PHASE RESOLVED HIGH SPEED PHOTOMETRY AND SPECTROSCOPY OF PULSARS

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Abstract. We describe the implementation of two High Time Resolution modes for ESO's new generation CCD controller FIERA. These new modes have been used to perform phase-resolved high speed photometry and spectroscopy of pulsars with the FORS instruments at the VLT.

Keywords: CCDs, ESO Very Large Telescope, high time resolution, pulsars, variable signals

Introduction

During recent years FIERA has become ESO's new generation high performance CCD controller and is now used for all existing and forth-coming Very Large Telescope (VLT) instruments. FIERA enables high-speed readout of CCDs (up to 2 megapixel/sec/port) at a readout noise limited only by the CCD. Peak data rates of 16 megapixel/sec can be handled. For detailed specifications of the controller see [2],[3],[4]. In combination with the large collecting power of the VLT, the high time resolution of FIERA (25 nsec) opens a new observing window for objects which show variations on very short time scales. Among these are many of the most fascinating objects in astronomy like pulsars, black hole candidates, cataclysmic variables, flare stars and burst sources. The typical time scales range from milliseconds to seconds and are easily within the range of the FIERA controller. Therefore we proposed to implement a high time resolution mode for FORS (FOcal Reducer and Spectrograph, [9],[1]) at the VLT [7]. A first implementation of two HIgh Time resolution (HIT) modes has been tested. These modes have been used with the FORS instruments at the VLT, which are equipped with FIERA controllers, to perform phase resolved high speed photometry and spectroscopy of pulsars [10].

So far, more than 100 pulsars have been identified, most in the radio band. Due to their intrinsic faintness, only a few of them have also been identified in the optical band. Although since the first discovery of a pulsar in 1967 [6] much observing time has been dedicated to pulsar research, there still exists no coherent theory which is able to explain all the emission features observed throughout the various wavelength bands. More recent broad-band optical observations indicate that there may be a thermal contribution to the pulse emission, which is in contra-

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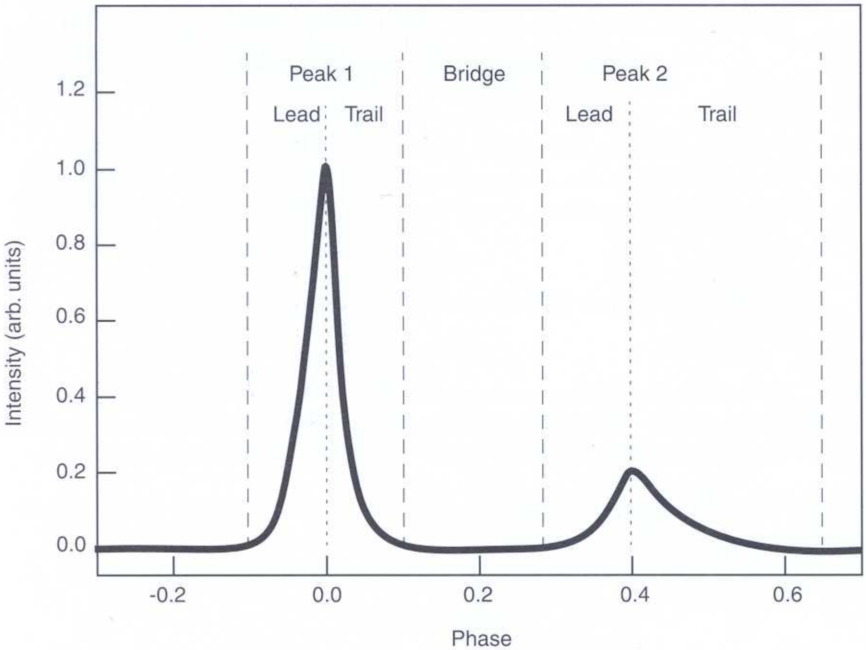

Figure 1. Pulse profile of the Crab Pulsar.

diction to existing theories [5]. In addition, a mean spectrum of the Crab pulsar shows unidentified structures, which cannot be explained within the context of standard theory [8]. A clarification on this subject can be achieved by ruling out or, alternatively, confirming the existence of thermal emission and by investigating the emission structure of individual pulses by performing phase resolved spectroscopy of single pulses (the pulse profile of the Crab Pulsar is shown in Figure 1). Such research work can only be done by exploiting the large collecting power of the VLT and the high time resolution mode of FIERA.

A new way of operating CCDs

In order to perform phase resolved spectroscopy and photometry of variable signals, two new techniques for operating a CCD have been developed. The idea behind both techniques is to expose only a small area of the CCD to the incoming radiation, shifting the charges on the chip, thereby obtaining data, which are a sampling in time of the varying signal. All the samples (spectra or images) are collected on the same area of the CCD, therefore they are not affected by changes in sensitivity on the chip

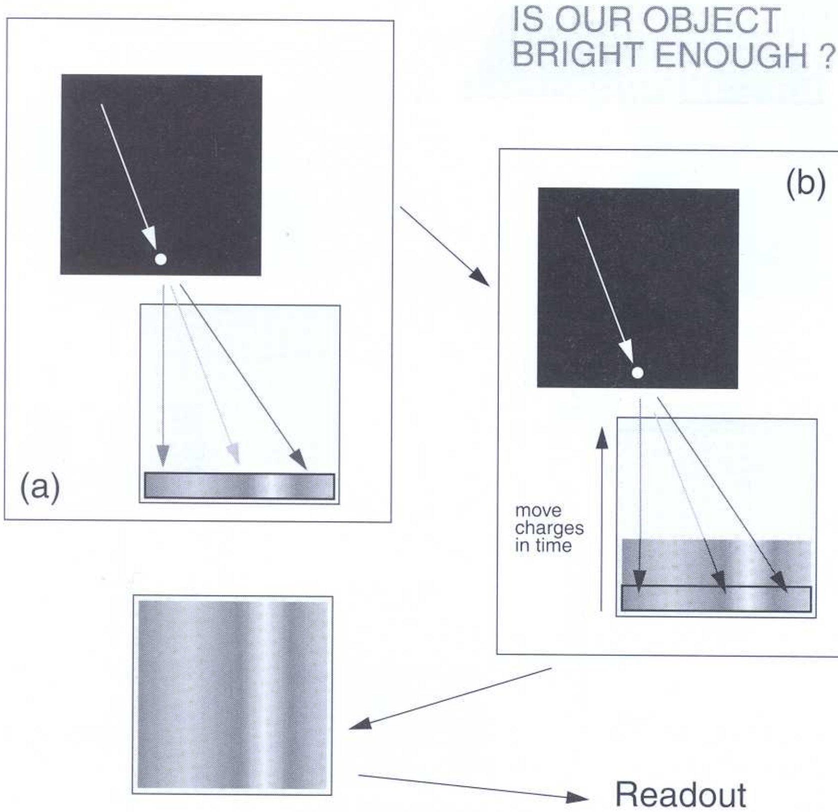

Figure 2. One shift mode.

HIgh Time resolution – One Shift Mode (HIT-OS)

The first technique is called One Shift Mode (HIT-OS) and has been implemented for the spectroscopy or the photometry of variable objects with a sufficiently strong signal (see Figure 2). When operating the CCD in the HIT-OS, a mask with a slit at the lower end covers the CCD chip. The CCD is wiped, then the shutter is opened. The slit image is projected on the area of the CCD close to the serial register and the spectrum is spread on the first rows of the chip (Figure 2a). During the exposure, the charges on the chip are shifted along the parallel registers (Figure 2b). In this way, several spectra of the object are taken at different times. The CCD is then continuously read out, while the charges are synchronously shifted on the chip, which is still exposed and collecting spectra. The result is a series of images, showing the variation of the spectrum with time.

HIgh Time resolution – Periodic Shift Mode (HIT-PS)

The second technique is called Periodic Shift Mode (HIT-PS) and has been implemented for the spectroscopy or the photometry of pulsars and other faint periodic

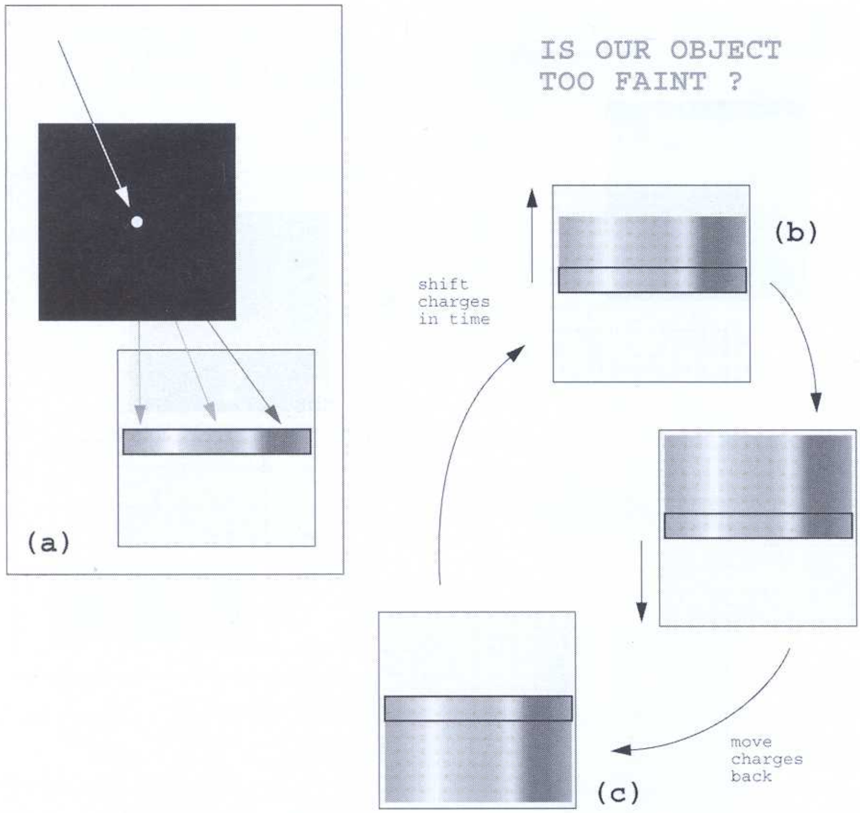

Figure 3. Periodic Shift Mode.

objects, whose exact periodicity is known (see Figure 3). When operating the CCD in the HIT-PS, a mask with a slit in the middle covers the CCD chip. The CCD is wiped, then the shutter is opened. The slit image is projected on the centre of the CCD and the spectrum is spread on the central rows of the chip (Figure 3a). During the exposure, the charges on the chip are shifted along the parallel registers (Figure 3b). In this way, several spectra are taken at different times during the period of the signal. Once the first spectrum has reached the border of the chip (i.e., several spectra have been collected on half of the CCD), the shutter is closed and the charges on the chip are shifted back along the parallel registers (Figure 3c). After an interval of time that is equal to an integer multiple of the signal period, the shutter is reopened and the shifting of the charges on the CCD is then restarted. Several spectra are therefore superimposed, improving the signal-to-noise ratio. The synchronisation of the charge motion with the signal period is accurate to 25 μsec. At the end of the exposure the single image containing the phase resolved superimposed spectra is read out. The advantage of a superimposition done on the chip instead of summing multiple images after the readout is that the main source of noise, i.e., the CCD readout noise, becomes less significant, affecting the data only once.

Final remarks

Two new techniques for operating a CCD have been developed to perform phase resolved spectroscopy and photometry of variable signals. Both the HIgh Time Resolution modes have been successfully tested with FORS at the VLT. Phase resolved spectra of the Crab pulsar have been collected, to search for phase dependent spectral features.

At the moment, the FORS instruments are equipped with Tektronix and SITe 2K$\times$2K CCDs. The time resolution of these chips is limited by the line shift time, which is at least 1.2 msec. The usage of new generation CCDs, which are able to shift a line 100 to 1000 times faster, could achieve an improved resolution of the pulse profile.

Appendix: Questions and Answers

Q: Have phase-resolved spectra of pulsars been collected in the optical bandwith before?
A: Yes, but not with CCDs. So far, Transition Edge Sensor (TES) devices (Romani et al., 1999, *ApJ*, 521 L153-L156) have been used for phase-resolved spectra in the optical band. Superconducting Tunnel Junction (STJ) devices (Perryman et al. *A&A*, 346, L30-L32) have been used for broad band photometry of the Crab pulsar, with a spectral resolution of 100nm.

Q: What timing accuracy is needed for the resynchronising?
A: The time needed to shift a line of the chips on the FORS systems is 1.2 ms. The image of the slit is spread over 4 rows of the CCD, therefore with the HIT-PTR mode we can collect on the chip 256 spectra with a time resolution of about 4.8ms (covering about 36 periods). The timing accuracy needed when restarting the motion of the charges on the chip should be such that the maximum misallignement between the first and the last spectra is one third of a single spectrum. In the case of 100 motions, this means an accuracy of about 16 μs. It is very easy with FIERA to reach this time resolution: it only depends on the frequency of the crystal oscillator, that clocks the DSP. This oscillator is 40 MHz in the case of FORS, and therefore gives an accuracy of 25 nsec.

Q: What is the spectrographic resolution needed?
A: We expect to see synchrotron radiation, although there have been claims for spectral features found in mean spectra (e.g. Nasuti et al. *A&A*, 314, 849).

In order to search for such features, a spectroscopic resolution of the order of a few Angstroms would be sufficient. More important than the exact number of the spectroscopic resolution is the accuracy of the data reduction (i.e., the correct subtraction of the sky background and the nebula component).

Q: What is the slit width?
A: The slit width can be 0.51″, 0.70″, 1.00″, 1.31″, 1.60″, 2.00″ with FORS1 (using the longslit mask) and any value (using the MXU, Mask eXchange Unit) with FORS2. Because of the simultaneously high time and spectral resolution we need a good seeing for phase resolved spectroscopy. Therefore we usually use the small slit widths which are better adapted to the actual seeing conditions.

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