CFHT's FlyEyes: assessing on-sky performance of the new MIT/LL CCID-35 CCD curvature wavefront sensor

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ABSTRACT

Due to the strict requirements of very short integration time and very low readout noise, only avalanche photodiodes (APD) have been used, until now, as the detectors in curvature wavefront sensors in astronomy. In 1999, Beletic et al. [2] presented a new CCD design which should achieve the same performance as APDs but with higher reliability and lower cost. In addition, this CCD has higher quantum efficiency than APD modules and larger dynamic range, eliminating the need for neutral density filters on bright objects. In close collaboration with ESO and IfA, MIT Lincoln Laboratory designed and fabricated the device, the CCID-35. R. Dorn [4] extensively tested the CCD in laboratory at ESO and proved that it achieves the predicted performance. CFHT is currently implementing this CCD on PUEO, the Canada-France-Hawaii Telescope (CFHT) Adaptive Optics system, to assess its performance for the first time in real conditions on the sky for a direct comparison with the current 19 APD detector system. In this overview we present the current implementation scheme and discuss the upgrade we foresee for PUEO NUI, a 104-element high-order curvature AO system envisaged to replace the current AO system at CFHT [5,6].

1. INTRODUCTION

We present a CFHT/UH-IfA collaboration to integrate a newly designed CCD based curvature wavefront sensor on PUEO, the CFHT adaptive optics system. The CCID-35 detector was designed by MIT Lincoln Laboratory, ESO and UH between 1999 and 2000 [2] with the first front illuminated devices successfully integrated and tested in laboratory at ESO in 2001 [4]. ESO won't offer itself an opportunity to test the CCID-35 on the sky before 2004 despite the attractive cost effective solution, hence there was no immediate opportunity to prove in real observing conditions on the sky, as of today, that CCDs can do as well, in terms of sensing, as APDs in such specific application.

For CFHT's PUEO NUI project, a proposal to upgrade PUEO into a 104 actuators system [5,6], a solution based on APDs as wavefront sensors is not reasonable due to budget limitations (one APD costs about $3K). Hence this proposal for PUEO-FlyEyes, a project with the limited scope of substituting temporarily for a few engineering nights the APDs with the CCID-35. A direct comparison between the well known current performances of PUEO with APDs (years of experience) with a CCD wavefront sensor system offers CFHT a unique opportunity in the world today to participate in an effort that could bring great benefits for the future of AO curvature systems.

The PUEO-FlyEyes project can be split in seven distinct parts: 1) Integration of two detectors in a dewar [IfA]; 2) SDSUII Controller & DSP code (CCD control + membrane synchronization) [CFHT]; 3) CCD selection

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and optimization [MIT/LL & CFHT]; 4) Coupling of the fibers to the CCD cells [CFHT & IfA]; 5) Feeding the pixel intensities into the existing RT computer [CFHT]; 6) Mechanical integration on the outside skin of PUEO [CFHT]; 7) On-sky performance evaluation [CFHT].

PUEO-FlyEyes is a fairly straightforward project with potential large return to CFHT, as it provides a fully integrated and operational 160 cells system for wavefront analysis on PUEO NUI. A test on the sky in the spring of 2002 is our current goal.

Integrating two CCID-35 in a single dewar represents almost the same effort as integrating a single detector. To produce a system fully scaled for PUEO NUI, we plan on integrating two CCDs (the back illuminated version, available since January 2002) in a dewar designed by G. Luppino [7]. This provides two "eyes" with 80 cells each, whose light will be analyzed by a computer to reconstruct a coherent image of what is happening in the pupil. This is very similar to fly eyes made of many facets and lenses working together to produce a single image, a process made possible with a highly ordered process of organization of neurons that identify specific regions of space in the visual field. Hence FlyEyes.

2. PUEO OVERVIEW

The CFHT Adaptive Optics Bonnette (AOB), also called PUEO (Hawaiian owl), is based on the curvature concept. It saw first light during the first semester of 1996. Extensive documentation and information exists on this instrument adaptor mounted at the f/8 Cassegrain focus [1,8]. It has been used with a variety of instruments: KIR (1K×1K infrared direct imaging camera), FOCAM (2K×2K optical direct imaging camera) and OASIS, an integral field spectrograph, to name a few.

PUEO uses a 19 element deformable mirror requiring 19 APDs. Another relevant issue related to the FlyEyes project is the real time computer (dual processor) that not only makes the real time calculation but also optimization and modal control. The machine is a Sparc5 (few tens of MHz dual CPU), a very slow machine by today's standard where PCs dominate with dual CPU cadenced at 2 GHz each.

3. CCID-35 OVERVIEW

In 1999, ESO and UH-IfA funded a development of a detector by the MIT Lincoln Laboratory to address a major drawback of curvature systems: the highly expensive Avalanche Photo Diodes (APDs), about $3K per unit and only available from a single manufacturer (and there have been reports within the AO community that the failure rate of these actively quenched APDs is quite high). ESO was then launching the AO project MACAO, a multi purpose 60-element curvature system developed for the Very Large Telescope (VLT), and in particular for the VLT Interferometer (VLTI) requiring four identical systems.

The new nature and working principle of the detector is extensively covered in Beletic et al. [2]. The CCD has been successfully produced and subsequent extensive testing on an optical bench at ESO allowed a complete evaluation of the detector to build predicted comparisons with APDs [4].

Extensive computer simulation comparison of CCDs and APDs for curvature wavefront sensing were also conducted by Thomas Craven-Bartle at ESO [3]. The simulated AO-system was the MACAO 60 elements curvature system and the results indicated a difference in performance of 5% Strehl in K-band for a 15th magnitude guide star, 2% Strehl for a 16th magnitude star, and less than 0.6% Strehl for all other magnitude guide stars.

Unfortunately, due to some delay in the production of this new detector, the CCID-35 could not eventually be considered as WFS for the MACAO systems due to time constraints. However, as per January 2002, the CCID-35 in backside illuminated version is available and the only prospect of having it seeing starlight in the near future is having it tested on CFHT's PUEO.

PUEO uses passively quenched APDs which are more robust than the actively quenched ones (known now for their higher failure rate due to extreme sensitivity to over illumination) but present a quantum efficiency a factor of two lower (40% versus 80%). The thinned version of the CCID-35 should have a QE peaking in the red at 95%: this should overcome some of the penalty induced by the readout noise and reduce the relative time lag due to the readout time by reducing the exposure time when using faint guide stars.

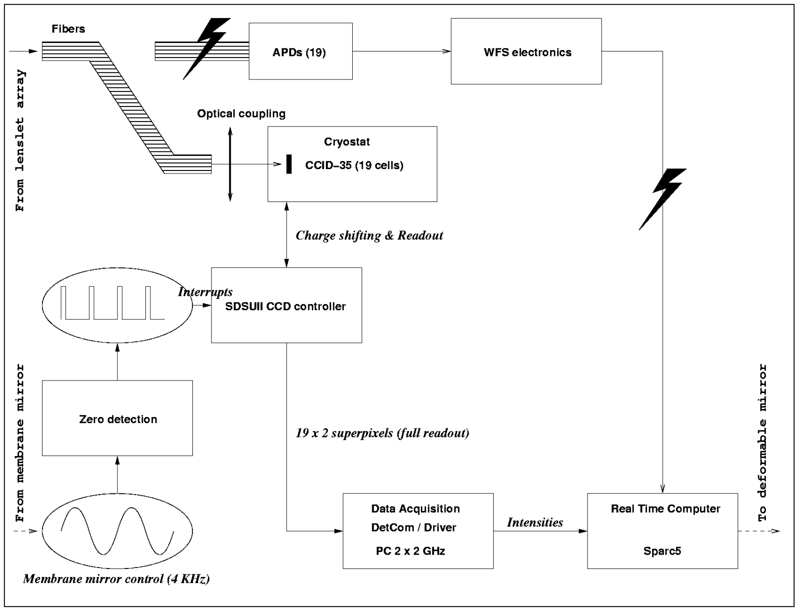

Figure 1. FlyEyes: overview of the new elements.

4. WORK PACKAGES

4.1. CCD cryostat

These CCDs need to be cooled at cryogenic temperatures in order to remove the dark current component from the noise. A standard dewar designed by G. Luppino [7] will be used.

The camera head wiring will be designed will all outputs (18 total, 8 per CCD for the cells and two for the tip-tilt arrays that won't get used on PUEO-FlyEyes but will represent an added benefit for PUEO NUI) wired out to the main cryostat connector even though the PUEO-FlyEyes experiment requires only 4 outputs (see section below). Using this camera head on PUEO NUI will only imply connecting a single controller since our current plan is to use a SDSUII system with limited ultra-fast parallel readout capabilities.

4.2. CCD controller

The SDSUII CCD controller will be used to run the two devices. Each readout will consist of $19 \times 2 = 38$ superpixels read from the camera. If the 19 light beams can not be arranged on a single CCD due to the physical crowding of the optical design, they could be split between the two CCDs. There will be a total of 160 cells available in FlyEyes, 80 cells per CCD! To keep the readout time as low as possible, parallelism is a requisite. The default controller box provided in a SDSUII system has six slots. With one for the timing board, one for the utility board and one for the clocking board, this leaves enough room for up to three video boards, each with two video channels; we will limit the FlyEyes system to four video channels. Each of the four video channel dealing with 5 cells from a row, i.e. 20 pixels per output per dual-readout (in and out of the pupil plane).

Using the performance numbers established by R. Dorn at ESO [4], say a 250 μsec readout time when using 6 rows of 10 cells each, and scaling it down to using only 5 cells in 4 rows (total 20, with one empty cell), the predicted readout time is about 150 μsec (including pre-scan pixels and other overheads). This figure allows a 1.5 electron readout noise with front illuminated CCDs. However, the SDSUII controller is a different architecture than the ESO CCD controller (CDS vs. clamp and sample). Only experimentation will demonstrate the noise level we will be able to achieve with SDSUII.

The top sampling/command frequency of PUEO is 1 KHz, or a cycle time of 1 ms. The lag induced by the 150 μs CCD readout is only 15%. Note that the lag is important to the correction only at the highest frame rate - on bright objects - when the correction is already very good. As the flux decreases and the frame rate is adjusted to increase the exposure time, the relative contribution of the readout delay becomes less and less important in the loop.

We will "plug" the readout values into the RTC computer in order to simulate exactly (signal and timing) the information passed to it in the current APD based system. This will require the development of an interface electronic board connecting the CCD acquisition host (running real-time Linux) to the RTC.

A crucial part of the operation of this new WFS device is the perfect synchronization required between the membrane vibration in and out of the pupil plane (4 KHz) with the shifting of the charges on the CCD in order to achieve symmetric integration timing for both sides. The SDSUII controller will easily solve this technical issue since it can operate in an interrupt mode based on an external signal. The membrane sinusoidal signal simply needs to go through a zero crossing circuitry that will generate a pulse. Each pulse will trigger an interrupt causing immediate shifting of the charges in the storage areas. This interrupt feature of SDSUII has actually been tuned and used for the first time within the SDSU community in 1998 at CFHT to synchronize within 6 ns the readout of both CFH12K controllers.

4.3. Optical coupling

We first investigated a coupling through the silicate cryostat window but the optical losses appeared somewhat high. It is however possible to produce a 1 to 1 optical coupling through the window that would preserve a decent image quality without any overlap between the fibers' signal on the CCD. A new design is currently being developed by G. Luppino and CFHT to allow the fibers to go through a front plate and come within 200 μm of the CCD surface.

5. REFERENCE

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