High-speed multicolor 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" on Peak Terskol. CMOS sensor allows to perform photometry in 3 filters simultaneously that gives a great advantage compared with monochrome CCD detectors. The Bayer BGR color system of CMOS sensors is close to the Johnson BVR system. The results of testing show that we can measure the stars up to $V \simeq 14$ with the precision of 0.01 mag. Stars up to magnitude $V \sim 10$ can shoot at 24 frames per second in the video mode.

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

INTRODUCTION

Synchronous multicolor observations are important in many cases, for instance, for the study of transit of extrasolar planets, afterglow of gamma-ray burst, small-scale variations during flares on dwarf stars and cataclysmic variables and many others. Fast simultaneous photometry in several bands is especially important to obtain information about the spectra of radiation at short time intervals during transient events. Traditional methods lose a signal due to the serial measurements in different filters. Multicolor sensors based on metal-oxide semiconductors (CMOS) allow to refuse the use of filters in general [1]. In recent years, CMOS sensors have made a serious competition to CCD. CMOS sensors provide simultaneous imaging of the object in the Bayer color system: the blue filter "B", ($\lambda > 400$ nm), the red "R" ($\lambda <900$ nm) and the intermediate filter "G". Transformation of the Bayer color system BGR to the international Johnson BVR system is a relatively simple problem. CMOS sensors allow non-destructive reading of digital images. Currently, algorithms are developed that allow achieve a high dynamic range, to avoid blooming, to correct tracking errors of the telescope, the variation of atmospheric transparency [1]. The disadvantage of CMOS sensors is relatively low quantum efficiency. However, it plays a role only under observations of extremely faint stars. Commercial CMOS sensors allow us to perform fast high-precision multicolor 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 $V \sim 10$ magnitude 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 the 15 to 20 or more electrons. Newer CCDs tend to run in the 4 to 3 electron range. As mentioned by Clark [2], the technology improvements of CMOS sensors have led recently to that read noise dropped to about 2.5 electrons (commercially available cameras Canon 5D Mark II, 50D, 7D). As mentioned by Clark [2], 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 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 $\sim 26$ electrons/sec at $20$ °C. It should be noted that Canon develops CMOS image sensor independently. Table 1 shows that the value of dark current of Canon EOS 20D at room temperature is less than for Peltier cooled 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 $E_m$:

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

where $C_m$ is the illumination from a star of magnitude $m$, $T_a$ and $T_i$ are the transmittance of the atmosphere and of the instrument, $S$ and $s$ are the areas of telescope aperture and stellar image.

Illumination of 1 lux creates a flux of $\sim 5 \cdot 10^{11} \text{ cm}^{-2} \text{ s}^{-1}$. Hence the expression for the flux through the pixel is equal to

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

where $\varepsilon$ is the pixel dimension.

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

We analyzed 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 observatory Peak Terskol, confirmed results of our calculations. We can measure the stars up to 14 mag with high accuracy, as shown in Fig. 2. We can also observe stars up to 10 mag in video mode as shown in Fig. 3.

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

| Camera          | Apogee ALTA U42 | FLI PL-1001E | Canon EOS 20D |
|-----------------|-----------------|---------------|---------------|
| Image format, pixels | 2048 x 2048    | 1024 x 1024   | 3504 x 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/sec | 1 (-20°C)       | 0.2 (-45°C)   | 0.2 (+20°C)   |
| Dynamic         | 16; 12-bit      | 16-bit        | 12-bit        |
| Peak QE (550 nm) | $\sim 93\%$    | $\sim 70\%$  | $\sim 50\%$  |
| Full Well in electrons | 100K            | 500K          | $\sim 50K$    |

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

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

RESULTS AND CONCLUSIONS

Fig. 1 shows a graph of the flux through pixel depending on the magnitude $V$ calculated for the Celestron 11" telescope equipped with Nikon D90 camera, ISO = 200. As can be seen from the graph, we can measure...
the stars of $V \approx 18$ in the photon mode when the signal from the star becomes comparable to the dark current $\sim 1$ electron/pixel/sec.

The processing of the observational data obtained at the observatory Peak Terskol, confirmed results of our calculations. We can measure the stars up to 14 mag with high accuracy, as 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 us to study rapid variability of bright stars up to 7 mag with high photometric precision and of 9 mag with acceptable accuracy. This opens the way 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. 4 shows the comparative data obtained with the CCD cameras ALTAU42, Rolera MGi and CMOS camera Nikon D90 with the telescopes Celestron 11" and 14". The exposure time is from 15 to 30 sec. The one sigma error is proportional to the inverse value of the S/N ratio. We can conclude from this graph that CMOS Nikon D90 provides more accurate observations.

If we assume that the limiting stellar magnitude corresponds to the signal-to-noise ratio equal to three, 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 on Peak Terskol ($\sim 21.5$ mag from square arc sec) enables long-term accumulation of the signal. From this it is easy to estimate that the limiting magnitude for the telescope Celestron 11" equipped with Nikon D90 camera will be 19.5 magnitudes for one hour exposure time. Thus, the testing results reveal that commercial CMOS cameras can create very serious competition with modern CCD cameras in astronomy.

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