A new photon counting spectrometer for the COAST

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ABSTRACT
Electron multiplying CCDs, e.g. as delivered by E2V Technologies and Texas Instruments, have the potential to become the detectors of choice for all future optical interferometers, replacing expensive fibre-fed arrays of APDs. We report here on the development of a new 500-channel spectroscopic back end for the COAST interferometer that exploits such a device. An E2V Technologies CCD97 (back illuminated) EMCCD with sub-electron readout noise is used as the detector, and can be read out at pixel rates of up to 30 MHz. We present software and hardware approach used to integrate a new CCD controller with the COAST as well as results from lab tests of the detector and controller.

Keywords: Optical interferometry, spectrometer, EMCCD, L3CCD, CCD, fringe tracker, group delay

1. INTRODUCTION
Electron multiplying CCDs (EMCCDs) are the first CCDs to be commercially available with an effective internal gain mechanism [Mackay et al., 2001]. An extension of the output register used with high voltage clock waveforms allows electrons to be accelerated on passing through each pixel, with a small probability – typically this is up to two percent – of generating a second electron by avalanche multiplication. The combination of several hundred multiplication stages means that an overall mean gain of up to 10000 can be achieved. Any initial signal has then been amplified well above the readout noise of the CCD, meaning that the signal from individual photons can be detected, i.e. a sub-electron effective readout noise has been achieved. These EMCCDs can be operated at high pixel rates (up to and above 30 MHz), and still achieve sub-electron effective readout noise.

The Cambridge Optical Aperture Synthesis Telescope (COAST, Haniiff et al. [2000]) is an optical interferometer, with baselines currently extending up to 67 m, and the ability to measure closure phase (it can be used to combine light from up to four telescopes simultaneously) and hence produce model independent images. It has the ability to modulate the optical path difference (OPD) of starlight temporally, and so to obtain an adequate signal-to-noise ratio (SNR) for visibility parameter estimation, many fringe maxima and minima must be sampled within a few times the atmospheric coherence time – typically we sample at 5 kHz, taking 500 samples over a fringe (the OPD modulation cycle, or scan). By using an EMCCD as the detector, it is simple to introduce spectroscopic capability to the COAST, dispersing a spectrum of interfered light across a single row of the detector, and reading the row out every 0.2 ms (5 kHz), as shown in Fig. 1. The high quantum efficiency of the EMCCDs (which can be as high as 90 percent) combined with the effective sub-electron readout noise makes them ideal as spectroscopic-interferometric detectors.

Spectroscopic detection of a fringe pattern produced by temporal modulation of the OPD allows the use of group delay fringe tracking (GDFT) algorithms [Lawson, 1995]. Fringe tracking is a process which involves locating the maximum of the fringe pattern envelope, and then centring the fringe pattern in the OPD modulation cycle (scan) at this maximum. It is important to be able to measure the visibility amplitude at this point, since this is where maximum contrast is found, and where the visibility amplitude is defined. If there are many narrow spectral channels (and hence a large coherence length), it is still important to centre the fringe envelope since otherwise the fringe pattern envelopes from different spectral channels will be offset by different amounts. We report on progress made on a GDFT for the COAST which uses the new EMCCD spectrometer.

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2. HARDWARE DESCRIPTION

2.1. Optics

At the COAST, we are using an E2V Technologies CCD97 (a thinned, 512 × 512 pixel, frame transfer EMCCD) as the detector for an interferometric spectrometer. It is possible to use up to 512 spectral channels, the wavelengths and bandwidths of which are dependent on the optics used. Currently, we have a low resolution dispersion mode using a prism as the dispersing element, and covering wavelengths between 650-1000 nm dispersed over 200 pixels (the optics were designed for a smaller CCD than is actually used). We also have a high resolution dispersion mode using a diffraction grating, which disperses wavelengths between 650-665 nm over 200 pixels, specifically for looking at Hα emission. This mode has a resolution of $R \approx 6500$, the spectral channels having a bandwidth of approximately 0.1 nm.

The spectrometer optics are designed to minimise the number of surfaces between the input beam and the detector, and to reduce the realignment required when switching between dispersing modes. Fig. 2 shows the design for the low resolution mode using a prism, mirror and near-infrared achromatic lens. The use of an achromatic lens means that the focal length is virtually independent of wavelength (between about 700-1100 nm), and so each spectral channel can be focussed on the detector simultaneously. For the spot size at each wavelength to remain smaller than the pixel size, there is a tolerance of order 0.1 mm in the lens position when focusing the spectrum on the CCD, which is achieved using a fine thread focus tube.

Fig. 3 shows the optical design for the high resolution mode, using a diffraction grating, mirror and achromatic lens. To switch between dispersion modes, the dispersing element (prism or grating) and mirror form one unit, which must be manually placed on a kinematic baseplate. The same lens is used for both dispersion modes, meaning that minimal refocusing is required when switching between modes. Realignment of the spectrum on the CCD (to compensate for alignment differences between the prism and grating) is obtained by adjusting the mirror angle and CCD orientation in addition to focusing of the lens.

2.2. CCD controller

Due to the demands placed on detectors required for spectroscopic interferometric applications (very low noise at high readout rates), it was necessary to design a custom controller. Standard commercial astronomical controllers
Figure 2: (a) Ray diagram for the low resolution spectroscopic mode, showing the prism, input light beam with a 15 mm diameter input aperture and a 512 pixel CCD (16 micron pixels). (b) A close up view of the CCD surface, with horizontal bars showing one 16 micron pixel for scale, and light rays with wavelengths of 650, 652 and 654 nm. (c) A close up view of the CCD surface for light rays with wavelengths 710, 712.5 and 715 nm. (d) A close up of the CCD surface for light rays with wavelengths 987, 993.5 and 1000 nm. It is evident that the focal plane is not perfectly flush with the detector (due to an imperfect achromatic lens), but at all points the spot size is less than the pixel size.
Figure 3: (a) Ray diagram for high resolution spectrometer, composed of a diffraction grating, mirror and lens showing wavelengths between 640-670 nm. (b) A close up view of the CCD surface with horizontal bars showing the 16 micron pixel size and light rays with wavelengths of 650, 650.1 and 650.2 nm. (c) A close up view of the CCD surface with horizontal bars showing the 16 micron pixel size and light rays with wavelengths of 665, 665.1 and 665.2 nm. The focal plain is slightly curved with respect to the detector (due to an imperfect achromatic lens), but at all desired wavelengths, the spot size is less than the pixel size. The difference in spot size for these wavelengths is due to the positioning of the lens and CCD which have been kept in the same position as in Fig. 2, showing that refocusing should not be required.
Figure 4: An overview of the CCD controller design showing the signal flow (solid arrows) through the EMCCD controller hardware. Data flow is shown by dotted arrows and the custom hardware is also shown. The uWeb is an ethernet enabled device used to communicate with the controller.

typically do not operate at the pixel rates required, and EMCCD specific commercial controllers do not offer the flexibility required to be properly integrated with the COAST.

Controller development has been ongoing in Cambridge (UK) over the past few years, and an overview of the system is given in Fig. 4. The CCD clock waveforms are generated using the external bus of an Analog Devices TigerSHARC-101 DSP (with an external bus speed of 83 MHz which is multiplexed to provide 166 MHz signals, i.e. 6 ns time resolution), and a maximum pixel rate of 28 MHz is obtainable assuming 36 ns per pixel. The CCD controller is designed for use with multiple applications, and so there is some flexibility when configuring it for a particular situation. It is ideal for use with the COAST, since it can be synchronised line by line to the timing signals at the COAST, appropriate for temporal OPD modulation.

The controller contains a 14 bit ADC which can be operated with correlated double sampling at rates of up to 30 MHz, and allows flexible control of the post-readout signal amplification. The data obtained from the CCD is passed via LVDS cable to a frame grabber (Matrox Meteor-II/dig⁺), and can then be stored in a computer. The frame grabber can be operated with both Microsoft Windows and QNX⁴ operating systems, and so it is suitable for use with applications requiring hard real-time control, such as GDFT. Communication with the controller is via ethernet, and a uWeb ethernet device⁵ is used to interface between the DSP and the user.

Development of this controller has not been as fast as hoped (numerous factors meant that the first estimate for a working controller, Christmas 2002, was not met). However, on 25th May, 2004, the first image was obtained, though this did not use the high gain multiplication. The EMCCD has since been operated in high gain mode, though further improvements are required to make this reliable. Once the CCD controller is functional, it is hoped the system can then be integrated with the COAST by early August.

To use the EMCCD with the COAST, it is necessary to read out a single spectrum every 0.2 ms (at 5 kHz). The CCD97 is a frame transfer CCD, and so each spectra must first be transferred through the store region before reaching the serial register. However, due to the high spectrum sampling rate, there is not enough time to transfer a newly obtained spectrum from the CCD image area to the output register in 0.2 ms. Therefore, after each spectrum as been exposed (each 0.2 ms period), 16 parallel transfers are carried out, with the bottom 16 rows (containing a previously recorded spectrum) being binned into the serial register, which is then read out. Combining 16 rows together has two advantages: If the lens is not focused optimally, or atmospheric fluctuations cause the fringe pattern to shift, all of a given spectrum will still be read out together. Additionally, it then

*Matrox: http://www.matrox.com
⁴QNX: http://www.qnx.com
µWeb ethernet module: http://www.comtech.uk.com
Figure 5: A schematic diagram for the readout scheme used to integrate the EMCCD with the COAST. 16 CCD rows are combined together and read out of the CCD with a 5 MHz pixel rate, every 0.2 ms.

takes less time for a given spectrum to be read out of the CCD (after 512/16 instead of 512 transfers), reducing the latency in the system. A schematic of the readout scheme is shown in Fig. 5.

3. SOFTWARE

Software is required both to initialise and operate the CCD controller, and to capture, store and analyse the data obtained, as demonstrated in Fig. 6. The user can control the way in which the CCD is read out using configuration scripts which are checked and compiled on the host computer before being uploaded to the CCD controller. Software is also required to apply the GDFT algorithms to the data, used to minimise the OPD of interfered starlight.

3.1. CCD controller

The configuration scripts used to control the CCD give the user the ability to control how the CCD is read out, exposure times, triggering etc, and so these scripts can be tailored to an individual situation (for example for use with an interferometer). The EMCCD can be configured as free-running (continuously reading out), or triggered (frame, line or pixel triggers), depending on the application in question. The frame grabber is controlled using the same control software, and stores recently grabbed OPD scans in RAM memory so that they can be accessed even after the next few scans have been obtained. This is necessary because saving of the data cannot be carried out in real-time on heavily loaded systems and so some backlog will build up. The data rate will typically be 16 MBits per second, which could result in delay if passed over a heavily loaded network. However, for interferometric applications, this is not a problem as typically only up to 100 seconds of data are saved at one time, and so a large backlog does not occur. Fig. 7 shows a screen-shot of the CCD control software.

3.2. Fringe data visualisation

Fringe data are grabbed and stored in shared memory arrays in a real-time computer. The number of scans that can be stored simultaneously before being overwritten is dependent on available memory but is typically between 100-1000 scans, with each scan consisting of all the spectra taken during half an OPD modulation cycle (typically 500 spectra). A separate process running on this computer is able to send the fringe data over TCP/IP sockets to clients that request it. The client has the option of receiving all spectral channels, or a
Figure 6: Control flow (solid arrows) and data flow (dotted arrows) for the CCD controller. The CCD controller is configured by user scripts. The frame grabber is an essential part of the CCD controller, though is placed inside the computer.

Figure 7: A screen shot of the control software for the CCD controller.
selection, possibly combined together if desired. This means that the data visualisation and storage can be carried out on a non-real-time computer, making it easier for the observer to use.

Fig. 8 shows a screen-shot of the visualisation software. This software gives the user the ability to view the raw data, to view histograms of single rows or columns (spectral channels) of data, and to view the power spectrum of the data: Both a two dimensional gray-scale plot, and a one dimensional power versus wavenumber histogram of given spectral channels. The one dimensional power spectra provide a quick way to estimate the fringe frequency and the SNR. The correlation amplitude and phase of two adjacent spectral channels can also be computed, useful as a quick estimate for the OPD when the fringe tracker is not operating.

Fringe data is saved in 3D FITS format with the dimensions as follows:

1. Spectral channel
2. Position within OPD modulation period
3. OPD modulation period
Figure 9: An overview of the COAST spectrometer data reduction stream. Raw data is used to compute uncalibrated visibility amplitudes and closure phases. Calibrated visibilities are then computed using calibrator measurements and written to OI-FITS format files. These files are then used with model fitting software, e.g. mfit.

Information about the time the fringe was obtained and the direction of the OPD path compensators at this time is also included in a FITS table within this file. The FITS header includes all information necessary to obtain visibility estimates from the data.

3.3. Data reduction

Data reduction is carried out using modified COAST software, and an overview of the data reduction process is given in Fig 9. The raw data is first used to obtain uncalibrated visibility amplitudes and closure phases. If calibrator measurements have been made, calibrated visibility measurements for each spectral channel can then be computed, and are written to OI-FITS format files [Young, 2003], which can then be used with standard optical interferometry model fitting software, for example mfit⁵.

During the initial stages of data reduction (while estimating uncalibrated fringe parameters) it is possible to view raw data in any spectral channel (or combined channels). Additionally, the power spectra of any spectral channel (or combined channels) can be viewed, along with closure phase estimates if available. When computing the uncalibrated fringe parameter estimates, the SNR of the estimate, as well as an estimate for the atmospheric coherence time, the fringe frequency, mean detector counts and fringe envelope position are all computed.

3.4. Fringe tracker

The fringe tracking software operates in real-time, using GDFT algorithms for each newly grabbed data scan to estimate the OPD, and then adjusting the OPD path compensators so that the mean OPD can be minimised, centring the fringe envelope. The fringe tracking software is user controllable, and highly configurable, and an example of the interface is shown in Fig. 10. It is possible to control integration times, interferometric baselines on which to use the GDFT algorithms, the path compensators to move (and speed), spectral channels and sections of the OPD modulation to use in the algorithm, along with windowing functions etc. Further details of the GDFT algorithm used are given by Basden and Buscher [2004].

The OPD estimate can be visualised as a plot of position against likelihood of being at this position (Fig. 11), and as a grey-scale plot of the history of estimated positions (Fig. 12). This is useful in cases where the SNR is low, or the fringe has been temporarily lost, for example due to cloud.

4. RESULTS

Although the new spectrometer at the COAST is not yet complete, it is possible to test various parts of this system, and tests carried out so far are detailed here.

⁵mfit software: http://www.mrao.cam.ac.uk/~jsy1001/mfit/
Figure 10: A screen shot of the fringe tracker control software, displaying some of the configuration options available to the user.

Figure 11: A screen shot of the OPD location signal, with the peak in the spectrum representing the current OPD. A similar signal is available on all baselines currently in use.
Figure 12: A screen shot of the fringe tracker OPD estimation history time series, showing how the OPD has changed with time. The previous ten seconds (100 scans) are shown.

Figure 13: A channelled spectrum obtained using a Starlight Xpress camera on the new spectrometer. To obtain this image, the OPD was made slightly non-zero, so that the fringe pattern could be observed.

4.1. Optics tests
A Starlight Xpress camera was used with the spectrometer in place of the EMCCD. The Starlight Xpress camera has a fairly low readout noise (typically 10 electrons), and so channelled fringes can be obtained using the artificial star (essentially a lamp placed at infinity) at the COAST, without OPD modulation. Fig. 13 shows a fringe pattern obtained with the Starlight Xpress camera. The spectrum obtained here is slightly out of focus to demonstrate smearing of the fringe pattern over several rows of pixels. The exposure time was 300 ms (compared with 0.2 ms when the EMCCD is used) and so temporal atmospheric fluctuations also add to the smearing.

4.2. Controller tests
The new EMCCD controller was initially operated without the high multiplication gain, i.e. as a conventional CCD, with a high read noise of about 1700 electrons in full frame mode. Initially, poor charge transfer efficiency in the serial direction was observed (0.9995, i.e. about 25 percent of flux left behind after 600 serial transfers). Alterations to the timings and a low bandpass filter on the CCD output enabled this readout noise to be reduced to 200 electrons, while displaying good charge transfer efficiency (>0.99999). It is hoped that by placing the electronics in a metal enclosure, the readout noise can be substantially reduced, though this has not yet been investigated. This readout noise, while high, is acceptable since the EMCCD can be used with a high multiplication gain (up to 10000), meaning most signals will be well above the noise threshold. Rigorous testing of the high multiplication gain has not yet been carried out.

The readout mode to be used at the COAST was also tested and found to work. This means that the CCD controller can now be synchronised with the COAST subsystems, such as the optical delay lines, and other fringe sampling detectors.

*Starlight Xpress: http://www.starlight-xpress.co.uk/*
4.3. Fringe tracker tests

Initial tests of the fringe tracker were carried out using fake fringe data, and the GDFT algorithms found to work correctly. The communication with the path compensation trolleys has been tested and so it is hoped that once the spectrometer is operational, the fringe tracker will function properly. This however cannot be tested until the CCD controller has been completed.

5. CONCLUSION

We have reported on the development and testing of a low light level spectrometer at the COAST, consisting of an EMCCD, and capable of measuring up to 512 spectral channels simultaneously dependent appropriate optics are used. Data visualisation and processing software has also been developed for this application and a group delay fringe tracker is available for use at the COAST. The functional components of this system have been tested and found to work as expected.

It is hoped that a fully functional EMCCD controller will be ready shortly, after which it should take less than a month before the system is fully integrated with the COAST.

References


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