SuperCam : A 64 pixel superheterodyne camera

Christopher Groppi[1], Christopher Walker[1], Craig Kulesa[1], Dathon Golish[1], Patrick Pütz[1,6], Paul Gensheimer[1], Abby Hedden[1], Shane Bussmann[1], Sander Weinreb[2,3], Niklas Wadefalk[3], Glenn Jones[3], Joseph Barden[3], Hamdi Mani[3], Tom Kuiper[2], Jacob Kooi[3], Art Lichtenberger[4], Gopal Narayanan[5]

1: University of Arizona, 2: NASA Jet Propulsion Laboratory, 3: California Institute of Technology, 4: University of Virginia, 5: University of Massachussetts, 6: Universität Zu Köln

Abstract—We report on the development of *SuperCam*, a 64 pixel, superheterodyne camera designed for operation in the astrophysically important 870 µm atmospheric window. *SuperCam* will be used to answer fundamental questions about the physics and chemistry of molecular clouds in the Galaxy and their direct relation to star and planet formation. 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 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. *SuperCam* will be constructed by stacking eight, 1x8 rows of tunerless, SIS mixers. The IF output of each mixer will be connected to a low-noise, broadband MMIC amplifier integrated into the mixer block. The instantaneous IF bandwidth of each pixel will be ~2 GHz, with a center frequency of 5 GHz. A spectrum of the central 500 MHz of each IF band will be provided by the array spectrometer. Local oscillator power is provided by a frequency multiplier whose output is divided between the pixels by using a matrix of waveguide power dividers. The mixer array will be cooled to 4K by a closed-cycle refrigeration system. *SuperCam* will reside at the Cassegrain focus of the 10m Heinrich Hertz telescope (HHT) with a dedicated re-imaging optics system. We report on single pixel integrated LNA testing, cryogenic system testing, performance of the prototype backend spectrometer module, and the fabrication of the first 1x8 array module. This module will be tested on the HHT in 2006, with the first engineering run of the full array in late 2007. The array is designed and constructed so that it may be readily scaled to higher frequencies.

***Index Terms*—Submillimeter heterodyne array**

I. Introduction

SuperCam will operate in the astrophysically rich 870 micron atmospheric window, where the HHT has the highest aperture efficiency of any submillimeter telescope in the world and excellent atmospheric transmission more than 40% of the time. The proposed Superheterodyne Camera (SuperCam) will be an 8x8, integrated receiver array fabricated using leading-edge mixer, local oscillator, low-noise amplifier, cryogenic, and digital signal processing technologies.

Manuscript received May 18, 2006. This work is supported by the National Science Foundation Major Research Instrumentation Program, grant number AST-0421499.

SuperCam will be several times larger than any existing spectroscopic imaging array at submillimeter wavelengths. The exceptional mapping speed that will result, combined with the efficiency and angular resolution achievable with the HHT, will make SuperCam the most uniquely-powerful instrument for probing the history of star formation in our Galaxy and the distant Universe. SuperCam will be used to answer fundamental questions about the physics and chemistry of molecular clouds in the Galaxy and their direct relation to star and planet formation. Through Galactic surveys, particularly in CO and its isotopomers, the impact of Galactic environment on these phenomena will be realized. These studies will serve as "finder charts" for future focused research (e.g. with ALMA) and markedly improve the interpretation, and enhance the value of numerous contemporary surveys.

II. SuperCam Science

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:

- The transformation of neutral, molecular gas clouds into stars and star clusters (star formation).
- the interaction of the interstellar medium (ISM) with the young stars that are born from it, a regulator of further star formation.
- 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, starforming properties, and subsequent destruction by the nascent stars they spawn. The life cycle of interstellar clouds is summarized pictorially in Figure 1. 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~70K) atomic clouds are not distinguishable from the warm (T~8000K) neutral medium that pervades the Galaxy. Furthermore, neither atomic helium nor molecular hydrogen (H2) 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 1. 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.

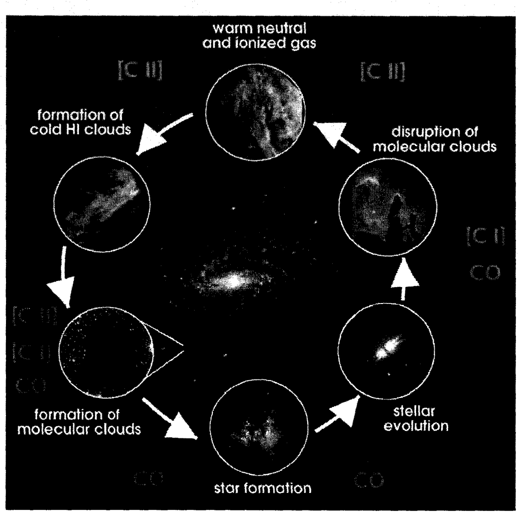

Figure 1: Life cycle of the ISM

III. SUPERCAM INSTRUMENT DESCRIPTION

A. *Instrument Design*

Unlike all other millimeter/submillimeter arrays composed of individual mixers and discrete components, SuperCam has a high degree of integration. Well conceived, efficient packaging is essential to the successful implementation of large format systems. The enormous complexity of even a small discrete system suggests a more integrated approach for larger systems. At the heart of the array is an 8x8 integrated array of low-noise mixers. The array mixer contains first stage, low-noise, MMIC IF amplifier modules with integrated bias tees. A single solid-state source provides local oscillator power to each array mixer via a waveguide corporate power divider and a simple Mylar diplexer. Below we discuss SuperCam's key components.

1) Cryogenics

The SuperCam cryostat is shown in Figure 2. Light from the telescope enters the cryostat through a 127 mm diameter AR coated, crystalline quartz vacuum window and passes through an IR blocking filter on the 40 K radiation shield before illuminating the 4 K mixer array. SuperCam uses a Sumitomo SRDK-415D cryocooler. The cooler has 1.5 W of thermal capacity at 4.2 K and 45W at 40K with orientation-independent operation. The operating temperature of the cryocooler is stabilized by the addition of a helium gas pot on the 2nd stage. A CTI cryogenics CTI-350 coldhead supplements the cooling of the 40K shield, and provides 12K heatsinking for the 64 stainless steel semi-rigid IF cables. The addition of this second coldhead permits the use of moderate lengths of standard coaxial cable while maintaining low heat load at 4K. Calculations indicate the SRDK-415D load capacity is sufficient to cool the mixers, magnets, and amplifiers to the proper operating temperatures. The cryostat was constructed by Universal Cryogenics in Tucson, Arizona, USA. Cryogenic load testing using heaters at all temperature stages have verified that both the cryocoolers meet their rated load specifications. The cooling capacity is adequate given the expected heat loading from the DC wiring, semi-rigid cable,

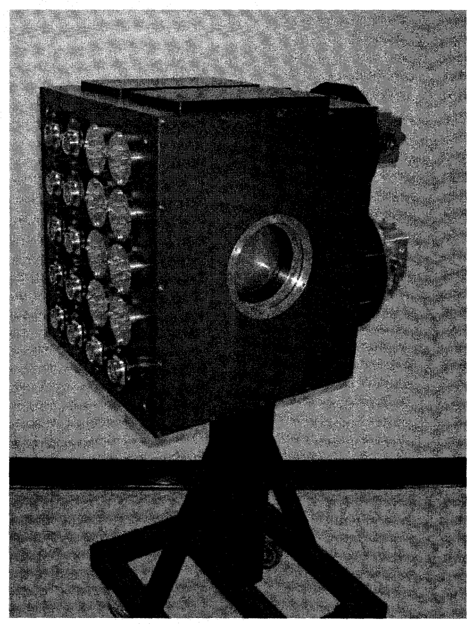

Figure 2: The SuperCam cryostat

amplifiers and magnets, with an expected load capacity margin of ~50%.

2) Mixer Array

We are developing 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 SIS devices fabricated on Silicon-On-Insulator (SOI) substrates, with beam lead supports and electrical contacts. The waveguide probe and SIS junction are based on an asymmetric probe design currently in use at the Caltech Submillimeter Observatory in their new facility 350 GHz receiver. The measured DSB noise temperature of this receiver (40 K) is excellent and essentially frequency independent across the band. The 1x8 mixer subarrays will be constructed from tellurium copper using the splitblock technique. Stainless steel guide pins and screws are used to ensure proper alignment and good contact between parts. Figure 3 is a pictoral representation of one mixer in a 1x8 subarray. A low-loss, dielectric lens couples energy from the telescope into a diagonal feedhorn. The energy in the horn passes through a 90° waveguide bend before reaching the impedance transformer to full height rectangular waveguide. The SIS device is suspended above the suspended stripline channel via four small beamlead supports. Both the hot and ground beamleads are tack-bonded with a wirebonder to the MMIC module input pad and block, respectively. The mixer blocks will be fabricated at the University of Arizona using a Kern MMP micromilling machine purchased for this project. This numerically controlled mill can fabricate structures to micron accuracy with a high level of automation.

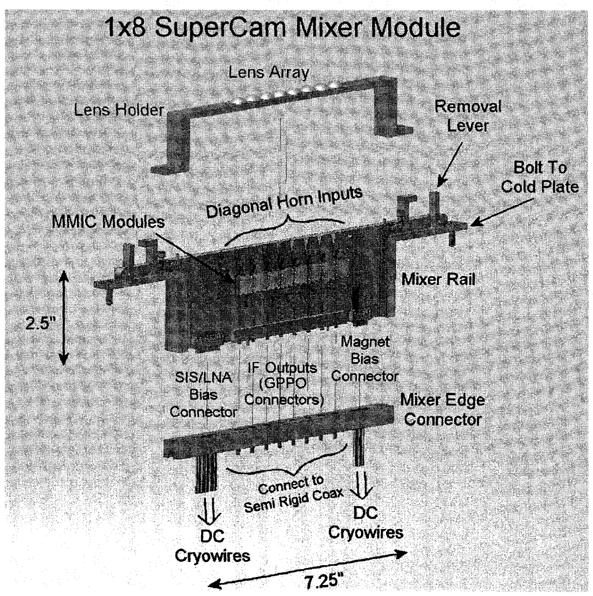

Figure 3: Assembly diagram of a single mixer module.

3) Local Oscillator

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 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 a hybrid waveguide/quasioptical LO power injection scheme. 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. The output of the multiplier is coupled to an eight-way waveguide corporate power divider with splitblock machineable waveguide twists. Each of the eight outputs provides the drive power for a 1x8 subarray via an identical 8 way corporate divider with diagonal waveguide feedhorn outputs. A lens array similar to the mixer lens system then matches the LO beams to the mixers through a simple Mylar beamsplitter diplexer. This scheme ensures uniform LO power in each beam since the waveguide path lengths are identical for each beam. In addition, the waveguide feedhorns and lenses provide well controlled and predictable LO power distribution and coupling to each mixer. Accounting for conduction and surface roughness losses, we expect this 64-way network to add an additional 2dB of LO power loss compared to a lossless divider.

4) IF/Bias Distribution System

The IF outputs from the SIS devices are bonded directly to the input matching networks of low-noise, InP MMIC amplifier modules located in the array mixers. These amplifier modules have been designed and fabricated by Sander Weinreb's group at Caltech. The IF center frequency of the array is 5 GHz. The MMIC chip is contained in an 11mm x 11mm amplifier module that contains integrated bias tees for the SIS device and the amplifier chip. The module achieves noise temperature of ~5 K consuming 8 mW of power at 4K. The first 10 amplifier modules are complete. An example is shown in figure 4, with measured gain and noise data at 8 mW power dissipation. We have integrated an amplifier module into a single pixel SIS mixer and have verified that the amplifier module operates as expected. Allan varience times and mixer noise temperatures are unchanged within the measurement errors compared to a similar mixer used with an external commercial LNA and cryogenic isolator.

5) Array Spectrometer

The SuperCam spectrometer will deliver 64 channels at 512 MHz/channel with 125 kHz resolution, or 32 channels at 1 GHz with 250 kHz resolution. The system will be capable of resolving lines in the coldest clouds, while fully encompassing the Galactic rotation curve. Operated in 32 pixel mode with 1 GHz (880 km/s) of bandwidth, extragalactic studies are enabled. This leap in spectrometer ability is driven by the rapid expansion in the capabilities of high speed Analog to Digital Converters (ADCs) and Field Programmable Gate Arrays (FPGAs). The SuperCam spectrometer, to be provided by Omnisys AB of Sweden, is based on a real-time FFT architecture. High speed ADCs digitize the incoming RF signal at greater than 10 bits resolution, preventing any significant data loss as with autocorrelation based schemes. Then, large, high speed FPGAs perform a real time FFT on the digitized signal and integrate the incoming signal. Only recently has Xilinx released FPGAs fast enough and large enough to accommodate the firmware capable of this task. These systems are fully reconfigurable by loading new firmware into the FPGAs. In addition, the spectrometer can be easily expanded to increase bandwidth. We will receive 16 boards capable of processing 64x512 MHz or 32x1 GHz.

6) 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 just behind the primary. A system of re-imaging optics transforms the f number of the telescope to f/5. Since the physical separation between array elements in the instrument focal plane scales as 2fλ, lower f/#'s serve to reduce the overall size of the instrument. The reimaging optics are composed of a hyperbola and an ellipse with two flat mirrors. All the reimaging optics can be mounted on a single optical breadboard and left in the apex room. The cryostat and optics frame have been designed using finite element analysis to minimize gravitational deflection, and the calculated deflections have been fed into the tolerancing of the optical design. The optical system was initially designed and optimized with Zemax, and was then verified by BRO research using their ASAP physical optics package. The system's efficiency exceeds 80% for all pixels, and has been verified to be robust to alignment and fabrication tolerances.

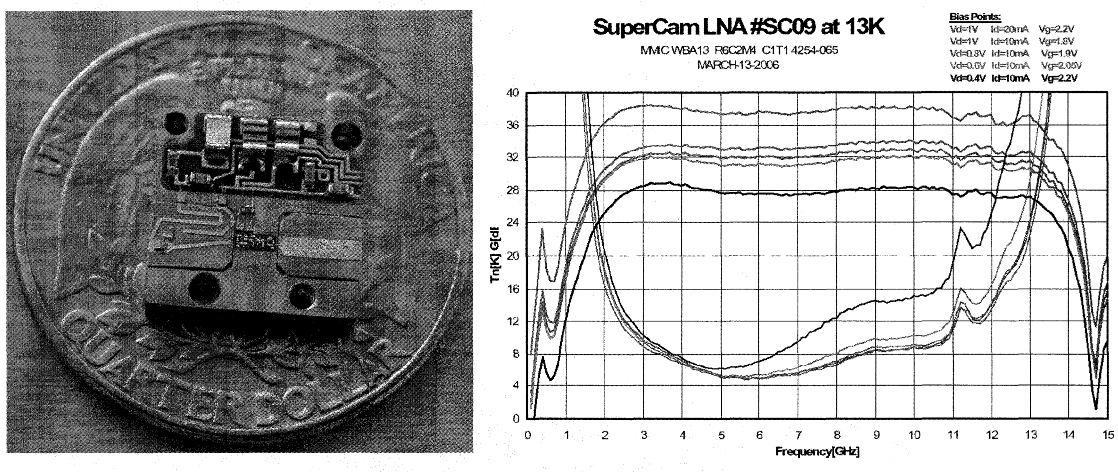

Figure 4: A SuperCam MMIC amplifier module, and typical measured results at 13K bath temperature for several bias points. Amplifier noise remains low for bias powers as low as 8 mW. Gain remains above 30 dB.

IV. Conclusion

We are constructing SuperCam, a 64-pixel heterodyne imaging spectrometer for the 870 micron atmospheric window. A key project for this instrument is a fully sampled Galactic plane survey covering over 500 square degrees of the Galactic plane and molecular cloud complexes. This $^{12}CO(3\text{-}2)$ and $^{13}CO(3\text{-}2)$ survey has the spatial (23") and spectral (0.25 km/s) resolution to disentangle the complex spatial and velocity structure of the Galaxy along each line of sight. SuperCam was designed to complete this survey in two observing seasons at the Heinrich Hertz Telescope, a project that would take a typical single pixel receiver system 6 years of continuous observing to complete. Prototypes of all major components have been completed or are being fabricated now. The first 1x8 mixer row will be integrated and tested in 2006, and the full array will be populated and tested in 2007. We expect first light observations in winter 2007.

References

[1] R.B. Bass, J.C. Schultz, A.W. Lichtenberger (University of Virginia); C. Walker (University of Arizona); J. Kooi (CalTech), "Beam Lead Fabrication Using Vacuum Planarization", submitted to Proceedings of the Fourteenth International Symposium on Space THz Technology, May 2003.

[2] Carpenter, J. M., Snell, R. L., & Schloerb, F. P. 1995, "Star Formation in the Gemini OB1 Molecular Cloud Complex", ApJ, 450, 201

[3] Dame, T. M. et al. 1987, "A composite CO survey of the entire Milky Way", ApJ, 322, 706

[4] Dame, T. M., Hartmann, D., & Thaddeus, P. 2001, "The Milky Way in Molecular Clouds: A New Complete CO Survey", ApJ, 547, 792

[5] Gillespie, A. R. & Phillips, T. G., 1979, "Array Detectors for Millimetre Line Astronomy", A&A, 73, 14.

[6] Goldsmith, P., in "Quasioptical Systems", pub. IEEE Pressm 184.

[7] Groppi, C. E. et al. 2003, "DesertSTAR: a 7 pixel 345 GHz heterodyne array receiver for the Heinrich Hertz Telescope", SPIE, 4855, 330

[8] J.W. Kooi, C.K. Walker, and J. Hesler, "A Broad Bandwidth Suspended Membrane Waveguide to Thin Film Microstrip Transition", 9th Int. Conference on Teraherz Electronics, 15th - 16th October 2001.

[9] Sakamoto, S., Hasegawa, T., Hayashi, M., Handa, T., & Oka, T. 1995, "The Five College Radio Astronomy Observatory CO Survey of the Outer Galaxyî" ApJS, 100, 125

[10] Simon, R., Jackson, J. M., Clemens, D. P., Bania, T. M., & Heyer, M. H. 2001, "The Structure of Four Molecular Cloud Complexes in the BU-FCRAO Milky Way Galactic Ring Survey", ApJ, 551, 747

[11] E. Schlecht, G. Chattopadhyay, A. Maestrini, A. Fung, S. Martin, D. Pukala, J. Bruston, and I. Mehdi, "200, 400, and 800 GHz Schottky diode substrateless multipliers: Design and Results," 2001 IEEE, MTT-S International Microwave Symp. Digest, Phoenix, Az, pp. 1649-1652, May 2001.

[12] Walker, C. K., Groppi, C., d'Aubigny, C., Kulesa, C., Hungerford, A., Jacobs, K., Graf, U., Schieder, R., & Martin, C., 2001, PoleSTAR: A 4-Pixel 810 GHz Array Receiver for AST/RO, "Proceedings of the 12th International Symposium on Space Tera- Hertz Technology", San Diego, CA, Eds. Mehdi & McGrath, JPL.