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Large-format photodetecting system pCam6060 with a GSENSE6060BSI CMOS detector, developed at SAO RAS and optimized for photometric methods

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Abstract. The pCam6060 photodetecting system has been developed at SAO RAS based on the GSENSE6060BSI photodetector manufactured by GPixel (China) with a frame format of 6144×6144 active pixels and a pixel size of 10 µm. The readout speed reaches 11 fps. The back-illuminated detector has a wide spectral range of 200–1040 nm with a minimum quantum efficiency (QE) of 10% and a maximum sensitivity of 95% at 580 nm. The quantum efficiency in the near-infrared range is 58% at 850 nm. The pCam6060 system controller implements a mode of simultaneous image readout via two 12-bit video channels with different gain and their subsequent combination in the controller into a single frame with an extended 16-bit dynamic range. This method achieves simultaneously a low readout noise level (about 3 e^-) in the high-gain channel and a large dynamic range (full well capacity of about 100 000 e^-) in the low-gain channel. Back-illuminated CMOS detectors, unlike front-illuminated devices, are not susceptible to the long-term preservation of the residual charge from previous exposures, which makes them suitable for recording faint objects in photometric long-exposure observing methods. Communication between the host computer and the camera is carried out via a fiber optic line at distances of up to 50 m. Video data are recorded on the computer hard drive in real-time. The pCam6060 photodetecting system is designed for astronomical applications and has a moisture-proof design.

Keywords: instrumentation: detectors; methods: statistical

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1 Introduction

CMOS photodetector technologies and cameras based on these technologies have long been proven in the field of astronomy (Stefanov 2022; Vlasyuk et al. 2024). Modern CMOS detectors have key parameters (noise, dark current) equal in values to CCDs, but their frame rate is ten times higher. Photometric studies in astronomy place increased demands on the characteristics of photodetecting systems such as image registration accuracy and sensitivity, low readout noise, and high coordinate and temporal accuracy. The use of large-format high-speed CMOS photodetectors with backside illumination (BSI) significantly increases camera sensitivity, both by reducing light losses in the detector itself and by expanding the spectral range in the red region of the spectrum, which enables meeting most of these requirements (Shen et al. 2022; Rogowska et al. 2019).

In this paper, we present an implementation of pCam6060: a photodetecting system based on a large-format GSENSE6060BSI scientific-class back-illuminated (BSI) photodetector manufactured by GPixel (China) with a format of 6144×6144 ten-micron pixels. The development, manufacturing, and laboratory tests of the camera prototype were carried out at the Special Astrophysical Observatory of the Russian Academy of Sciences (SAO RAS). We present the laboratory measurements of the camera photometric characteristics and describe the image correction methods used to obtain optimal characteristics in photometric observations.

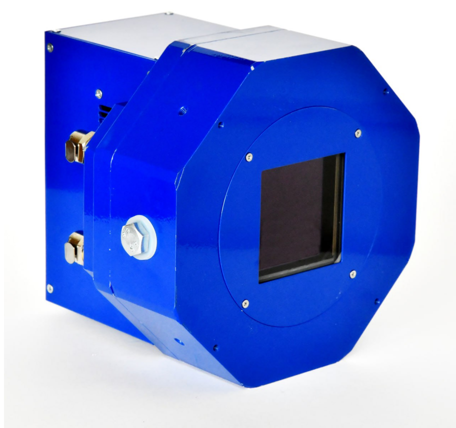
2 Controller architecture and camera design

The principles of building CMOS controllers, methods for controlling high-speed CMOS photodetectors, and software design for photodetecting systems are described in detail in Ardilanov et al. (2021, 2022). The controller architecture, interaction of its nodes, structure, and characteristics of the system are described in Afanasieva et al. (2019); Ardilanov et al. (2020), where the GSENSE4040 photodetector is used.

In distinction to the described implementation, the GSENSE6060BSI photodetector video data are read via 50 digital lines. The pCam6060 controller implements simultaneous image readout via two 12-bit video channels with high (HG) and low (LG) gain outputs. The HDR (High Dynamic Range) operating readout mode allows one to combine two high and low gain frames into one 16-bit frame with a linear light–signal transfer characteristic in real time. In this mode, a low level of readout noise in the high-gain channel and a large dynamic range in the low-gain channel are simultaneously achieved, which allows us to display details of both bright and weak objects. The set of supply voltages was also changed to suit the new photodetector

(Ardilanov et al. 2021). Communication between the host computer and the photodetecting system is organized via a fiber optic line at distances of up to 50 m. The controller has an eight-channel Ethernet interface with a performance of 40 Gbit/s, providing a full-frame readout rate of 11 fps.

The GSENSE6060BSI-based camera and its internal structure are shown in Fig. 1. The camera has an optical head and a housing with electronic components. To reduce heat transfer in the optical head, the photodetector is placed in an inert gas medium. The photodetector is cooled using a set of two-stage Peltier elements, which makes it possible to reach an operating temperature of −60°C lower than the temperature of the external heat exchanger radiator. The radiator design allows air and liquid cooling. The controller's electronics are housed in two moisture-proof housings. On the back of the chamber opposite the optical input, there are connectors for the power supply, external synchronization, and interface cable.



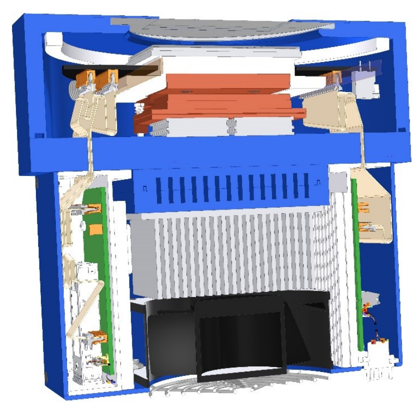


Fig. 1. Exterior view of the pCam6060 photodetecting system (left) and the design scheme of the pCam6060 vacuum chamber internal structure (right).

The camera is attached to the optical equipment via side mounting holes. If necessary, the camera can be equipped with a lens adapter. The small dimensions of the camera (190 × 190 × 170 mm) make it possible to minimize light loss when placing the camera in the input light beam of the telescope.

The control of the GSENSE6060BSI-based camera and data acquisition are performed using a specially developed software package for Windows Server 2012 R2.

The control program allows users to set photodetector modes, control the exposure, view, analyze, and process the received images, and monitor telemetry information.

3 Results of laboratory tests

Laboratory measurements were carried out on a flat-field stand at a detector temperature of −30°C. The photometric characteristics of the pCam6060 system for the three readout modes (LG, HG, HDR) are summarized in Table 1.

Table 1. Photometric characteristics of pCam6060.

	Measured Values			**Datasheet Values**		
Parameter	LG	HG	HDR	LG	HG	HDR
Gain factor, e^-/ADU	23.8	2.39	1.43	24.2	2.42	–
Readout noise (rms), e^-	23.6	3.47	3.19	22–30	3–4	–
Full well capacity, e^-	93 200	9 300	91 500	83 000–95 000	7 000–9 500	–
Dynamic range, dB	71.9	68.6	89.1	73	70	90
Non-linearity, %	0.63	0.80	0.69	0.5–1.0	0.8–1.0	–
Photoresponse non-uniformity, %	0.5			0.7–1.5		
Gain instability, %	0.064			–		
Image lag, e^-/pixel	3–4			<2		
Dark current, e^-/s/pixel	0.2–0.3			0.04		

The GSENSE6060BSI detector does not have the long-term residual bulk image effect characteristic of FSI detectors (Janesick et al. 2014; Karpov et al. 2020). However, there was small retention: when the detector pixels had been illuminated to saturation in the previous frame, in the next frame after reset a charge of about 3 e^- remained in these pixels.

In photometry methods the stability of the video channel transfer characteristics is important. We revealed a significant dependence of the video channel gain on the detector temperature: 0.32% per degree Celsius. Therefore, to obtain the required accuracy, it is necessary to precisely stabilize the detector temperature. The controller stabilizes the photodetector temperature within ±0.1°C, and the gain instability does not exceed 0.064%.

To reduce the dark current during long exposures, the device has the following modes: lowering the pixel supply voltage and using the low-power output amplifier mode. Both of these modes were implemented in the controller. Nevertheless, the dark current we measured at long exposures remained at a fairly high level: 0.2 e^-/s/pixel at −30°C. The reasons for this are currently investigated. It is possible that this is due to the quality degree of the detector (Grade 2).

The CMOS system with a maximum QE of 95% at 580 nm is more powerful than the GSENSE4040-based system with a maximum QE of 74% at 600 nm (Ardilanov et al. 2020).

4 Methods of image correction

In the raw images obtained with the CMOS detector, there exists geometric noise caused by the interference from the operation of the multiplexer control signals and the heterogeneity of the readout channels. In addition, in the frame for the LG mode we revealed the presence of a significant number of pixels for which the bias value was significantly higher than the average value for the frame.

To reduce the geometric noise, the controller implements a real-time method for subtracting the average bias frame from each read frame (Fig. 2). This made it possible to reduce the readout noise in the corrected frames by 1.8 times in the HG mode and 12 times in the LG mode.

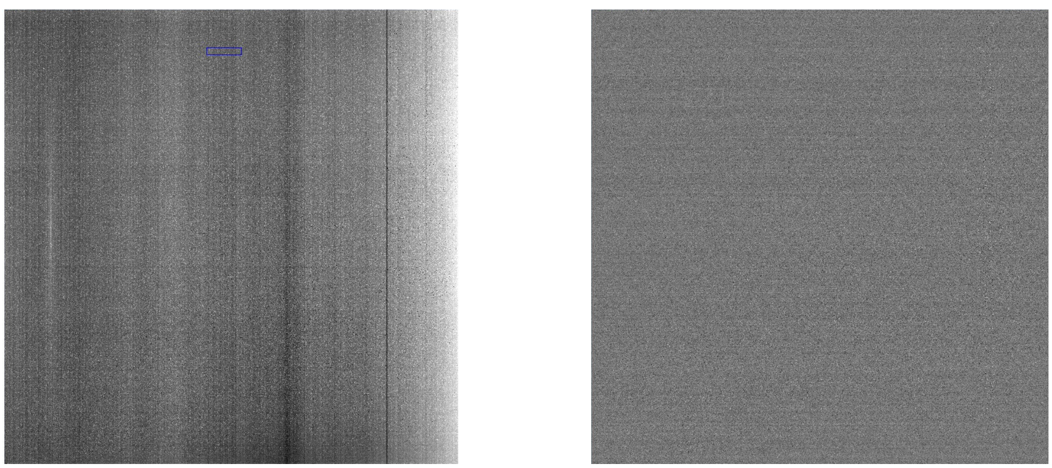


Fig. 2. The original (left) and corrected (right) bias frames in HDR mode.

To couple high and low-gain frames into an HDR frame with a linear light-signal transfer characteristic, multiplicative and additive coefficients are used, which have been previously calculated based on the measured transfer characteristics of the LG and HG channels. The resulting transfer characteristics exhibit no gain (Fig. 3, left) or dispersion shift (Fig. 3, right) in the area of the junction point.

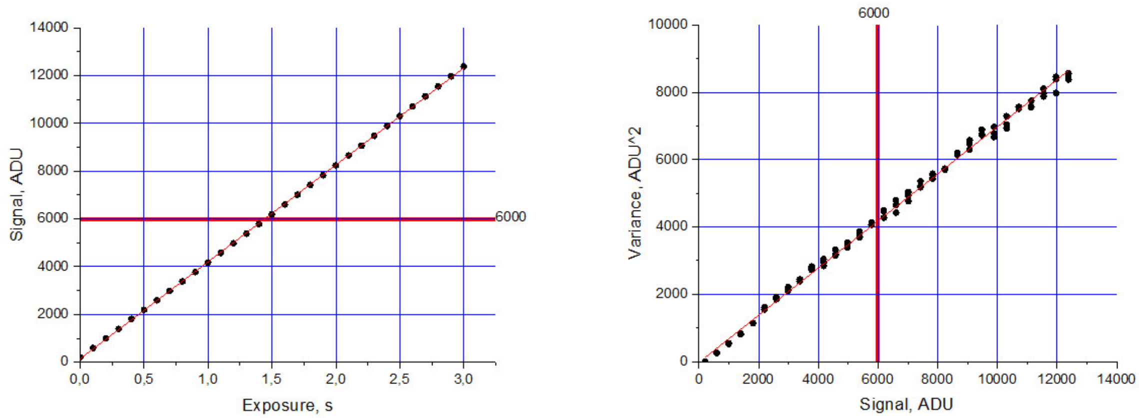


Fig. 3. Gain (left) and dispersion (right) at the junction (red line) of the LG and HG channels.

5 Summary

The developed large-format camera system with a frame rate of 11 fps and low readout noise is undoubtedly excellent for short-exposure observations. For use in long-exposure photometry, the proposed method implements dark-current reduction modes, bias frame subtraction, and video channel gain stabilization. In addition, to achieve the necessary accuracy, it will be necessary to use postprocessing of the obtained images: subtraction of the dark frame, correction of photoresponse nonuniformity in each pixel over a flat field, and correction of nonlinearity.

References

Afanasieva I.V., Murzin V.A., Ardilanov V.I., et al., 2019, Space Debris: Fundamental and Practical Aspects of the Threat, Proc. All-Russian Conf., ed. L.M. Zelenyi, B.M. Shustov, p. 52

Ardilanov V.I., Murzin V.A., Afanasieva I.V., et al., 2020, Ground-Based Astronomy in Russia. XXI century, Proc. All-Russian Conf., ed. I.I. Romanyuk, I.A. Yakunin, A.F. Valeev, D.O. Kudryavtsev, p. 115

Ardilanov V.I., Murzin V.A., Afanasieva I.V., et al., 2021, System synthesis and applied synergetics, Proc. All-Russian Conf., p. 216

Ardilanov V.I., Murzin V.A., Afanasieva I.V., et al., 2022, Astronomy at the epoch of multimessenger studies, Proc. All-Russian Astron. Conf., p. 52

Janesick J., Elliott T., Andrews J., et al., 2014, Proc. SPIE, 9211, id. 921106

Karpov S., Bajat A., Christov A., et al., 2020, Proc. SPIE, 11454, id. 114540G

Rogowska B., Konacki M., Chimicz A., et al., 2019, 20th Advanced Maui Optical and Space Surveillance Technologies Conference (AMOS 2019), p. 75

Shen C., Ma C., Gao W., 2022, Sensors, 22, p. 9991

Stefanov K.D., 2022, CMOS Image Sensors, Bristol: IOP Publishing

Vlasyuk V.V., Afanasieva I.V., Ardilanov V.I., et al., 2024, Physics-Uspekhi, 67, p. 405