DesertSTAR II: The addition of a 230 GHz subarray to an existing 345 GHz array receiver system

1 Introduction

Array receivers have the potential of revolutionizing astronomy at millimeter and submillimeter wavelengths. Over the past few years our group at the University of Arizona has built two array receivers: *PoleSTAR*, a 4 pixel 810 GHz receiver now in operation on the 1.7 m AST/RO telescope at the South Pole and *DesertSTAR*, a 7 pixel 345 GHz array receiver for the 10-meter Heinrich Hertz Telescope (HHT) on Mt. Graham, Arizona. DesertSTAR will go into routine operation on the HHT with an initial complement of 3 pixels in October 2003. The remaining four pixels will be implemented next summer. Work on PoleSTAR was funded by the NSF Office of Polar Programs. The DesertSTAR development has been a joint effort between the University of Arizona, the University of Massachusetts, and the University of Virginia with partial funding through the NSF ATI program.

Here we request funds to add four, 230 GHz pixels to Desert STAR. The Desert STAR closed-cycle, array cryostat was designed to have ample thermal capacity and sufficient volume to support the additional subarray. The system will be configured to allow simultaneous observations with both subarrays. The large increase in mapping speed afforded by the arrays, together with the capability of observing multiple transitions of molecules simultaneously, will make Desert STAR a powerful and unique instrument for a variety of projects, including unbiased high resolution Galactic Plane CO surveys, deep submillimeter line surveys over extended regions, star formation studies, and probing the mass loss from the extended envelopes of evolved stars. Desert STAR will be a facility instrument on the HHT, available to all users.

In this proposal we describe potential key projects for Desert STAR and provide a technical description of the instrument design and expected performance.

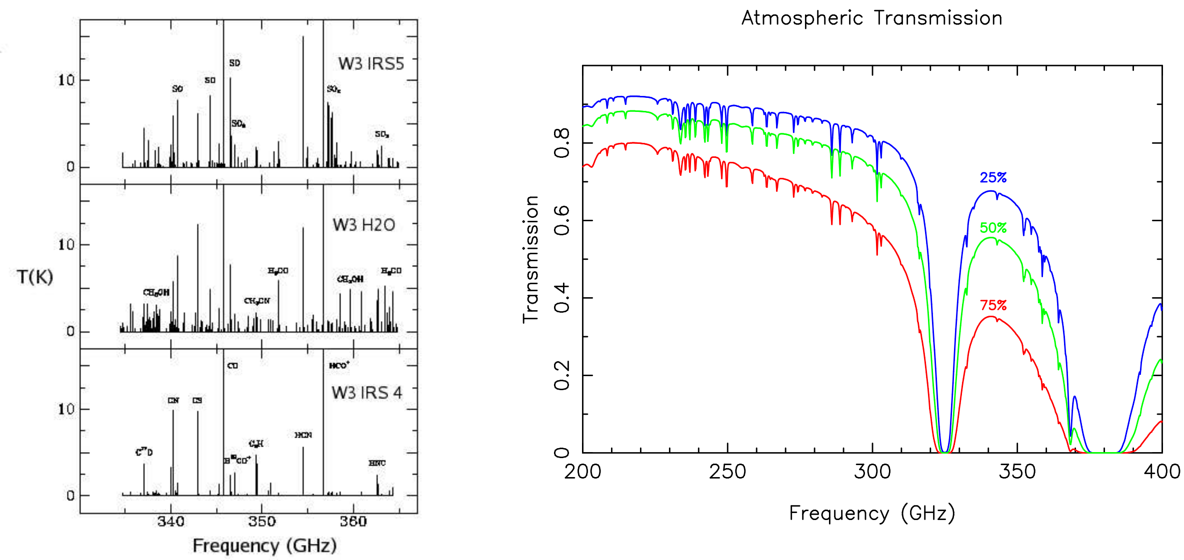
2 Scientific Motivation

Species	Transition	Frequency (GHz)	Importance
^{12}CO	J=2 $\rightarrow$ 1	230.538	Excitation and structure
^{12}CO	J=3 $\rightarrow$ 2	345.795	of molecular clouds; PDR's,
^{13}CO	J=2 $\rightarrow$ 1	220.398	shocks, protostellar outflows
C^{18}O	J=2 $\rightarrow$ 1	219.560	star-forming regions
C^{17}O	J=3 $\rightarrow$ 2	337.061	& Galactic chemical evolution
CO^{+}	$3_4 \rightarrow 2_3$	354.014	Molecules in hostile environments,
			UV and X-ray dominated regions
HCN	J=3 $\rightarrow$ 2	265.886	Dense gas in molecular cloud cores
HCN	J=4 $\rightarrow$ 3	354.505	and circumstellar disks
HNC	J=3 $\rightarrow$ 2	271.981	
HNC	J=4 $\rightarrow$ 3	362.630	
HCO^{+}	J=3 $\rightarrow$ 2	267.557	Excitation and kinematics of
HCO^{+}	J=10 $\rightarrow$ 9	356.734	YSO envelopes, protostellar collapse
SiO	J=5 $\rightarrow$ 4	217.504	Stellar ejecta
SiO	J=8 $\rightarrow$ 7	347.330	molecular shocks in disks & outflows

Table 1: Selected spectral line diagnostics in the 200-400 GHz atmospheric windows

Desert STAR in its proposed, upgraded form will be a sensitive, dual-frequency, 11-pixel, superconducting heterodyne camera for the 800-1400 μm atmospheric windows. Its development will serve as a stepping stone to larger format submillimeter arrays and significantly broaden the scientific capabilities that submillimeter spectroscopy can address.

The atomic and molecular transitions accessible in this spectral range are important diagnostics of a variety of astronomical phenomena including planetary atmospheres, molecular clouds, star-forming regions, young stellar objects, circumstellar envelopes, and planetary nebulae (Figure 1(a). The 200–400 GHz atmospheric windows are relatively well-explored, due to good atmospheric transmission at high, dry mountain sites. Figure 1(b) depicts the atmospheric transmission for Mt. Graham that is attainable 25% (blue curve), 50% (green curve) and 75% (red curve) of the time during the year, based upon tipping radiometer measurements at 225 GHz performed over the last 6 years. Labels mark spectral lines of highest importance, and their frequencies and diagnostic capability are tabulated in Table 1.



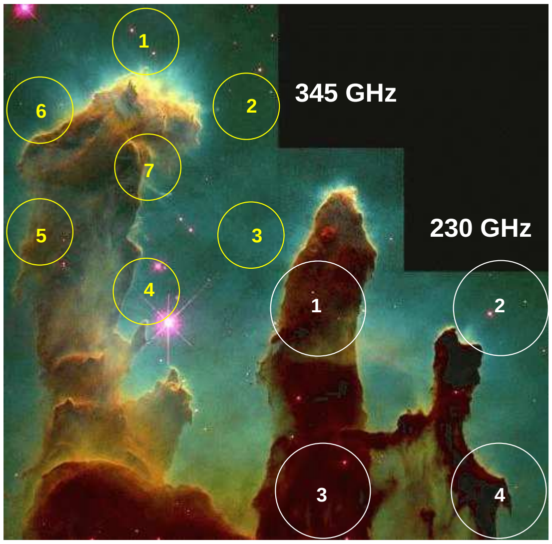
a) b)

Figure 1: a) The 345 GHz spectral line survey toward three positions in the W3 molecular cloud by Helmich et al. (1997) shows a rich diversity of spectral diagnostics. b) Modeled submillimeter atmospheric transparency for the HHT on Mt. Graham in 75 percentile (red), median (green), and 25 percentile (blue) atmospheric conditions, derived from 24hour/7day 225 GHz radiometer measurements over the last 6 years.

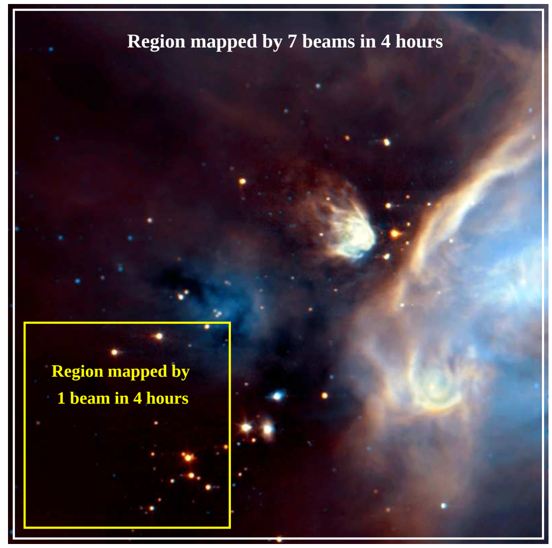
Despite the relative transparency in these atmospheric windows (compared to the more opaque and transient atmospheric windows at higher frequencies) and the development of SIS devices that approach the quantum sensitivity limit to within factors of a few, the scientific productivity of even modern receivers is severely limited by their single-beam nature. This limitation places a stranglehold on the large-scale mapping capabilities needed to address crucial issues, such as the Galactic-scale origin and evolution of (molecular) clouds and their pivotal, delicate interplay with the stars that are born from them.

High spatial dynamic range imaging of molecular line emission is essential to accurately describe interstellar processes that regulate cloud evolution and the formation of newborn stars. High resolution is required to detect the small scale spatial variability and compact objects. Yet one also demands wide field imaging to place those features into an environmental context and to identify patterns that provide clues to interstellar dynamics (ex. gravitational instabilities). Heterodyne receiver *arrays* will maximize the scientific return from good submillimeter weather conditions and revolutionize the spectral line mapping of interstellar clouds. For illustration, Figure 2 portrays the footprint of the 7+4 element arrays on the sky, and the portion of the ρ Ophiuchi molecular cloud that can be mapped with $15''$ grid spacing, <1 km s^{-1} spectral resolution, and 1σ=0.5 K km s^{-1} sensitivity in one 4-hour shift at the HHT with the array, as compared to a conventional single-beam receiver.

While focal plane arrays augment the imaging capability of a telescope, the productivity of a system



a)



b)

Figure 2: a) Beam footprints of the 230 GHz and 345 GHz arrays at the HHT, atop the HST WFPC image of the Eagle Nebula, M16. Note that the two arrays will actually be cospatial on the sky, but are separated in the diagram for clarity. b) Heterodyne receiver arrays will revolutionize the mapping of molecular clouds and star forming regions. The proposed 7+4 pixel arrays can fully sample the nearby ρ Ophiuchi molecular cloud ($40' \times 40'$ ISOCAM image from Abergel et al. 1996) at $15''$ grid spacing in CO $J = 3 \rightarrow 2$ and CO $J = 2 \rightarrow 1$ to 0.5 K RMS within one 4-hour shift, with median T_{sys}'s of 750 and 450 K, respectively.

can be further increased by multiplexing the spectral domain. A dual frequency system generates data on two or more molecular emission lines from which the excitation conditions can be derived. As these spectral lines are measured simultaneously, the relative intensities are more reliable leading to more accurate modeling of the gas properties.

Lines in the 200-400 GHz atmospheric windows share a number of common traits; all probe warmer, denser environments ($T > 20$ K, $n \sim 10^{4-7}$ cm^{-3}) than typically observed at longer millimeter wavelengths. These properties make them unique and powerful probes of energetic molecular gas which provides the crucial link between luminous stars, their remnant descendants, and the cold molecular clouds that form them and are subsequently destroyed by them. The following sections describe several key science objectives for large-format submillimeter arrays on ground-based submillimeter telescopes, initiated by the 11-pixel array at the HHT and extended using future $\sim 10 \times 10$ pixel second-generation instruments. Among these are studies of molecular cloud physics/chemistry, evolved stars, and protostellar evolution. Here we will limit our discussion to a few key research projects, but the Desert STAR array will be accessible to all users of the HHT for targeted PI proposals.

2.1 An Unbiased Galactic Plane Survey

Molecular clouds still pose a host of fundamental questions regarding their nature and role in the coupling of matter in the interstellar medium (ISM). How do molecular clouds form and evolve? How does star formation start and propagate through these clouds? What factors determine the stellar initial mass function, multiplicity, and clustering properties? How does the molecular ISM respond to the radiation and outflows from the stars that form from it, and how does this relate to the global Galactic evolution? What are the mass-spectra and kinematic properties of the clouds and the substructures that they contain? How do cloud properties change across the Galaxy? What are the relative roles of spiral density waves, super-bubbles, gravitational instabilities, and Galactic infall in the formation and destruction of molecular clouds?

Because the dominant H_2 molecule lacks a dipole-allowed radio spectrum, most of our knowledge of the molecular ISM comes from the second-most abundant molecule, CO. The early surveys of molecular gas were obtained either with large beams (e.g. $> 9'$, Dame et al. 1987, 2001), or were undersampled (e.g. the $3'$ sampling of the UMass/Stonybrook survey, Solomon et al. 1987; Scoville et al. 1987). The development of focal plane arrays in the 3mm band over the last 10 years has enabled CO surveys with moderate resolution ($45''$) and broad, areal coverage (Heyer et al. 1998; ongoing BU-FCRAO Galactic Ring Survey). However, these surveys are limited to meauring the J=1→0 rotational transitions of CO; the column density and mass derived from optically thin (isotopic) J=1→0 emission is sensitive to the badly constrained excitation temperature.

The following features represent a definitive CO survey that would not only provide the clearest view of the star forming clouds in the Galaxy, but would also serve as the reference map for focused studies with the SMA, CARMA and ALMA.

- **Multi-line**: Surveys carried out in a single line of ^{12}CO make it difficult to conclusively disentangle the competing effects of abundance, line opacity, and excitation. Significant systematic uncertainties are present with surveys consisting of one spectral line per species. At least two lines of differing excitation are necessary, with at least one line in an optically-thin isotopomer of CO, such as ^{13}CO or C^{18}O to diagnose temperature and (column) density. *The simultaneous dual-frequency operation of Desert STAR will dramatically improve the speed, uniformity and scientific return of important new surveys to be undertaken at the HHT.* These higher-J transition observations provide a critical complement to the recent surveys of CO and ^{13}CO J=1-0 emissions conducted at the Five College Radio Astronomy Observatory. Together, these surveys can place important constraints upon the excitation conditions throughout the Galaxy at a resolution of $45''$ [1]. To date, such multi-line, wide field measurements have been made at $9'$ resolution (Sakamoto et al. 1995). The derived excitation conditions provide a relative barometer to gauge the variation of gas pressure with radius in the Galaxy as may be induced by the gravitational potential of the disk. High excitation conditions are a valuable beacon/signature to sites of strong interaction with a molecular cloud (ex. supernova remnants, enhanced UV fields) that might otherwise be missed with a singular transition.

- **High Sensitivity**: CO survives in the ISM in part because of the UV shielding from dissociation provided by H_2; thus CO's survivability depends upon a molecular, H_2-dominated environment. For typical molecular clouds, the sharp transition from H to H_2 typically occurs by a visual extinction of $\sim$1 magnitude in the local interstellar radiation field, or N(H)= 1.8×10^{21} cm^{-2}. We therefore aim to detect all CO down to this hydrogen column density limit. This corresponds to a 3σ detection limit of N(^{12}CO)$\sim 10^{15}$ cm^{-2}, which implies an integrated intensity for cold gas (10K $< T_k <$ 50K) of 1.5 K km s^{-1} in the $J = 2 \rightarrow 1$ transition at a gas density of $n_H = 10^4$ cm^{-3}, but only 0.7 K km s^{-1} if $n_H = 10^3$ cm^{-3}. The corresponding $J = 3 \rightarrow 2$ intensities are 1.2 and 0.2 K km s^{-1}. *Even the strongest limit we require in CO $J = 2 \rightarrow 1$ is readily detectable (3σ) within 10 seconds of integration time per independent beam in median 230 GHz conditions (T_{sys}=500K) at the SMT. Detection (or limits) on J=3→2 in that time would constrain the gas density.*

- **High Angular Resolution**: Disentangling the complicated structures of molecular clouds in the Galaxy requires high angular resolution. Low resolution data wash out CO gradients and enhancements at molecular interface regions. For example, to resolve a feature such as the Orion warm ridge at the distance of the Molecular Ring ($\sim$5 kpc) requires better than $1'$ resolution. *A survey with $30''$ resolution is needed. The diffraction-limited beamwidth of the SMT at 200-400 GHz is 18-35$''$.*

- **Unbiased Survey Coverage**: While specific studies of individual clouds is highly meritorious, building a statistical picture of the molecular clouds, cores, and kinematics of the Galaxy requires an unbi-

[1] Highly sampled DesertStar data smoothed to the resolution of the FCRAO 14m telescope at 110 GHz will further improve its sensitivity.

ased survey of significant area. From existing low-resolution CO maps, the majority of CO emission is found within one degree of the Galactic Equator, from the Galactic Center to the tangent arms near $|l| \sim 100^o$. *The mapping efficiency of Desert STAR will make large, unbiased mapping surveys possible.*

From these requirements, it becomes clear that the unique blend of high sensitivity, fine velocity resolution, mapping speed, and high angular resolution that Desert STAR offers on the HHT is ideally suited for such a survey. Figure 3 demonstrates the target region defined by the 1st Galactic quadrant and ($-1^o < b < +1^o$). Because the "field of view" of the 230 GHz and 345 GHz arrays is so well matched (90″), a survey could be simultaneously performed in both CO $J = 3 \rightarrow 2$ and $J = 2 \rightarrow 1$ with comparable sensitivity and identical (resampled) resolution. With 2-second integration time per 15″-spaced grid element (i.e. 8 seconds integration per convolved independent beam) of an on-the-fly (OTF) map, one square degree of sky could be mapped to a sensitivity of $1\sigma \sim 0.25$ K per 1 km s^{-1} resolution element in about twelve hours. 180 square degrees of the 1st quadrant of the Galactic Plane, including the Galactic Center ($0^o < l < 90^o$, $-1^o < b < +1^o$) would then be mappable in approximately 2000 hours of observing time, or about 80 complete days of observable weather conditions. The AST/RO telescope at the South Pole could extend the survey from the Galactic Center onward. (The PI is a Co-I on AST/RO and his lab has constructed most of its receiver systems.)

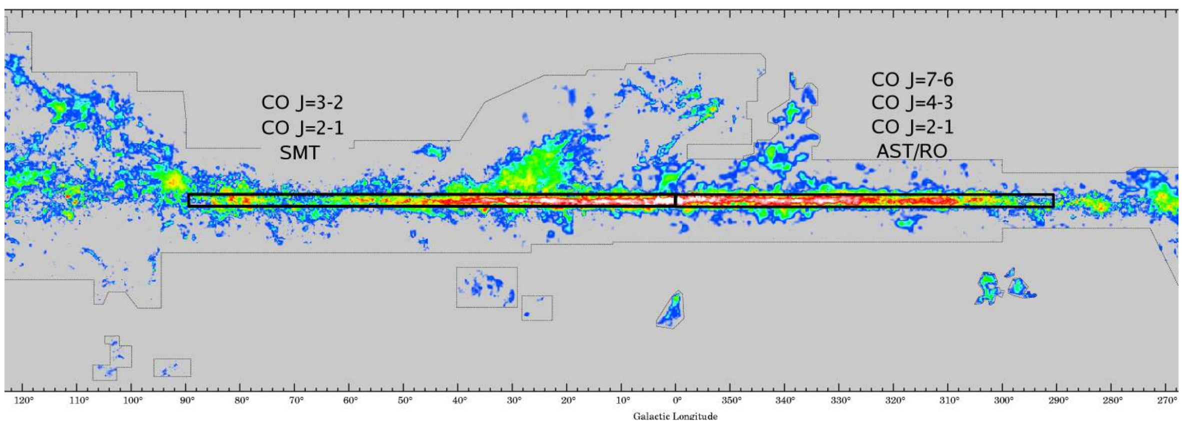


Figure 3: Overlaid atop the Dame et al. (1987) CO J=1→0 map of the Galaxy is the proposed Desert STAR key project to map 180 square degrees of the 1st quadrant of the Galactic Plane, including the Galactic Center ($0^o < l < 90^o$, $-1^o < b < +1^o$). AST/RO could extend the Galactic Plane coverage from the Southern Hemisphere ($-70^o < l < 0^o$) in CO $J = 2 \rightarrow 1$ and $J = 4 \rightarrow 3$. The surveys will have a 3σ sensitivity of N(CO)< 10^{15} cm^{-2} per independent beam and will take approximately 2000 observing hours to complete.

This survey will provide the most detailed "ecological" study of the molecular ISM and the evolution of giant molecular clouds. It will probe the entire life cycle of star-forming molecular clouds, and will allow an unprecedented, unbiased view of the interplay between the molecular ISM and the stars which are born from it. It will discover tens of thousands of star-forming and starless cloud cores and allow measurement of their statistical properties. The dynamical evolution of clouds and their relation to each other and to stars and atomic ISM components will provide the clearest view of the large scale structure of the Galaxy. The proposed survey has the potential of being as fundamental to the investigation of the cold ISM as the IRAS survey is to the study of warm dust, and the Palomar Sky Survey to the study of the optical sky.

2.2 Targeted Deep Surveys of Molecular Clouds and Star Forming Regions

One of the major goals of ground, airborne, and space-based observational astronomy is the identification and study of protostellar objects. A study of protostars provides insight into the initial conditions required for star formation, protostellar evolution, and the formation of solar systems like our own.

Specific molecular clouds at high Galactic longitude will not be included in the Unbiased Galactic Plane Survey. These regions, such as the Orion, Perseus, Serpens, Ophiuchus, and Gem OB1 clouds will be targeted separately as a part of a deep survey of individual clouds. Like the unbiased survey, the targeted survey will map a total of 100 square degrees in the $J = 2 \rightarrow 1$ and $J = 3 \rightarrow 2$ lines of ^{12}CO, ^{13}CO, with more focused mapping in $C^{18}O$ or $C^{17}O$ as needed to obtain optically-thin tracers for column density determination. Focused mapping in HCO^+ will provide density indicators for the dense core regions. This survey is synchronous with several other contemporary surveys, such as the SIRTF Legacy program "From Cores to Disks", which will map 5 molecular cloud complexes photometrically from 2-70 microns, and will target specific sources with low-dispersion mid-IR spectroscopy. Toward those same clouds, A. Goodman's COMPLETE survey will add submillimeter continuum mapping, CO $J = 1 \rightarrow 0$ maps with 45″ resolution, and deep near-infrared imaging. Our proposed survey will overlap these regions, adding significant value to these existing investments of ground- and space-based telescope time; higher-J transitions of CO will probe the warmer and denser gas that participates in core evolution and star formation, and with much less contamination from foreground material. Well-defined gas excitation conditions provided by a multi-line analysis will dramatically improve the interpretation of the CO data.

The multi-beam array will also allow small cloud cores to be mapped in a spectral survey mode at selected frequencies. This spectral survey mode will allow different portions of a star forming core to be distinguished chemically. The prospects of using time-dependent chemistry as a chronometer for the evolution of protostellar cores, disks, and outflows is tantalizing, and only made practical through the use of heterodyne arrays.

Accessibility of high-J CO and HCO^+ lines will probe the physical conditions of the dense, hot envelope gas located much closer to the protostar than is currently accessible at lower frequencies [e.g. 5,6 and references therein]. The statistical study of the excitation and structure of star-forming cores versus starless cores, particularly those uncovered by the Biased and Unbiased Surveys previously described, is an exciting prospect. Furthermore, the excitation and abundance of HCO^+ J=4 $\rightarrow$ 3 with $n_{crit} \sim 10^7$ cm^{-3} directly reflects the ambient radiation field, provides an estimate of ionization fraction, and kinematics of protostellar envelopes. Indeed, direct detection of infall is tractable through these transitions, as the inner envelope is expected to collapse faster than the colder outer envelope traditionally probed at lower frequencies. Linewidth correlations of CO and HCO^+ at low- and high-J could provide direct tests of protostellar collapse models. The high angular coverage and resolution provided by the proposed array is critical for disentangling the complicated kinematics of star-forming environments.

2.3 *Synergy with Contemporary Surveys*

The surveys conducted with the expanded Desert STAR system on the HHT will serve as a 'finder chart' for future, more focused surveys (e.g. with ALMA) and markedly improve the interpretation, and enhance the value, of numerous contemporary surveys.

- The SIRTF Legacy program GLIMPSE, headed by E. Churchwell, will provide a thermal infrared survey of the Galactic plane that provides a complete census of star formation, the stellar structure of the molecular ring, will map the warm interstellar dust, constrain extinction laws as a function of galactocentric radius and will detect all young embedded O and B stars. Yet, there is no survey of the molecular gas that relates to this stellar population study that has (even vaguely) comparable resolution. The proposed Unbiased Galactic Plane Survey will provide the highest resolution, large-area CO survey to date. The use of lines with higher excitation will better account for the dense cloud material that forms stars, cloud interaction with formed stars via their warmed photodissociated surfaces, and their kinematic disruption by mass ejection, outflow, and supernova remnants.

- A second SIRTF Legacy proposal, "C2D", will survey a sample of giant molecular clouds and complexes in infrared continuum emission to provide a complete base for nearby star formation and to follow the transition from starless cloud cores to low-mass disks. It is critical, then, to provide a similar survey of the targeted clouds in higher-J CO emission to account (and disentangle) the complicated kinematics and physical structures in star-forming regions. The COMPLETE survey of A. Goodman will provide a reference study of the millimeter wave dust continuum emission in these clouds and their molecular line survey will support the $J = 1 \rightarrow 0$ lines of CO and ^{13}CO using the FCRAO Sequoia array. The complementary need of a higher-J survey is particularly important for the study of star forming regions, where many excitation components are often present and cannot be disentangled with only one spectral line. Our Targeted Deep Surveys of selected GMC's will provide thermal and barometric maps that will uniquely disentangle the physical structure of these complicated regions and add significant value to the baseline $J = 1 \rightarrow 0$ study.

- The ongoing FCRAO Molecular Ring Survey led by J. Jackson will provide the most sensitive study of the inner Galaxy to date, but will only map the ^{13}CO $J = 1 \rightarrow 0$ line. The angular resolution of the survey is 47″. The proposed study will improve upon this resolution by up to a factor of 4 in area and yield the crucial higher-J lines that make proper interpretation of existing CO surveys possible.

- The PI of this proposal has proposed a NASA SMall EXplorer mission, the Galactic Terahertz Observatory (GTO), which will map 240 square degrees of the Galactic Plane ($-60^o < l < +60^o$, $-1^o < b < +1^o$) in the pivotal fine structure recombination lines of carbon and nitrogen at 158 μm and 205 μm. The [C II] line is the dominant cooling line of the atomic ISM, and the [N II] line is an extinction-free probe of ionizing photons throughout the Galaxy. The principal aim of the survey is to study the life cycle of atomic and molecular clouds. The [C II] survey will be able to study H_2 clouds that have not yet recombined into CO – but it will probe the photoilluminated surfaces of the dark CO clouds, not their contents. A CO survey of comparable ($\sim 1'$) resolution in the higher-J transitions of CO matches the excitation of the [C II] line and makes an ideal companion survey that will enhance the interpretation of [C II] emission in the Milky Way and other star forming galaxies. Together, the [C II] and CO surveys probe nearly all stages of carbon in the cold ISM. The proposed Unbiased Galactic Plane CO Survey is a perfect match to these goals.

3 Technical Description

3.1 Overview

The addition of a 4 pixel, 230 GHz subarray to DesertSTAR will make it an extremely powerful, versatile instrument for probing the ISM in our Galaxy and, ultimately (with an expanded backend spectrometer), other galaxies as well. A schematic diagram of the expanded DesertSTAR system is shown in Figure 4. Components to be built or added as part of the proposed effort are shown in (bold) red type. Laboratory measurements indicate the NRAO style, closed-cycle, J-T refrigerator has ample capacity (1.8 W at 4 K) to simultaneously cool both the 345 and 230 GHz subarrays.

The converging *f/13.8* beams from the HHT tertiary first pass through a 0.5 mil Mylar beamsplitter before entering the array cryostat through a 4.5 in diameter, low-loss, Zotefoam vacuum window. The Mylar beam splitter is used to inject the multiple 345 GHz LO beams into the optical path without significant loss (<3%) to either the 345 or 230 GHz sky beams. The beams then pass through a Gortex 40 K IR blocking filter and are subsequently split into horizontal and vertically-polarized components by a 45° wire grid. The vertically-polarized beams are intercepted by 7 hexagonally packed, low-density polyethylene lenses which provide efficient Gaussian beam coupling to seven, 345 GHz, SIS waveguide mixers. The physical separation between mixers (29 mm) is three times the Gaussian beam waist diameter. On the sky this optical configuration separates the beams by two, full-width-half-maximum (FWHM) spacings (44″ at 345 GHz). The 4-6 GHz intermediate frequency (IF) output of each mixer passes through an isolator before entering low-noise ($\sim$ 5 K), Miteq amplifiers. The lenses, mixers, isolators, and IF amps are all at $\sim$ 4 K. The polarizing grid is at 40 K. At room temperature the signals are further amplified and downconverted to meet the requirements of the array spectrometer. In its initial implementation, the 345 GHz array will employ

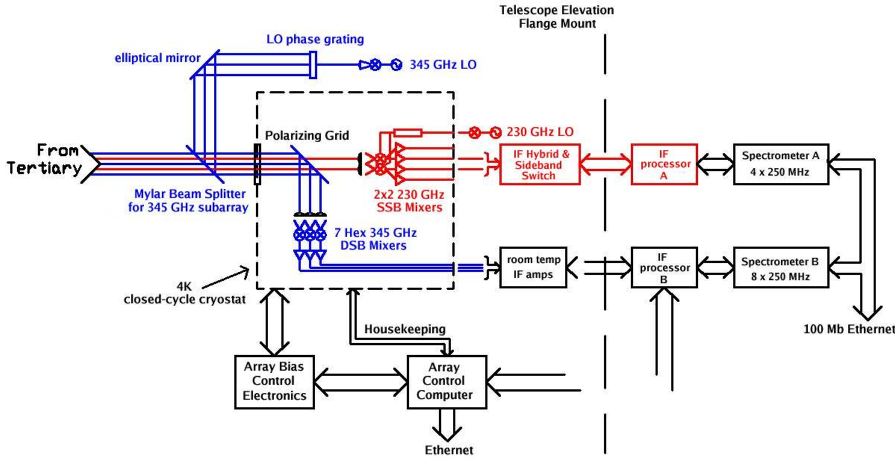
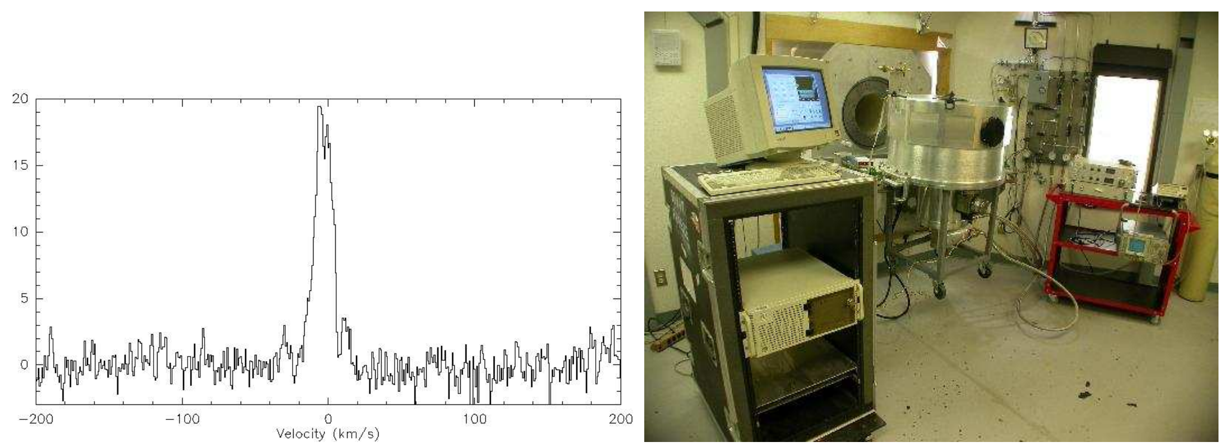


Figure 4: Schematic Diagram of DesertSTAR II. The existing 345 GHz array system is shown in blue/black. The proposed 230 GHz array addition is shown in (bold) red.

seven, 250 MHz wide, 1 MHz resolution filterbanks. The seven LO beams needed to drive the 345 GHz array are produced using a holographic phase grating illuminated by a single solid-state source. As with the proposed effort, the development of the 345 GHz array was a collaborative effort between NRAO (cryostat), the University of Virginia (SIS devices), the University of Massachusetts (mixer design and fabrication), and the PI's lab at the University of Arizona (system design and integration). This collaboration has worked extremely well, yielding excellent receiver performance (~ 55 K DSB at 350 GHz) and a successful first run. A representative spectrum from the run is shown in Figure 5a. A photograph of DesertSTAR mounted to the elevation flange of the HHT is shown in Figure 5b.



a) b)

Figure 5: The first engineering run with DesertSTAR. a) CO $J = 3 \rightarrow 2$ spectrum of DR21 made with the first DesertSTAR pixel. b) Photograph of DesertSTAR bolted on the elevation flange of the HHT.

In the proposed expansion, the horizontally polarized beams emerging from the 40 K wire grid intercept a 2x2 array of dielectric lenses which in turn couple the light into four, 230 GHz SIS waveguide mixers. Unlike the simple, single-ended, double-sideband (DSB) mixers used at 345 GHz, the 230 GHz mixers will be balanced, sideband-separating mixers based on a successful ALMA design. In the following sections we will discuss the merits and implementation of the 230 GHz array.

3.2 Balanced, Sideband-Separating SIS Waveguide Mixers

Most receivers currently in operation at millimeter and submillimeter-wave observatories utilize simple, single-ended, DSB mixers. This is because such mixers are relatively easy to fabricate and implement.

However, in most instances the molecular or atomic lines of interest to the observer appear in only one of the mixer's sideband. The unwanted image sideband can degrade sensitivity by adding atmospheric noise and causing spectral confusion. Observatories sometimes use quasi-optical devices such as Martin-Pulplett interferometers or Fabry-Perot filters to suppress the image sideband. However, such devices have limited bandwidth and require termination of the image sideband in a cold load. These devices are also often bulky and have significant optical loss.

In response to the need for large numbers of mm/submm receivers with the best possible sensitivity and lowest cost, the ALMA project has developed a balanced, sideband-separating 230 GHz mixer with the following properties (Claude et al. 2000):

- Separates the two sidebands without the use of an interferometer.
- Provides a good 4 K image termination inside the mixer block.
- Makes efficient use of LO power.
- Supresses local oscillator noise.
- Contains no moving parts.

Not surprisingly, these are exactly the desired characteristics in a focal plane array mixer. Therefore, with the help of NRAO (see support letter from Tony Kerr), we will base our 230 GHz focal plane array on the ALMA design.

A schematic representation of the mixer architecture to be used in the 230 GHz subarray is shown in Figure 6. Sideband separation is achieved by dividing the incoming signal (RF) with a 90^o phase shift between two balanced mixers (Marked 'A' and 'B'). Power division and the addition of a phase shift is achieved using a branchline coupler (a type of waveguide quadrature hybrid; Srikanth and Kerr 2000). The incoming LO power is split and coupled in-phase to the balanced mixers. Each of the balanced mixers is itself composed of two, single-ended, SIS mixers interconnected by a branchline coupler. The SIS junctions are on quartz substrates which project into the waveguide outputs of the coupler. Impedance matching circuitry and RF choke structures are fabricated on the substrates along with the SIS junctions. For balanced operation, the pair of SIS junctions comprising each balanced mixer must be biased with opposite polarity and their IF outputs combined. To achieve sideband separation, the single IF output from each pair of SIS junctions must be combined in a quadrature hybrid. The IF quadrature hybrid can exist outside the cryostat as long as it is proceeded by low-noise amplifiers. Since the IF hybrid operates at microwave frequencies (here 4-6 GHz), it can be implemented using a simple 3-branch microstrip coupler. The two outputs of the IF hybrid are the upper and lower sideband of the incoming radiation.

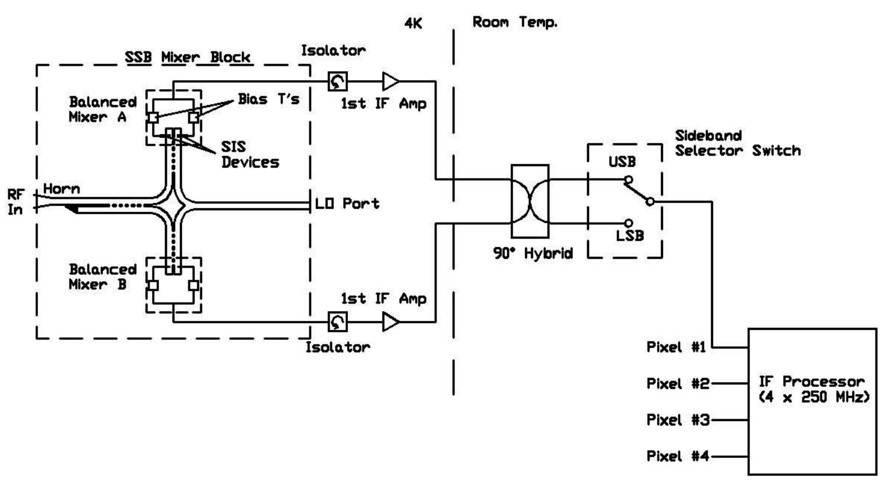


Figure 6: Schematic representation of SSB mixer architecture. The design is based on the ALMA band-6 mixer.

A preliminary CAD drawing of the proposed 230 GHz mixer subarray is shown in Figure 7. Radiation is coupled into each mixer by a dielectric lens and corrugated feedhorn. Each mixer has its own electromagnet for suppressing Josephson noise. The mixer is designed to split into halves along the centerline of the waveguide. The bottom half contains the SIS junctions, IF matching networks, and bias-T's. All four SIS junctions in each SSB mixer can be independently biased. The mixer LO is injected through a waveguide port in the back.

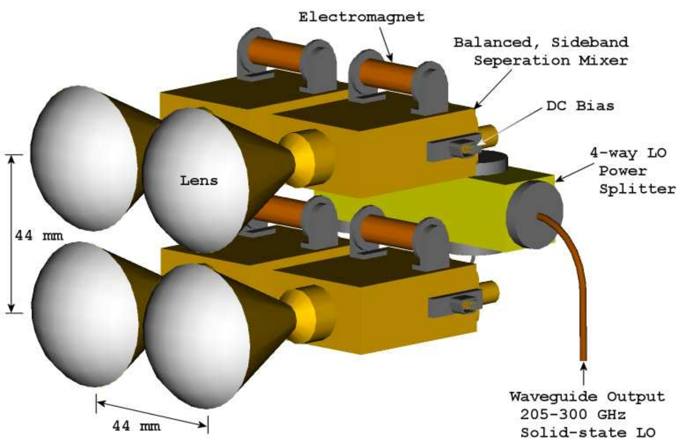


Figure 7: CAD drawing of the proposed 2x2, 230 GHz balanced, sideband-separating mixer array. Each mixer has an AR grooved, dielectric lens to efficiently couple the telescope's beam to a corrugated feedhorn. Four, full-height waveguide, SIS junctions are used in each mixer. An electromagnet and field concentrators are used to suppress the Josephson effect.

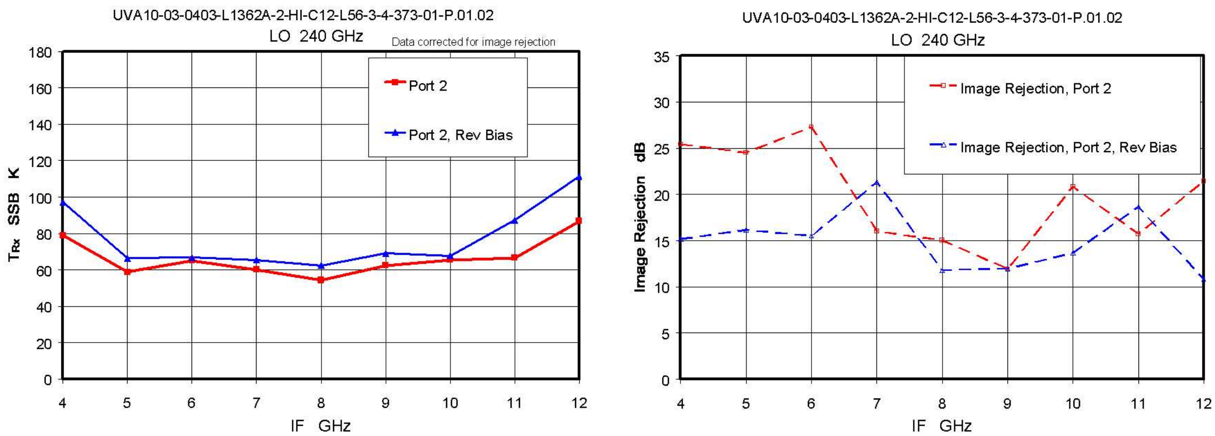
Using this design approach, the ALMA team has constructed and tested a prototype sideband-separating mixer. The measured SSB noise temperature and image sideband suppression performance are shown in Figures 8a and 8b. The results are excellent, with SSB noise temperatures of $\sim$ 60K and image suppression greater than 15 dB over $\sim$ 6 GHz of IF bandwidth (Kerr 2003). In a standard DSB noise measurement the mixer's noise temperature would be $\sim$ 30 K. The proposed array mixers will utilize the same waveguide hybrids and SIS devices as the prototype ALMA mixer. To achieve greater LO coupling efficiency, the array mixers will use a balanced configuration. Single-chip (MMIC) balanced and sideband separating mixers have also been developed by NRAO. These also had excellent performance, however, due to their large surface area, had low wafer yields. With the waveguide hybrid approach, large numbers of devices can be made in a single run.

An exciting aspect of this SSB mixer design approach is its scalability. With conventional CNC techniques, these mixers can be fabricated to $\sim$ 700 GHz. Utilizing new micromachining techniques together with advances in HEB technology, it should be possible to realize high performance SSB mixers to $\sim$ 5 THz.

3.3 *Local Oscillator System*

Since the balanced, sideband-separating mixer described above uses four single-ended mixers, it may at first seem it requires four times the LO power of the standard single-ended mixer and this indeed the case. However, in unbalanced applications these same single-ended mixers require 20 dB LO coupler. A balanced mixer has an LO port into which all available power can be injected. Therefore, even with 4 single-ended mixers, a balanced, sideband-separating mixer requires $\sim$ 14dB *less* power than the most commonly used single-ended mixer. All available LO power can be delivered to a single-ended mixer if a Fabry-Perot or Martin-Pulplett interferometer is used as a diplexer. However, these quasi-optical devices are bulky and have comparatively limited instantaneous bandwidth.

A Virginia Diode solid-state, 210-270 GHz LO source will be used to drive the array. The LO is driven from an Agilent K-band synthesizer and does not require subsequent phase locking or mechanical tuning. The LO is capable of providing $\sim$ 2 mW of power across the band, more than sufficient to drive the array. The LO power divider is cooled to 4 K, all other components in the chain operate at room temperature. A standard waveguide vacuum feedthrough conveys the LO power into the cryostat. The cryostat has a single 40 K radiation shield. A waveguide thermal choke (Hesler 2003) on the 40 K shield will be used to



a) b)

Figure 8: a) SSB Noise performance and b) image suppression of the 250 GHz ALMA mixers to be used in the Desert-STAR 2x2 array at 230 GHz.

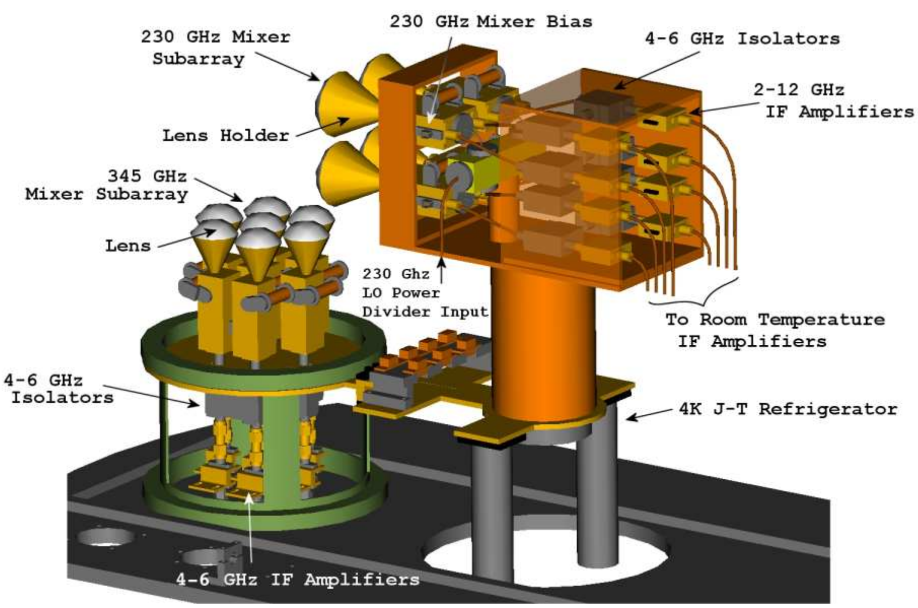


Figure 9: 230 GHz subarray assembly. The LO power divider mounts just behind the mixers. Pamtech isolators are used between the mixers and the Weinreb IF amplifiers.

isolate the 300 K input waveguide from the 4 K waveguide going to the LO power splitter.

Four-way LO power division will be achieved in waveguide using 3 branching, E-plane Y-junctions (Kerr 2001). The LO power splitter mounts just behind the mixer array (See Figure 9). Output power from the power divider is coupled to the LO port of each mixer through a short length of WR 3.7 waveguide. A CAD drawing of the full implementation of the DesertSTAR II system as it will look on the HHT is shown in Figure 10.

3.4 IF System

As outlined above, each 230 GHz array pixel contains two balanced mixers. The IF bandwidth of each mixer and the subsequent low-noise amplifier can be made quite broad (4-8 GHz). Indeed, for our array application it is the availability of backend spectrometers that limits system bandwidth. As with the 345 GHz array, we have chosen a 2 GHz IF bandwidth centered on 5 GHz. The same type of Pamtech 4-6 GHz isolators used between the mixer and 1st IF amplifier of the 345 GHz array will also be used here. The

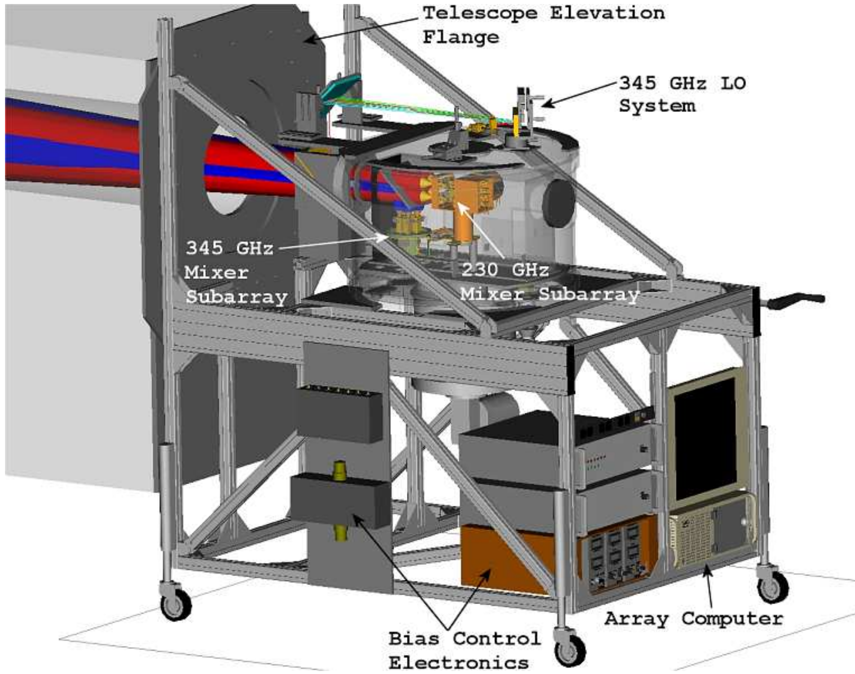


Figure 10: Cut-away view of the DesertSTAR II system with both the 345 GHz and 230 GHz arrays implemented.

cryogenic amplifiers for the array will be built by Sandy Weinreb at Caltech (see attached letter of support). These MMIC amplifiers have excellent performance, providing ~ 5 K noise temperatures and ~ 35 dB of gain over our entire IF band. The amplifiers also have low power dissipation (~ 10 mW). For the entire subarray 8 amplifiers are needed. The existing cryogenic system can easily cool the amplifiers to 4 K. Once at room temperature, the 2 IF outputs of each SSB mixer pass through an IF hybrid. The two output ports of the hybrid contain the upper and lower sidebands of the incoming radiation. In the majority of observing programs the desired spectral information resides in only one of the two sidebands. Naturally, one way to simplify the system and reduce cost is to perform further processing on just one of the sidebands. However, the optimal sideband can change depending on system performance and atmospheric constraints. Kerr 2003 has demonstrated that it is possible to switch sidebands on the output ports of an IF hybrid by simply changing the polarity of the mixer bias voltages. As with the 345 GHz array, the 230 GHz mixer bias voltages will be computer controlled. This feature will allow us to easily switch between sidebands and simplifies the IF processor design. A block diagram of the IF processor is shown in Figure 11.

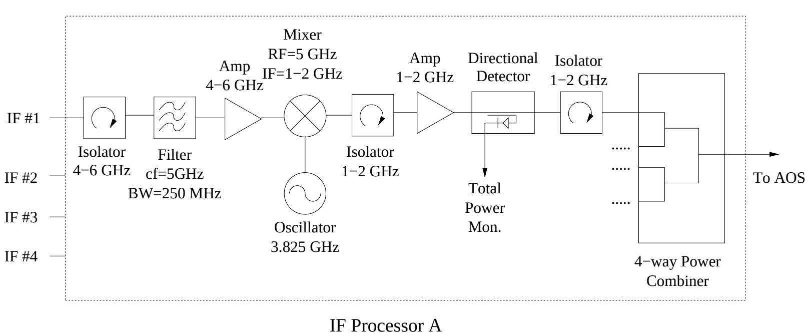


Figure 11: Block diagram of 230 GHz array IF processsor.

3.5 *Array Spectrometer*

The room temperature IF chain will amplify, condition, and then downconvert the IF of each 230 GHz SSB mixer to the baseband frequency required by the spectrometer. To service the array we plan to divide the passband of one of the HHT facility 1 GHz wide, 1 MHz resolution AOS's into four, 250 MHz sub-bands. An effective IF bandwidth of 250 MHz means each array pixel will have 326 km/s of velocity coverage at 1.3 km/s resolution. This velocity coverage and resolution is well suited to the requirements of a Galactic plane survey.

3.6 *Array Bias Control System*

A computer controlled array bias system has already been developed by the PI's group and is currently being used with their 4-channel, SIS 810 GHz array (PoleSTAR) on the AST/RO telescope at the South Pole and the 7-channel, 345 GHz array. The system allows manual tuning of each mixer and amplifier, plus automated bias point selection. All voltages (and currents) are controlled and monitored through a flexible graphical user interface (GUI) written in C. The control system is already designed to be extensible to 100 or more channels. The existing DesertSTAR system can be readily modified to accommodate the additional mixer, magnet, and IF amplier bias requirements of the proposed array.

3.7 *On the Fly Mapping*

The most efficient mode of data collection with a focal plane array and one which produces the highest fidelity images is On-the-Fly (OTF) mapping. In this mode, the telescope continuously scans back and forth across a field while the backends are read-out at a sufficent rate to eliminate aliasing and beam smearing (typically 4x/beam). The primary advantage of OTF mapping with an array is that a given position on the sky is observed by all pixels in the array. This redundancy removes any noise and gain imhomogeneities between pixels and reduces the degree to which the data are correlated as a singular off-source measurement is distributed to on-source data.

Mapping projects at the HHT routinely and efficiently use the OTF technique. However, the primary challenge of OTF mapping is data management and the co-add and resampling of data onto a regular grid. This challenge is particularly acute with an array for which the data rates are typically 10x larger. We therefore plan to adopt the scheme developed at FCRAO for OTF mapping with the 32 pixel SEQUOIA array (see `http://www.astro.umass.edu/~fcrao/library/manuals/otfmanual.html`). In this scheme, a scan consists of all data from all pixels taken between and including the two bookend off-source measurements. An OTF map may be comprised of several of such scans. The header for each scan is written into a relational data base program (MySQL) which facilitates efficient logging and retrieval of the data. The observer executes a gui-based program, (*otftool*, which accesses the data base, consolidates the requested scans into a list, provides tools for inspecting the raw data, and most importantly, co-adds and resamples the data onto a regular grid. The output is a FITS cube or Grenoble/CLASS file. Access to these data products to the greater scientific community will be provided through a Java-based web browser interface that will interface with MySQL and the FITS data cubes.

3.8 *Plan of Action*

Year 1

During the first year of funding our efforts will be focused on building and testing one complete 230 GHz array channel. Critical tasks include:

1. repackaging the ALMA band 6 (230 GHz) mixer to meet the optical requirements of the array. As part of this work we will design, fabricate, and test an IF matching/bias network for the balanced mixer.

2. building the subarray bias control system. This system will be very similar to what we have developed for our earlier arrays. The hardware and software will be expanded to handle the 16 single-ended mixers that make up the 4 balanced, sideband-separation mixers.

3. building one complete channel of the IF processor.

4. characterizing the performance of the prototype mixer. Sensitivity, stability, sideband separation ratios, and beam patterns are some of the properties that will be measured. This work will be performed using the same cryogenic testbed (wet dewar, optics, data acquisition system, antenna range) employed in testing the individual 345 GHz mixers.

Year 2

In the second year we will complete the construction of the subarray and conduct performance tests in the array cryostat. Tasks include:

1. fabricate and test the remaining three SSB mixers.

2. fabricate and test the 4-way LO power splitter.

3. design and fabricate the cryogenic assembly that houses the mixers, LO power splitter, isolators, and IF amps.

4. install the subarray in the close-cycle cryostat and characterize its performance.

Year 3

In the third year our goal will be to install the upgraded, dual-frequency, DesertSTAR system on the HHT and begin commissioning observations of the Galactic plane and selected star formation regions.

4 Education and Public Outreach

The proposed 230 GHz array will become part of the DesertSTAR facility instrument on the HHT, available to all users. A key project for the instrument will be to conduct a sensitive, high angular resolution, CO $J = 3 \rightarrow 2$ and $J = 2 \rightarrow 1$ survey of the Galactic plane. Survey data products will be made available to the general scientific community via the web in a timely manner. A Guest Observer Program will be established to facilitate use of the array by outside users.

The training of students in the development of state-of-the-art instrumentation is essential to the future of science. This is particularly true in mm/submm astronomy where technological advances are happening so rapidly. Ironically, there are only a handful of laboratories in the world where students gain hands-on experience in the design, fabrication, and fielding of radio astronomy instrumentation. In the PI's lab we have been fortunate to have had a number of talented students pursue their research. Over the past 10 years the lab has produced 6 Ph.D.'s and numerous undergraduate senior projects. All the Ph.D.'s are still pursuing astronomical research and a number of the undergraduates have gone on to receive Ph.D.s at other institutions. In recent years research in the lab has drawn an increasing number of students from other departments, particularly optical sciences and electrical engineering. Many students in science and technology have an interest in astronomy. It is this interest and the interdisciplinary nature of the research that attracts them to the PI's lab. In an effort to reach this population of students, the PI and fellow faculty members in other departments are seeking to establish an interdisciplinary program in astronomical instrumentation. Two of the PI's past Ph.D. students have received majors and minors in different departments. The PI currently has 4 graduate and 2 undergraduate students participating in interdisciplinary studies.

In the proposed budget, funds for only one graduate student are requested. The development and ultimate use of the array on the HHT will be the focus of the students research. However, as has been the case for all major projects in the PI's lab, a number of other students will also participate in making the progress a success. Indeed, one of the most important aspects of training students in instrument development is giving them experience in working in teams. Astronomical instrumentation is becoming ever more complex, with their successful implementation requiring the talents of many individuals. Providing students with both technical training and team-work experience increases their probability of success.

5 Results from Prior NSF Support

- A NSF Young Investigator Award (AST-9457445) was made to the PI for the period 7/1/94 - 7/1/99 of $62,500 per year (matching funds have been obtained for all 5 years). This award was used to support research and teaching efforts. Research included further development of the laser micromachining waveguide technology, the construction of submillimeter receiver systems at 230 and 490 GHz for the Arizona/MPIfR Submillimeter Observatory, a 492/810 GHz receiver system for the AST/RO telescope at the South Pole, the funding of graduate and undergraduate students for the study of protostellar evolution, and the construction of a submillimeter polarimeter and student radiotelescope. The receiver systems described above are (except for the polarimeter) facility instruments. We estimate $\sim$ 30 papers from the HHT and 20 papers from AST/RO will contain observations made with these instruments. Papers describing the instruments are Groppi et al. (2000), Walker et al. (2001).

- A grant (AST-9622569) from the NSF ATI program was made to the PI to construct the 7-channel, 345 GHz array (DesertSTAR I) for the HHT. (formal title: "An 870 micron Array Receiver for the Heinrich Hertz Telescope") The award period was from 8/1/96 - 7/31/99 for a total of $380,931. DesertSTAR has been a successful collaboration between the University of Arizona (PI: system design and construction), NRAO (John Payne: J-T cooler), the University of Massachusetts (Gopal Narayanan and Neil Erickson: mixers and LO), and the University of Virginia (Art Lichtenberger: SIS junction fabrication). It will be the first array receiver to operate in the 870 micron atmospheric window (Groppi et al. 2000; 2002).

- An award (ECS-9800260) from the NSF Physical Foundations of Enabling Technologies Program was made to the PI to construct and utilize a laser micromachining system at the University of Arizona (Drouet d'Aubigny et al. 2001). The award period was from 6/1/98 - 5/31/00 for a total of $280,000. The system is fully operational and has been used to make waveguide components for integrated array development and prototype quasi-optical structures for NASA's *Terrestrial Planet Finder*.

- A grant from the NSF ATI program was awarded to the PI and Co-I Daniel Prober (Yale University) to develop "An Integrated 370 micron Heterodyne Imaging Array". This is an ongoing effort to combine laser micromachining technology with recent developments in Hot Electron Bolometer (HEB) mixers to develop the first truly integrated submillimeter-wave heterodyne imaging arrays (Groppi et al. 2002). The arrays are being designed to permit scaling to higher frequencies and formats. The award amount ($450K) is being divided over a three year period (02/01/02 to 01/31/05) between the participating institutions.

- A subaward of $99,348 was provided to the PI from the NSF ATI program for his contribution to "A 1.5 THz Common User Receiver System" (S. Yngvesson- PI). Over the two year award period (01/01/00 to 12/31/02) the PI's group designed and built the cryogenic, electronic, and optical system for the TREND 1.5 THz receiver system now on the AST/RO telescope at the South Pole. The laser LO system and high frequency mixer were provided by the University of Massachusetts (Yngvesson et al. 2002).

- A subaward of $290K from the NSF Office of Polar Programs was made to the PI for his group's work in "Continuing Operation of the Antarctic Submillimeter Telescope and Remote Observatory" (A. Stark- PI: OPP-0126090). The PI's group built most of the facility receivers for AST/RO. This 3 year award (02/01/02 to 01/31/05) supports the continued maintenance and upgrade of these systems (Stark et al. 2002).