Third Annual Report for SuperCam:
A SuperHeterodyne Camera for the Heinrich Hertz Telescope
AST-0421499

1 Summary

SuperCam is 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 at the Arizona Radio Observatory (ARO) 10-meter 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 $\sim$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 once the northern survey is complete.

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 one-dimensional integration is crucial to the realization of large heterodyne arrays and has been successfully completed by the SuperCam team.

After initial design work in 2004-5, we successfully tested a one pixel prototype of SuperCam (see Puetz et al. 2006). Using this as a starting point, in 2006-7 our team completed the baseline design of the optical, cryogenic, RF, and electronics subsystems for the array. A single-pixel end-to-end test of all SuperCam technologies was successfully conducted in August, 2006. In 2007 we have performed an end-to-end test of the 1×8 integrated SuperCam subsystems using the final cryostat and spectrometer. In the first 2/3rds of 2008, optimizations to the final mixer design, cryostat layout, and integration plan with the HHT have taken place. **The final production of mixers and bias electronics, and assembly of the optical mounting framework is currently underway. The project is on schedule for completion by the end of 2008, with first light expected at the HHT during the upcoming winter observing season.**

The following sections discuss the status of each component of SuperCam in more detail.

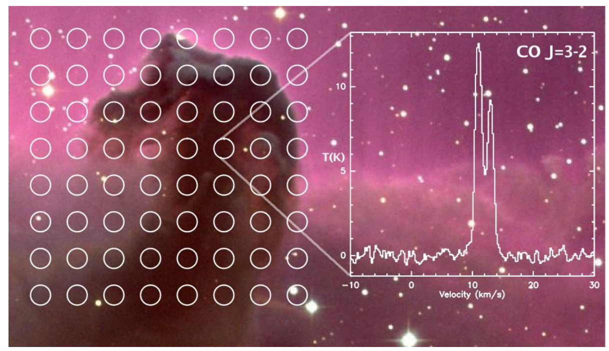

Figure 1: The 64 beams of SuperCam overlaid upon the Horsehead Nebula (B33). Each beam will measure a high-resolution spectrum (right).

2 Optical System

2.1 Telescope Matching Optics

SuperCam will initially reside on the HHT. The goal of the instrument's optical system is to produce an 8×8 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.

Trade studies were performed in 2007 and 2008 to determine the optimal optical arrangement that allows SuperCam to be feasibly installed into the HHT while minimizing impact on the observatory. For example, to eliminate the need to change secondary mirrors, re-imaging optics are necessary to reduce the f/13.8 beam of the HHT to f/5. Two optical and mechanical systems placing Supercam inside and,

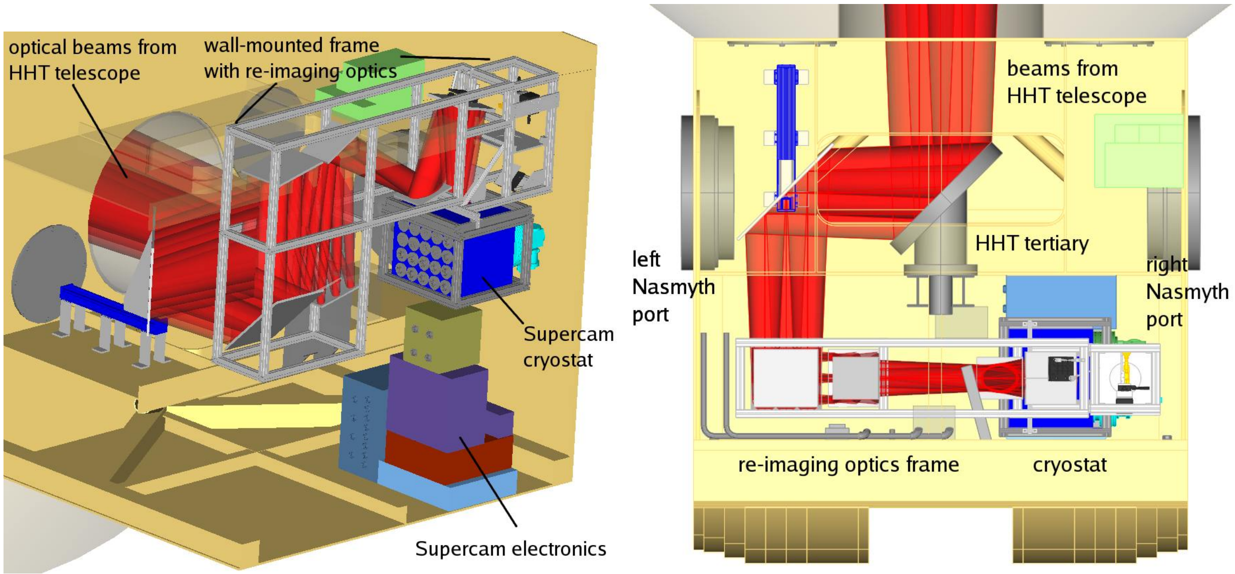

Figure 2: 3D CAD model showing SuperCam integrated in the HHT tertiary room, viewed (left) from behind and to the left, and (right) from above.

alternately, on top of the tertiary cabin, were fully explored and presented to the ARO staff.

Recently, the go-ahead to fully develop the optical system that places Supercam inside the tertiary cabin was achieved between the Supercam and Arizona Radio Observatory (ARO) teams. Figure 2 shows a 3D CAD drawing of this optical system, which fulfills Supercam's design requirements and fits within the tertiary room. The design was first made using Zemax and then optimized with the more sophisticated ASAP optical design package.

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

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.

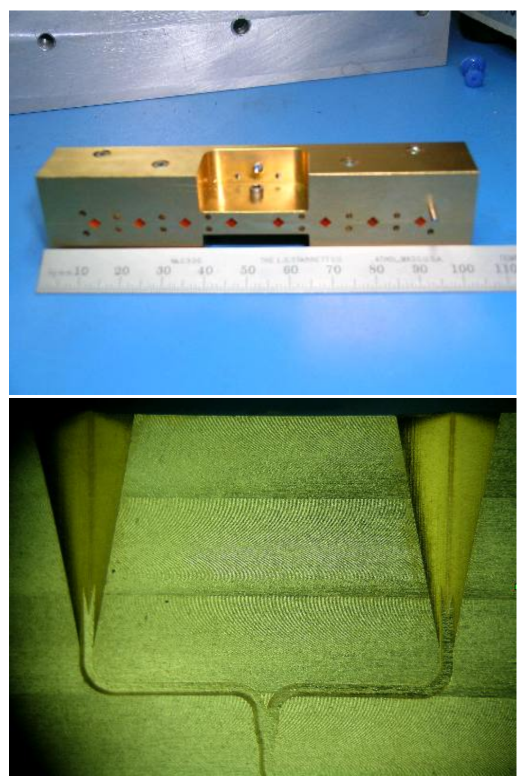

Figure 3: 1x8 LO power splitter block, and zoom-in on a single waveguide junction

An 8×8 way waveguide, corporate power divider has been machined (using the Kern micro-milling

Figure 4: Fully machined extended feed horns for the mixers and LO power dividers, and split-block halves of the corporate 8x8 LO power divider, machined using the Kern micromilling machine purchased largely through this grant.

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 3 and all 8 splitters and extended feed horns are shown in Figure 4. The measured output power from each horn is in excellent agreement with theory. After encountering the mylar beamsplitter, the combined LO and signal beams enter the cryostat through an AR-coated, 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 utilizes 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.

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 2007 and 2008, the SIS junctions were fabricated with beam leads on thin silicon (SOI) substrates, making device mounting more straightforward and reliable. This was a singificant departure from the initial design, but its successful implementation represents a fully scalable design for SIS array receivers from 200-1400 GHz.**

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 8. The module produces >30dB 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 4-8mW 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.

3.2 *Mixer Performance*

Single pixel test devices have demonstrated excellent RF performance, as shown in Figures 6 through 7. The final design optimizations on the prototype 1x8 mixer block are being completed in August-September 2008, with full-scale machining, assembly, and testing to occur starting in October 2008. Completion of all mixer fabrication is expected near the end of 2008.

4 Cryostat

The SuperCam cryostat is shown with its LO system in Figure 9. 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 ther-

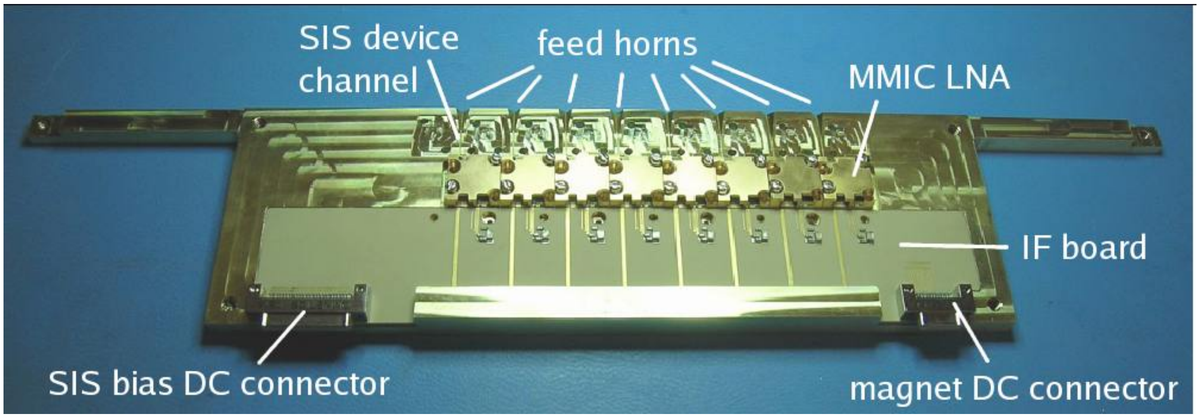

Figure 5: (left) Photograph of a completed 1x8 mixer array.

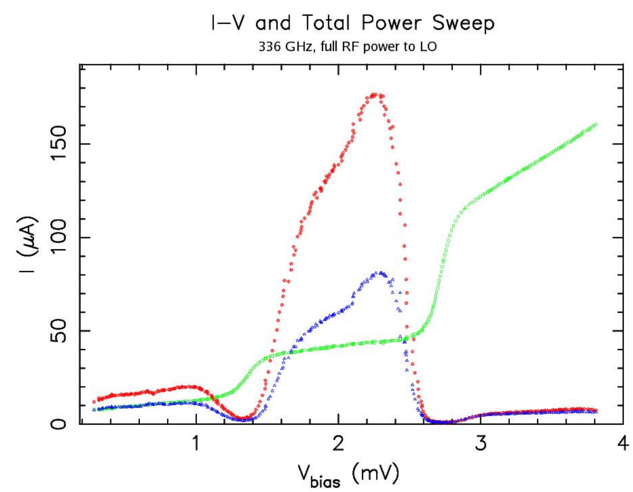

Figure 6: Sample I-V curve of a Supercam SOI SIS mixer and RF performance at 336 GHz using a synthesized LO source. The 70K DSB noise temperature is within 10K of the modeled performance.

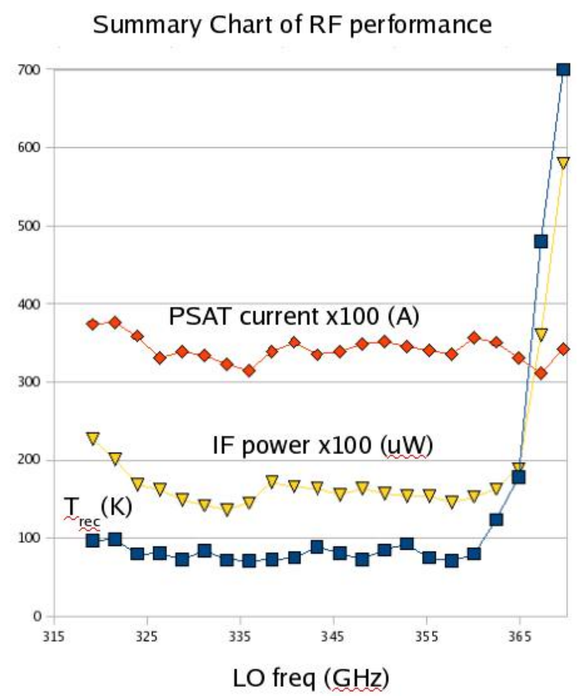

Figure 7: The RF performance of Supercam mixers is excellent over the broad tuning range of an available synthesized LO source. The degradation seen at 370 GHz represents amplitude instability in the local oscillator, not the mixer. Normal LO operating points for the key project science programs, ^{12}CO and ^{13}CO surveys are 341 and 335 GHz, respectively.

mal load capacity. IF connections to the outside are made via 64 SMA style, hermetic, bulk-head connectors. Twelve 55-pin hermetic connectors are used to convey DC bias signals in and out of the cryostat. The cryostat was wired in 2007 for conducting tests with the first 1x8 row of the array, and is currently being wired (Fall 2008) for the remaining 7 rows.

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. The designed 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

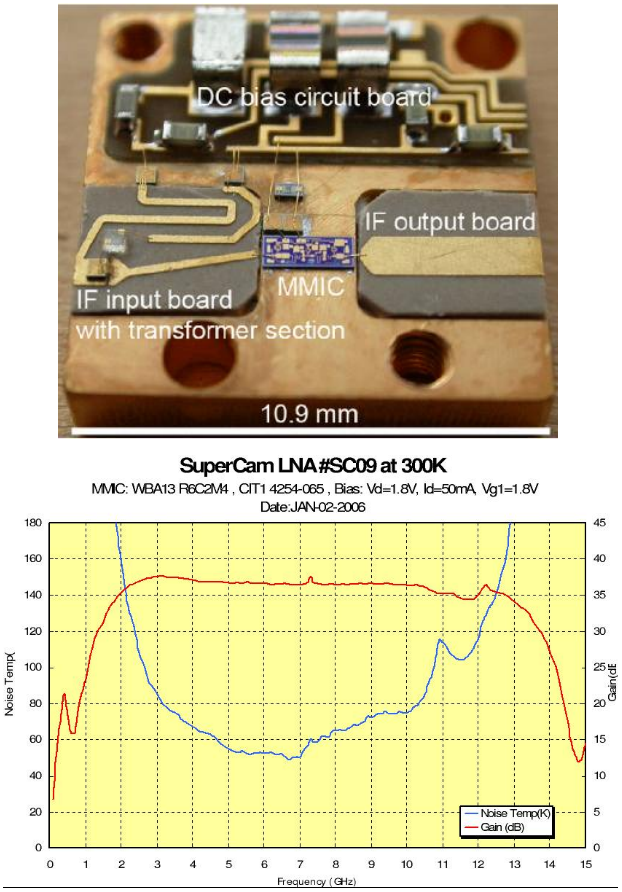

Figure 8: (TOP) 4-6 GHz MMIC Module. (BOTTOM) MMIC performance plots show >30 dB of gain from 1-14 GHz.

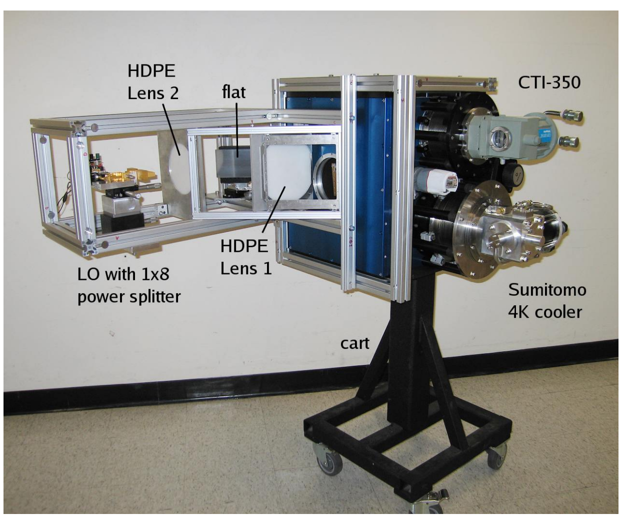

Figure 9: SuperCam dewar and Virginia Diodes LO (with 1x8 power splitter) in their combined support frame.

total-power measurement of the IF power for telescope pointing and continuum measurements.

Sander Weinreb and his graduate students Joe Bardin and Glenn Jones have designed, constructed and delivered fully-tested 2-channel and modular 1×8 IF processor prototypes for SuperCam. The 2-channel prototype is now in operation at Dome A, Antarctica as part of the NSF-funded `Pre-HEAT` robotic submillimeter observatory (ANT-0735854). The full 8x8 assembly of IF downconverter modules have been constructed and only await final testing at Caltech before delivery to Arizona in October 2008. A picture of the 8-channel IF processor module and a sample 512 MHz bandpass is shown in Figure 10.

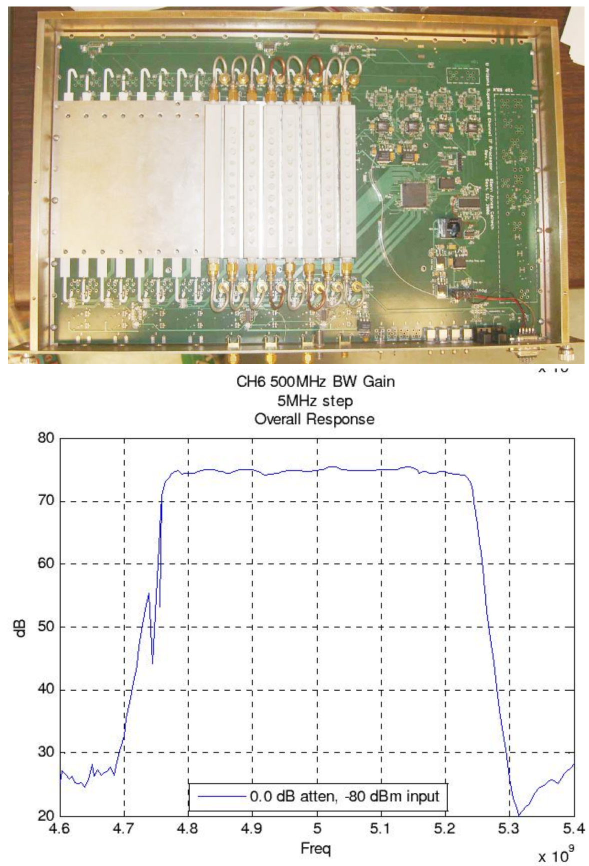

Figure 10: 8-channel IF processor module and sample bandpass

6 FFT-in-FPGA Spectrometer

The science goals of the Supercam instrument drive the development of the backend array spectrometer toward two distinct requirements. First, 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. Secondly, the divergence of the velocity field of the inner Galaxy requires a bandwidth of 256 MHz or greater at 345 GHz.

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 autocorrelator 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 and rack-mounted system 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). The prototype spectrometer card, like the prototype IF processor, was deployed to Dome A, Antarctica in late 2007 as part of the NSF-funded `Pre-HEAT` remote submillimeter observatory (ANT-0735854). **The full 64-pixel spectrometer system was delivered in 2008.** 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 the spectrometer has proven to be exceptional, with Allan variance (spectroscopic stability) times in excess of 600 seconds, including the analog IF processing electronics.

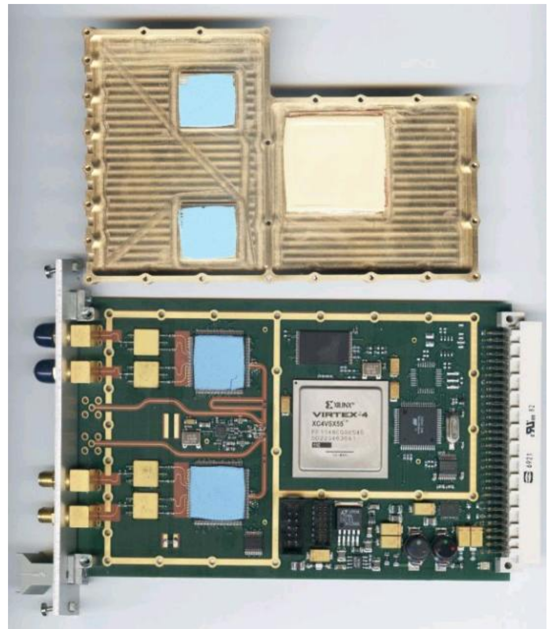

Figure 11: SuperCam spectrometer card as constructed by Omnisys Inc. The board features 2 GHz of bandwidth, software selectable between two 1 GHz inputs, four 512 MHz inputs, or eight (power combined) 256 MHz inputs.

Figure 12: Completed and delivered polyphase filterbank spectrometer system from Omnisys AB. Eight spectrometer cards provide 64 independent receivers with 256 MHz of bandwidth in 1024 channels each, in a single PC-style case with 200 watts of power consumption.

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 the successful electronics implementations used for previous DesertSTAR and PoleSTAR heterodyne arrays. Single channel preamp were integrated into 1×8 preamp boards by the University of Massachusetts/Amherst in 2005; all preamp boards for the full 8×8 array were delivered in 2006.

Similarly, a single 6U electronics bias board controls all functions of an entire 8-pixel row of Supercam. Operation of the bias board prototype has been completely validated. The final bias electronics boards are currently being fabricated and assebled into their ultimate electromagnetically-shielded rack-mounted case. With all hardware-level software already written, all that remains is the final development of the GUI array control software, scheduled for completion this Fall.

8 Data Pipeline

A schematic of the SuperCam data pipeline is shown in Figure 13. 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 750 GB drives in a RAID0/1 array will provide >3 TB of 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.

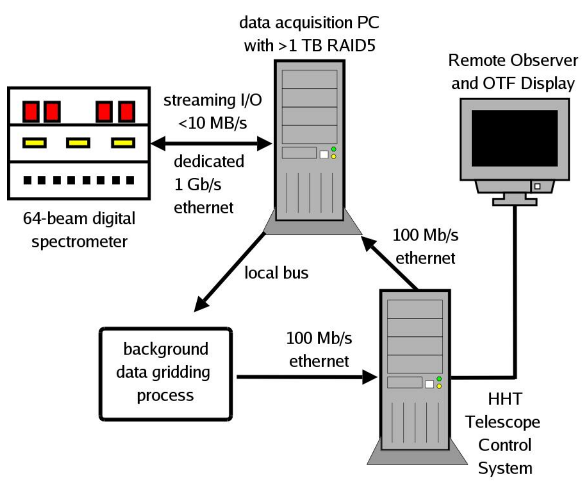

Figure 13: Schematic of SuperCam data pipeline

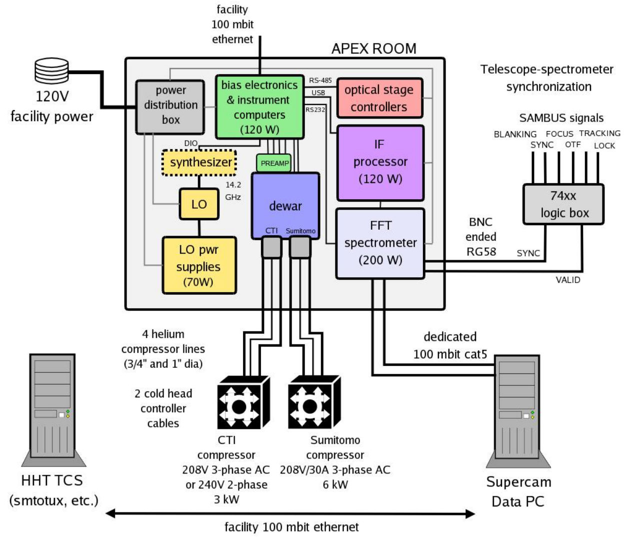

Figure 15: Schematic of the streamlined interface between Supercam and the HHT: only power, cryogenic lines, digital control signals, and ethernet are needed.

9 Integration and Testing

Thorough integration and testing of the Supercam array is vital to its successful implementation on the HHT and its long-term scientific impact. Thus, end-to-end tests of the entire Supercam system has been a continuous process since the inception of the program. For example, the single-pixel Supercam prototypes underwent a complete end-to-end test in 2006, from Supercam test mixer with integrated MMIC LNA, to prototype IF processor and Omnisys FFT spectrometer (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. The same end-to-end analysis was performed for the 1×8 mixer blocks in the SuperCam cryostat in 2007, and will again be performed for the full 64-beam system prior to deployment by the end of 2008. The electrical and mechanical interfaces between the HHT and Supercam have been streamlined to the most necessary and simple interfaces possible (Figure 15). At the conclusion of lab tests, integration of the optical system to the HHT telescope and data system to the HHT telecope control system will be performed, so that first light will be achieved during the winter of 2008-9. A schedule of remaining activities for Supercam is shown in Figure 14.

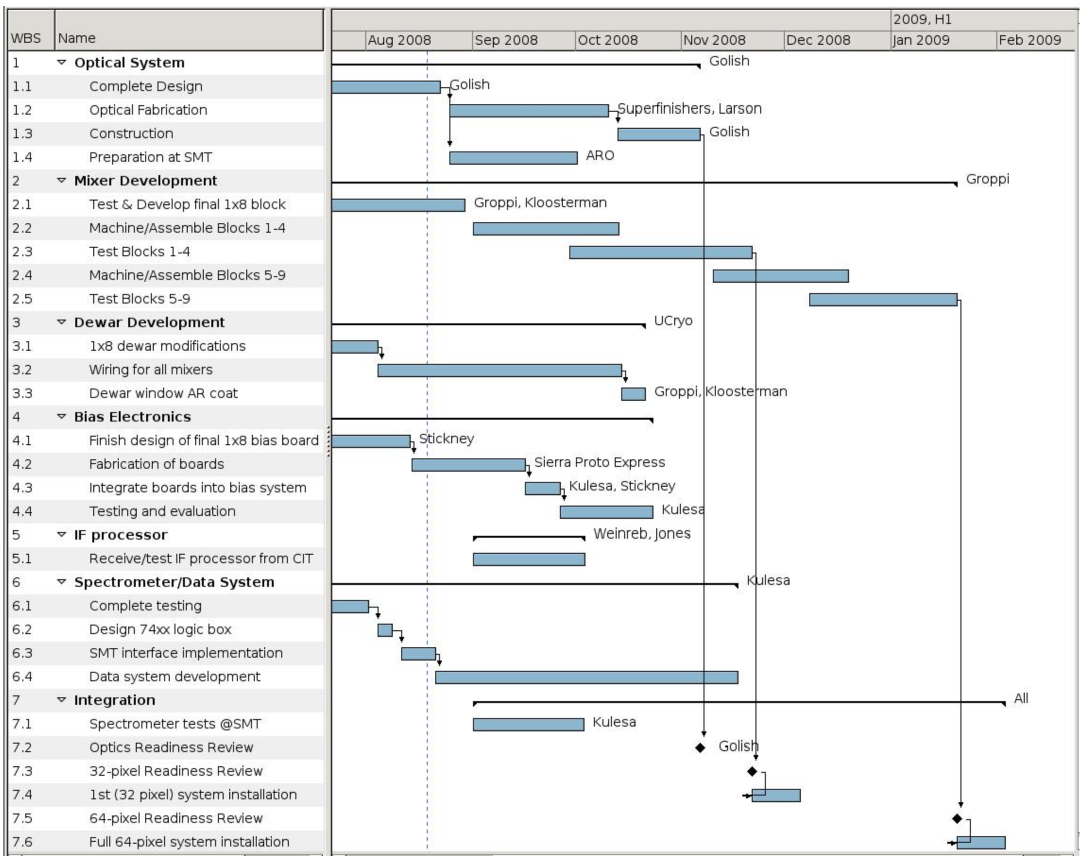

Figure 14: Gantt chart of remaining Supercam tasks for the remainder of 2008, before installation at the HHT.

References

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