Project Description

1 Results from Prior NSF Support

Over the past few years, the PI's group at the University of Arizona has built two spectroscopic heterodyne 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. Both instruments are the very first of their kind. PoleSTAR has been fully integrated with the AST/RO telescope and offers excellent ($T_{rec} <$ 700 K) receiver performance on all 4 pixels. DesertSTAR went into routine operation on the HHT with an initial complement of 3 pixels in October 2003. First-light spectra and a photograph of the instrument mounted at the f/13.8 Nasmyth focus of the HHT are shown in Figures 1–2. Excellent main-beam efficiencies (80%) were derived from observations of Mars. DesertSTAR will be expanded to the final hexagonal array of 7 pixels during summer 2004. Both instruments were funded by NSF programs; work on PoleSTAR was funded by the NSF Office of Polar Programs (A. Stark–PI: OPP-0126090), and 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 (AST-9622569). The experience and heritage of many constructive collaborations gained in the construction of both arrays will be exploited in the proposed development of the first large-format, integrated submillimeter heterodyne camera.

Figure 1: DesertSTAR mounted at the Nasmyth focus of the HHT during its first multipixel engineering run.

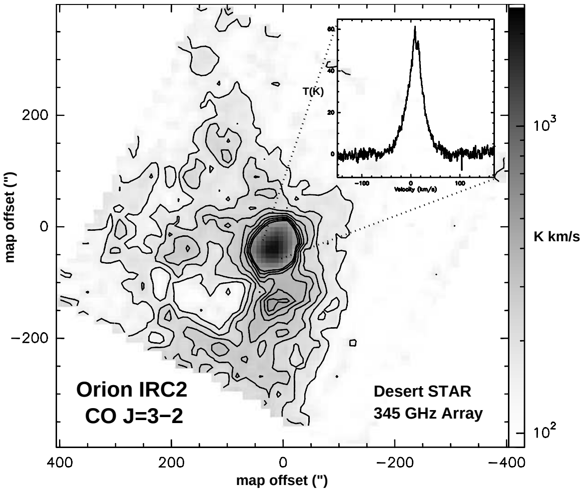


Figure 2: First multipixel light of DesertSTAR at the HHT from the Orion Molecular Cloud. The $10' \times 10'$ On-The-Fly (OTF) map was performed in 1 hour; the 2-pixel noise floor is 1.4 times lower than that of a single pixel.

2 Research Activities

The proposed SuperCam instrument will enable innumerable new astronomical research opportunities as a facility instrument at the HHT, **open to all users.** However, its high angular and spectral resolution, coupled with an exceptional field of view makes it *a truly exceptional Galactic Survey instrument*. Here, we outline a SuperCam "key project", a submillimeter CO survey of the Galactic Plane observable from Arizona. Indeed, the scientific requirements of this survey define the characteristics of the SuperCam instrument, which is then presented in detail in Section 3.

2.1 *Introduction*

From the Milky Way to the highest-redshift protogalaxies at the onset of galaxy formation, the internal evolution of galaxies is defined by three principal ingredients that closely relate to their interstellar contents:

1. the transformation of neutral, molecular gas clouds into stars and star clusters (star formation).
2. the interaction of the interstellar medium (ISM) with the young stars that are born from it, a regulator of further star formation.
3. the return of enriched stellar material to the ISM by stellar death, eventually to form future

generations of stars.

The evolution of (the stellar population of) galaxies is therefore determined to a large extent by the life cycles of interstellar clouds: their creation, star-forming properties, and subsequent destruction by the nascent stars they spawn.

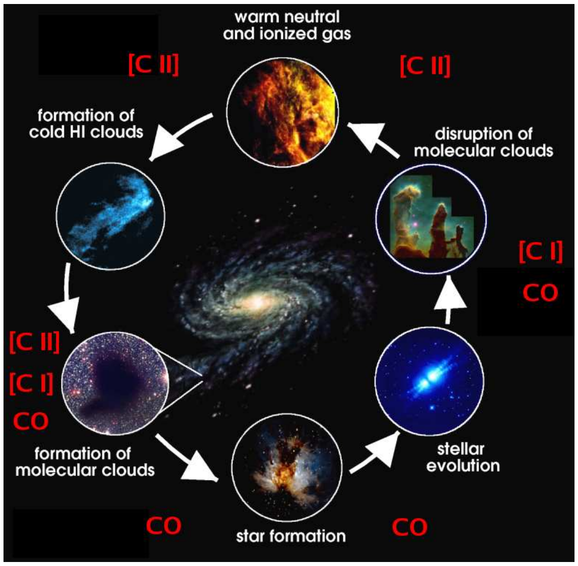


Figure 3: Life Cycles of the ISM

The life cycle of interstellar clouds is summarized pictorially in Figure 3. Although these clouds are largely comprised of neutral hydrogen in both atomic and molecular form and atomic helium, these species are notoriously difficult to detect under typical interstellar conditions. Atomic hydrogen is detectable in cold clouds via the 21 cm spin-flip transition at 1420 MHz, but because the emission line is insensitive to gas density, cold (T$\sim$70K) atomic clouds are not distinguishable from the warm (T$\sim$8000K) neutral medium that pervades the Galaxy. Furthermore, neither atomic helium nor molecular hydrogen (H_2) have accessible emission line spectra in the prevailing physical conditions in cold interstellar clouds. Thus, it is generally necessary to probe the nature of the ISM via rarer trace elements. Carbon, for example, is found in ionized form (C^+) in neutral HI clouds, eventually becoming atomic (C), then molecular as carbon monoxide (CO) in dark molecular clouds. The dominant ionization state(s) of carbon accompany each stage of a cloud's life in Figure 3.

In general, however, only global properties can be gleaned from the coarse spatial resolution offered by studies of external galaxies. Therefore detailed interstellar studies of the widely varying conditions in our own Milky Way Galaxy serve as a crucial diagnostic template or "Rosetta Stone" that can be used to translate the global properties of distant galaxies into reliable estimators of star formation rate and state of the ISM. These studies are very incomplete, however. Though we are now beginning to understand star formation, the formation, evolution and destruction of molecular clouds remains shrouded in uncertainty.

The need to understand the evolution of interstellar clouds as they directly relate to star formation has become acute. The National Research Council's most recent Decadal Survey, under the the advisory of a distinguished committee, has identified the study of star formation as one of the key recommendations for new initiatives in this decade. Similarly, understanding the processes that give rise to star and planet formation represent the central theme of NASA's ongoing Origins program.

A new, comprehensive survey of the Galaxy must address the following questions to make significant progress toward a complete and comprehensive view of Galactic star formation:

- How do molecular clouds form, evolve, and get disrupted? How do typical atoms and grains cycle through the ISM?
- How and under what conditions do molecular clouds form stars?
- How do the energetic byproducts of stellar birth, UV radiation fields and (bipolar) mass outflows regulate further star formation in molecular clouds?
- How does the Galactic environment impact the formation of clouds and stars? What are the specific roles of spiral arms, central bars, and infall and other influences from outside the Galaxy?

2.2 *Properties of the Proposed Survey*

The following features represent a definitive 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 future focused studies with the LMT, and SMA, CARMA and ALMA interferometers.

2.2.1 *High Resolution Spectroscopic Imaging*

Techniques commonly used to diagnose the molecular ISM include submillimeter continuum mapping of dust emission (Hildebrand, 1983) and dust extinction mapping at optical and near-infrared wavelengths (Lada, Lada, Clemens, & Bally, 1994). Large format detector arrays in the infrared are now

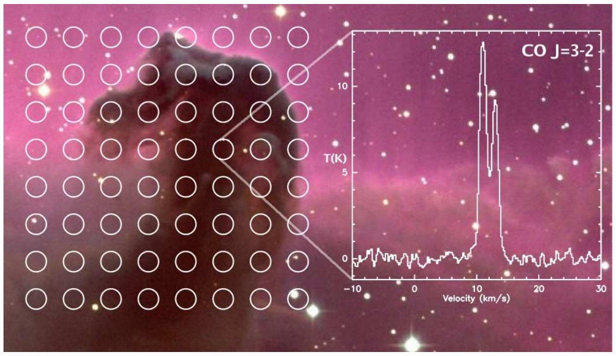


Figure 4: The 64 beams of SuperCam overlaid upon the Horsehead Nebula (B33). Each beam will measure a high-resolution spectrum, a small portion (15%) of which is shown at right. The depicted spectrum was taken with the existing 345 GHz facility receiver at the HHT, and resampled to match the spectral resolution of the proposed SuperCam instrument.

commonplace, and with the advent of bolometer arrays like SCUBA at the JCMT and SHARC at the CSO, both techniques have performed degree-scale maps of molecular material. However, these techniques have limited applicability to the study of the large-scale evolution of molecular clouds due to the complete lack of kinematic information.

The confluence of many clouds along most Galactic lines of sight can only be disentangled with spectral line techniques. Fitting to a model of Galactic rotation is often the only way to determine each cloud's distance and location within the Galaxy. With resolution finer than 1 km s^{-1}, a cloud's kinematic location can be even distinguished from other phenomena that alter the lineshape, such as turbulence, rotation, and local effects such as protostellar outflows. These kinematic components play a vital role in the sculpting of interstellar clouds, and a survey that has the goal of understanding their evolution must be able to measure them.

CO is second only to H_2 as the most abundant molecule in the ISM, and it remains the most accurate, most sensitive tracer of H_2 on large scales (Figure 4). The proposed SuperCam instrument will resolve the intrinsic profiles of Galactic CO lines, with a per-channel resolution of 0.2 km s^{-1} over 230 km s^{-1} of spectrometer bandwidth, comparable to the Galactic rotational velocity.

2.2.2 *First Submillimeter Galactic Plane Survey*

Molecular line surveys have been performed over the entire sky in the light of the 2.6 millimeter $J = 1-0$ line of ^{12}CO, and have been used to synthesize our best understanding of the molecular content of the Galaxy. Still, our understanding of Galactic molecular clouds is incomplete. Early results were obtained with large beams, e.g., $>9'$ (Dame et al., 1987; Dame, Hartmann, & Thaddeus, 2001)); were undersampled, e.g., $3'$ for the UMass/Stonybrook survey – (Solomon, Rivolo, Barrett, & Yahil, 1987; Scoville et al., 1987); or had limited areal coverage, e.g., the early FCRAO surveys – (Carpenter, Snell, & Schloerb, 1995; Stark & Brand, 1989; Bally, Langer, & Liu, 1991; Miesch & Bally, 1994). The Galactic Ring Survey (GRS) at FCRAO is by far the most comprehensive survey of the inner Galaxy to date (Simon et al., 2001). However, this survey traces only the $J = 1-0$ line of ^{13}CO, which is less sensitive to warm, low-opacity, high velocity gas such as produced by outflows, photodissociation regions (PDRs), and shocks. This point is illustrated in Figure 5, with images of a synthetic model cloud constructed in the integrated light of different spectral lines of CO. The model cloud is externally illuminated by a B star and cloud excitation, temperature and chemical abundances are determined self-consistently using Monte Carlo methods. The integrated spectral line images show that the heated portion of the cloud is largely missed by the J=1-0 lines, but captured by the J=3-2 lines. Reconstruction of the cloud based on observation of the ^{13}CO J=1-0 line alone recovers only 60% of the total cloud mass, whereas the combination of J=1-0 and J=3-2 lines recovers 90% of the H_2 mass.

A more comprehensive view of molecular clouds can therefore be gleaned from measurement of the submillimeter lines of CO and its isotopes, in combination with existing millimeter-wave observations. The gas probed by higher-J transitions is of greatest interest to our posed questions – it is the *energetic* gas that 1) participates in molecular outflows, 2) senses radiation fields at the photodissociated surfaces of clouds, and 3) is warmed by star-formation in cloud cores. Higher-J lines are also needed to properly interpret even basic properties of clouds derived from existing CO $1-0$ observations.

Due to the prevailing physical conditions in the interstellar medium, the 870 μm (320-370 GHz) atmospheric window is one of the richest in the electromagnetic spectrum (Figure 6-a). This window also has the highest atmospheric transmission of any submillimeter band. At this wavelength the HHT has the highest aperture efficiency (80%) of any submillimeter telescope in the world and excellent atmospheric transmission more than 40% of the

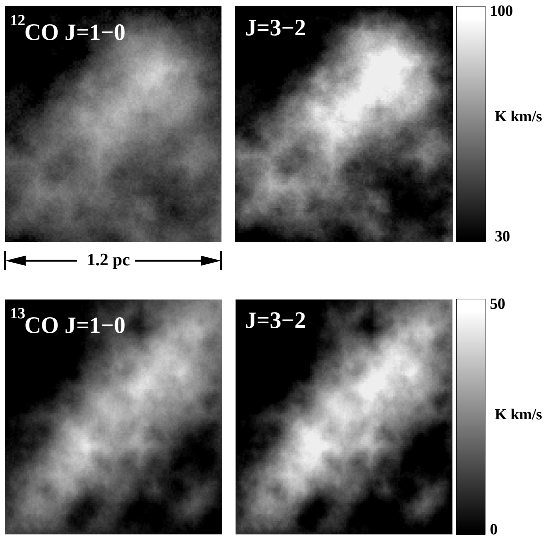


Figure 5: **The need for a submillimeter survey**: Simulated image of a fractal molecular cloud in several CO transitions. The energetic gas that interacts with stars is far better probed by the $3-2$ lines, however both $1-0$ and $3-2$ lines are needed together to extract a comprehensive understanding of cloud properties, dynamics & evolution.

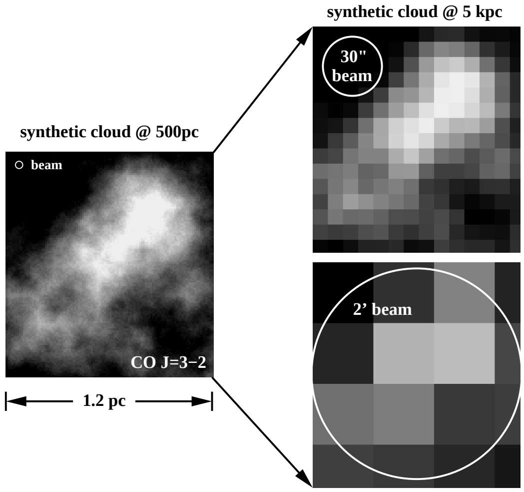


Figure 7: **The need for high angular resolution:** The synthetic cloud from Figures 5 as seen in the ^{12}CO $J = 3-2$ transition at a distance of 500 pc (left) and at 5 kpc, with beam sizes of $30''$ (top) and $2'$ (bottom). The structure of the cloud is essentially lost in the larger beam. In order to probe cloud structure and excitation over the entire Galactic disk, high angular resolution is vital.

time (Figure 6-b). These prospects make the design of a large format multibeam receiver in the 345 GHz atmospheric window most attractive.

2.2.3 High Angular Resolution

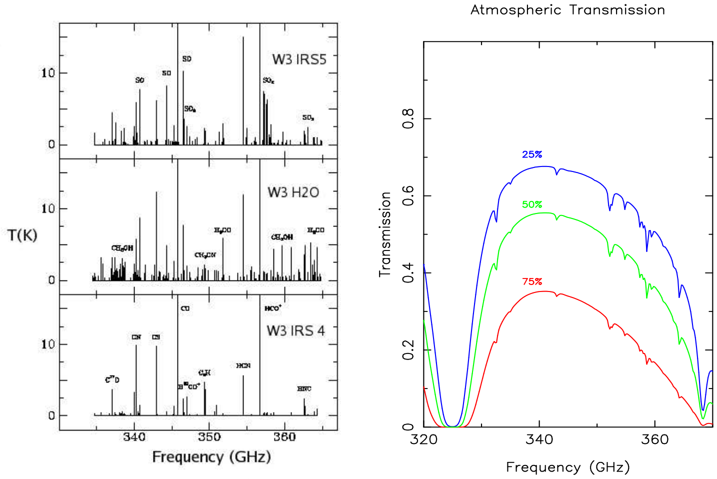
Angular resolution is a critical aspect of improvement for a new Galactic survey. Figure 7 depicts the model cloud of Figures 5, projected to distances of 500 pc and 5 kpc. Clearly, disentangling different clouds and cloud components can only be accomplished with sub-arcminute angular scales. The angular resolution of SuperCam at the HHT is $23''$ at 345 GHz.

2.2.4 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 ~1 magnitude in the local interstellar radiation field, or N(H)$= 1.8 \times 10^{21}$ 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 1.2 K km s^{-1} in the $J = 3 \rightarrow 2$ transition at a gas density of $n_H = 10^4$ cm^{-3}. This sensitivity limit is achievable (3σ) within 10 seconds of integration time per independent beam in *median* atmospheric conditions (T$_{sys}$ ~700K) at the HHT, or (100/#pixels) hours per mapped square degree, with $10''$ grid spacing. Detection (or limits) on J=3→2 in that time would constrain the gas density, based upon the line brightness of millimeter wave transitions.

2.2.5 Mapping Coverage of the Galactic Plane

Figure 8 demonstrates the needed sky coverage of a submillimeter-wave Galactic plane survey. From previous CO surveys it is known that the scale height of CO emission toward the inner Galaxy is less than one degree (Dame et al., 1987; Dame, Hartmann, & Thaddeus, 2001). The interstellar pressure, abundances, and physical conditions vary strongly as a function of Galactocentric radius, so it is necessary to probe the inner Galaxy, the outer Galaxy, and the $l = \pm 100^o$ tangent arms to obtain a statistically meaningful survey that encompasses the broad dynamic range of physical conditions in the Galaxy. We propose therefore to probe the entire Galactic plane as seen from Arizona ($0 < l < 240^o$). Below $l = 90^o$, a *completely unbiased survey* will be undertaken, covering 180 square degrees ($-1^o < b < 1^o$). This "inner" Galaxy survey will coincide with two synergistic surveys: the FCRAO-BU Galactic Ring Survey (GRS) and GLIMPSE, a Spitzer Space Tele-



a) b)

Figure 6: a) The 345 GHz spectral line survey toward three positions in the W3 molecular cloud by Helmich & van Dishoeck (1997) shows a rich diversity of spectral diagnostics. b) Modeled submillimeter atmospheric transparency for the HHT on Mt. Graham in 75 percentile (top), median (middle), and 25 percentile (bottom) atmospheric conditions, derived from 24 hour 225 GHz radiometer measurements over the last 6 years.

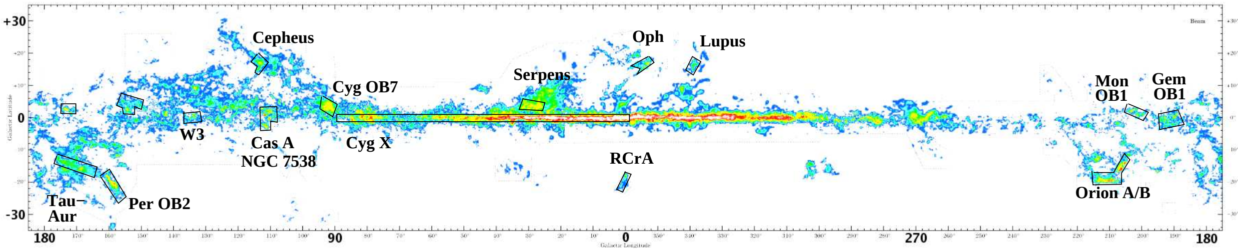


Figure 8: The power of SuperCam: a definitive chemical and kinematic survey of star forming clouds in ^{12}CO & ^{13}CO J=3-2 over 500 square degrees (^{12}CO) of the sky can be performed in 33 full days per spectral line. A corresponding survey with contemporary single pixel receivers would take over 6 years each.

scope (SST) Legacy Program (Benjamin et al., 2003). Above $l = 90^o$, most of the CO emission is located at higher Galactic latitude, so the same solid angle will be distributed according to the Dame et al. (1987); Dame, Hartmann, & Thaddeus (2001) survey to follow the CO $1-0$ distribution and the best characterized star forming regions in the Galaxy – while maximizing synergies with the "Cores to Disks" SST Legacy program (Evans et al., 2003), and other SST GTO programs.

As discussed in Section 3, the proposed SuperCam array exceeds all of these needs and constitutes the ideal Galactic survey instrument.

2.3 *Survey Activities*

2.3.1 *Mapping Strategy*

The most efficient mode of data collection with a focal plane array and 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.

The broad coverage of the Galactic Plane Survey lends itself naturally to efficient, 24-hour/day mapping. Only the region defined by $0 < l < 40^o$ enters the 30^o Sun-avoidance circle (during the month of December), and $150 < l < 210^o$ during May-June. With 64 pixels, SuperCam can reach the requisite sensitivity of 1σ=0.35K over a full square degree in 1.6 hours (Section 2.2.4). A Galactic Plane Visibility diagram (Figure 9) shows the nominal observing strategy in which the entire survey can be accomplished in 2 months of observing time per spectral line. We will therefore use a total of 4 months of observing time over two years to perform the baseline survey; year #1 of observing will be devoted to ^{12}CO $J = 3-2$ mapping (346 GHz), and year #2 will be devoted to ^{13}CO $J = 3-2$ mapping (331 GHz), with followup spectroscopy in e.g. HCO^+ $J = 4 - 3$ (356 GHz) and $C^{18}O$ $J = 2 - 1$ (230 GHz facility receiver) to identify the most opaque, densest cloud cores. *SuperCam's wide instantaneous IF bandwidth (ultimately 8 GHz; see Section 3.5.1 for details) also allows sensitive detection of 870 μm dust continuum emission.* Thusly, we will also simultaneously record total power scans and construct dust continuum maps, particularly in regions where the ^{13}CO lines become optically thick.

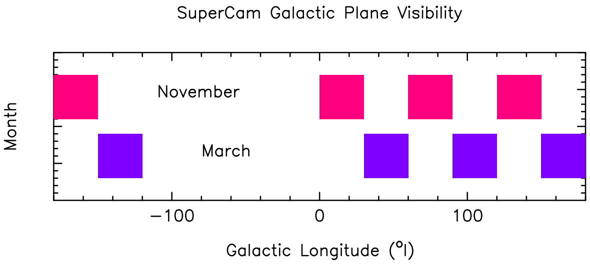


Figure 9: The entire Galactic Plane survey can be accomplished in 2 months of observing time per spectral line. This visibility diagram denotes how the Galactic Plane will be partitioned for efficient observing.

2.3.2 *Science Products and Dissemination*

The primary challenge of OTF mapping is data management, which becomes particularly acute with an array for which the data rates are typically 100x 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/*), whereby coadded and regridded data is written as a FITS cube or CLASS file, and headers for each scan are written into a MySQL relational database, which facilitates efficient logging and retrieval of the data. Our most demanding storage requirements for a 500 square degree map, gridded to 10″ spacing, with 1024 spectral points per grid position, is 130 GB. The total disk requirements for the survey will be about 260 GB. Even today, this volume can be readily handled by a single computer with a redundant disk array for data integrity. 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.

All science tools, packaged reduction software, data products and science products will be made available from the SuperCam survey's web page.

In addition to data products, important science tools include the following:

Clumpfinder and *Outflowfinder*: All Galactic cloud cores and star forming regions will be separated, identified and analyzed from the master dataset as a function of position in the Galaxy. An unbiased survey of Galactic outflows, and their energy inputs to the ISM will be tabulated.

CO Analysis Package and Cloud Models: Numerous tools used to extract physical properties of clouds, such as volume density and temperature, will be released. These tools will include statistical equilibrium calculations, radiative transfer codes based upon LTE, LVG, and Monte Carlo techniques, basic chemical network capable of following hydrogen and carbon chemistries, and foundational models of molecular clouds and photodissociation regions.

2MASS Extinction Maps and the Formation of Molecular Clouds: The release of the 2 μm All Sky Survey will be used to make extinction maps in the photometric J, H, and K bands, to be compared with the measured CO emission and used to search for molecular cloud formation in the Galaxy; regions where large amounts of gas have become molecular, but CO has not yet formed. The ideal probe of nascent H_2 is the 158 μm fine-structure line of the C^+ ion, owing to its intensity and utility as a densitometer (Kaufman, Wolfire, Hollenbach, & Luhman, 1999), but very limited far-IR spectroscopic observations are available, and none have the requisite angular resolution. Instead, we will adopt the innovative use of recombination lines of carbon (Roshi, Kantharia, & Anantharamaiah, 2002) to probe the [C II] emission and hence the H_2 in forming clouds, just as Hα emission at visible wavelengths is used to probe hydrogen-ionized regions. We will use SuperCam to make selected deep pointings in the 26α recombination line of carbon at 353 GHz, in combination with similar measurements of the 39α line from the Kitt Peak 12-meter (or FCRAO 14-meter) and high-n lines from, for example, the NRAO Green Bank Telescope or the VLA. *These measurements will enable the crucial first measurement of the formation of Galactic molecular clouds.*

Systematic calibration of the dataset: D-PI Kulesa is executing a unique survey of Galactic molecular clouds, using high resolution infrared absorption line spectroscopy of H_2 and ^{12}CO, using ARIES (Arizona Infrared Image and Echelle Spectrometer) at the 6.5-meter MMT. These observations directly measure the ^{12}CO and ^{13}CO abundances relative to a precisely measured column density of H_2 (Kulesa & Black, 2002). These pointed measurements will be used to calibrate the submillimeter dust continuum maps and molecular line observations provided by SuperCam and the generated infrared extinction maps from the 2MASS survey.

2.3.3 *Roles of the Collaboration Participants*

Personnel who will initially develop and use the SuperCam instrument comprise the Science (S) and Instrument (I) Teams tabulated in Table 1. They are also represented in an organization chart, Figure 19 in Section 5. *In addition to the two teams, numerous students will participate in the instrument and science development; at least 4 graduate students and 2 undergraduates at the University of Arizona, and at least one graduate student each at UVa and Caltech.*

3 Description of Research Instrumentation and Needs

3.1 *Overview*

In order to achieve our scientific objectives we propose to build the first large format (64 pixel) superheterodyne camera (SuperCam) at submillimeter wavelengths. The advent of such a system will provide an order of magnitude increase in mapping speed over what is now available and revolutionize how observational astronomy is performed in this important wavelength regime.

Unlike the situation with bolometric detectors, heterodyne receiver systems are coherent, retaining information about both the amplitude and phase of the incident photon stream. From this information a high resolution spectrum of the incident light can be obtained without multiplexing. Indeed, **each** SuperCam pixel will provide 1,024 simultaneous spectral measurements. In terms of raw power, each observation made with *SuperCam* will provide $\sim \mathbf{65,536}$ independent measurements of the properties of the object under study. High resolution spectroscopy 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 the scientific objectives of the proposed study.

The possibility of large format arrays at submillimeter wavelengths has been discussed for more than two decades (Gillespie & Phillips, 1979), but 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 in the field, these hurdles have now been overcome. In realizing SuperCam, the design team will pull heavily on the experience gained building a variety of submillimeter-wave heterodyne receiver systems, including:

- 230, 345, 490, and 810 GHz single pixel receivers for the Heinrich Hertz Telescope (HHT) and Antarctic Submillimeter Telescope and Remote Observaory (AST/RO).
- the first 345 GHz array receiver (*DesertSTAR* on the HHT).
- the first 810 GHz array receiver (*PoleSTAR* on AST/RO).

SuperCam represents the next phase in the evolution of high spectral resolution imaging systems. The technology developed in the proposed effort has applications in a number of research areas outside of astronomy. These include remote imaging, space-based communications, and hazardous material detection.

3.2 *Proposed Design*

Unlike all other millimeter/submillimeter arrays composed of individual mixers and discrete components, the proposed array has a high degree of integration. Well conceived, efficient packaging is essential to the successful implementation of large format systems. Figure 10 shows the crowded interior of the 4 pixel (*PoleSTAR*) array cryostat built by the PI's team from discrete components. The enormous complexity of even a small discrete system suggests a more integrated approach for larger systems. A 3D rendering of the proposed SuperCam array cryostat together with a block diagram of the full system is shown in Figure 12. At the heart of the array is an 8x8 integrated array of low-noise mixers. The array mixer block is mounted on a motherboard containing mixer bias and first stage, low-noise, MMIC IF

Participant	Team	Affiliation	Partipation Activity
Christopher Walker	I, S	U. Arizona	Project PI Establishes science & instrument requirements Reviews and approves operations plans and execution Reviews and approves science data products
Hop Bailey	I	U. Arizona	Project Manager Manages science and instrument implementation
Craig Kulesa	I, S	U. Arizona	DPI: Electronics, bias systems & software for SuperCam. Lead for survey science products, data processing pipeline. Collaborative activities with 2MASS and SST surveys.
Harry Fagg	I	U. Arizona	Project Systems Engineer, integration with HHT
Chris Groppi	I, S	NRAO	Array systems, dynamics of star forming regions
Sander Weinreb	I	JPL	PI for IF Amplifiers and IF processing chain
Mark Heyer	S	U. Mass	Provides synergistic access to GRS survey data Leads integration of data pipeline with FCRAO OTF tools Experience with Galactic Surveys and physics of the ISM
Alyssa Goodman	S	Harvard	Provides synergistic access to COMPLETE survey data Integration of C2D & COMPLETE with SuperCam survey
Jürgen Stutzki	S	U. Köln	Physics & Chemistry of the ISM
Gopal Narayanan	I, S	U. Mass	Mixer design, star formation studies
John H. Bieging	S	U. Arizona	Integration of SuperCam data with 3-2-1 survey
Ed Churchwell	S	Wisconsin	Provides synergistic access to GLIMPSE SST survey
Neil Erickson	I	U. Mass	mm/submm array receivers
Larry d'Addario	I	NRAO	Correlators and cryogenics
Jacob Kooi	I	Caltech	Broadband mixer design and device integration
Art Lichtenberger	I	UVa	PI for SIS device fabrication
John Payne	I	NRAO	mm-wave receiver systems

Table 1: Activities of the Science (**S**) and Instrumentation (**I**) Teams

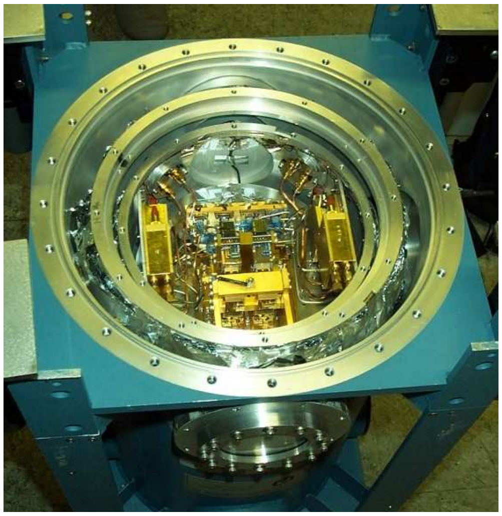


Figure 10: Inside the PoleSTAR dewar.

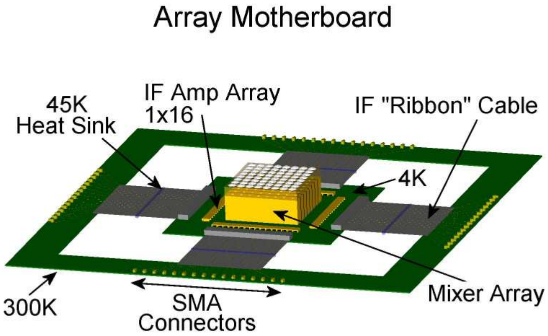


Figure 11: The high degree of integration in the SuperCam design also extends to the "motherboard" that houses the mixers and IF chain.

amplifiers. The motherboard design is depicted in Figure 11.

The mixers and IF amplifiers operate at 4 K. Novel microstrip ribbon cables carry the IF's from all 64 mixers in the array to break-out boards attached to the inside of the vacuum housing of the array cryostat. The microstrip ribbon cables are heat sunk to the 45 K stage of the closed-cycle refrigerator to reduce thermal loading at 4 K. A single waveguide-coupled, solid-state source provides sufficient local oscillator power to pump all the mixers in the array. SuperCam is fully automated, with a field-proven control system that provides the user

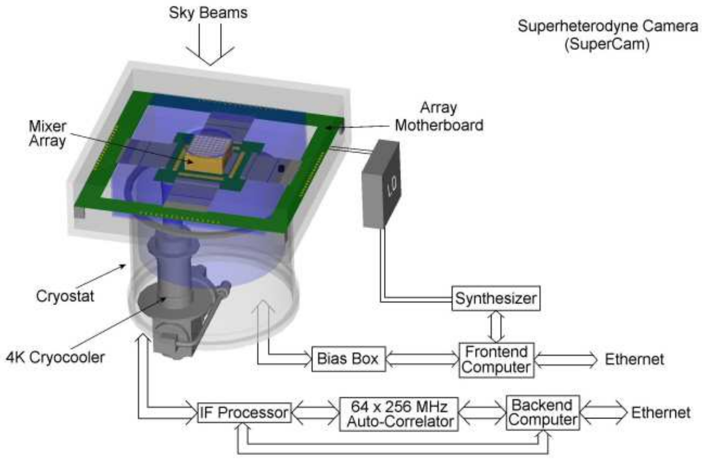


Figure 12: Block diagram of the 345 GHz, 64-pixel SuperCam heterodyne array.

with a full range of instrument control and characterization options. Below we discuss SuperCam's key components.

3.3 *Mixer Array*

In the 300-400 GHz range no amplifiers exist, so incoming signals must first be down-converted to frequencies where low noise amplifiers are available. At these high frequencies two types of mixing devices are currently in use; Schottky diodes and superconductor-insulator-superconductor (SIS) junctions. Schottky diode mixers have been in use on ground, airborne, and space-based platforms for many years. They are reliable and provide modest sensitivity that improves as they are cooled. However, they require prodigious amounts ($\sim$mW) of local oscillator (LO) power to efficiently pump a single mixer. State-of-the-art SIS mixers in the 350 GHz band have 20 times the sensitivity of Schottky mixers. Their greater sensitivity and lower LO power requirements make SIS mixers the best choice for array applications. To operate, these mixers must be cooled to ~ 4 K. We propose to develop a compact, sensitive, 64 pixel array of SIS mixers optimized for operation in the 320-360 GHz atmospheric window.

The two dimensional, 8x8 array will be composed of eight, 1x8 subarrays. The array mixers will utilize the same simple, single-ended, double-sideband design that was successfully employed in our existing 7-pixel, 345 GHz array (DesertSTAR). Indeed, the same SIS devices used in DesertSTAR will be initially used in the proposed SuperCam instrument development. The measured DSB noise temperature of a typical DesertSTAR mixer (50 K) is excellent and essentially frequency independent across the band. The 1x8 mixer subarrays will be composed of three major parts; a horn block, an LO power injection block, and a junction block. The blocks are machined out of copper using standard split-block construction techniques. Stainless steel guide pins and screws are used to ensure proper alignment and good contact between parts. An assembly diagram is shown in Figure 13.

Figure 14 is a pictoral representation of one mixer in a 1x8 subarray. A low-loss, dielectric lens couples energy from the telescope into an efficient, broadband, dual-mode feedhorn (Neilson, 2002) located in the Horn Block. The horn uses an optimized nonlinear taper to generate multimodes, which have a fundamental Gaussian mode power fraction of 99%. This power fraction rivals that of corrugated feedhorns but without the associated difficulties in fabrication. The energy in the horn passes through a circular to full-height rectangular transition before entering the LO injection block. The LO injection block consists of a $\lambda/2$ length of waveguide with a half-height transition on the output. One or two small holes are drilled into the sidewall of the waveguide to permit LO power ($\leq 2\,\mu$W) from a waveguide running along the backside of the block to be coupled into the mixer. LO power distribution details are discussed in Section 3.4, below. The sky signal and LO energy then enter the Junction Block. The Junction Block consists of a 1/2 wavelength section of half-height waveguide, a slot for the SIS junction, a fixed-tuned backshort, and a small microstrip board. The SIS junction is a $\sim 1 \times 1$ μm Nb/AlO$_x$/Nb device fabricated on a 3 mil crystalline quartz substrate. Tuning structures fabricated on the substrate permit broadband, low-noise operation. The junction resides in a suspended stripline slot (Groppi et al., 2003). In the current design, one end of the device is grounded to the mixer block. The other, "hot" end of the device serves as both IF output and DC bias input and connects to the microstrip board located on the facing

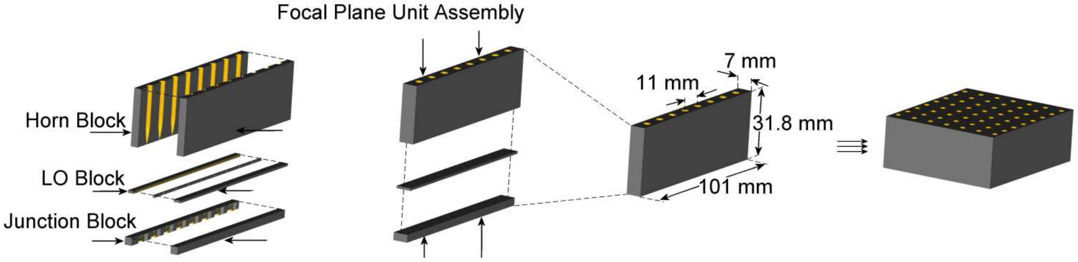


Figure 13: Assembly diagram of an integrated 8×8 pixel mixer array.

half of the split-block via a spring loaded contact. The microstrip connects the IF output/DC bias input of the mixer to the array motherboard via a contact pad on the bottom edge of the junction block.

Several companies have the capability of machining the mixer array. In particular, Custom Microwave of Longmont, CO has a proven track record of fabricating high quality, submillimeter-wave waveguide mixers and feedhorn arrays. We include the cost of Custom Microwave fabricating the mixer array in our budget.

3.4 *Local Oscillators*

With an array receiver, LO power must be efficiently distributed among pixels. Depending on the mechanical and optical constraints of the array, a balanced distribution can be achieved using quasioptical techniques or waveguide injection. With the quasioptical approach, dielectric beam splitters or holographic phase gratings are used to divide the LO energy between array pixels. The multiple LO beams are then combined with the corresponding sky beams before entering the array mixers using a beam splitter, Martin-Puplett interferometer, or Fabry-Perot interferometer. The quasioptical approach works well for modest sized arrays. However, for the large format system being proposed here, the size of the required quasi-optical power splitter and diplexer become prohibitive. Therefore we have chosen to use waveguide LO power injection. Waveguide LO injection has the added advantage that the optical alignment issues associated with the quasioptical approach are nonexistent.

The LO power for the array will be provided by a single solid-state, synthesizer-driven source available from Virginia Diode Inc. The active multiplier chain consists of a high power solid-state amplifier followed by a series of tunerless broadband multipliers. An example of such an LO chain is shown in Figure 15. There are no mechanical tuners, so the output frequency simply tracks the synthesized input frequency. The chain utilizes a series of broadband varactor doublers that have been developed at Virginia Diode Inc. These doublers have a tunerless bandwidth of 15-20% and exhibit efficiencies from 60% at 50 GHz to 10-20% at 300 GHz. In order to increase output power and reduce waveguide path length loss, the final multipler in the chain will be mounted on the 45 K radiation shield of the array cryostat. With the final multiplier cooled to this temperature, the output power of the LO chain from 320-360 GHz is expected to be in excess of 5 mW. Using realistic estimates for waveguide path length loss, this power level is ~ 8 times greater than that required by the array. The output of the array is coupled to an eight-way waveguide power divider located on one side of the array. Each of the eight outputs provides the drive power for a 1x8 subarray. Power is delivered to each array pixel via a coupling hole as described above. A similar LO power injection scheme was successfully used by Erickson (priv. comm.) in the 100 GHz, 15 pixel, Quarry array. A novel waveguide "thermal choke" is used between the 45 and 4 K stages of the cryostat to minimize heat loading (Hesler, private comm.).

Figure 15: Virginia Diode solid state LO chain.

3.5 *IF/Bias Distribution system*

3.5.1 *IF Amplifiers*

The IF outputs from the array mixers are conveyed via microstrip to 4, 1×16 low-noise, InP MMIC am-

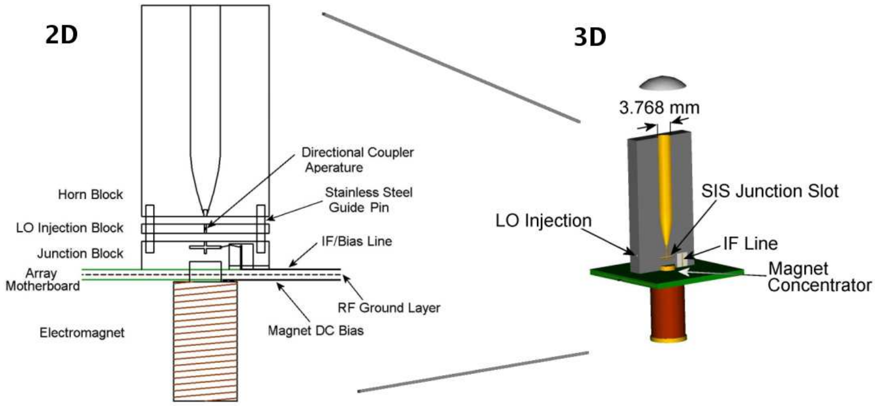


Figure 14: Assembly diagram of a single mixer block.

plifier modules located on the array motherboard. These amplifier modules have been designed and fabricated by Sander Weinreb's group at Caltech. Initially, the IF center frequency of the array will be 5 GHz. This is the standard IF frequency at the HHT and lies within the operating range of the existing generation of IF amplifier modules.

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 indium phosphide, 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 4 to 12 GHz, 1 to 60 GHz, and 1 to 110 GHz with noise temperature increasing with frequency. The 4 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 4–12 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. 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. Ultimately, we plan to raise the center IF frequency of the array to 8 GHz to take advantage of the wide bandwidth of these IF amplifier modules.

Compact packaging compatible with large focal-plane arrays is also important to this program. 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 matching. 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. As isolation of the amplifier input and output is also important, we will design appropriate shields and absorbers.

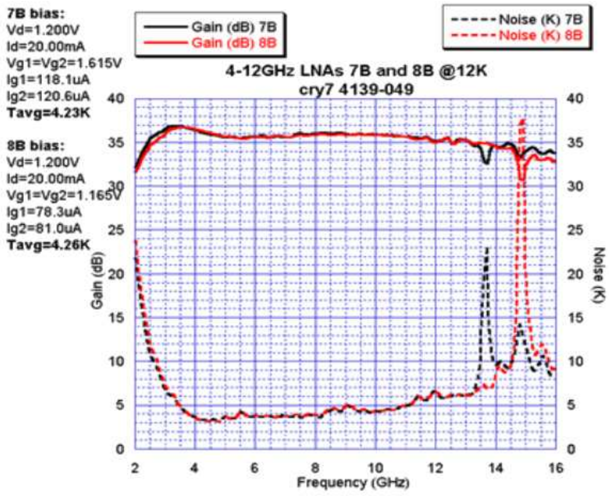


Figure 16: Performance of the 4–12 GHz IF amplifiers produced by S. Weinreb's group at Caltech. Noise temperatures are $\leq$5 K, with gains of $\sim$35 dB when cooled to 12 K.

3.5.2 *Array Spectrometer*

A backend spectrometer is required to create the spectrum of each pixel from the downconverted base-band signal. Recent advanced in on-chip integration make autocorrelators an efficient, low-cost approach for achieving the bandwidth (256 MHz) and spectral resolution (0.25 MHz) required for the proposed science program. Spaceborne Inc. has built a number of autocorrelator systems for radio astronomy applications and can provide an array spectrometer for SuperCam that meets the proposed science requirements (Table 2).

a) 64 spectrometers enclosed in a VXI mainframe
b) 300 MHz maximum sampling clock
c) 300 MHz maximum analog bandwidth
d) 1024 frequency channels per spectrometer
e) integration timer from 150ms to 20s
f) packaged in a VXI, C-size enclosure
g) 1000 W power consumption
h) computer interface via a fast USB port of a PC
i) virtual instrument software for Windows 2000

Table 2: Spaceborne digital autocorrelator specifications

A photograph of a Spaceborne correlator chip (here a 2 GHz bandwidth device) is shown in Figure 17a, and laboratory measurement of the spectral response is shown in Figure 17b. The SuperCam correlator chips will be fabricated with a 0.18 μm CMOS process and provide efficient (87%) 2-bit/4-level digital correlation with 1024 lags. The correlator cost includes two separate device runs to ensure a sufficient number of devices are available. The SuperCam correlator will be delivered as a "turn-key" system with virtual instrument software. A backend computer will communicate with the correlator, perform the first-order data reduction, and store the reduced scans.

We will construct an IF processor that downconverts each of the 64, 5 GHz IF's from the array to the 0-500 MHz frequency range required at the input of the correlator. The IF processor will also provide a measurement of the total power level in each of the IF channels. This total power level will be used for characterizing the array performance independent of the spectrometer and to sample the broad-band continuum emission from astronomical objects. A second IF processor will be constructed to combine the 64 IF inputs of the array correlator into eight, 2 GHz wide channels to be used as a backend spectrometer for DesertSTAR. *This addition will allow DesertSTAR to reach its full potential as an extragalactic instrument and will preserve its value alongside SuperCam at the HHT.* Funds for the second IF processor are not being requested here.

3.6 *Array Cryostat*

A 3-D rendition of the SuperCam cryostat is shown in Figure 12. The cryostat's outer dimensions are ~546x546x481 mm. Light from the telescope enters the cryostat through a 127 mm (5″) diameter AR coated, crystalline quartz vacuum window and passes through an IR blocking filter on the 50 K radiation shield before illuminating the 4 K mixer array. SuperCam will use a Sumitomo Model a SRDK-415E-A71A cryocooler. The cooler has 1.5 W of thermal load capacity at 4.2 K and 45W at 50K with orientation-independent operation. The operating temperature of the cryocooler is stabilized by the addition of a helium gas pot on the 2nd stage. Once the 2nd stage cools to 4 K, the helium gas liquifies. The SuperCam array motherboard is heatsunk to this pot via low-loss, vibration-damping copper straps. Calculations indicate the SRDK-415E load capacity is sufficient to cool the mixers, magnets, and amplifiers to the proper operating temperatures. Should additional cooling become necessary, the cryostat is designed to permit the addition of second cryocooler. Janis Research is the Sumitomo distributor in the US. Janis has reviewed our array cryostat drawings and given us an estimated cost for the complete cryostat/cryocooler system.

3.7 *Bias Control System & Software*

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-pixel, SIS 810 GHz array (PoleSTAR) on the AST/RO telescope at the South Pole and a 7-pixel, 345 GHz SIS array (DesertSTAR) 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 and controlled by a single Linux-based PC. The hardware and control software have been specifically designed to support SIS arrays of ≈ 100 pixels.

3.8 *Optics*

The existing secondary mirror of the Heinrich Hertz Telescope provides a f/13.8 beam at the Nasmyth focus. The clear aperture available through the elevation bearing prevents the possibility of a large format array at this position. To efficiently illuminate a large format array like SuperCam, the telescope focus must fall within the apex room located

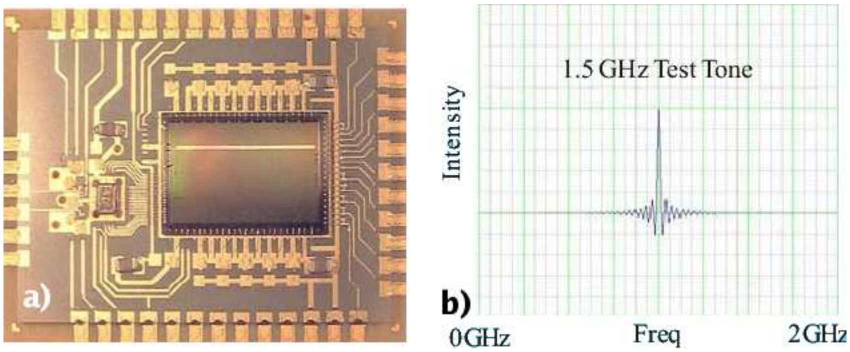


Figure 17: The Spaceborne digital autocorrelator provides an ideal "off-the-shelf" multichannel spectrometer for SuperCam. a) 2 GHz Spaceborne correlator chip. b) Laboratory measurement of spectral response.

just behind the primary. A new f/7.5 secondary is required. The new secondary will be optimized to guarantee a Strehl ratio (coupling efficiency) greater than 0.9 across the whole field of view of the array. The relatively fast focal ratio permits simpler and smaller re-imaging optics to match the f/5 beams of the array receiver. Since the physical separation between array elements in the instrument focal plane scales as $2f\lambda$, lower f/#'s serve to reduce the overall size of the instrument. The reimaging optics are composed of two offset parabolas and three flat mirrors. The two off-axis parabolas are in a coma-canceling configuration (Serabyn, 1995). All the reimaging optics can be mounted on a single vertical optical breadboard and left in the apex room. Only one flat mirror needs to be rotated to take the reimaging optics (and SuperCam) out of the telescope's optical path. The secondary can be changed in under an hour. The optical system is depicted in Figure 18.

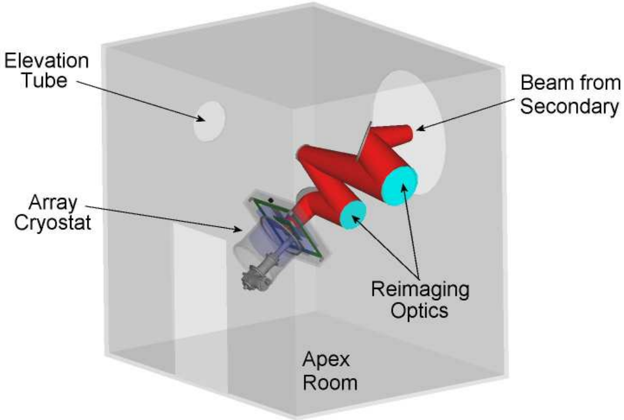


Figure 18: Optical system matching SuperCam to the HHT

4 Impact of Infrastructure Projects

4.1 *Institutional Impact*

SuperCam will provide an order of magnitude leap in the mapping speed of the HHT and serve as a technological roadmap for the realization of large format heterodyne arrays at submillimeter and far-infrared wavelengths. At the design wavelength of SuperCam (870 μm) the HHT has one of the highest aperture efficiency of any submillimeter telescope in the world (80%) and excellent atmospheric transmission more than 40% of the time. SuperCam will be an order of magnitude larger than any existing spectroscopic imaging array at submillimeter-wavelengths, will be the most powerful instrument for probing the history of star formation in our Galaxy, and will put the University of Arizona at the forefront of research and technology in this wavelength regime. This will in turn attract more highly qualified students, technical staff, and faculty to the University, not just in Astronomy, but also Chemistry, Optical Sciences, and Electrical Engineering. The technological spin-offs from building and operating SuperCam will be substantial and place the University in an excellent position to propose for even larger arrays for use on ground, airborne, or space platforms.

4.2 *Educational Impact*

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. It is interest in astronomy 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 student's research. However, as is customary in the PI's lab, many other students will also participate in making the program a success. Indeed, one of the most important aspects of training students in instrument development is experience in working in teams. Astronomical instrumentation is becoming ever more complex, and requires the talents of many individuals. Providing students with both technical training and team-work experience increases their probability of success.

4.3 Global Impact: Survey Synergies

The surveys conducted with the SuperCam array receiver 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.

4.3.1 SST Galactic Plane Survey

The Spitzer Space Telescope 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. The proposed Galactic Plane survey will provide the best corresponding molecular cloud survey that will account for the dense cloud material that forms stars, cloud interaction with formed stars, and kinematic disruption by mass ejection, outflow, and supernova remnants. Collaborator E. Churchwell will provide guidance in accessing and interpreting this data for comparison with the SuperCam survey.

4.3.2 From Molecular Clouds to Young Stars

A second SST Legacy proposal, "From Cores to Disks", or "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. The COMPLETE survey of Alyssa 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. Our target surveys of Outer Galaxy and high latitude GMC's add significant value to the baseline by providing higher-J CO data critical for the study of star forming regions where many excitation components are often present and cannot be disentangled with only one spectral line. Collaborator Alyssa Goodman (CfA) will provide assistance in accessing COMPLETE data for combination with the SuperCam survey. The "C2D" Legacy project data itself will be available in 2005.

4.3.3 Molecular Ring Survey

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. This proposed study will improve upon the GRS 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. Collaborator Mark Heyer (U.Mass) is a member of the GRS team and will provide assistance in accessing this data for combination with SuperCam surveys.

4.3.4 3-2-1 Survey

John Bieging (Arizona) has proposed "3-2-1", a collaborative survey of ^{12}CO $J = 2 - 1$, $J = 3 - 2$, and ^{13}CO $J = 2 - 1$ in the inner 50 square degrees of the Galaxy over the next 3 years, using the existing HHT and KPNO 12-meter facilities. The SuperCam Galactic Plane surveys will dovetail with the coverage that 3-2-1 obtains by the time SuperCam is completed. Many of the science products and tools will be shared between the two surveys, and the OTF data acquisition and archival methods will be identical. Nearly all of the collaborators of 3-2-1 are collaborators in SuperCam as well. In particular, John Bieging will provide guidance in merging the SuperCam and 3-2-1 surveys and products.

4.3.5 2MASS & Formation of Molecular Clouds

The 2 Micron All Sky Survey (2MASS) has imaged the northern and southern hemisphere skies in the

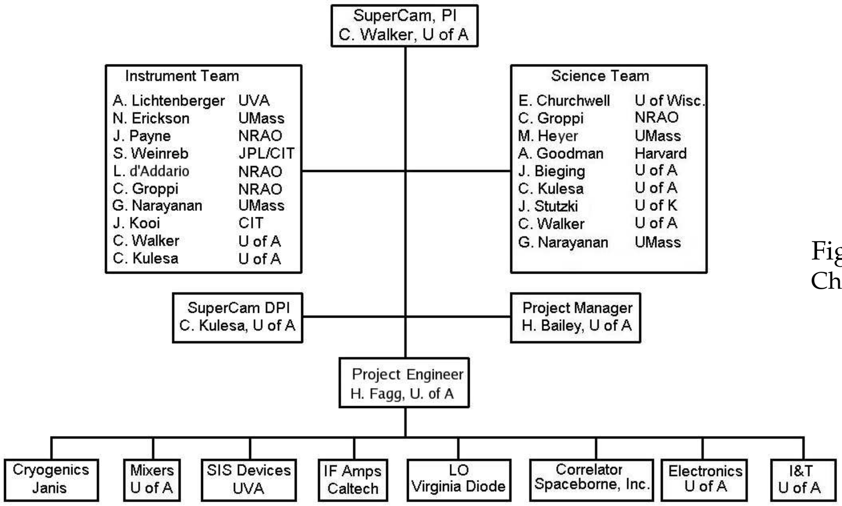


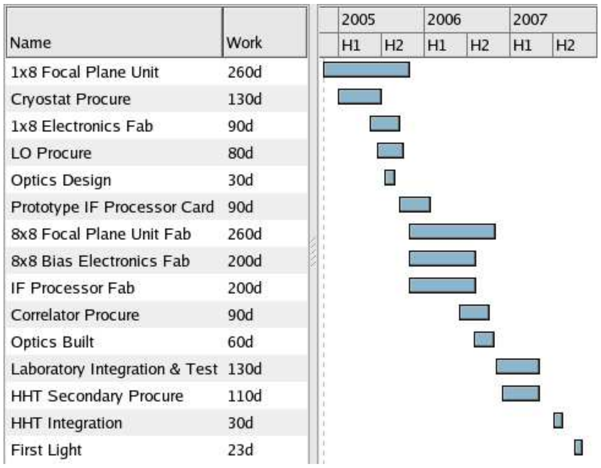
Figure 19: SuperCam Organizational Chart

photometric J, H, and K bands from 1–2.5 μm. This survey will be used to construct extinction maps over the entire region to be surveyed by SuperCam (Lada, Lada, Clemens, & Bally, 1994; Alves, Lada, & Lada, 1999), which will be used to locate regions in the Galaxy where new molecular clouds are being formed; i.e. where gas has become molecular (i.e. H_2), but CO has not yet formed. These measurements will enable the crucial first measurement of the formation of Galactic molecular clouds, and will leverage the investment of the 2MASS survey in an innovative way.

5 Project Management

SuperCam is an exciting, challenging project that requires the coordinated participation of scientists and engineers from several academic institutions and leading-edge companies to succeed. We have developed an organizational structure (shown in Figure 19) to meet this task. Collectively the SuperCam team members represent many years of successful instrument development and observing programs. The organizational structure of the SuperCam project provides effective control of the project while allowing the delegation of authority to be made at the proper level within the organization. The main components of the organization are the PI, who has overall responsibility for the project and coordinates the activities of the participants, the DP-I (Kulesa) who assists the PI and is responsible for developing the bias control system and writing SuperCam support software, the Project Manager (PM-Bailey) who oversees the fiscal realities of the project, the Project Engineer (PE–H. Fagg) who will oversee the integration of the array hardware, and the Science and Instrument Teams who will provide extensive scientific and technical guidance throughout the course of the project. Table 1 provides a listing of the roles and responsibilities of each member in the organization.

A schedule of key project milestones and tasks is provided in Figure 20. Routine communications between project participants is essential. There will be quarterly telecons between Science and Instrument team members to monitor progress, provide insight into solutions to emerging problems, and redefine priorities as needed. There will be weekly telecons and quarterly meeting (either in person or through teleconferencing) between the PI, D-PI, PM, PE, and IF technical lead Weinreb (CIT) and Device technical lead Lichtenberger (UVa).



Name	Work
1x8 Focal Plane Unit	260d
Cryostat Procure	130d
1x8 Electronics Fab	90d
LO Procure	80d
Optics Design	30d
Prototype IF Processor Card	90d
8x8 Focal Plane Unit Fab	260d
8x8 Bias Electronics Fab	200d
IF Processor Fab	200d
Correlator Procure	90d
Optics Built	60d
Laboratory Integration & Test	130d
HHT Secondary Procure	110d
HHT Integration	30d
First Light	23d

Figure 20: SuperCam Organizational Timeline

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