Testing and Integration of Supercam, a 64-Pixel Array Receive for the 350 GHz Atmospheric Window

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***Abstract*— We report on laboratory testing and telescope integration 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. The Supercam instrument is currently undergoing laboratory testing with four of the eight mixer array modules installed in the cryostat (32 pixels). Work is now underway to perform the necessary modifications at the 10m Heinrich Hertz Telescope to accept the Supercam system. Supercam will be installed in the cassegrain cabin of the HHT, including the optical system, IF processing, spectrometers and control electronics. Supercam will be integrated with the HHT during the 2009-2010 observing season with 32 pixels installed. The system will be upgraded to 64 pixels during the summer of 2010 after assembly of the four additional mixer modules is completed.

I. SuperCam Instrument Description

A. Instrument Design

The enormous complexity of even a small discrete heterodyne array suggests a more integrated approach is needed for larger systems [1]. At the heart of SuperCam are 8 pixel, linear integrated arrays of low-noise mixers. Each mixer array contains low-noise, MMIC IF amplifier modules with integrated bias tees. Eight of these mixer modules are then stacked to produce the final 64 pixel array.

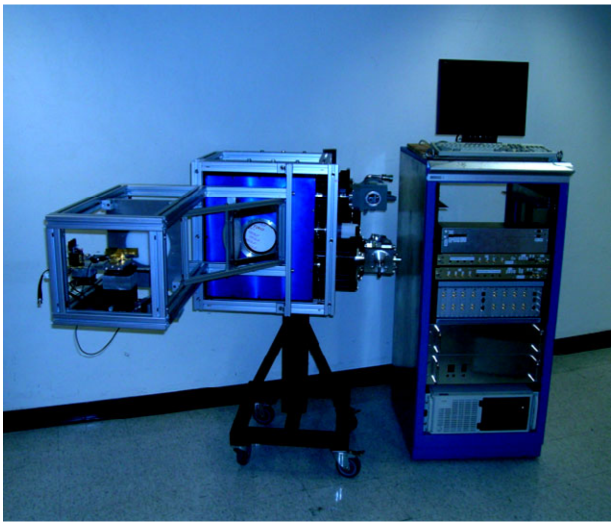

Figure 1: The SuperCam cryostat, LO optics and support electronics.

B. Cryogenics

The SuperCam systen with attached LO optics, frontend support electronics and backend electronics is shown in Figure 1. 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.

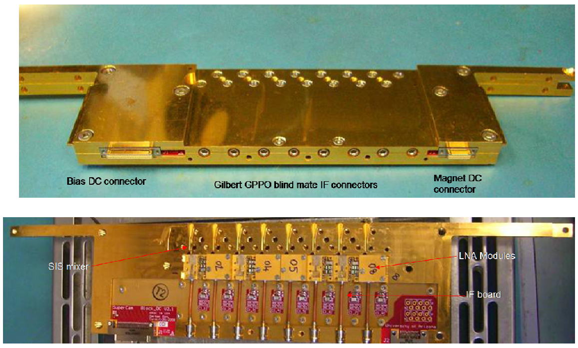

Figure 2: A completed Supercam 1x8 mixer module, fully assembled (top) and with the top cover removed (bottom).

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. 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 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 2 shows a photograph of a production gold plated tellurium copper 1x8 mixer array fabricated at the University of Arizona. 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 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 were 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. All mixer blocks have been machined and gold plated. To date 4 modules (32 pixels) have been assembled and tested.

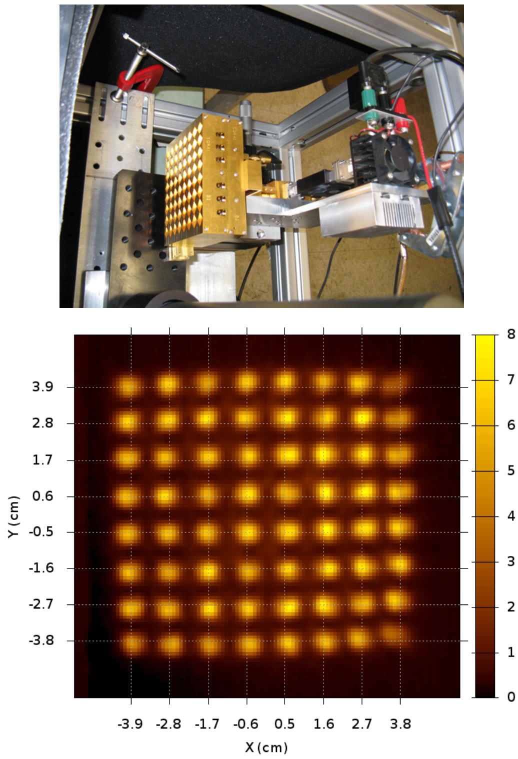

Figure 3: SuperCam 64-way waveguide LO power divider (top) and measured power pattern from this divider (bottom). Amplitude scale is linear. Power is evenly divided to the +/- ~10% level. Some asymmetrical barrel distortion is evident, due to optical misalignment in the test setup.

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 chain 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. Figure 3 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 3. Power division is equal to the ~10% level.

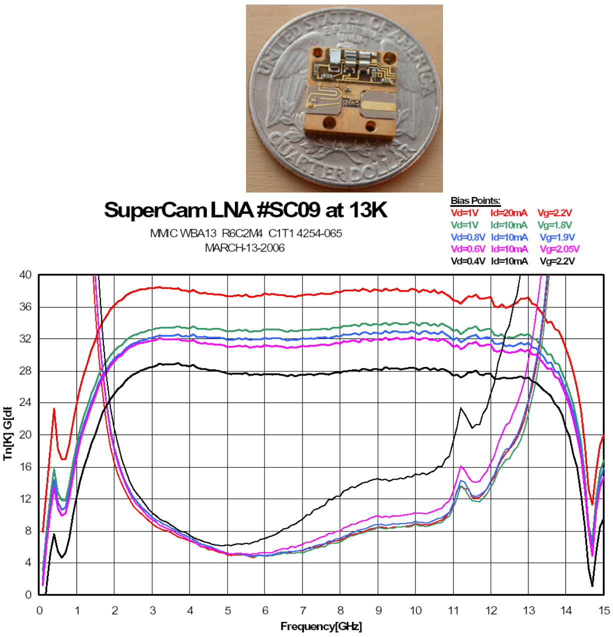

Figure 4: A SuperCam MMIC amplifier module (top), and typical measured results at 13K bath temperature (bottom) for several bias points. Amplifier noise remains low for bias powers as low as 6 mW. Gain remains above 30 dB.

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 only 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 4). 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 5). 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.

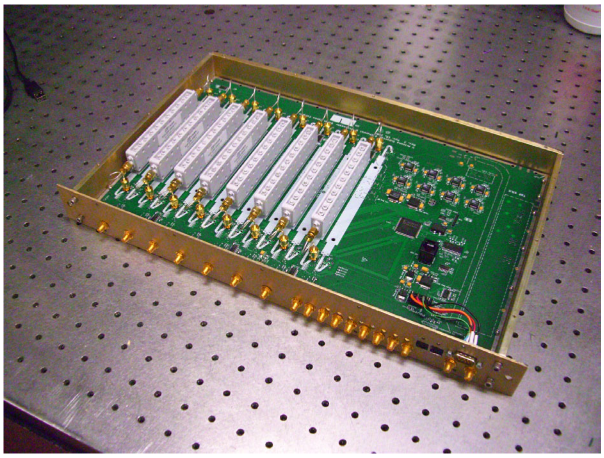

Figure 5: The inside of a SuperCam IF processor. This module provides amplification, programmable attenuation, passband filtering and total power detection for 8 channels.

F. Array Spectrometer & Interfaces

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, 32x500

MHz or 16x1GHz IF signals (Figure 6 bottom). 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 above (Figure 6 top).

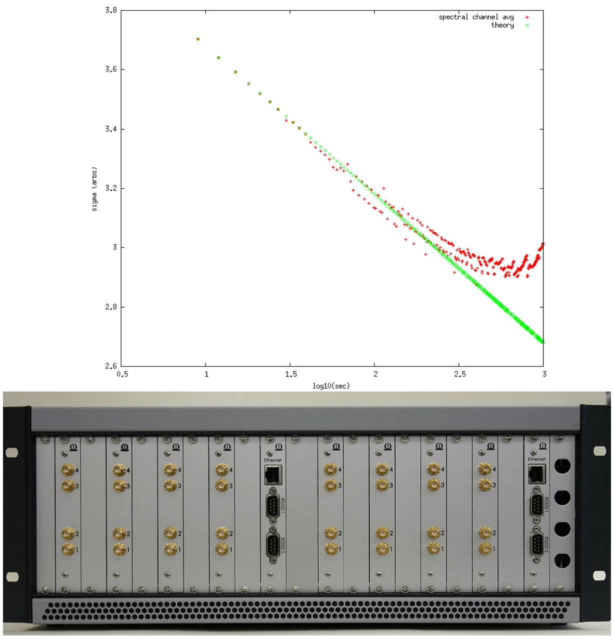

Figure 6: Measured Allan variance of the Supercam spectrometer system, including the Caltech IF processor. Allen time is 650s (top). The Supercam spectrometer system, built by Omnisys AB (bottom). This single 3U crate can process 16 GHz of IF bandwidth at 250 kHz spatial resolution. It consumes less than 200W of AC power.

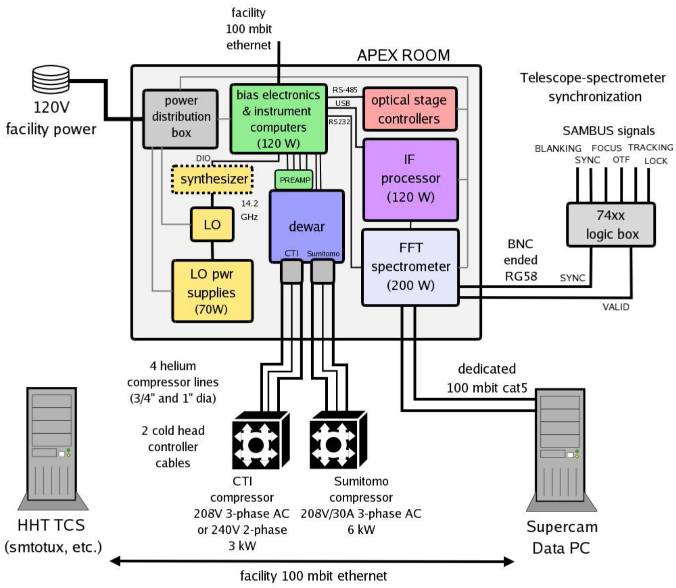

Figure 7: Schematic of the streamlined interface between Supercam and the HHT: only power, cryogenic lines, digital control signals, and ethernet are needed.

The electrical and mechanical interfaces between the HHT and Supercam have been streamlined to the most necessary and simple interfaces possible (Figure 7).

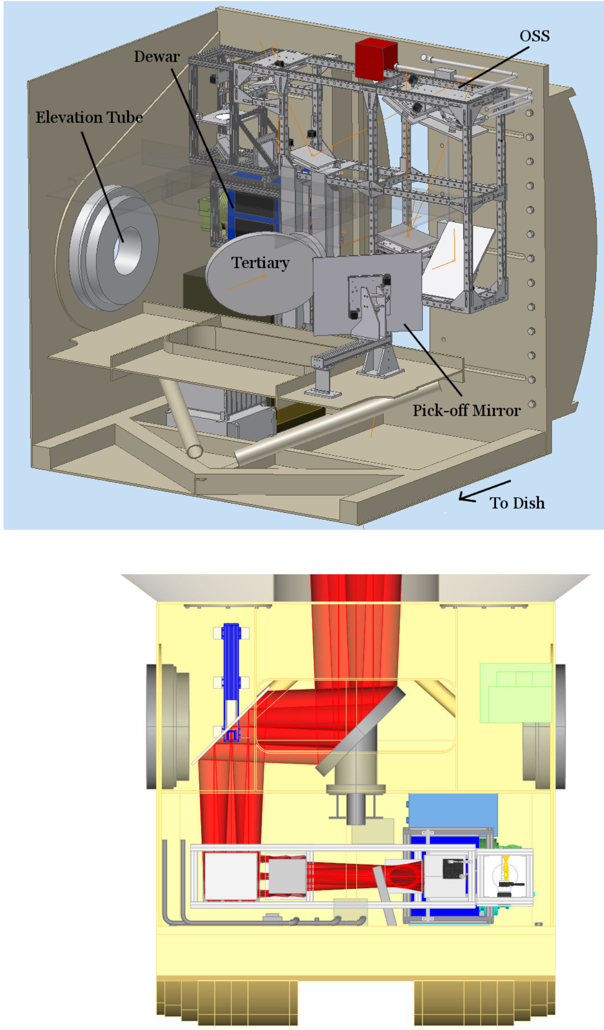

Figure 8: The SuperCam optical design viewed from behind the primary reflector, (top), and viewed from the top (bottom). The apex room is transparent to visualize the design. The beam bundles are displayed in red.

G. Optics

The existing secondary mirror of the Heinrich Hertz Telescope provides an 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 2fλ, 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.

H. Data Pipeline

A schematic of the SuperCam data pipeline is shown in Figure 9. The spectrometer will have a dedicated, 1Gb 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 Tsys. 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.

II. LABORATORY TESTING

For testing the SuperCam mixer design in the laboratory, we designed two single pixel mixers. The first design used an existing SIS junction design from the DesertStar 7-pixel array [2], but incorporated the Caltech designed MMIC module. This work was reported in other papers [3, 4]. 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 I.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 was extensively tested for noise performance across the band. Its frequency response was measured using a Fourier Transform Spectrometer and stability measurements made using the complete backend system (Figure 6 top).

32 pixels (4 mixer modules) have been undergoing extensive laboratory tests. Representative DC IV and total power curves measured using one of these mixers is shown in Figure 10. Noise temperature measurements of 27 pixels are presented in Figure 11. The average noise temperature is ~100K across the measured band (LO limited to 330 to 365 GHz).

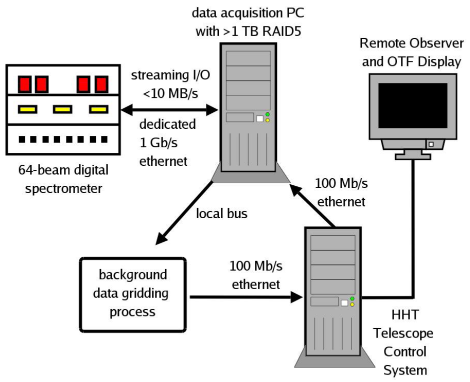

Figure 9: Schematic of SuperCam data pipeline.

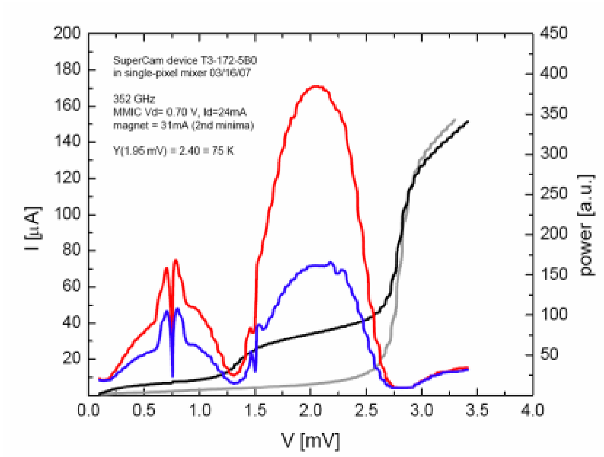

Figure 10: A representative pumped and pumped IV curve from a Supercam mixer element with hot and cold IV curves. Measured uncorrected noise temperature is 75K.

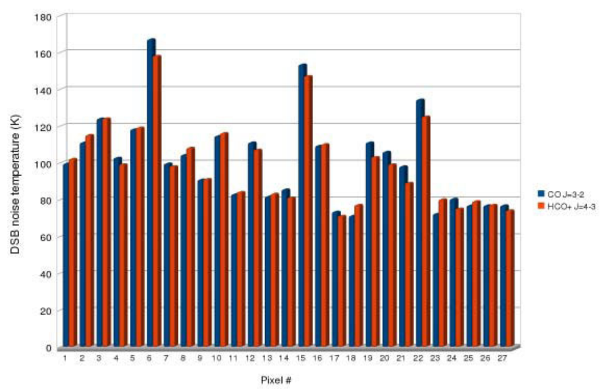

Figure 11: Uncorrected receiver temperature from the 27 out of 32 operating pixels in Supercam now, at LO frequencies for CO(3-2) and HCO+(4-3). Pixels 6, 16 and 22 are affected by issues with LO pumping or LNA performance.

III. Schedule

SuperCam is rapidly nearing completion. All key components have been designed, machined, manufactured, and tested. Four modules (32 pixels) are in the SuperCam cryostat now. Four more will be delivered by July 2010. SuperCam will then be mounted on the HHT with a full of complement of 64 pixels. Routine observations with SuperCam will begin on the HHT by the end of 2010.

References

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