Introduction to MIOSOTYS: a multiple-object, high-speed photometer

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ABSTRACT

MIOSOTYS is a multiple-object, high-speed photometer. It is currently operating on the 1.93m telescope at Observatoire de Haute-Provence (OHP), France. The instrument consists of a multi-fibre positioner which can access maximum 29 targets simultaneously, and an EMCCD camera which is capable of recording low-level light at high frame rate. This paper will describes the instrument's specifications as well as the performance, i.e., signal-to-noise ratio, under the current configuration (ProEM CCD + 1.93m telescope).

Keywords: Instrumentation, MIOSOTYS, Time resolution, Imaging, Photometry

1. INTRODUCTION

MIOSOTYS is based on MEFOS (Meudon ESO Fibre Optical System) which is a multiple-fibre positioner and was first designed for multi-objects spectroscopy, and was mounted on the 3.6-m ESO telescope at La Silla, Chile in the 90'. It remains in excellent shape and, recently, has been re-commisioned by LESIA, Paris Observatory to conduct high time resolution photometry. The instrument now consists of a multi-objects fibre system and a high speed EMCCD camera. It has be implemented at the cassegrain focus of the 193 cm telescope at the Observatoire de Haute-Provence (OHP), France*. The fibre positioner moves 29 arms to the targets within a field of view of **25?** arc-minute. Each arm is equipped with an individual viewing system for accurate setting and carries one individual fibre that intercept **12?**" arc-sec on the sky. All the 29 fibre images are projected onto a EMCCD camera for fast photometry acquisition. Thus, the instrument will provide the observational abilities for various astronomical researches, such as surveying the small objects in Kuiper Belt, fast variability in compact binaries, young stellar objects in star formation, etc.

Three technical observations have been carried in November 2008, March and April 2009 at OHP. We have test the newly designed mechanical interface, calibrated the instrument in this configuration with the existing guiding system and bonette, and investigated the observation ability for future science operations. The science observations begin in February 2010 with a dedicated high speed EMCCD camera which replaces the moderate one used for technical evaluation. In this paper, we discuss the instrument's properties and performance measured in laboratory as well as in actual observation. This is to provide potential observers with a practical guideline to plan their observation strategies.

2. INSTRUMENT

The instrument consists of three parts: 30 fibre positioning arms fixed on a platform, an Acquisition and Guiding Image System (AGIS) above the arm platform, and a CCD camera.

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[*] http://www.obs-hp.fr/guide/t193.shtml

2.1 Arms and fibres

There are 30 positioning arms arranged in a circle of **200?** mm diameter of at the edge of the field. One of the arm (#1) is used solely for guiding system, and rest of 29 arms are for observing targets. Each arm sweeps a triangular zone by 2 motions: translation by 130mm and rotation by ± 7 degree. The image fibre is fixed on the arm tip which is electrically insulated. The image fibre is a glass fibre bundle of 900mm long, the diameter of the elementary fibre is 18μm. Its transmission efficiency is about 40-45%. The viewing surface is 1.9×1.9mm. The output end of the 29 image fibres are projected on to a CCD camera through the optics of AGIS with a reduction factor.

2.2 EMCCD camera

We chose the ProEM^{TM} camera manufactured by Princeton Instruments[†] as the imaging sensor for the instrument. The sensor of e2v CCD201B is a back-illuminated, frame-transfer EMCCD with 1024×1024 image pixels (or active area 13.3×13.3 mm). The large image area can cover all of 29 fibre images. The peak Q.E. at 530 nm is 95%. The air cooling system maintains the operating temperature at -55°C or lower. At the temperature the typical dark current is $\lesssim$ 0.008 electron/pixel/second. The readout noise then depends on the readout modes: electron-multiplying (*EM*) or low-noise (*LN*).

The EMCCD has dual readout amplifiers (or *ports*, see figure 1), one is a traditional series register for LN mode. The other, for EM mode, is an extended multiplication register which provide 1 to 1000 times multiplication which can be controlled in linear, absolute step. The dual ports design means that the camera can be optimised to perform different type of observations. For example, EM mode is suitable for low-light, high speed conditions, and LN mode is for more conventional observation (i.e., long exposure). The readout noise in EM mode is significant greater (50 electron rms at readout rate 10 MHz), but is effectively reduced to $\lesssim$ 1 electron rms when multiplication gain is sufficiently applied (see section 3.2).

3. INSTRUMENT CHARACTERISTICS

The CCD camera's ability largely decides the performance of MIOSOTYS. This section describes some important characteristics of the ProEM CCD camera, such as timing properties, and signal-to-noise ratio. Other components of the instrument and the telescope (O.H.P. 1.93 m) also play roles here.

3.1 Effective exposure time

Effective exposure time is restricted by CCD's transferring and readout processes from imaging sensor to ADC register output. By default, the ProEM camera operates at the "Frame Transfer" mode. Initially, the exposed sensor receives incoming photons within a pre-programmed time (T_p). Once the exposure is finished, all the electrons are shifted to an identical, but masked sensor (see figure 1). It takes certain amount of time (readout time, T_r) for electrons in the masked sensor to be transferred through a readout register. During the transferring, the emptied exposed sensor can immediately receive new photons. Thus it is very useful in applications which require continuous imaging (100% duty cycle).

If $T_p < T_r$, however, one should be aware of that the exposed sensor has to wait for the electrons in the masked sensor to completely be read out. While in waiting, the exposed sensor still remains open to the source. Consequently, the actual exposure time (T_e) is effectively equal to T_r. For example, the T_r of a full 1024×1024 pixels image at readout rate of 10 MHz is ≈100 ms, thus one can have time resolution which is at least equal to or longer than T_r.

[†] http://www.princetoninstruments.com/

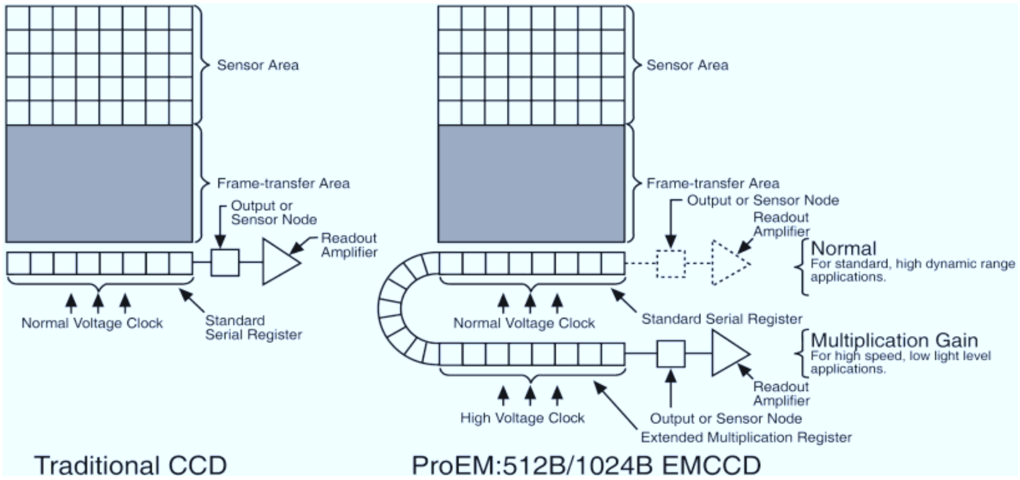

Figure 1. Comparison of traditional CCD and ProEM EMCCD array structures. Credit: Princeton Instruments

Fortunately, ProEM camera provides observers several methods to reduce T_r. One is to define sensor's region of interest (R.O.I.). The pixels outside the selected regions will be skipped during the readout process, thus reducing T_r. In MIOSOTYS' general operating mode, its 29 fibres are arranged into a 6 by 6 square matrix, and the size of each fibre image projected on the CCD is $\sim$80 × 80 pixels (see figure 2). As a result, only an area of 480 × 480 pixels are read out instead of 1024 × 1024 pixels. Consequently, T_r at the same readout rate is reduced to $\lesssim$ 60 ms. Second is to bin the pixels, i.e. 2×2, during the readout process, thus T_r can further be reduced. To achieve finer time resolution, one can combine fewer R.O.I. and/or binning configurations, as long as the data quality is acceptable.

3.2 Signal-to-noise ratio

The signal-to-noise ratio (S/N) of a CCD is given by the well-known "CCD equation" which has the form[1]

$$S/N = \frac{N_*}{\sqrt{N_* + n_{pix}(N_s + N_d + N_r^2)}}, \tag{1}$$

where N_* is the total (sky subtracted) number of photons from the source; n_{pix} is the number of pixels contained within the software aperture; N_s is the number of sky photons per pixel; N_d is the dark current in electrons per pixel per second; and N_r is the readout noise in electrons per pixel. In case the background and instrument noises are low enough compared with N_*, the S/N will approximately equal to $\sqrt{N_*}$.

However, in the situation of high time resolution photometry, the level of incoming photons from source may be comparable to that of the instrument noises, so that the S/N deteriorates. The dark current, with sufficient cooling and very short exposure time, is low enough to be ignored, therefore the readout noise becomes the dominant noise factor term. Ever worse, the readout noise increases dramatically when readout rate goes faster.

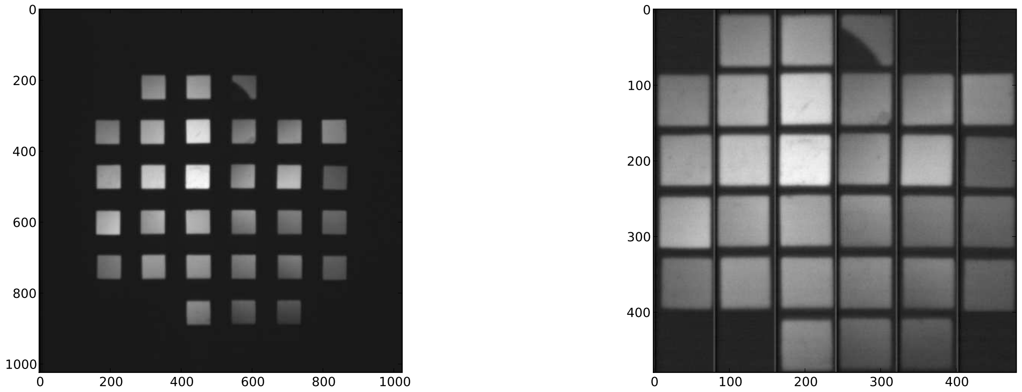

Figure 2. (Left) Image of all 29 fibres projected on the CCD sensor (1,024×1,024 pixels). (Right) Output of R.O.I., in which the active size reduces to 480×480 pixels. The vertical lines are artificially added by data acquisition software, and can be removed after bias correction.

3.2.1 Electron-multiplying technique

To amplify the signal (photoelectrons) from instrument background, the camera uses electron-multiplying gain technology. The multiplication takes place in the extended multiplication register through a process called impact ionisation. The process is to amplify the electrons before they reach the output amplifier and subsequent electronics. This will effectively boost the signal above the readout noise of the system. The process can take as many as stages which corresponds to one pixel in the register. The probability of multiplication per stage is p, and the total effective gain, G, is related to the number of stages, N. This gain factor is then given by

$$G = (1 + p)^N, \tag{2}$$

The probability of multiplication in each stage is actually small, in the range of 1% to 1.5%; however, by passing through large number of stages, the total multiplication gain can be quite high. Reading image out through the multiplication register introduces an additional noise term called excess noise factor (F), thereby the S/N of an EMCCD is given by

$$S/N = \frac{N_*}{\sqrt{(N_* \times F^2) + n_{pix}((N_s \times F^2) + (N_d \times F^2) + (N_r/G)^2)}}, \tag{3}$$

where F is $\sim$1.4.

Applying appropriate amount of EM gain (G) effectively reduces the readout noise to below $\sim$1 electron. However, the excess noise factor due to multiplication process also consequently reduces the S/N by the factor. As a result, the advantage of EMCCD becomes apparently only whenever it is operated in high-speed, low-light situations. Because the number of incoming photons per frame is low, the penalty of F is not so significant (see figure 3).

3.3 Transmission efficiency

Fibre images are projected onto the CCD sensor through a lens component (within AGIS), and it is realised that the transmission efficiency varies depending on the light passing through different part of the lens: images at centre have better transmission than that at the edge. To quantify the transmission efficiency, we measured all 29 fibres individually using the same, stable light source. Table 1 lists the relative transmission efficiency

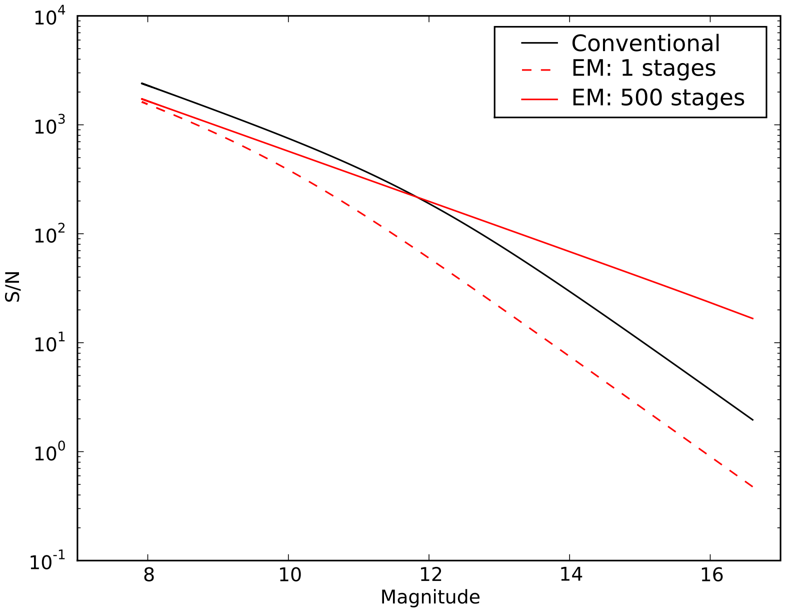

Figure 3. Simulation of CCD S/N relating to conventional and EM gain modes. `Conventional` (black solid line): traditional readout register. In ProEM camera, its fastest readout rate (5 MHz) is lower than that in EM gain register (10 MHz), so that the S/N is higher. `EM: 1 stage` (red dashed line): the readout goes through EM register, but no gain is applied, thereby readout noise is not suppressed, and its S/N is even worse. `EM: 500 stages` (red solid line): 500 stage gain is applied in the register. The S/N begins to improve as source becomes fainter. The magnitude scale is derived from the observation took place in March 2009.

compared to the fibre 28, and figure 4 shows the geometric distribution of the transmission efficiency. In cases if it is possible observers are suggested to assign central fibres to fainter targets to achieve reasonable signal-to-noise ratio.

Table 1. Relative transmission efficiency by optical system.

Fibre	eff.	Fibre	eff.	Fibre	eff.	Fibre	eff.	Fibre	eff.
28	1.00	22	0.89	24	0.79	18	0.63	25	0.53
30	0.98	15	0.86	10	0.76	11	0.62	3	0.48
16	0.96	29	0.83	12	0.76	21	0.61	13	0.45
8	0.94	7	0.81	27	0.70	5	0.58	20	0.45
9	0.92	17	0.81	6	0.67	4	0.55	26	0.40
23	0.91	2	0.80	14	0.66	19	0.53		

3.4 O.H.P. 1.93m telescope

The telescope is the host for MIOSOTYS mission. Because the instrument typically operates at time scale of $\lesssim$ 1s, it is clear that the signals from targets with magnitude $\gtrsim$ 12 will be overwhelmed by the readout noise if EM gain is not applied. Based on recent observation, figure 5 shows the improvement on S/N using EM gain of $\sim$500 at time resolution of $\lesssim$0.1s. One can obtain acceptable S/N of $\sim$ several hundreds from targets with magnitudes

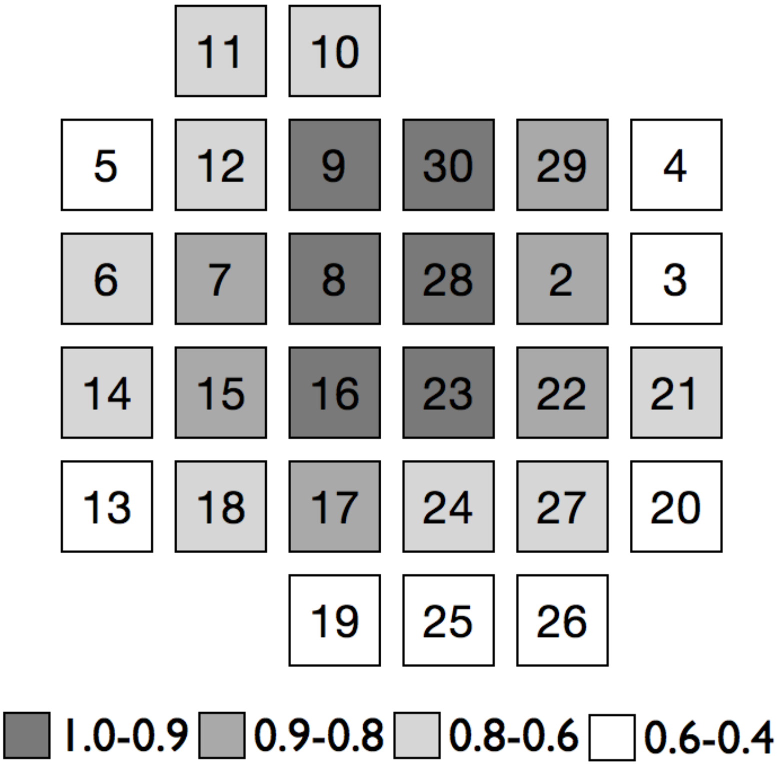

Figure 4. The geometric distribution of transmission efficiency.

between ∼12.0 and ∼14.5. Furthermore, it is worth to notice that increasing EM gain would not improve S/N linearly, the experience suggests that ∼500 is enough for our mission.

As discussed earlier, EM gain is only useful when the received photon is lower than certain level. One has to justify the use of EM gain by considering important parameters, such as time resolution, and target brightness.

4. SUMMARY

We introduced MIOSOTYS, a multi-object, fast photometry instrument based on EMCCD camera. The instrument is mounted on the 1.93m telescope at O.H.P. and maximum 29 targets can be observed simultaneously at time resolution of $\gtrsim$50 ms. The electron-multiplying technology on the camera allows observers to access fainter targets with higher time resolution. It opens a new door for temporal-related astronomical researches, such as searching small Kuiper Belt objects, fast oscillation in compact objects and young stellar objects. We also welcome and invite other observers to use this instrument.

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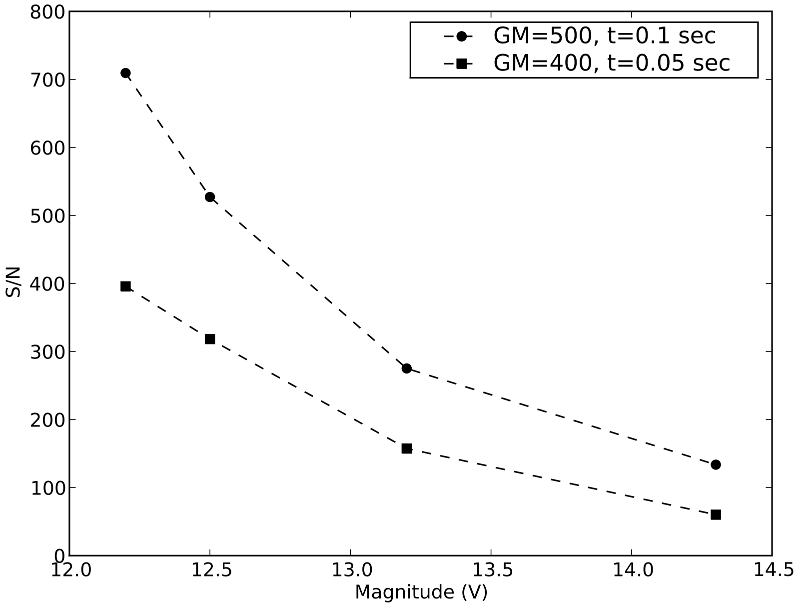

Figure 5. Comparison of S/N to different configurations of EM gain and exposure time. The results were derived from the same group of stars and the same fibres were used. The magnitudes are quoted from the NOMAD catalogue. Observation date: (circle) 01 March 2010; (square) 28 February 2010

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