ULTRASPEC: High-speed spectroscopy with zero readout noise

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Abstract. ULTRASPEC is a high-speed, spectroscopic camera based on electron-multiplying CCDs (EMCCDs) and the data acquisition system of ULTRACAM. The camera saw first light in December 2006 on the EFOSC2 spectrograph of the ESO 3.6m telescope at La Silla. In this paper we describe the motivation behind ULTRASPEC, present an outline of its design and report on its measured performance. The results show that EMCCDs are likely to revolutionise astronomical spectroscopy.

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INTRODUCTION

Conventional CCD detectors suffer from two major weaknesses: they are slow to read out and they suffer from detector noise. These weaknesses combine to make high-speed astronomical spectroscopy of faint targets the most demanding of observations, where by "high-speed" we mean timescales of tens of seconds and below.

It is possible to overcome the problem of slow speed by using frame-transfer CCDs and detector-limited data acquisition systems. Such an approach has been adopted by ULTRACAM, the high-speed, triple-beam CCD imager we recently commissioned on the VLT [2]. Reducing readout noise in CCDs to negligible levels is more difficult, and has only recently been solved by the development of electron-multiplying CCDs (EMCCDs) [7]. These are conventional CCDs, but with an extended serial register to which a higher-than-usual voltage is applied. Secondary electrons are produced as the photon-generated electrons are clocked through it, resulting in a signal amplification which dwarfs the readout noise, rendering it negligible.

EMCCDs have generated a lot of interest in the high spatial-resolution community [5, 1, 10, 4], but have received much less attention for other astronomical applications, such as spectroscopy. To address this problem, a consortium from the Universities of Sheffield, Warwick, the UK Astronomy Technology Centre and ESO, were awarded 180 kEuro funding under EU OPTICON Joint Research Activity 3: *Fast readout, high-performance optical detectors* to investigate the use of EMCCDs for high-speed spectroscopy. The resulting camera took 2 years to build and is called ULTRASPEC, since it is essentially a spectroscopic version of ULTRACAM.

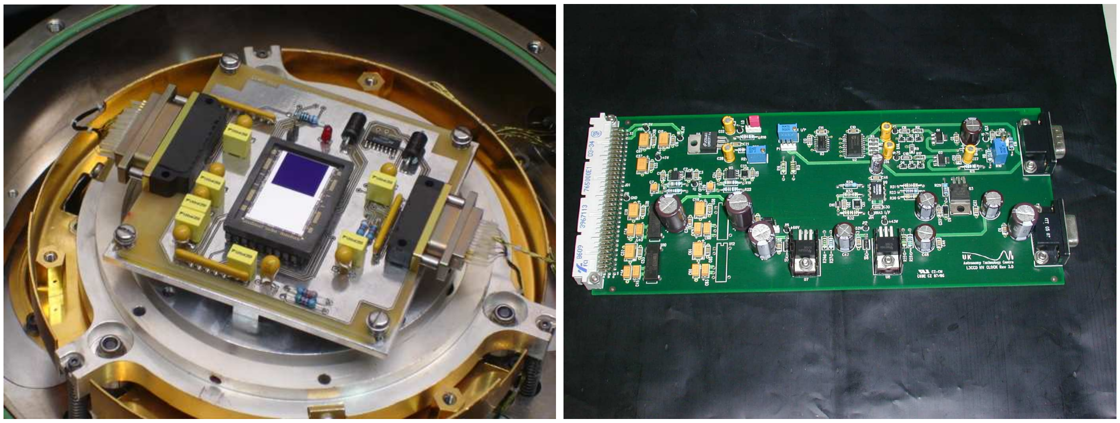

FIGURE 1. Left: The frame-transfer EMCCD chip mounted in the ESO cryostat. Right: The third and final version of the high-voltage clock board that we developed for the SDSU controller.

High-speed spectroscopy is an unexplored region of observational parameter space, with many promising applications [8]. Hence, although primarily a technology demonstrator, ULTRASPEC has also been used to do science, as described below.

DESIGN

At the heart of ULTRASPEC is an EMCCD – we chose to use an E2V CCD201-20 detector (see figure 1), which has an imaging area of 1024×1024 pixels (each of 13 μm). The CCD201 is also a frame-transfer device, thereby offering high frame rates (up to hundreds of Hertz) with negligible dead time, as well as essentially zero readout noise. The chip is mounted in a standard (old-style) ESO cryostat, cooled by liquid nitrogen and temperature-regulated by a Lakeshore controller. The chip readout is controlled by a San Diego State University (SDSU) Generation III CCD controller, which incorporates a custom-made, high-voltage clock board (see figure 1) to power the serial gain (or "avalanche") register. The SDSU controller is hosted by a rack-mounted dual-processor PC running Linux patched with RealTime Application Interface (RTAI) extensions. The use of RTAI allows one processor to be strictly controlled so as to obtain accurate timestamps from the GPS antenna located outside the dome and connected to the PC via a serial port.

The data acquisition, instrument control and user interfaces are all virtually identical to the tried and tested hardware/software used in ULTRACAM, as shown in figure 2. The user interface allows an astronomer to switch between the normal and avalanche outputs of the CCD201-20. The former forces the CCD to operate in an identical manner to a conventional CCD. The latter forces EMCCD operation, i.e. on-chip amplification. Other parameters which can be adjusted on the user interface include: avalanche gain (10 different levels ranging from 1 to 1000), slow and fast readout speeds, clearing/no clearing of the chip prior to each exposure (see [2]), exposure delay (see q[2]), number of exposures, binning factors in both dimensions, and the choice of full-frame, one window or two window formats (the latter being useful if a comparison star is to be placed on

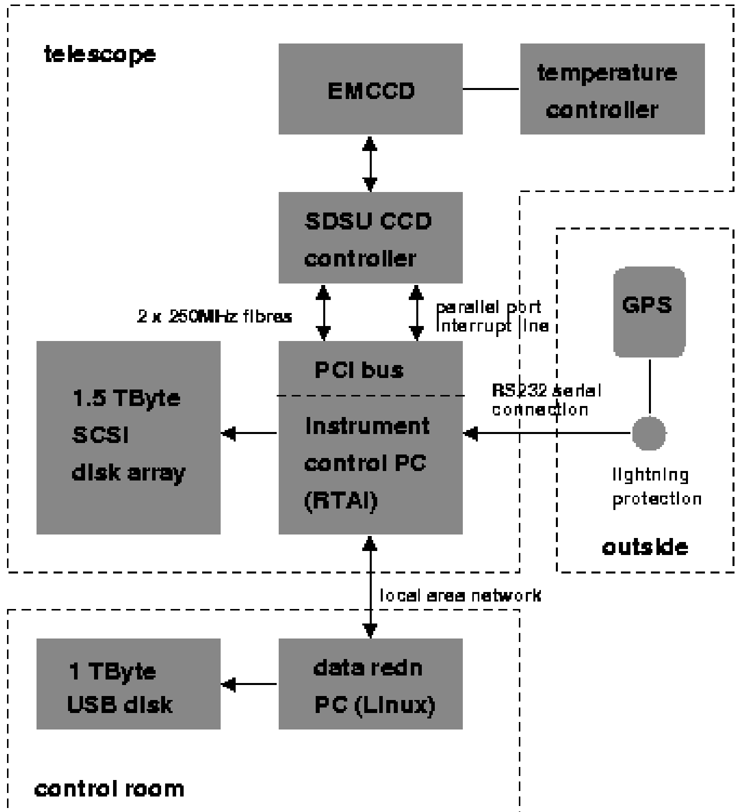

FIGURE 2. The ULTRASPEC data acquisition system

the slit).

Building a new spectrograph to test ULTRASPEC would have been prohibitively expensive and time consuming, and is unnecessary as so many excellent spectrographs with external focii able to accept visiting cryostats already exist. We identified the EFOSC2 spectrograph on the ESO 3.6m telescope as ideal for our purposes, and the Director of Paranal/La Silla Observatory awarded us 4 nights of technical time in December 2006 to commission and test ULTRASPEC on the sky (see figure 3).

PERFORMANCE

The ULTRASPEC commissioning run was a great success. Installation, integration and alignment proceeded without problems, no telescope time was lost due to technical problems with ULTRASPEC, and we completed the characterisation of the EMCCD chip with a spectrograph on the sky. This latter task was the main aim of the run, and the main deliverable of our OPTICON-funded project, and was achieved by observing a series of standard stars ranging from magnitude 13 to 19 with different avalanche gains and exposure times (from hundredths of a second to hundreds of seconds). As an added bonus, we were also able to observe some demonstration science objects, which serve as

FIGURE 3. Left: View inside the Cassegrain cage of the ESO 3.6m telescope, showing ULTRASPEC mounted on EFOSC2. The cryostat containing the EMCCD is visible at the bottom of EFOSC2. Close to this is the SDSU controller. The ULTRASPEC electronics rack containing the Lakeshore and PC is the unit on the left with a square black sticker on its door. Right: The ULTRASPEC commissioning team. From left to right: Emilio Barrios (ESO), Naidu Bezawada (UKATC), Kieran O'Brien (ESO, standing), Vik Dhillon (Sheffield), Chris Copperwheat (Warwick), Tom Marsh (Warwick), Andy Vick (UKATC, standing).

useful examples of the power of EMCCDs for astronomical spectroscopy. The results, which show that EMCCDs are likely to revolutionise certain types of (i.e. readout-noise limited) astronomical spectroscopy, will shortly be submitted for publication [3], and in this section we present only a brief summary.

Table 1 shows some key characteristics of the EMCCD used in ULTRASPEC. Two points are worth noting. The first is the clock-induced charge rate. As discussed by [8], it is critical that this is reduced to an absolute minimum, as it ultimately determines the signal-to-noise ratio obtained with EMCCDs. A great deal of effort was invested in reducing this number in ULTRASPEC. Second, it can be seen that many of the characteristics (e.g. readout noise, dark current, quantum efficiency, linearity, charge-transfer efficiency) compare very favourably with the normal CCDs found on the world's largest telescopes, highlighting the point that astronomers without readout-noise limited observations would lose nothing by using EMCCDs. As described below, however, astronomers with readout-noise limited observations (arguably the majority of those doing optical spectroscopy on the world's largest telescopes), would gain very considerably by using EMCCDs. In fact, no-one loses, implying that EMCCDs should become the detector of choice for spectroscopy at the world's major observatories, providing that larger formats become available.

An example ULTRASPEC data frame is shown in the left-hand panel of figure 4. The science target, a $V \sim 17$ magnitude cataclysmic variable (CV) with a 90-minute orbital period known as OY Car, is in the lower window on the CCD. CVs are close binaries consisting of a red dwarf transferring mass via a gas stream, bright spot and accretion disc onto a white dwarf. The emission line that can be seen is that of Hβ λ4861Å, and it originates from the accretion disc surrounding the white dwarf. The upper window on the CCD contains the spectrum of a comparison star, used to correct for light losses on the

TABLE 1. Key characteristics of the EMCCD in ULTRASPEC.

Parameter	**Value**
Dark current	20 e^-/pix/hr (non-inverted), 4 e^-/pix/hr (inverted), @160 K
Readout noise in slow/fast mode	4/10 e^- (normal output), 11/25 e^- (avalanche output)
Clock-induced charge	0.02 e^-/pix/frame
Quantum efficiency	$\sim$ 90% @600nm
Speed: vertical clocking	7 μs/pix/row
Speed: serial clocking	0.48 μs/pix
Speed: CDS* and ADC† (slow/fast)	3.2/1.7 μs/pix
Frame rates	$\sim$ 1.5s for a full frame, $\sim$ 0.1s for a 1024×100 window
Charge-transfer efficiency	$>$ 99.999%
Linearity	linear up to 50 000 e^-/pix

* Correlated double sampling
† Analogue-to-digital conversion

slit and so allow us to obtain differential spectrophotometry. The central panel of figure 4 shows the trailed spectrum of Hβ in OY Car obtained with ULTRASPEC. Each spectrum in the trail is the accumulation of 20 photon-counted exposures from the avalanche output of ULTRASPEC, each of 0.5 seconds, giving a total exposure time per spectrum of 10 seconds. The eclipse of the white dwarf, bright spot and accretion disc by the secondary star can clearly be seen in the continuum. In addition, the Hβ emission line is double peaked and displays a strong rotational disturbance, where the blue-shifted peak is eclipsed prior to the red-shifted peak. Both effects are characteristic of an accretion disc and can be used to probe its structure [9]. The right-hand panel in figure 4 shows the light curve of OY Car, obtained by summing the flux in the trailed spectrum of the CV and then correcting it for slit losses using the corresponding comparison star light curve. The hump just prior to eclipse is due to the bright spot coming into view. The sequence of events is then: white dwarf eclipse, bright spot eclipse, white dwarf comes out of eclipse, bright spot comes out of eclipse. Each phase is clearly seen in the light curve, and can be used to measure the system parameters of the binary [6]. These data are of remarkably quality given the faintness of the target and the fact that the eclipse transitions occur on timescales of seconds: only a frame-transfer EMCCD could have obtained data of this quality on a 4m-class telescope.

To illustrate this last point further, and quantify the signal-to-noise improvement possible with EMCCDs, figure 5 shows a comparison between the normal and avalanche outputs of ULTRASPEC. The spectra are of the AM CVn-class cataclysmic variable ES Cet, a binary star of magnitude $V \sim 17$ consisting of two helium-rich white dwarfs in a very close 10-minute orbit. One of the white dwarfs is filling its Roche lobe and transferring material to its companion, producing the strong He II λ4686Å emission visible in its spectrum. The upper spectrum shows the sum of 74 photon-counted exposures from the avalanche output of ULTRASPEC, each of 0.13 seconds, giving a total exposure time per spectrum of 10 seconds. The lower spectrum shows a single 10 second exposure of ES Cet taken using the normal output of ULTRASPEC. Note that the latter is identical to what would be obtained using a conventional CCD. The gain in signal-to-noise is approximately a factor of 3. Given that these are readout-noise limited observations, using

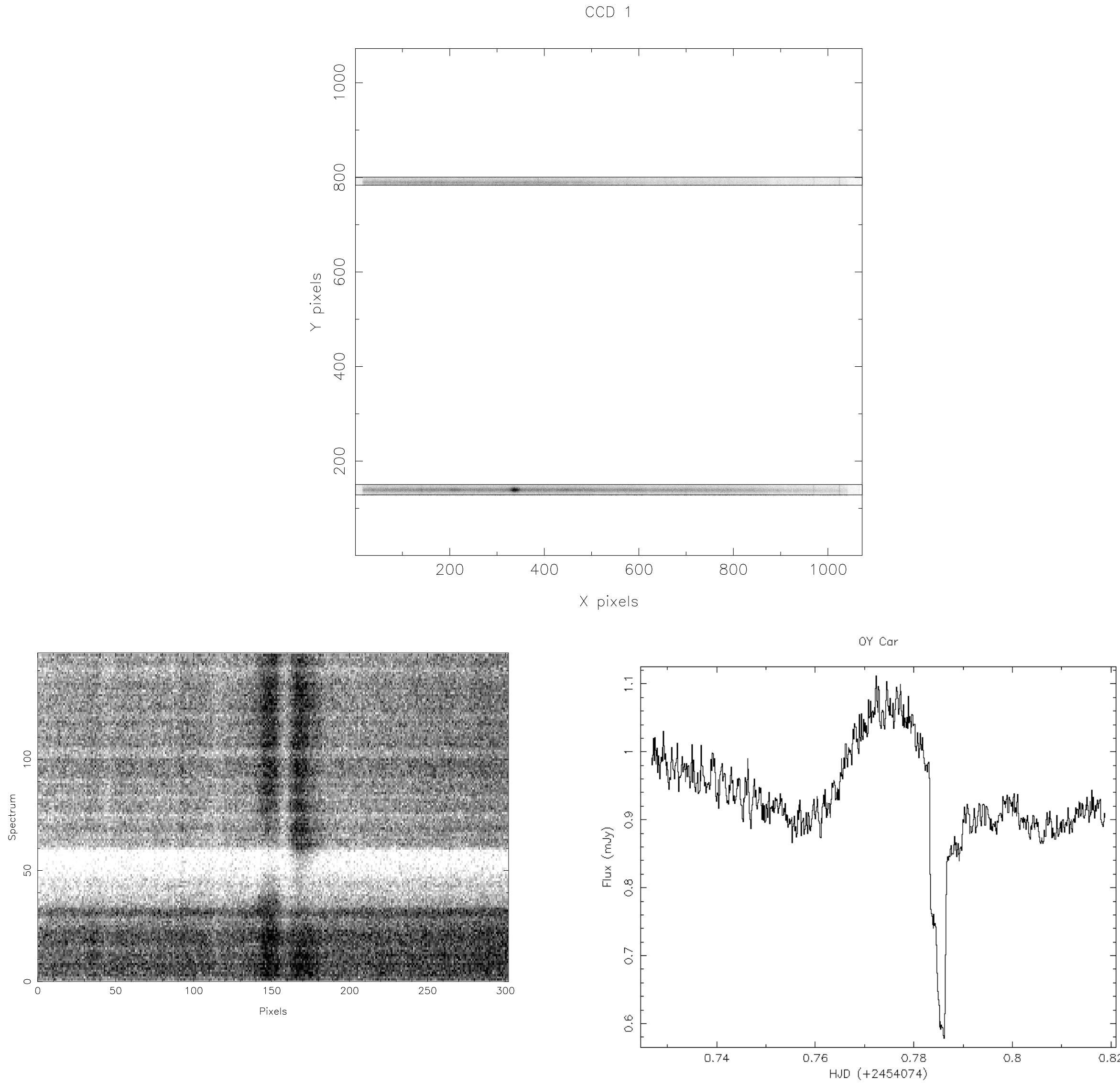

FIGURE 4. Left: Example ULTRASPEC data frame, showing two windows. The lower window contains the spectrum of the science target (the cataclysmic variable OY Car) around Hβ. The upper window contains the spectrum of a comparison star to correct for slit losses. Centre: The trailed spectrum of OY Car obtained with ULTRASPEC in photon-counting mode. Note that the wavelength scale on the *x*-axis is reversed, with red to the left and blue to the right, and darker greyscale represents higher flux. Each spectrum in the trail is of 10 seconds duration, and hence the *y*-axis represents a total time interval of $\sim 1500\,$s. Right: Light curve of OY Car, obtained by summing the flux in the trailed spectrum. The eclipse transitions due to the white dwarf, bright spot and accretion disc can clearly be seen. See text for details.

an EMCCD on the ESO 3.6m is therefore equivalent to using a conventional CCD on a 6.3m telescope. In other words, we have effectively doubled the diameter of the telescope by using an EMCCD! In actual fact, the improvement is even greater than this, as by "conventional CCD", we actually mean a conventional *frame transfer* CCD, which is

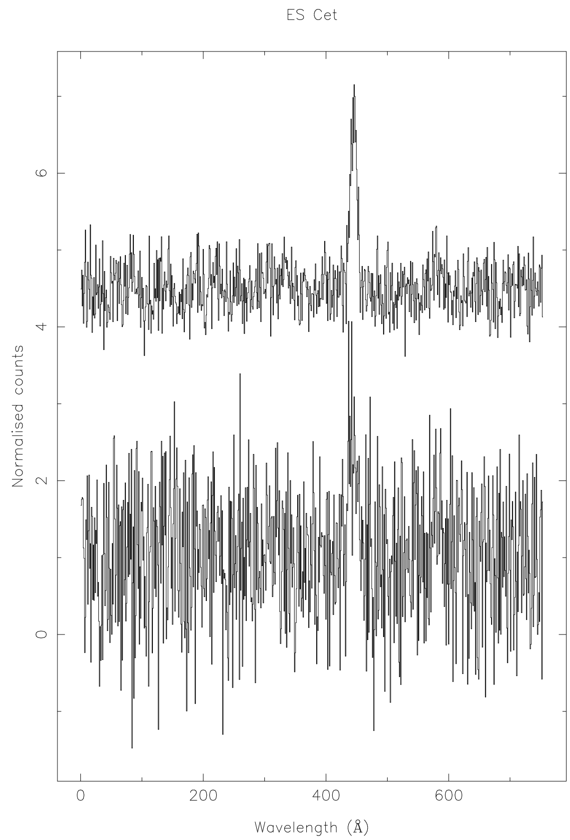

FIGURE 5. ULTRASPEC spectra of the AM CVn-star ES Cet. Top: A 10-second spectrum using the avalanche output of ULTRASPEC. Bottom: A 10-second spectrum taken using the normal output of ULTRASPEC. The latter is identical to what would be obtained using a conventional CCD. The gain in signal-to-noise is approximately a factor of 3, turning the ESO 3.6m into a 6.3m telescope! See text for details.

already a significant improvement on the non-frame transfer CCDs used on most of the world's major spectrographs due to the much improved duty cycle they provide.

FUTURE WORK

With ULTRASPEC successfully commissioned, we are now keen to start using it to do science and we have a 17-night science run scheduled on the ESO 3.6m during February 2008. The targets of this science run will be X-ray binary stars, pulsars, white dwarfs and CVs. There is little additional work to be done on ULTRASPEC in preparation for this proposed run, although we are procuring new VPH-based grisms for EFOSC2, providing higher resolutions and better-matched central wavelengths for ULTRASPEC's smaller CCD.

In the longer term, we are also investigating the possibility of procuring a larger-format, multi-output EMCCD designed specifically for astronomical spectroscopy and using this in combination with the ESO NGC controller. When this larger device be-comes available, it is likely to be adopted by many of the world's observatories as the detector of choice for astronomical spectroscopy.

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