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Long Wavelength Infrared Camera (LWIRC): A 10 Micron Camera for the Keck Telescope

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ABSTRACT

The Long Wavelength Infrared Camera (LWIRC) is a facility instrument for the Keck Observatory designed to operate at the f/25 forward Cassegrain focus of the Keck I telescope. The camera operates over the wavelength band 7–13 μm using ZnSe transmissive optics. A set of filters, a circular variable filter (CVF), and a mid-infrared polarizer are available, as are three plate scales: $0.05''$, $0.10''$, $0.21''$ per pixel. The camera focal plane array and optics are cooled using liquid helium. The system has been refurbished with a 128×128 pixel Si:As detector array. The electronics readout system used to clock the array is compatible with both the hardware and software of the other Keck infrared instruments NIRC and LWS. A new pre-amplifier/A-D converter has been designed and constructed which decreases greatly the system susceptibility to noise.

Keywords: Mid-Infrared Camera, Astronomical Instrumentation, 10 Micron Camera, Si:As FPA

1. INTRODUCTION

The Long Wavelength Infrared Camera (LWIRC) is a facility class mid-infrared, 7–13 μm camera designed for the Keck I telescope. On nights with good seeing we expect that it will provide diffraction limited imaging with background limited sensitivity. The expected point source sensitivity at 10 μm, using a 1 μm bandwidth filter, is 0.37 mJ/hr, where this takes into account that while chopping only 50% of the observation time is spent on-source. For example, the suggested 25 mJ source at the position of SgrA* at the center of the Galaxy[1] can be observed with a signal-to-noise ratio of over 10 in only a couple of minutes observation time, provided systematic issues are accounted for properly.

Since the LWIRC shares a good deal of the electronics readout system with the previous Keck infrared instruments NIRC[2] and LWS,[3] we anticipate that integration with the telescope infrastructure will proceed smoothly and that observers will be able to quickly utilize the the camera. This readout system is a hardware and software platform called the IRE, the Infrared Readout Electronics. The LWIRC project has benefited greatly from the experience and improvements to the IRE made by the earlier instruments. Likewise, we have contributed to the ongoing development of the IRE by improving the efficiency of data collection, developing and testing substantially more robust software, and improving the immunity of the system to electronic noise.

The LWIRC project was initiated by J.F. Arens and J.G. Jernigan[4] at the Space Sciences Laboratory (SSL) of the University of California at Berkeley. The project is currently a joint effort of SSL and Lawrence Livermore National Laboratory, and the principal investigator is W.C. Danchi.

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2. FOCAL PLANE ARRAY AND OPTICS CONFIGURATION

The LWIRC is mounted on the optical bench of the IR module at the f/25 forward Cassegrain focus of the Keck I telescope. This module is situated within the volume of the telescope, on a pillar which rises from the hexagonal hole in the primary mirror.[5] It will sit alongside the instruments NIRC and LWS, and the guider camera. The IRE readout system sits beneath the optical bench in a refrigerated enclosure. Radiation from the f/25 gold coated chopping secondary mirror is reflected by a tertiary mirror through a ZnSe window into the camera dewar. Beyond this point all the optics are cooled to about 10 K.

The camera has recently been upgraded from a 20×64 pixel Si:As focal plane array (FPA) to a Boeing/Rockwell 128×128 pixel Si:As FPA. The array is a moderate flux device, with a well depth of $\sim 1\times 10^7$ electrons and a read noise of about 500 electrons. The pixel size is 75×75 μm. The array has four output lines and it is read out at 2.4 μsec/pixel, yielding a 100 Hz frame rate. The array is sensitive over the 4–25 μm wavelength range, and it is anti-reflection coated for the 8–12 μm region. The manufacturer's stated responsivity, ηG, where η is the detective quantum efficiency, and G is the photoconductive gain, ranges from 0.5 to 5, depending on detector bias. Currently we are operating at an ηG of $\sim$0.7 with a bias of 1 V. A useful feature of this array is a partial frame integration mode. By inhibiting the collection of charge during the frame period, this mode acts as a neutral density filter and near room temperature sources can be used for calibration, where otherwise these sources would saturate the array.

The FWHM of the telescope diffraction pattern for 10 μm radiation corresponds to an angle of 0.21 arcsec. LWIRC has three plate scales giving a variation in the sampling of the diffraction pattern shown in Table 1. The plate scales are characterized by the f-number of the light cone at the detector.

Table 1. Optical Plate Scales. The telescope diffraction spot at 10 μm is 0.21 arcsec FWHM.

f/#	field of view (arcsec)	plate scale (arcsec/pix)	PSF (FWHM) (pixels)
f/30	6.6	0.05	4.1
f/15	13.2	0.10	2.06
f/7.5	26.4	0.21	1.03

The camera optics consist of a set of lens pairs with pupil stops in a Lyot configuration. Lenses and filters are mounted on turrets or wheels which are computer controlled. Figure 1 shows the three optical configurations. There are optical stops placed at the image plane of the telescope, the Lyot stop, and the camera focal plane, and the optical paths are additionally baffled. All surfaces are painted with a high emissivity black paint.[6] To change optics, the fore optic lens turret is rotated as is the pupil wheel; the rear optic is the same for all configurations. The Lyot system has very good rejection of stray light, and a coronagraph has been added to the f/15 configuration. The coronagraph is a simple obscuring disk located at the telescope focus, with an angular size of 1″, or 10 pixels at the array.

Ray tracing spot diagrams for the f/30 and f/15 configurations are shown in Figure 2. The dominant optical problem is spherical aberration. For both these configurations, the spot size is smaller than a 75 μm pixel, and the spot diagram for the f/7.5 configuration is exactly one pixel in size. Because all the lenses are made of anti-reflection coated ZnSe, the system suffers from chromatic aberration. The chromatic aberration over the range 7–13 μm leads to an equivalent spot size less than a pixel for the f/30 system and the center portions of the f/15 and f/7.5 configurations. The corners of the array for the two lower f-number systems have spot sizes slightly larger than one pixel. The telescope can, of course, be refocussed for different filters within the N-band.

The camera carries a complement of infrared filters over the range 2–12.5 μm[7]; these are shown in Table 2. Each of the mid-infrared filters is installed with a CaF_2 or BaF_2 blocking filter, as appropriate. At present, no filters for the 20 μm band are available, nor are the ZnSe lenses appropriate here. CdTe lenses and 20 μm filters could, however, be installed in the future. There is also a circular variable filter (CVF) with a 0.2 μm bandwidth over the wavelength range 7–14 μm, and a 10 μm polarizer on a ZnSe substrate. The polarizer cannot be rotated within the camera dewar, but because the Keck telescope has an alt-azimuth mount, different polarization orientations for an object can be measured during the course of a night.

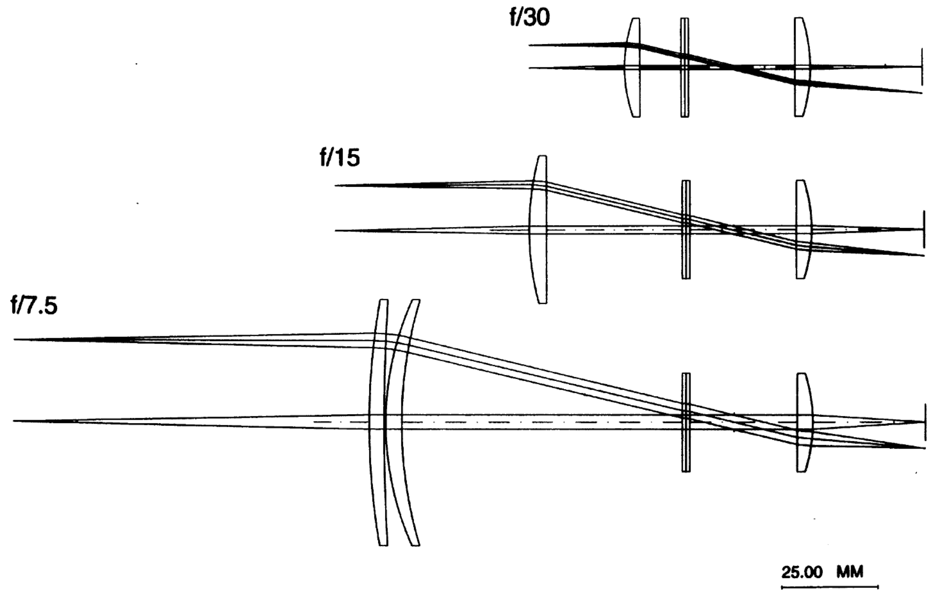

Figure 1. The three LWIRC optical configurations. The telescope focus is at the left side of the diagram, followed by the fore optic, the infrared filter with dielectric "blocker", the pupil (the Lyot stop), the rear optic, and the detector. The rays drawn are those for the extreme corner of the array.

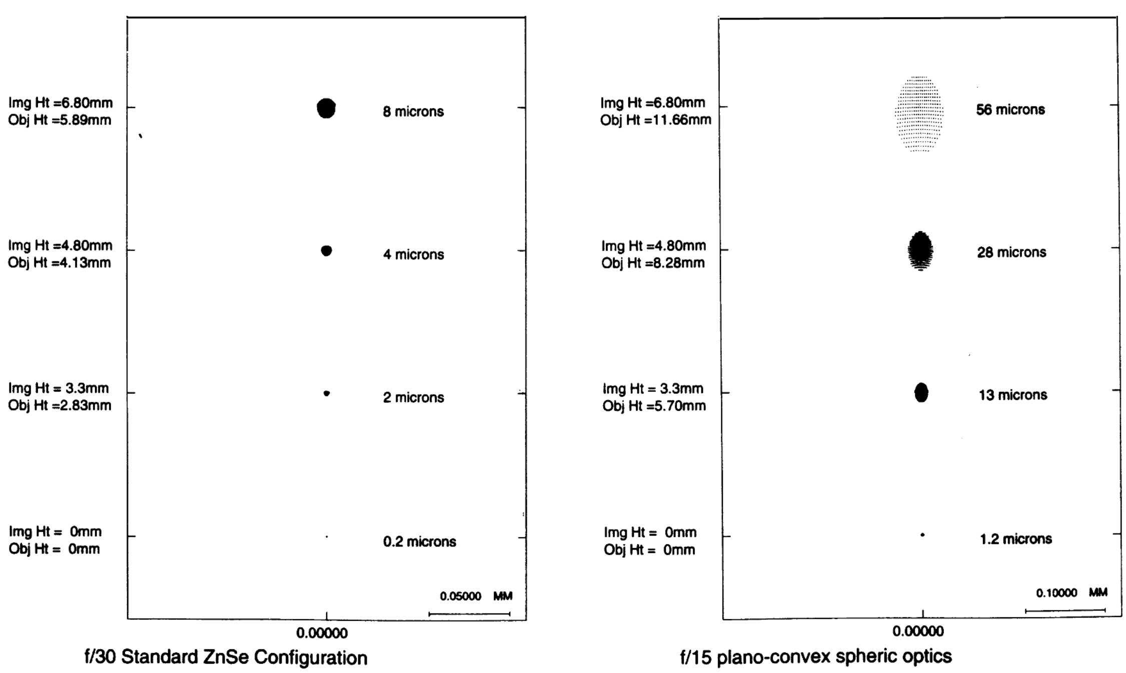

Figure 2. Ray tracing spot diagrams for the f/30 and f/15 optical configurations. The pixel size is $75\times75\ \mu$m. From top to bottom the spots correspond to: the corner of the array, the center of an edge, ~mid-way to the corner, and on the optic axis.

Table 2. Available Filters

Std. Silicate Set (b.w. 1 μm)	7.9	8.8	9.9	10.3	11.7	12.5
Astronomical Set	K 2-2.4	K-wide 2-2.5	L 3.5-4.1	M 4.4-5	10.3 1.5 μm b.w.	N 7.5-12.5
Other	Circular Variable Filter Polarizer					

3. CRYOGENICS

The LWIRC has a simple cooling system consisting of a liquid helium and a liquid nitrogen reservoir. Each reservoir has a re-entrant fill tube and the dewar can therefore hold liquids in any orientation. The liquid helium capacity is 20 liters. The helium boil off rate with the window closed and the array off is $\sim$0.3 l/hr, while during observations the rate is $\sim$0.42 l/hr With judicious planning, the system should hold liquid helium for 48 hours.

It is very important that the array temperature remain stable despite variations in radiation falling upon it, changes in the liquid helium level, and the dewar orientation. We have built a temperature controller for the array. The circuit is a "proportional-integral" controller and it stabilizes the voltage of a temperature sensing diode to better than 0.15 mV or $\pm$0.005 K at 8.5 K.[8] The circuit stabilizes within 30 seconds after changing the temperature set point. The diode is mounted as close as possible to the focal plane array on the ceramic chip carrier. The array is spring loaded against an OFHC copper plug onto which a 500 ohm wirewound resistor is mounted for a heater. The plug is connected to the helium cold plate via a heavy copper braid. The heater can provide up to 60 mW of power, raising the temperature of the array to 11.7 K.

The lens turrets and filter wheels can be rotated while the system is cold via a cryogenic transmission. The system permits seven motions while using only two stepper motors and two mechanical vacuum feedthroughs. The positions of the filters and optics are monitored by potentiometers mounted to each wheel. Once we established a clean electrical system, this system has provided accurate and repeatable positioning of the wheels.

4. DATA COLLECTION SYSTEM

The data collection system is a complex electronics and software system shown in Figure 3. The real-time functions of the system which provide the clock signals for the FPA and A-D converter, and the image acquisition, are performed by a set of boards based on the Motorola 56001 Digital Signal Processor. Most of these boards are shown in the top row of Figure 3. The boards share a custom data bus, the "Peckbus" designed by Berkeley Camera Engineering of Hayward, CA. The "metronome" for the system is the "timing generator". The timing generator emits the digital signals for operating the array pixel, row, and frame shift registers, the pixel reset pulse, and the sample and hold and A-D converter trigger pulses for the preamplifier/A-D system. The "level shifter" tailors the clock signals for the array to the appropriate analog levels and provides the array voltage biases.

The outputs of the array are amplified and digitized by a new preamplifier/A-D converter described below. The digitized data is accumulated in the coadder boards, one for each array output line, and then sent to the "pass-through processor". The pass-through processor, another DSP system, controls the data flow, and the chopping secondary mirror.

The real-time system is governed by a single board SPARC computer (made by Force) on a VME bus, called the "target". The VME bus is shown in the middle row of the drawing. The target computer receives the data from the camera, and in turn, delivers the data to a disk mounted by the "host" computer located in the telescope control room. The images written to disk are written in the FITS format and the file header records all pertinent parameters of the data acquisition system and the telescope. Both the host and the target operate under the UNIX operating system, where the key software programs are a set of remote procedure calls (rpc) running on the target computer. The host computer, a Sun Sparc20, communicates with the Keck "keyword" system through which it can control and monitor all the telescope operations. A "quick-look" program written for the LWS instrument has been adapted to provide real-time display of the camera images.[3] Processes associated with the host computer are shown in the bottom row of the drawing.

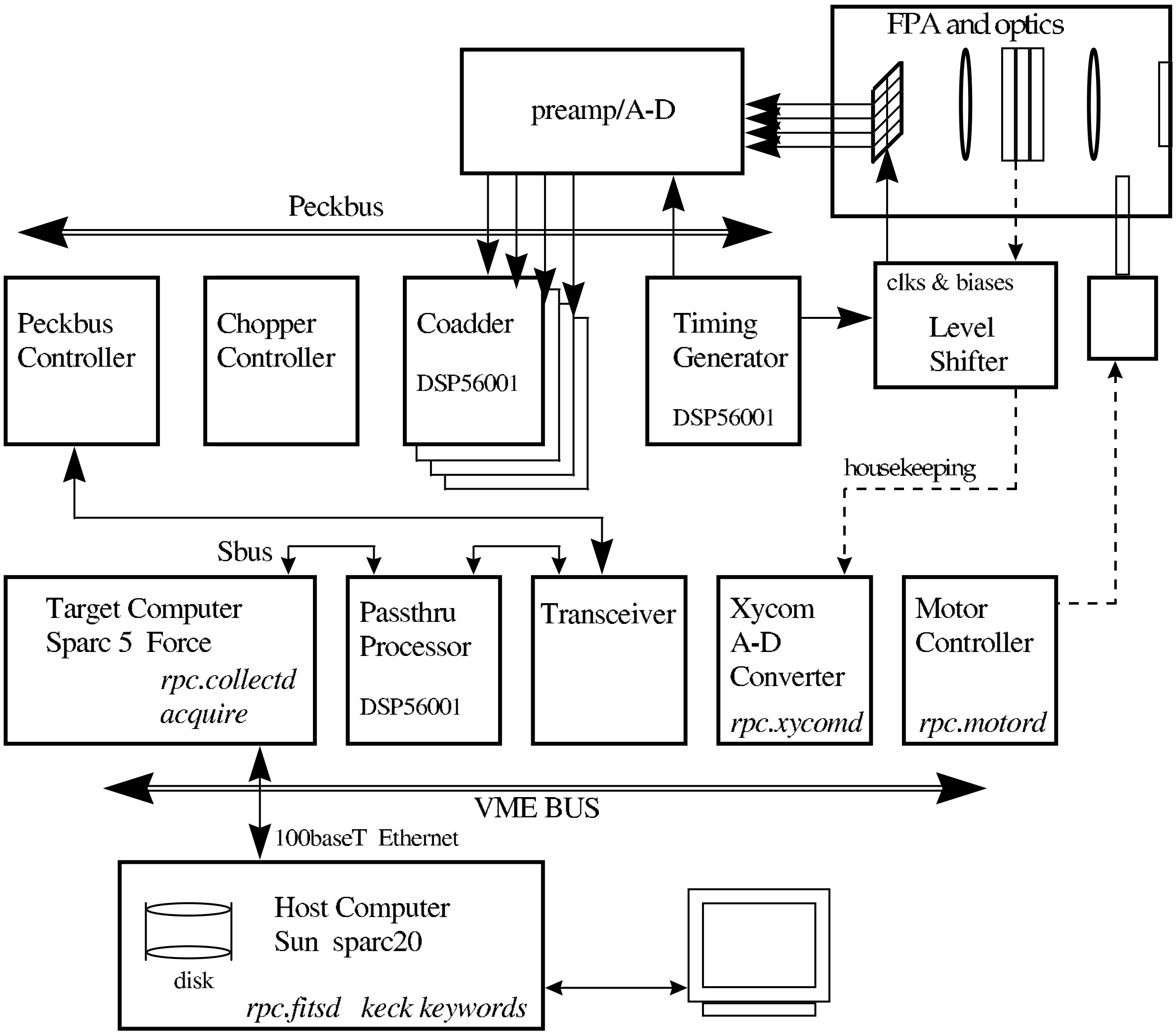

Figure 3. Schematic of the IRE data collection system. Double lines show the upper "Peckbus" and middle "VME" data buses of the electronics rack. Processes based on the DSP's are indicated. Solid lines trace the flow of data from the timing generator to the FPA, the pre-amp/A-D, and the coadders. Images are transmitted from the coadders to the target computer, and then onto disk of the host computer in the control room. The dashed lines show the flow of housekeeping data for the camera such as temperatures and wheel positions. Particularly significant programs are shown in italic.

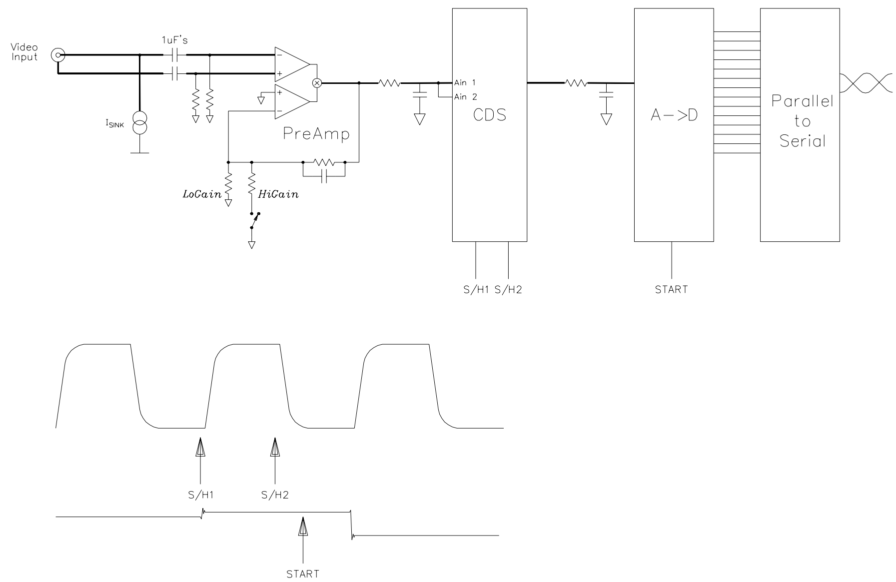

Figure 4. Schematic of the preamplifier/A-D circuit. The FPA output at the left is driven by a current sink, and amplified. The resulting signal is shown shown below the circuit, with a period of 2.4 μsec/pix. Sample and Hold 1 is applied at the full pixel value, S/H 2 at the reset pixel value. The CDS circuit performs an analog subtraction which is shown with with the location of the A-D start pulse. The data is sent to the coadders on a twisted pair.

A set of boards[9] on the VME bus provide housekeeping data to the target computer in order to monitor various temperatures within the camera, and the positions of the filter and lens wheels. The motors[10] for driving the wheels are also controlled by the target computer. The entire system is mounted on the IR module and communication between the host and target computers occurs via a 100baseT Ethernet connection. The observer controls the camera by issuing keyword commands from the host computer. A series of observations can be performed by running "C shell" scripts; for example, collecting a cycle of images through a filter set.

We have modified the software to operate the new Boeing array. During this period extensive testing of the software and hardware took place and we have greatly improved the robustness and efficiency of data collection. Long overnight data sets are now routinely acquired at chopping rates of 10 Hz, with parallel housekeeping and real-time image display processes running; this is a dramatic improvement over earlier IRE systems. The system can acquire data with very high efficiency (>90%) at frame rates of 100 Hz when many frames are coadded. When a "speckle imaging" mode is used with chopping, image pairs can be recorded to disk at 5 Hz, with a 50% duty cycle; this is a considerable improvement over earlier IRE based systems.

5. PREAMPLIFIER/A-D CONVERTER SYSTEM

We have built a preamplifier and A-D converter system as a single unit which is mounted right at the hermetic connector at the dewar wall.[11] In this manner the system is immune to electronic pickup noise that was formerly induced in the long coaxial cables that ran from the camera dewar to the electronics rack. The circuit is shown in Figure 4. The system uses a current sink for each array output that draws 500 μA. The signal is amplified with a gain of 6 (or 18) and then processed by a Correlated Double Sampling (CDS) integrated circuit.[12] In fact, this is more conventionally a "delta reset" circuit. The CDS circuit performs an analog subtraction between the full pixel level and the reset pixel level of the output waveform. The subtracted signal is then sampled by a 14 bit A-D converter. The digital data is buffered and transmitted serially over twisted pair to a receiver in the electronics rack. The data is then loaded into the coadder DSP to construct the image.

Tests of the preamplifier system at a speed of 2.4 μsec/pixel show that the system has an accuracy of better than 2 ADC units FWHM. Figure 5 shows histograms for 6 input waveform amplitudes: 0.167, 0.667, 1.5 V, with a gain of 6; and 0.056, 0.222, 0.5 V, with a gain of 18. Note that the maximum array output amplitude is 1.4 V. In the figure

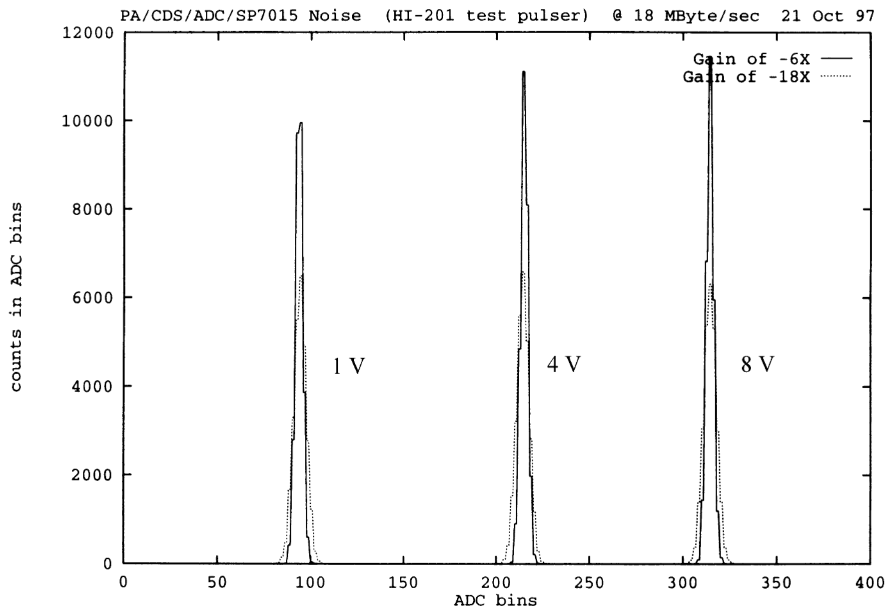

Figure 5. Six histograms resulting from sampling waveforms with the preamplifier/A-D system. The amplitude of the waveform at the A-D is given on the graph. The FWHM of the distributions is less than 2 ADC units.

each voltage case has been shifted along the x axis so that they appear on the same graph. The system demonstrates better than 12 bit accuracy. It should be mentioned that the development of a test signal which is synchronized with the collection system and has an accuracy of better than 13 bits required care and attention in and of itself.

6. CLOSING REMARKS

We have recently tested the system and found that the camera performs well. The wheel mechanisms work properly cold and the system has good sensitivity. No "ghost images" from multiple reflections off lenses or filters have been observed, where this was an issue of concern prior to the test. As a further test of the system, we mounted a 200 mm focal length ZnSe lens as a surrogate primary telescope mirror to provide an input image. Figure 6 was obtained using the f/15 camera optics, and a 9.9 μm filter looking out the window from our laboratory in Berkeley.

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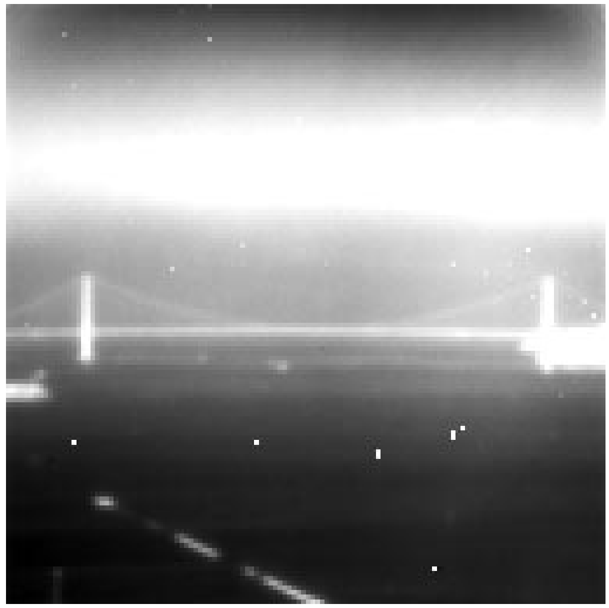

Figure 6. The Golden Gate Bridge at 9.9 μm from the Space Sciences Laboratory in the Berkeley Hills.

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