Update report on FlyEyes - a dual CCD detector system upgrade for PUEO

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ABSTRACT

CFHT is planning to upgrade its adaptive optics system, PUEO, to a high order system with 104 elements, PUEO NUI. Currently PUEO uses a 19 element deformable mirror with the equivalent 19 avalanche photodiode (APD) detectors as its curvature wavefront sensor. PUEO NUI plans to implement the curvature wavefront sensor using back illuminated CCID-35 detectors developed by J. Beletic et al.[1] instead of 104 APDs, which are prohibitively expensive under the present budget conditions. The CCID-35 detectors, developed at ESO and MIT/LL, were specifically designed to serve as direct replacements for APDs in curvature sensing. The first step in the upgrade is to build and test a system using two CCID-35 detectors, dubbed FlyEyes. These new detectors were successfully tested and integrated in the lab by R.Dorn at ESO but have yet to see sky time [2]. FlyEyes will be their first opportunity. They will directly replace the 19 APDs in PUEO temporarily for a few engineering nights in January of 2005.

Keywords: CCD, adaptive optics, wavefront sensing

1. INTRODUCTION

FlyEyes was presented by J.C. Cuillandre and O. Lai at CFHT in 2002 as a technology project for the PUEO upgrade. The desire was to find an alternative for the expensive APDs typically used in curvature wavefront sensing. A paper written by J.C.Cuillandre, et al. [3] describes in detail the FlyEyes concept.

The goal at the start of the FlyEyes project was to have the CCID-35 system fully tested, characterized and integrated in PUEO in the beginning of 2004 with sky time tests a few months later. However due to limited manpower resources and competing higher priority tasks at CFHT, limited progress had been made and subsequently the sky time tests have been pushed back to January of 2005.

This paper gives a brief background of the project, describes the initial design and presents the progress thus far.

2. PUEO OVERVIEW

The CFHT adaptive optics system known as PUEO, is based on curvature wavefront sensing and has been in use since achieving first light in 1996. It is a 19 order system with a 19 element bimorph deformable mirror (DM) and 19 passively quenched APDs. Light from each subpupil of the lenslet array is

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fed into the APDs through optical fibers. PUEO is mounted at the f/8 Cassegrain focus and is mostly used with KIR, 1K x 1K infrared direct imaging camera. A diagram of PUEO is shown in Figure 1. A detailed description of the instrument can be found in articles by R. Arsenault et al. [4], F. Rigault et al. [5], O. Lai et al. [6], F. Rigault et al. [7].

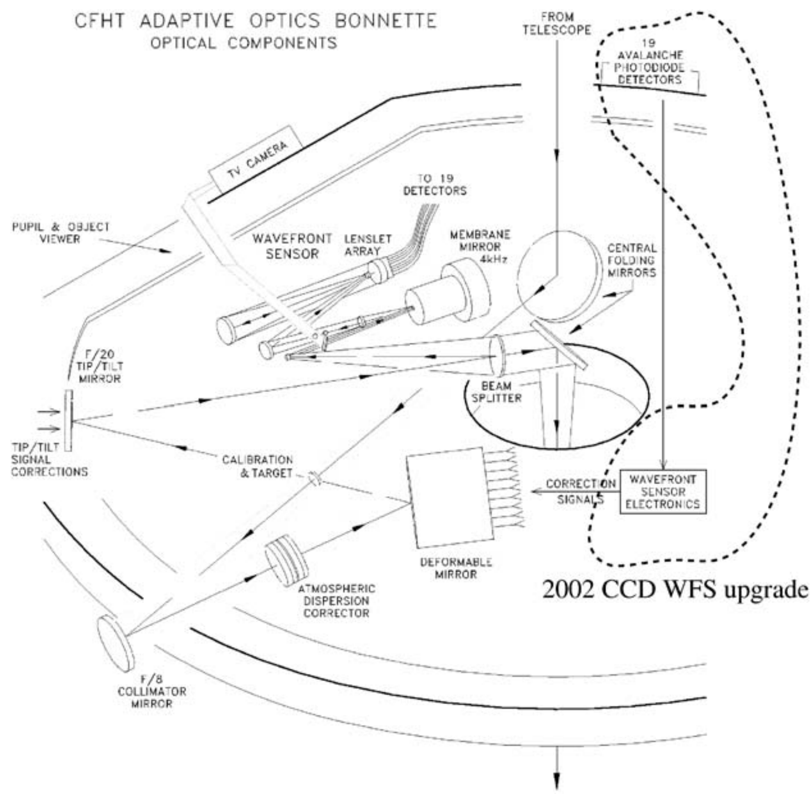

Figure 1. PUEO diagram

3. BRIEF DESCRIPTION OF CCID-35

In curvature sensing, the wavefront sensor measures the intensity of an image at a location between the pupil plane and the image plane. Depending on the curvature of the waveform, the intensity will be brighter or dimmer on either side of focus. Image before focus is referred to as the intrafocal image and the image after focus the extrafocal image [2]. A perfectly flat waveform will have the same intensity on either side of focus thus the goal of an AO control loop is to drive the deformable mirror to achieve equal interfocal and extrafocal intensities.

A very thin membrane mirror is used to modulate the focus to create the intrafocal and extrafocal images. The intensities of which are sampled and measured by APDs and are normalized by the real-time computer (RTC) to compensate for atmospheric scintillation and for systematic errors such as quantum efficiency and electronic gain [2].

In the case of PUEO, the membrane mirror is modulated at 4 kHz with each half cycle defining the integration time of the intrafocal and extrafocal images. In the highest bandwidth mode, intensities are integrated over four 4 kHz cycles, stored in hardware counters, then sampled and fed into the control loop at a 1 kHz rate.

One of the unique design aspects of the CCID–35 are storage registers on either side of the imaging array that are used to integrate charge from interfocal and extrafocal images. Having the storage registers eliminates the need to read out the images at each half cycle of the 4 kHz rate. The images can be clocked out at the slower 1 kHz sample rate, thereby minimizing readout noise. Readout noise should be less than 2 electrons for the CCID-35 to be considered a viable replacement for APDs, which have no readout noise. Low readout noise is requisite since noise limits how faint and how fast the AO system can operate. R. Dorn successfully developed and tested a system at ESO with readout noise of less than 2 electrons using the front illuminated devices.

Although APDs have better noise, the CCID-35 is superior in other performance aspects - higher dynamic range, higher quantum efficiency and lower dark current. Other characteristics of the CCID-35 include - pixel readout speed of less than 250 usec, capability to switch between half-cycle integration within 10 usec, on chip binning and multiple readout ports [2]. FlyEyes will use the thinned back illuminated version of CCID-35, which has a factor of two better quantum efficiency.

The imaging area of the CCID-35 consists of 80 unit cells where light from each subpupil can be focused. Ten cells are arranged in 8 columns with each column having its own summing well and output amplifier. A unit cell is made of 20 x 20 pixels at 18 um per pixel. The column widths of the CCID-35 are fixed but cell lengths are arbitrary and defined through the binning parameter. Figure 2 shows a diagram of the unit cell. A three-phase clock is used to clock the imaging areas. Storage areas, SA and SB, store the charge for the half-cycle interfocal and extrafocal images. SC storage area is used to temporarily hold the charge as one half-cycle image is clocked out through the serial output register. Charge is binned into a superpixel at the summing well before being output at the source follower amplifier.

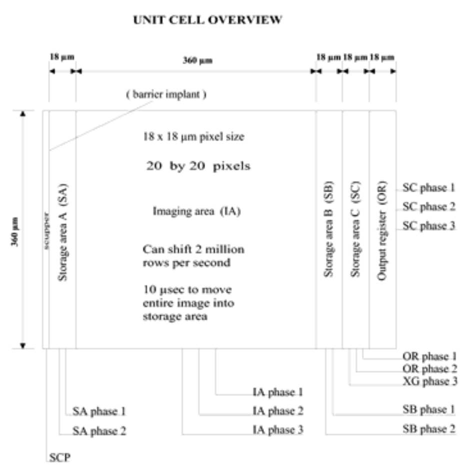

Figure 2. CCID-35 unit cell [2]

One can find an excellent and comprehensive description of CCID-35 as well as a brief tutorial of curvature wavefront sensing in an article by Beletic, et al. [1]

4. FLYEYES DESIGN

FlyEyes was designed with the following constraints – maintain current AO control loop performance (80 Hz loop bandwidth at 1 kHz sample rate), use the existing software, hardware and interfaces, make no modifications to the existing hardware (system must be able to be restored to its original condition) and provide capability to rapidly switch between APDs and CCID-35 so that side by side comparison testing can be done easily during the night.

A block diagram of the system is presented in Figure 3. Two CCID-35s are mounted in a liquid nitrogen cooled cryostat. Light from the lenslet array is brought into the cryostat via optical fibers. A SDSU2 controller from Astronomical Research Cameras, Inc. provides the clocks and biases for the CCDs. Two video processor boards with dual channels handle the amplification and digitization of the 4 video channels from the CCD. (Only 19 cells distributed over 4 columns are required for FlyEyes). The SDSU2, which sits next to the cryostat mounted on the outside skin of the bonnette, transmits the readout data via fiber to the data acquisition PC in the computer room, roughly 70 meters from the telescope. A custom interface board ties in the existing interfaces to the SDSU controller and data acquisition PC. It performs address and control signal multiplexing between the digital I/O board in the data acquisition PC and the existing wavefront sensor board (WFS). It also generates a sync signal from the 4 kHz clock which is used to synchronize timing patterns between the SDSU2 controller and membrane mirror.

The data acquisition PC is a dual Pentium 2 GHz machine running real-time Linux. The PC processes the readout data from the SDSU2, which are summed and differenced and then made available to the LaserDot real-time computer (RTC) through the custom interface board. The LaserDot RTC reads and normalizes the intensities, computes the control matrix and outputs actuator drive commands to the deformable mirror.

In PUEO, the APDs feed directly into the WFS. The train of pulses from the APDs representing photoelectron detection, clock a set of up-down counters. The outputs of which are sampled by the LaserDot RTC. Although the intensity data will be read from the data acquisition computer, there are functions on the WFS that are still required - master clock and membrane mirror drive signals.

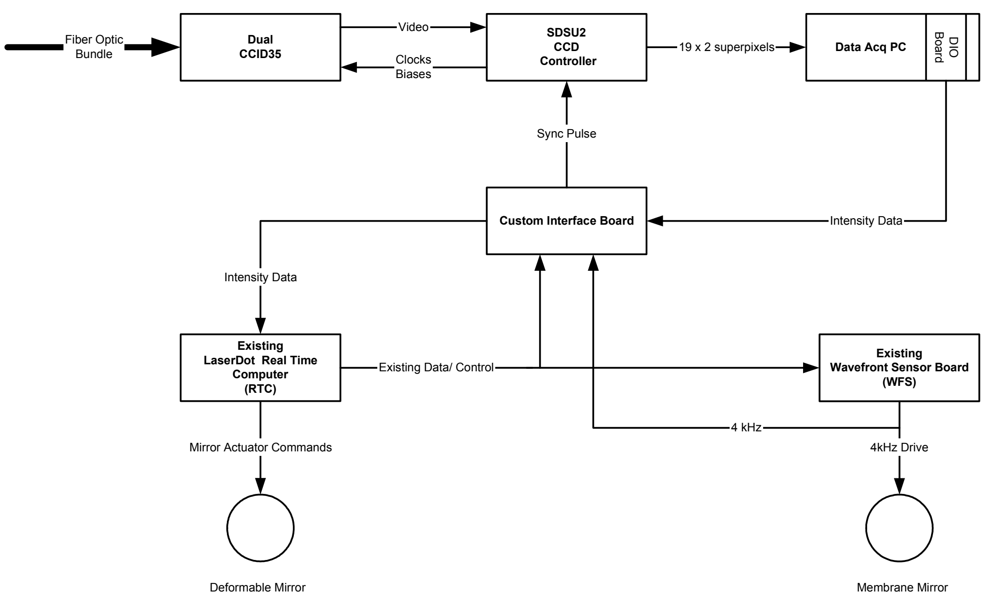

Figure 3. FlyEyes block diagram

4.1 Timing Analysis

The sampling frequency of the control loop varies from 1 kHz to 50 Hz depending on the magnitude of the reference star. The most stringent timing requirement is at the 1 kHz sampling rate. Intensity data readout and control matrix computations must be completed within 1 msec sample period in order to meet the operating bandwidth requirements. The readout of the CCD requires an additional 138 usec beyond that needed by the APDs. The time to compute the control matrix and output the DM actuator commands once the intensity data has been read, is 320 usec. Coupled with the readout time of 138 usec, the total processing time is 458 usec. This leaves a margin of 542 usec before the end of the 1 msec cycle. If readout noise becomes problematic, the clocking of the serial register can decreased without significantly affecting control loop performance. A timing diagram of the CCD clocking is shown below in Figure 4.

4.2 Optical Fiber Feed

One of the challenges of FlyEyes was to develop the means to focus the light from the 19 optical fibers onto the CCD in the cryostat. In his test system at ESO, R. Dorn used an Oeffner optical relay to bring in the light from his 60-element fiber bundle. Two spherical lenses outside of the cryostat re-imaged the light onto the CCD. This method is quite attractive in many respects. There is no chance of damaging the CCD die nor bond wires with the fiber bundle during alignment. The alignment can be adjusted while the detector is cold and there is no vacuum feedthru for the fibers needed. But the penalties of using an Oeffner optical relay for PUEO are - loss of light due to reflections, additional volume space, stability issues of the optics and cost.

In the case of FlyEyes, we settled on a different approach. We decided to feed our fiber bundle into the cryostat and focus directly onto the CCD - primarily to minimize light loss and also to gain experience in developing technology that would most likely be used for PUEO NUI.

The ends of the fibers inside the cryostat are bundled in such a way to match the geometry of the cells on the CCD. Each unit cell is 360 um x 360 um in dimension and vertically spaced apart 550 um on center. The other ends of the fibers are terminated with FC connectors in order to mate with the 19 fibers coming off the lenslet array. The fibers are coupled together at an interface panel mounted on PUEO, which allows the fibers to be easily removed and connected back to the APDs.

The fiber selected is a 100 um core diameter, low OH hydrogenated CeramOptec step-index fiber with a numerical aperture of 0.22, 120 um cladding, 140 um polyamide 1st coat and 250 um epoxy 2nd coat. The core diameter matches that of the existing lenslet array fiber so light transmission should not be a problem. The 2nd epoxy coat will be removed prior to assembly leaving a 140 um diameter fiber.

Two methods of bundling the fibers are currently being developed. One is epoxying the fibers onto a ferrule which has the same dimensioning as the cell layout of the CCD. The other is building a fiber stack with silicon V groove spacers.

In the ferrule design, the layout of the holes on the ferrule, shown in Figure 5, matches the cell pattern on the CCD. The holes are 145 um, sufficient to accommodate the 140 um fiber. The ferrule is relatively thin, about a couple of millimeters thick. The fibers are epoxied into place and polished as a collective unit. We plan to populate all the holes with fibers but only terminate 42 to keep the cost down. This will provide the 19 requisite fibers, a couple of alignment cells at the corners plus sufficient spares in case a whole column is lost.

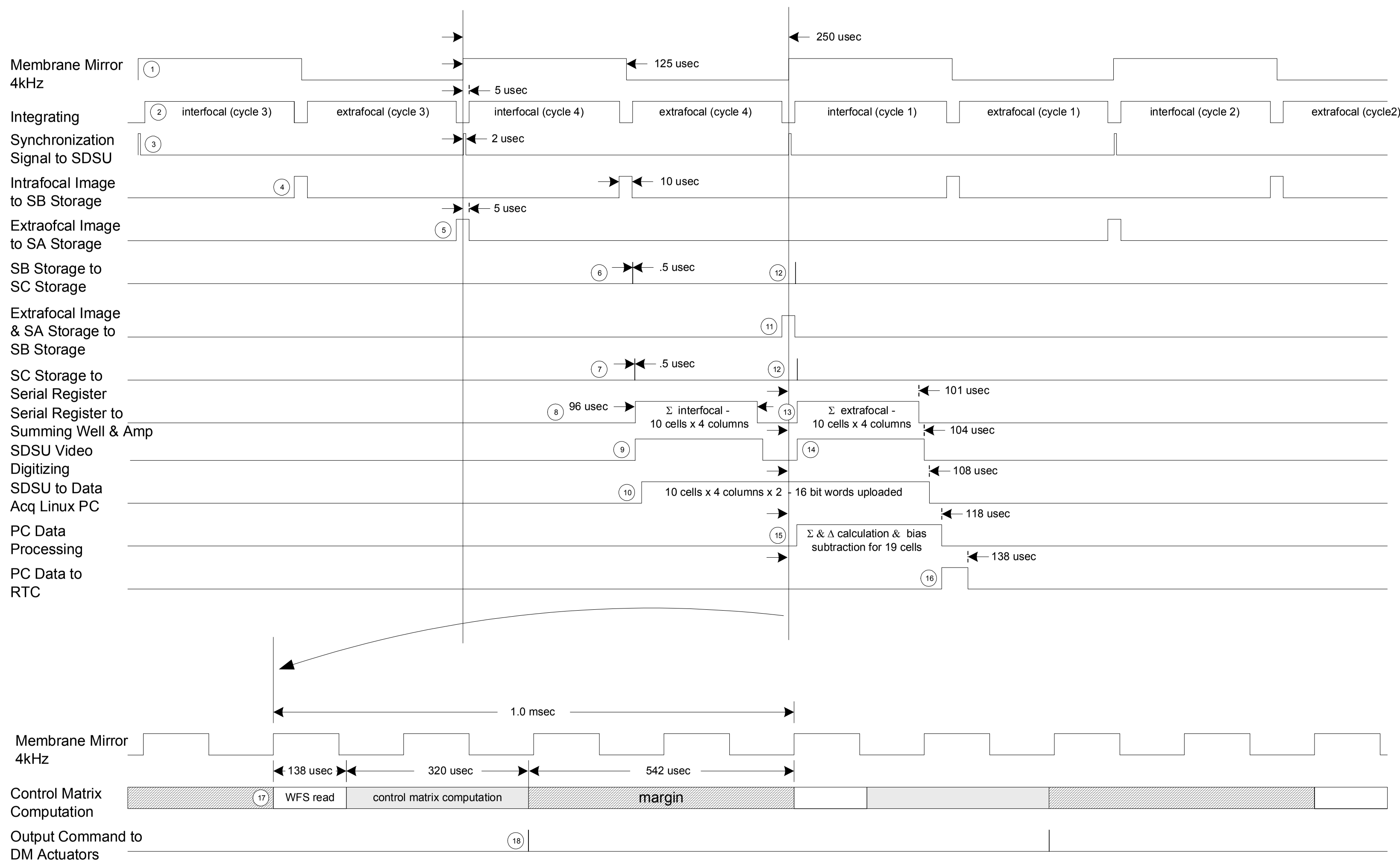

Figure 4. CCID-35 timing diagram

Notes for timing diagram.

1. A 4 kHz signal is generated by the WFS board to drive the membrane mirror. Note that, the timing diagram does not show any phasing adjustments due to time delays in the system.
2. Charge is integrated during each half cycle of the 4 kHz except for 5 usec from either edge of the cycle during which charge is transferred to the storage register.
3. A 4 kHz rising edge detected signal interrupts the SDSU2 to synchronize the membrane drive and CCD timing pattern.
4. Charge integrated during the interfocal phase is transferred to the SB storage register, a process that takes 10 usec – 20 pixels * .5 usec/ pixel. The 20 column pixels are binned in the SB storage register. Charge is integrated and summed for four 4 kHz periods before being read out at the 1 kHz sampling rate.
5. Analogous to the interfocal image phase process, photoelectrons generated during the extrafocal phase are transferred to the SA storage register.
6. At the completion of the 4th interfocal cycle, charge in the SB storage register is transferred to the SC storage register.
7. Charge in the SC storage register is moved to the serial register.
8. Charge in the output serial register is clocked to the summing well. The 20 row pixels are binned at the summing well thus forming a superpixel for each cell. Pixels are clocked at a 3 MHz rate or .33 usec per pixel.
9. Each superpixel is processed by the SDSU2 as soon as it becomes available. The SDSU2 does CDS on each superpixel, which takes 3 usec in the fast readout mode or 5 usec in the slow readout mode. The total time to form and process the superpixel is 9.6 usec - 20 row pixels * .33 usec/ pixel + 3 usec. For the 10 superpixels in the each column, the total time is 96 usec. All 4 columns are processed concurrently. Note that all 10 cells are read out but only 5 cells are necessary. Reading all the cells in the column simplifies the timing pattern and provides the freedom to place the fibers over any cell within the 4 columns. If readout noise is problematic, the serial clock can be decreased or the number of cells read reduced to 5. There is sufficient margin within the 1 ms sample period to handle the additional time.
10. Superpixel data is downloaded to the data acquisition PC via a 250 MHz optical fiber link.
11. At the end of the 4th extrafocal cycle, the image plane charge is moved directly to the SB storage register along with the charge in the SA storage register rather than moving the charge to the SA storage register and then back across the image plane to the SB storage register.
12. Charge integrated during the extrafocal cycles is moved from the SB storage register to the SC storage register and then to the serial register.
13. Charge is clocked through the serial register and superpixels formed.
14. Superpixels are processed by the SDSU2 video processor boards.
15. The superpixels, which are intensity measurement, are biased corrected and then summed and differenced.
16. Intensity data is read by the RTC.
17. RTC computes control matrix, deformable mirror commands, modes and noise. Calculations are completed within 320 usec. Timing margin is 542 usec.
18. RTC outputs actuator commands to deformable mirror.

The edges of the ferrule are 300 um from the center of the adjacent holes. The outline of the ferrule is kept to a minimum in order to provide sufficient margin to position it. The apexes of the bond wires, in worst case, extend approximately 600 um above the plane of the die and the ferrule is expected to be positioned ~500 um above the surface. Care must be taken in positioning the ferrule in the all directions so as not to shear off the bond wires or crush the die.

The vacuum feedthru plate for the fibers uses the same ferrule technology. The fibers pass through the ferrule and are fixed in place with low outgas epoxy. The holes follow the same pattern but are spread out more to ease the assembly process. The ferrule is a bit thicker than the internal one to provide structural support.

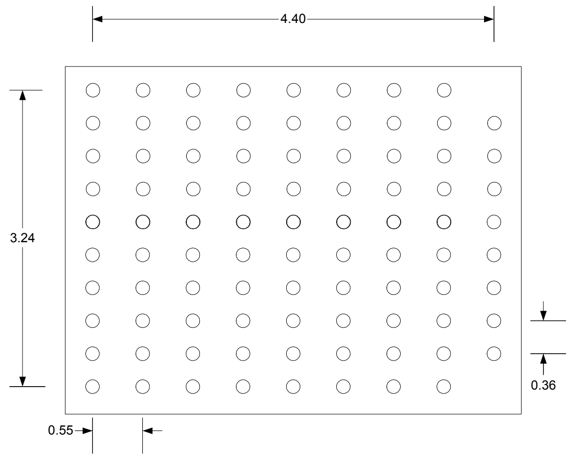

Figure 5. Ferrule hole pattern (dimensions in mm)

In the V groove method, the fibers are positioned in V grooves etched into the silicon die and epoxied in place. The fiber silicon die sets are then stacked and epoxied together to form the fiber bundle. The spacing of the V grooves corresponds to the column spacing of the CCD cells. The thickness of the fiber and die define the vertical dimensions which approximates the cell division along each column. The vertical dimensioning is not so critical since the cell borders are arbitrary and can be redefined. A diagram of the V groove assembly is shown in Figure 6.

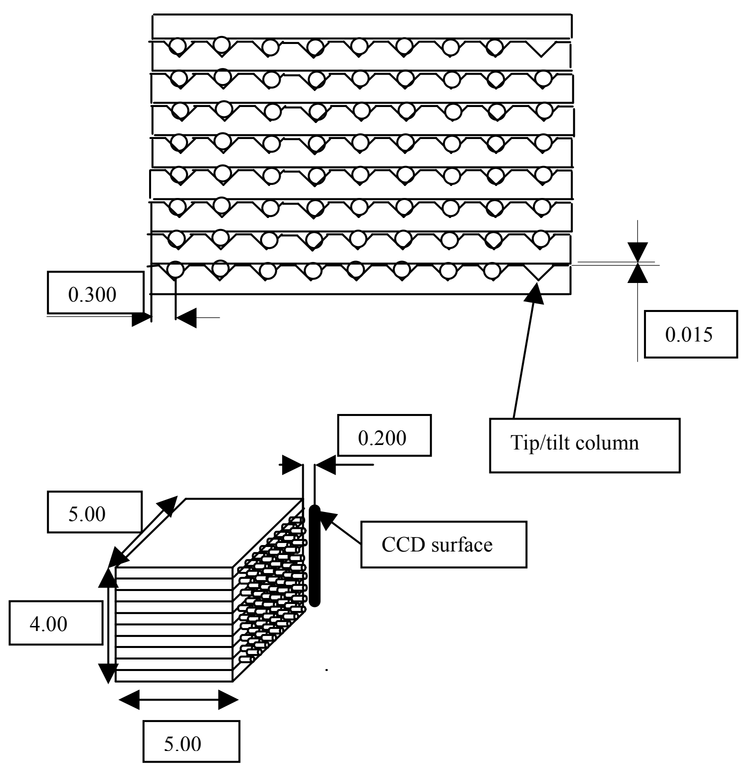

Figure 6. V Groove assembly (dimensions in mm) [9]

4.3 Cryostat

The camera head is a G. Luppino design. It bolts onto the MOCAM dewar which has been recently resurrected after years in retirement.

In the camera head, the CCDs are mounted on two PCBs, Figure 8a, which have filters and decoupling capacitors for the clock and bias lines. Waveshaping the clock lines helps reduce the spurious charge when the CCD is clocked into inversion . An adjustment assembly, Figure 8b, for the fiber bundle sits above the surface of the CCDs. The carrier block for the fibers are spring loaded and slide against a set of wedges to provide 2 axis positioning and rotation. Access to the adjustment is only available internal to the camera head so alignment must be done warm prior to cooling down the head. A few microns of misalignment are expected as cryostat cools downs to operating temperature but should not present a problem. There is margin since the spot size from the fiber is much smaller than the CCD cell dimensions. The wedges are clamped in place after alignment. Z-axis positioning is done by sliding the fiber bundle along the carrier block. The machined components, Figure 7, are stainless steel except for the wedges which are nickel plated brass. The dissimilar metals prevent galling and allows the carrier block to slide easier along the wedges during alignment. The entire assembly, Figure 8c, sits on four G-10 fiberglass standoffs mounted to the bottom face of the camera head.

Cold fingers attached to the bottom of the CCDs provide the thermal conduction path for cooling. A resistor network provides heat for temperature regulation and will be controlled by SDSU2. We plan to operate the CCDs at around –70 C to keep the dark current low.

Figure 7. Camera head components (courtesy of G. Luppino)

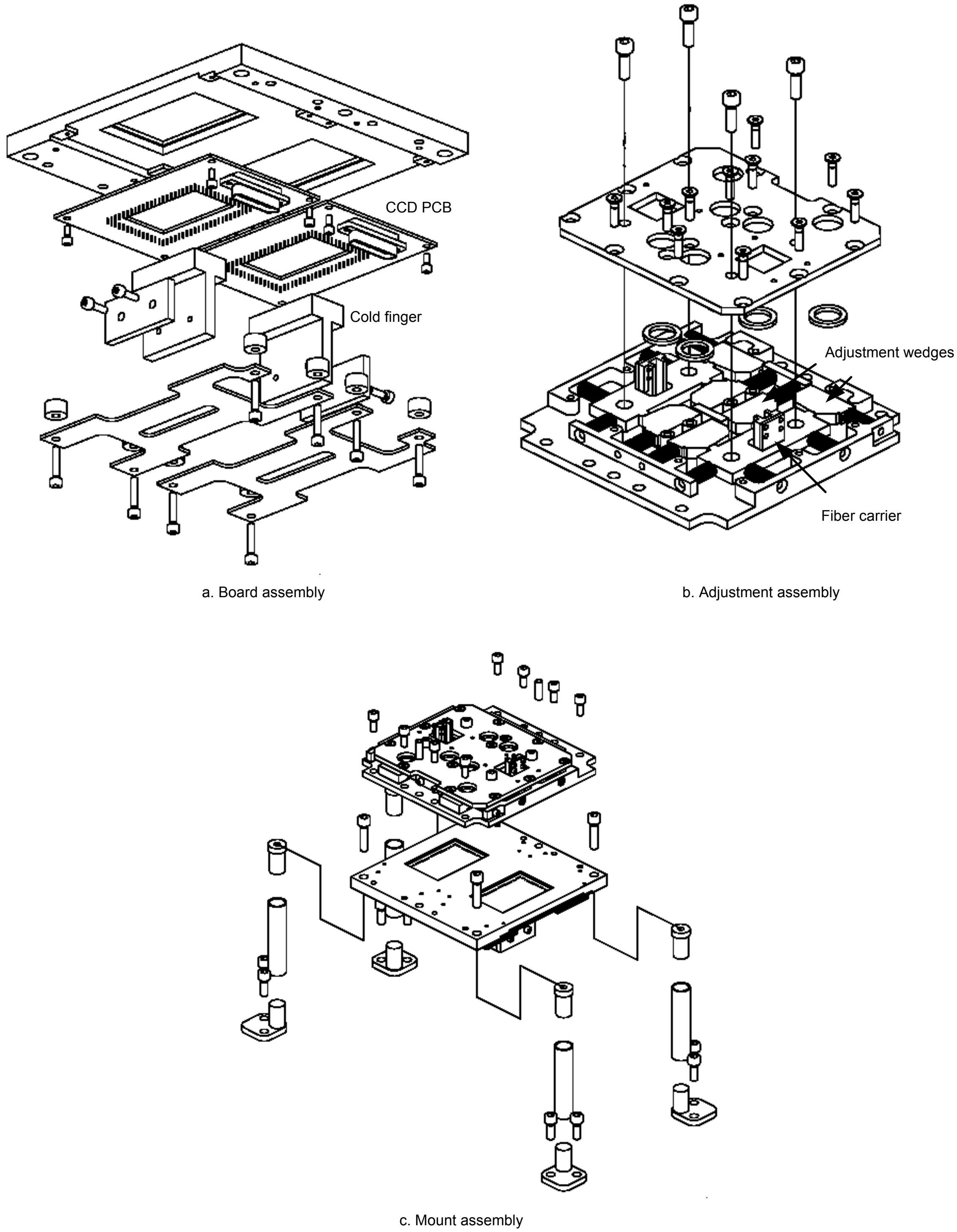

Figure 8. CCD mount assembly (courtesy of G. Luppino)

5. SUMMARY

Progress on FlyEyes is proceeding along as well as expected. The cryostat should arrive sometime in late June 2004 with integration to the SDSU2 controller soon after.

We expect to spend the summer fully characterizing the CCDs and tuning the system to optimize noise performance. One question is whether FlyEyes can obtain as good or better noise performance than that achieved at ESO. FlyEyes is different from the ESO system in that it will use back illuminated CCID-35s instead of the front illuminated versions. Also, its controller does correlated double sampling instead of clamp and sample as done by the ESO CCD controller.

The fiber assemblies, custom interface board for the electronics and software modifications should be completed by the end of summer. Integration into PUEO should begin in the fall. On sky testing is scheduled for late January 2005.

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