Supplemental Request for SuperCam:
A SuperHeterodyne Camera for the Heinrich Hertz Telescope
AST-0421499

1 Introduction

We request supplemental funding for the completion 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. Initially, SuperCam will be used on the 10 m Heinrich Hertz Telescope (HHT) on Mt. Graham, Arizona to conduct a Galactic Plane survey in the ^{12}CO and ^{13}CO J=3$\rightarrow$2 lines. A long history of water vapor measurements (>10 years) indicate the 870 μm atmospheric window is available 50% of the time from the HHT. Discussions are underway for taking SuperCam to a comparable Atacama telescope to conduct the southern portion of the Galactic Plane survey.

Each component of Supercam has been modularized in units of **1×8 rows** of the full heterodyne array. Thus, the mixer blocks, bias electronics, IF processors, and spectrometers are quantized into modules that correspond to 8 detector "pixels" each. This quantization is crucial to the realization of large heterodyne arrays and has been successfully completed by the SuperCam team.

In 2005 we successfully tested a one pixel prototype of SuperCam (see Puetz et al. 2006). Using this as a starting point, in 2006 our team completed the design of the optical, cryogenic, RF, and electronics subsystems for the array. A one-pixel end-to-end test of SuperCam technologies was successfully conducted in August, 2006. All the subsystems required to perform an end-to-end lab test of the first 1x8 row of SuperCam have been built and tested. **With the completion of this test in January 2007, all technological components of SuperCam will have been demonstrated. From that point, only funds to fabricate the remaining "rows" of the array will be needed. The project is on schedule for completion by the end of 2007.**

Projecting expenditures forward, we foresee a budget shortfall of ~19% at project completion. We request supplemental funds to cover this amount. Below we summarize the operation and status of each SuperCam subsystem. In the "Justification For Supplement" section of this request we describe how the supplement will be implemented to complete the project.

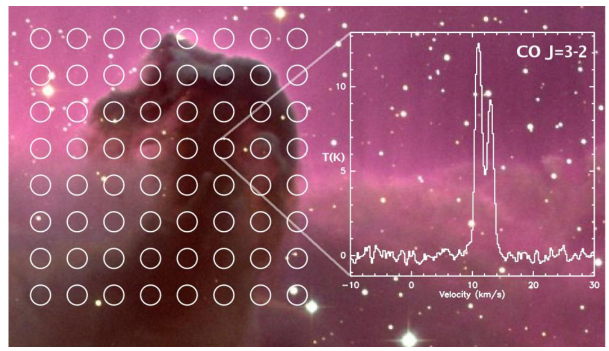

Figure 1: The 64 beams of SuperCam overlaid upon the Horsehead Nebula (B33). Each beam will measure a high-resolution spectrum (right).

2 Optical System

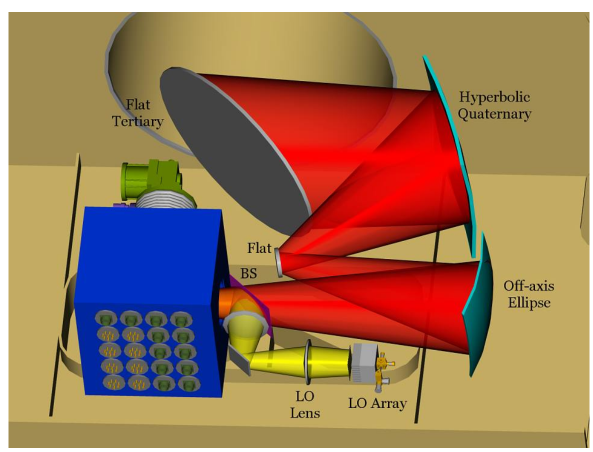

Figure 2: SuperCam integrated in the HHT Apex Room.

2.1 *Telescope Matching*

SuperCam will initially reside on the HHT. The goal of the instrument's optical system is to produce an

8x8 array of diffraction limited beams on the sky with <1% overlap in their power patterns (Figure 1). This can be achieved if the separation between pixels in the instrument focal plane is 2.5 $f\ \lambda$. A faster beam makes the focal plane more compact, but produces more rapidly diverging beams. The lower limit to the focal ratio is set by the requirement that the emerging beams clear the cryostat window at the 3ω level (ω is the Gaussian beam waist). For our application an f/5 beam is a good compromise, yielding a pixel separation of 11 mm in the focal plane. Re-imaging optics are necessary to reduce the f/13.8 beam of the HHT to f/5. In Figure 2 is a 3D CAD drawing of a re-imaging system that fulfills these design requirements and fits comfortably within the apex room (located just behind the primary) of the HHT where SuperCam will reside. The design was first made using Zemax and then optimized with the more sophisticated ASAP optical design package.

The dewar and optical system will be mounted in a common frame capable of being positioned in x and y, permitting the beams to be accurately centered on the secondary.

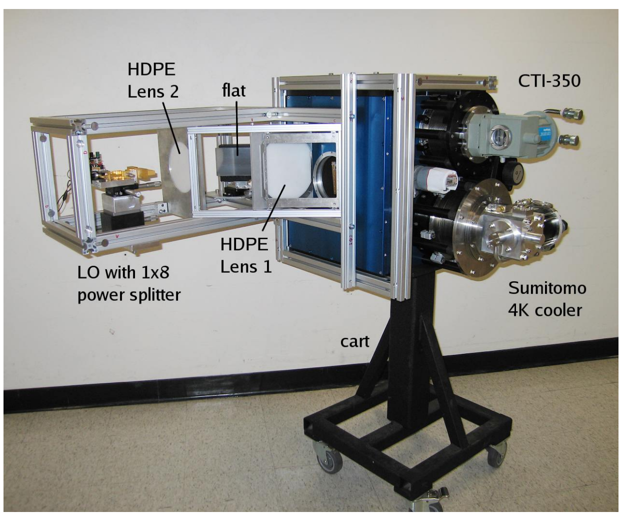

Figure 3: SuperCam dewar and Virginia Diodes LO (with 1x8 power splitter) in their combined support frame.

2.2 *Local Oscillator (LO) Injection*

Several local oscillator (LO) injection schemes were considered, including waveguide cross-guide couplers. The large number of pixels makes waveguide coupling very cumbersome and difficult to fabricate. We are fortunate that high-powered LO chains (>1mW) using commercially available frequency multipliers permit simple, quasi-optical coupling into the signal beam with a dielectric beam splitter. In a "standard" quasi-optical beam splitter Mylar is often used as the dielectric. In such instances of order 1% of the LO power is injected into the cryostat, with the balance being terminated in an absorbing load. In order to conserve LO power, SuperCam will employ a precision polished silicon etalon whose thickness is tuned for it to serve as a Fabry-Perot diplexer at the frequency of interest. Such diplexers are capable of injecting ~50% of the LO power into the cryostat while passing ~98% of the sky signal (Mueller & Waldman 1994). The primary science goal of SuperCam is to map the Galactic Plane in ^{12}CO and ^{13}CO. A silicon etalon will be fabricated for each of these line frequencies.

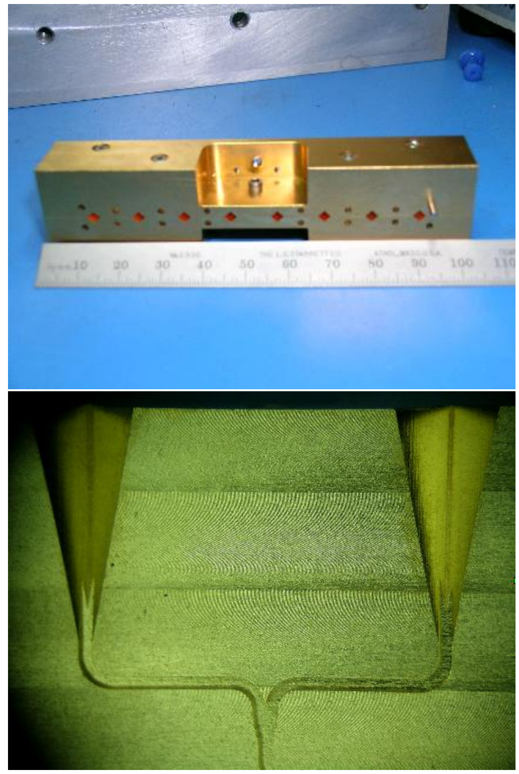

Figure 4: 1x8 LO power splitter block, and zoom-in on a single waveguide junction

An 8×8 way waveguide, corporate power divider will be machined (using the Kern micro-milling machine purchased largely through this grant) to produce an independent LO beam for each pixel. One row of the LO power splitter is shown in Figure 4. The measured output power from each horn is in excellent agreement with theory. After encountering the silicon diplexer, the combined LO and signal beams enter the cryostat through an AR-coated,

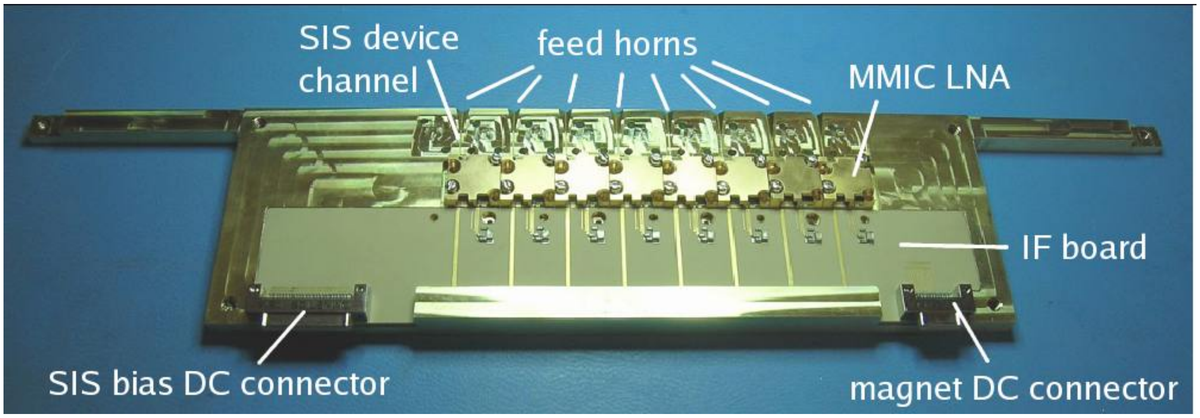

Figure 5: (left) Photograph of completed 1x8 mixer array.

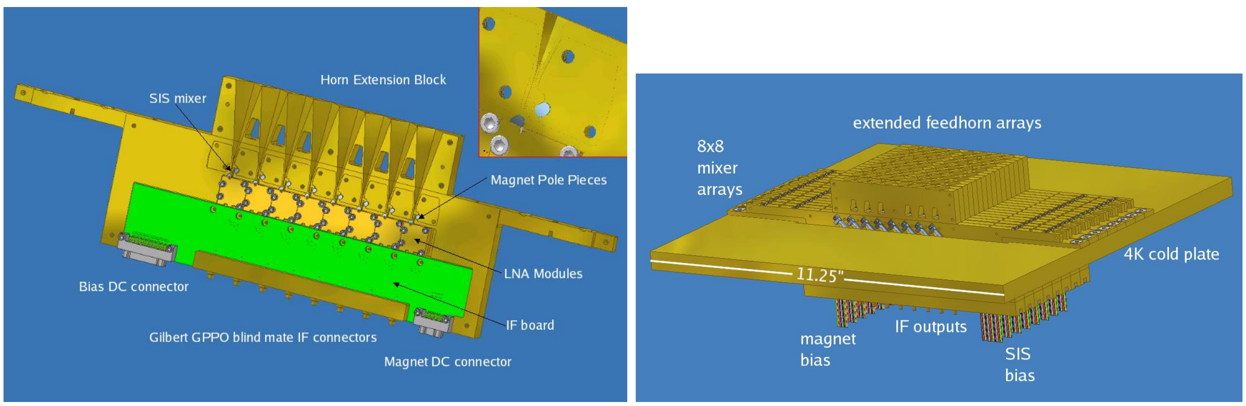

Figure 6: (left) 1x8 SuperCam mixer block exploded view. (right) Fully assembled focal plane array.

crystalline quartz vacuum window. They then pass through a cooled Goretex GR infrared filter before entering an 8x8 array of feed horns.

3 Mixer Arrays

3.1 *Design Approach*

SuperCam will utilize eight, 1×8 rows of integrated mixer arrays. For large (>25 pixels) format arrays like SuperCam, the relative ease of assembly and low-cost of single-ended, DSB mixers make them preferable over single-sideband approaches. Figure 5 is a photograph of the bottom half of a 1x8 mixer array that was machined in 1 day using the Kern micro-milling machine at the UofA. The mixer module is shown assembled with waveguide feed horns, IF MMIC modules, and DC bias board. 3D renderings of an exploded view of a mixer module and the fully assembled array are shown in Figure 6.

The signal/LO beams are gathered by the feed horns and launched into half-height rectangular waveguide. The waveguide carries the energy around a 90 degree bend to the SIS junction (fabricated by Arthur Lichtenberger at the University of Virginia) and fixed backshort. The first single pixel mixer prototype (Puetz et al 2006) utilized the same quartz substrate SIS devices used in Desert STAR. In the final version of SuperCam, the SIS junctions will be fabricated with beam leads on thin silicon (SOI) substrates, making device mounting more straightforward and reliable. SuperCam test devices (see Figure 7), with everything but the SIS device itself, were delivered and tested for form and fit in the summer of 2006. These tests were successful, showing that a SOI device can be mounted and wire bonded easily into the block. Fabrication of SOI SIS devices is underway. The first Supercam device wafer was fabricated at the Univ. of Virginia in early December 2006 up to the final thinning and patterning of the backside of the wafer. The layout was designed so that a full thickness portion of the wafer can be diced off and electrically dip tested in liquid helium before proceeding to the final thinning and chip definition process. The electrical characteristic of a typical mixer from this dip test is shown in Figure 8. Delivery of the devices to Arizona is expected in January 2007, once the final thinning and chip definition process have been completed. The 4-6 GHz intermediate frequency (IF) output of each junction is then wire bonded to the input of a custom, low-noise, MMIC amplifier module designed by Sandy Weinreb and his group. A close-up of the module design and performance data are provided in Figure 9.

The module produces ∼35dB gain at a noise temperature of ∼5K over SuperCam's IF range (nominally 4-6 GHz). Besides having excellent performance, the MMIC module has a power dissipation of <9mW which permits it to be integrated directly into the mixer block, adjacent to the SIS junction as shown in Figure 5. The outputs of the MMIC modules are wire bonded to a multilayer PC board that carries the signals via microstrip to a 1x8 array of miniature, push-on (GPPO) connectors located on the back of the module. DC bias for the SIS junctions, MMIC modules, and electromagnets (required to suppress the Josephson effect) are provided by multi-pin edge connectors and conveyed to the components through underlying layers in the PC board. All electrical connections to the 1x8 mixer subarray are made through connectors on the rear of the unit, allowing it to be removed without disturbing the cryogenic wiring harness.

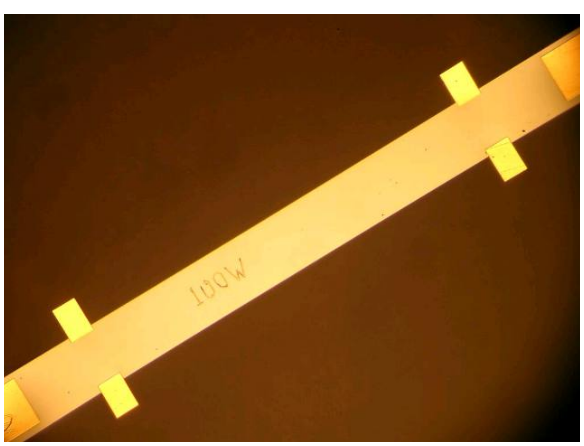

Figure 7: SuperCam SOI substrate test device with beam leads.

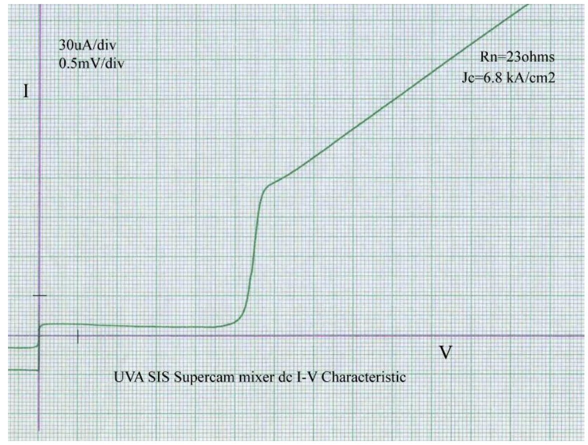

Figure 8: Sample I-V curve of a Supercam SOI SIS junction at the Univ. of Virginia. The electrical characteristics are excellent; measured junction parameters are very close to the design.

3.2 *Prototype Mixer Tests*

In July 2005 a prototype, single pixel SuperCam mixer was tested. The mixer, shown in Figure 10 is a DesertSTAR spare that was modified to accept a SuperCam style MMIC module. The RF design of the modified mixer is operationally identical to that of a SuperCam mixer. Key concerns were whether the presence of the MMIC module so close to the SIS junction would cause unwanted heating (which could reduce device sensitivity) or instabilities. However, neither of these problems materialized and the mixer worked well the first time. Plots of the mixer performance are shown in Figure 11. Even with an un-optimized IF impedance match, the mixer was low-noise and stable. A paper describing the test results in detail has been published in the Journal of Infrared and Millimeter Waves (Puetz et al. 2006).

4 Cryostat

The SuperCam cryostat is shown with its LO system in Figure 3. The cryostat has a 150mm diameter AR coated, crystalline quartz window, is 20 inches on a side, and utilizes two closed-cycle refrigerators: a Sumitomo RDK-415D to cool the mixer array and a CTI 350 to take the heat load of the 64 stainless steel coaxial (0.085 in) cables. Laboratory measurements indicate the system has a 50% margin in thermal load capacity. IF connections to the outside are made via 64 SMA style, hermetic, bulk-head connec-

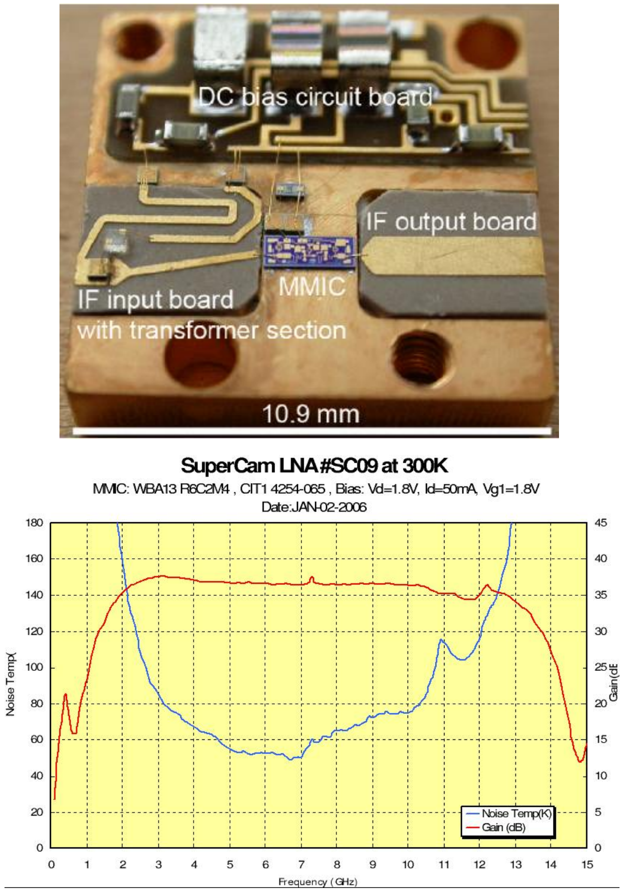

Figure 9: (TOP) 4-6 GHz MMIC Module. (BOTTOM) MMIC performance plots show >30 dB of gain from 1-14 GHz.

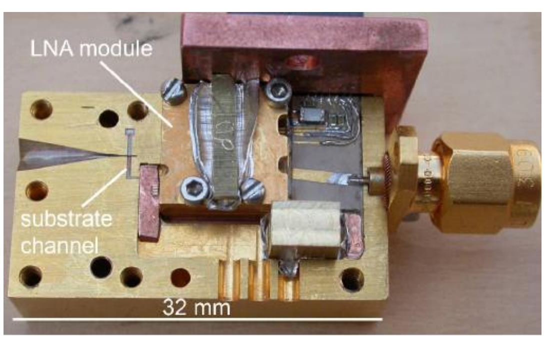

Figure 10: Photograph of the single-pixel prototype SuperCam mixer

tors. Twelve multi-pin connectors are used to convey DC bias signals in and out of the cryostat. The cryostat is now wired for conducting tests with the first 1x8 row of the array.

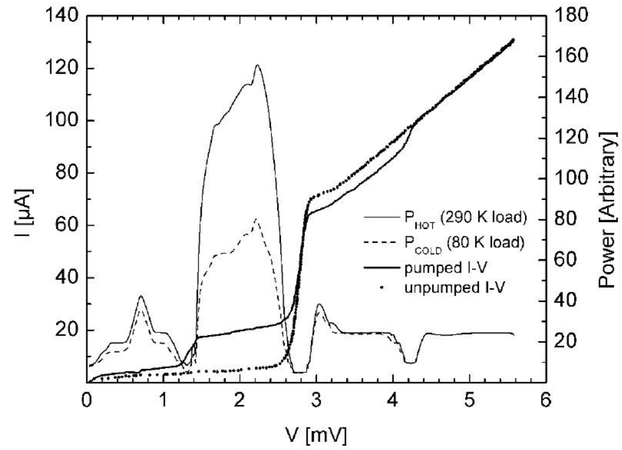

Figure 11: Performance curves for the prototype SuperCam mixer using a spare DesertSTAR SIS junction.

5 IF Processors

The 4-6 GHz IF signal emerging from the SuperCam dewar must be filtered, downconverted to baseband, and amplified to 0 dBm to be properly conditioned for the input of the spectrometer system. Sander Weinreb and his graduate students Joe Bardin and Glenn Jones have designed and constructed a fully-tested 2-channel prototype and the first 1×8 modular row of IF processors for SuperCam. The IF processor provides each channel an initial 48 dB of gain, a variable (0-31 dB) digital attenuator, a selectable 256 MHz or 512 MHz bandpass filter, a mixer conversion to baseband, low-pass filter and 50 dB of baseband gain. An additional circuit provides total-power measurement of the IF power for telescope pointing and continuum measurements. A picture of the 8-channel IF processor module and a sample 512 MHz bandpass is shown in Figure 12.

6 FFT-in-FPGA Spectrometer

Science drivers for the SuperCam spectrometer stipulate two principal requirements. Sufficient kinematic resolution of molecular cloud components in CO emission will only be achieved with frequency resolution of finer than 512 KHz per channel, with 256 KHz preferred. The divergence of the velocity field of the inner Galaxy requires a bandwidth of 256 MHz or greater. **Rapid advances in digital logic have made the spectrometer solution even more powerful than envisioned originally.** Though we had originally baselined a 64×128 MHz 2-bit auto-

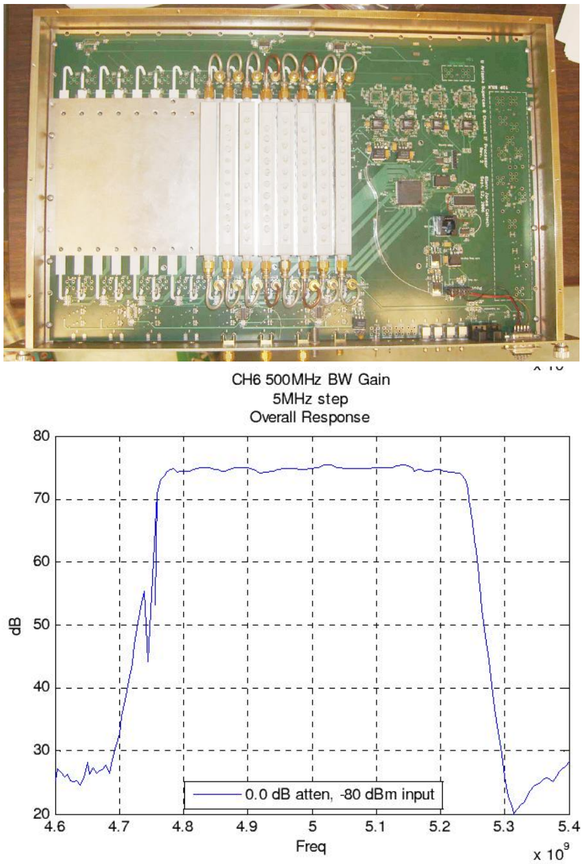

Figure 12: 8-channel IF processor module and sample bandpass

correlator system from Spaceborne Inc., recent gains in high-speed ADCs and FPGAs have made a direct-digitization spectrometer economically feasible. In this scenario, the entire IF signal is digitized in real time with high 8-bit fidelity (using multiple Atmel 1Gs ADCs) and a Fast Fourier Transform is then performed by a (Virtex4) FPGA. Omnisys Inc. was consigned to construct a prototype spectrometer card capable of processing a total of 2 GHz of bandwidth, software-selectable between 8-input mode (256 MHz per input), 4 input mode (512 MHz each), and 2-input mode (1 GHz each). Initially, we will power-combine in pairs the beams from an entire row to a single spectrometer card, yielding 256 MHz of bandwidth per beam, and thus requiring 8 spectrometer cards in total. A future upgrade path will be to install 8 more boards, for 512 MHz of bandwidth per channel. The performance of this spectrometer card has proven to be exceptional (Figure 14).

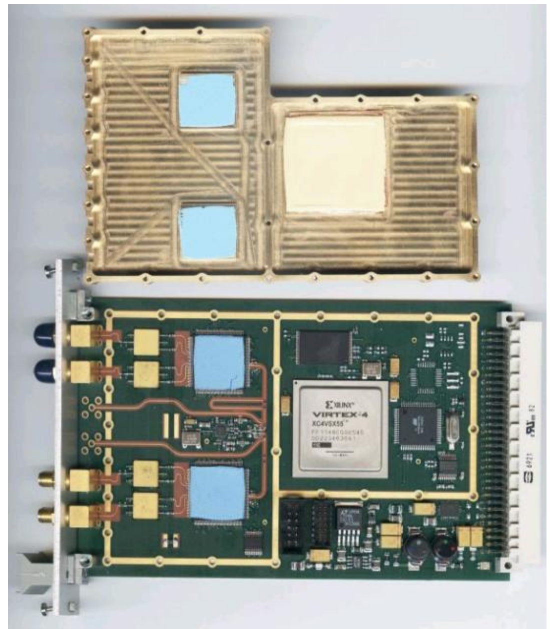

Figure 13: SuperCam spectrometer card as constructed by Omnisys Inc. The board features 2 GHz of bandwidth, software selectable between two 1 GHz inputs, four 512 MHz inputs, or eight (power combined) 256 MHz inputs.

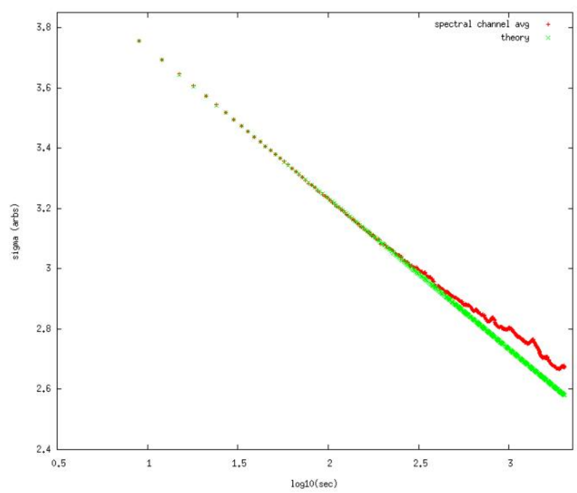

Figure 14: Allan variance of the prototype SuperCam spectrometer is >2000 seconds with a reference noise source as its input.

7 Electronics

The control electronics for the biasing of the SIS detector array, and its attendant electromagnets and MMIC Low Noise Amplifiers is a consolidation of

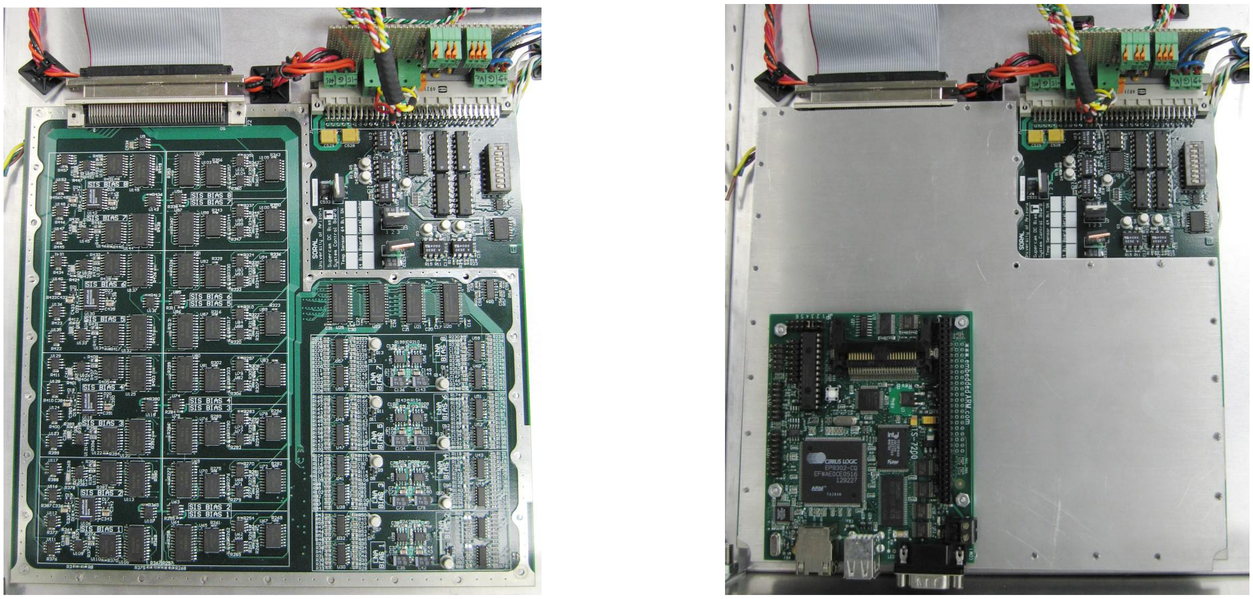

Figure 15: (LEFT) 1×8 bias electronics card exposed in its test box. (RIGHT) Bias electronics card with top shield installed and controlling Single Board Computer attached.

the successful electronics implementations used for previous DesertSTAR and PoleSTAR heterodyne arrays. A single 6U electronics bias board controls all functions of an entire 8-pixel row of Supercam (Figure 15). Operation of the bias board prototype has been completely validated. All 1×8 preamp boards for the full 8×8 array have been provided by UMass/Amherst; a picture of one preamp board in a test box is shown in Figure 16. Remaining work on the bias electronics involves the fabrication of the final bias electronics boards, acquisition and installation of electronics components, integration into the final electromagnetically-shielded rack-mounted case, and the completion of array control software.

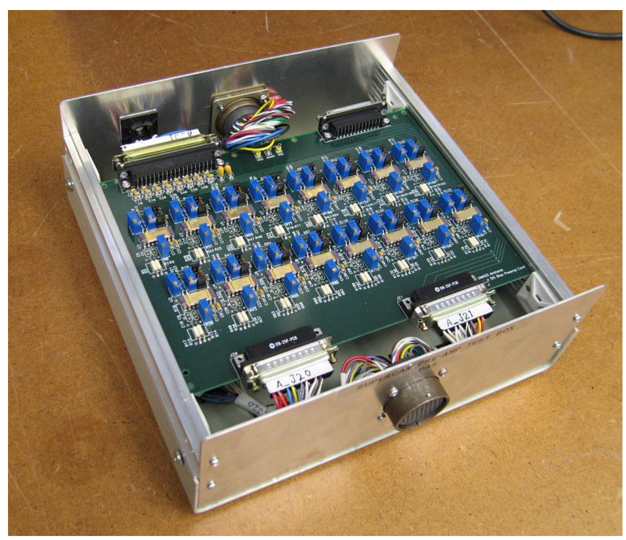

Figure 16: 1×8 preamp board from UMass/Amherst mounted in its test box.

8 Data Pipeline

A schematic of the SuperCam data pipeline is shown in Figure 17. The spectrometer will have a dedicated, 1 Gb ethernet connection to a data acquisition/spectrometer (DAS) control PC. The DAS PC will have two ethernet cards and a RAID5 array for local data storage and fault tolerance. Five >500 GB drives will provide >2.5 TB storage. During the Galactic Plane survey the data rate will be 400 GB/day. The DAS disk array will provide at least a week of raw storage at 90% duty cycle.

The DAS PC will stream the raw data to a background process that will be responsible for regridding the data into a more manageable format; approximately 200 GB for the entire Supercam Galactic plane survey. The data processing task will also be responsible for determining the quality of the data and flagging bad OTF scans that need to be repeated. Quality will be assessed by evaluating the RMS noise after subtracting the baseline from each spectrum and comparing with that expected from T_{sys}. The data processing task will spool preprocessed data images to the telescope control computer(s) for the observer to see, upon request. The HHT telescope control computer in return will send data acquisition requests to the DAS PC, thus closing the communications loop.

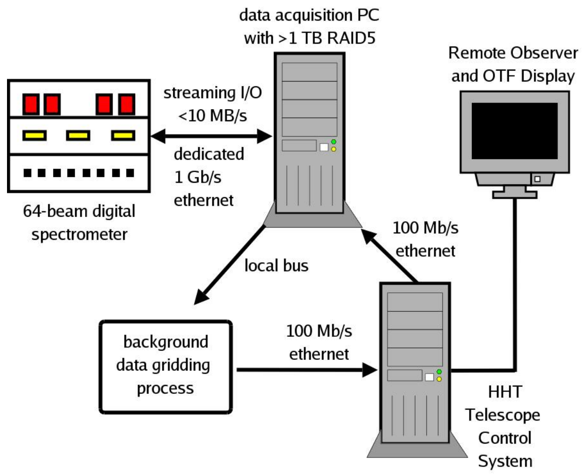

Figure 17: Schematic of SuperCam data pipeline

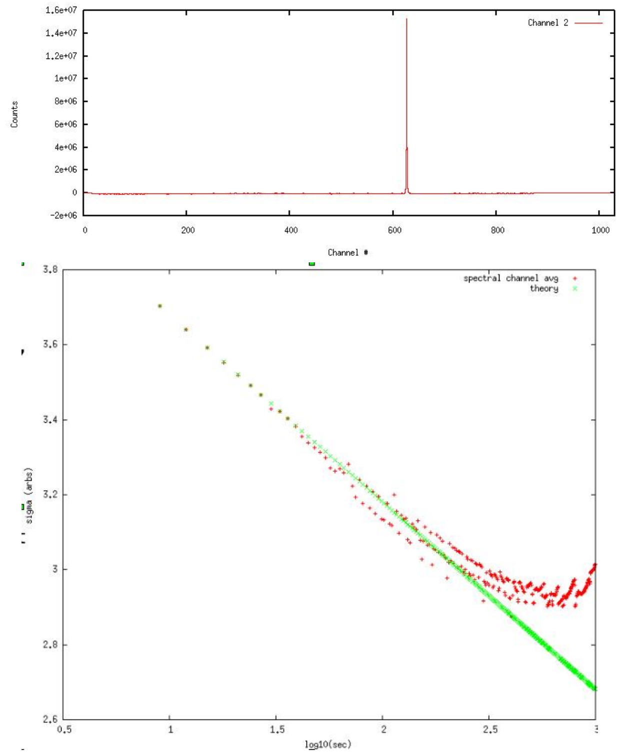

Figure 18: Sample results from the end-to-end SuperCam test in August 2006: (TOP) First spectral light of an injected line at 346 GHz as detected by the SuperCam FFT spectrometer. (BOTTOM) Allan-variance of the combined Caltech IF processor and Omnisys FFT spectrometer. Classical spectroscopic Allan time is 650 seconds.

9 Integration and Testing

Integration and testing of the Supercam array is second in importance only to its fabrication! The one-pixel Supercam prototypes underwent a complete end-to-end test, from Supercam test mixer with integrated MMIC LNA, to IF processor, to Omnisys FFT spectrometer. In addition to the tests performed earlier in Puetz et al. (2006), the entire chain of IF technologies were validated and assessed, with "first spectral light" and stability tests of the IF chain system performed (Figure 18). A picture of the overall lab configuration is shown in Figure 19. The same analysis will be performed for the 1×8 mixer blocks in the SuperCam cryostat in January 2007, and again for the full 8×8 mixer array near the end of 2007. At the conclusion of lab tests, integration of the optical system to the HHT telescope and data system to the HHT telexcope control system will be perfomed, so that first light will be achieved during the winter of 2007-8.

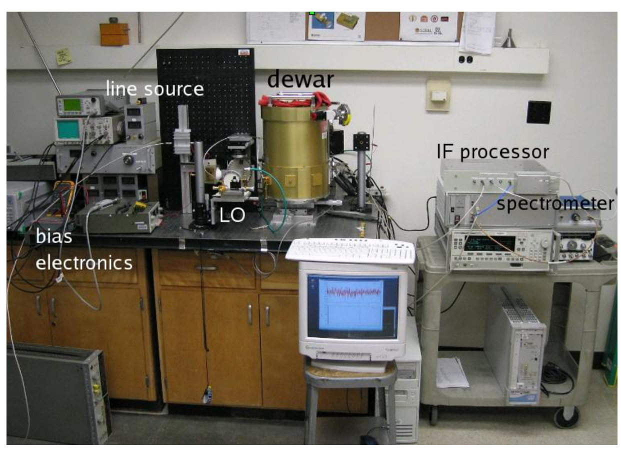

Figure 19: Lab setup of the August 2006 end-to-end test of key SuperCam technologies, from an integrated SuperCam mixer module in a test dewar, to prototype IF processor and FFT spectrometer.

References

1. Puetz, P., Hedden, A., Gensheimer, P., Golish, D., Groppi, C.E., Kulesa, C., Narayanan, G., Lichtenberger, A., Kooi, J.W., Wadefalk, N., Weinreb, S., & Walker, C.K., "345 GHz Prototype SIS Mixer with Integrated MMIC LNA", *International Journal of Infrared and Millimeter Waves*, 2006, in press

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2. Mueller, E., & Waldman, J., "Power and Spatial Mode Measurements of Sideband Generated, Spatially Filtered, Submillimeter Radiation", *IEEE Transactions on Microwave Theory and Techniques*, 42, 1891.

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