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High-speed multicolour photometry with CMOS cameras

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We present the results of testing the commercial digital camera Nikon D90 with a CMOS sensor for high-speed photometry with a small telescope Celestron 11″ at the Peak Terskol Observatory. CMOS sensor allows to perform photometry in 3 filters simultaneously that gives a great advantage compared with monochrome CCD detectors. The Bayer BGR colour system of CMOS sensors is close to the Johnson BVR system. The results of testing show that one can carry out photometric measurements with CMOS cameras for stars with the V-magnitude up to $\simeq 14^m$ with the precision of 0.01^m. Stars with the V-magnitude up to ∼10 can be shot at 24 frames per second in the video mode.

Key words: instrumentation: detectors, methods: observational, techniques: image, processing techniques: photometric, stars:imaging

INTRODUCTION

Synchronous multicolour observations are important for different astrophysical challenges, e. g., for study of transit of extrasolar planets, afterglows of gamma-ray bursts, small-scale variations during flares on dwarf stars and cataclysmic variables, and many others. Fast simultaneous photometry in several bands is needed for obtaining spectral information in a short period of time during a transient event. Traditional methods suffer from losing signal due to the serial measurements in different filters. Multicolour sensors based on metal-oxide semiconductors (CMOS) allow to refuse the use of filters in general [1]. In recent years, CMOS sensors have presented a serious competition for CCD. CMOS sensors provide simultaneous imaging of the object in the Bayer colour system: the blue filter "B" ($\lambda >$400 nm), the red "R" ($\lambda <$900 nm) and the intermediate filter "G". Transformation of the Bayer colour system BGR to the international Johnson BVR system is a relatively simple problem. CMOS sensors allow nondestructive reading of digital images. Recently, algorithms that allow to achieve a high dynamic range, to avoid blooming, to correct for tracking errors of the telescope and the variation of atmospheric transparency, were developed [1]. The disadvantage of CMOS sensors is relatively low quantum efficiency. However, it plays a significant role only for observations of extremely faint stars. Commercial CMOS sensors allow us to perform fast high-precision multicolour photometry of relatively bright objects with small telescopes. Using high values of ISO, 6400 and above, up to ISO 25600, provides a great opportunity to capture objects up to V$\sim 10^m$ with a frequency up to 24 frames per second and higher with small telescopes. This allows us to study high-frequency variability in the range of 10 Hz and above.

LIMITING MAGNITUDES

Read noise and thermal noise are the main controlling factors for detecting faint objects. Old CCDs have read noise levels in 15–20, or more electrons. Newer CCDs tend to run in 4 to 3 electron range. As it was mentioned in [2] the technology improvements of CMOS sensors have led recently to the fact that the read noise dropped to about 2.5 electrons (commercially available cameras Canon 5D Mark II, 50D, 7D). It was also mentioned in [2], that Nikon's technology currently restricts the average read noise at zero level, losing some data. Canon includes an offset, so processing by some raw converters can preserve the low end noise, which can be important for averaging of multiple frames to detect very low intensity objects. The dark current of CMOS image sensors is typically of the order of 60–100 electrons/sec at room temperature. In the latest models for professional use (Fairchild Imaging CIS1021) it is ∼26 electrons/sec at 20° C. It should be noted that Canon develops CMOS image sensor independently. Table 1 shows that the value of the dark current of Canon EOS 20D camera at room temperature is less than for cooled Peltier CCDs. It defines the boundary of the photon mode when the signal from a star becomes comparable to the dark current. The boundary of the photon mode can be found from the expression for the illumination of the star image on the matrix, E_m:

$$E_m = C_m T_a T_i S/s \text{ [lux]}, \qquad (1)$$

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Table 1: The parameters of the CCD cameras ALTA U42, FLI PL-1001E, and CMOS Camera EOS 20D.

Camera	Apogee ALTA U42	FLI PL-1001E	Canon EOS 20D [2]
Image format, pixels	2048×2048	1024×1024	3504×2336
Pixel size, microns	13.5	24.0	6.4
Readout noise in electrons	14.9	9	7.5 (ISO 400)
Dark Current, e-/px/s	1 (−20°C)	0.2 (−45°C)	0.2 (+20°C)
Dynamic	16; 12-bit	16-bit	12-bit
Peak QE (550 nm)	∼ 93%	∼ 70%	∼ 50%
Full Well in electrons	100 K	500 K	∼ 50 K

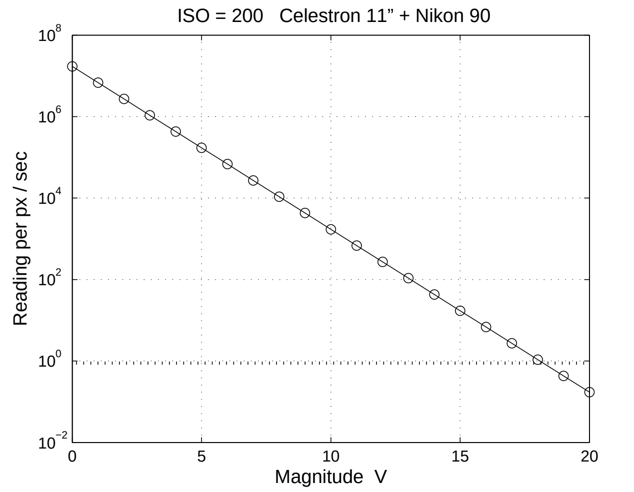

Fig. 1: Dark current-limited boundary is around V= 18^m.

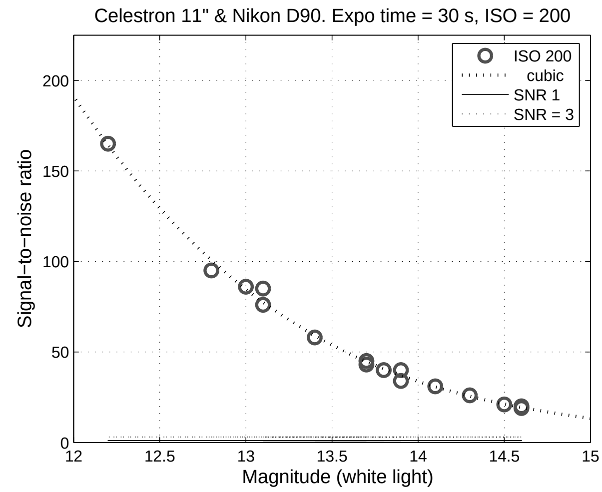

Fig. 2: The S/N ratio vs. B+G+R magnitude. The exposure time is 30 s.

where C_m is the illumination from a star with magnitude m, T_a and T_i are the transmittance of the atmosphere and of the instrument, respectively, S and s are the areas of telescope aperture and stellar image. Illumination of 1 lux creates a flux of $\sim 5 \cdot 10^{11}$ photon cm^{-2} s^{-1}. Hence the expression for the flux through the pixel is equal to

$$F_m = 5 \cdot 10^{11} E_m \, \varepsilon^2 \ [\text{photon s}^{-1}], \qquad (2)$$

where ε is the pixel dimension.

As one can see from Fig. 1 the dark current-limited boundary for the Celestron 11″ telescope equipped with Nikon D90 camera is around of V$\simeq 18^m$.

We analysed some parameters of the professional astronomical sensors and compared them with the professional commercial camera Canon EOS 20D (Table 1).

The processing of the observational data obtained at the Peak Terskol Observatory, confirmed results of our calculations. We can measure the stars up to 14^m with high accuracy, as shown in Fig. 2. We can also observe stars up to 10^m in video mode as it is shown in Fig. 3.

RESULTS AND CONCLUSIONS

Fig. 1 shows the V-magnitude dependence of the flux through pixel calculated for the Celestron 11″ telescope equipped with Nikon D90 camera, ISO=200. As can be seen from this plot, we can measure the stars of V$\approx 18^m$ in the photon mode when the signal from the star becomes comparable to the dark current ∼1 electron/pixel/s.

The processing of the observational data obtained at the Peak Terskol Observatory confirmed our results. We can measure the stars up to 14^m with high accuracy, as it is shown in Fig. 2.

Fig. 3 shows the signal-to-noise ratio of Nikon D90 in serial shooting mode depending on the white light magnitude for the exposure time of 33 ms. One can see that the continuous shooting allows to study rapid variability of bright stars up to 7^m with high photometric precision and of 9^m with acceptable accuracy. It gives a possibility to study the rapid variability of the large number of stars, among which there are many objects, which gave the name to the prototypes of stellar variability.

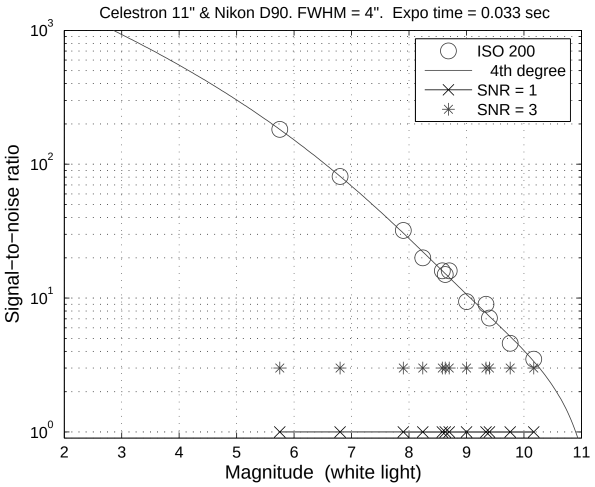

Fig. 3: The S/N ratio vs. B+G+R magnitude. The exposure time is 0.033 s.

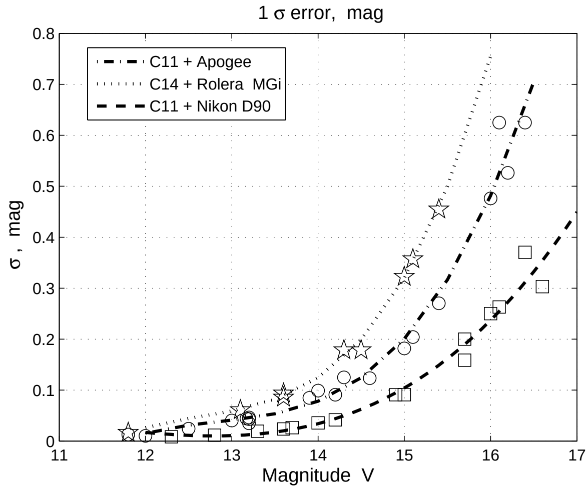

Fig. 4: The photometric errors vs. V magnitude for three cameras: APOGEE (circles), Rolera MGi (stars), and Nikon D90 (squares).

Fig. 4 shows the comparative data obtained with the CCD cameras ALTA U42, Rolera Mgi and CMOS camera Nikon D90 with the telescopes Celestron 11″ and 14″. The exposure time is from 15 to 30 s. The one sigma error is proportional to the inverse value of the S/N ratio. We can conclude from this plot that CMOS Nikon D90 provides more accurate observations.

If we assume that the limiting stellar magnitude corresponds to the signal-to-noise S/N= 3, then these magnitudes in the V band for the 11″ telescope equipped with the cameras Rolera MGi, Apogee ALTA E47 and Nikon D90 are 15.0, 15.5 and 16.5, respectively. Note that the low dark sky background at the Peak Terskol ($\sim 21.5^m$ from square arcsec) enables long-term accumulation of the signal. Hence it is easy to estimate that the limiting magnitude for the Celestron 11″ telescope equipped with the Nikon D90 camera is 19.5^m for one hour exposure time. Thus, the results of our testing reveal that commercial CMOS cameras can create very serious competition for modern CCD cameras in astronomy.

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