A novel “skew” readout mode: 
CCD RON suppression by summing echelle orders on-chip

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ABSTRACT

Nice abstract here…

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1 INTRODUCTION

Scientific requirements for a successful spectroscopic observation are sufficient spectral resolution and a sufficient signal to noise ratio (S/N), with precise requirements varying from application to application. A spectral resolution (λ/Δλ) of 10 000 (30 km/s) is sufficient for the purpose of resolving sky absorption lines. A S/N of 5 is already sufficient for a coarse analysis of intrinsic line strengths. A S/N of 2 is already sufficient for coarse derivation of redshifts.

The Fiber-coupled Echelle Spectrograph (FIES) at the Nordic Optical Telescope (NOT) has a fiber connection to the telescope enabling the instrument to be located in a stable temperature controlled environment outside the rotating telescope building. This means that the echellogram (echelle spectral image) position and shape should be stable on the CCD. In a future configuration, the fiber will be always mounted at the Cassegrain focus of the NOT, and can be illuminated via a pickoff-mirror in the main beam. This puts FIES in a position to do stand-by observations at request, making it an ideal instrument for target-of-opportunity observations.

The normal operating resolution of FIES is ~ 60 000 over the whole wavelength coverage from 3800Å to 8400Å. The readout-noise level of FIES is 4.7 to 6.1 e− depending on the amplifier used. For faint sources, in order to get enough light per spectral pixel bin to be photon-noise limited
instead of read-noise limited, we have to bin pixels. This way, one pixel in a spectral order is the sum of many CCD pixels, but is read out only once. Using such a readout mode one can expect to get 2.2 - 9.5 times lower readout noise per spectral pixel bin, depending on the binning size used.

The main purpose of this project is to increase the available effective spectral resolution range for faint-object spectroscopy and specifically to be able to observe gamma-ray burst’s optical afterglows with FIES at NOT. As a side effect we obtain the possibility to choose the effective spectral resolution and obtain a much faster readout of the CCD. Now the instrument can also be used for time-resolved studies.

2 TECHNIQUE

In a few words, the technique is to sum the CCD pixels of the echelle orders on the CCD instead of reading out and summing afterwards. In order to be able to observe faint objects, quite large bin sizes will be used, which reduces the effects of readout noise considerably. However, coarse binning in normal fashion (constant binning value over all columns and/or rows) would incorrectly sample the detected spectrum, due to the curvature and proximity of the echelle orders.

The CCD on FIES is a E2V CCD42-40-1-B83. It is back-side illuminated with 2048 by 2048 imaging pixels, each 13.5 $\mu$m square. This detector has 50 CCD pixels of overscan and underscan, making the default image size 2148 by 2052 pixels. The CCD is linear within 1% from 100 e$^-$ to 50 000 e$^-$ when used with the controller described below. The peak quantum efficiency is 88% at 4500 Å.

The “Copenhagen” CCD controller was developed at Niels Bohr Institute for Astronomy, Physics and Geophysics (NBIfAFG). It is one of the most linear controllers in the world. The drawback from the very stable and high linearity is the slow readout speed of 55 000 pixels per second. The controller program handling all CCD instructions and actions is located in a programmable ROM chip, and written in assembler like most time-critical applications. We have taken advantage of this programmability to develop our “skew” readout mode.

An echellogram consists of a set of curved spectral orders, whose distance to each other typically decreases towards longer wavelengths. Part of the FIES echellogram can be seen in Fig. 1. Each order contains a small part of the observed spectrum, sometimes with overlap in wavelengths between adjacent orders. For FIES the spectral order profile FWHM is 5.5 pixels, and 85 orders fit on the CCD with order overlap.

In order to keep the curved profile of a spectral order intact while binning, we devised a ”skew”
readout mode, for which the binning pattern follows the shape of the curved echelle orders. First an exposure of a calibration lamp is acquired without any binning. For the resulting echelle spectrum the orders are traced in order to generate a "mask" file. The readout mask file contains an array with 76 lines. Each mask line specifies which CCD pixels should be read allowing for the curvature of the orders. Each mask line consists of a number of interorder distances, and applies to a given range in $Y$ (see Table 1). This mask is uploaded to the controller before an image can be taken in "skew" readout mode.

When a CCD readout starts, the controller shifts $N_{Y-bin}$ lines into the serial register, effectively binning in the $Y$ direction by $N_{Y-bin}$, and then reads the first element of the first line of the mask and reads out that many pixels from the serial register without using any binning. No binning is used to be able to start readout of the first spectral order at the desired $X$ pixel. Then it sets binning to 5 CCD pixels, and reads out one such binned pixel, effectively transferring 5 pixels containing the profile of the first spectral order into the summing well before reading it out only once. This implies that now the total length of a line to read out has shortened by 4 pixels, and that the total resulting image size is not clear for the image acquisition program.

Next, the controller reads the second element of the first mask line and reads out the corresponding number of pixels without binning. Then it reads the 5 pixels spanning the 2nd order with one read. And so on, until the last spectral order defined in the mask file has been read. After the last order to bin, the controller checks if there are still pixels left to read out, and reads them out without binning. Now we set the clock to “stuck state” to read dummy pixels until the end of the line in order to fill the expected image size. Then the controller shifts the next $N_{Y-bin}$ lines to the serial register and the loop starts all over again.

Since the controller is equipped only with a limited amount of memory, some sort of approximation of the order curvature is necessary. After analyzing some test images taken with FIES, it was apparent that in spite of the curved shape of the orders, they are relatively straight within $\sim 50$ pixels. This means that when using, for example, $Y$-binning of 6 pixels, 6 consecutive binned lines can be read out with the same mask line and still keep the spectral order well centered within the 5 pixel space given by the memory constraints. The largest possible mask is 85 orders by 76 lines.

Another advantage of using this readout mode is the reduced readout time. This is naturally not critical for faint objects, since one would in any case expose on the order of 30 minutes on the object, so the readout time of FIES’ 2Kx2K E2V CCD chip of 81 seconds is not too much. But as an added bonus, the readout time with this skew-mode is only $\sim 7 - 81$ seconds depending on
Figure 1. A part of the FIES echellogram with three skew pixels painted black. Three order separations from the mask file are marked with an X. Y marks the amount of binning along CCD columns.

Table 1. Binning properties of different spectral resolutions. “R” is the resolution, “ybin” is the binning in dispersion direction, “similar” is the number of binned lines read out with same mask line definition, “ub sim” is the number of corresponding CCD pixels, “ysize” is the size of the final image in Y-direction, “lines” is the number of lines in mask file and time is the readout time in seconds for the resolution mode.

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<th>similar</th>
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the spectral resolution used, adding a possibility to do time-resolved medium-resolution echelle spectroscopy.

After the readout, a postprocessing program extracts the summed spectral orders (picks out the binned pixels) and writes a copy of the image. These FITS images then only contain extracted, continuum normalized and wavelength calibrated spectra, and are very small and ready for immediate analysis.

2.1 Implementation

The algorithm was added to the C code from (Østensen 2000) written for windowed fast-photometry readout mode of ALFOSC (Andalucia Faint Object Spectrograph and Camera). The controller it-
self uses Motorola 68010 processor, so the code was cross-compiled to assembler using standard Gnu C to m68k cross-compiler library.

2.2 Calibrating the readout mode

The only negative side-effect of this readout mode is that there is a significant difference in counts in zero second dark frames (bias frames) at the positions of the orders. The difference is reproducible and follows the bias level of the overall image. The implication of this is that a bias frame should be obtained before and after an object exposure, in order to correct for this effect.

Wavelength calibration should be done using the same binning as was used to obtain the science exposures. Bad pixels can be flatfielded/bias subtracted out. Flatfielding with FIES is a bit tricky in the sense that one can not get a uniform illumination of the CCD. Using halogen lamps one can flatfield the order positions, and correct for pixel to pixel variations inside orders, as is done normally, even for “skew” readout mode.

3 OBSERVATIONS

Observations of the late-B type star $\phi$ Hercules (HD145389) were taken the 28th of April 2004. The seeing was somewhat variable during the night due to the varying humidity level. The $V$ magnitude of $\phi$ Her is 4.26. This enabled the use of the star itself for creating the readout mask. Then, to demonstrate faint object performance, we took 0.5 second exposures of the star in all available spectral resolution modes. The strength of the readout mode was demonstrated, as can be seen from figure (Fig. 2). One can clearly see how the signal gets swamped by the readout noise when the resolution increases.

The most important comparison is between the two lowest-resolution spectra at the bottom of the image. The lower one of the two is a full-frame normal-readout 0.5 second exposure (seen unbinned as the second from the top) which has been binned after the readout to the resolution of the second lowest spectra. The increase in S/N by binning after the readout is 4, and increase in S/N by using “skew” readout mode is $\sim 36$. Just by using the least decrease in spectral resolution increases the S/N by the same amount as binning afterwards, and one can still bin more if necessary.

In theory, the increases in S/N should be from 2.2 times the S/N of a normal readout for full resolution using the “skew” readout up to 9.5 using the strongest binning.
Figure 2. Spectrum of Hα-line of φ Her, used to compare different resolutions. From bottom to top: R=60000 0.5s normal exposure summed afterwards to R=3333; R=3333 0.5s skew; R=5000 0.5s skew; R=6666 0.5s skew; R=10000 0.5s skew; R=15000 0.5s skew; R=20000 0.5s skew; R=30000 0.5s skew; R=60000 0.5s normal and R=60000 300s normal exposure.

4 CONCLUSIONS

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REFERENCES


Østensen, R. H., 2000, Time Resolved CCD Photometry, PhD Thesis, University of Tromsø