# SuperCam: A 64 pixel heterodyne array receiver for the 350 GHz Atmospheric Window

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*Abstract*— We report on the development of SuperCam, a 64 pixel imaging spectrometer designed for operation in the astrophysically important 870 micron 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 Supercam key project is a fully sampled Galactic plane survey covering over 500 square degrees of the Galaxy in $^{12}$CO(3-2) and $^{13}$CO(3-2) with 0.3 km/s velocity resolution

SuperCam will have several times more pixels than any existing spectroscopic imaging array at submillimeter wavelengths. The exceptional mapping speed that will result, combined with the efficiency and angular resolution provided by the HHT will make SuperCam a powerful instrument for probing the history of star formation in our Galaxy and nearby galaxies. 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.

In the past, all heterodyne focal plane arrays have been constructed using discrete mixers, arrayed in the focal plane. SuperCam reduces cryogenic and mechanical complexity by integrating multiple mixers and amplifiers into a single array module with a single set of DC and IF connectors. These modules are housed in a closed-cycle cryostat with a 1.5W capacity 4K cooler. IF signals are downconverted to baseband with a custom surface-mount board with 8 channels of IF processing. An Omnisys AB real time FFT spectrometer processes these IF signals to produce 64x250 MHz spectra with 0.25 km/s velocity resolution. The Supercam system is largely complete, and is now undergoing final fabrication and assembly, and should be deployed on the HHT this observing season.

*Index Terms*— Submillimeter wave spectroscopy, Submillimeter wave imaimg, Submillimeter wave mixers, Submillimeter wave receivers

## I. INTRODUCTION

SUPERCAM has been designed to operate in the astrophysically rich 870μm atmospheric window. The Heinrich Hertz Submillimeter Telescope has a 13μm RMS surface, making it one of the most accurate large submillimeter telescope currently in operation. In addition, the 10,500ft elevation site on Mt. Graham offers weather sufficient for observing in this window more than 50% of the observing season, 24 hours per day. The receiver is an 8x8 array constructed from integrated 1x8 mixer modules, with state of the art mixer, local oscillator, low noise amplifier, cryogenic and digital signal processing technologies.

SuperCam will have several times more pixels than any existing spectroscopic imaging array at submillimeter wavelengths. The resulting exceptional mapping speed, combined with the efficiency and angular resolution provided by the HHT will make SuperCam a powerful instrument for probing the history of star formation in our Galaxy and nearby galaxies. 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.
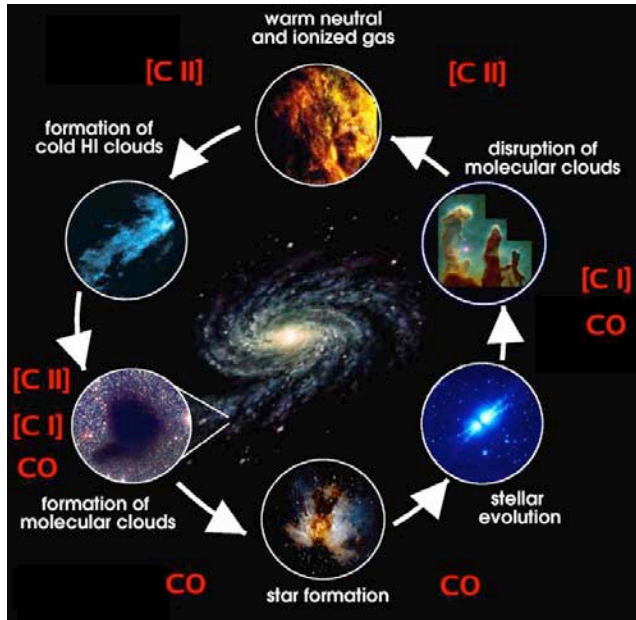


Figure 1: Life cycle of the ISM.

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 ($H_2$) 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 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.

SuperCam has been designed to complete a key project Galactic plane survey in the $^{12}CO(3-2)$ and $^{13}CO(3-2)$ transitions of carbon monoxide. This survey, covering 500 square degrees of the Galaxy including a fully sampled survey from l=0º-90º and -1º<b<1º in addition to many molecular cloud complexes visible from the northern hemisphere, will improve the spatial resolution of existing surveys by more than a factor of 10. In addition, this will be the first submillimeter CO Galactic plane survey, providing a census of molecular gas actively participating in star formation. When combined with existing CO(1-0) surveys, a complete excitation temperature map of the survey region can be constructed. The depth of the survey is sufficient to detect CO to a level consistent with Av~1, detecting all CO that has formed in-situ.

### III. SUPERCAM INSTRUMENT DESCRIPTION

#### A. Instrument Design

In the past, all heterodyne focal plane arrays have been constructed using discrete mixers, arrayed in the focal plane. SuperCam reduces cryogenic and mechanical complexity by integrating multiple mixers and amplifiers into a single array module with a single set of DC and IF connectors. 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 [1,2]. At the heart of the array is an 8 pixel linear integrated array of low-noise mixers. The array mixer contains first stage, low-noise, MMIC IF amplifier modules with integrated bias tees. Eight of these modules are then stacked to produce the final 64 pixel array.
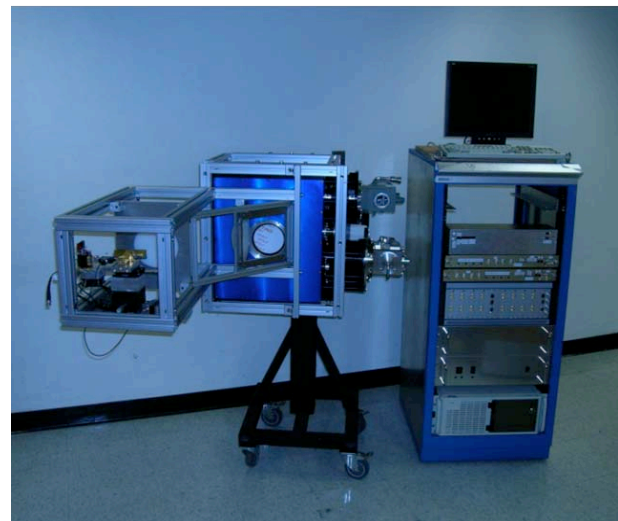


Figure 2: The SuperCam cryostat, LO optics and support electronics.

## B. Cryogenics

The SuperCam system with attached LO optics, frontend support electronics and backend electronics is shown in Figure 2. The cryostat was constructed by Universal Cryogenics in Tucson, Arizona, USA. Light from the telescope enters the cryostat through a 150 mm diameter AR coated, crystalline quartz vacuum window and passes through a Teflon coated crystalline quartz IR filter on the 40 K radiation shield before illuminating the 4 K mixer array. The Teflon layers on this filter serve as both the IR blocking filter and the antireflection coating. 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. Annealed and gold plated copper straps with a flex link connect the 4K cold tip to the cold plate, with less than a 0.2K temperature differential. Tests using heaters on the 4K cold plate, and system tests using prototype 1x8 mixer modules demonstrate adequate performance of the cryogenic system with the expected heat load from all 64 pixels.
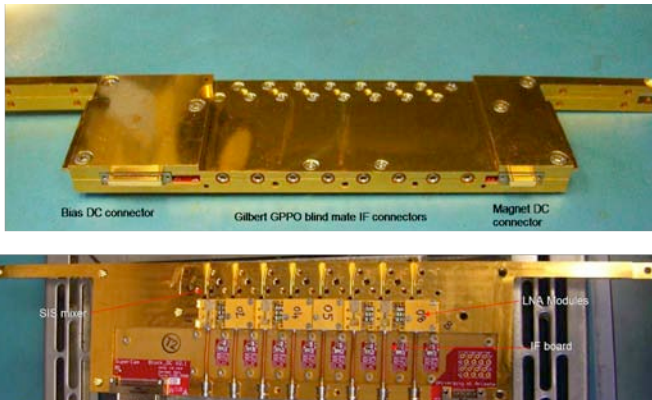


Figure 3: A completed Supercam 1x8 mixer module, fully assembled (top) and with the top cover removed (bottom).

## C. Mixer Array

The SuperCam 64 beam focal plane is constructed from eight linear array modules with eight pixels each. Each pixel consists of a sensitive single ended SIS mixer optimized for operation from 320-380 GHz. The array mixers utilize SIS devices fabricated on Silicon-On-Insulator (SOI) substrates, with beam lead supports and electrical contacts [3]. 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 [4]. The 1x8 mixer subarrays are 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 shows a photograph of a production gold plated tellurium copper 1x8 mixer array fabricated at the

University of Arizona using a Kern MMP micromilling machine. This block meets all design specifications, with 3 μm dimensional accuracy for all waveguide circuits. A diagonal feedhorn extension block is bolted to the front of the mixer array assembly, extending the diagonal horns to 11mm aperture size. This eliminates the need for dielectric lenses and their associated manufacturing and alignment difficulties. The energy in the horn passes through a 90° waveguide bend before reaching the device. The waveguide environment is designed around full height rectangular waveguide, with a fixed quarter wave backshort. The SIS device is suspended and self-aligned above the suspended stripline channel via eight small beamlead supports. The hot beamleads are tack-bonded with a wirebonder to the MMIC module input pads. Ground beamleads are glued to the mixer block using Epo-tek H20E conductive epoxy. The mounting method is designed such that the block can be opened repeatedly without disturbing the SIS devices. Single devices can be removed and replaced without disturbing neighboring devices. The mixer blocks are 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. A SuperCam 1x8 module can be produced in ~8 hours of machine run time. The machine's 24 position tool changer allows a complete block to be fabricated with minimal user intervention during the machining process. Integrated workpiece and tool metrology systems, along with sophisticated computer aided manufacturing (CAM) software result in high part yield. Verification of fabricated parts though a high precision measurement microscope and 3D interferometric microscope insure dimensional accuracy and waveguide surface finish are within design tolerance. Testing, described in section IV, has been carried out using a single-pixel version of the SuperCam mixer design in a test cryostat, and with both prototype and production 8-pixel mixer modules. All mixer blocks are complete and are now undergoing gold plating and assembly.

## D. 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. 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 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 [5,6]. Figure 5 shows the complete 64-way power

divider constructed with the Kern micromilling machine at the University of Arizona. The power pattern of this divider and its injection optics is also shown in figure 5. Power division is equal to the ~10% level. In addition, we have constructed a 8 channel linear power divider for testing single mixer units with a lower power laboratory LO source. This power divider has been used in system tests with the prototype and production 1x8 mixer arrays, with excellent results. An extended diagonal horn array similar to the mixer horn extension blocks then matches the LO beams to the mixers through a Gaussian beam telescope comprised of two large dielectric lenses. A 1.0 mil Mylar beamsplitter is used to inject the LO power. Testing has shown that a 2mW LO source is sufficient to optimally pump a 1x8 mixer array with this scheme, running at only ~20% of the maximum power output. An already purchased 12 mW source from Virginia Diodes will be more than sufficient to pump the final 64 pixel array, also with a 1.0 mil Mylar 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 provide well controlled and predictable LO power distribution and coupling to each mixer.
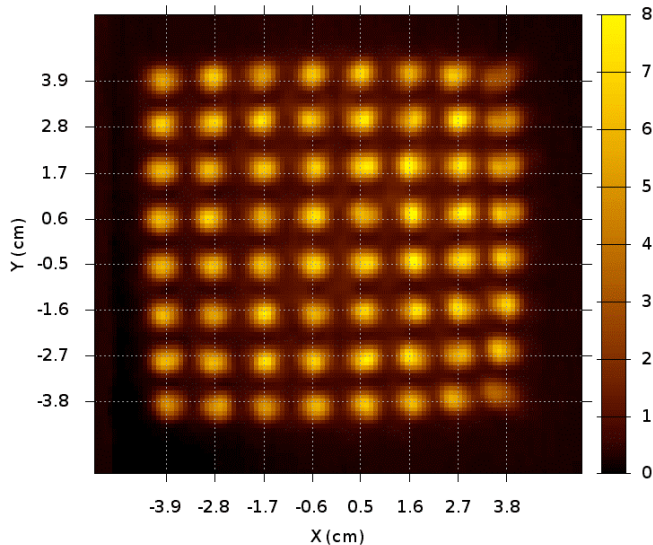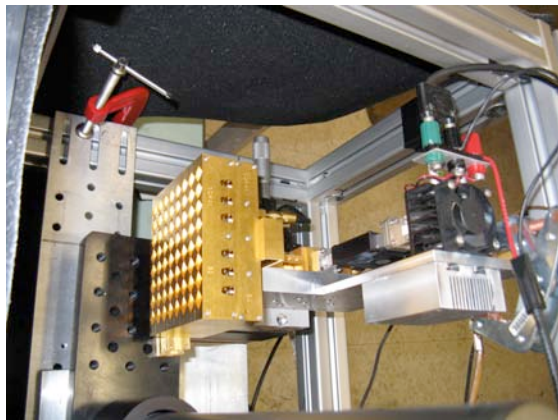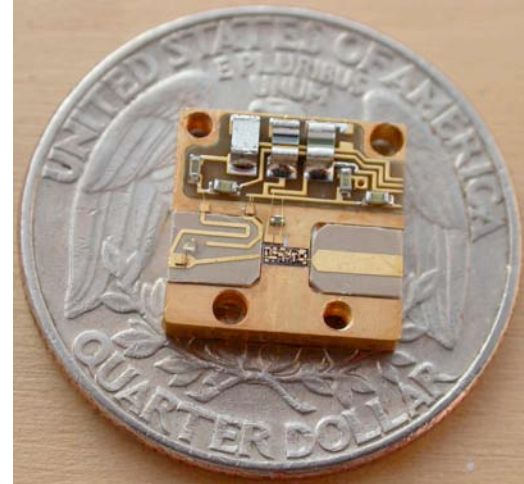




Figure 4: Supercam 64-way waveguide LO power divider (top) and measured power pattern from this divider (bottom). Amplitude scale is linear. Power is evenly divided to the +/- ~10% level. Some asymmetrical barrel distortion is evident, due to optical misalignment in the test setup.
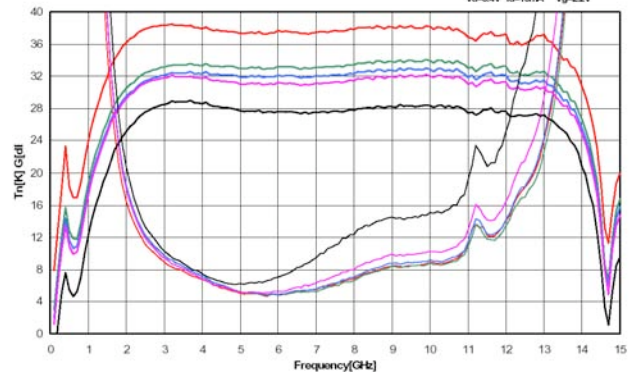


Figure 5: A SuperCam MMIC amplifier module (top), and typical measured results at 13K bath temperature (bottom) for several bias points. Amplifier noise remains low for bias powers as low as 6 mW. Gain remains above 30 dB.

### E.  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 and delivers 32 dB of gain while consuming 8 mW of power. An example is shown in figure 4, with measured gain and noise data at 4 mW through 20 mW power dissipation. Noise remains virtually unchanged down to 6 mW power dissipation, while gain is reduced modestly (Figure 5). Several tests have been performed with these modules to ensure oscillation free operation, low noise, high stability, and no heating effects on the SIS device. Modules have been integrated into both single pixel and 1x8 array mixers, and have shown performance as good or better than expected with connectorized amplifiers. No heating effects are visible, although care must be taken to avoid oscillation due to

feedback.

In addition to the LNA modules, the Caltech group has designed and constructed a warm IF system for SuperCam that will condition the IF signal for use with the SuperCam Array Spectrometer (figure 6). This IF system consists of a single large microwave printed circuit board with 8 channels of signal conditioning mounted in a modular chassis. The module contains a 5 GHz gain stage, switchable filters for both 250 MHz and 500 MHz bandwidth modes, baseband downconversion and baseband amplification.
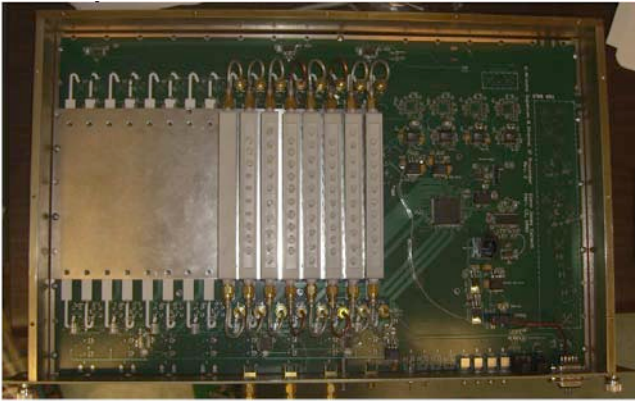


Figure 6: The inside of a SuperCam IF processor. This module provides amplification, programmable attenuation, passband filtering and total power detection for 8 channels.

### F. Array Spectrometer

The SuperCam spectrometer delivers 64 channels at 250 MHz/channel with 250 kHz resolution, or 32 channels at 500 MHz with 250 kHz resolution. The system will be capable of resolving lines in all but the coldest clouds, while fully encompassing the Galactic rotation curve. The system is easily extendible to deliver 64 500 MHz bandwidth channels or 32 1 GHz bandwidth channels. 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, built by Omnisys AB of Sweden, is based on a polyphase filterbank architecture. High speed ADCs digitize the incoming RF signal at 8 bits resolution, preventing any significant data loss as with autocorrelation based schemes. A polyphase filterbank spectrometer is implemented on a FPGA. In our board architecture, 4 ADCs feed a single Xilinx Virtex 4 FPGA on each spectrometer board. Each board can process 4 500 MHz IF bandwidth signals or two 1 GHz IF bandwidth signals at 250 kHz resolution. These systems are fully reconfigurable by loading new firmware into the FPGAs. In addition, the spectrometer can be easily expanded to increase bandwidth. We have received an 8 board system capable of processing 64x250 MHz, 32x 500 MHz or 16x1GHz IF signals (figure 7). In the 64x250 MHz mode, we power combine two IF signals into one spectrometer input. Stability testing shows the spectrometer is capable of delivering a spectroscopic Allan time of ~650s, including the effects of the IF processor described in section III.E.
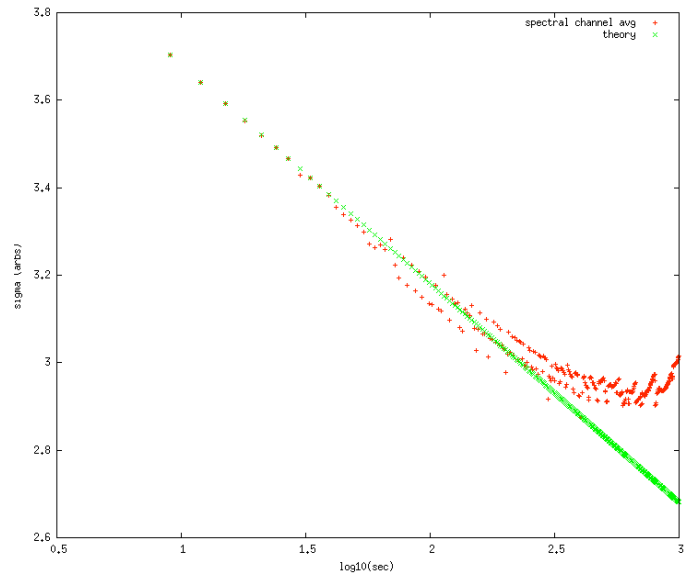




Figure 7: Measured Allan variance of the Supercam spectrometer system, including the Caltech IF processor. Allen time is 650s (top). The Supercam spectrometer system, built by Omnisys AB (bottom). This single 3U crate can process 16 GHz of IF bandwidth at 250 kHz spatial resolution. It consumes less than 200W of AC power.

### G. 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 located in the apex room transforms the f number of the telescope to f/5 (figure 8). 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 several flat mirrors. All the reimaging optics can be mounted on a single modular optical frame. This frame can be completely constructed, aligned and tested off the telescope, disassembled into modules and reassembled in the apex room. All electronics, including the backend, are located 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.
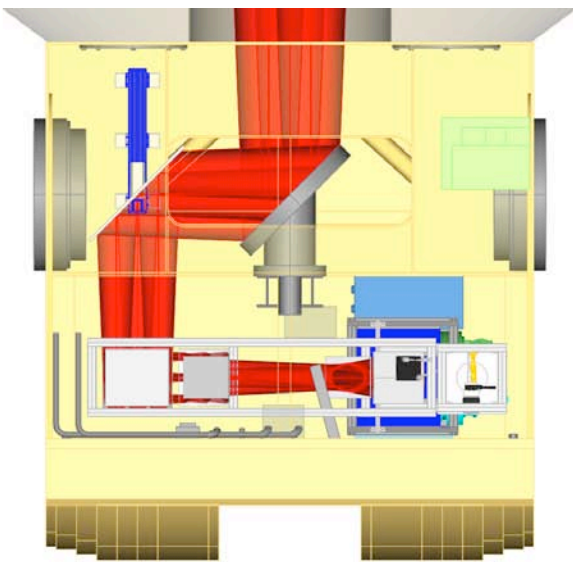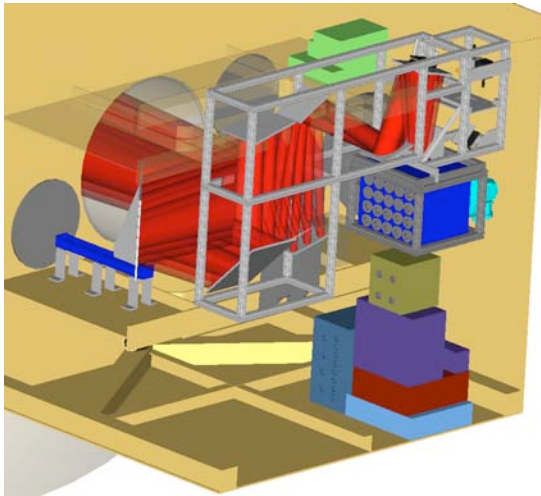
Figure 8: The Supercam optical design viewed from behind the primary reflector, (top), and viewed from the top (bottom). The apex room is transparent to visualize the design. The beam bundles are displayed in red.

## IV. LABORATORY TESTING

For testing the SuperCam mixer design in the laboratory, we have designed two single pixel mixers. The first design uses an existing SIS junction design from the DesertStar 7-pixel array [2], but incorporates the Caltech designed MMIC module. This work has been reported in other papers [7]. We determined that the SIS receiver with integrated MMIC amplifier worked as well as a receiver with a separate connectorized amplifier and cryogenic amplifier, and resulted in no heating effects at the SIS device from the close proximity of the amplifier. We later designed a second single pixel amplifier that is an exact copy of a single pixel of the 1x8 mixer array design discussed in section III.B. This mixer was designed to test the self-aligning beam-lead-on-SOI SIS devices that will be used in the SuperCam array, as well as the compact, low power electromagnet, MMIC amplifier module and extended diagonal feedhorn.

This mixer has been extensively tested for noise

performance across the band, frequency response using a Fourier Transform Spectrometer, and stability measurements using the complete backend system. Tests with the latest wafer of SIS on SOI devices from UVa show close to optimal tuning, and measured noise temperatures of ~65 K with less than 10K variation across the measured band (LO limited to 330 to 365 GHz). A plot of uncorrected receiver temperature versus LO frequency is shown in figure 9.
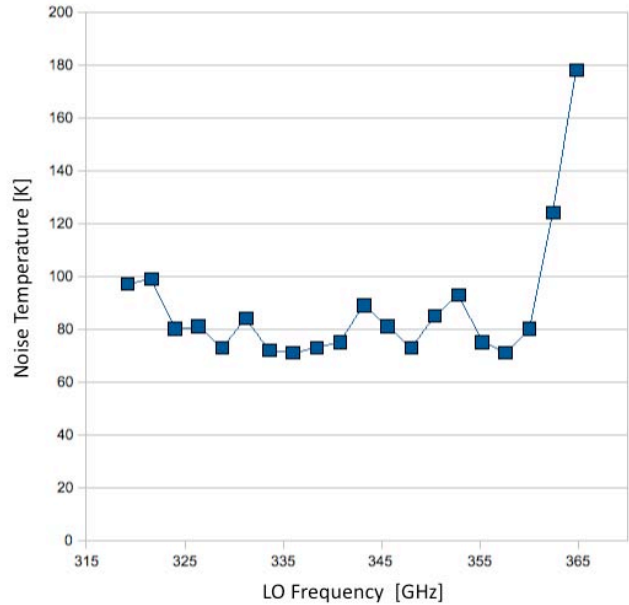


Figure 9: Supercam single pixel test mixer noise vs. LO frequency. Noise performance at the low and high ends of the band are influenced by lack of available LO power from our LO chain. The "bumps" in noise performance are due to residual sideband noise from the LO source, and are not present when measured with a Gunn diode driven LO.

In addition, measurements of both a prototype and production 1x8 mixer array have been completed using prototype or final electronics for the entire system. Performance testing of the first production mixer module is summarized in figure 10. The SIS devices for this test were selected randomly and screened only for their room temperature resistance. Device yield was 100% after this screening process. Noise temperatures have been corrected for the loss introduced by the currently uncoated quartz vacuum window. In addition, these measurements were made using a Goretex GR infrared filter rather than a Teflon coated quartz IR filter. The significantly increased IR load resulted in a higher than desired mixer temperature (~5K), also increasing noise somewhat. With an AR coated vacuum window and quartz IR filter, we expect to achieve the same noise performance as we have measured using the single pixel test mixer.
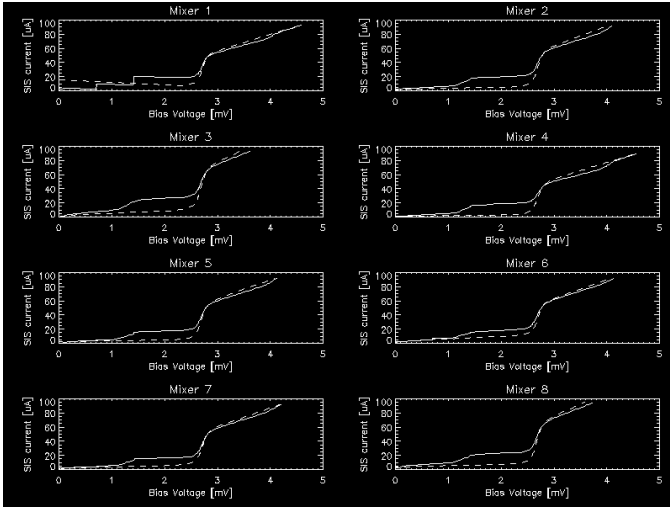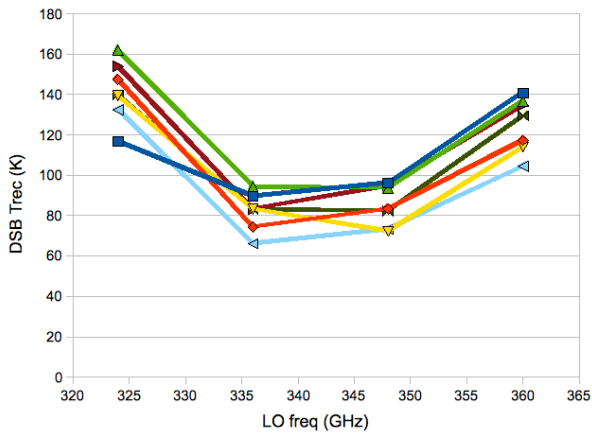
Figure 10: Noise vs. frequency measurements (top) and pumped and unpumped IV curves, of the eight pixels in the first Supercam production mixer (bottom). Mixer #1's magnet was not functioning during this test, and is not included in the noise measurements. LO sideband noise is contaminating the noise measurements at the low and high ends of the measured band.

## V. CONCLUSION

We are constructing SuperCam, a 64-pixel heterodyne imaging spectrometer for the 870 μm 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(3-2) and $^{13}$CO(3-2) 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 and tested. Fabrication of the final waveguide components is now complete, and assembly is underway. One 1x8 mixer module is installed in the cryostat for testing at the University of Arizona, while the remaining modules are being assembled at Caltech. We expect to complete the instrument this summer, and deploy on the HHT during the fall observing season.

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