suf cient to hold vacuum with no other materials present, with acceptable de ection under v acuum, and no noticeable helium permeability or outgassing problems. While loss is signi cant at high frequencies, the performance from 300-400 GHz is quite good. The transmission of the DesertStar window is 96%-98% from 300-400 GHz, adding noise of ~10K. This is about twice the added noise of a 0.5 mil Mylar window or a Polyethylene coated crystalline quartz window, but can span large openings and is economical. It has been in use as a window material in an instrument at the South Pole (AKBAR) for over two years with no reliability problems (Kuo et al. 2002).

Local Oscillator

Local oscillator power delivery is another dif cult problem for array receivers. LO power must be ef ciently and equally divided into each pixel. While many waveguide techniques are available, they are complicated, dif cult to implement and lossy at high frequencies. Quasi-optical techniques can also be lossy and complicated, with dif cult alignment issues. Recent work by the Cologne and MPIfR groups in Germany have lead to the development of both transmissive and re ecti ve phase gratings that form multiple LO beams from a single input beam through diffraction.

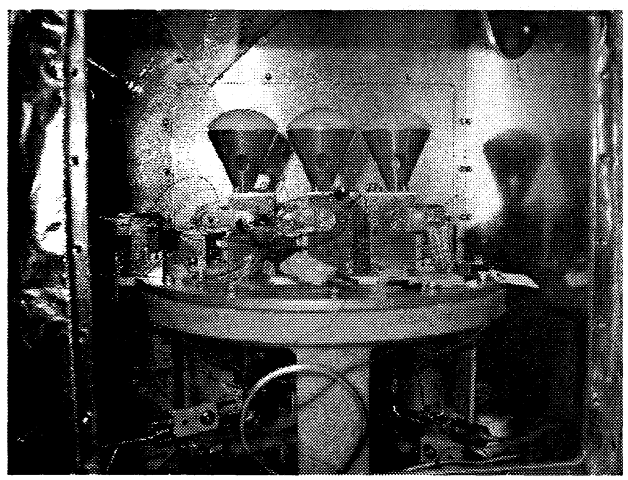

Figure 8: A photograph of three mixers installed in the JT cryostat before testing.

Our LO distribution system uses a novel re ecti ve grating design from the University of Cologne (Heyminck et al. 1998). This design creates a 7 beam array with hexagonal symmetry with 80% ef cienc y and is superimposed on a parabolic mirror. This optic then acts as a collimating mirror for the LO beam, and also forms the 7 beam array. The phase grating has an operational bandwidth of ~10% centered on 345 GHz. A simple Mylar beamsplitter acts as the LO diplexer. Figure 7 is a cutaway CAD drawing of the LO optics and receiver optics.

Cryogenics

DesertSTAR was designed to allow for cooled optics and have room for a second subarray. To achieve these goals, we designed a cryostat, with a 28" cold plate, a large 4K volume for cold optics, and a large 4K cooling capacity. The cryocooler is based on the proven NRAO JT refrigerator, used for the facility receivers at the NRAO 12m telescope. The unit has a 180W capacity at 77K, a 1.8W capacity at 4K, a 20K helium precooler stage and a self-cleaning JT expansion valve. The refrigerator is mated to a commercial Balzers cold head, and driven by a custom NRAO compressor. Cooldown tests show stable 4K operation is achieved in ~13 hours. In addition, we have used a resistive heater on the 4K cold plate to measure a cooling capacity of 1.44W. This measurement was made with full infrared (IR) loading on the cold plate. Calculations show that the total heat load including amps and infrared loading is 0.9W. The IR heat load is dumped to the 77K shield with a Gore-Tex GR IR lter . Since cryogenic testing began in 2000, we have experienced no failures of the cryogenic system.

Mixers and Cold Electronics

DesertSTAR uses 7 independent single ended mixers, each mounted together with a HDPE lens, isolator and ampli er in a modular rock et, which is cooled by the JT refrigerator via a cold nger . The simple, single ended waveguide design uses a diagonal feedhorn to couple the telescope beam through a multi section impedance transformer to half height waveguide. The waveguide backshort is x ed and there is no E-plane tuner. The cross-guide probe uses the proven suspended stripline design of Blundell & Tong (Blundell et al. 1995). The Nb SIS junctions were designed with an on-chip tuning structure for low return loss across the atmospheric window, permitting a x ed backshort.The optimum backshort position was determined via HFSS modeling. The diagonal horn was chosen because it could be readily made with the UMass micro milling machine. While their coupling to the fundamental gaussian mode is less than a scalar corrugated horn, diagonal feedhorns still provide adequate broadband performance at a fraction of the cost (Johansson et al. 1992). The beam pattern is gaussian, but the diagonal horn has about 14% crosspolarization, lowering it's ef cienc y when used in combination with a linearly polarized input signal. A 4-wire bias tee is mounted in the mixer block, and monitors junction voltage and current

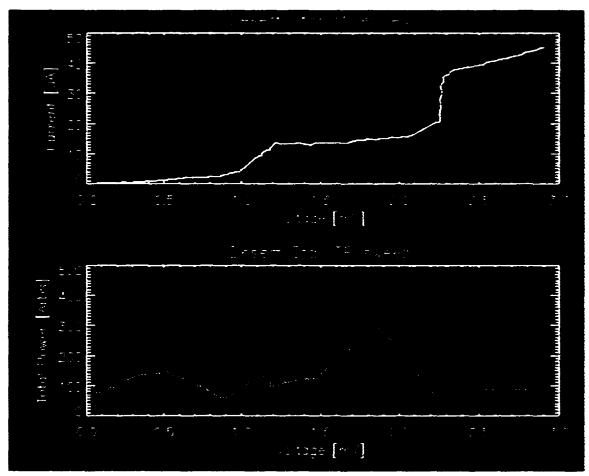

Figure 9: Representative IV and hot/cold total power curves.

with a precision current-sense resistor. Return loss is better than -20 dB from 4-6 GHz and leakage is less than -40 dB. Insertion loss is ~0.1 dB. The mixer produces a 4-6 GHz IF, and is connected via a Pamtech cryogenic ferrite isolator to a Miteq 4-6 GHz cryogenic low noise ampli er (LN A). Losses of the bias tee and isolator are less than 1.5dB from 4-6 GHz, as measured via vector network analyzer. The Miteq ampli ers ha ve 27 dB gain, less than 1 dB passband ripple, 30 mW power dissipation and a measured noise temperature of 7K at 4K operating temperature. The ampli ers require only a single, unipolar 0.6V bias, greatly simplifying the wiring and bias supplies. A simple superconducting coil electromagnet provides the necessary magnetic ux to minimize Josephson noise with soft iron eld concentrators embedded in the mix er block. Figure 8 shows the mixer array inside the cryostat with 3 mixers installed.

Backends

The HHT is currently upgrading the telescope control system and backend electronics for all receivers. As a part of this effort, a modern, e xible lterbank spectrometer with a 2x1 GHz bandwidth and 1 MHz resolution is being constructed. The IF processor for this backend can process 8x256 MHz IF sub-bands for use with DesertSTAR. This bandwidth and velocity resolution is adequate for a large variety galactic astronomy projects. The lterbank should provide extremely high stability without the platforming problems often associated with hybrid correlators. During the fall, 2003 season, we will operate the receiver in three pixel mode using the existing facility acousto-optical spectrometers and chirp transform spectrometers.

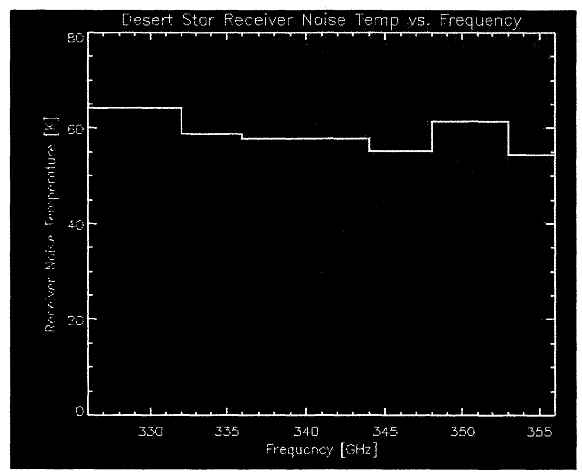

Figure 10: Receiver noise temperature (Mixer 1) as a function of LO frequency.
Noise temperature is relatively at from 326-356 GHz, as expected from simulation.

Preliminary Results

Initial tests of a single array mixer/IF chain have been conducted in an IR Laboratories $LN_2/^4He$ cryostat. The test system uses a 0.5 mil Mylar LO diplexer, a 1.0 mil Mylar cryostat vacuum window, and a single layer of Zitex A for IR ltering. The rst prototype mixer has a very long backshort channel, that is then shortened to the proper length with aluminum shim stock. This allows some adjustability of the backshort position. All other mixers were fabricated with a machined, non-adjustable backshort. A room temperature total power box and a Hewlett-Packard power detector were used for the Y-factor measurements. The bias control system interrogates the output of this meter to allow total power vs. bias voltage sweeps. Before mounting a device in the mixer block, we tested ~20 devices using a dipstick inserted into a liquid helium storage dewar. Of the ~20 devices tested, only 3 were nonfunctional, and the remaining devices appeared to be virtually identical. The device mounted in the test block was randomly selected from the good devices.

Test Receiver Performance

Figure 9 shows a pumped I-V curve of the test mixer, along with hot and cold total power curves. The bias system uses the slope of the supercurrent at 0V to measure the contact resistance, and then remove it from the I-V curve. We measured R_n~48.5 Ω, a leakage current of ~3 μA and a transition voltage of ~2.3 mV. Optimum bias voltage for the highest Y-factor was ~1.6 mV. Uncorrected receiver noise temperatures as a function of LO frequency are plotted in Figure 10. We expect T_{rx} to remain fairly constant from ~300 GHz to ~390 GHz. Preliminary measurements indicate receiver temperatures between ~55K and ~65K across the available band, with fairly at response, as shown in gure 20. These are uncorrected noise temperatures, and include the losses of the LO diplexer, window and unmatched lens, along with noise from the IF chain. The LO source used in the test was unable to tune below 326 GHz or above 356 GHz, so we could not measure the receiver temperature over the full band of the waveguide probe.

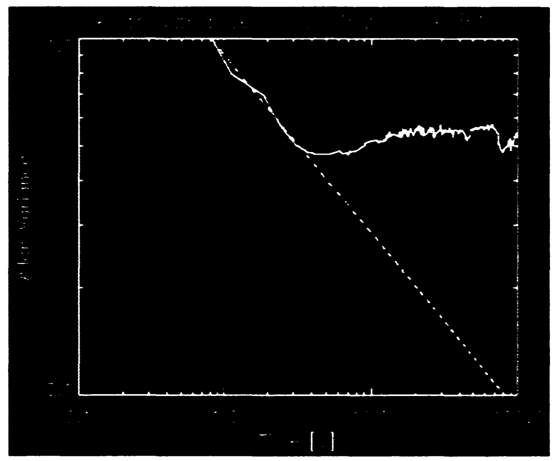

Figure 11: An Allan variance plot from 160 minutes of total power data taken every 50 ms. This result has been scaled to 100 MHz post-detection bandwidth from the measured data taken with a 2 GHz post-detection bandwidth. The dotted line represents a $t^{1/2}$ decrease in noise with time as theoretically expected.

Instrument Performance Characterization

After characterizing the performance of a single mixer in the test system, we installed the prototype mixer, and two additional mixers with x ed, machined backshorts into the JT cryostat. We repeated the same tests done in the test setup, and found that the mixers behaved identically, but with receiver noise temperatures of 60-70K. It is not uncommon for the noise of a mixer in an array dewar to be slightly higher than in a highly optimized single pixel test system. We believed that losses in the cryostat window material and IF losses in the long runs of semi-rigid coaxial cable were responsible for the increase in noise temperature. We measured the loss of the window material by inserting a slab of

ZoteFoam in the beam and observing the change in Y-factor. We found the ZoteFoam contributed ~5K to the receiver noise temperature.

Stability Analysis

We performed an Allan variance stability analysis of the receiver to determine if microphonics from the large Balzers cryo-head would negatively effect receiver stability. We used a Hewlett-Packard power meter, sampled every 50 ms with a data acquisition card in the computer control system. Data was taken for ~1.5 hours, and folded every 5 minutes to lower the noise due to the short integration time. We measured the total power over the entire 4-6 GHz IF for this test, and then scale the result to a 100 MHz post-detection bandwidth, since we did not have a narrow-band 5 GHz center frequency lter on hand. The data were analyzed following Kooi et al. (2000), with the help of an algorithm from Narayanan (2003). We assume a power law noise spectrum proportional to t^2. Then the Allan time scales like $BW^{1/2}$. The results in Figure 11 show an Allen variance time of ~3s for a 100 MHz bandwidth. This translates to an Allan variance time of ~30s with a 1 MHz post detection bandwidth. This stability time is adequate for all observing modes at the HHT.

Beam Pattern Measurement

Using a computer controlled XY stage system, we measured E and H plane cuts of the receiver beam pattern. The source was a liquid nitrogen cold load behind a sheet of room temperature absorber. A small hole in the absorber created a strong, negative source which could be detected using a lock-in ampli er and room temperature chopper wheel. The 3cm source size allowed adequate sampling of the receiver beam, and provided suf cient signal. Several scans were co-added and then t with a 5 component gaussian. Results showed the beam to be gaussian in shape, but the beam was more broad and elliptical than expected. We found that the original paper on diagonal horns has an error in the formula for the expected beam waist of the horn. The lenses were designed from the results of this paper, but our later HFSS simulations show the actual horn beam to be wider (Johansson et al. 1992). The over illumination of the lens results in a emergent beam 15% too broad. We are currently redesigning the lens mounts to compensate for this effect.

Telescope Performance and Initial Results

In early June, 2003 DesertStar was taken to the HHT for a 6 day engineering run. The goal was to identify areas of dif culty in using the receiver on the telescope, and to perform as many performance tests and veri cations of the central mix er as possible. Overall, the results were good with some minor disappointments. Initial installation and cooldown were trouble free, but the receiver's mount proved to be inadequate. The weight of the receiver caused the mount to deform under load, and it was obvious that the mount was not rigid enough to prevent the receiver oscillating due to the cold-head cycle. The mount was reinforced as a stop-gap measure, and we continued to align the receiver to the telescope. Within two days, we had the central beam of the array on the sky, and had easily achieved receiver noise temperatures of ~90K. Measurements with a laser level proved the cryostat was indeed oscillating with a peak to peak amplitude of more than 40." This oscillation prevented us frommaking ne pointing or focus measurements. We used spectra and maps from extended regions to coarsely point the telescope. On centrally concentrated sources, peak line temperature was diluted since the receiver beam was not on-source for all the integration time. Spectra were obtained from a variety of sources including IRAS16293, IRC+10216, DR21, CepA and S140. These data were used to verify the proper operation of the receiver system. A representative spectrum is shown in Figure 12.

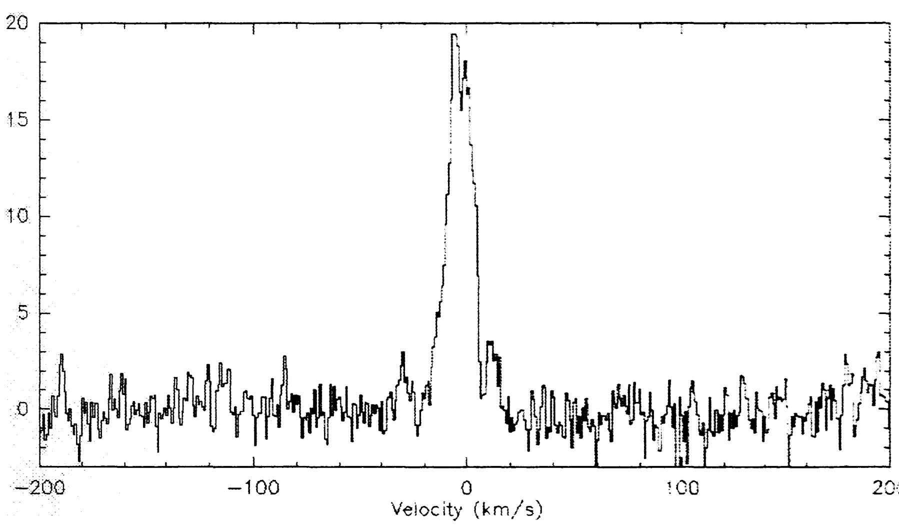

Figure 12: ^{12}CO (3-2) Spectrum from the central position of a map of the high mass star forming region DR21.
This observation was made in position switched mode with an off position of 30' in azimuth. A *linear* baseline has been t and subtracted.

Summary

We have constructed a 2x2, 810 GHz array receiver for the AST/RO telescope. The array utilizes a common set of re-imaging optics, an ef cient 4-w ay quasi-optical LO power splitter, a solid-state LO, low noise mixers, a e xible computer controlled bias system, and an array AOS. A state-of-the-art planar, tunerless LO chain with W-band power ampli ers can easily pump all the mixers with only a 0.5 mil Mylar LO diplexer. Upgrades and repairs have reduced the receiver noise temperatures to between 625K and 640K per mixer, making the system ~15 times faster for mapping than the previous 810 GHz system on the AST/RO telescope. We have complete the rst phase of constructing and testing a 345 GHz heterodyne array receiver for use on the Heinrich Hertz Telescope on Mt. Graham in Arizona. The instrument uses x ed backshort, suspended stripline SIS mixers with 2 GHz IF bandwidth. Cooling is provided by a high capacity closed cycle refrigerator in a large, expandable cryostat. We have demonstrated proper operation of the cryogenic system and computer controlled bias system. Preliminary measurements indicate the prototype array mixer can provide uncorrected receiver noise temperatures of ~60K-70K from 326-356 GHz. Performance has been veri ed in the JT cryostat with 3 mix ers, and the instrument has had a engineering run on the HHT, where it successfully collected data. The instrument will go into regular operation on the HHT in October 2003 with 3 pixels. The remaining 4 mixers will be added to the system in the summer of 2004, bringing the array up to its full compliment of 7 pixels. DesertStar is the rst operational 345 GHz array receiver.

REFERENCES

Baars, J. W. M., Martin, R.N., Mangum, J.G., McMullin, J.P., Peters, W.L. , PASP, 111, 759, 1999.

Blundell, R., Tong, C-Y.E., Papa, D.C., Leombruno, R.L., Zhang, X., Paine, S., Stern, J.A., LeDuc, H.G. & Bumble,B.IEEE MTT Symp. on Space Terahertz Technology,Vol. 43, 1995.

Dent, W.R.F. Imaging at Radio Through Submillimeter Wavelengths, ASP Conference Proceedings Series, Vol. CS-217, 2000.

Dotson, J.L., Novak, G., Renbarger, T., Pernic, D., & Sundwall, J.L. Proc. SPIE Vol. 3357, 1998.

Graf, U. U., Haas, S., Honingh, C. E., Jacobs, K., Schieder, R., Stutzki, J., Proc. SPIE Vol. 3357, 1998.

Groppi, C.E. et al. Imaging at Radio Through Submillimeter Wavelengths, ASP Conference Proceedings Series, Vol. CS-217, 2000.

Gusten, R. Imaging at Radio Through Submillimeter Wavelengths, ASP Conference Proceedings Series, Vol. CS-217, 2000.

Heyminck, S. & Graf, U.U. Proc. SPIE Vol. 4014, 1998.

Jewell, P.R. & Mangum, J.G. ALMA Memo 170, 1997.

Johansson, J.F., & Whyborn, N.D. IEEE MTT, Vol. 40, No, 5, 1992.

Kooi, J.W. CSO Memo, 1998.

Kooi, J.W., Chattopadhyay, G., Thielman, M., Phillips, T.G., & Schieder, R. Int J. IR and MM Waves, Vol. 21, No. 5, May, 2000.

Kuo, C.L. et al. American Astronomical Society Meeting 200, #06.03, 2002.

Lamb, J.W. ALMA Memo 301, 2001.

Martin, D. H., El-Atawy, S., Duncan, W. D., Puplett, E. F., Fonti, S. Societa Astronomica Italiana, Memorie, vol. 49,1978.

Mehdi, I., Schlecht, E., Chattopadhyay, G., Siegel, P.H. Proc. SPIE Vol. 4855, 2003.

Mueller, E., 2001, DeMaria ElectroOptics Systems, Inc., 1280 Blue Hills Ave.,
Bloom eld, CT 06002.

Narayanan, G. Private Communication, 2003.

Schieder, R.T. et al. Proc. SPIE Vol. 4855, 2003.

Schuster, K., Blondel, J.,Carter, M., Fouilleux, B., Lazareff, B.,Mattiocco, M., Pollet, J. Imaging at Radio Through Submillimeter Wavelengths, ASP Conference Proceedings Series, Vol. CS-217, 2000.

Stark, A. et al. PASP, Volume 113, Issue 783, 2001.

Sunada, K.,Yamaguchi, C.,Kuno, N. & Ukita, N. Imaging at Radio Through Submillimeter Wavelengths, ASP Conference Proceedings Series, Vol. CS-217, 2000.

Thompson, A.R., & Kerr, A.R. ALMA Memo 168, 1997.