SUMMARY OF PERSONNEL AND WORK EFFORTS

			Work Commitment		
Name	**Organization**	**Role**	**Year 1**	**Year 2**	**Year 3**
Dr. Christopher K. Walker	Univ. of Arizona	PI	10%	10%	10%
Dr. Gordon Chin	NASA/GSFC	Co-I	10%	10%	10%
Dr. Jonathan Kawamura	JPL	Co-I	10%	10%	10%
Mr. Jacob Kooi	Caltech	Co-I	. . .[a]	. . .	. . .
Dr. Craig Kulesa	Univ. of Arizona	Co-I	25%	25%	25%
Dr. Gopal Narayanan	Univ. of Massachusetts	Co-I	10%	10%	10%
Dr. Art Lichtenberger	Univ. of Virginia	Co-I	10%	10%	10%
Dr. Sander Weinreb	Caltech	Co-I	. . .	. . .	. . .

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[1] Dots (. . .) represent contributed effort.

Development of Space Terahertz Array Receivers (STARs)

1 Objectives and Significance of the Proposed Research

The advent of large format (∼100 pixel) spectroscopic imaging cameras in the far-infrared (FIR) will fundamentally change the way astronomy is performed in this important wavelength regime. While the possibility of such instruments has been discussed for more than two decades (Gillespie & Phillips, 1979), only recently have advances in mixer technology, device fabrication, micromachining, low-noise amplifiers, and digital signal processing made the construction of such an instrument tractable. Here we propose to implement these technologies to develop the first integrated, far-infrared heterodyne arrays. The arrays will utilize state-of-the-art SIS and phonon-cooled Hot Electron Bolometers (HEB) mixing devices in efficient, micromachined, waveguide mounts. The goal of the proposed effort is to demonstrate the viability of large format arrays in the FIR by developing proof-of-concept compact, integrated, 1x8 SIS and HEB array receivers at 810 GHz and 1.5 THz respectively. The arrays will serve as building blocks for much larger 2 dimensional arrays. As a technological demonstration, the prototype arrays will be incorporated into a dual polarization receiver system for use on the AST/RO telescope at the South Pole. We have developed a work plan that will place this technology at a TRL of 4+ at by the end of the investigation. Once such arrays have been demonstrated, a technological roadmap to achieving the goal of large format, far-infrared (FIR) heterodyne arrays will become clear. The STARs team will submit an E/PO proposal to develop hands-on activities for grades K-12 based upon the proposed research activities.

2 Scientific Motivation

High Resolution, Spectroscopic Imaging Arrays in the Far-Infrared

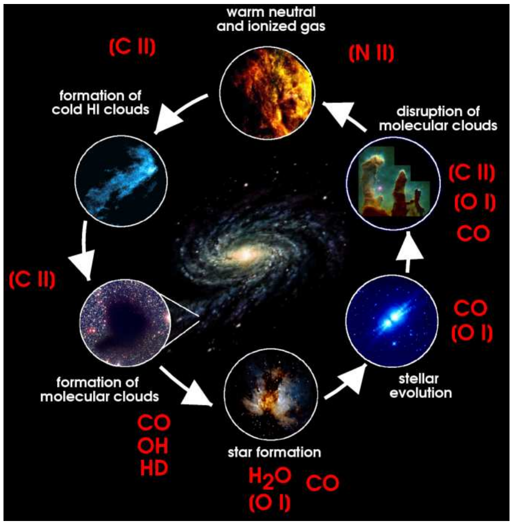


Figure 1: The life cycle of the interstellar medium and the stars that form from it; this relationship constitutes the basis for the evolution of galaxies, including our own Milky Way. Throughout this cycle, different (labeled) ionic and molecular species with strong emission lines at far-infrared and submillimeter wavelengths play pivotal roles in shaping the relevant physical processes.

The wavelength regime between 300 and 60 microns hosts numerous atomic and molecular emission lines that are key diagnostic probes of the interstellar medium. These include transitions of [C II], [N II], [O I], HD, H_2D^+, OH, CO, and H_2O. In Giant Molecular Clouds (GMCs), evolved star envelopes, and planetary nebulae, these emission lines can be extended over many arc minutes and possess complicated line profiles that can only be disentangled using high resolution ($R = \lambda/\Delta\lambda > 10^6$) spectroscopy. Observations of these lines are crucial to understanding the delicate interplay between the interstellar medium and the stars that form from it (see Figure 2). This feedback is central to all theories of galactic evolution, and it must be understood at high angular resolution in the Milky Way before it can be properly interpreted in external galaxies near and far. These spectral lines are pivotal probes of important physical processes because they relate directly to the chemistry and energy balance of the ISM; it is the cooling provided by these lines that partially regulates the collapse of molecular cloud cores into stars and traces the formation of molecules in evolved stars that ultimately replenish the ISM. Due to the hot (T $\geq$ 300K) and dense ($n_{\mathrm{H}} > 10^{10}$ cm^{-3}) conditions expected in many protoplanetary disks, emission lines in the FIR will also play a pivotal role in cooling and molding young planetary systems. Both high spectral resolution and imaging capabilities are necessary to probe velocity fields and disentangle the emission of protoplanetary disks from that of ubiquitous molecular outflows and ambient envelope and cloud material.

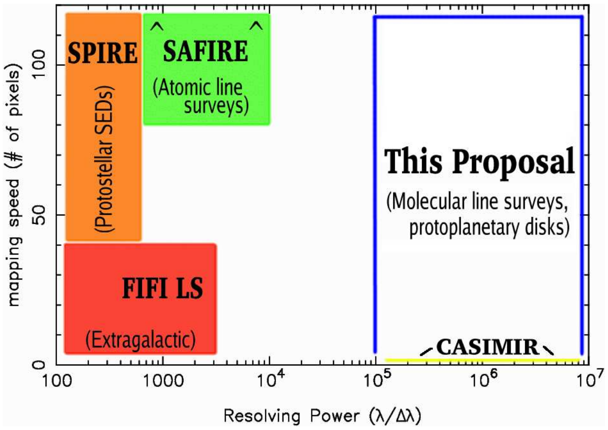


Figure 2: Overview of SOFIA/Herschel Terahertz-frequency spectroscopic instruments in development. The proposed instrument will provide a technological roadmap to making heterodyne arrays with 100+ pixels.

The only instruments capable of realistically providing the required spectral resolution and spatial coverage for these studies are heterodyne array receivers. Unfortunately, above 1 THz none exist. Figure 2 compares the capabilities of SOFIA & Herschel's first light instruments in terms of number of pixels versus spectral resolution. When viewed in this way, there is a clear, urgent need for large format heterodyne instruments (Young et al. 2003). Fortunately, recent breakthroughs in detector technology, micromachining, local oscillators, amplifier technology, and backend spectrometers now make the construction of large arrays of heterodyne receivers possible. The proposed array development will not only provide a technological roadmap for large format spectroscopic imaging cameras, it will also serve to demonstrate how such arrays can maximize the scientific return from single aperture telescopes such as AST/RO, the South Pole Submillimeter Telescope (SPST), SOFIA, and SAFIR. In terms of relevancy to the OAT program, the proposed work will help fulfill Goal 10, Mission and Science Measurement Technology Theme, RFA 10.2(b).

We have assembled a team with experience in each aspect of the proposed investigation. Members of this team have worked together in the past on a number of successful projects, including:

- a 4 pixel, 810 GHz SIS array receiver (PoleSTAR) for AST/RO
- a 1 pixel, 1.1 THz HEB receiver for the Heinrich Hertz Telescope (HHT)
- a dual polarization 492/810 GHz receiver for AST/RO
- a 7 pixel, 345 GHz SIS array receiver (DesertSTAR) for the HHT

The HEB and SIS array receivers are the first astronomical receivers of their kind. As in the proposed work, waveguide technology was used to optimize mixer performance in each of these instruments. Representative spectra taken with these instruments are shown in Figures 3 and 4. The experience gained in building these instruments will be fully utilized in the development of the proposed integrated arrays.

3 Technical Approach

Unlike the situation with bolometric detectors, heterodyne receiver systems are coherent, retaining information about both the amplitude and phase of the incident photon stream. High resolution spectroscopy

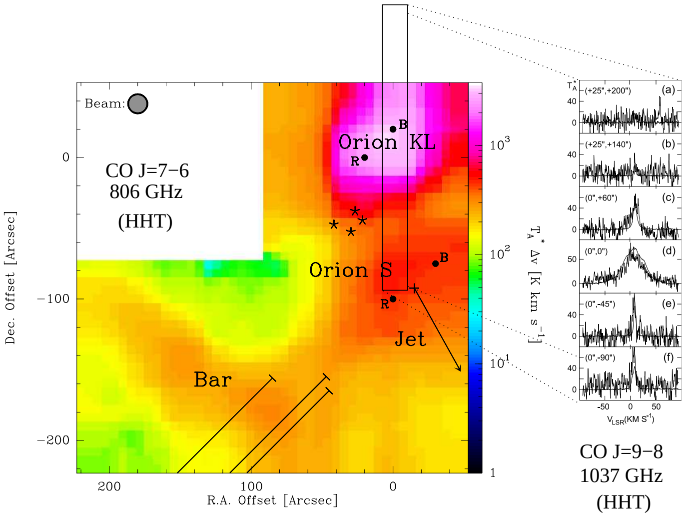


Figure 3: Integrated intensity of the J = 7 → 6 line of CO from the Orion molecular cloud, observed at the Heinrich Hertz Telescope on Mt. Graham, Arizona (Wilson et al., 2001). The intensity scale is shown as a bar on the right side of the map. Selected positions of the map have been measured in the 1.037 THz line of CO J = 9 → 8 from the HHT (Kawamura et al., 2002), and are displayed on the far right. This demonstrates the feasibility of near-THz submillimeter astronomy from ground-based observatories.

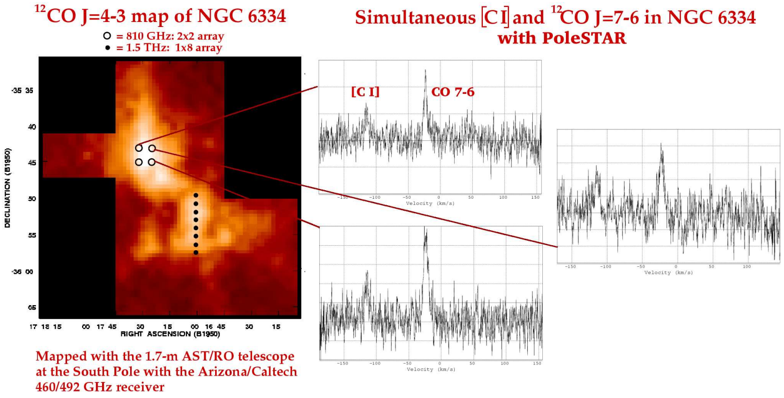


Figure 4: Integrated intensity map of the J=4→3 line of CO from the NGC 6334 molecular cloud. The first heterodyne array spectra at 810 GHz are shown at right, taken with 3 of the 4 channels of the PoleSTAR array at AST/RO, built by the PI's group in collaboration with teams at the University of Cologne and Caltech. The footprint of the proposed 1x8 array at 1.5 THz is shown for comparison.

can, in principle, be performed in this same wavelength regime using incoherent detectors together with frequency dispersive quasi-optical devices such as gratings and Fabry-Perot interferometers. However, the size requirement of quasi-optical devices and/or the need to scan in order to construct a spectrum make them too cumbersome or insensitive for many applications.

In the past the fabrication of integrated arrays of heterodyne mixers at submillimeter wavelength was prohibited by several factors:

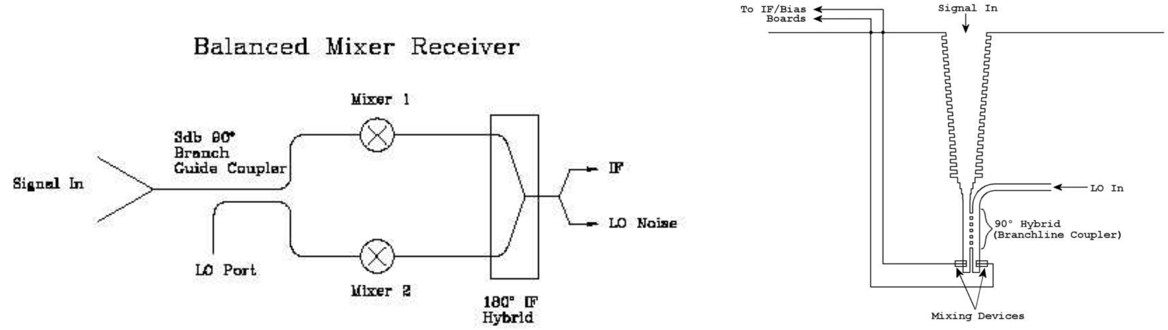
- Sensitive mixing devices either did not exist or were difficult to fabricate.
- When mixers were available, their performance would often vary significantly from device to device.
- There was insufficient LO power to simultaneously pump more than one or two detectors.
- Stacking more than a few mixer blocks together in the focal plane with their associated backshorts (if necessary), IF amps, magnets, bias lines, etc. was mechanically complex and could overload the cryogenic system.
- The cost of the frontend components and the required backend spectrometer were prohibitive.

However, through the arduous efforts of many researchers, most of these hurdles have now been overcome.

3.1 Mixer Design

At frequencies above 200 GHz no amplifiers exist and incoming signals must first be down converted to frequencies where low noise amplifiers are available. At these high frequencies three types of mixing devices are currently in use; Schottky diodes, superconductor insulator superconductor (SIS) junctions, and hot electron bolometer (HEB) mixers. Schottky diode mixers have been in use on ground, airborne, and space-based platforms for many years. They are reliable and provide modest sensitivity, which improves as they are cooled. However, they require prodigious amounts (of order mW) of local oscillator (LO) power to work efficiently. At submillimeter wavelengths gas lasers are often used to provide this level of LO power. Both SIS and HEB mixers utilize superconductors to realize significant increases in sensitivity over that of Schottky devices and require orders of magnitude less LO power. State-of-the-art SIS mixers have 30 times the sensitivity of the Schottky mixers used on SWAS and the two Microwave Limb Sounder (MLS) instruments. SIS mixers are used to 1.2 THz. Above this frequency the bandgap structure of SIS devices severely limits their performance and HEB mixers are employed. To operate, these mixers must be cooled to ~ 4 K. We propose to develop prototype 1x8 arrays of SIS and HEB mixers. The SIS array will be optimized for observing the ~ 810 GHz lines of [^{12}CI], [^{13}CI], and CO ($J = 7 \rightarrow 6$). The HEB array will provide low noise performance between 1.4 to 2.2 THz. Over this frequency range several astrophysically important lines occur, including [NII] and [CII].

Most receivers currently in operation at millimeter and submillimeter-wave observatories utilize simple, single-ended, DSB mixers. For our array development work we will utilize a balanced mixer architecture. Balanced mixers have two principal advantages: (1) sideband noise from the LO is suppressed (the sideband noise can get significant with the large multiplications required for THz LOs), and (2) all the available LO power is coupled into the mixer, eliminating the need for cumbersome, lossy, band-limiting, quasi-optical diplexers (e.g. Martin-Puplett or Fabry-Perot interferometers). The main disadvantage of balanced mixers compared to traditional single-ended mixers is that they require two mixing devices operating in quadrature. However, with modern micromachining and photolithographic processing techniques it is now possible to fabricate entire balanced mixer receivers in a single mixer block and achieve the device uniformity required for proper operation.



a) b)

Figure 5: a) Overview of balanced mixer topology: the sky and LO signals are coupled to the individual mixers through a quadrature hybrid. IF output is combined either by opposite biasing of the two mixers, or with a 180° IF hybrid. b) Pictoral representation of how the balanced mixer topology will be realized in an array mixer.

One common topology of balanced mixers is one in which the signal and the LO are coupled to the individual mixers through a quadrature hybrid (see Figure 5a). A 180 degree IF hybrid then combines the IF output of the two mixers, so that all the down-converted signal appears in one port and all the LO noise appears at the other port. It is possible to omit the IF hybrid and simply connect the two IF ports in parallel, if the two mixers are biased with opposite polarity (Kerr, 2003).

Figure 5b is a pictoral representation of how the balanced mixer topology will be realized in an array mixer. A scalar feedhorn residing in the telescope's focal plane efficiently couples energy into full height rectangular waveguide. A branchline coupler (Claude et al., 2000) functions as the 90° hybrid. The waveguide output of the feedhorn goes into one input port of the coupler and LO power into the other. Each output port of the hybrid contains both signal and local oscillator power. These are mixed by either an SIS or HEB device (depending on the design frequency) fabricated on a thin ($\leq 2\ \mu$m) SOI beamlead substrate that partially extends across each output waveguide. LO power enters the mixer block from the back and is distributed to each mixer using waveguide power dividers. Since the 'rear' of the mixer block contains the LO power distribution system, the IF output of each mixing device is conveyed via coplanar waveguide on silicon (in the 1.5 THz block) or a microstrip PC board (in the 810 GHz block) to bonding pads on the 'front' (horn side) of the mixer. An IF distribution board is bump-bonded to the front of the mixer block (see Figure 6). Clearance holes are drilled in the board at the location of each horn aperture. The mixer block/IF distribution board assembly is mounted onto an array motherboard containing mixer bias and IF power combining circuitry. The power-combined IF outputs are amplified by low-noise, MMIC devices also mounted on the motherboard. The mixer and IF amplifier operate at 4 K. A novel microstrip ribbon cable carries the IF's from all 8 mixers in the array to a break-out board located on the 80 K radiation shield of the array cryostat. A 3-D CAD rendition of the array subassemblies is shown in Figure 6. Below we discuss how the subassemblies will be fabricated.

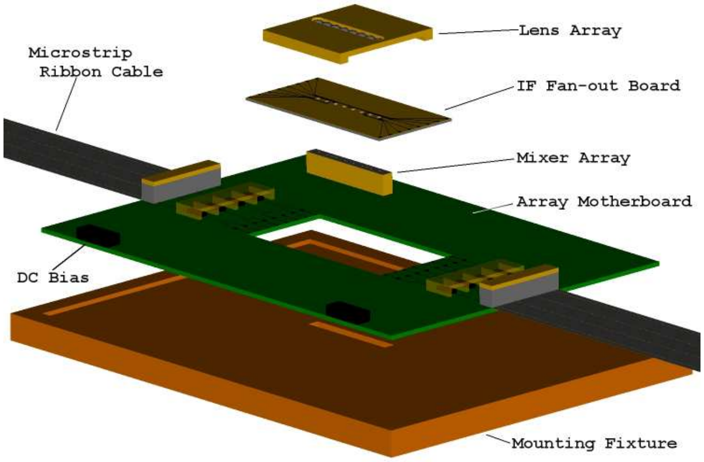


Figure 6: CAD representation of an array subassembly.

3.2 *Waveguide Mount*

Excellent progress in the development of submillimeter-wave SIS and HEB mixers has been demonstrated in recent years. At frequencies below 800 GHz these mixers are typically implemented using waveguide techniques, while above 800 GHz quasi-optical (open structure) methods are often used. In many instances the use of waveguide components offers advantages over quasi-optical techniques. The principal advantages of waveguide are:

1. Due to its larger cross sectional area, waveguide has a lower loss per unit length than any other transmission line. At any frequency they can be built, waveguide mixers are capable of providing the lowest noise performance.

2. High efficiency, $\sim$ 99%, feedhorns can be used to couple energy in and out of waveguide circuits. In comparison, the dielectric lens-planar antennas used with quasioptical mixers typically have an efficiency $\leq$ 89% (Goldsmith, 1998).

3. As discussed above, balanced mixers offer several significant advantages for array applications. When implemented in waveguide, the mixing devices can be configured so they can be reversed bias relative to each other. With this arrangement the IF output of each mixing device can be combined in a simple microstrip Wilkinson power combiner, obviating the need for a bulky IF hybrid (Kerr, 2003). In quasioptical balanced mixers the mixing devices are biased in series. In this instance, an IF hybrid is required, making it difficult to realize compact, integrated arrays.

4. With waveguide, over half a century of technological developments can be brought to bear on a problem. Recent advances in micromachining techniques, together with the availability of sophisticated E&M modelling software permit the scaling of successful waveguide well into the far-infrared (Walker et al., 1998).

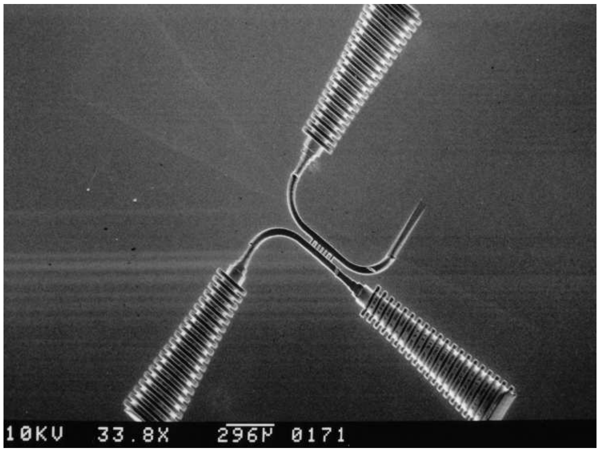


Figure 7: SEM imaging of a 1.5 THz branchline coupler based on the ALMA design, fabricated in 2003 using the laser micromachining system at the University of Arizona.

At THz frequencies, the hardest part of realizing a balanced, waveguide mixer design is the input quadrature hybrid. A 3 dB, 90 degree hybrid can be realized in waveguide using a branch-line coupler. The branch-line coupler consists of two or more quarter wavelength sections (branches) that bridge across a pair of waveguides, between the broad walls. A six-branch, branch-line hybrid with a percentage bandwidth of $\sim$ 30% has been designed and tested at WR-10 for ALMA receivers [4]. The width of the branch-lines at 100 GHz was 15 mils. Scaling these dimensions to 1.5 THz, the width of the required branch lines is $\sim$1.0 mils. Using the laser micromachining system at the University of Arizona, we have succeeded in fabricating a 1.5 THz branchline coupler based on the ALMA design. A photograph of a laser micromachined 1.5 THz split-block, quasioptical power combiner that utilizes a branchline coupler is shown in Figure 7. An array of 1.5 THz corrugated feedhorns made with the same system is shown in Figure 8. With the laser micromachining system these structures are etched in silicon and then plated with several skin depths of gold to make them behave as traditional hollow waveguide. At the University of Massachusetts a complementary micro-milling system has been developed which is also capable of machining similar waveguide structures directly in copper (Narayanan, Erickson & Grosslein, 1999). The two micromachining approaches are quite complementary. The laser micromachining system can make small waveguide structures to micron accuracy, but has relatvely low volumetric removal rates. It is best suited for making waveguide structures above 1 THz. The UMass system is not optimized for making structures as small, but has higher volumetric removal rates. In the proposed development effort, the University of Arizona will laser machine the 1.5 THz mixer array. The University of Massachusetts will use their micromilling system to fabricate the 810 GHz array.

3.3 *Mixing Devices*

3.3.1 *Probe Design*

Over the years a number of waveguide to microstrip transitions have been proposed; most of which are implemented in reduced height waveguide with <35% RF bandwidth (Tong et al., 1996). Unfortunately reducing the waveguide height makes machining of mixer components at THz frequencies more difficult. It also increases RF loss as the current density in the guide is increased. An additional disadvantage of existing high frequency waveguide mixers is the way the active device (SIS, HEB, Schottky diode) is mounted in the waveguide. Traditionally the junction, and its supporting substrate, is positioned in a narrow channel across the waveguide. This structure forms a partially filled dielectric waveguide, whose dimensions must

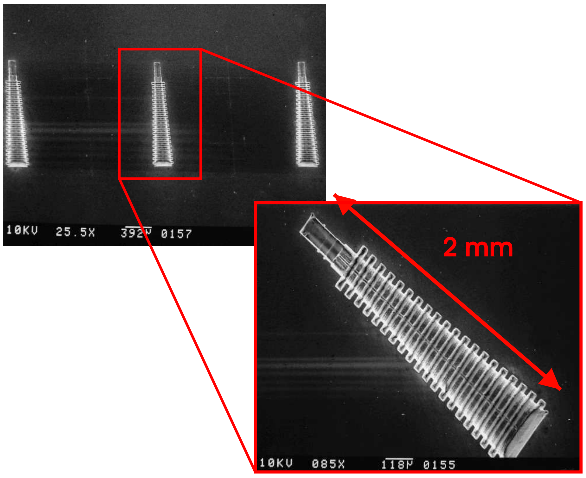


Figure 8: SEM of three laser-machined 1.5 Thz corrugated horns in a 1 × 10 array, demonstrating the accuracy and consistency of the Arizona micromachining system.

kept small to prevent energy from leaking out the channel. At frequencies exceeding a THz this mounting scheme becomes impractical. Because of the fabrication and mounting challenges, quasi-optical mixers are typically used at the shorter wavelength. However, published results from quasi-optical THz mixers have all been single pixel, and their designs are not readily scalable to the kind of imaging arrays we are proposing to build.

We believe that to move forward into the THz regime a much more integrated approach is required. To do so however one has to consider the requirements of the actual mixing device. For frequencies >1 THz phonon-cooled, hot electron bolometer (HEB) mixers have demonstrated the best performance (Khosropanah et al., 2003; Yngvesson, 2003).

The IF bandwidth of phonon-cooled HEBs is directly related to how rapidly accumulated heat can be dumped to the thermal bath. Therefore the device mounting must provide an efficient heat conduction path. Secondly, HEB mixers exhibit extremely large instantaneous bandwidth at signal frequencies. Though advantageous in many respects, one has to be careful to avoid saturating the device with incident thermal radiation. A waveguide structure naturally does this. Thirdly, HEB devices produced to date have not proven to be very uniform across a wafer. Thus basing an entire focal plane array on the uniformity of single wafer is risky. A better approach is to have a design of many densely packed HEB mixer chips that (after processing) can be RF pre-selected. The added advantage of such a design is that the chips can be used in any type of mixer configuration, e.g. array, balanced or sideband separating.

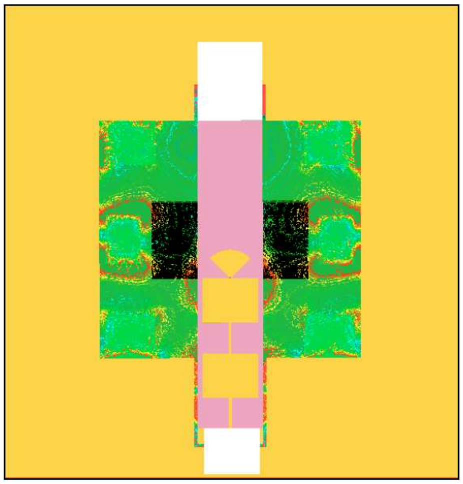


Figure 9: Top view of the silicon beamlead chip. Note how the photonic crystals (just 4 μm in height) help disperse the E-field leakage outside the waveguide. The beamlead chip is suspended in 6 μm of "air".

Fortunately, development in several key areas make it now practical to consider integrated imaging arrays for the THz regime. For one, laser micromachining techniques allow successful waveguide designs to be scaled to THz frequencies (Walker et al., 1998). Secondly, GaAs beamlead techniques in high frequency multipliers have been used with great success (Schlecht, et al., 2001; Chattopadhyay et al., 2002). We propose to use a similar beamlead approach for mounting HEB (and SIS) devices in our micromachined mixer blocks. Because of its excellent thermal properties and high device yields, we will make our beamlead device substrates out of silicon. The silicon beamlead substrates will provide an excellent cooling path for both HEB and SIS devices. Thirdly, a very broad bandwidth full-height waveguide to thin film microstrip transition has recently been reported on by Kooi et al. (2003). The combination of a 45% RF bandwidth and full-height waveguide turns out to be ideal for HEB THz mixer designs. Fourthly, extensive membrane experience (Kooi et al., 1998) has shown the importance to suspend the substrate. Fifthly, photonic crystals junctions (Hesler, 2001) can be used to suppress stray (or scatter) fields. Finally, progress in electromagnetic field simulation tools such as HFSS (Ansoft Corp., 2002) has given us an important tool in not only optimizing, but also analyzing the designs against misalignment in any special dimension. It should be noted that our design approach is equally well applicable to SIS arrays for frequencies below a THz. In the latter case the magnetic field required to suppress the Josephson currents will have to be applied uniformly across the entire wafer (HEB mixers do not require a magnetic field making them attractive mixing devices for larger scale spectroscopic imaging arrays). The UMass team will use Ansoft Maxwell 3D modelling software to design efficient magnetic field concentrators for the SIS array mixer block.

The results of an HFSS simulation of a 1.8 THz HEB silicon beamlead device suspended across full height waveguide is shown in Figure 9.

The silicon chip (described in Section 3.3.2) vertical alignment is set by the beamleads. Extensive HFSS computer simulations show the chip height variation to be very tolerant (Figure 10), and in any event to be much larger that the specified “SOI” (Si “device-layer”/insulator “thin” /Si “handle”) substrate variation of 0.5 μm. Sideways alignment of the beamlead chip is set lithographically, and is not an issue (small fraction of a wavelength). For the 1400–2200 GHz design, the silicon chip is suspended by 6 μm of space on both the top and bottom giving it an effective dielectric constant of 3.2. We anticipate using a combination of wet etching, reactive ion etching (RIE), and laser silicon micromachining techniques. All dimensions are well within the capabilities of these techniques. Test chips with less than 10 μm of clearance have been fabricated and yield no handling problems.

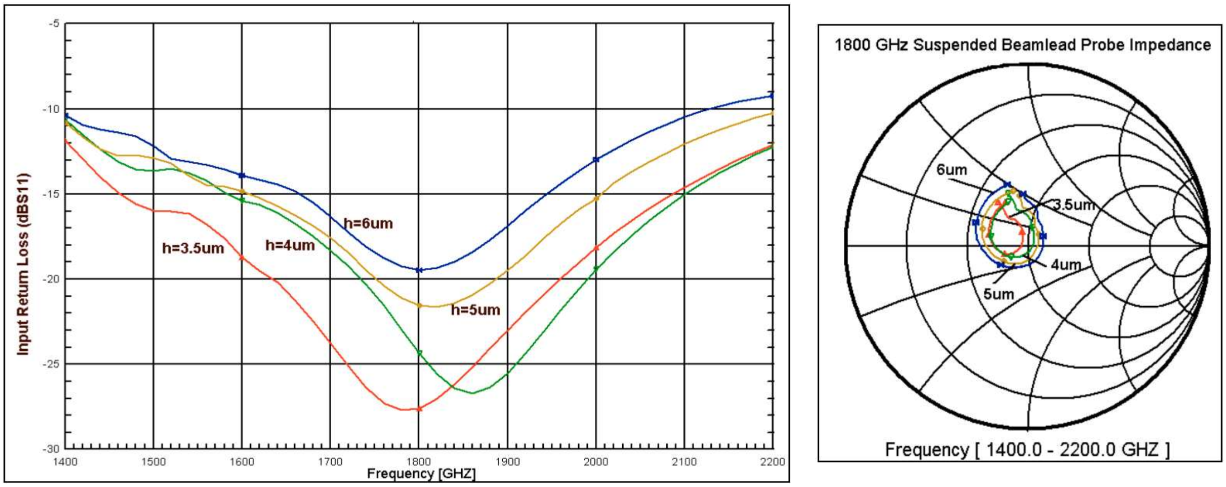


Figure 10: **[LEFT]:** Input return loss for the silicon beamlead chip as the substrate thickness is increased from 3.5 μm to 6 μm. In each case the backshort position was adjusted to optimize the results. It is evident that the silicon substrate height variation is very non-critical as long as the backshort depth is compensated accordingly. **[RIGHT]:** Beamlead chip input impedance. The impedance locus is centered around 40 Ω, which is determined by the structure. Varying the substrate height has little effect on the probe impedance, e.g. performance.

3.3.2 Beamlead Device Fabrication

At UVA we have developed a high yield, precise quartz beam lead process for SIS millimeter array applications (Bass et al., 2003a, 2002). We are currently working toward a Si based thin-chip beam lead process suitable for the micromachined HEB and SIS receiver applications discussed in this proposal. While our existing quartz based beam lead process uses a dicing saw and lapping to define the finished chip dimensions, the requirements of our proposed THz elements require much greater dimensional control than these techniques could afford.

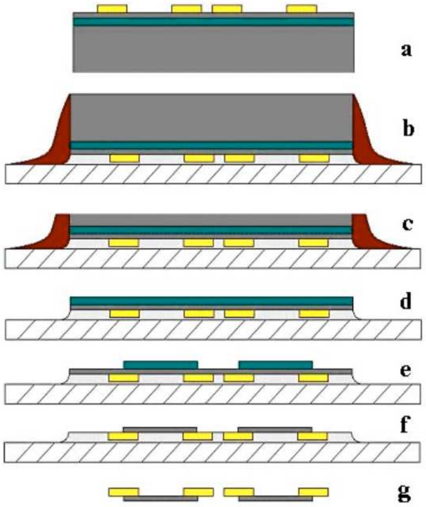


Figure 11: UVA SOI process for fabricating beam lead ultra thin Si mixers: (a) the beam leads and mixer circuitry are first fabricated atop an SOI wafer, (b) the SOI wafer is then mounted device side down on a glass carrier wafer and (c, d) the handle silicon removed, (e) the oxide layer is patterned and etched and (f) then used as a mask for an anisotropic Si reactive ion etch to precisely define the chip perimeter and then removed, and (g) the chips are complete following separation from the carrier wafer.

Our Si based approach begins by first fabricating the desired superconducting circuits atop the device layer of a "SOI" (Si'device-layer'/insulator'thin'/Si'handle') substrate. We have access to SOI wafers with Si device layer thickness between 0.5 and 10 μm with a tolerance of better than 0.5μm. The remaining beamlead process is shown in Figure 11. The beam leads are next fabricated using our established thick resist and plating process. The SOI chip is then mounted, device side down, atop a quartz carrier wafer using a clear mounting wax that has a melting point of ∼100C. Mounting the wafer with a transparent wax and carrier wafer allows for a subsequent backside lithographic alignment process to properly orient the wafer with respect to the circuit and beam lead structures for the subsequent precise chip perimeter lithographic and RIE steps. A combination of mechanical lapping and chemical etching is next used to remove the thick bulk "handle" silicon layer. The revealed oxide layer is next patterned using backside photolithographic alignment and RIE etching. The patterned oxide then serves as an etch mask for a reactive ion etch of the exposed device silicon. The device silicon is etched through to the quartz carrier and gold beam leads, thereby precisely defining the individual chips. The chips are then removed from the carrier wafer by dissolving the mounting wax.

To date we have developed an SOI wafer process (Bass et al., 2003b) that is compatible thermally and chemically with the processing of the HEBs and mixer circuitry on the SOI wafer. **Our initial efforts have demonstrated that we are able to fabricate chips with this process and handle Si chips with a single thickness (no frame) as thin as 1 micron as shown in Figure 12**. We have gone to pains to develop this process so that it will be compatible with our existing beam lead technology. Likewise, this process should also be compatible with our established HEB processes.

We propose to integrate this new SOI process with our existing beam-lead technology and our proven ability to fabricate HEB and SIS structures in order to fabricate ultra-thin chip beam-lead mixer elements suitable for the proposed integrated focal plane arrays. We have previously demonstrated the ability to form high yield beam lead structures on quartz. We have also an established HEB fabrication process using a focused ion beam (FIB) tool to carve the HEB structure (Datesman & Lichtenberger, 1999; Datesman et al., 2001). We have recently also developed a more traditional Ebeam resist process for fabricating HEB structures (Bass et al., 2003c). It should be noted that these processes are suitable for defining both phonon cooled and diffusion cooled HEB geometries. Our UHV magnetron sputtering system is also equipped for sputtering Nb and NbTiN films for these devices. In support of our ongoing array development efforts, our colleagues at Moscow State Pedagogical University have recently deposited high quality NbN films on SOI wafers for device fabrication at UVa. Devices made using Moscow State films are in wide use and have excellent performance.

With this SOI process we have excellent control of both final chip thickness and lateral dimensions to better than 0.5μm. Final chip thickness can also be measured in our laboratory to better than 100nm accuracy. Coupled with the capabilities of Arizona's and UMass' micromaching tools in forming the remaining waveguide blocks and 'accepting' fixturing for the beam lead arms, along with the use of UVA's FIB system for local trimming of the critical waveguide block features, we should be able to use this beam lead thin-chip technology with integrated receiver arrays to great advantage.

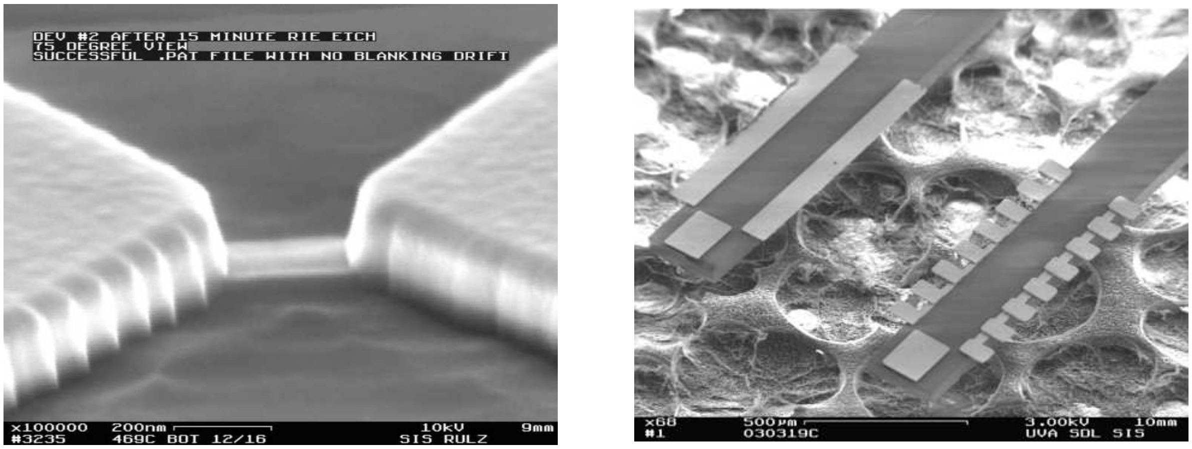


Figure 12: **[LEFT]:** SEM image of an HEB structure formed with our focused ion Beam (FIB) process. It should be noted that these processes are suitable for defining both phonon cooled and diffusion cooled HEB geometries. **[RIGHT]:** The chip is a prototype for future THz chip designs that will feature non-linear superconducting mixing elements, microwave circuitry, as well as thick gold beam leads. The gold beam leads will provide electrical and thermal contact for the chip. The beam leads will also serve as a mechanical support, allowing the chip to be suspended in the middle of a waveguide.

3.4 Local Oscillators

3.4.1 LO Power Distribution

With an array receiver LO power must be efficiently distributed between pixels. The balanced mixer architecture being proposed here is ideal for this purpose, allowing efficient, broad-band, waveguide power splitters to be utilized. A schematic representation of the proposed LO power distribution system is shown in Figure 13. LO power is coupled into the array via a scalar feedhorn. The power is then subdivided into 8 equal parts by a 'tree' network of 7, E-plane, Y-junctions (Narayanan & Erickson, 2002; Kerr et al., 2001).

All the mixer and LO waveguide components are machined together in a single split block structure. This is true whether the waveguide is laser machined in silicon or micromilled in copper. Guide pins are used to ensure alignment between the two halves of the block.

3.4.2 SIS – 810 GHz Array

The PI's team has recently completed construction of a 4-pixel, 810 GHz array receiver (PoleSTAR) for the AST/RO telescope at the South Pole (Walker et al., 2001). A photograph of PoleSTAR mounted on the focal plane of AST/RO is provided in Figure 14. A solid-state, JPL 810 GHz LO chain, a by-product of

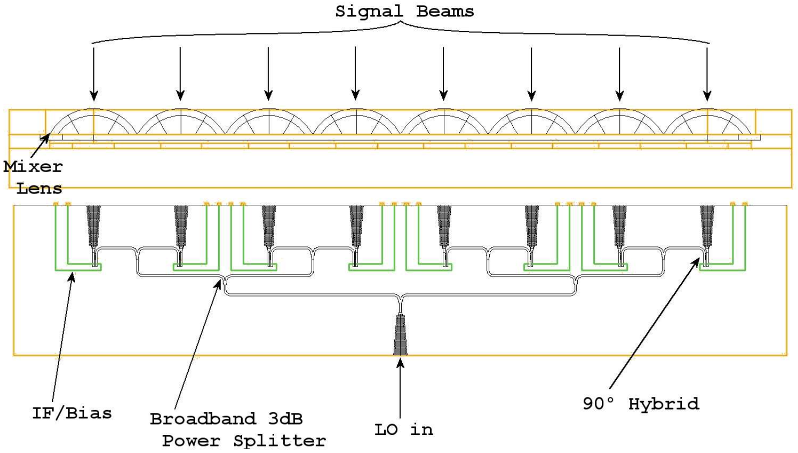


Figure 13: CAD representation of the LO power distribution system. LO power is coupled into the array via a scalar feedhorn, then subdivided into 8 equal parts by a ‘tree’ network of 7, E-plane, Y-junctions.

the *Herschel* program, is used with the array. The LO produces so much output power (~ 0.25 mW) that even after being split 4 ways a simple, Mylar beam splitter can be used to inject the LO into the signal beams. With the beamsplitter, only $\sim$ 3% of the LO power ($\sim 2\,\mu$W) actually makes it into each mixer. In contrast, the balanced mixer design being proposed here can theoretically couple LO power into the mixer with an efficiency approaching 100%. There could be as much as $\sim$ 12 dB of loss in the waveguide power splitter and there would still be enough LO power to efficiently drive all 8 mixers. LO power levels can be controlled by adjusting bias voltages on the multiplier or slightly detuning the Gunn oscillator driving the chain.

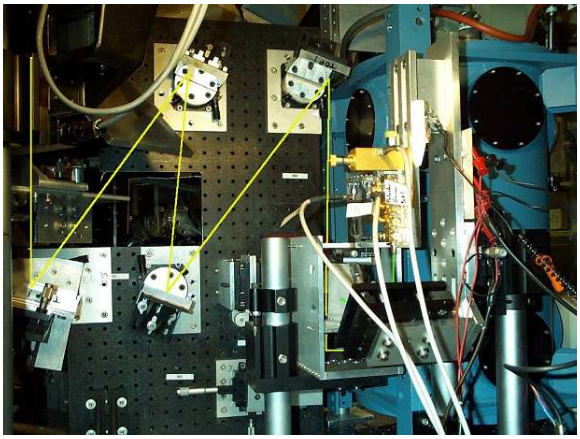


Figure 14: PoleSTAR, the PI’s four-pixel, 810 GHz array receiver mounted at the AST/RO telescope at the South Pole. Optical path through the focal plane reimaging optics is highlighted in yellow. The gold anodized solid state JPL 810 GHz LO chain is seen in the foreground.

3.4.3 HEB - 1.4 - 2.2 THz Array

The laser LO system for the 1.4 - 2.2 THz array has already been supplied by NASA/GSFC and is in operation in the PI’s lab (Figure 15; see supporting letter from Co-I G. Chin). The FIR laser system was designed and built by DeMaria ElectroOptics Systems (DEOS, now part of Coherent), of Bloomfield, Conn. specifically for use as a THz LO source on *SOFIA*. It is a self-contained, computer controlled, turn-key system capable of providing 5-10 mW of LO power at the frequencies of interest (Mueller, 2003), orders of magnitude more than needed to pump the proposed array. The output power of the DEOS/Coherent laser can be set under control computer.

Figure 15: DEOS laser system for the 1.4–2.2 THz array, supplied by NASA/GSFC and in operation in the PI's lab.

3.5 IF/Bias Distribution system

3.5.1 IF Amplifiers

As discussed above, IF outputs from each balanced mixer are power combined on the array motherboard and then amplified by indium phosphide (InP) MMIC amplifier modules. These amplifier modules have been designed and fabricated by Sander Weinreb's group at Caltech.

During the past 4 years wideband, very low noise, cryogenic monolithic microwave integrated circuit (MMIC) amplifiers have been developed with design and testing at JPL and Caltech and foundry fabrication at TRW (now Northrop Grumman Space Systems, NGST) and HRL. These LNA's utilize 0.1 μm gate length, high electron-mobility transistors (HEMT's) and match the requirements needed for densely packed focal plane arrays in terms of noise temperature, chip size, DC power dissipation, yield, and bandwidth.

Prototype chips tested at 12 K and higher temperatures are available with frequency ranges of 1 to 12 GHz, 1 to 60 GHz, and 1 to 110 GHz with noise temperature increasing with frequency. The 1 to 12 GHz chip is most appropriate for this application because of its match to the IF bandwidth of SIS and HEB devices and its very low noise and power consumption. A typical 1-12 GHz amplifier is described in Figure 16. The chip achieves noise temperature of <5 K consuming 20 mW of power at 12 K when driven from a 50 ohm generator impedance. The input match of the LNA is close to 50 ohms over the 4 to 12 GHz range; this is often required for stable operation with an SIS mixer (but not with an HEB mixer where a lower frequency IF is advantageous). We propose to optimize the LNA using external microstrip input circuit design and chip revisions if needed, for the proposed mixers in terms of frequency range, power consumption at 4 K, input match, and noise temperature.

In addition to the MMIC design an important issue for this program is compact packaging compatible with large focal plane arrays. A custom designed ribbon cable with alloy conductors for low thermal conductivity and ground-signal-ground coplanar waveguide output transmission lines will be designed and tested for cross-talk and impedance match. The "ground" conductors can be at RF ground but also serve as DC conductors for transistor and mixer bias. Miniature strip connectors with 0.5 mm conductor spacing are available. We believe this strip MMIC IF amplifier approach can be realized with pixel spacing in the 2 to 5 mm range. An important parameter is the isolation of the amplifier input and output. We will design appropriate shields and absorbers for this purpose.

It is entirely feasible to integrate a line array of IF amplifiers in a larger chip with 4, 8, or 16 amplifiers. We do not propose implementing this in our prototype program but will investigate this possibility.

3.5.2 Array Bias Control System

A computer controlled array bias system has already been developed by the PI's group at Arizona and is currently being used with their 4-channel, SIS 810 GHz array (PoleSTAR) on the AST/RO telescope at the South Pole and a 7-channel, 345 GHz SIS array (DesertSTAR) soon to be installed on the HHT. 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

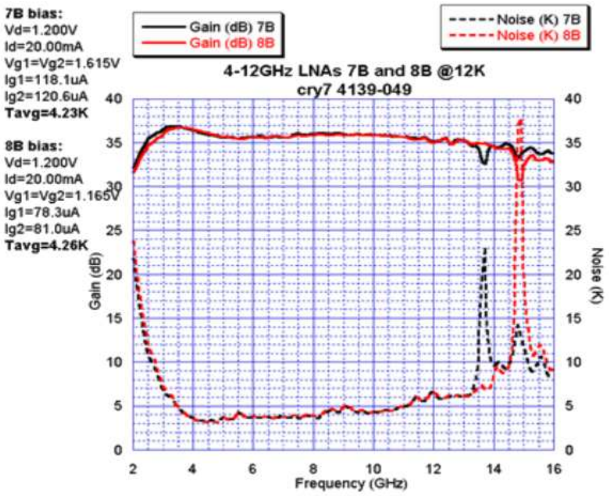


Figure 16: Performance of the 4–12 GHz IF amplifiers produced by S. Weinreb's group at Caltech. Noise temperatures are $\leq$5 K, with gains of $\sim$35 dB when cooled to 12 K.

and controlled by a single Linux-based PC. We will build a 16 channel version of this system to allow simultaneous operation of the 810 GHz SIS and 1.5 THz HEB arrays.

3.6 Implementation on AST/RO

Once the arrays have been fully characterized in the laboratory, we plan to implement them on the AST/RO telescope at the South Pole (see support letter from AST/RO PI Stark). The atmospheric transparency of the site, together with its mechanical and optical design, make AST/RO an excellent testbed for new THz technologies. AST/RO is the home of the first 810 GHz SIS array receiver (PoleSTAR) and the first 1.5 THz HEB receiver (TREND). The PI's team played a key role in the design and construction of both prototype systems. The proposed effort is a natural extension of these earlier efforts.

3.6.1 Array Spectrometer

AST/RO has 6 Cologne AOSs, each of which can provide 1 GHz of bandwidth. We will build an IF processor that will take the 16 IF outputs from the array and downconvert them so that three of them will share a single AOS. The resulting bandwidth of each pixel is 330 MHz at 1 MHz resolution. This translates into 123 km/s of velocity coverage at a resolution of 0.4 km/s for the 810 GHz array and 67 km/s of velocity coverage at 0.2 km/s resolution for the 1.5 THz array. These bandwidths and resolutions are suitable for a wide variety of Galactic astronomy projects; from large scale mapping of molecular clouds to searching for emission from protoplanetary disks.

3.6.2 Array Cryostat

Before building the prototype arrays, we will conduct performance tests on single channel versions of the SIS and HEB array mixers using a conventional wet dewar. Our ultimate goal is to implement the arrays on the Nasmyth focus of AST/RO (see Figure 17). For this we will need a closed-cycle cryostat capable of 4 K operation with very low microphonics. Commercially available (CryoMech Inc.) pulse-tube refrigerators are now available that meet these requirements. These refrigerators have mounting rings similar to that of a standard CTI-350 coldhead. For this project, we will modify an existing Precision Cryogenics dewar to accommodate the pulse tube refrigerator. The load capacity of the pulse tube at 4K is more than adequate to cool both array mixers and the first stage IF amplifiers. If necessary, a small Helium 4 reservoir can be added to the system to ensure thermal stability.

3.6.3 Optics

The array will be bolted on the Nasmyth focus of AST/RO as shown in Figure 17. This position was chosen because of the greater field of view it provides. The converging *f*/6.5 telescope beam passes through an

AR coated, crystalline quartz vacuum window and IR blocking filters before being split by a polarizing wire grid mounted on the 4 K coldplate. One polarization is reflected into the 810 GHz array. The orthogonal polarization passes through the grid and is incident on the 1.5 THz array. By employing polarization diplexing it is possible to observe at both frequencies simultaneously. Given the variability of the 1.5 THz atmospheric window, this is a significant advantage. Not only will it be possible to observe in two lines at once, but the arrangement permits the radio pointing obtained in the much more transparent 810 GHz atmospheric window to be readily applied to the 1.5 THz array. With the proposed balanced mixer approach, LO power is coupled into the mixer via waveguide, significantly reducing the complexity of the fore-optics.

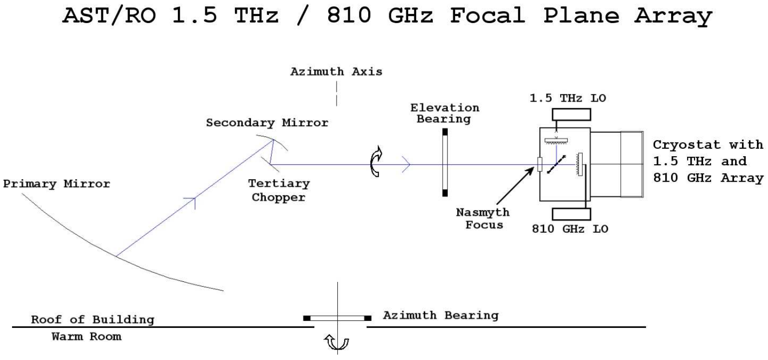


Figure 17: AST/RO optical path to the proposed heterodyne receiver array at the Nasmyth focus

4 Project Management

4.1 Organization

The STARs team brings together the instrument design, development, and management experience of Co-Investigors from 4 universities and two NASA centers. Our team of Co-Is has worked together on a number of successful projects in the past and is looking forward to continuing our collaboration through the proposed effort. The organizational structure of the STARs project is shown in Figure 18. A description of the role each team member will play is provided below.

PI Walker (Univ. of Arizona): The proposed effort will be a major component of the PI's research over the next three years. He will have overall responsibility for the project and coordinate activities between the various groups.

Co-I Chin (NASA/GSFC) comes to this project with extensive experience as a project scientist for SWAS. He will provide the DEOS laser LO for the 1.5 THz array.

Co-I Kawamura (JPL) has a great deal of expertise in the area of phonon-cooled HEBs and will participate in the modeling, fabrication, and testing of devices.

Co-I Kooi (Caltech) is a world leader in the design of submillimeter mixers and receiver systems. He will perform extensive simulations to optimize the performance of the arrays and will participate in their performance characterization and integration on the AST/RO telescope.

Co-I Kulesa (Univ. of Arizona) brings experience with the bias electronics and software used for submillimeter heterodyne arrays and has taken part in the integration of such instruments at AST/RO and the HHT. He will apply this experience to the development of similar systems for the proposed arrays.

Co-I Lichtenberger (Univ. of Virginia) leads the team at the University of Virginia which has considerable experience in the fabrication of SIS and, more recently, HEB devices. His team will be responsible for making the high quality SIS and HEB beamlead devices on thin SOI membranes.

Co-I Narayanan (Univ. of Mass.) has played a key role in the development of the micromilling machine at the University of Massachusetts and has performed and extensive study of HEB and SIS balanced mixers. He will lead the effort to machine the 810 GHz SIS array mixer.

Co-I Weinreb (Caltech) will lead the effort in developing the intermediate frequency amplifiers and distribution system for the proposed arrays. His team at Caltech has already developed IF amplifier modules that meet many of our design requirements.

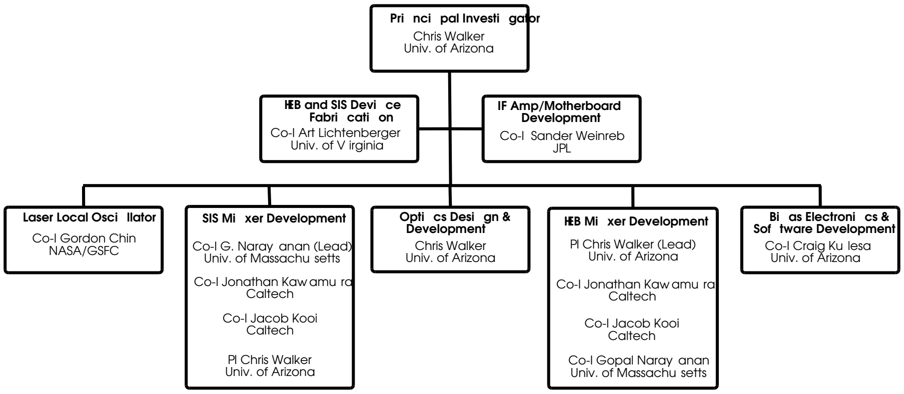


Figure 18: The STARs organizational chart shows clear lines of accountability.

4.2 Plan of Action

A chart showing project milestones and responsibilities is provided below.

	Arizona	**UMass**	**UVa**	**Caltech**	**JPL**
YEAR 1: Optimize Single Pixel					
• Complete single-pixel mixer models in HFSS	**X**	**X**		**X**	**X**
• Design IF motherboard using ADS	**X**			**X**	
• Fabrication of first beamlead HEBs & SIS's			**X**		
• Laser-micromachine 1.5 THz mixer blocks	**X**				
• Machine 810 GHz mixer blocks		**X**			
• Fabricate single channel IF	**X**			**X**	
• Assess single pixel performance at 810 GHz & 1.5 Thz in test dewar	**X**	**X**		**X**	**X**
YEAR 2: Array Implementation					
• Construct array bias control system	**X**				
• Complete array mixer models in HFSS	**X**	**X**		**X**	**X**
• Optimization of HEB & SIS beamlead devices			**X**	**X**	
• Optimize design and fabricate array motherboard	**X**			**X**	
• Build array cryostat	**X**				
YEAR 3: Array Integration and Testing					
• Mount 810 GHz & 1.5 THz arrays in cryostat	**X**				
• Fabrication of spare HEB & SIS devices			**X**		
• Build optics and mount for AST/RO	**X**				
• Characterize performance of array at Arizona	**X**	**X**		**X**	**X**
• Prepare instrument for shipment to AST/RO in following year	**X**	**X**		**X**	**X**

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FACILITIES, EQUIPMENT & OTHER RESOURCES

University of Arizona, Steward Observatory

In 1992 the PI established a laboratory (the Steward Observatory Radio Astronomy Laboratory, SORAL) for the development of state-of-the-art submillimeter-wave receiver systems. The laboratory contains (or has ready access to) all the equipment (spectrum analyzers, network analyzers, vacuum pumps, cryogenic support facilities, etc.) needed for the development of receivers.

The NSF Division of Astronomical Sciences awarded the PI funds to construct a 7 element array receiver at 345 GHz. This array will begin full operation on the HHT in October 2003. In the past, SORAL has produced facility 230 and 492 GHz receivers for the HHT and, recently, was the lead group in the design and construction of a dual channel 492/810 GHz receiver and 4 pixel 810 GHz array receiver (PoleSTAR) for AST/RO at the South Pole. The 492/810 GHz receiver has been in operation for 5 years and is the primary facility receiver for the telescope. The 810 GHz array was commissioned in November 2000 and is the first array to go into operation in this important atmospheric window. In Fall 2002, SORAL worked very closely with Sigfrid Yngvesson at UMass in preparing a single pixel, 1.5 THz HEB receiver for integration onto AST/RO. This instrument, TREND, is now in operation. The experience SORAL personnel have gained in the design and deployment of these receiver systems will be fully utilized in the construction of the proposed prototype systems.

As a result of its successful collaboration with Lincoln Laboratory in applying laser micromachining technology to the fabrication of THz components, the Physical Foundations of Enabling Technologies Program in the Engineering Division of the NSF awarded the PI a grant to construct a laser micromachining facility at Steward Observatory. This system is now fully operational. The design of this facility is based on the successful Lincoln Laboratory system and optimized for fabricating the mixer arrays described in this proposal. The availability of a state-of-the-art laser micromachining system at Steward Observatory provides the community with a *powerful, new* ability to develop a wide variety of needed THz components. Photolithographic facilities are also available at Steward Observatory and the Electrical Engineering Department for fabricating the wet-etched portions of the focal plane arrays.

Through a grant through the Defense University Research Instrumentation Program (DURIP), SORAL has recently purchased a new laser for the micromachining system, an e-beam evaporator for metallizing micromachined components, and a thin film deposition system for depositing nitride and other films.

SORAL also has licenses for both Ansoft's High Frequency Structure Simulator (HFSS) and Agilent Advanced Design Systems (ADS) software packages. These programs are used to accurately model and optimize mixers and other crucial receiver components.

University of Virginia

The Superconductor Device Laboratory (SDL) operates within the Applied Electrophysics Laboratory (AEpL) in the Department of Electrical Engineering at the University of Virginia. The primary facility consists of a 6,000 square foot laboratory, of which roughly two-thirds is clean room space. This facility is indicative of the institutional support that the SDL enjoys as a result of our long term commitment to excellent research in solid state technology, and also to education. The AEpL program involves graduate and undergraduate students, approximately thirty-five of which are currently involved in ongoing research.

The laboratory is fully equipped for the investigation and fabrication of complex Nb superconductive circuits. These processing capabilities include: UHV loadlocked 3″ DC magnetron sputtering of aluminum, niobium and gold in a dedicated trilayer system, high vacuum loadlocked 3″ magnetron sputtering of insulators and metals, UV and deep UV contact photolithography with sub-micron resolution, a Karl Zeiss 982 field emission scanning electron microscope with 1 nm resolution, two fluorine and a chlorine based reactive ion etchers, plasma etching, a multisource Temescal E-beam vacuum evaporation, dedicated ion milling station, and electrochemical plating and etching. The laboratory also has two high speed dicing saws, a computer controlled Tencor surface profiler, an FSM laser based thin film stress measurement system, and a Westbond wirebonder.

The SDL also benefits greatly from cooperative research efforts with other departments. In particular the Materials Science and Electrical Engineering Departments share an FEI-200 focused ion beam system ($500K). Also, a cooperative research program with the Department of Physics has led to the establishment of our Far Infrared Receiver Laboratory. This facility is fully equipped to design, assemble and evaluate millimeter and submillimeter wavelength mixers and multipliers. Sources include two submillimeter wavelength gas laser systems (300 GHz - 4.5 THz) and a variety of millimeter wavelength sources, multipliers and amplifiers from Millitech, J.E. Carlstrom and Radiometer Physics GmbH. A Bruker IFS 66V Fourier Transform Infrared Spectrometer (120 GHz - 225 THz) is available for materials and component evaluation, as well as HP network analyzers to 100 GHz (8510 and 8720s), spectrum analyzers to 110 GHz, and a variety of power meters, microscopes and probe stations. Computer systems include two HP 735 Apollo Workstations each running Hewlett-Packard's high frequency structure simulator and microwave design software.

University of Massachusetts

The University of Massachusetts (UMass) operates a 14 m millimeter telescope facility called the Five College Radio Astronomy Observatory (FCRAO). In collaboration with the Instituto Nacional de Astrofisica, Optica y Electronica (INAOE), Mexico, UMass is also building a 50 meter telescope called Large Millimeter Telescope/Gran Telescopio Milimetrico (LMT/GTM) in Puebla, Mexico, to operate between 1 and 3 mm wavelength bands. In support of the operation of the FCRAO 14 m, and to develop receiver systems for the LMT/GTM. we have three radio astronomy laboratories spread over the functionalities of heterodyne receivers (Millimeter Wave Instrumentation Laboratory), continuum receivers (Cryogenic Device Laboratory), and a digital technology Laboratory (involved in High-speed autocorrelator spectrometer work). The Millimeter Wave Lab has state-of-the-art facilities for the development of millimeter, submillimeter and terahertz receivers and local oscillator systems and backend spectrometers. The laboratory contains all the equipment (spectrum analyzers, network analyzers, vacuum pumps, cryogenic support facilities, etc.) needed for the development of receivers. The NSF Division of Astronomical Sciences funds the operation and instrument development program on the FCRAO as a university radio astronomy facility. The list of instrumental accomplishments of the radio group include QUARRY (QUabbin ARRaY), the first fully integrated mm-wave array receiver, SEQUOIA (SEcond QUabbin Observatory Imaging Array), currently the world's fastest 3 mm array receiver that uses MMIC preamplifiers, and development of receivers for SWAS (Submillimeter Wave Astronomy Satellite). Current projects also include receiver development for SOFIA, the NASA/DARA Airborne Observatory, and the HIFI system on the FIRST spacecraft.

The experience of FCRAO personnel, gained in the design and deployment of these receiver systems will be fully utilized in the construction of the proposed prototype systems.

UMass also has licenses for both Agilent's and Ansoft's High Frequency Structure Simulator (HFSS), Ansoft's Maxwell 3D, CST Microwave Studio (a time-domain structure simulator), Advanced Design System (ADS), and Microwave Design System (MDS) software packages. These programs are used to accurately model and optimize mixers, multipliers, and other crucial receiver components.

Micro-assembly facilities include three long working distance high resolution stereo microscopes (Nikon SMZ-10 and SMZ-U), two very high resolution metallurgical scopes.

UMass radio astronomy has a full machine shop with a Bridgeport 2 axis CNC milling machine, a Haas Mini Mill 3-axis CNC milling machine, jig bores, jeweler's lathe and conventional mills, lathes and grinders. UMass radio astronomy also has a special purpose high-speed micro-NC machine that is custom-built for the fabrication of high frequency waveguide components. This custom-built micromilling machine employs high-speed pneumatic spindles, precision positioners, custom milling software, a multi-tool holding capability, and has been used for fabricating successful waveguide blocks for frequency multipliers and mixers up to 2.5 THz.